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FIBER OPTIC SENSORS II

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FIBER OPTIC SENSORS II

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INTRODUCTION

This conference is the second of the Optical Fiber Sensors series organized by the ANRT and SPIE in Europe. The first was held in Cannes in November 1985.

The aim of the conference was to provide a forum for presentation and discussion of the latest results in research and development in the optical fiber sensors field, related technologies, and their applications. Physical and chemical parameter sensing devices in which the fibers are used as a guiding structure or as a sensing element, special fibers, and other passive components constitute other topics of the conference. Particular attention was devoted to the different applications and to distributed sensors and multisensors systems, as well as to signal processing and detection techniques.

The conference began with an Opening Session and continued with sessions on Distributed Sensors, Measurements of Pressure, Vibration, and Displacement, Temperature Measurement, Signal Processing and Detection Techniques, Chemical Sensors, Applications in Electrical Machinery, and Components and Devices. This proceedings includes papers from the Plenary and Poster sessions.

The large number of papers distributed among the different sessions give a good indication of the high level of interest and of activity dedicated to this particular field of optical fiber application.

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FIBER OPTIC SENSORS II

SPIE Volume 798

Plenary Session

Optical Technology in The Netherlands

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Invited Paper

Signal Processing for Optical Fiber Sensors

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Abstract

Presently there is considerable research interest in the development of all-fiber multi-sensor networks for use in arrays, and applications where a large number of different measurands are of interest (i.e., process control). A number of optical and opto-electronic multiplexing schemes have been developed for use with such networks in recent years. This paper will review this area of OFS technology and discuss some recent development in the multiplexing of interferometric sensors.

Introduction

Recently there has been considerable interest in the multiplexing of fiber optic sensors. This trend has been driven by the realization that the generic sensing technology base fiber optics provides may be used to construct efficient, passive multi-sensor networks. The ability to couple fiber sensor technology and fiber telemetry in applications where the monitoring of a large number of different measurands is required may be a major breakthrough in the acceptance of fiber optic sensors in industry. Application areas include chemical plants, manufacturing plants, ships, offshore drilling platforms, and aircraft.

In this paper the area of signal processing, multiplexing and sensor networks will be considered. Initially, sensor systems coupled to conventional telemetry systems will be described, then specifically the multiplexing of intensity based sensors, and finally the multiplexing of interferometric sensors for higher performance arrays will be discussed in detail.

Hybrid Conventional-Fiber Optic Schemes

During the past few years a number of fiber optic sensors have become commercially available (see Figure 1). Usually these sensors have been in the form of switches, discrete point liquid level gauges, pressure set point, temperature set point, etc. In contrast to the more expensive analog fiber sensors, these items are moderately priced and may be ready to incorporate into systems. These devices have usually been designed to operate with a relatively short fiber cable and, in general, little attention has been paid to the multiplexing of these devices. However, to utilize this presently available sensor base a number of companies have considered the approach shown in Figure 2. Here, the optical outputs of the sensors are converted to an electrical signal which is then suitably formated for transmission along a conventional fiber optic telemetry link. An advantage for this approach is that a number of applications require a local readout of the sensors at the signal conditioning module as well as at the central control point. Disadvantages include expense, reliability as well as the undesirability of having an electro-optic interface in close proximity to the sensor. However, the components for this approach are on the market now.

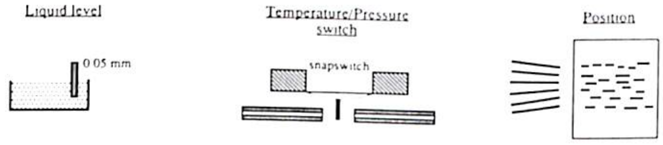

Figure 1. Examples of commercially available fiber optic switches.

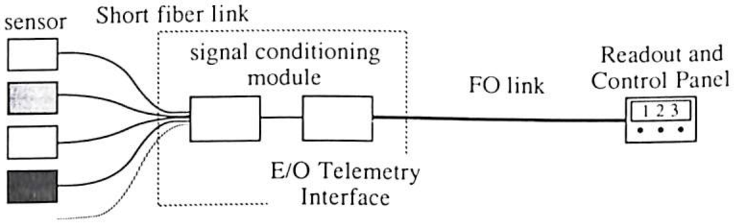

Figure 2. Fiber optic sensor-conventional telemetry system.

Intensity Sensors

In general multiplexing techniques for intensity based sensors[1-3] may be classified as time, wavelength or frequency division; typical configurations of these are shown in Figure 3. For wavelength multiplexing, a broadband source is split into N fibers by a $1 \times N$ coupler, each output traverses a band filter at the sensor to select the wavelength. The various modulated wavelengths then leave the sensing element and are recombined by the power splitter, thus the power bus and the signal bus use a common fiber. Two fiber implementations of this approach may also be used. The example of time division multiplexing shows the modulated source and the sensor network, the fiber lengths contribute a time delay of 2τ between sensors such that the series of modulated pulses emerging from the signal bus carries, in a predetermined time sequence, the information corresponding to each sensor. An example of such a network is that based on the microbend sensor, as proposed by Davis, *et al.*, (see Figure 4). This approach may also be used in a reflective mode providing a single power and signal bus, as employed in optical time domain reflectometry.[4] Major considerations in the approaches concern optical power budget, crosstalk, sensor bandwidth and the number of multiplexed

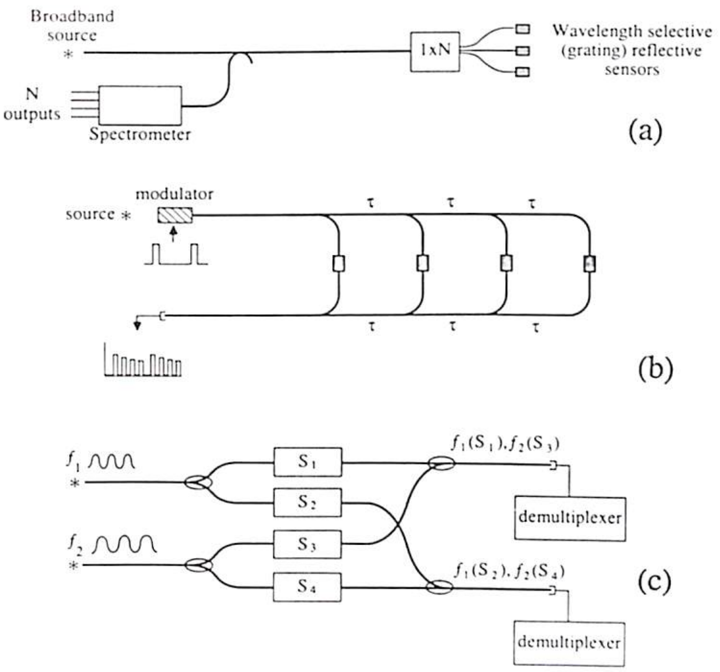

Figure 3. Multiplexing approaches for intensity sensors; (a) wavelength, (b) time, and (c) frequency.

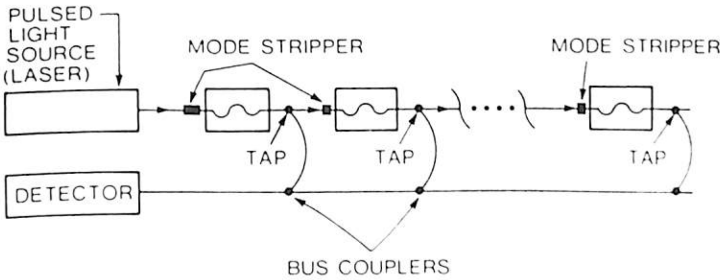

Figure 4. Microbend sensor multiplexed system.

sensors. For networks employing switches obviously many sensors may be multiplexed. There has been little work published on practical multiplexed intensity sensor systems and, therefore, data concerning performance features such as crosstalk levels is sparse. The area of distributed fiber sensing has however received more attention, at least at the concept/experimental level.[4,5] A current review of this area has been made by Kist.[6]

Interferometric Sensors

Although there is much interest in relatively inexpensive low performance sensor arrays, for certain applications there is also interest in higher performance arrays. The generic technology for high performance sensors appears to be the interferometric sensor, hence the recent upsurge in interest in multiplexing interferometric sensors. The remainder of this paper will describe the various approaches, and review the status of this field.

Although the response of the fiber (in terms of phase shift) to a particular measurand may be linear, the resultant output of the interferometer is non-linear and periodic. Consequently, fading of this signal can occur, and much research effort has been devoted to the development of demodulation techniques which solve this problem. Many of the early approaches employing active phase tracking homodyne techniques required piezoelectric fiber stretchers in one arm of the interferometer. Other techniques (heterodyne) required Bragg cells in one arm of the interferometer. Methods which allowed remote operation of single sensors were also investigated. Although these techniques, some of which are still used today, provided high performance laboratory prototypes, they were not suitable for remote operation of arrays of sensors.[7] In the 1982 time frame, the use of passive techniques for demodulation were investigated. These approaches are intrinsically more applicable to array applications and multiplexing. A number of the approaches allow for ''All Optical Interrogation,'' whereby the actual sensing head can be remotely located from the source, detector and electronics. Depending on the application, this distance can vary between a few meters and tens of km.

At this point it is worthwhile pointing out the dual requirements of a multiplexing approach for interferometric sensor arrays; the approach must not only reduce the number of fibers between the passive array of sensors and the electrooptics module (i.e., provide some multiplexing gain) but also allow for the demodulation of the interferometric signals. Initial approaches to multiplexing interferometric sensors did not fulfill both these requirements. The three multiplexing approaches described for use with intensity based sensor are also applicable here; namely, time, frequency and wavelength. Although these approaches allow the various signals from each sensor to the separated at the output, no provision is made for the demodulation of the remote sensors. It is obvious, however, that one can combine the time multiplexing approach with a form of remote interrogation, e.g., the phase generated carrier (PGC) or synthetic heterodyne approach, employing a frequency modulated source and slightly unbalanced interferometer (FMPGC). Thus, time division provides the interrogation and multiplexing, and FM PGC provides the demodulation. Multiplexing of interferometric sensors must therefore be considered a two stage process of demultiplexing (information division) and subsequent demodulation, as shown schematically in Figure 5.

The methods of remote demodulation suitable for use in multiplexing schemes include.

1. Phase Generated Carrier using a Frequency Modulated source (FMPGC) and slightly unbalanced sensing interferometer.

2. Path—Matched Differential Interferometry (PMDI) using matched unbalanced sensor and compensator (receiver) interferometers.

3. Heterodyne detection using an unbalanced sensor and a pulsed frequency modulated source.

In PMDI the demodulation is effected on the compensator interferometer; this allows practically any demodulation scheme, whether passive (FMPGC) or active (PGC, P/Z phase modulator) to be adopted.

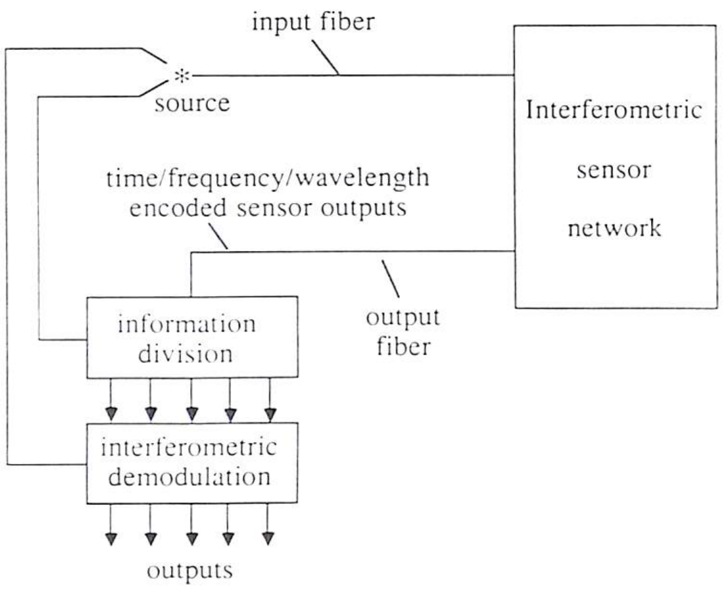

Figure 5. Schematic representation of the two-stage (interogation and demodulation) process involved in the multiplexing of interferometric sensors.

Table I — Interferometric Sensors

Interrogation / Demodulation	Multiplexing
Phase Generated Carrier - FM source,slightly unbalanced interferometer : FMPGC	FM FREQUENCY AM FREQUENCY TIME WAVELENGTH
Path - Matched Differential Interferometry - matched unbalanced sensor and compensator interferometer : PMDI	COHERENCE TIME AM FREQUENCY
Heterodyne Detection using an unbalanced sensor and pulsed FM source : HD	TIME

Although only time, frequency and wavelength division have been mentioned so far, for interferometric sensors a fourth type of multiplexing is available-coherence multiplexing. This technique is based on the fact that an interference signal can only be generated if the mixed light is mutually coherent. The various combinations of interrogation and multiplexing approaches which have been experimentally tested are shown in Table I. This is not meant as an exhaustive description but just an indication of the possible combinations.

Although the general concepts have been around since approximately 1982, it is only recently that demonstrations of multiplexing have been forthcoming. Consequently, a number of experiments which show proof-of-principle have only demonstrated single sensor operation (i.e., the multiplexing of one sensor signal in a format that is expandable). The following sections describe in more detail the principle and reported experimental performance of the various multiplexing techniques. The general attributes that will be considered in characterizing multiplexing performance, will be the number of sensors multiplexed, the noise floor of the multiplexed system in μrad/$\sqrt{}$Hz (at 1 kHz) and finally the crosstalk between sensors.

Coherence Multiplexing

The first paper published concerning the remote interrogation of an interferometer using coherence techniques was by Al-Chalabi, *et al.*[8] Using two interferometers (bulk in this instance) whose optical path differences were greater than the coherence length of the source, these authors showed that by matching the path imbalances, reasonable fringe visibility of the combined interferometer network was regained. The measurements were made with a superluminescent diode (SLD), hence paths have to be balanced to better than ~30 μm. No noise figures were quoted for this system.

The first paper seriously addressing a coherence multiplexed all-fiber system was by Brooks, et al.[9] Their system required matched sensing and receiving interferometers, the latter being near the electrooptic module, with the sensors remotely located. A schematic of their experimental configuration is shown in Figure 6. The technique requires that the path imbalance of each sensor be significantly greater than the coherence length of the source. The phase information of the sensor is recovered by balancing the path differences of the sensing and receiving interferometer. A single-mode laser diode was used as the optical source, which required large (>20m) path imbalances to be used in the sensor and receivers. The combined interferometer can then be demodulated in a conventional manner using a PZT fiber stretcher in the compensating interferometer. Even though each interferometer has a path imbalance longer than the coherence length of the source, the coherence of the laser is still finite at these large path imbalances. This leads to sizable phase induced intensity noise in these coherence multiplexed systems.[10] Early results where one sensor was "multiplexed" led to noise levels of approximately 4000 μrad/$\sqrt{}$Hz.[9] However, by combining coherence multiplexing with high frequency (wavelength) modulation of the laser diode, Kersey and Dandridge[11] showed that the phase induced intensity noise from the unbalanced paths can be upconverted out of the signal band of interest. Interrogation of single sensors using this technique led to interferometer noise of approximately 45 μrad/$\sqrt{}$Hz. An indication of the performance of this technique is shown in Figure 7, where a 40 dB improvement over the conventional coherence multiplexed system was achieved. Further work with this technique[12] demonstrated two multiplexed sensors. The modulation technique showed improved crosstalk (~-15 dB prior to modulation, ~-40 dB after modulation) and distortion performance over the conventional operation of the sensors,

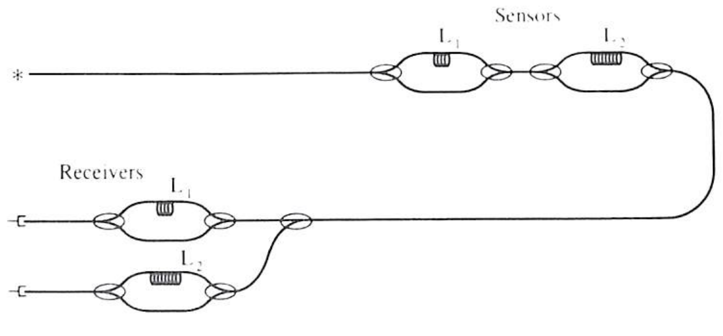

Figure 6. Coherence multiplexed system.

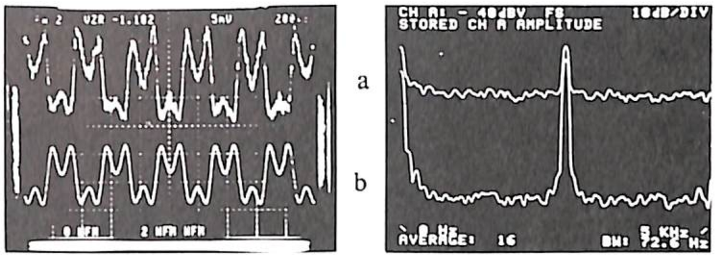

Figure 7. Noise reduction in a coherence multiplexed system by high frequency FM laser modulation: (a) without modulation, (b) with modulation.

however, the noise floor deteriorated to 70 and 100 μrad/√Hz for the two multiplexed sensor system. This represents the current state-of-the-art of coherence multiplexed systems.

Frequency Multiplexing

In fiber interferometric sensing there are two distinct approaches that employ frequency modulation. The first approach uses intensity modulation of the optical source, which is then coupled with a remote demodulation approach such as PMDI. Although components of this approach have been tested at NRL, the noise floor would shown no improvement over the 45 μrad/√Hz demonstrated by the single sensor coherence multiplexed system.[13] The approach has been used on a number of occasions to multiplex and demultiplex two optical signals on a single sensor (both gyro and temperature sensors).[14]

The second approach employing frequency modulation relies not on an intensity modulation of a current-modulated laser diode but on the frequency (FM) or wavelength modulation of the emitted light. Typical laser diode sources have modulation coefficients $d\nu/\mathrm{di}$ in the 1-3 GHz/mA range for frequencies between 100 Hz and 1 MHz (i.e., a 1 mA laser current modulation would lead to ~1-3 GHz frequency excursion). When this light is used as a source for an interferometer an optical phase shift is produced by the frequency shift $d\upsilon$, which is given by

$$\Delta\phi = \frac{2\pi n D}{c}\, d\nu \tag{1}$$

where D is the optical path difference in the interferometer, n is the core effective index, and c is the velocity of light. This effect has been used in a number of demodulation approaches. Two distinct approaches have been employed for multiplexing; a) using a frequency ramped continuous wave technique (FMCW)[15] and b) using sinusoidal FM modulation of the laser output.[16] This second approach is based on that of the phase generated carrier aproach to demodulation and will be referred to as FMPGC.

Initial work on the FMCW technique in 1983 by Giles, *et al.*[17] showed the output of two interferometers in series. However, no attempt was made to fully demultiplex and demodulate the outputs. The raw multiplexed signal outputs of the system were noisy and intermodulation terms between the two interferometers could be observed. Later work by Economou, *et al.*[15] using the FMCW technique gave better results, where single interferometer operation gave approximately 200 μrad/√Hz. It should be noted for single sensor remote operation, the FMCW technique operated as a phase-generated pseudo-heterodyne demodulation technique, with the use of smaller path differences, results in lower noise (see Kersey, *et al*)[15] The most current FMCW multiplexing work by Sakai, *et al.*[18] demonstrated the multiplexing of two sensors (approximately 30 m and 50 m path imbalances) with a noise level of >1000 μrad/√Hz. This work used a PZT fiber phase modulator to provide the frequency modulation of the light rather than direct current modulation of the laser.

The second FM multiplexing approach is based on the phase generated carrier demodulation technique which was first demonstrated in 1982 by Dandridge, *et al.*[16] The diode laser source is modulated by a high frequency sinusoid(typically 20 kHz — 1 MHz) which, in conjunction with a slightly unbalanced interferometer (few cm), provides the FMPGC (see Eq. 1). The array constructed with this type of approach, as shown in Figure 8, is of the form of a matrix. Using this technique the multiplexing and demultiplexing of four interferometric sensors has been demonstrated.[19] The demultiplexing/demodulation was achieved by the standard NRL PGC circuitry originally developed for single sensor systems. The actual test configuration is shown in Figure 9, the frequency spectrum on the signal bus is shown in Figure 10. Test results indicated an approximately 18 μ rad/√Hz noise level for both single sensor and four sensor operation. This noise level corresponds to the phase noise of the laser (note: emission frequency stabilization of the laser has been shown to yield approximately 1-2 μrad performance for single sensors with approximately 3-cm path imbalance). Measurement of crosstalk of the full demodulated system (4 sensors and demodulators) indicated values of approximately −60 dB sensor to sensor crosstalk and approximately -55 dB between the array (3 sensors) and the monitored demodulator output. Measurements of the performance of this approach using electronically generated interferometer signals (no phase noise) gave 2 μrad/√Hz noise level for the four multiplexed sensors and gave similar values of crosstalk, indicating the origin of the crosstalk was in the electronics rather than optics. This four channel system appears to be the state-of-the-art of frequency division multiplexing.

A third approach to frequency multiplexing has been demonstrated by Bucholtz, *et al.*[20] This approach was developed specifically for low frequency applications and implicit in its operation is the use of so called 'nonlinear displacement to strain conversion' (NDSC) sensors.[21] Whereas all the other approaches described in this paper require at least one interferometer per sensor, this approach uses a single interferometer which provides the accurate phase measurement for a number of sensors. The multiplexing of three low frequency sensors (to detect magnetic field, displacement and pressure) on a single interferometer has been demonstrated using this approach, achieving better than 10 μrad/√Hz noise performance and better than -40 dB crosstalk. This configuration employed an electrical input to the nonlinear element in each sensor, however, Kersey *et al.*

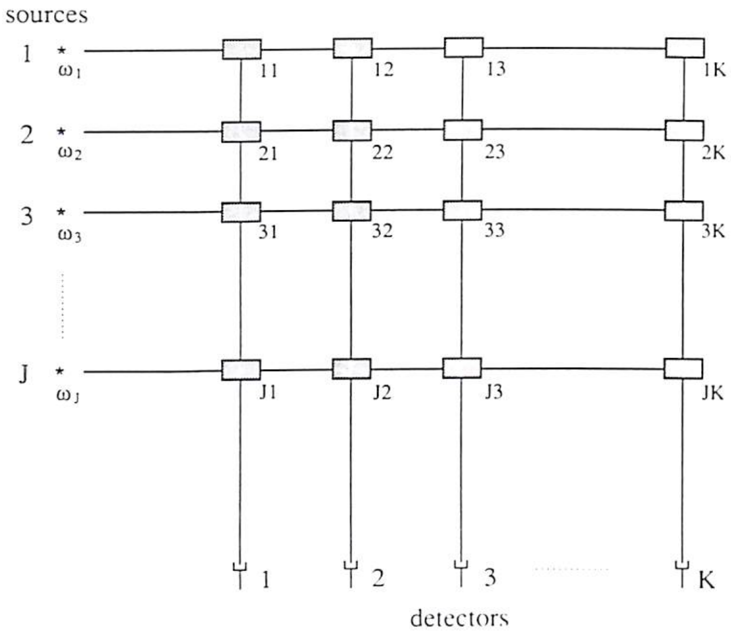

Figure 8. Matrix configuration of a frequency division multiplexed system.

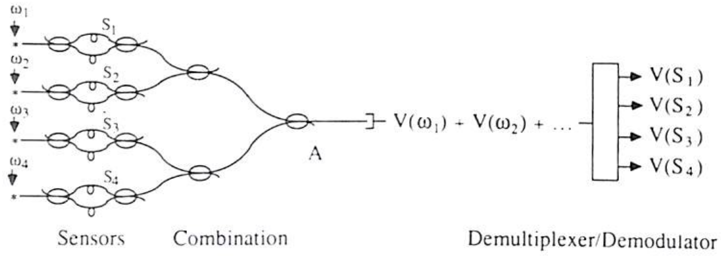

Figure 9. Test configuration for a four sensor frequency multiplexed system.

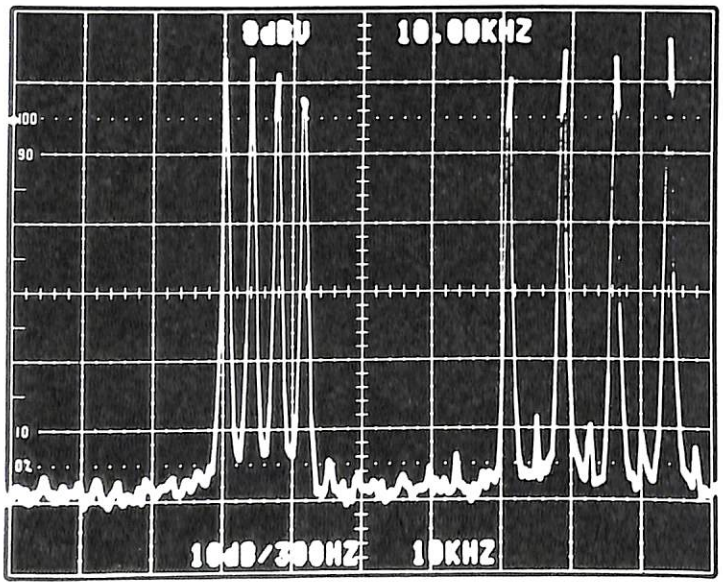

Figure 10. Frequency spectrum of photodiode output obtained with the four sensor FMPGC frequency multiplexed system (Note components at $f_{1,2,3,4}$ and $2f_{1,2,3,4}$).

have demonstrated an all optical version of this approach for a single sensor operation.[21] By careful design of the nonlinear element, a multimode fiber could excite a number of these sensors.

Time Multiplexing

As indicated in Table I, time division multiplexing itself does not provide a direct means of remote demodulation; however, coupled with FMPGC, PMDI or pulsed heterodyning this can be achieved. Experiments at NRL combining time division multiplexing and FMPGC have indicated performance in the 20 μrad range, (three sensor operation).[22] Again the noise was due to the uncompensated laser phase noise. The schematic for this system is basically that in Figure 11, with a 40 kHz carrier applied to the laser and a small path imbalance (4 cm) in each of the sensors. The delay coils between the sensors provided ~250 ns time delay, allowing the input to be pulsed at a maximum repetition rate of ~1.3 MHz (max duty cycle for whole array = 1, each sensor $1/N$). Due to the finite rise and fall times of the input Bragg cell the pulse width was set at ~200 ns. Both optical and electronic gating of the output pulses was investigated as a means of demultiplexing the outputs. The three sensor outputs obtained directly at the photodiode, and in demodulated form are shown in Figure 12.

A more widely reported form of time division multiplexing employs path-matched differential interferometry (PMDI) interrogation. One embodiment of this approach is an extension of the coherence multiplexing described in the relevant section. The initial motivation for this technique was the avoidance of the phase noise terms which produced the 4000 μrad/$\sqrt{\text{Hz}}$[9] of the coherence approach. The method employs optical gating of the source, such that from a single input pulse the output from the unbalanced sensor interferometers consists of two pulses. If the time delay (owing to the different transit times of the two paths) between the two pulses is greater than or equal to the width of the pulse they do not overlap and, therefore, do not interfere. When these pulses pass through the compensation interferometer (of OPD matched to the sensor) and impinge on the photodetector, four pulses, two of which fully overlap, emerge,

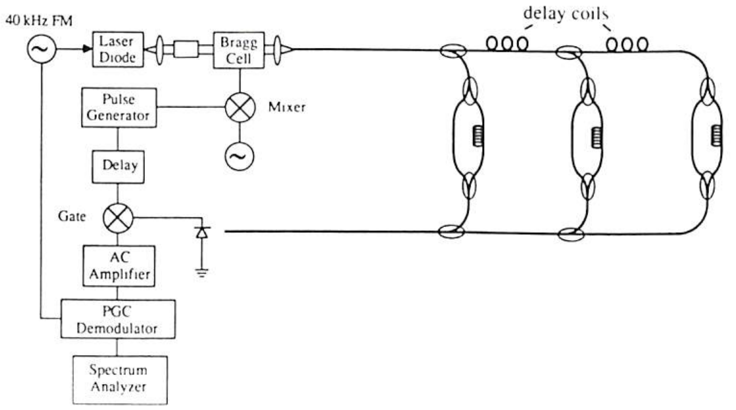

Figure 11. Configuration for a three sensor FMPGC-time-multiplexed system.

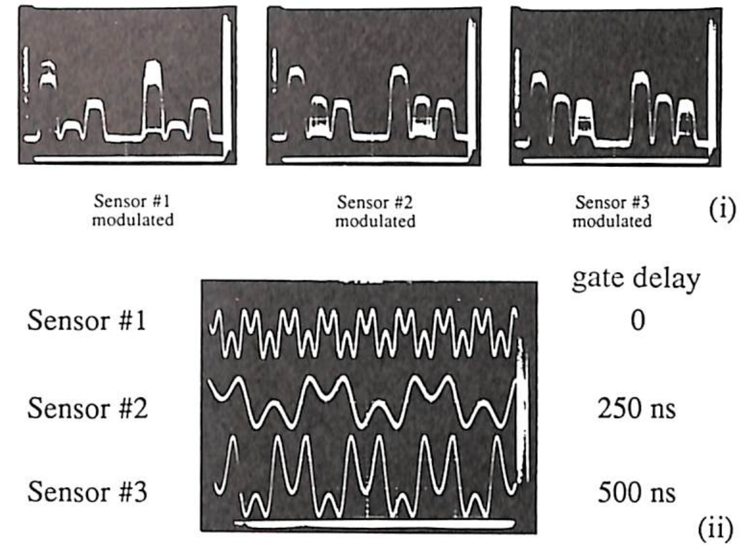

Figure 12. Three sensor FMPGC-time-multiplexed system; (i) output pulses (ii) demodulated sensor outputs (each sensor driven 2π p-p at low frequency; 8 KHz, 2.8 KHz and 4 KHz for S_1, S_2 and S_3, respectively).

firstly the pulse which traversed the two short paths, followed by the two pulses which tranversed the long and the short (and the short and the long). Finally, the pulse corresponding to the two long paths arrives. Consequently, by using appropriate optical or electronic gating at the receiver, the signal pulse can be recovered, while rejecting the non-signal bearing pulses. Work from the Stanford group has demonstrated two element multiplexed operation and by using the NRL PGC approach (Figure 13) has achieved approximately 10 μrad/$\sqrt{}$Hz noise performance.[24] Crosstalk measurements of this approach have been made, and indicate sensor to sensor crosstalk of better than -40 dB.

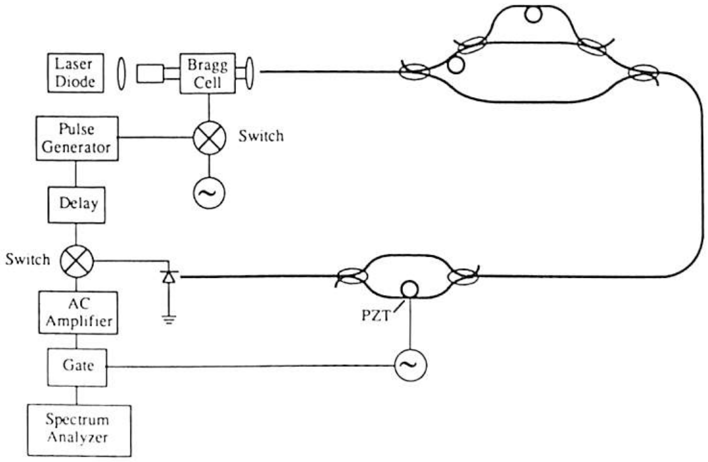

Figure 13. Test configuration for a two sensor PMDI-time-multiplexed system.

Another implementation of the time multiplexing, PMDI interrogation approach uses low reflectance Fabry-Perots[25] as the sensing element rather than the Mach-Zehnder used in the Stanford configuration. The sensor response function does not resemble the high reflectivity Fabry-Perots described by Petuchowski, *et al.*,[26] but resemble the response function of a two beam interferometer—better described as an in-line Michelson as demonstrated by Kersey, *et al.*[27] Unfortunately there has been little experimental work on this configuration, although the noise floors of this approach should be similar to that obtained by the Mach-Zehnder configuration. There have been no measurements of crosstalk of this approach, however, it is obvious that an intrinsic level will exist due to multiple reflections.

The third variant of time multiplexing employs a pulsed heterodyne method for remote interrogation of the sensor.[28,29] This method has been pioneered by Plessey and is similar to the method described above. The basic array configuration is shown in Figure 14. Here a long coherence length gas laser is used as the source, and pairs of optical pulses, generated by applying pulses of RF to the Bragg cell, are launched into one end of the array. The first and second pulses of each pair have slightly different frequencies (ω_1) and (ω_2), respectively. As the launched pulses propagate down the array, a small proportion is reflected back from each partially-reflecting joint, and a series of reflections is received on a photodiode. The delay between the two transmitted pulses is chosen to be equal to the two-way propagation time through each sensing section, so that the reflection of the first pulse from a particular joint is received simultaneously with the reflection of the second pulse from the preceding joint. The two therefore mix on the photodiode and generate a heterodyne signal, the phase of which depends on the difference in optical paths followed by the pulses. As their paths only differ by twice the length of the fiber that separates the two relevant reflecting joints, changes in the length of this 'sensing' fiber modulate the phase of the heterodyne signal. The photodiode output consists of a sequence of short bursts of phase-modulated heterodyne signals, each corresponding to a particular fiber section (sensor) in the array. If the whole cycle is repeated continuously the photodiode output consists of a set of phase-modulated carriers time-division-multiplexed together. The signal from a particular sensor can then be recovered by demultiplexing and phase-demodulating photodiode output.

Plessey has been working on a number of components to enhance the practicality of this scheme, including low-loss partially reflecting joints (transmission losses of approximately 0.5 dB) and the development of fiber components to make an all-fiber approach. They have fabricated a series of

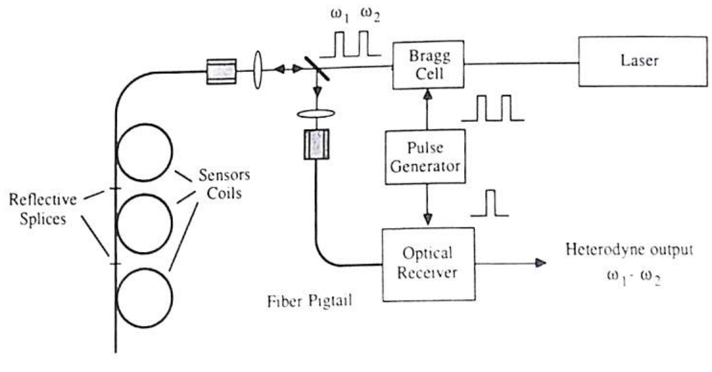

Figure 14. Test configuration for a pulsed heterodyne-time-division multiplexed system.

seven interferometers; however, the number of demodulated channels, noise floors of the sensors and crosstalk measurements, have not been published.

Wavelength Multiplexing

In the area of wavelength multiplexing very little practical work has been demonstrated, although this approach may be used in conjunction with some of the previously mentioned approaches. The reason for the lack of attention in this area is due to the uncertainty of the exact emission wavelength of diode lasers, poor side mode suppression and the consequences of the above to sensor to sensor crosstalk. However, with the advent of DFB lasers, wavelength multiplexing may become more attractive in the future.

Shown in Table II is the current status of the various multiplexing and interrogation approaches.

Table II — Interferometric Sensor Multiplexing

Interrogation / Demodulation	Multiplexing	Sensors	Noise (µrad/√Hz)	Crosstalk (dB)
PMDI	Coherence	1	4000	-
PMDI / FM	Coherence / mod	1	45	-
PMDI / FM	Coherence / mod	2	70/100	-40
FMCW	Frequency	1	200	-
FMCW	Frequency	2	1000	?
FMPGC	Frequency	4	18(2)	-60/-55
NDSC	Frequency	3	10	-40
PMDI	Time	1	40/50	-
PMDI / PGC	Time	2	40(10)	-40
FMPGC	Time	3	20	-55
Pulse Heterodyne	Time	?	?	?

Summary

A number of multiplexing approaches for a variety of optical fiber sensors have been described. The current status of the multiplexing of interferometric sensors has been described in detail.

References

1. A.R. Nelson, D.H. McMahon and R.L. Gravel, "Passive Multiplexing System for Fiber Optic Sensors," *Appl. Opt.*, 19, p. 2917, 1980.
2. B. Culshaw, "Optical Fiber Sensing and Signal Processing," (Peter Peregrinus) 1984.
3. C.M. Davis, T.A. Litovitz and P.B. Macedo, "Dark-Field Microbend-module-fed Fiber Optic Sensor System," *Proc. of the 1st Int'l Conf. on Optical Fiber Sensors*, London, April 1983.
4. A.J. Rogers, "Intrinsic and Extrinsic Distributed Optical Fiber Sensors ," SPIE, Vol. 566 *Proc. Fiber Optic and Laser Sensors III*, p. 234, 1985.
5. D.E.N. Davies, "Signal Processing for Distributed Optical Fiber Sensors," *Proc. 2nd Int. Conf. on Optical Fiber Sensors*, Stuttgart, p. 285, 1984.
6. R. Kist, "Fiber Optic Sensors for Networks," *Proc. of the 4th Int'l Conf. on Optical Fiber Sensors*, Tokyo, Oct. 1986.
7. T.G. Giallorenzi, *et al.* "Optical Fiber Sensor Technology," *IEEE J. Quant. Electron.*, QE-18, p. 626, 1982.
8. S.A. Al-Chalabi, B. Culshaw, and D.E.N. Davis, "Partially Coherent Sources in Interferometric Sensors," *Proc. the 1st Int'l Conf. on Optical Fibre Sensors*, London, April 1983.
9. J.L. Brooks, R.H. Wentworth, R.C. Youngquist, M. Tur, B.Y. Kim and H.J. Shaw, "Coherence Multiplexing of Fiber-Optic Interferometric Sensors," *IEEE J. Lightwave Tech.*, LT-3, p. 1062, 1985.
10. A. Dandridge and A.B. Tveten, Phase Noise of Single Mode Diode Lasers in Interferometer Systems," *Appl. Phys. Lett.*, 39, p. 530, 1981.
11. A.D. Kersey and A. Dandridge, "Phase Noise Reduction in Coherence Multiplexed Interferometric Fiber Sensors," *Electron. Lett.*, 22, p. 61, 1986.
12. A.D. Kersey and A. Dandridge, "Suppression of Excess Baseband Intensity Noise in Coherence Multiplexed Sensors Using Laser Frequency Modulation Techniques," *Proc. of the 4th Int'l Conf. on Optical Fiber Sensors*, Tokyo, Oct. 1986.
13. A.D. Kersey and A. Dandridge, Unpublished work.
14. A.D. Kersey, A. Dandridge and W.K. Burns, "Two Wavelength Gyroscope with Wide Dynamic Range," *Electron. Lett*, 22, p. 935, 1986; A.D. Kersey and A.Dandridge, "Two Wavelength Interferometric Fiber Temperature Sensor" OFC/100C 87, Reno, Jan. 1987.
15. A.D. Kersey, M. Corke, J.D.C. Jones and D.A. Jackson, "Signal Recovery Techniques for Unbalanced Fiber Interferometric Sensors Illuminated by Laser Diodes," 1st Int'l Conf. on Optical Fiber Sensors, London, April 1983, Also: G. Economou, SR. C. Youngquist and D.E.N. Davies, "Limitations and Noise in Interferometric Systems Using Frequency Ramped Single-Mode Diode Lasers," *IEEE J. of Lightwave Technology*, LT-4, p. 1601, 1986.
16. A. Dandridge, A.B. Tveten and T.G. Giallorenzi, "Homodyne Demodulation Schemes for Fiber Optic Sensors Using Phase Generated Carrier," *IEEE J. Quant. Electron*, 18, p. 1647, 1982.
17. I.P. Giles, D. Uttam, B. Culshaw and D.E.N. Davis, "Coherent Optical-Fiber Sensors with Modulated laser Sources," *Electron. Lett.*, 19, p. 14, 1983.
18. I. Saki, G. Parry and R.C. Youngquist, "Frequency Division Multiplexing of Optical Fibre Sensors Using a

Phase/Frequency Modulated Source and Gated Output,'' *Proc. of the 4th Int'l Conf. on Optical Fiber Sensors*, Tokyo, Oct. 1986.

19. A. Dandridge, A.B. Tveten, A.D. Kersey and A.M. Yurek, ''Multiplexing of Interferometric Sensors Using Phase Generated Carrier Techniques,'' IEEE *Journal of Lightwave Technology*, accepted for publication.

20. F. Bucholtz, A.D. Kersey and A. Dandridge, ''Multiplexed Nonlinear Interferometric Fiber Sensors,'' *Proc. of the 4th Int'l Conf. on Optical Fiber Sensors*, Tokyo, Oct. 1986.

21. A.D. Kersey, F. Bucholtz, K. Sinansky and A. Dandridge, ''Interferometric Sensors for DC Measurands—A New Class of Fiber Sensors,'' *SPIE Proc. of the Conf. on Laser and Fiber-Optic Sensors IV*, Cambridge, MA, Sept. 1986.

22. A.D. Kersey and A. Dandridge unpublished work.

23. J.L. Brooks, M. Tur, B.Y. Kim, K.A. Fester and H.J. Shaw, ''Fiber-Optic Interferometric Arrays with Freedom from Source Phase-Induced Noise,'' *Opt. Lett.*, 11, p. 473, 1986.

24. J.L. Brooks, B.Y. Kim, M. Tur and H.J. Shaw, ''Sensitive Fiber-Optic Interferometric Sensor Arrays,'' *SPIE Proc. of the Conf. on Laser and Fiber-Optic Sensors IV*, Cambridge, MA, Sept. 1986.

25. E.L. Green, G.E. Holmberg, J.C. Gremillion and F.C. Allard, ''Remote Passive Phase Sensor,'' *Proc. of the 3rd Int'l Conf. on Optical Fiber Sensors*, San Diego, February 1985.

26. S.J. Petuchowski, T.G. Giallorenzi and S.K. Sheem, ''A Sensitive Fiber-Optic Fabry-Perot Interferometer,'' *IEEE J. Quant. Electron.* QE-17, p. 2168, 1981.

27. A.D. Kersey, D.A. Jackson and M. Corke, ''A Simple Fibre Fabry-Perot Sensor,'' *Optics and Laser in Engineering*, 5, p. 141, 1984.

28. M.L. Henning, S.W. Thornton, R. Carpenter, W.J. Steward, J.P. Dakin and C.A. Ward, ''Optical Fibre Hydrophones with Down Lead Insensitivity,'' *Proc. of the 1st Int'l Conf. on Optical Fibre Sensors*, London, April 1983.

29. J.P. Dakin, C.A. Wade and M.L. Henning, ''Novel Optical Fibre Hydrophone Array Using a Single Laser Source and Detector,'' *Electron. Lett*, 20, p. 53, 1984.

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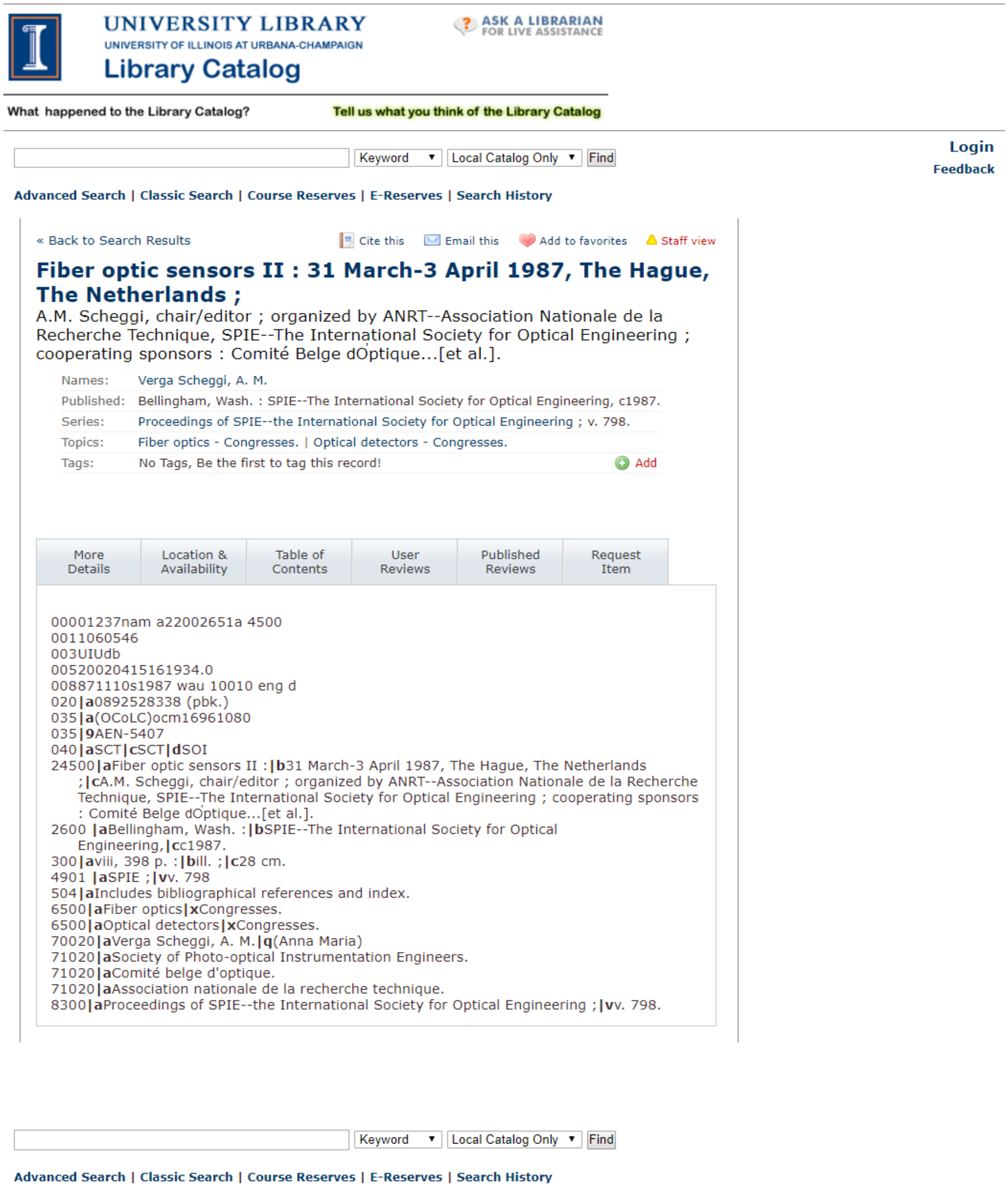

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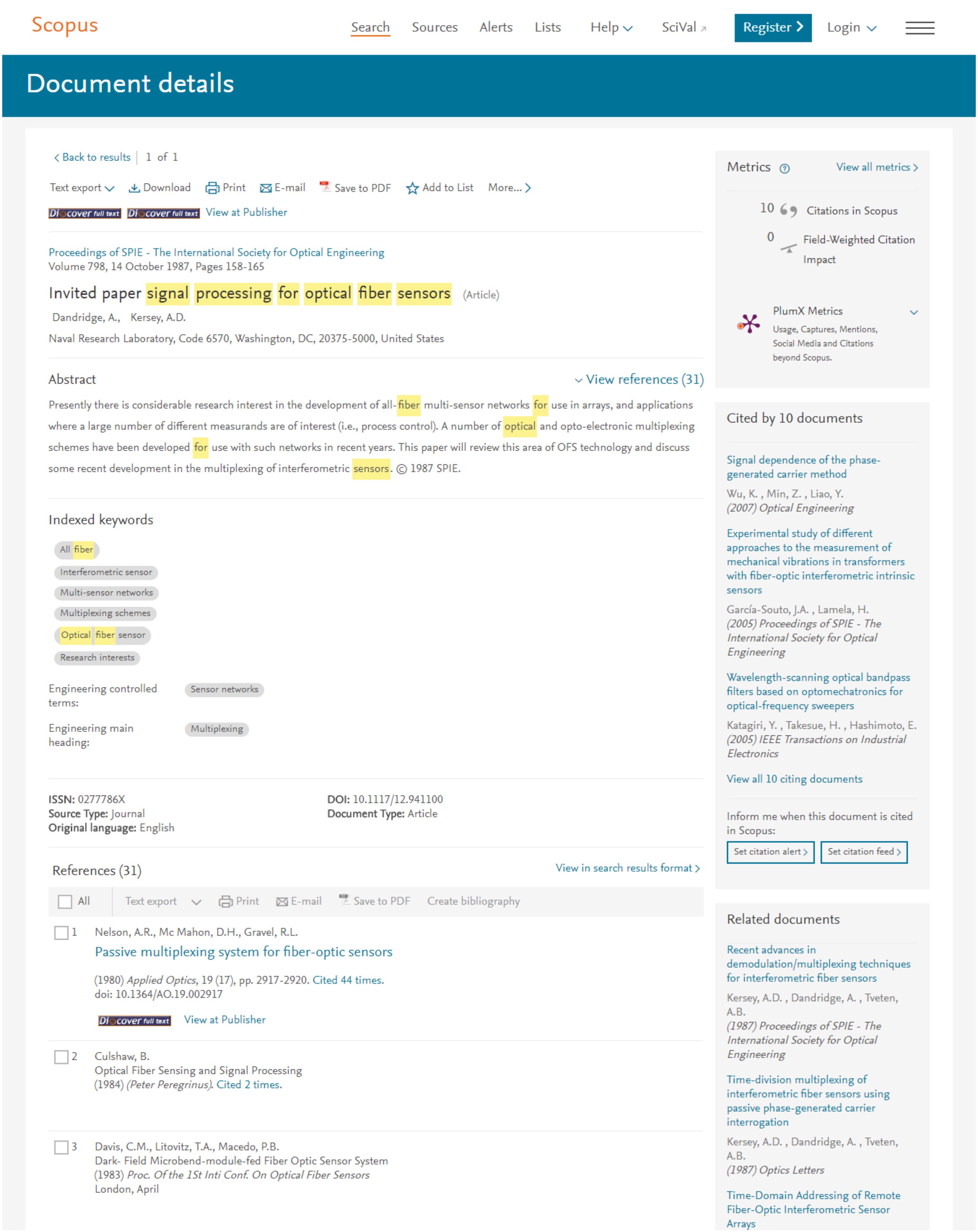

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Dandridge, A., Kersey, A.D.
Naval Research Laboratory, Code 6570, Washington, DC, 20375-5000, United States

Abstract

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Presently there is considerable research interest in the development of all-fiber multi-sensor networks for use in arrays, and applications where a large number of different measurands are of interest (i.e., process control). A number of optical and opto-electronic multiplexing schemes have been developed for use with such networks in recent years. This paper will review this area of OFS technology and discuss some recent development in the multiplexing of interferometric sensors. © 1987 SPIE.

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☐ 1 Nelson, A.R., Mc Mahon, D.H., Gravel, R.L.
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doi: 10.1364/AO.19.002917
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☐ 2 Culshaw, B.
Optical Fiber Sensing and Signal Processing
(1984) *(Peter Peregrinus)*. Cited 2 times.

☐ 3 Davis, C.M., Litovitz, T.A., Macedo, P.B.
Dark- Field Microbend-module-fed Fiber Optic Sensor System
(1983) *Proc. Of the 1St Intl Conf. On Optical Fiber Sensors*
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(2007) Optical Engineering

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García-Souto, J.A. , Lamela, H.
(2005) Proceedings of SPIE - The International Society for Optical Engineering

Wavelength-scanning optical bandpass filters based on optomechatronics for optical-frequency sweepers
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(2005) IEEE Transactions on Industrial Electronics

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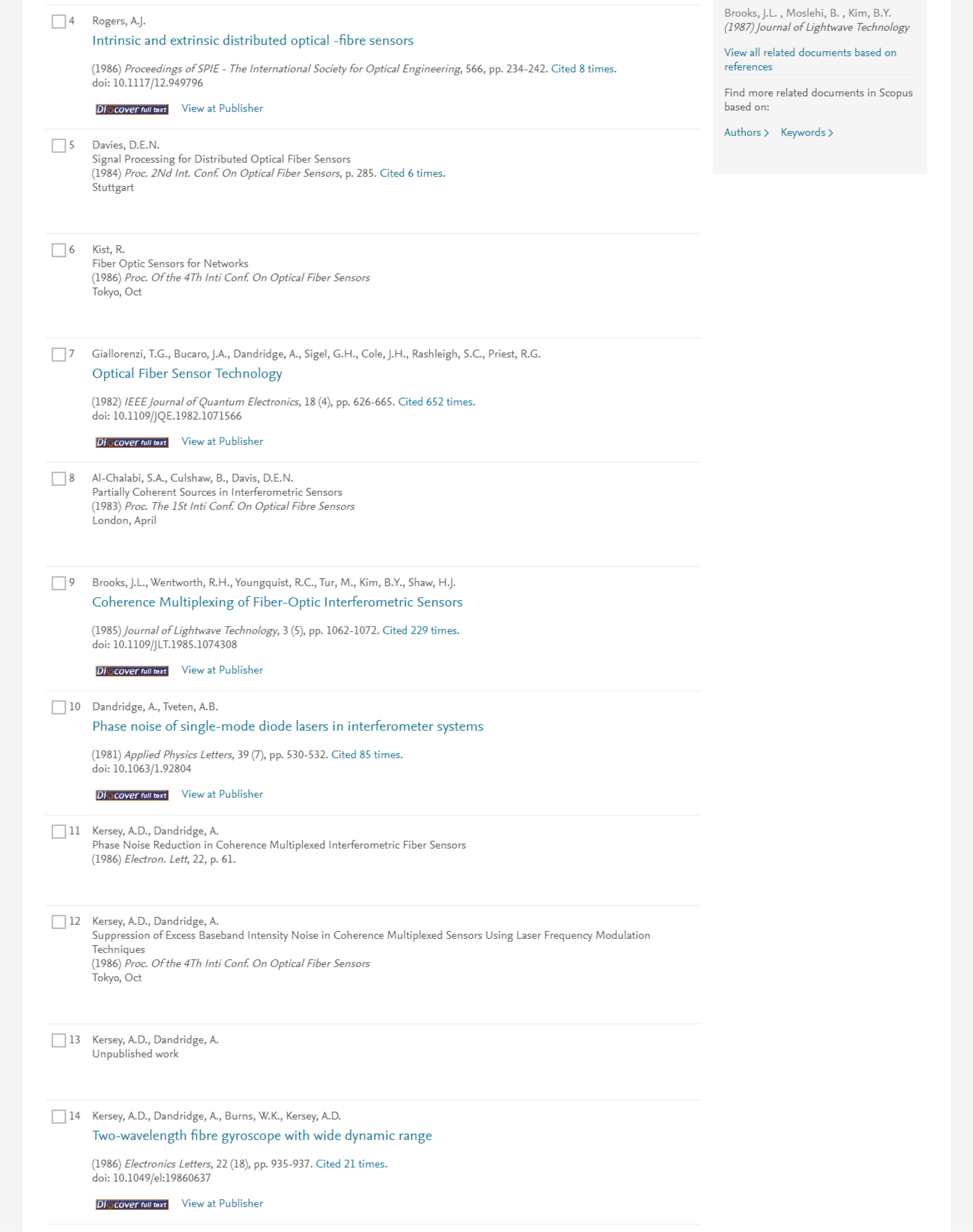
Kersey, A.D. , Dandridge, A. , Tveten, A.B.
(1987) Optics Letters

Time-Domain Addressing of Remote Fiber-Optic Interferometric Sensor Arrays



☐ 4 Rogers, A.J.
Intrinsic and extrinsic distributed optical -fibre sensors

(1986) *Proceedings of SPIE - The International Society for Optical Engineering*, 566, pp. 234-242. Cited 8 times.
doi: 10.1117/12.949796

Discover full text View at Publisher

☐ 5 Davies, D.E.N.
Signal Processing for Distributed Optical Fiber Sensors
(1984) *Proc. 2Nd Int. Conf. On Optical Fiber Sensors*, p. 285. Cited 6 times.
Stuttgart

☐ 6 Kist, R.
Fiber Optic Sensors for Networks
(1986) *Proc. Of the 4Th Inti Conf. On Optical Fiber Sensors*
Tokyo, Oct

☐ 7 Giallorenzi, T.G., Bucaro, J.A., Dandridge, A., Sigel, G.H., Cole, J.H., Rashleigh, S.C., Priest, R.G.
Optical Fiber Sensor Technology

(1982) *IEEE Journal of Quantum Electronics*, 18 (4), pp. 626-665. Cited 652 times.
doi: 10.1109/JQE.1982.1071566

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☐ 8 Al-Chalabi, S.A., Culshaw, B., Davis, D.E.N.
Partially Coherent Sources in Interferometric Sensors
(1983) *Proc. The 1St Inti Conf. On Optical Fibre Sensors*
London, April

☐ 9 Brooks, J.L., Wentworth, R.H., Youngquist, R.C., Tur, M., Kim, B.Y., Shaw, H.J.
Coherence Multiplexing of Fiber-Optic Interferometric Sensors

(1985) *Journal of Lightwave Technology*, 3 (5), pp. 1062-1072. Cited 229 times.
doi: 10.1109/JLT.1985.1074308

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☐ 10 Dandridge, A., Tveten, A.B.
Phase noise of single-mode diode lasers in interferometer systems

(1981) *Applied Physics Letters*, 39 (7), pp. 530-532. Cited 85 times.
doi: 10.1063/1.92804

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☐ 11 Kersey, A.D., Dandridge, A.
Phase Noise Reduction in Coherence Multiplexed Interferometric Fiber Sensors
(1986) *Electron. Lett*, 22, p. 61.

☐ 12 Kersey, A.D., Dandridge, A.
Suppression of Excess Baseband Intensity Noise in Coherence Multiplexed Sensors Using Laser Frequency Modulation Techniques
(1986) *Proc. Of the 4Th Inti Conf. On Optical Fiber Sensors*
Tokyo, Oct

☐ 13 Kersey, A.D., Dandridge, A.
Unpublished work

☐ 14 Kersey, A.D., Dandridge, A., Burns, W.K., Kersey, A.D.
Two-wavelength fibre gyroscope with wide dynamic range

(1986) *Electronics Letters*, 22 (18), pp. 935-937. Cited 21 times.
doi: 10.1049/el:19860637

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(1987) Journal of Lightwave Technology

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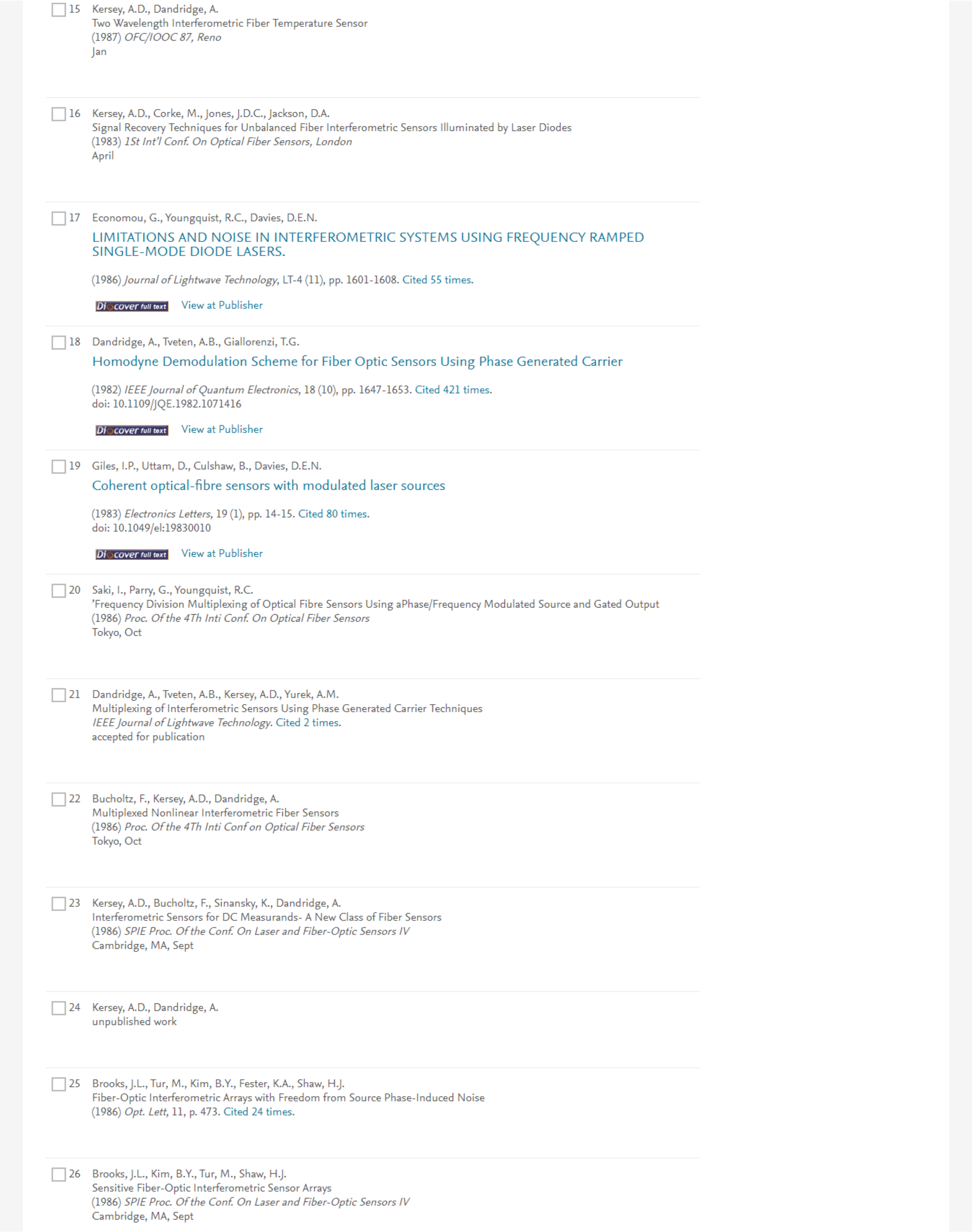

☐ 15 Kersey, A.D., Dandridge, A.
Two Wavelength Interferometric Fiber Temperature Sensor
(1987) *OFC/IOOC 87, Reno*
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☐ 16 Kersey, A.D., Corke, M., Jones, J.D.C., Jackson, D.A.
Signal Recovery Techniques for Unbalanced Fiber Interferometric Sensors Illuminated by Laser Diodes
(1983) *1St Int'l Conf. On Optical Fiber Sensors, London*
April

☐ 17 Economou, G., Youngquist, R.C., Davies, D.E.N.
LIMITATIONS AND NOISE IN INTERFEROMETRIC SYSTEMS USING FREQUENCY RAMPED SINGLE-MODE DIODE LASERS.
(1986) *Journal of Lightwave Technology*, LT-4 (11), pp. 1601-1608. Cited 55 times.
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☐ 18 Dandridge, A., Tveten, A.B., Giallorenzi, T.G.
Homodyne Demodulation Scheme for Fiber Optic Sensors Using Phase Generated Carrier
(1982) *IEEE Journal of Quantum Electronics*, 18 (10), pp. 1647-1653. Cited 421 times.
doi: 10.1109/JQE.1982.1071416
Discover full text View at Publisher

☐ 19 Giles, I.P., Uttam, D., Culshaw, B., Davies, D.E.N.
Coherent optical-fibre sensors with modulated laser sources
(1983) *Electronics Letters*, 19 (1), pp. 14-15. Cited 80 times.
doi: 10.1049/el:19830010
Discover full text View at Publisher

☐ 20 Saki, I., Parry, G., Youngquist, R.C.
'Frequency Division Multiplexing of Optical Fibre Sensors Using aPhase/Frequency Modulated Source and Gated Output
(1986) *Proc. Of the 4Th Inti Conf. On Optical Fiber Sensors*
Tokyo, Oct

☐ 21 Dandridge, A., Tveten, A.B., Kersey, A.D., Yurek, A.M.
Multiplexing of Interferometric Sensors Using Phase Generated Carrier Techniques
IEEE Journal of Lightwave Technology. Cited 2 times.
accepted for publication

☐ 22 Bucholtz, F., Kersey, A.D., Dandridge, A.
Multiplexed Nonlinear Interferometric Fiber Sensors
(1986) *Proc. Of the 4Th Inti Conf on Optical Fiber Sensors*
Tokyo, Oct

☐ 23 Kersey, A.D., Bucholtz, F., Sinansky, K., Dandridge, A.
Interferometric Sensors for DC Measurands- A New Class of Fiber Sensors
(1986) *SPIE Proc. Of the Conf. On Laser and Fiber-Optic Sensors IV*
Cambridge, MA, Sept

☐ 24 Kersey, A.D., Dandridge, A.
unpublished work

☐ 25 Brooks, J.L., Tur, M., Kim, B.Y., Fester, K.A., Shaw, H.J.
Fiber-Optic Interferometric Arrays with Freedom from Source Phase-Induced Noise
(1986) *Opt. Lett*, 11, p. 473. Cited 24 times.

☐ 26 Brooks, J.L., Kim, B.Y., Tur, M., Shaw, H.J.
Sensitive Fiber-Optic Interferometric Sensor Arrays
(1986) *SPIE Proc. Of the Conf. On Laser and Fiber-Optic Sensors IV*
Cambridge, MA, Sept

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☐ 27 Green, E.L., Holmberg, Gerald E., Gremillion, J.C., Allard, F.C.
REMOTE PASSIVE PHASE SENSOR.

(1985) , pp. 130-131. Cited 6 times.

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☐ 28 Petuchowskl, S.J., Giallorenzi, T.G., Sheem, S.K.
A Sensitive Fiber-Optic Fabry-Perot Interferometer

(1981) *IEEE Journal of Quantum Electronics*, 17 (11), pp. 2168-2170. Cited 44 times.
doi: 10.1109/JQE.1981.1070682

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☐ 29 Kersey, A.D., Jackson, D.A., Corke, M.
A simple fibre Fabry-Pérot sensor

(1984) *Optics and Lasers in Engineering*, 5 (3), pp. 141-154. Cited 4 times.
doi: 10.1016/0143-8166(84)90007-1

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(1983) *Proc. Of the 1St Inti Conf. On Optical Fibre Sensors*
London, April

☐ 31 Dakin, J.P., Wade, C.A., Henning, M.
Novel optical fibre hydrophone array using a single laser source and detector

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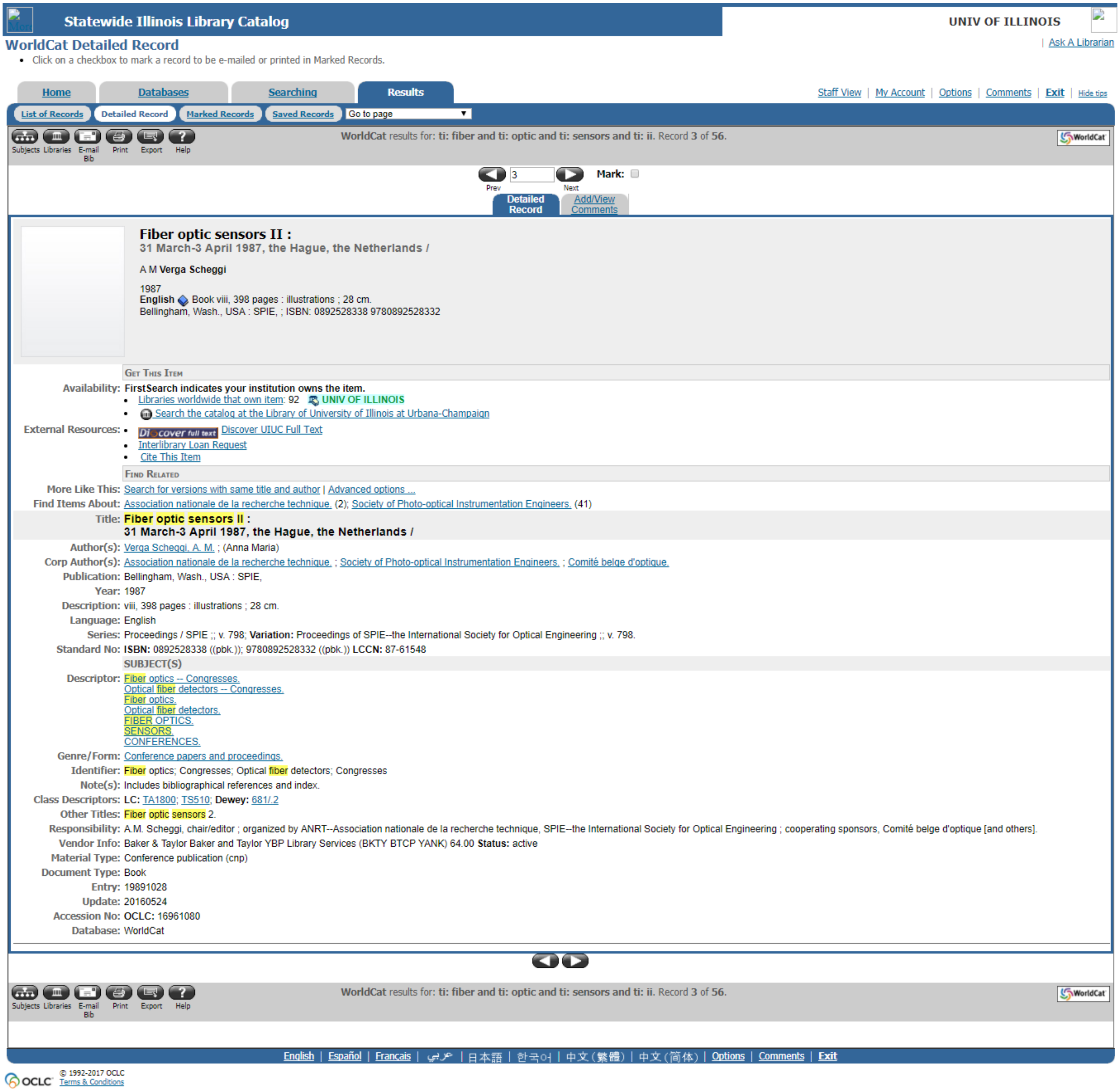

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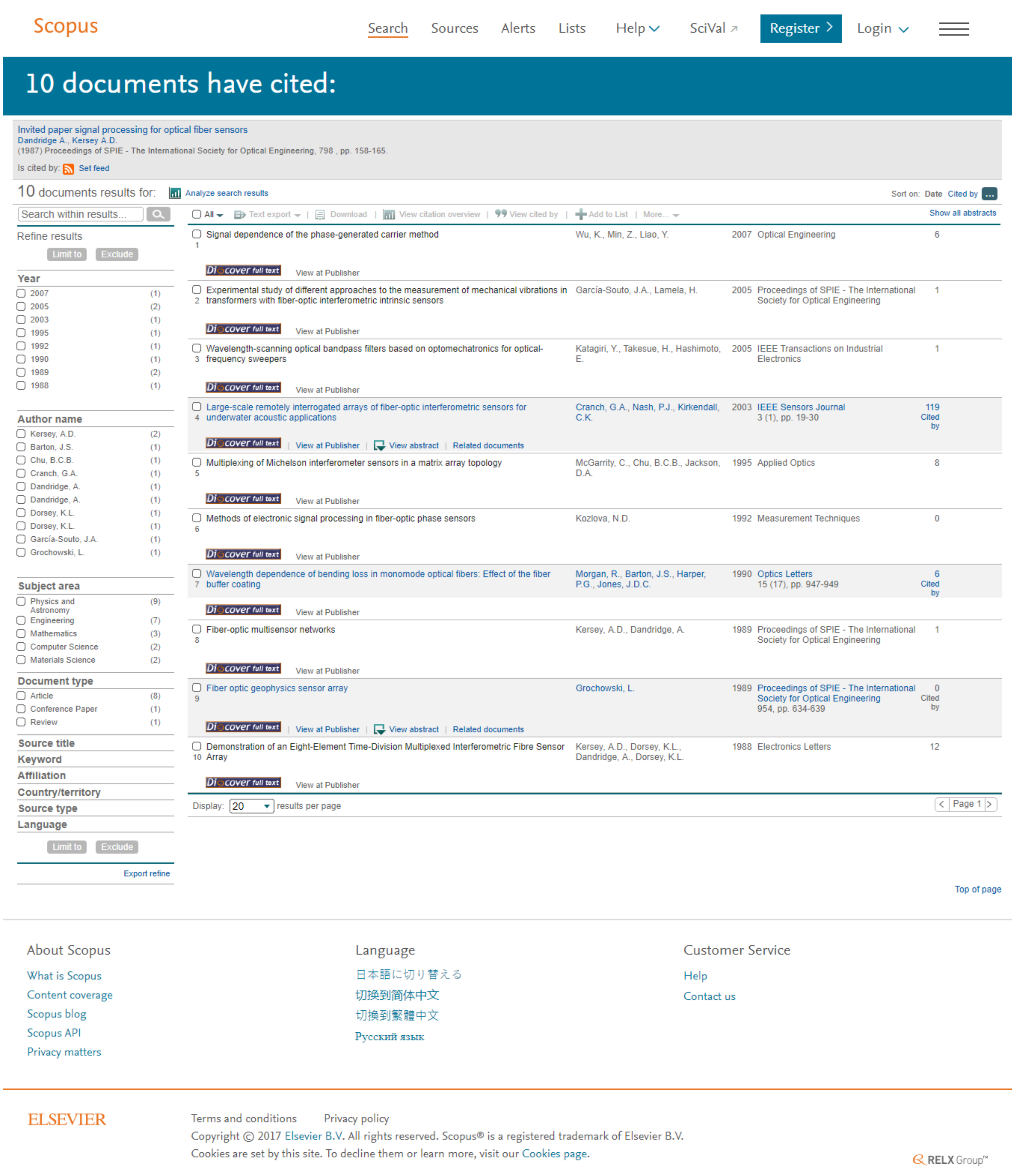

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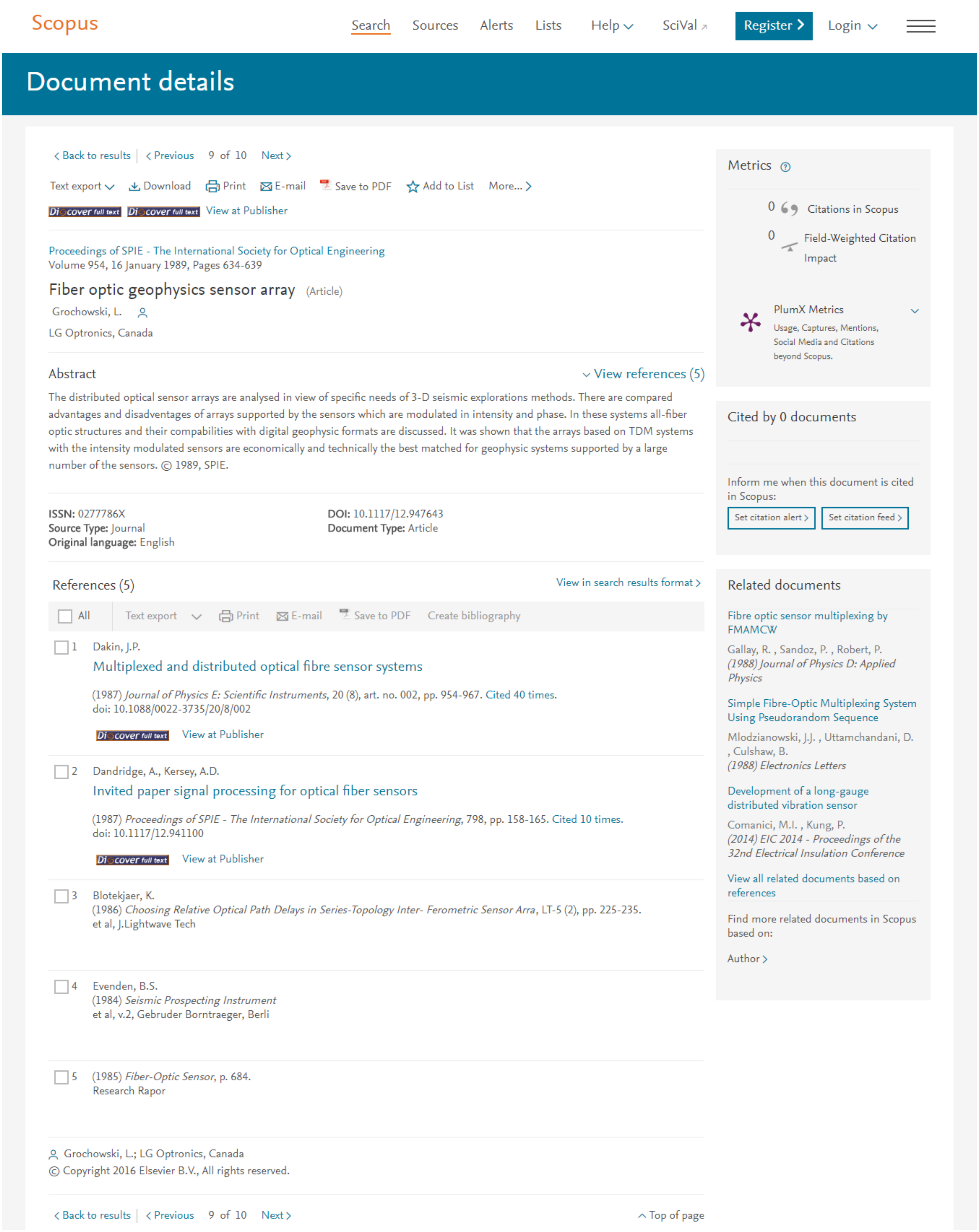

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LG Optronics, Canada

Abstract

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The distributed optical sensor arrays are analysed in view of specific needs of 3-D seismic explorations methods. There are compared advantages and disadvantages of arrays supported by the sensors which are modulated in intensity and phase. In these systems all-fiber optic structures and their compabilities with digital geophysic formats are discussed. It was shown that the arrays based on TDM systems with the intensity modulated sensors are economically and technically the best matched for geophysic systems supported by a large number of the sensors. © 1989, SPIE.

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☐ 3 Blotekjaer, K.
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et al, J.Lightwave Tech

☐ 4 Evenden, B.S.
(1984) *Seismic Prospecting Instrument*
et al, v.2, Gebruder Borntraeger, Berli

☐ 5 (1985) *Fiber-Optic Sensor*, p. 684.
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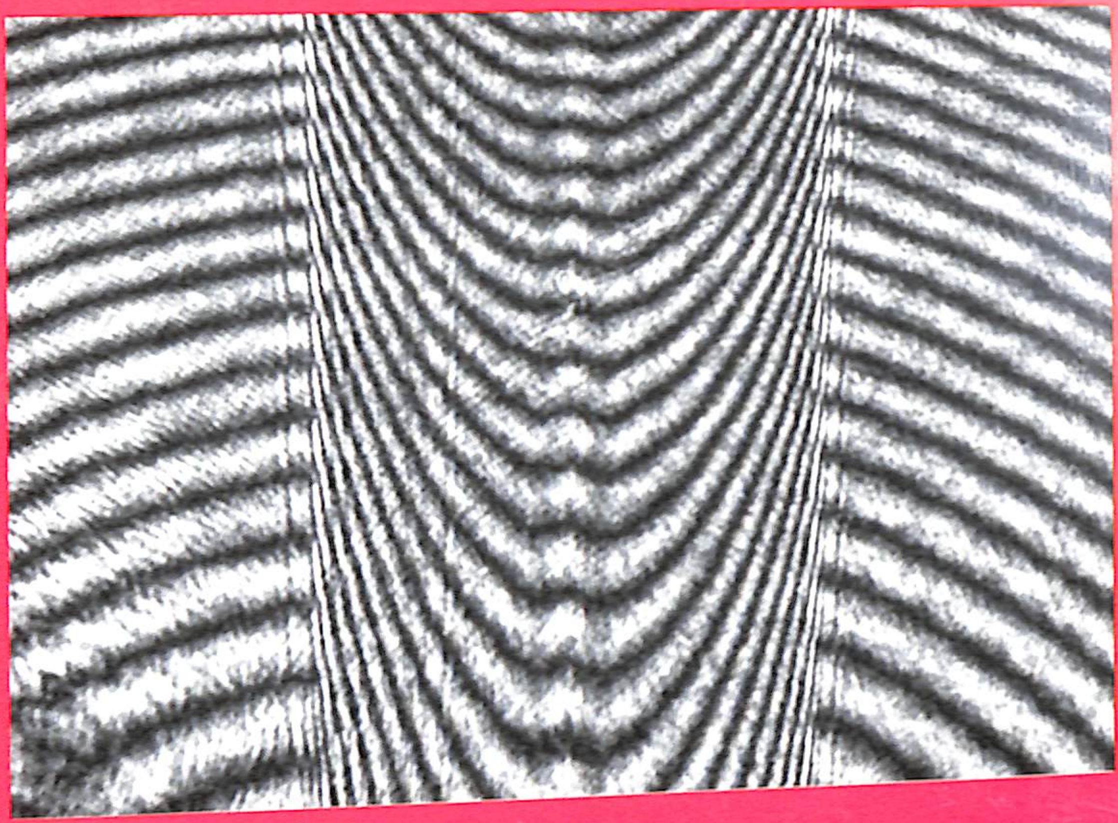

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Simultaneous distributed fibre temperature and strain sensor using microwave coherent detection of spontaneous Brillouin backscatter

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Abstract
Simultaneous optical fibre distributed strain and temperature measurements have been obtained, by measuring the spontaneous Brillouin intensity and frequency shift, using the technique of microwave heterodyne detection. The enhanced stability from using a single coherent source combined with optical preamplification results in a highly accurate sensor. Using this sensor, distributed temperature sensing at 57 km and simultaneous distributed strain and temperature sensing at 30 km were achieved, the longest reported sensing lengths to date for these measurements. As a simultaneous strain and temperature sensor, a strain resolution of 100 $\mu\varepsilon$ and temperature resolution of 4 °C were achieved.

Keywords: temperature, strain, coherent distributed fibre sensor, spontaneous Brillouin scattering, structural monitoring

1. Introduction

Distributed fibre sensing is currently attracting considerable research interest due to its unrivalled capability to provide a measured property of interest, such as strain or temperature, as a continuous function of linear position along the sensing fibre. The ability to measure strain and temperature independently over a long range with a high spatial resolution has many applications, including those in the power and oil industries and also in structural monitoring.

Several methods have been proposed and demonstrated for distributed sensing measurements. One popular method is the time-domain technique known as optical time-domain reflectometry (OTDR), first demonstrated in 1976 by Barnoski and Jensen [1], which utilizes the backscattered Rayleigh signal to determine optical loss along a length of fibre. In an OTDR system, a pulse of light is transmitted down the fibre and the light which is backscattered within the numerical aperture of the fibre is detected and measured. The time between sending the pulse of light and detecting the backscattered signal gives a measure of the distance along the fibre, whilst the intensity of the backscattered light provides information about the measurand. An alternative, novel method for distributed sensing, using a frequency-domain approach, was performed by Ghafoori-Shiraz and Okoshi [2]. The frequency-domain analysis is based on the measurement of a complex baseband transfer function, which then provides the amplitude of both pump and Stokes wave along a fibre length using a network analyser. With the frequency-domain approach, distributed temperature and strain measurements have been performed with a spatial resolution of 3 m over a 1 km sensing range [3].

Systems based on Raman backscatter have proved commercially successful as instruments for performing distributed temperature measurements, due to the practical approach of using conventional silica-based optical fibre as the sensing element. However, these sensors are unable to achieve measurement of distributed strain. As a result, another category of sensors, utilizing Brillouin scattering, have received much attention. Simultaneous measurement of temperature and strain is possible using Brillouin scattering since both its frequency shift and power are dependent on both of these quantities. Several techniques have been developed for obtaining the backscattered Brillouin signal, in order to enable the measurement of distributed strain and/or temperature. Both stimulated and spontaneous Brillouin scattering regimes for distributed sensing have previously been reported.

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In the case of stimulated scattering, access to both ends of the sensing fibre, or provision of an end-reflection, is required. In either the Brillouin-gain or Brillouin-loss stimulated scattering mechanism, the measured quantity is usually just the Brillouin frequency shift, which is found using the interaction between counterpropagating pulsed and CW radiation, separated by approximately the Brillouin frequency shift [4, 5]. The frequency shift distribution is determined by maximizing the increase (or decrease) of the signal at each desired point along the sensing fibre; this maximum occurs when the frequency difference between the two lasers is equal to the Brillouin frequency shift at that point. In this way, it is possible to measure either strain or temperature, provided that the fibre is either at a constant temperature or strain, respectively. Simultaneous measurements using the Brillouin-loss technique have been attempted, utilizing the Brillouin-loss peak power as well as the frequency shift. However, this was only for a sensing length of 50 m of polarization-maintaining fibre and required a portion of this length to be kept at a known temperature and strain, as a reference [6]. Errors of 178 $\mu\varepsilon$ and 3.9 C were measured, for a spatial resolution of 3.5 m, over this 50 m length.

With spontaneous scattering, access to only one end of the fibre is necessary. Furthermore, measurement of the spontaneous backscattered Brillouin power (normalized to the temperature- and strain-insensitive Rayleigh power) along with the Brillouin frequency shift, allows simultaneous measurement of temperature and strain over tens of kilometres. We focus on this type of sensor in this paper. Techniques for spontaneous Brillouin backscatter measurement fall broadly into two categories: direct detection and coherent (heterodyne) detection. In direct detection, the Brillouin signal must be optically separated from the much larger, elastic, Rayleigh component prior to detection. This has been done, for example, using Fabry–Perot [7, 8] or fibre Mach–Zehnder [9, 10] interferometers, but these optical filters must necessarily be highly stable due to the small frequency difference between Brillouin and Rayleigh components (~11 GHz at 1.5 μm). Simultaneous strain and temperature measurements have been performed using direct detection, for a sensing length of 15 km and a spatial resolution of 10 m, with an RMS temperature error of 4 C and an RMS strain error of 290 $\mu\varepsilon$ [10].

Coherent detection employs a strong, narrow linewidth, optical local oscillator (OLO) which allows very good electrical filtering of the Brillouin component and so a much greater tolerance of Rayleigh contamination than direct detection. Coherent detection also results in a greater dynamic range, since the detector photocurrent, at the beat frequency, has only a square root dependence on signal power. Also, since the RMS signal photocurrent is much higher than that for direct detection, due to optical mixing with the OLO, a detector with a higher noise-equivalent power (NEP) may be used, for instance a broader-bandwidth detector. To date, coherent detection of spontaneous Brillouin backscatter has been achieved by arranging for the frequency shift between the OLO and sensing pulses to be approximately equal to the Brillouin shift, bringing the Brillouin/OLO beat frequency within the bandwidth of a conventional heterodyne receiver. This frequency shift has previously been attained using a Brillouin laser [11], an acousto-optic modulator (AOM) ring circuit [12] and an electro-optic modulator (EOM) [13, 14].

A technique for obtaining distributed spontaneous Brillouin backscattered spectra, which employs an 11 GHz microwave heterodyne system in conjunction with optical preamplification of the signal, has recently been introduced [15]. This sensor combines the advantages of coherent detection and spontaneous Brillouin measurement, allowing simultaneous single-ended measurement of temperature and strain over a long range, but it also exhibits further advantages due to the microwave detection frequency. In particular, since the expected range of Brillouin frequency shift (up to ~500 MHz) lies within a very small percentage of the total bandwidth of the detector (~20 GHz), the detector gain is almost constant for the entire signal. Also, the 11 GHz detection frequency allows independent observation of both Stokes and anti-Stokes spectra using the same optical arrangement: the signals are separated in frequency due to the shift of the AOM and also filtered optically by a narrow-band fibre Bragg grating. Furthermore, since high-frequency optical shifting elements are not required, as was the case in previous heterodyne systems, the frequency stability of the sensor is exceptionally good.

A brief overview of spontaneous Brillouin scattering and the technique for simultaneous strain and temperature measurements are provided in section 2. The construction and operation of the sensor is described in section 3 and the results obtained, including the first simultaneous temperature and strain measurements using this technique, are presented in section 4. Section 5 contains a summary of our findings.

2. Spontaneous Brillouin scattering for temperature and strain measurements

The initial observation of Brillouin scattering in bulk silica occurred in 1950 [16]. It has been shown [6, 17–19] that the Brillouin backscattered intensity and frequency shift exhibit both strain and temperature dependence. If the sensing fibre is subjected to both temperature and strain effects it is necessary to measure both the Brillouin intensity and frequency shift along the sensing fibre to obtain accurate information regarding temperature and/or strain.

Spontaneous Brillouin scattering results when a small fraction of the incident light is inelastically scattered by thermally excited acoustic waves (acoustic phonons) in the optical fibre. A periodic modulation of the dielectric constant and hence refractive index of the medium is generated due to density variations produced by the acoustic wave. The scattered light undergoes a Doppler frequency shift and has maximum scattering in the backwards direction. This frequency shift is given by

$$\nu_B = \frac{2nv_a}{\lambda_p} \tag{1}$$

where v_a is the acoustic velocity in the fibre, n is the refractive index and λ_p is the pump wavelength. The exponential decay nature of the acoustic waves results in a Lorentzian spectral profile.

The frequency shift of the backscattered signal is approximately three orders of magnitude smaller than for Raman scattering, corresponding to the much smaller acoustic phonon frequencies involved in Brillouin scattering (~11 GHz for a pump wavelength in the 1.5 μm wavelength region), which makes separation of the Brillouin from the Rayleigh signal more difficult.

The change in Brillouin frequency shift and power due to strain and temperature may be represented by the matrix equation

$$\begin{bmatrix}\Delta\nu_B\\ \Delta P_B\end{bmatrix} = \begin{bmatrix} C_{\nu_B\varepsilon} & C_{\nu_B T}\\ C_{P_B\varepsilon} & C_{P_B T}\end{bmatrix}\begin{bmatrix}\Delta\varepsilon\\ \Delta T\end{bmatrix} \qquad (2)$$

where $C_{\nu_B\varepsilon}$ and $C_{\nu_B T}$ are the strain and temperature coefficients for frequency shift and $C_{P_B\varepsilon}$ and $C_{P_B T}$ are the coefficients for power variations. The two variables of strain and temperature can be resolved by taking the inverse of the above equation. If the inverse matrix is non-singular, i.e. if $C_{\nu_B\varepsilon}C_{P_B T} \neq C_{\nu_B T}C_{P_B\varepsilon}$, then a solution exists. For the values of the coefficients obtained in this paper, $C_{\nu_B\varepsilon}C_{P_B T}/C_{\nu_B T}C_{P_B\varepsilon} = -19.3$ and so simultaneous distributed temperature and strain measurement is possible. The inverse equation is given by

$$\begin{bmatrix}\Delta\varepsilon\\ \Delta T\end{bmatrix} = \frac{1}{|C_{\nu_B\varepsilon}C_{P_B T} - C_{P_B\varepsilon}C_{\nu_B T}|} \times \begin{bmatrix} C_{P_B T} & -C_{\nu_B T}\\ -C_{P_B\varepsilon} & C_{\nu_B\varepsilon}\end{bmatrix}\begin{bmatrix}\Delta\nu_B\\ \Delta P_B\end{bmatrix} \qquad (3)$$

and the corresponding errors in the derived strain and temperature measurements are given by [20]

$$|\delta\varepsilon| = \frac{|C_{P_B T}||\delta\nu_B| + |C_{\nu_B T}||\delta P_B|}{|C_{\nu_B\varepsilon}C_{P_B T} - C_{P_B\varepsilon}C_{\nu_B T}|} \qquad (4)$$

$$|\delta T| = \frac{|C_{P_B\varepsilon}||\delta\nu_B| + |C_{\nu_B\varepsilon}||\delta P_B|}{|C_{\nu_B\varepsilon}C_{P_B T} - C_{P_B\varepsilon}C_{\nu_B T}|}. \qquad (5)$$

3. Experimental arrangement

The experimental configuration for the microwave heterodyne spontaneous Brillouin-based fibre sensor is shown in figure 1.

3.1. The source

Excellent frequency stability was ensured by deriving both the sensing pulses and the local oscillator from the same seed laser: a 100 μW continuous wave, fibre-pigtailed laser, tunable from ~1520 to 1560 nm. The source itself was designed to be of dual nature. In one setting, used for the Brillouin measurements, the source was narrowband, with the linewidth of the seed laser (1 MHz); this was achieved with the fibre optic switch in position 1, the seed laser being amplified by the erbium-doped fibre amplifier, EDFA1. In the second setting, with the switch in position 2, the source was broadband (~6 nm) and partially polarized, due to ASE feedback into EDFA1 from a broadband reflecting mirror via a pigtailed polarizer. The partial polarization of the ASE was necessary to aid its subsequent passage through the polarization-sensitive electro-optic modulator (EOM). The source output was ~12 mW in either setting. Radiation from the source was split by a 3 dB fibre coupler into pulse and local oscillator arms.

3.2. Pulse formation

Pulses were initially formed by a 110 MHz, downshifting, fibre-pigtailed AOM before amplification by EDFA2 to give pulses up to 4.5 W peak power at 150 ns pulse width. An electro-optic modulator (EOM), of 5 dB insertion loss, was then used to gate the pulses in order to attenuate the throughput of ASE between pulses. The pulses were then passed through a PZT-based polarization scrambler (insertion loss 3 dB) to help reduce polarization noise observed on the signal. A second polarization scrambler, also with 3 dB insertion loss, was placed in the local oscillator arm to further reduce the noise. Using this arrangement, pulses of up to 350 mW could be launched down the 30 km of sensing fibre using a 3 dB coupler. In these experiments, pulses of between 150 and 160 mW and 150 and 200 ns were chosen, since spectral distortion occurs for much higher powers. A 95/5 fibre coupler was used as a tap for 5% of the backscattered signal, enabling separate direct detection of the Rayleigh trace, when operating in the broadband mode.

3.3. Brillouin preamplification

In narrowband mode, due to the low sensitivity of the detection system, the backscattered traces were preamplified using EDFA3 (small signal gain of 26.4 dB). Both the Rayleigh backscatter and the ASE from EDFA3 were then filtered out by reflection from an in-fibre Bragg grating (FBG) (reflectivity = 99.4%, λ = 1533.11 nm, $\Delta\lambda$ = 0.12 nm), via a circulator. Either the anti-Stokes or Stokes signals could be observed by tuning the narrowband source to 1533.20 nm or 1533.02 nm respectively. Contact with the heavy metal optical bench and the use of air conditioning both increased the stability of the grating and so no thermal drift problems were encountered. Since a typical FBG central wavelength temperature sensitivity is 10–15 pm K^{-1} and the grating had a flat transmission peak of width 50 pm, ambient temperature changes of a degree or two were tolerable. Use of a thermally compensated grating package would have reduced this problem still further. The attenuation of the Rayleigh component rendered negligible its behaviour as a weak secondary oscillator. This is the principal method by which the Rayleigh can affect the Brillouin signal and is much less significant than an equivalent amount of contaminating Rayleigh power in direct detection, since it is the ratio of OLO power to Rayleigh power which is important, not the ratio of Brillouin power to Rayleigh power.

3.4. Detection system

The amplified, filtered backscatter was mixed with the local oscillator via a 3 dB coupler and then detected using a 20 GHz optical detector (responsivity of 35 V W^{-1}). The Brillouin/OLO beat spectra were observed using a 26.5 GHz RF spectrum analyser, set in zero span mode. In this mode, a time-domain trace is obtained for the selected RF beat frequency. The maximum available RF resolution bandwidth, of 5 MHz, was selected, allowing a spatial resolution of 20 m to be achieved. The spectra were built up by taking time-domain backscatter traces for a series of beat frequencies, covering the expected range of Brillouin shifts. Since the required

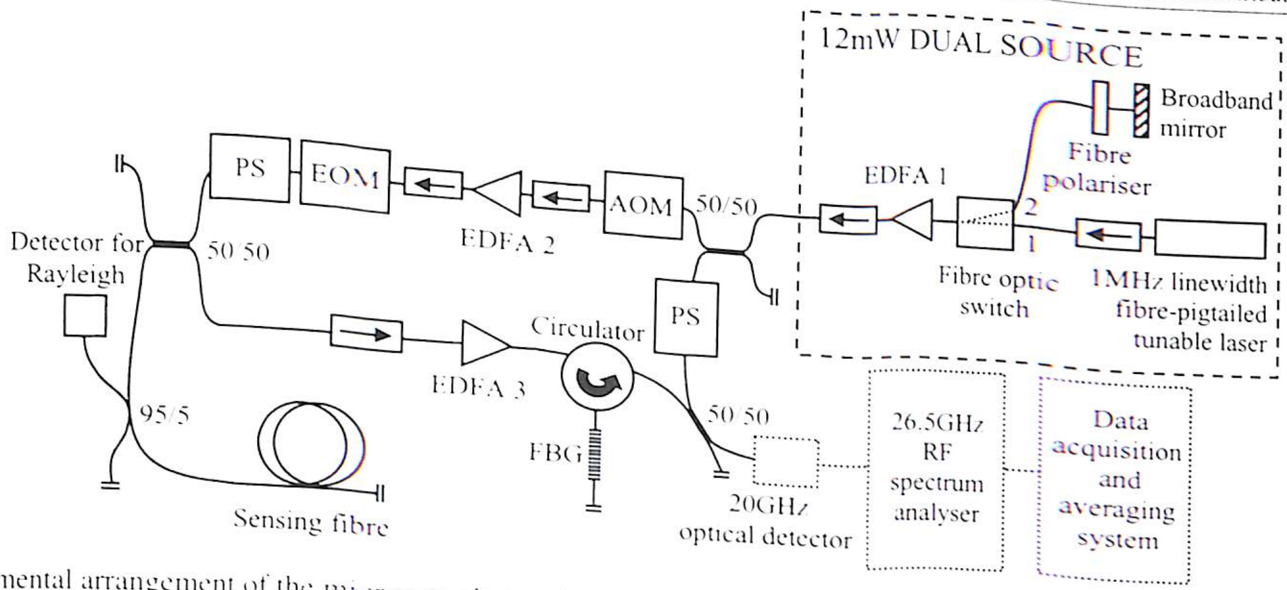

Figure 1. Experimental arrangement of the microwave heterodyne spontaneous Brillouin-based temperature and strain sensor. PS = polarization scrambler, AOM = acousto-optic modulator, EOM = electro-optic modulator, EDFA = erbium-doped fibre amplifier, FBG = fibre Bragg grating.

Brillouin power was necessarily proportional to RF power, but the recorded traces were proportional to RF voltage, squaring of the data was necessary. Any dc interpulse level was then subtracted and processing of the spectra was undertaken.

3.5. Spectrum processing

After each set of spectra was obtained, the frequency shift and power of the Brillouin backscatter was determined for each point of interest along the fibre. This was done by fitting each individual spectrum to a Lorentzian curve, since the spontaneous Brillouin line is known to be of this shape. The Levenberg–Marquardt nonlinear least squares algorithm was used for this purpose [21]. The total power, being proportional to the area under the curve, was then found. For the Lorentzian spectral profile, total power is proportional to peak power multiplied by linewidth. At certain points along the sensing fibre, where the frequency shift changes significantly over a distance smaller than the spatial resolution, a single Lorentzian curve is insufficient to determine the backscatter characteristics. To overcome these visible transitional hiccups, a double or even triple Lorentzian was fitted.

4. Distributed sensing results

Firstly, examples of the Lorentzian curve fitting are presented, to show the validity of the process. After this, distributed results for a 57 km sensing length are discussed, revealing the range limit for this system as a simultaneous temperature and strain sensor. A calibration of the dependence of both frequency shift and backscattered power on temperature was undertaken at this stage and the coefficients compared to previously measured values. Finally, simultaneous measurement of temperature and strain are discussed for a 30 km sensing fibre.

4.1. Lorentzian curve fitting

A sample set of distributed anti-Stokes Brillouin spectra is shown in figure 2(a) for a 3.5 km section, located 25 km down the sensing fibre. A 500 m heated portion (at 65 °C) is clearly visible due to its frequency shift from the unheated regions. Figure 2(b) shows a single spectrum from this 3.5 km section and its corresponding fitted Lorentzian curve. To estimate the goodness of fit, the value χ^2/N was calculated, which is defined by

$$\frac{\chi^2}{N} = \frac{1}{N}\sum_{i=1}^{N}\frac{(y_i - f(x_i))^2}{\sigma_i^2} \tag{6}$$

for a data set of N points, $(x_{i=1\ldots N}, y_{i=1\ldots N})$, with standard errors in y of $\sigma_{i=1\ldots N}$, being modelled to a function $f(x)$. χ^2/N should be roughly equal to unity for a good fit with the expected noise characteristics, with a closer fit being indicated by a lower value. To obtain an estimate in this case, the noise on each point was assumed to be identical and dominated by electrical noise, which was calculated as the standard deviation of the inter-pulse, flat, spectrum. The measured value of χ^2/N for figure 2(b) is 0.82, validating the choice of spectral profile. Examples of double and triple curve fitting results at ~31 km down the sensing fibre are shown in figure 3. χ^2/N values for these two curves, measured in an identical manner as before, are 1.24 and 0.86, again showing agreement with the model. Of course, the inclusion of any additional noise sources would decrease χ^2/N, for any given measured spectrum, since the standard error used in equation (6) would be larger. Automation of the processing may be achieved by firstly fitting to each spectrum a single Lorentzian curve; if χ^2/N is high, however, a double peak may then be tried, or a triple peak, and so on, until a good fit is obtained.

4.2. Measurements over a 57 km sensing fibre

In order to gauge the potential performance of the sensor, distributed anti-Stokes Brillouin spectra were obtained over a 57 km sensing fibre, the longest yet presented using single-ended detection of spontaneous Brillouin backscatter. The frequency shift and backscattered power measurements are shown in figure 4 for this fibre. These were obtained by taking a series of 25 different backscatter traces, each separated by 5 MHz, starting at 10.84 GHz; each trace was averaged 4096 times. The frequency measurements highlight the boundaries between different fibre sections, with the sharp troughs being

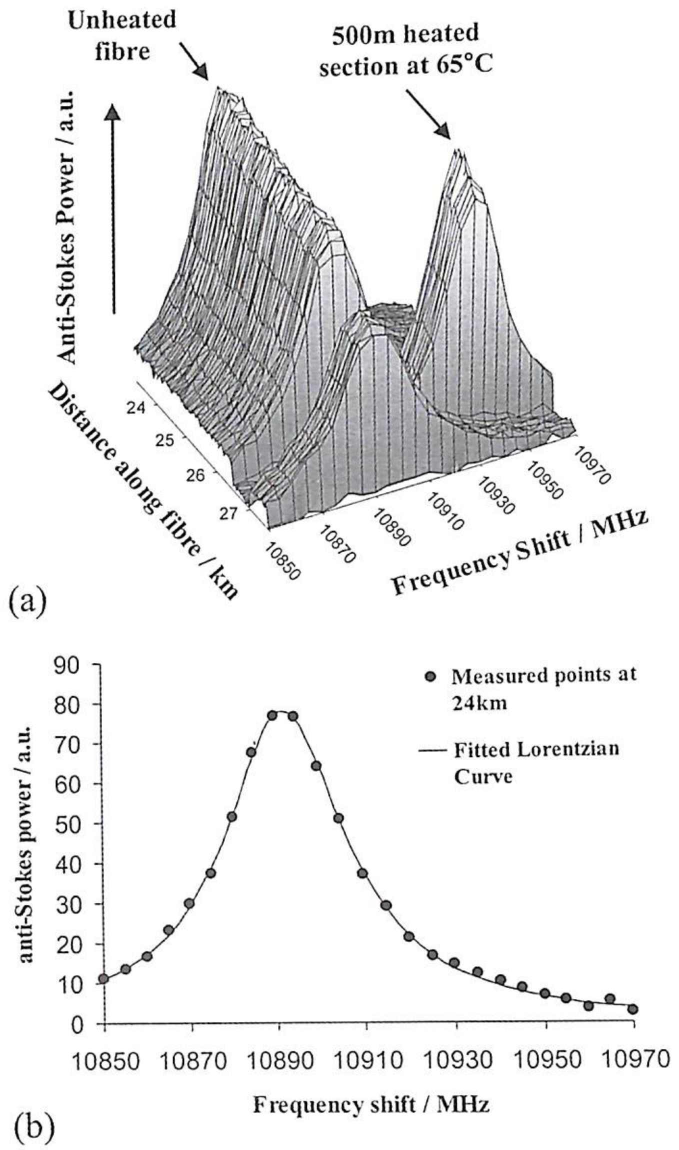

Figure 2. (a) Example distributed anti-Stokes Brillouin spectrum at ~25 km distance along the sensing fibre. A 500 m heated section at 65 °C is clearly visible. (b) Sample fitted Lorentzian curve (solid line) and the original data points (circles) for a single point at 24 km along the fibre.

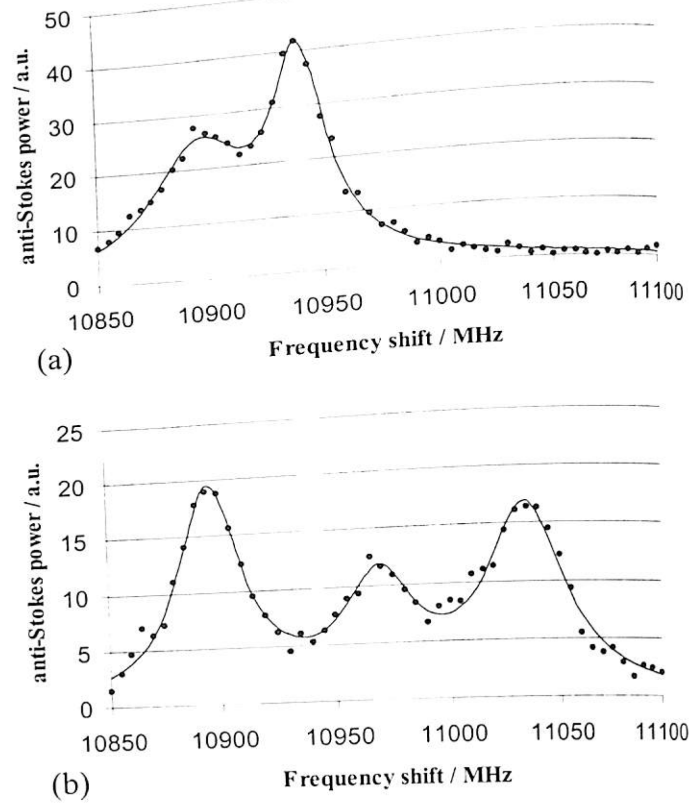

Figure 3. Example (a) double and (b) triple fitted Lorentzian curves. These are both for points ~31 km along the sensing fibre.

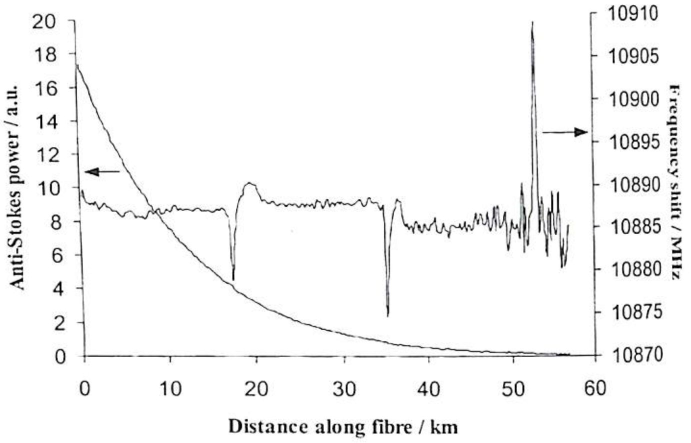

Figure 4. Distributed anti-Stokes Brillouin measurements for an entire 57 km fibre length. Both frequency shift and power traces are shown.

attributed to slack regions between wound drums. The sensing fibre comprises five separate fibre lengths, 17 500 m, 17 500 m, 17 500 m, 500 m and 4000 m, with the 500 m portion being placed in an oven and unwound from the drum to ensure the absence of strain and the rest of the fibre kept at the room temperature of 22 °C. The frequency measurements show clearly, at ~53 km along the fibre, the shift due to the 500 m heated section, held at 40 °C. Each unheated fibre section has a different frequency shift, which may arise from differences in winding tension or intrinsic fibre properties (refractive index or acoustic velocity). The power measurements show the expected exponential decrease with fibre length, agreeing with the predicted attenuation coefficient (~0.4 dB km^{-1} double pass at 1.53 μm).

The RMS noise in both the frequency shift and power traces were found over 2 km sections (10 data points) located at several positions along the fibre. The power values were found after first normalizing the observed trace to a fitted exponential function, one for each separate section of fibre. This information is plotted in figure 5(a) for the frequency shift and figure 5(b) for the power. The noise levels increase to 1.3 MHz and 5.8% at 50 km, corresponding to ~1.2 °C/28 $\mu\varepsilon$ and ~16 °C/6500 $\mu\varepsilon$ respectively. The power trace is clearly too noisy to allow a useful simultaneous sensor at this distance. Figure 5(b) indicates that a 1.5% RMS error would occur at 30 km, which brings the temperature error due to the power measurement down to less than 5 °C. The RMS power error remains at an approximately constant value of 0.7–0.8% for the first 20 km of the sensing fibre, over which the backscattered power has decreased by ~8 dB. This indicates that polarization noise, which may be expected to have a constant percentage value, has not been fully eliminated and so improved scrambling is necessary, for optimum resolution.

For an unstrained fibre, the frequency shift gives a direct measurement of temperature and, with this application in mind,

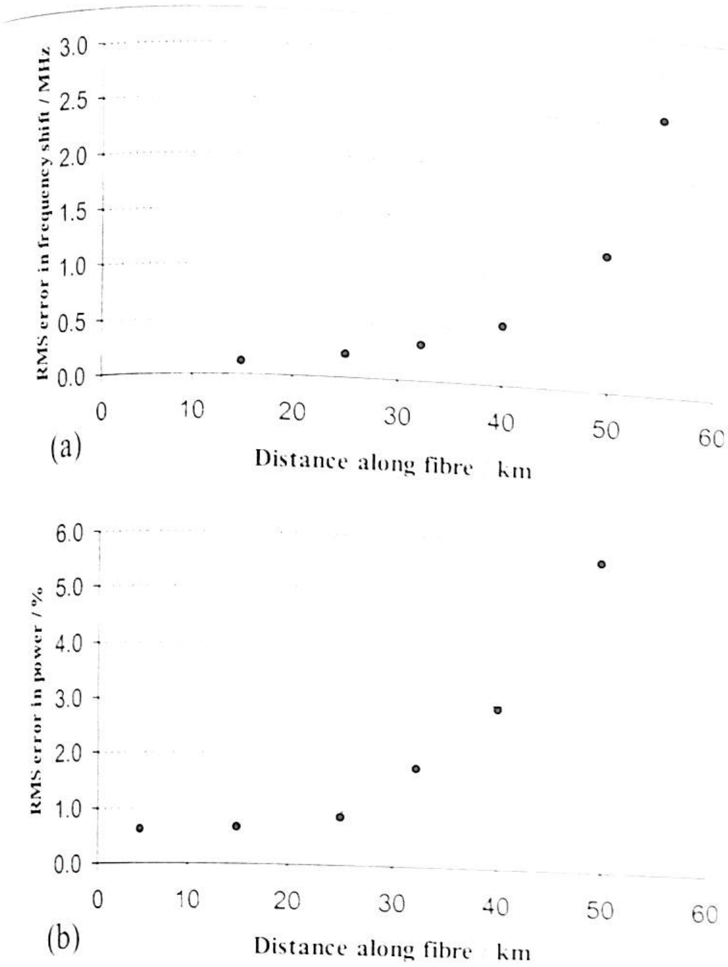

Figure 5. RMS error, taken over a 2 km window, in both (a) frequency shift and (b) power for the 57 km sensing fibre, plotted at several points along the fibre length.

calibrated temperature measurements were obtained for the heated section at 53 km. The RMS noise was calculated to be less than 2 MHz over the heated portion for each oven temperature: the traces are shown in figure 6(a). The expected linear relationship between frequency shift and temperature is clearly visible in figure 6(b), with the coefficient being 1.07 ± 0.06 MHz K^{-1}, agreeing in magnitude with other sources [22, 23].

4.3. *Power measurements over a 27 km sensing fibre*

Power measurements are more complicated to obtain than frequency shift measurements. Initially, the sensing length was merely reduced to 27.4 km (four sections of 17 500 m, 8900 m, 500 m and 500 m, with the third section being heated). The same technique as before was applied (this time for 25 frequencies separated by 5 MHz, starting at 10.85 GHz, each averaged 12 288 times) and a single Lorentzian was fitted for each point along the fibre. Discontinuities in temperature, however, resulted in sharp spikes in the recorded power, either side of the heated section. This is clearly visible in figure 7(a), which shows how the power measurements, at 26.5 km, depend on temperature. Ignoring the anomalies at either end of the heated section, another linear relationship is revealed and is shown in figure 7(b). The coefficient relating the percentage change in power to temperature was calculated as 0.36±0.04% K^{-1}, again agreeing with other sources [7, 22]. The artificial peaks may be removed, however, by fitting a double Lorentzian curve at the transitional points, as in figure 8. The RMS error in temperature was found to be less than 3.4 K (equivalent to 1.2% power error) at the heated section.

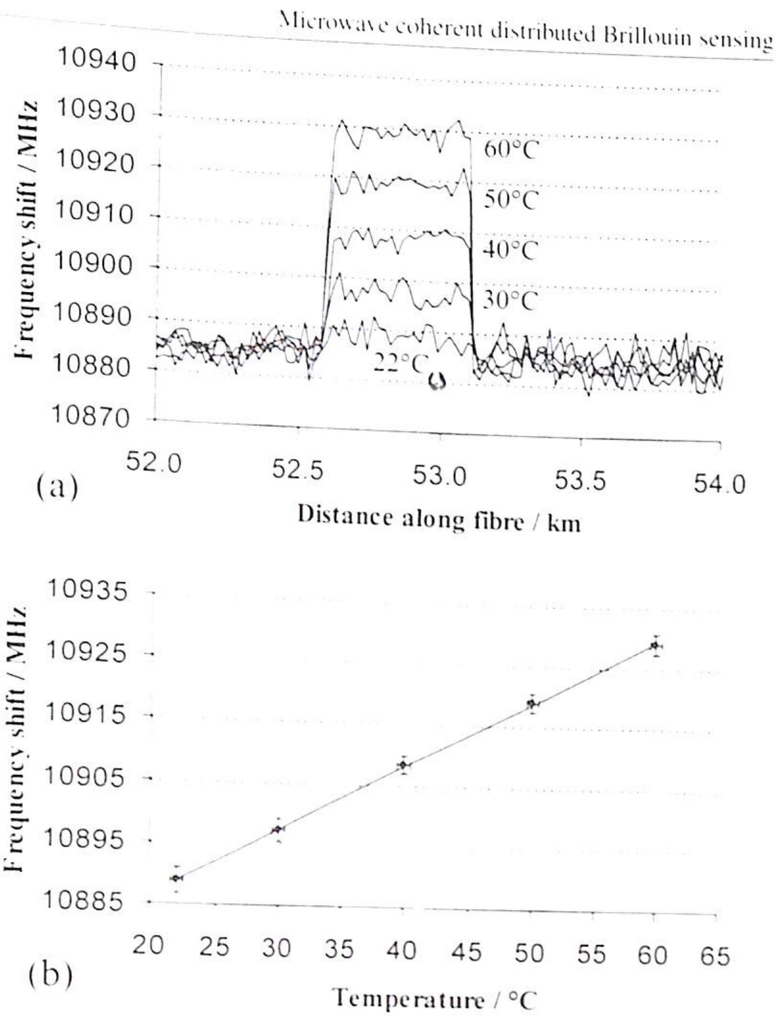

Figure 6. Variation of Brillouin frequency shift with temperature, for a 500 m heated region at 53 km along the sensing fibre. (a) Time-domain traces—RMS error is < 2 MHz. (b) Calibration of shift, yielding a coefficient of 1.07 ± 0.06 MHz °C^{-1}.

4.4. *Simultaneous strain and temperature measurement over a 30 km sensing fibre*

Simultaneous results were achieved with a slightly longer fibre of length 31.8 km; a length of 4000 m was inserted between the first two sections of the previous sensing length and a 115 m strainable section, followed by a 200 m length of unstrained fibre, was added at the end. In this manner, the heated (unstrained) section (the same 500 m length as before) and the strained (unheated) section were arranged to lie between 30.4 km and 31.6 km down the fibre. The 115 m fibre section was strained by being passed round 11 pairs of pulleys, each pair separated horizontally by ~5 m, and loaded by placing weights inside a plastic container suspended at the end of the rig (figure 9). This configuration inevitably results in considerable differential strain across the whole 115 m length. Since a spatial resolution of 20 m was used, the 5 m separation of the pulleys resulted in the appearance, in places, of triple-peaked spectra, requiring the fitting of a triple Lorentzian spectrum. Although possible, no evidence of quadruple peaks was found. Also, since the Brillouin frequency shift induced by the maximum applied strain (a peak of 4600 $\mu\varepsilon \equiv 210$ MHz) was considerably larger than for the maximum temperature change used (77.5 °C ≡ 83 MHz), this necessitated an increase in the frequency span of the collected traces. In fact, the span was increased to 400 MHz, since the degree of differential strain was not known; so 80 traces were taken at 5 MHz separation, starting at 10.85 GHz with 12 288 averages per trace. The differential strain can easily be seen in figure 10, a plot of distributed frequency shift for an applied extension of

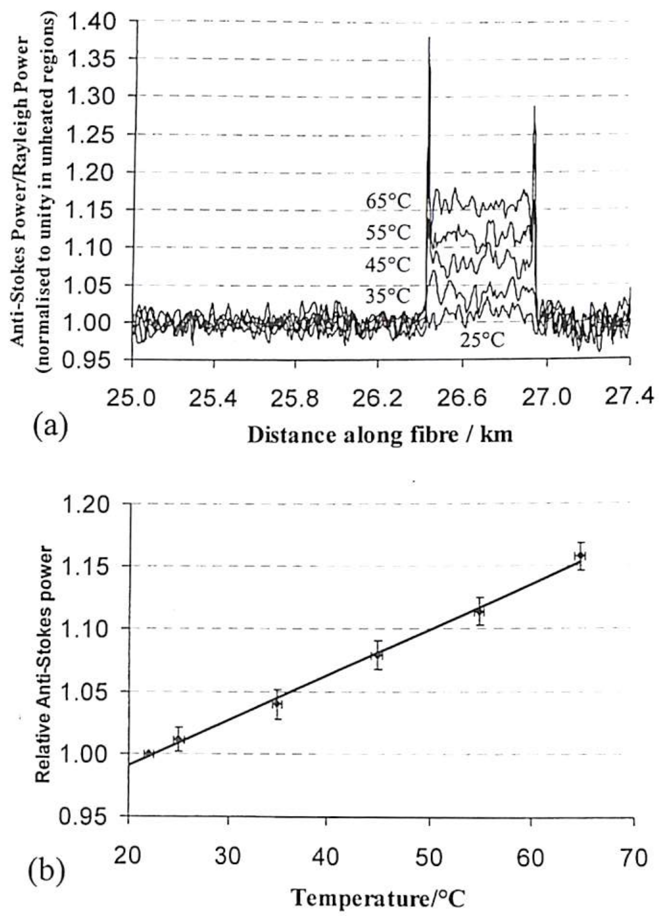

Figure 7. Variation of normalized anti-Stokes power measurements with temperature, for a 500 m heated section at 26.5 km along the sensing fibre. (a) Time-domain traces—RMS error is ~1.2%. Spikes are due to poor curve fitting of double peaks. (b) Calibration of power change, yielding a coefficient of 0.36% °C^{-1}.

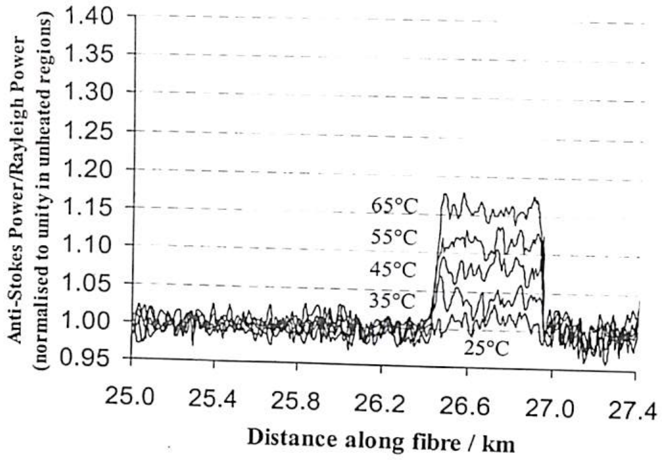

Figure 8. Elimination of anomalous peaks at temperature discontinuities, by fitting of a double Lorentzian curve, is demonstrated using the data of figure 7(a).

48.8 cm, corresponding to a strain of 4240 $\mu\varepsilon$. In this case, the peak-to-peak variation is approximately 50% of the average strain. The frequency shift is determined by finding its average value over the strained region; it is this value that is assumed to arise from a constant strain of 4240 $\mu\varepsilon$.

Before simultaneous measurements were attempted, however, both the frequency shift (figure 11) and power (figure 12) were calibrated against strain, in order to determine the two remaining coefficients required for the inverse matrix.

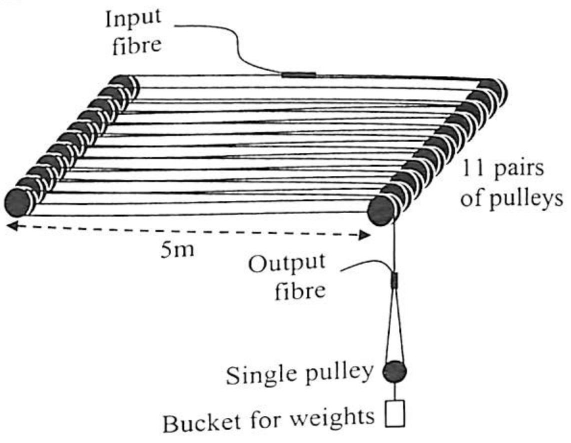

Figure 9. Illustration of the rig used to strain fibre for distributed measurements.

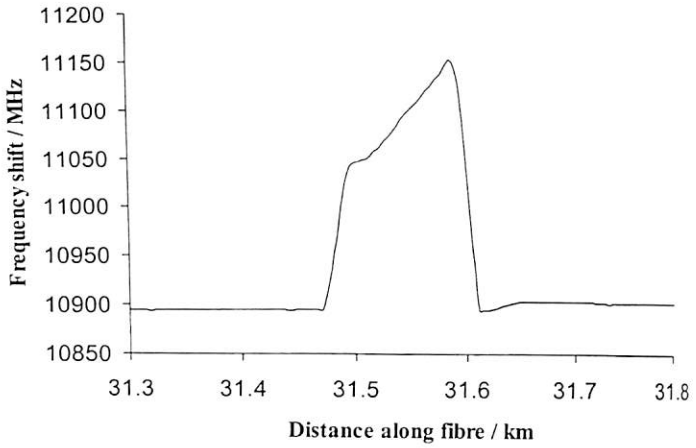

Figure 10. A frequency shift trace for 115 m of strained fibre located 31.5 km along the sensing fibre. It is clear, since the fibre is all at room temperature, that considerable differential strain is present over the 115 m length.

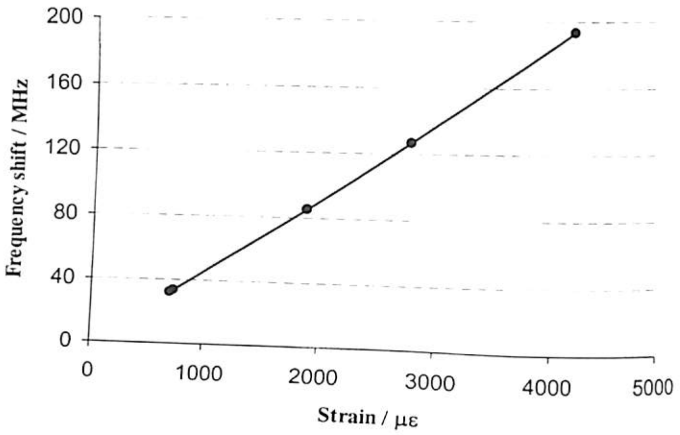

Figure 11. Dependence of the Brillouin frequency shift on applied strain. The coefficient of the dependence was measured to be 0.046 MHz $\mu\varepsilon^{-1}$.

The frequency response was linear with a coefficient of 0.046 MHz $\mu\varepsilon^{-1}$; however the power measurement was less conclusive due to the large noise present on the signal. Linear regression of the power dependence gave a coefficient of $-8\pm5\times10^{-4}\%\ \mu\varepsilon^{-1}$. Both of these values agree with previous results [17, 19, 22].

For the simultaneous results, all power measurements were referenced to the Rayleigh trace, obtained in broadband mode, and all frequency shift measurements referenced to that

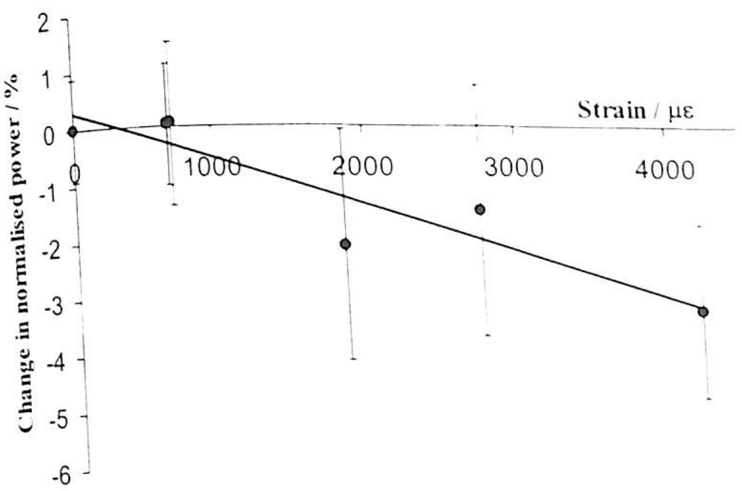

Figure 12. Dependence of the normalized anti-Stokes Brillouin power on temperature. The coefficient of the dependence was measured to be $-8 \pm 5 \times 10^{-4}\% \ \mu\varepsilon^{-1}$.

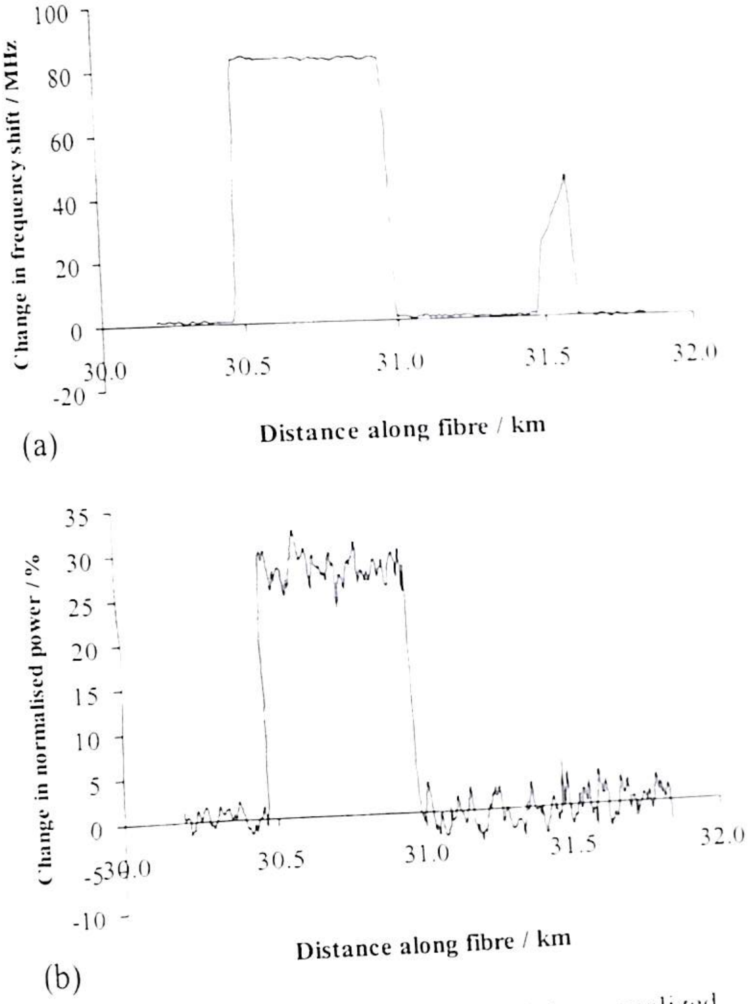

Figure 13. Measured (a) frequency shift and (b) normalized anti-Stokes power for a fibre section containing a 500 m heated region at 100 C and a 115 m strained region at an average strain of 730 $\mu\varepsilon$, located at ~30 km along the sensing fibre.

observed with zero strain. The frequency shift and percentage power change are shown in figure 13 for a heated section at 100 C and a strained section at 730 $\mu\varepsilon$. The RMS noise on the frequency shift trace, over the 500 m heated region, is 0.3 MHz and the RMS noise on the power measurement, over this same region, is 1.56%. From equations (4) and (5), the corresponding errors in temperature and strain are given by 4.1 C and 102 $\mu\varepsilon$, respectively. As a corroboratory measurement, the frequency shift and power RMS noise values for the fibre section between the heated and strained regions are 0.29 MHz and 1.49%, resulting in temperature and strain errors of 3.9 C and 97.5 $\mu\varepsilon$. It can be concluded that the RMS noise on the temperature and strain traces at 31 km along the fibre is ~4 C and ~100 $\mu\varepsilon$. The corresponding derived

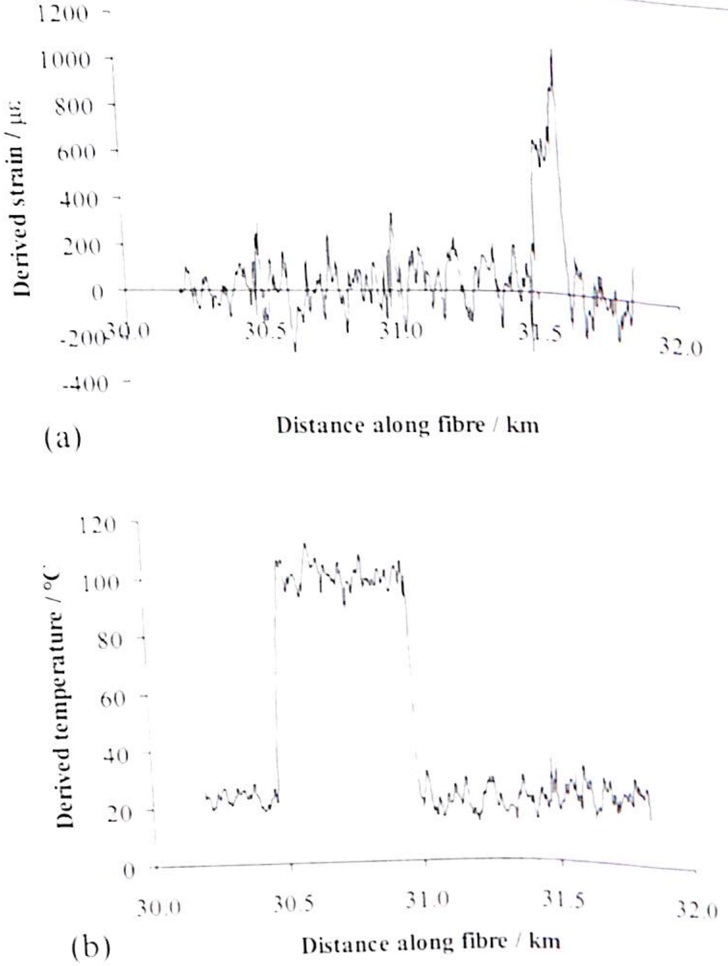

Figure 14. Derived distributed (a) strain and (b) temperature measurements, based upon the measured data in figure 13. The RMS error in strain was calculated as 100 $\mu\varepsilon$ and the RMS error in temperature as 4 C.

temperature and strain measurements are shown in figure 14. It can be seen that there is little cross-talk between strain and temperature. It is also clear that the noise on both derived traces is dominated by that on the measured power trace. Indeed, it can be calculated using equations (4) and (5) that, for errors of 4 C and 100 $\mu\varepsilon$, the noise on the power trace is responsible for 99.7% of the temperature error and 94% of the strain error, showing that the power measurements are by far the limiting factor on sensor resolution. It can also be seen from figure 14 that, with the heated section at 100 C, outside the range of temperatures used in the power and frequency shift calibration measurements, the heated temperature is measured faithfully by the sensor. This indicates that the linearity of the Brillouin frequency shift and power with temperature is maintained up to this higher temperature.

5. Conclusions

We have presented a spontaneous Brillouin-based distributed fibre temperature and strain sensor that uses microwave coherent detection of the backscattered signals at the 11 GHz Brillouin shift frequency. This technique benefits from the advantages inherent to both coherent detection and spontaneous Brillouin measurement as well as to the microwave nature of our detection system. Coherent operation gives very good intrinsic electrical separation of the Brillouin from the Rayleigh, which is hard to achieve using optical filtering methods. Furthermore, the heterodyne technique allows the use of a broader-band detector, with a higher NEP, since the signal photocurrent is increased by mixing with the strong optical local oscillator. Also the dynamic range is increased due to the square root dependence of detector photocurrent on signal power. In the spontaneous scattering regime, access to only one end of the sensing fibre is required, promoting sensor versatility. High-frequency detection ensures that the total expected range of Brillouin frequency shift lies within a very small percentage of the total detector bandwidth, giving an almost constant gain for the entire signal. Also, the 20 GHz bandwidth of the detector allows both Stokes and anti-Stokes spectra to be observed easily and independently. Furthermore, since high-frequency optical shifting elements are not required, as was the case in previous heterodyne systems, the frequency stability of the sensor is excellent.

We have demonstrated frequency shift measurements and power measurements which have temperature and strain dependences closely agreeing with previously published results. We have obtained long-range 57 km frequency shift measurements with an RMS error of less than 3 MHz for the entire length and less than 0.6 MHz for the first 40 km. A target 5 °C error in power measurement limited the range used for simultaneous temperature and strain measurements to 30 km. These simultaneous results yielded a 4 °C RMS temperature error and a 100 $\mu\varepsilon$ RMS strain error at the end of this fibre for a spatial resolution of 20 m.

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References

[1] Barnoski M K and Jensen S M 1976 Fiber waveguides: a novel technique for investigating attenuation characteristics *Appl. Opt.* **15** 2112–15

[2] Ghafoori-Shiraz H and Okoshi T 1986 Fault location in optical fibers using optical frequency domain reflectometry *J. Lightwave Technol.* **4** 316–22

[3] Garus D, Gogolla T, Krebber K and Schliep F 1997 Brillouin optical-fiber frequency-domain analysis for distributed temperature and strain measurements *J. Lightwave Technol.* **15** 654–62

[4] Horiguchi T, Kurashima T and Tateda M 1990 A technique to measure distributed strain in optical fibers *IEEE Photon. Technol. Lett.* **2** 352–4

[5] Bao X, Dhliwayo J, Heron N, Webb D J and Jackson D A 1995 Experimental and theoretical studies on a distributed temperature sensor based on Brillouin scattering *J. Lightwave Technol.* **13** 1340–8

[6] Smith J, Brown A, DeMerchant M and Bao X 1999 Simultaneous distributed strain and temperature measurement *Appl. Opt.* **38** 5372–7

[7] Wait P C and Newson T P 1996 Landau Placzek ratio applied to distributed fibre sensing *Opt. Commun.* **122** 141–6

[8] Parker T R, Farhadiroushan M, Handerek V A and Rogers A J 1997 A fully distributed simultaneous strain and temperature sensor using spontaneous Brillouin backscatter *IEEE Photon. Technol. Lett.* **9** 979–81

[9] Lees G P, Wait P C, Cole M J and Newson T P 1998 Advances in optical fiber distributed temperature sensing using the Landau–Placzek ratio *IEEE Photon. Technol. Lett.* **10** 126–8

[10] Kee H H, Lees G P and Newson T P 2000 All-fiber system for simultaneous interrogation of distributed strain and temperature sensing by spontaneous Brillouin scattering *Opt. Lett.* **25** 695–7

[11] Lecoeuche V, Webb D J, Pannell C N and Jackson D A 1999 16 km distributed temperature sensor based on coherent detection of spontaneous Brillouin scattering using a Brillouin laser *Tech. Dig. Optical Fiber Sensors 13* (Washington, DC: Optical Society of America) pp 349–52

[12] Shimizu K, Horiguchi T, Koyamada Y and Kurashima T 1994 Coherent self-heterodyne Brillouin OTDR for measurement of Brillouin frequency shift distribution in optical fibers *J. Lightwave Technol.* **12** 730–6

[13] Tsuji K, Shimizu K, Horiguchi T and Koyamada Y 1995 Coherent optical frequency domain reflectometry for a long single-mode optical fiber using a coherent lightwave source and an external phase modulator *IEEE Photon. Technol. Lett.* **7** 804–6

[14] Izumita H, Sato T, Tateda M and Koyamada Y 1996 Brillouin OTDR employing optical frequency shifter using side-band generation technique with high-speed LN phase-modulator *IEEE Photon. Technol. Lett.* **8** 1674–6

[15] Maughan S M, Kee H H and Newson T P 2001 57-km single-ended spontaneous Brillouin-based distributed fiber temperature sensor using microwave coherent detection *Opt. Lett.* **26** 331–3

[16] Krishnan R S 1950 Fine structure of the Rayleigh line in amorphous substances *Nature* **165** 933–4

[17] Horiguchi T, Kurashima T and Tateda M 1989 Tensile strain dependence of Brillouin frequency shift in silica optical fibres *IEEE Photon. Technol. Lett.* **1** 107–8

[18] Culverhouse D, Farahi F, Pannell C N and Jackson D A 1989 Potential of stimulated Brillouin scattering as a sensing mechanism for distributed temperature sensors *Electron. Lett.* **25** 913–15

[19] De Souza K, Wait P C and Newson T P 1997 Characterisation of strain dependence of the Landau–Placzek ratio for distributed sensing *Electron. Lett.* **33** 615–16

[20] Jones J D C 1997 Review of fibre sensor techniques for temperature-strain discrimination *12th Int. Conf. on Optical Fiber Sensors OFS-12* vol 16, OSA Technical Digest Series (Washington, DC: Optical Society of America) pp 36–9

[21] Press W H, Teukolsky S A, Vetterling W T and Flannery B P 1995 *Numerical Recipes in C—the Art of Scientific Computing* 2nd edn (Cambridge: Cambridge University Press)

[22] Parker T R, Farhadiroushan M, Handerek V A and Rogers A J 1997 Temperature and strain dependence of the power level and frequency of spontaneous Brillouin scattering in optical fibers *Opt. Lett.* **22** 787–9

[23] Kurashima T, Horiguchi T and Tateda M 1990 Thermal effects of Brillouin gain spectra in single-mode fibers *IEEE Photon. Technol. Lett.* **2** 718–20

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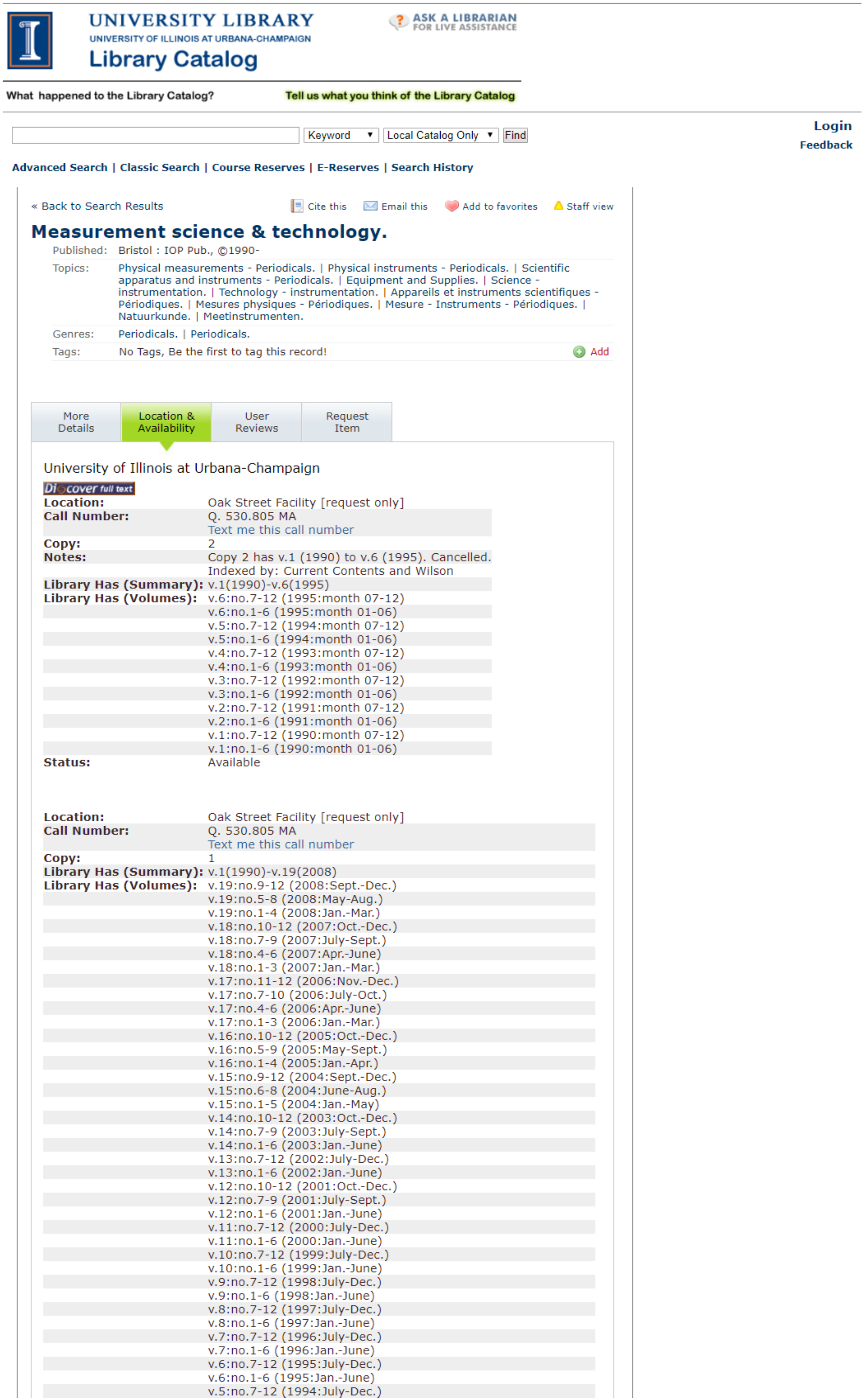

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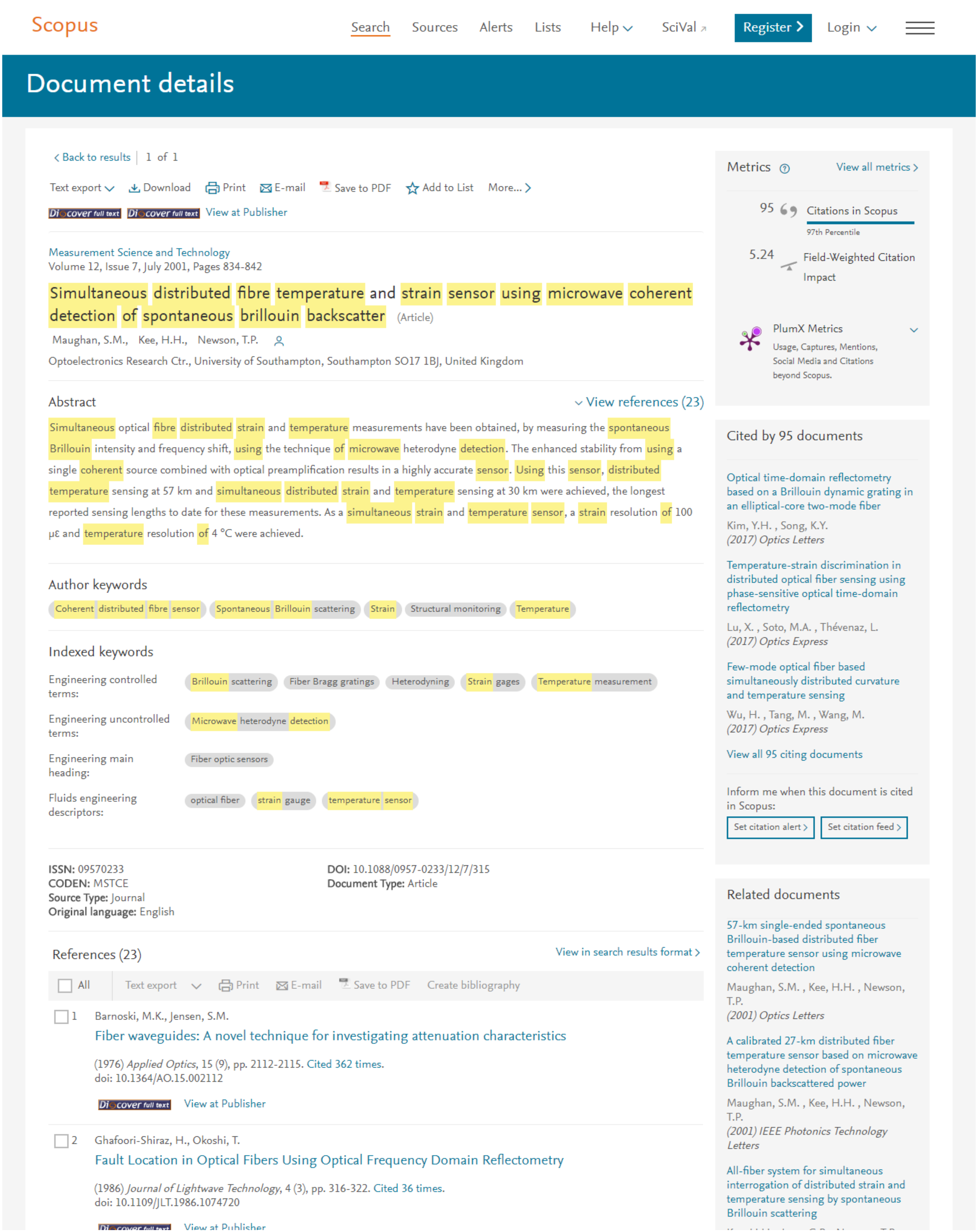

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Simultaneous distributed fibre temperature and strain sensor using microwave coherent detection of spontaneous brillouin backscatter (Article)

Maughan, S.M., Kee, H.H., Newson, T.P.

Optoelectronics Research Ctr., University of Southampton, Southampton SO17 1BJ, United Kingdom

Abstract

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Simultaneous optical fibre distributed strain and temperature measurements have been obtained, by measuring the spontaneous Brillouin intensity and frequency shift, using the technique of microwave heterodyne detection. The enhanced stability from using a single coherent source combined with optical preamplification results in a highly accurate sensor. Using this sensor, distributed temperature sensing at 57 km and simultaneous distributed strain and temperature sensing at 30 km were achieved, the longest reported sensing lengths to date for these measurements. As a simultaneous strain and temperature sensor, a strain resolution of 100 με and temperature resolution of 4 °C were achieved.

Author keywords

Coherent distributed fibre sensor | Spontaneous Brillouin scattering | Strain | Structural monitoring | Temperature

Indexed keywords

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Engineering uncontrolled terms:	Microwave heterodyne detection
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☐ 1 Barnoski, M.K., Jensen, S.M.
Fiber waveguides: A novel technique for investigating attenuation characteristics
(1976) *Applied Optics*, 15 (9), pp. 2112-2115. Cited 362 times.
doi: 10.1364/AO.15.002112
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☐ 2 Ghafoori-Shiraz, H., Okoshi, T.
Fault Location in Optical Fibers Using Optical Frequency Domain Reflectometry
(1986) *Journal of Lightwave Technology*, 4 (3), pp. 316-322. Cited 36 times.
doi: 10.1109/JLT.1986.1074720
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Lu, X. , Soto, M.A. , Thévenaz, L.
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(2001) IEEE Photonics Technology Letters

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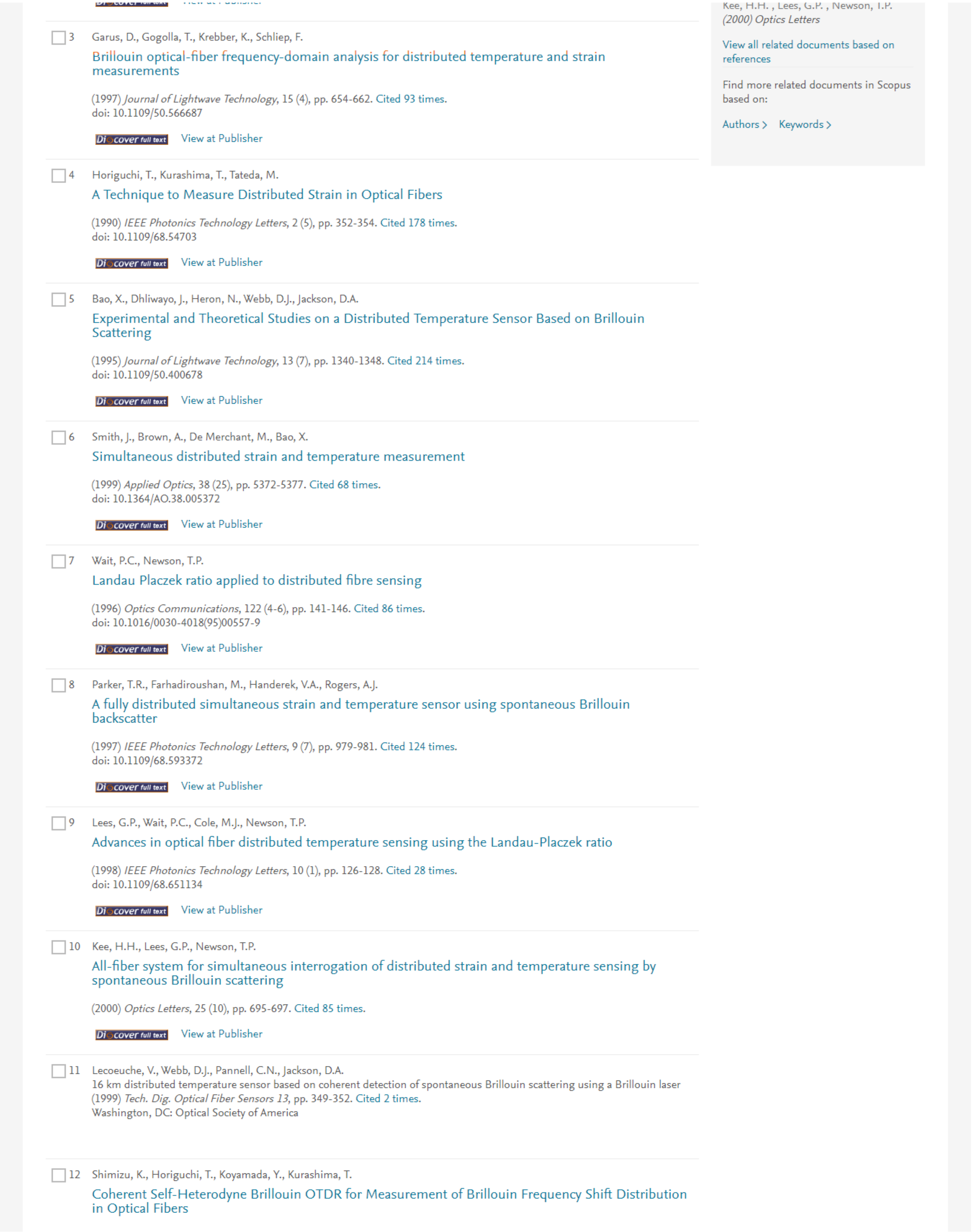

☐ 3 Garus, D., Gogolla, T., Krebber, K., Schliep, F.
Brillouin optical-fiber frequency-domain analysis for distributed temperature and strain measurements
(1997) *Journal of Lightwave Technology*, 15 (4), pp. 654-662. Cited 93 times.
doi: 10.1109/50.566687
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☐ 4 Horiguchi, T., Kurashima, T., Tateda, M.
A Technique to Measure Distributed Strain in Optical Fibers
(1990) *IEEE Photonics Technology Letters*, 2 (5), pp. 352-354. Cited 178 times.
doi: 10.1109/68.54703
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☐ 5 Bao, X., Dhliwayo, J., Heron, N., Webb, D.J., Jackson, D.A.
Experimental and Theoretical Studies on a Distributed Temperature Sensor Based on Brillouin Scattering
(1995) *Journal of Lightwave Technology*, 13 (7), pp. 1340-1348. Cited 214 times.
doi: 10.1109/50.400678
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☐ 6 Smith, J., Brown, A., De Merchant, M., Bao, X.
Simultaneous distributed strain and temperature measurement
(1999) *Applied Optics*, 38 (25), pp. 5372-5377. Cited 68 times.
doi: 10.1364/AO.38.005372
Discover full text View at Publisher

☐ 7 Wait, P.C., Newson, T.P.
Landau Placzek ratio applied to distributed fibre sensing
(1996) *Optics Communications*, 122 (4-6), pp. 141-146. Cited 86 times.
doi: 10.1016/0030-4018(95)00557-9
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☐ 8 Parker, T.R., Farhadiroushan, M., Handerek, V.A., Rogers, A.J.
A fully distributed simultaneous strain and temperature sensor using spontaneous Brillouin backscatter
(1997) *IEEE Photonics Technology Letters*, 9 (7), pp. 979-981. Cited 124 times.
doi: 10.1109/68.593372
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☐ 9 Lees, G.P., Wait, P.C., Cole, M.J., Newson, T.P.
Advances in optical fiber distributed temperature sensing using the Landau-Placzek ratio
(1998) *IEEE Photonics Technology Letters*, 10 (1), pp. 126-128. Cited 28 times.
doi: 10.1109/68.651134
Discover full text View at Publisher

☐ 10 Kee, H.H., Lees, G.P., Newson, T.P.
All-fiber system for simultaneous interrogation of distributed strain and temperature sensing by spontaneous Brillouin scattering
(2000) *Optics Letters*, 25 (10), pp. 695-697. Cited 85 times.
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☐ 11 Lecoeuche, V., Webb, D.J., Pannell, C.N., Jackson, D.A.
16 km distributed temperature sensor based on coherent detection of spontaneous Brillouin scattering using a Brillouin laser
(1999) *Tech. Dig. Optical Fiber Sensors 13*, pp. 349-352. Cited 2 times.
Washington, DC: Optical Society of America

☐ 12 Shimizu, K., Horiguchi, T., Koyamada, Y., Kurashima, T.
Coherent Self-Heterodyne Brillouin OTDR for Measurement of Brillouin Frequency Shift Distribution in Optical Fibers

Kee, H.H. , Lees, G.P. , Newson, T.P.
(2000) Optics Letters

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(1994) *Journal of Lightwave Technology*, 12 (5), pp. 730-736. Cited 98 times.
doi: 10.1109/50.293961

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☐ 13 Tsuji, K., Shimizu, K., Horiguchi, T., Koyamada, Y.
Coherent Optical Frequency Domain Reflectometry for a Long Single-Mode Optical Fiber Using a Coherent Lightwave Source and an External Phase Modulator

(1995) *IEEE Photonics Technology Letters*, 7 (7), pp. 804-806. Cited 43 times.
doi: 10.1109/68.393212

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☐ 14 Izumita, H., Sato, T., Tateda, M., Koyamada, Y.
Brillouin OTDR employing optical frequency shifter using side-band generation technique with high-speed LN phase-modulator

(1996) *IEEE Photonics Technology Letters*, 8 (12), pp. 1674-1676. Cited 28 times.
doi: 10.1109/68.544715

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☐ 15 Maughan, S.M., Kee, H.H., Newson, T.P.
57-km single-ended spontaneous Brillouin-based distributed fiber temperature sensor using microwave coherent detection

(2001) *Optics Letters*, 26 (6), pp. 331-333. Cited 52 times.

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☐ 16 Krishnan, R.S.
Fine structure of the rayleigh Line in amorphous substances

(1950) *Nature*, 165 (4206), pp. 933-934. Cited 13 times.
doi: 10.1038/165933b0

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☐ 17 Horiguchi, T., Kurashima, T., Tateda, M.
Tensile Strain Dependence of Brillouin Frequency Shift in Silica Optical Fibers

(1989) *IEEE Photonics Technology Letters*, 1 (5), pp. 107-108. Cited 363 times.
doi: 10.1109/68.34756

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☐ 18 Culverhouse, D., Farahi, F., Pannell, C.N., Jackson, D.A.
Potential of stimulated brillouin scattering as sensing mechanism for distributed temperature sensors

(1989) *Electronics Letters*, 25 (14), pp. 913-915. Cited 135 times.
doi: 10.1049/el:19890612

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☐ 19 De Souza, K., Wait, P.C., Newson, T.P.
Characterisation of strain dependence of the Landau-Placzek ratio for distributed sensing

(1997) *Electronics Letters*, 33 (7), pp. 615-616. Cited 30 times.

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☐ 20 Jones, J.D.C.
Review of fibre sensor techniques for temperature-strain discrimination
(1997) *12th Int. Conf. on Optical Fiber Sensors OFS-12*, 16, pp. 36-39. Cited 71 times.
OSA Technical Digest Series (Washington, DC: Optical Society of America)

☐ 21 Press, W.H., Teukolsky, S.A., Vetterling, W.T., Flannery, B.P.
(1995) *Numerical Recipes in C-the Art of Scientific Computing*. Cited 57317 times.
2nd edn. Cambridge: Cambridge University Press

☐ 22 Parker, T.R., Farhadiroushan, M., Handerek, V.A., Rogers, A.J.
Temperature and strain dependence of the power level and frequency of spontaneous Brillouin scattering in optical fibers

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(1997) *Optics Letters*, 22 (11), pp. 787-789. Cited 133 times.

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☐ 23 Kurashima, T., Horiguchi, T., Tateda, M.
Thermal Effects of Brillouin Gain Spectra in Singlemode Fibers

(1990) *IEEE Photonics Technology Letters*, 2 (10), pp. 718-720. Cited 59 times.
doi: 10.1109/68.60770

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Simultaneous distributed fibre temperature and strain sensor using microwave coherent detection of spontaneous Brillouin backscatter

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Abstract
Simultaneous optical fibre distributed strain and temperature measurements have been obtained, by measuring the spontaneous Brillouin intensity and frequency shift, using the technique of microwave heterodyne detection. The enhanced stability from using a single coherent source combined with optical preamplification results in a highly accurate sensor. Using this sensor, distributed temperature sensing at 57 km and simultaneous distributed strain and temperature sensing at 30 km were achieved, the longest reported sensing lengths to date for these measurements. As a simultaneous strain and temperature sensor, a strain resolution of 100 $\mu\varepsilon$ and temperature resolution of 4 °C were achieved.

Keywords: temperature, strain, coherent distributed fibre sensor, spontaneous Brillouin scattering, structural monitoring

1. Introduction

Distributed fibre sensing is currently attracting considerable research interest due to its unrivalled capability to provide a measured property of interest, such as strain or temperature, as a continuous function of linear position along the sensing fibre. The ability to measure strain and temperature independently over a long range with a high spatial resolution has many applications, including those in the power and oil industries and also in structural monitoring.

Several methods have been proposed and demonstrated for distributed sensing measurements. One popular method is the time-domain technique known as optical time-domain reflectometry (OTDR), first demonstrated in 1976 by Barnoski and Jensen [1], which utilizes the backscattered Rayleigh signal to determine optical loss along a length of fibre. In an OTDR system, a pulse of light is transmitted down the fibre and the light which is backscattered within the numerical aperture of the fibre is detected and measured. The time between sending the pulse of light and detecting the backscattered signal gives a measure of the distance along the fibre, whilst the intensity of the backscattered light provides information about the measurand. An alternative, novel method for distributed sensing, using a frequency-domain approach, was performed by Ghafoori-Shiraz and Okoshi [2]. The frequency-domain analysis is based on the measurement of a complex baseband transfer function, which then provides the amplitude of both pump and Stokes wave along a fibre length using a network analyser. With the frequency-domain approach, distributed temperature and strain measurements have been performed with a spatial resolution of 3 m over a 1 km sensing range [3].

Systems based on Raman backscatter have proved commercially successful as instruments for performing distributed temperature measurements, due to the practical approach of using conventional silica-based optical fibre as the sensing element. However, these sensors are unable to achieve measurement of distributed strain. As a result, another category of sensors, utilizing Brillouin scattering, have received much attention. Simultaneous measurement of temperature and strain is possible using Brillouin scattering since both its frequency shift and power are dependent on both of these quantities. Several techniques have been developed for obtaining the backscattered Brillouin signal, in order to enable the measurement of distributed strain and/or temperature. Both stimulated and spontaneous Brillouin scattering regimes for distributed sensing have previously been reported.

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In the case of stimulated scattering, access to both ends of the sensing fibre, or provision of an end-reflection, is required. In either the Brillouin-gain or Brillouin-loss stimulated scattering mechanism, the measured quantity is usually just the Brillouin frequency shift, which is found using the interaction between counterpropagating pulsed and CW radiation, separated by approximately the Brillouin frequency shift [4, 5]. The frequency shift distribution is determined by maximizing the increase (or decrease) of the signal at each desired point along the sensing fibre; this maximum occurs when the frequency difference between the two lasers is equal to the Brillouin frequency shift at that point. In this way, it is possible to measure either strain or temperature, provided that the fibre is either at a constant temperature or strain, respectively. Simultaneous measurements using the Brillouin-loss technique have been attempted, utilizing the Brillouin-loss peak power as well as the frequency shift. However, this was only for a sensing length of 50 m of polarization-maintaining fibre and required a portion of this length to be kept at a known temperature and strain, as a reference [6]. Errors of 178 $\mu\varepsilon$ and 3.9 °C were measured, for a spatial resolution of 3.5 m, over this 50 m length.

With spontaneous scattering, access to only one end of the fibre is necessary. Furthermore, measurement of the spontaneous backscattered Brillouin power (normalized to the temperature- and strain-insensitive Rayleigh power) along with the Brillouin frequency shift, allows simultaneous measurement of temperature and strain over tens of kilometres. We focus on this type of sensor in this paper. Techniques for spontaneous Brillouin backscatter measurement fall broadly into two categories: direct detection and coherent (heterodyne) detection. In direct detection, the Brillouin signal must be optically separated from the much larger, elastic, Rayleigh component prior to detection. This has been done, for example, using Fabry–Perot [7, 8] or fibre Mach–Zehnder [9, 10] interferometers, but these optical filters must necessarily be highly stable due to the small frequency difference between Brillouin and Rayleigh components (~11 GHz at 1.5 μm). Simultaneous strain and temperature measurements have been performed using direct detection, for a sensing length of 15 km and a spatial resolution of 10 m, with an RMS temperature error of 4 °C and an RMS strain error of 290 $\mu\varepsilon$ [10].

Coherent detection employs a strong, narrow linewidth, optical local oscillator (OLO) which allows very good electrical filtering of the Brillouin component and so a much greater tolerance of Rayleigh contamination than direct detection. Coherent detection also results in a greater dynamic range, since the detector photocurrent, at the beat frequency, has only a square root dependence on signal power. Also, since the RMS signal photocurrent is much higher than that for direct detection, due to optical mixing with the OLO, a detector with a higher noise-equivalent power (NEP) may be used, for instance a broader-bandwidth detector. To date, coherent detection of spontaneous Brillouin backscatter has been achieved by arranging for the frequency shift between the OLO and sensing pulses to be approximately equal to the Brillouin shift, bringing the Brillouin/OLO beat frequency within the bandwidth of a conventional heterodyne receiver. This frequency shift has previously been attained using a Brillouin laser [11], an acousto-optic modulator (AOM) ring circuit [12] and an electro-optic modulator (EOM) [13, 14].

A technique for obtaining distributed spontaneous Brillouin backscattered spectra, which employs an 11 GHz microwave heterodyne system in conjunction with optical preamplification of the signal, has recently been introduced [15]. This sensor combines the advantages of coherent detection and spontaneous Brillouin measurement, allowing simultaneous single-ended measurement of temperature and strain over a long range, but it also exhibits further advantages due to the microwave detection frequency. In particular, since the expected range of Brillouin frequency shift (up to ~500 MHz) lies within a very small percentage of the total bandwidth of the detector (~20 GHz), the detector gain is almost constant for the entire signal. Also, the 11 GHz detection frequency allows independent observation of both Stokes and anti-Stokes spectra using the same optical arrangement: the signals are separated in frequency due to the shift of the AOM and also filtered optically by a narrow-band fibre Bragg grating. Furthermore, since high-frequency optical shifting elements are not required, as was the case in previous heterodyne systems, the frequency stability of the sensor is exceptionally good.

A brief overview of spontaneous Brillouin scattering and the technique for simultaneous strain and temperature measurements are provided in section 2. The construction and operation of the sensor is described in section 3 and the results obtained, including the first simultaneous temperature and strain measurements using this technique, are presented in section 4. Section 5 contains a summary of our findings.

2. Spontaneous Brillouin scattering for temperature and strain measurements

The initial observation of Brillouin scattering in bulk silica occurred in 1950 [16]. It has been shown [6, 17–19] that the Brillouin backscattered intensity and frequency shift exhibit both strain and temperature dependence. If the sensing fibre is subjected to both temperature and strain effects it is necessary to measure both the Brillouin intensity and frequency shift along the sensing fibre to obtain accurate information regarding temperature and/or strain.

Spontaneous Brillouin scattering results when a small fraction of the incident light is inelastically scattered by thermally excited acoustic waves (acoustic phonons) in the optical fibre. A periodic modulation of the dielectric constant and hence refractive index of the medium is generated due to density variations produced by the acoustic wave. The scattered light undergoes a Doppler frequency shift and has maximum scattering in the backwards direction. This frequency shift is given by

$$\nu_B = \frac{2nv_a}{\lambda_p} \tag{1}$$

where v_a is the acoustic velocity in the fibre, n is the refractive index and λ_p is the pump wavelength. The exponential decay nature of the acoustic waves results in a Lorentzian spectral profile.

The frequency shift of the backscattered signal is approximately three orders of magnitude smaller than for Raman scattering, corresponding to the much smaller acoustic phonon frequencies involved in Brillouin scattering (~11 GHz for a pump wavelength in the 1.5 μm wavelength region), which makes separation of the Brillouin from the Rayleigh signal more difficult.

The change in Brillouin frequency shift and power due to strain and temperature may be represented by the matrix equation

$$\begin{bmatrix} \Delta\nu_B \\ \Delta P_B \end{bmatrix} = \begin{bmatrix} C_{\nu_B\varepsilon} & C_{\nu_B T} \\ C_{P_B\varepsilon} & C_{P_B T} \end{bmatrix} \begin{bmatrix} \Delta\varepsilon \\ \Delta T \end{bmatrix} \tag{2}$$

where $C_{\nu_B\varepsilon}$ and $C_{\nu_B T}$ are the strain and temperature coefficients for frequency shift and $C_{P_B\varepsilon}$ and $C_{P_B T}$ are the coefficients for power variations. The two variables of strain and temperature can be resolved by taking the inverse of the above equation. If the inverse matrix is non-singular, i.e. if $C_{\nu_B\varepsilon}C_{P_B T} \neq C_{\nu_B T}C_{P_B\varepsilon}$, then a solution exists. For the values of the coefficients obtained in this paper, $C_{\nu_B\varepsilon}C_{P_B T}/C_{\nu_B T}C_{P_B\varepsilon} = -19.3$ and so simultaneous distributed temperature and strain measurement is possible. The inverse equation is given by

$$\begin{bmatrix} \Delta\varepsilon \\ \Delta T \end{bmatrix} = \frac{1}{|C_{\nu_B\varepsilon}C_{P_B T} - C_{P_B\varepsilon}C_{\nu_B T}|} \times \begin{bmatrix} C_{P_B T} & -C_{\nu_B T} \\ -C_{P_B\varepsilon} & C_{\nu_B\varepsilon} \end{bmatrix} \begin{bmatrix} \Delta\nu_B \\ \Delta P_B \end{bmatrix} \tag{3}$$

and the corresponding errors in the derived strain and temperature measurements are given by [20]

$$|\delta\varepsilon| = \frac{|C_{P_B T}||\delta\nu_B| + |C_{\nu_B T}||\delta P_B|}{|C_{\nu_B\varepsilon}C_{P_B T} - C_{P_B\varepsilon}C_{\nu_B T}|} \tag{4}$$

$$|\delta T| = \frac{|C_{P_B\varepsilon}||\delta\nu_B| + |C_{\nu_B\varepsilon}||\delta P_B|}{|C_{\nu_B\varepsilon}C_{P_B T} - C_{P_B\varepsilon}C_{\nu_B T}|}. \tag{5}$$

3. Experimental arrangement

The experimental configuration for the microwave heterodyne spontaneous Brillouin-based fibre sensor is shown in figure 1.

3.1. The source

Excellent frequency stability was ensured by deriving both the sensing pulses and the local oscillator from the same seed laser: a 100 μW continuous wave, fibre-pigtailed laser, tunable from ∼1520 to 1560 nm. The source itself was designed to be of dual nature. In one setting, used for the Brillouin measurements, the source was narrowband, with the linewidth of the seed laser (1 MHz); this was achieved with the fibre optic switch in position 1, the seed laser being amplified by the erbium-doped fibre amplifier, EDFA1. In the second setting, with the switch in position 2, the source was broadband (∼6 nm) and partially polarized, due to ASE feedback into EDFA1 from a broadband reflecting mirror via a pigtailed polarizer. The partial polarization of the ASE was necessary to aid its subsequent passage through the polarization-sensitive electro-optic modulator (EOM). The source output was ∼12 mW in either setting. Radiation from the source was split by a 3 dB fibre coupler into pulse and local oscillator arms.

3.2. Pulse formation

Pulses were initially formed by a 110 MHz, downshifting, fibre-pigtailed AOM before amplification by EDFA2 to give pulses up to 4.5 W peak power at 150 ns pulse width. An electro-optic modulator (EOM), of 5 dB insertion loss, was then used to gate the pulses in order to attenuate the throughput of ASE between pulses. The pulses were then passed through a PZT-based polarization scrambler (insertion loss 3 dB) to help reduce polarization noise observed on the signal. A second polarization scrambler, also with 3 dB insertion loss, was placed in the local oscillator arm to further reduce the noise. Using this arrangement, pulses of up to 350 mW could be launched down the 30 km of sensing fibre using a 3 dB coupler. In these experiments, pulses of between 150 and 160 mW and 150 and 200 ns were chosen, since spectral distortion occurs for much higher powers. A 95/5 fibre coupler was used as a tap for 5% of the backscattered signal, enabling separate direct detection of the Rayleigh trace, when operating in the broadband mode.

3.3. Brillouin preamplification

In narrowband mode, due to the low sensitivity of the detection system, the backscattered traces were preamplified using EDFA3 (small signal gain of 26.4 dB). Both the Rayleigh backscatter and the ASE from EDFA3 were then filtered out by reflection from an in-fibre Bragg grating (FBG) (reflectivity = 99.4%, $\lambda = 1533.11$ nm, $\Delta\lambda = 0.12$ nm), via a circulator. Either the anti-Stokes or Stokes signals could be observed by tuning the narrowband source to 1533.20 nm or 1533.02 nm respectively. Contact with the heavy metal optical bench and the use of air conditioning both increased the stability of the grating and so no thermal drift problems were encountered. Since a typical FBG central wavelength temperature sensitivity is 10–15 pm K^{-1} and the grating had a flat transmission peak of width 50 pm, ambient temperature changes of a degree or two were tolerable. Use of a thermally compensated grating package would have reduced this problem still further. The attenuation of the Rayleigh component rendered negligible its behaviour as a weak secondary oscillator. This is the principal method by which the Rayleigh can affect the Brillouin signal and is much less significant than an equivalent amount of contaminating Rayleigh power in direct detection, since it is the ratio of OLO power to Rayleigh power which is important, not the ratio of Brillouin power to Rayleigh power.

3.4. Detection system

The amplified, filtered backscatter was mixed with the local oscillator via a 3 dB coupler and then detected using a 20 GHz optical detector (responsivity of 35 V W^{-1}). The Brillouin/OLO beat spectra were observed using a 26.5 GHz RF spectrum analyser, set in zero span mode. In this mode, a time-domain trace is obtained for the selected RF beat frequency. The maximum available RF resolution bandwidth, of 5 MHz, was selected, allowing a spatial resolution of 20 m to be achieved. The spectra were built up by taking time-domain backscatter traces for a series of beat frequencies, covering the expected range of Brillouin shifts. Since the required

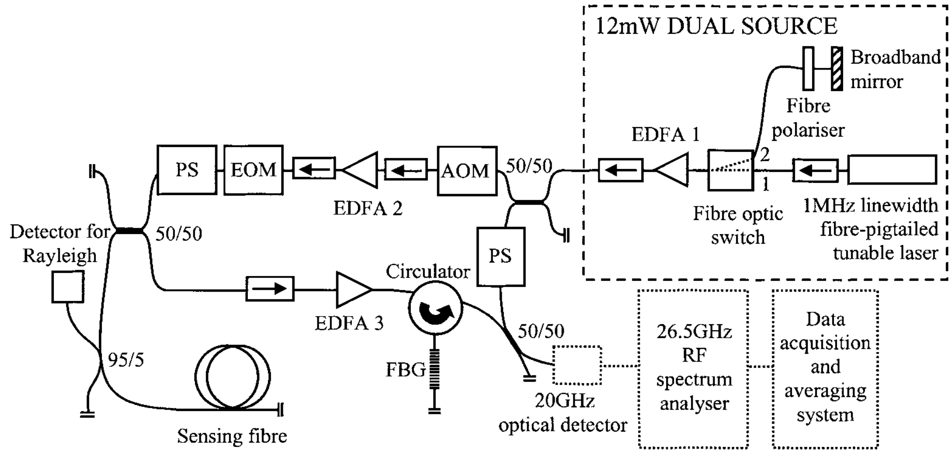

Figure 1. Experimental arrangement of the microwave heterodyne spontaneous Brillouin-based temperature and strain sensor. PS = polarization scrambler, AOM = acousto-optic modulator, EOM = electro-optic modulator, EDFA = erbium-doped fibre amplifier, FBG = fibre Bragg grating.

Brillouin power was necessarily proportional to RF power, but the recorded traces were proportional to RF voltage, squaring of the data was necessary. Any dc interpulse level was then subtracted and processing of the spectra was undertaken.

3.5. Spectrum processing

After each set of spectra was obtained, the frequency shift and power of the Brillouin backscatter was determined for each point of interest along the fibre. This was done by fitting each individual spectrum to a Lorentzian curve, since the spontaneous Brillouin line is known to be of this shape. The Levenberg–Marquardt nonlinear least squares algorithm was used for this purpose [21]. The total power, being proportional to the area under the curve, was then found. For the Lorentzian spectral profile, total power is proportional to peak power multiplied by linewidth. At certain points along the sensing fibre, where the frequency shift changes significantly over a distance smaller than the spatial resolution, a single Lorentzian curve is insufficient to determine the backscatter characteristics. To overcome these visible transitional hiccups, a double or even triple Lorentzian was fitted.

4. Distributed sensing results

Firstly, examples of the Lorentzian curve fitting are presented, to show the validity of the process. After this, distributed results for a 57 km sensing length are discussed, revealing the range limit for this system as a simultaneous temperature and strain sensor. A calibration of the dependence of both frequency shift and backscattered power on temperature was undertaken at this stage and the coefficients compared to previously measured values. Finally, simultaneous measurement of temperature and strain are discussed for a 30 km sensing fibre.

4.1. Lorentzian curve fitting

A sample set of distributed anti-Stokes Brillouin spectra is shown in figure 2(a) for a 3.5 km section, located 25 km down the sensing fibre. A 500 m heated portion (at 65 °C) is clearly visible due to its frequency shift from the unheated regions. Figure 2(b) shows a single spectrum from this 3.5 km section and its corresponding fitted Lorentzian curve. To estimate the goodness of fit, the value χ^2/N was calculated, which is defined by

$$\frac{\chi^2}{N} = \frac{1}{N}\sum_{i=1}^{N}\frac{(y_i - f(x_i))^2}{\sigma_i^2} \tag{6}$$

for a data set of N points, $(x_{i\ldots N}, y_{i\ldots N})$, with standard errors in y of $\sigma_{i\ldots N}$, being modelled to a function $f(x)$. χ^2/N should be roughly equal to unity for a good fit with the expected noise characteristics, with a closer fit being indicated by a lower value. To obtain an estimate in this case, the noise on each point was assumed to be identical and dominated by electrical noise, which was calculated as the standard deviation of the inter-pulse, flat, spectrum. The measured value of χ^2/N for figure 2(b) is 0.82, validating the choice of spectral profile. Examples of double and triple curve fitting results at ~31 km down the sensing fibre are shown in figure 3. χ^2/N values for these two curves, measured in an identical manner as before, are 1.24 and 0.86, again showing agreement with the model. Of course, the inclusion of any additional noise sources would decrease χ^2/N, for any given measured spectrum, since the standard error used in equation (6) would be larger. Automation of the processing may be achieved by firstly fitting to each spectrum a single Lorentzian curve; if χ^2/N is high, however, a double peak may then be tried, or a triple peak, and so on, until a good fit is obtained.

4.2. Measurements over a 57 km sensing fibre

In order to gauge the potential performance of the sensor, distributed anti-Stokes Brillouin spectra were obtained over a 57 km sensing fibre, the longest yet presented using single-ended detection of spontaneous Brillouin backscatter. The frequency shift and backscattered power measurements are shown in figure 4 for this fibre. These were obtained by taking a series of 25 different backscatter traces, each separated by 5 MHz, starting at 10.84 GHz; each trace was averaged 4096 times. The frequency measurements highlight the boundaries between different fibre sections, with the sharp troughs being

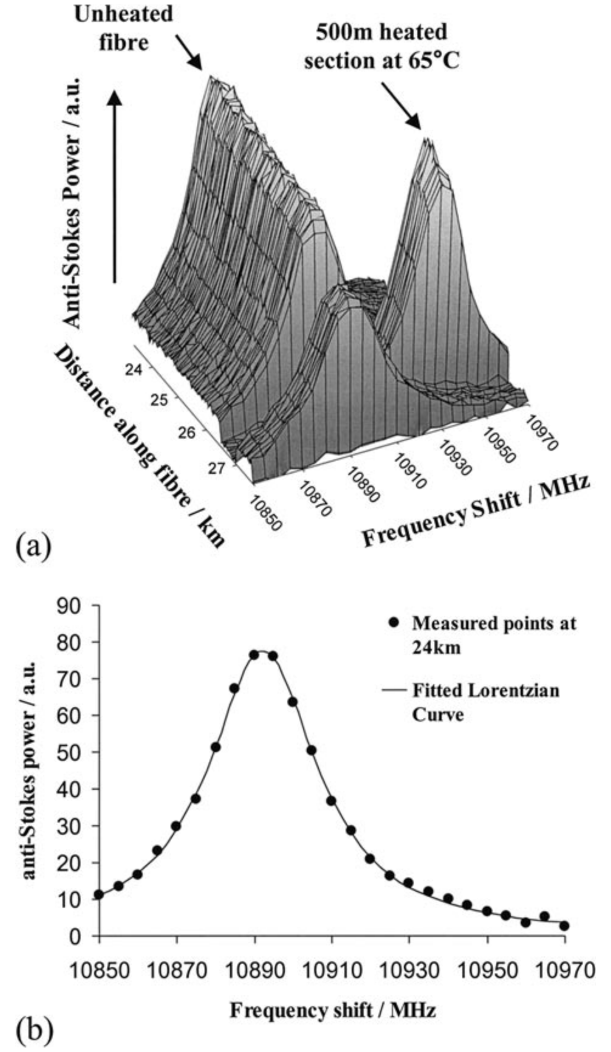

Figure 2. (a) Example distributed anti-Stokes Brillouin spectrum at ~25 km distance along the sensing fibre. A 500 m heated section at 65 °C is clearly visible. (b) Sample fitted Lorentzian curve (solid line) and the original data points (circles) for a single point at 24 km along the fibre.

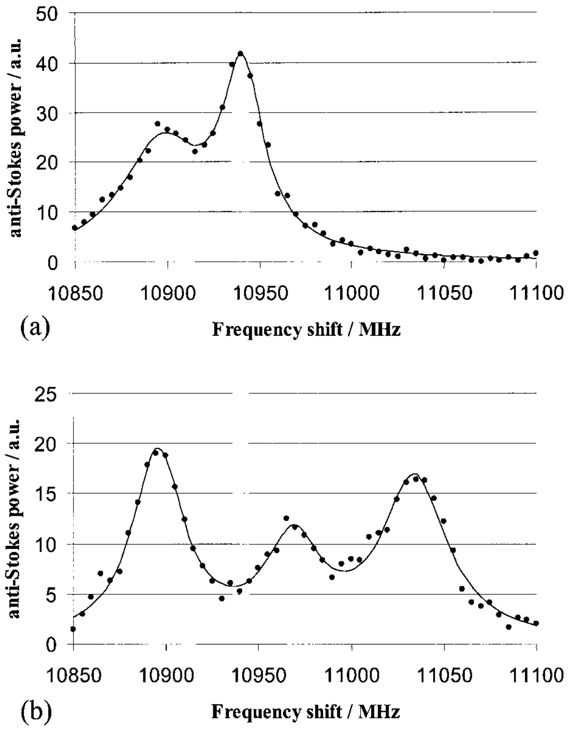

Figure 3. Example (a) double and (b) triple fitted Lorentzian curves. These are both for points ~31 km along the sensing fibre.

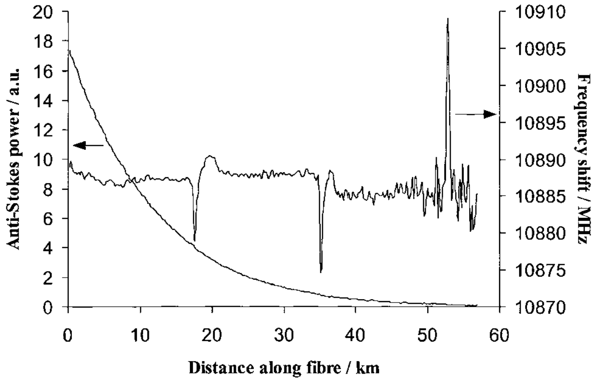

Figure 4. Distributed anti-Stokes Brillouin measurements for an entire 57 km fibre length. Both frequency shift and power traces are shown.

attributed to slack regions between wound drums. The sensing fibre comprises five separate fibre lengths, 17 500 m, 17 500 m, 17 500 m, 500 m and 4000 m, with the 500 m portion being placed in an oven and unwound from the drum to ensure the absence of strain and the rest of the fibre kept at the room temperature of 22 °C. The frequency measurements show clearly, at ~53 km along the fibre, the shift due to the 500 m heated section, held at 40 °C. Each unheated fibre section has a different frequency shift, which may arise from differences in winding tension or intrinsic fibre properties (refractive index or acoustic velocity). The power measurements show the expected exponential decrease with fibre length, agreeing with the predicted attenuation coefficient (~0.4 dB km^{-1} double pass at 1.53 μm).

The RMS noise in both the frequency shift and power traces were found over 2 km sections (10 data points) located at several positions along the fibre. The power values were found after first normalizing the observed trace to a fitted exponential function, one for each separate section of fibre. This information is plotted in figure 5(a) for the frequency shift and figure 5(b) for the power. The noise levels increase to 1.3 MHz and 5.8% at 50 km, corresponding to ~1.2 °C/28 $\mu\varepsilon$ and ~16 °C/6500 $\mu\varepsilon$ respectively. The power trace is clearly too noisy to allow a useful simultaneous sensor at this distance. Figure 5(b) indicates that a 1.5% RMS error would occur at 30 km, which brings the temperature error due to the power measurement down to less than 5 °C. The RMS power error remains at an approximately constant value of 0.7–0.8% for the first 20 km of the sensing fibre, over which the backscattered power has decreased by ~8 dB. This indicates that polarization noise, which may be expected to have a constant percentage value, has not been fully eliminated and so improved scrambling is necessary, for optimum resolution.

For an unstrained fibre, the frequency shift gives a direct measurement of temperature and, with this application in mind,

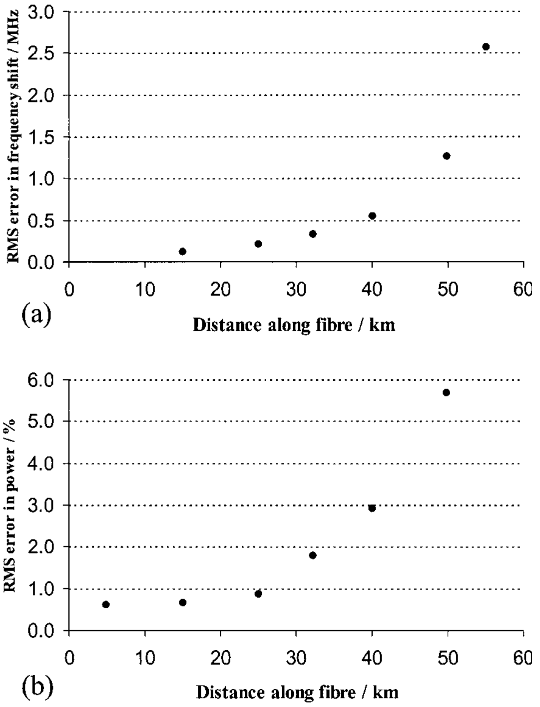

Figure 5. RMS error, taken over a 2 km window, in both (a) frequency shift and (b) power for the 57 km sensing fibre, plotted at several points along the fibre length.

calibrated temperature measurements were obtained for the heated section at 53 km. The RMS noise was calculated to be less than 2 MHz over the heated portion for each oven temperature; the traces are shown in figure 6(a). The expected linear relationship between frequency shift and temperature is clearly visible in figure 6(b), with the coefficient being 1.07 ± 0.06 MHz K^{-1}, agreeing in magnitude with other sources [22, 23].

4.3. *Power measurements over a 27 km sensing fibre*

Power measurements are more complicated to obtain than frequency shift measurements. Initially, the sensing length was merely reduced to 27.4 km (four sections of 17 500 m, 8900 m, 500 m and 500 m, with the third section being heated). The same technique as before was applied (this time for 25 frequencies separated by 5 MHz, starting at 10.85 GHz, each averaged 12 288 times) and a single Lorentzian was fitted for each point along the fibre. Discontinuities in temperature, however, resulted in sharp spikes in the recorded power, either side of the heated section. This is clearly visible in figure 7(a), which shows how the power measurements, at 26.5 km, depend on temperature. Ignoring the anomalies at either end of the heated section, another linear relationship is revealed and is shown in figure 7(b). The coefficient relating the percentage change in power to temperature was calculated as $0.36\pm0.04\%\ K^{-1}$, again agreeing with other sources [7, 22]. The artificial peaks may be removed, however, by fitting a double Lorentzian curve at the transitional points, as in figure 8. The RMS error in temperature was found to be less than 3.4 K (equivalent to 1.2% power error) at the heated section.

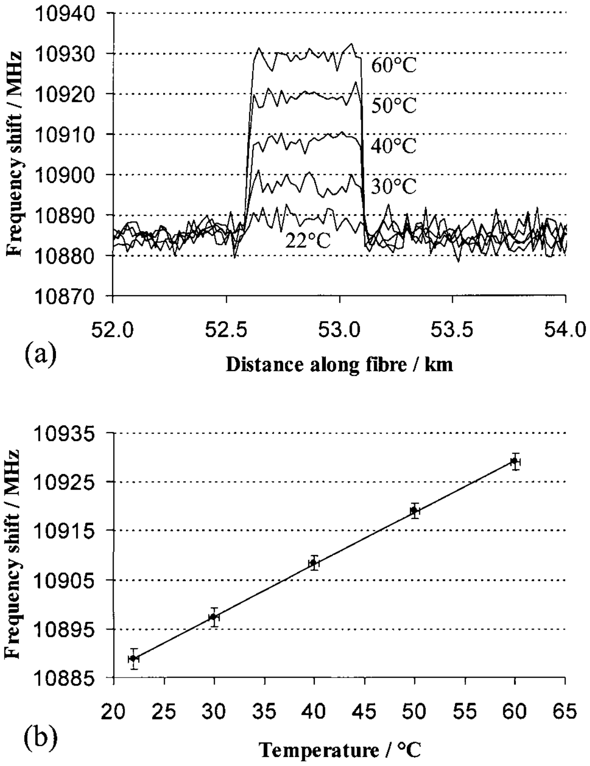

Figure 6. Variation of Brillouin frequency shift with temperature, for a 500 m heated region at 53 km along the sensing fibre. (a) Time-domain traces—RMS error is ~2 MHz. (b) Calibration of shift, yielding a coefficient of 1.07 ± 0.06 MHz $^{\circ}C^{-1}$.

4.4. *Simultaneous strain and temperature measurement over a 30 km sensing fibre*

Simultaneous results were achieved with a slightly longer fibre of length 31.8 km; a length of 4000 m was inserted between the first two sections of the previous sensing length and a 115 m strainable section, followed by a 200 m length of unstrained fibre, was added at the end. In this manner, the heated (unstrained) section (the same 500 m length as before) and the strained (unheated) section were arranged to lie between 30.4 km and 31.6 km down the fibre. The 115 m fibre section was strained by being passed round 11 pairs of pulleys, each pair separated horizontally by ~5 m, and loaded by placing weights inside a plastic container suspended at the end of the rig (figure 9). This configuration inevitably results in considerable differential strain across the whole 115 m length. Since a spatial resolution of 20 m was used, the 5 m separation of the pulleys resulted in the appearance, in places, of triple-peaked spectra, requiring the fitting of a triple Lorentzian spectrum. Although possible, no evidence of quadruple peaks was found. Also, since the Brillouin frequency shift induced by the maximum applied strain (a peak of 4600 $\mu\varepsilon \equiv 210$ MHz) was considerably larger than for the maximum temperature change used ($77.5\ ^{\circ}C \equiv 83$ MHz), this necessitated an increase in the frequency span of the collected traces. In fact, the span was increased to 400 MHz, since the degree of differential strain was not known; so 80 traces were taken at 5 MHz separation, starting at 10.85 GHz with 12 288 averages per trace. The differential strain can easily be seen in figure 10, a plot of distributed frequency shift for an applied extension of

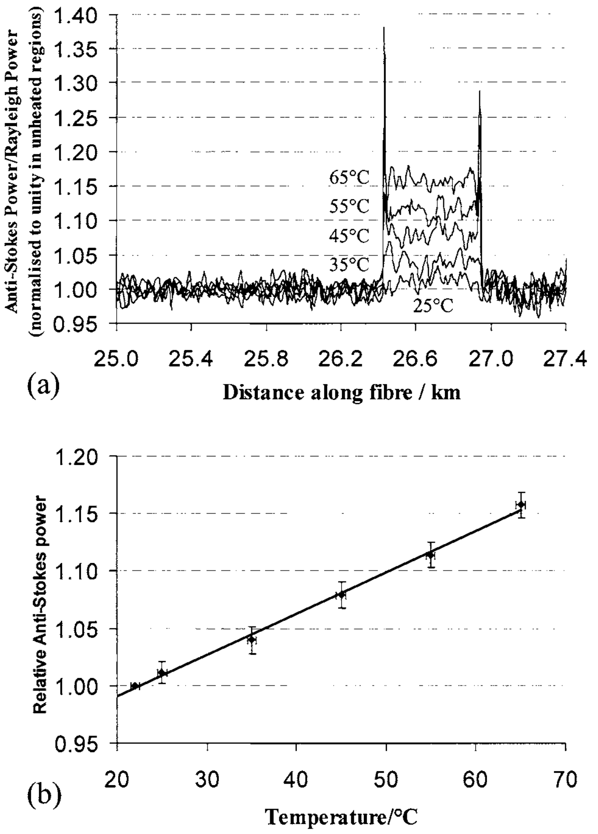

Figure 7. Variation of normalized anti-Stokes power measurements with temperature, for a 500 m heated section at 26.5 km along the sensing fibre. (a) Time-domain traces—RMS error is ∼1.2%. Spikes are due to poor curve fitting of double peaks. (b) Calibration of power change, yielding a coefficient of 0.36% °C^{-1}.

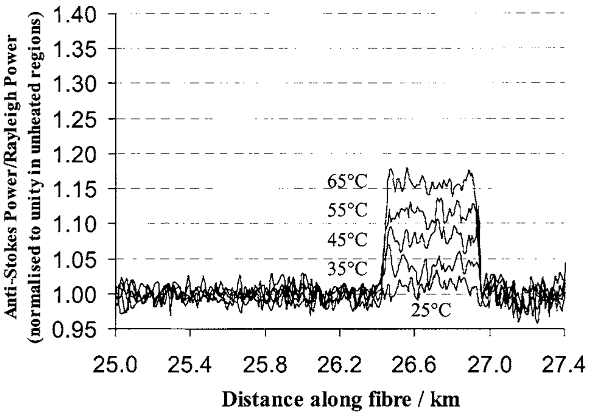

Figure 8. Elimination of anomalous peaks at temperature discontinuities, by fitting of a double Lorentzian curve, is demonstrated using the data of figure 7(a).

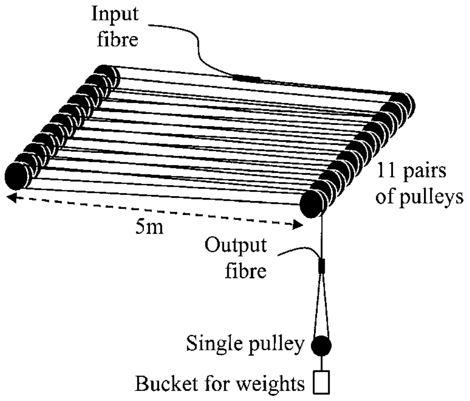

Figure 9. Illustration of the rig used to strain fibre for distributed measurements.

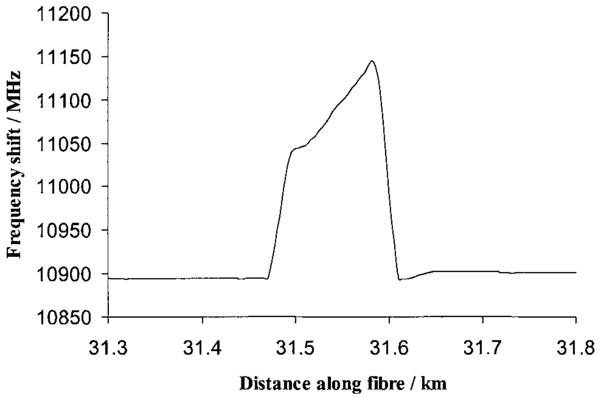

Figure 10. A frequency shift trace for 115 m of strained fibre located 31.5 km along the sensing fibre. It is clear, since the fibre is all at room temperature, that considerable differential strain is present over the 115 m length.

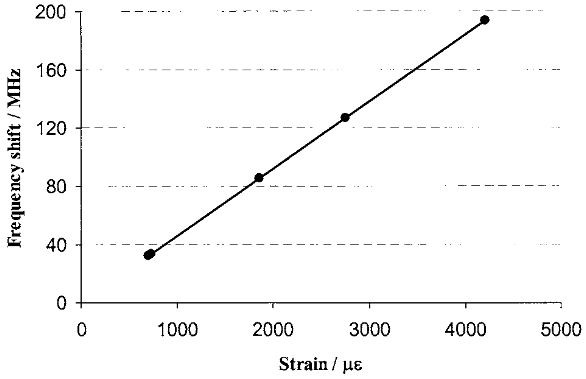

Figure 11. Dependence of the Brillouin frequency shift on applied strain. The coefficient of the dependence was measured to be 0.046 MHz $\mu\varepsilon^{-1}$.

48.8 cm, corresponding to a strain of 4240 $\mu\varepsilon$. In this case, the peak-to-peak variation is approximately 50% of the average strain. The frequency shift is determined by finding its average value over the strained region; it is this value that is assumed to arise from a constant strain of 4240 $\mu\varepsilon$.

Before simultaneous measurements were attempted, however, both the frequency shift (figure 11) and power (figure 12) were calibrated against strain, in order to determine the two remaining coefficients required for the inverse matrix. The frequency response was linear with a coefficient of 0.046 MHz $\mu\varepsilon^{-1}$; however the power measurement was less conclusive due to the large noise present on the signal. Linear regression of the power dependence gave a coefficient of $-8{\pm}5\times10^{-4}\%$ $\mu\varepsilon^{-1}$. Both of these values agree with previous results [17, 19, 22].

For the simultaneous results, all power measurements were referenced to the Rayleigh trace, obtained in broadband mode, and all frequency shift measurements referenced to that

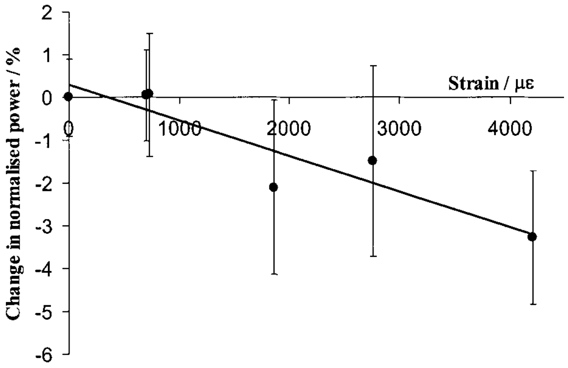

Figure 12. Dependence of the normalized anti-Stokes Brillouin power on temperature. The coefficient of the dependence was measured to be $-8 \pm 5 \times 10^{-4}\%\ \mu\varepsilon^{-1}$.

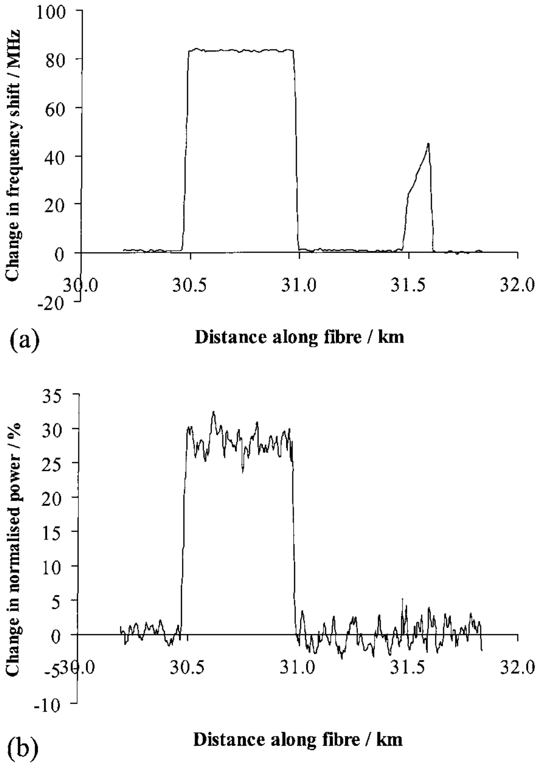

Figure 13. Measured (a) frequency shift and (b) normalized anti-Stokes power for a fibre section containing a 500 m heated region at 100 °C and a 115 m strained region at an average strain of 730 $\mu\varepsilon$, located at ~30 km along the sensing fibre.

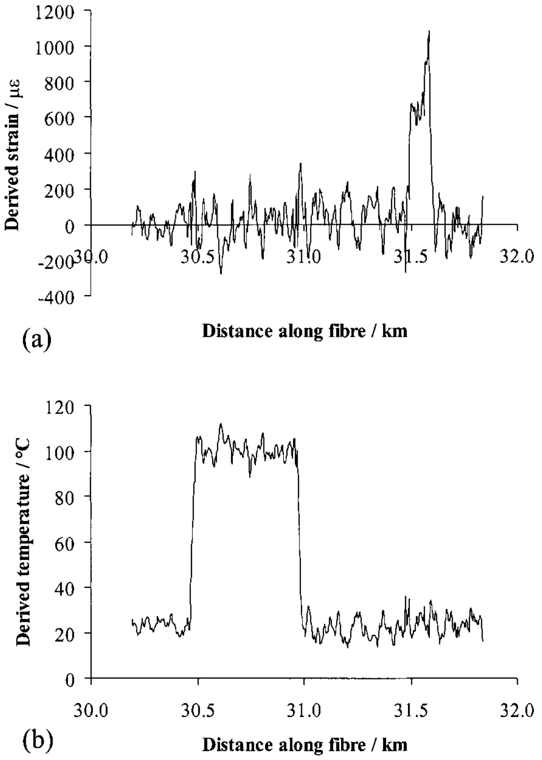

Figure 14. Derived distributed (a) strain and (b) temperature measurements, based upon the measured data in figure 13. The RMS error in strain was calculated as 100 $\mu\varepsilon$ and the RMS error in temperature as 4 °C.

observed with zero strain. The frequency shift and percentage power change are shown in figure 13 for a heated section at 100 °C and a strained section at 730 $\mu\varepsilon$. The RMS noise on the frequency shift trace, over the 500 m heated region, is 0.3 MHz and the RMS noise on the power measurement, over this same region, is 1.56%. From equations (4) and (5), the corresponding errors in temperature and strain are given by 4.1 °C and 102 $\mu\varepsilon$, respectively. As a corroboratory measurement, the frequency shift and power RMS noise values for the fibre section between the heated and strained regions are 0.29 MHz and 1.49%, resulting in temperature and strain errors of 3.9 °C and 97.5 $\mu\varepsilon$. It can be concluded that the RMS noise on the temperature and strain traces at 31 km along the fibre is ~4 °C and ~100 $\mu\varepsilon$. The corresponding derived temperature and strain measurements are shown in figure 14. It can be seen that there is little cross-talk between strain and temperature. It is also clear that the noise on both derived traces is dominated by that on the measured power trace. Indeed, it can be calculated using equations (4) and (5) that, for errors of 4 °C and 100 $\mu\varepsilon$, the noise on the power trace is responsible for 99.7% of the temperature error and 94% of the strain error, showing that the power measurements are by far the limiting factor on sensor resolution. It can also be seen from figure 14 that, with the heated section at 100 °C, outside the range of temperatures used in the power and frequency shift calibration measurements, the heated temperature is measured faithfully by the sensor. This indicates that the linearity of the Brillouin frequency shift and power with temperature is maintained up to this higher temperature.

5. Conclusions

We have presented a spontaneous Brillouin-based distributed fibre temperature and strain sensor that uses microwave coherent detection of the backscattered signals at the 11 GHz Brillouin shift frequency. This technique benefits from the advantages inherent to both coherent detection and spontaneous Brillouin measurement as well as to the microwave nature of our detection system. Coherent operation gives very good intrinsic electrical separation of the Brillouin from the Rayleigh, which is hard to achieve using optical filtering methods. Furthermore, the heterodyne technique allows the use of a broader-band detector, with a higher NEP, since the signal photocurrent is increased by mixing with the strong optical local oscillator. Also the dynamic range is increased due to the square root dependence of detector photocurrent on signal power. In the spontaneous scattering regime, access to only one end of the sensing fibre is required, promoting sensor versatility. High-frequency detection ensures that the total expected range of Brillouin frequency shift lies within a very small percentage of the total detector bandwidth, giving an almost constant gain for the entire signal. Also, the 20 GHz bandwidth of the detector allows both Stokes and anti-Stokes spectra to be observed easily and independently. Furthermore, since high-frequency optical shifting elements are not required, as was the case in previous heterodyne systems, the frequency stability of the sensor is excellent.

We have demonstrated frequency shift measurements and power measurements which have temperature and strain dependences closely agreeing with previously published results. We have obtained long-range 57 km frequency shift measurements with an RMS error of less than 3 MHz for the entire length and less than 0.6 MHz for the first 40 km. A target 5 °C error in power measurement limited the range used for simultaneous temperature and strain measurements to 30 km. These simultaneous results yielded a 4 °C RMS temperature error and a 100 $\mu\varepsilon$ RMS strain error at the end of this fibre for a spatial resolution of 20 m.

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References

[1] Barnoski M K and Jensen S M 1976 Fiber waveguides: a novel technique for investigating attenuation characteristics *Appl. Opt.* **15** 2112–15

[2] Ghafoori-Shiraz H and Okoshi T 1986 Fault location in optical fibers using optical frequency domain reflectometry *J. Lightwave Technol.* **4** 316–22

[3] Garus D, Gogolla T, Krebber K and Schliep F 1997 Brillouin optical-fiber frequency-domain analysis for distributed temperature and strain measurements *J. Lightwave Technol.* **15** 654–62

[4] Horiguchi T, Kurashima T and Tateda M 1990 A technique to measure distributed strain in optical fibers *IEEE Photon. Technol. Lett.* **2** 352–4

[5] Bao X, Dhliwayo J, Heron N, Webb D J and Jackson D A 1995 Experimental and theoretical studies on a distributed temperature sensor based on Brillouin scattering *J. Lightwave Technol.* **13** 1340–8

[6] Smith J, Brown A, DeMerchant M and Bao X 1999 Simultaneous distributed strain and temperature measurement *Appl. Opt.* **38** 5372–7

[7] Wait P C and Newson T P 1996 Landau Placzek ratio applied to distributed fibre sensing *Opt. Commun.* **122** 141–6

[8] Parker T R, Farhadiroushan M, Handerek V A and Rogers A J 1997 A fully distributed simultaneous strain and temperature sensor using spontaneous Brillouin backscatter *IEEE Photon. Technol. Lett.* **9** 979–81

[9] Lees G P, Wait P C, Cole M J and Newson T P 1998 Advances in optical fiber distributed temperature sensing using the Landau–Placzek ratio *IEEE Photon. Technol. Lett.* **10** 126–8

[10] Kee H H, Lees G P and Newson T P 2000 All-fiber system for simultaneous interrogation of distributed strain and temperature sensing by spontaneous Brillouin scattering *Opt. Lett.* **25** 695–7

[11] Lecoeuche V, Webb D J, Pannell C N and Jackson D A 1999 16 km distributed temperature sensor based on coherent detection of spontaneous Brillouin scattering using a Brillouin laser *Tech. Dig. Optical Fiber Sensors 13* (Washington, DC: Optical Society of America) pp 349–52

[12] Shimizu K, Horiguchi T, Koyamada Y and Kurashima T 1994 Coherent self-heterodyne Brillouin OTDR for measurement of Brillouin frequency shift distribution in optical fibers *J. Lightwave Technol.* **12** 730–6

[13] Tsuji K, Shimizu K, Horiguchi T and Koyamada Y 1995 Coherent optical frequency domain reflectometry for a long single-mode optical fiber using a coherent lightwave source and an external phase modulator *IEEE Photon. Technol. Lett.* **7** 804–6

[14] Izumita H, Sato T, Tateda M and Koyamada Y 1996 Brillouin OTDR employing optical frequency shifter using side-band generation technique with high-speed LN phase-modulator *IEEE Photon. Technol. Lett.* **8** 1674–6

[15] Maughan S M, Kee H H and Newson T P 2001 57-km single-ended spontaneous Brillouin-based distributed fiber temperature sensor using microwave coherent detection *Opt. Lett.* **26** 331–3

[16] Krishnan R S 1950 Fine structure of the Rayleigh line in amorphous substances *Nature* **165** 933–4

[17] Horiguchi T, Kurashima T and Tateda M 1989 Tensile strain dependence of Brillouin frequency shift in silica optical fibres *IEEE Photon. Technol. Lett.* **1** 107–8

[18] Culverhouse D, Farahi F, Pannell C N and Jackson D A 1989 Potential of stimulated Brillouin scattering as a sensing mechanism for distributed temperature sensors *Electron. Lett.* **25** 913–15

[19] De Souza K, Wait P C and Newson T P 1997 Characterisation of strain dependence of the Landau–Placzek ratio for distributed sensing *Electron. Lett.* **33** 615–16

[20] Jones J D C 1997 Review of fibre sensor techniques for temperature-strain discrimination *12th Int. Conf. on Optical Fiber Sensors OFS-12* vol 16, OSA Technical Digest Series (Washington, DC: Optical Society of America) pp 36–9

[21] Press W H, Teukolsky S A, Vetterling W T and Flannery B P 1995 *Numerical Recipes in C—the Art of Scientific Computing* 2nd edn (Cambridge: Cambridge University Press)

[22] Parker T R, Farhadiroushan M, Handerek V A and Rogers A J 1997 Temperature and strain dependence of the power level and frequency of spontaneous Brillouin scattering in optical fibers *Opt. Lett.* **22** 787–9

[23] Kurashima T, Horiguchi T and Tateda M 1990 Thermal effects of Brillouin gain spectra in single-mode fibers *IEEE Photon. Technol. Lett.* **2** 718–20

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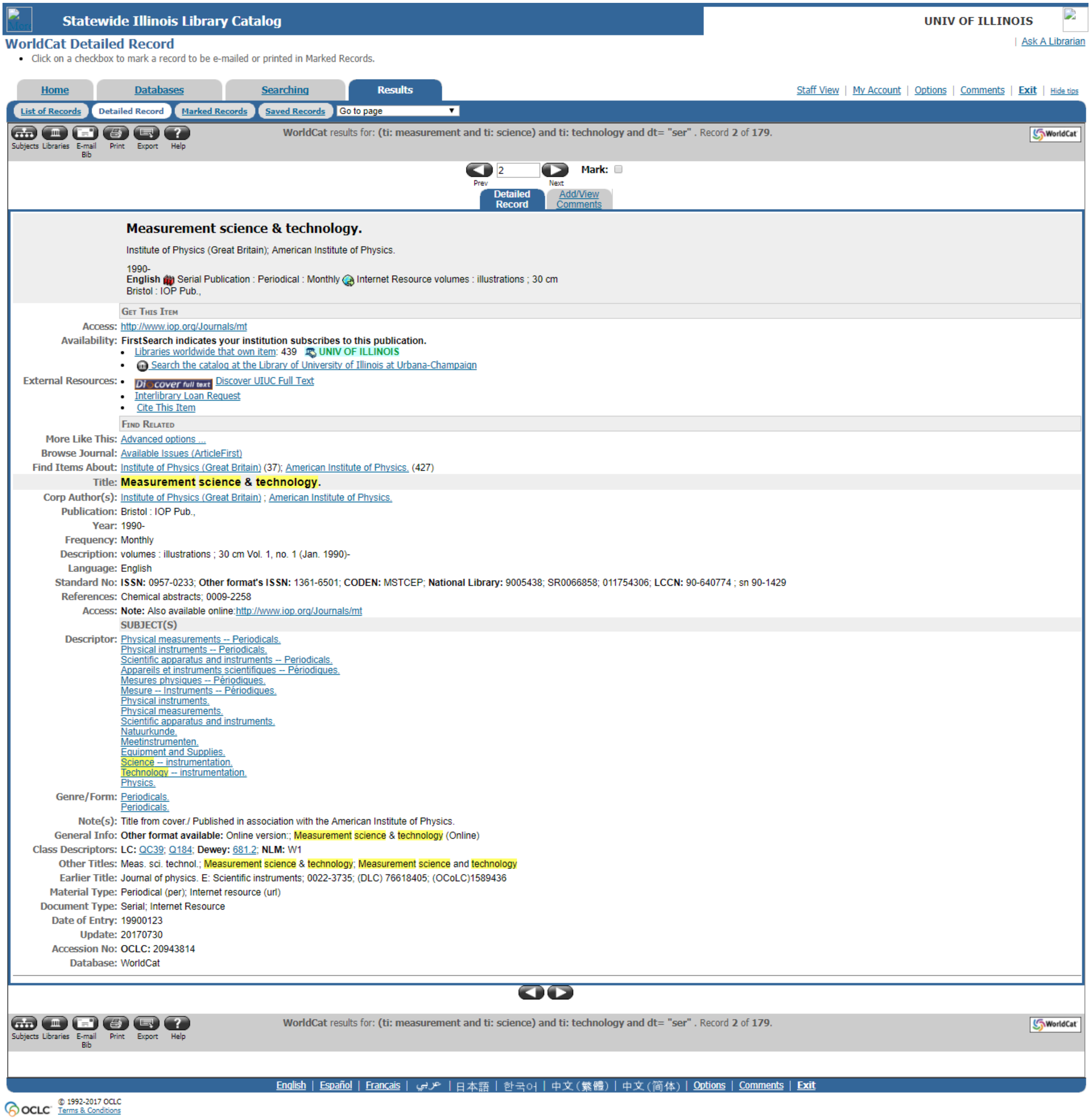

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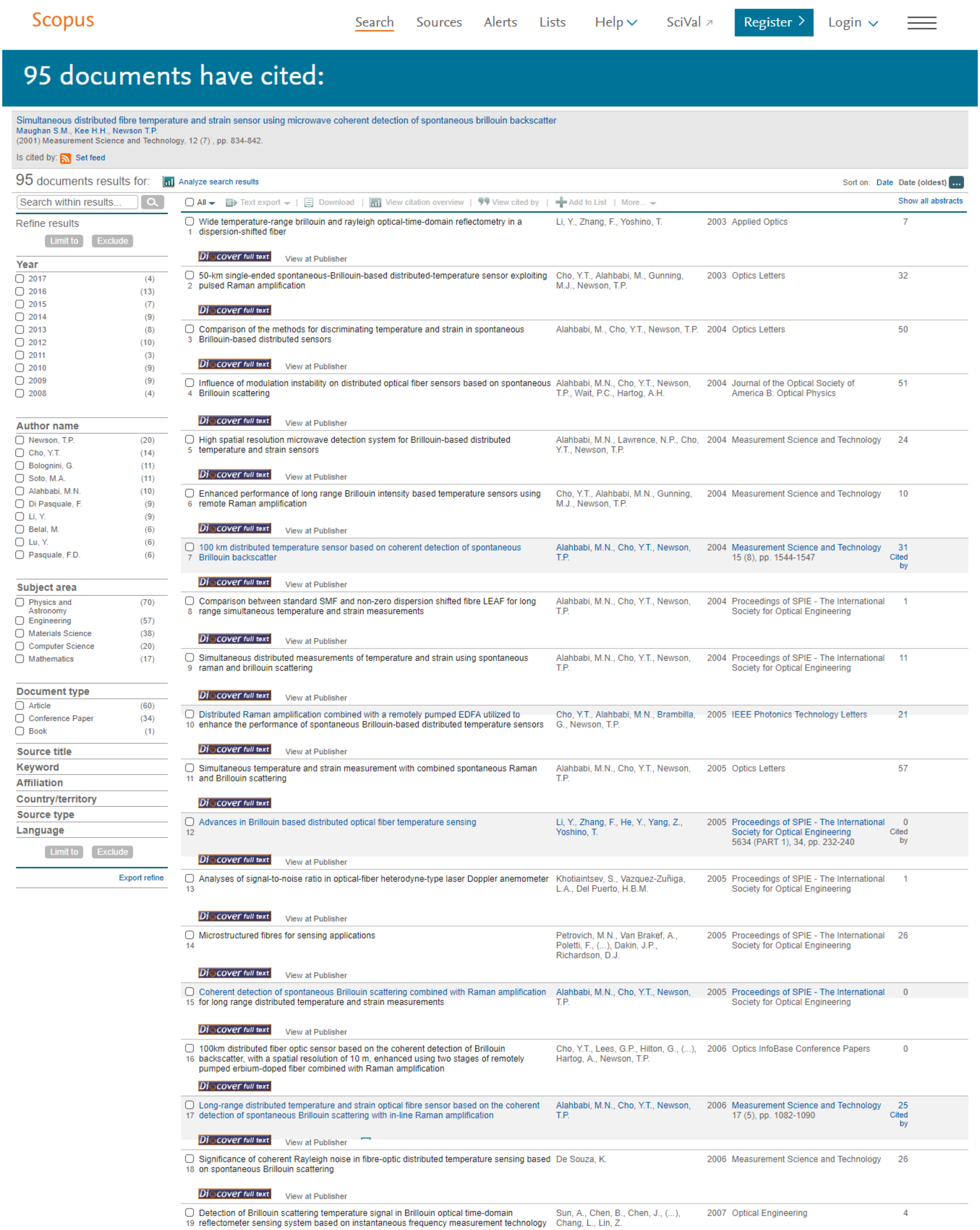

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☐ 2	50-km single-ended spontaneous-Brillouin-based distributed-temperature sensor exploiting pulsed Raman amplification	Cho, Y.T., Alahbabi, M., Gunning, M.J., Newson, T.P.	2003	Optics Letters	32
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☐ 4	Influence of modulation instability on distributed optical fiber sensors based on spontaneous Brillouin scattering	Alahbabi, M.N., Cho, Y.T., Newson, T.P., Wait, P.C., Hartog, A.H.	2004	Journal of the Optical Society of America B: Optical Physics	51
☐ 5	High spatial resolution microwave detection system for Brillouin-based distributed temperature and strain sensors	Alahbabi, M.N., Lawrence, N.P., Cho, Y.T., Newson, T.P.	2004	Measurement Science and Technology	24
☐ 6	Enhanced performance of long range Brillouin intensity based temperature sensors using remote Raman amplification	Cho, Y.T., Alahbabi, M.N., Gunning, M.J., Newson, T.P.	2004	Measurement Science and Technology	10
☐ 7	100 km distributed temperature sensor based on coherent detection of spontaneous Brillouin backscatter	Alahbabi, M.N., Cho, Y.T., Newson, T.P.	2004	Measurement Science and Technology 15 (8), pp. 1544-1547	31 Cited by
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☐ 9	Simultaneous distributed measurements of temperature and strain using spontaneous raman and brillouin scattering	Alahbabi, M.N., Cho, Y.T., Newson, T.P.	2004	Proceedings of SPIE - The International Society for Optical Engineering	11
☐ 10	Distributed Raman amplification combined with a remotely pumped EDFA utilized to enhance the performance of spontaneous Brillouin-based distributed temperature sensors	Cho, Y.T., Alahbabi, M.N., Brambilla, G., Newson, T.P.	2005	IEEE Photonics Technology Letters	21
☐ 11	Simultaneous temperature and strain measurement with combined spontaneous Raman and Brillouin scattering	Alahbabi, M.N., Cho, Y.T., Newson, T.P.	2005	Optics Letters	57
☐ 12	Advances in Brillouin based distributed optical fiber temperature sensing	Li, Y., Zhang, F., He, Y., Yang, Z., Yoshino, T.	2005	Proceedings of SPIE - The International Society for Optical Engineering 5634 (PART 1), 34, pp. 232-240	0 Cited by
☐ 13	Analyses of signal-to-noise ratio in optical-fiber heterodyne-type laser Doppler anemometer	Khotiaintsev, S., Vazquez-Zuñiga, L.A., Del Puerto, H.B.M.	2005	Proceedings of SPIE - The International Society for Optical Engineering	1
☐ 14	Microstructured fibres for sensing applications	Petrovich, M.N., Van Brakef, A., Poletti, F., (...), Dakin, J.P., Richardson, D.J.	2005	Proceedings of SPIE - The International Society for Optical Engineering	26
☐ 15	Coherent detection of spontaneous Brillouin scattering combined with Raman amplification for long range distributed temperature and strain measurements	Alahbabi, M.N., Cho, Y.T., Newson, T.P.	2005	Proceedings of SPIE - The International Society for Optical Engineering	0
☐ 16	100km distributed fiber optic sensor based on the coherent detection of Brillouin backscatter, with a spatial resolution of 10 m, enhanced using two stages of remotely pumped erbium-doped fiber combined with Raman amplification	Cho, Y.T., Lees, G.P., Hilton, G., (...), Hartog, A., Newson, T.P.	2006	Optics InfoBase Conference Papers	0
☐ 17	Long-range distributed temperature and strain optical fibre sensor based on the coherent detection of spontaneous Brillouin scattering with in-line Raman amplification	Alahbabi, M.N., Cho, Y.T., Newson, T.P.	2006	Measurement Science and Technology 17 (5), pp. 1082-1090	25 Cited by
☐ 18	Significance of coherent Rayleigh noise in fibre-optic distributed temperature sensing based on spontaneous Brillouin scattering	De Souza, K.	2006	Measurement Science and Technology	26
☐ 19	Detection of Brillouin scattering temperature signal in Brillouin optical time-domain reflectometer sensing system based on instantaneous frequency measurement technology	Sun, A., Chen, B., Chen, J., (...), Chang, L., Lin, Z.	2007	Optical Engineering	4

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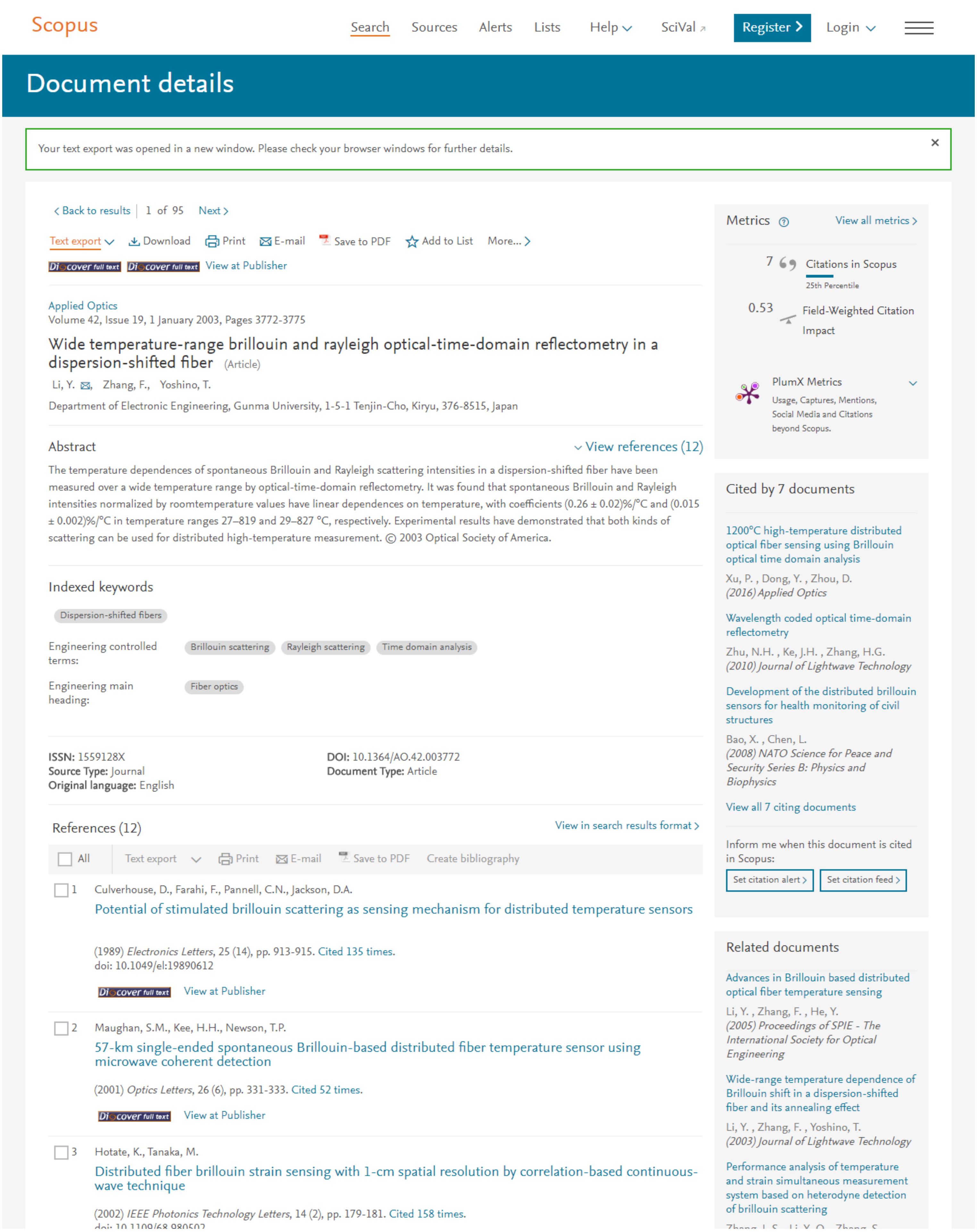

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Wide temperature-range brillouin and rayleigh optical-time-domain reflectometry in a dispersion-shifted fiber (Article)

Li, Y., Zhang, F., Yoshino, T.
Department of Electronic Engineering, Gunma University, 1-5-1 Tenjin-Cho, Kiryu, 376-8515, Japan

Abstract

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The temperature dependences of spontaneous Brillouin and Rayleigh scattering intensities in a dispersion-shifted fiber have been measured over a wide temperature range by optical-time-domain reflectometry. It was found that spontaneous Brillouin and Rayleigh intensities normalized by roomtemperature values have linear dependences on temperature, with coefficients (0.26 ± 0.02)%/°C and (0.015 ± 0.002)%/°C in temperature ranges 27–819 and 29–827 °C, respectively. Experimental results have demonstrated that both kinds of scattering can be used for distributed high-temperature measurement. © 2003 Optical Society of America.

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References (12)

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☐ 1 Culverhouse, D., Farahi, F., Pannell, C.N., Jackson, D.A.
Potential of stimulated brillouin scattering as sensing mechanism for distributed temperature sensors
(1989) *Electronics Letters*, 25 (14), pp. 913-915. Cited 135 times.
doi: 10.1049/el:19890612
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☐ 2 Maughan, S.M., Kee, H.H., Newson, T.P.
57-km single-ended spontaneous Brillouin-based distributed fiber temperature sensor using microwave coherent detection
(2001) *Optics Letters*, 26 (6), pp. 331-333. Cited 52 times.
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☐ 3 Hotate, K., Tanaka, M.
Distributed fiber brillouin strain sensing with 1-cm spatial resolution by correlation-based continuous-wave technique
(2002) *IEEE Photonics Technology Letters*, 14 (2), pp. 179-181. Cited 158 times.

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Xu, P. , Dong, Y. , Zhou, D.
(2016) Applied Optics

Wavelength coded optical time-domain reflectometry
Zhu, N.H. , Ke, J.H. , Zhang, H.G.
(2010) Journal of Lightwave Technology

Development of the distributed brillouin sensors for health monitoring of civil structures
Bao, X. , Chen, L.
(2008) NATO Science for Peace and Security Series B: Physics and Biophysics

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Performance analysis of temperature and strain simultaneous measurement system based on heterodyne detection of brillouin scattering

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☐ 4 Parker, T.R., Farhadiroushan, M., Handerek, V.A., Rogers, A.J.
A fully distributed simultaneous strain and temperature sensor using spontaneous Brillouin backscatter

(1997) *IEEE Photonics Technology Letters*, 9 (7), pp. 979-981. Cited 124 times.
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☐ 5 Maughan, S.M., Kee, H.H., Newson, T.P.
Simultaneous distributed fibre temperature and strain sensor using microwave coherent detection of spontaneous brillouin backscatter

(2001) *Measurement Science and Technology*, 12 (7), pp. 834-842. Cited 95 times.
doi: 10.1088/0957-0233/12/7/315

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☐ 6 Kurashima, Toshio, Horiguchi, Tsuneo, Izumita, Hisashi, Furukawa, Shin-ichi, Koyamada, Yahei
Brillouin optical-fiber time domain reflectometry

(1993) *IEICE Transactions on Communications*, E76-B (4), pp. 382-390. Cited 222 times.

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☐ 7 De Souza, K., Wait, P.C., Newson, T.P.
Double-pass configured fibre Mach-Zehnder interferometric optical filter for distributed fibre sensing

(1997) *Electronics Letters*, 33 (25), pp. 2148-2149. Cited 17 times.

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☐ 8 Parker, T.R., Farhadiroushan, M., Handerek, V.A., Rogers, A.J.
Temperature and strain dependence of the power level and frequency of spontaneous Brillouin scattering in optical fibers

(1997) *Optics Letters*, 22 (11), pp. 787-789. Cited 133 times.

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☐ 9 Perina, J.
(1984) *Quantum Statistics of Linear and Nonlinear Optical Phenomena*. Cited 627 times.
(Reidel, Dordrecht, The Netherlands

☐ 10 Shiota, T., Hidaka, H., Fukuda, O., Inada, K.
High-Temperature Effects of Aluminum-Coated Fiber

(1986) *Journal of Lightwave Technology*, 4 (8), pp. 1151-1156. Cited 10 times.
doi: 10.1109/JLT.1986.1074838

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☐ 11 Lines, M.E.
Scattering losses in optic fiber materials. I. A new parametrization

(1984) *Journal of Applied Physics*, 55 (11), pp. 4052-4057. Cited 81 times.
doi: 10.1063/1.332994

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☐ 12 Bucaro, J.A., Dardy, H.D.
High-temperature Brillouin scattering in fused quartz

(1974) *Journal of Applied Physics*, 45 (12), pp. 5324-5329. Cited 104 times.
doi: 10.1063/1.1663238

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(2008) 2008 1st Asia-Pacific Optical Fiber Sensors Conference, APOS 2008

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Fiber Optic Sensors

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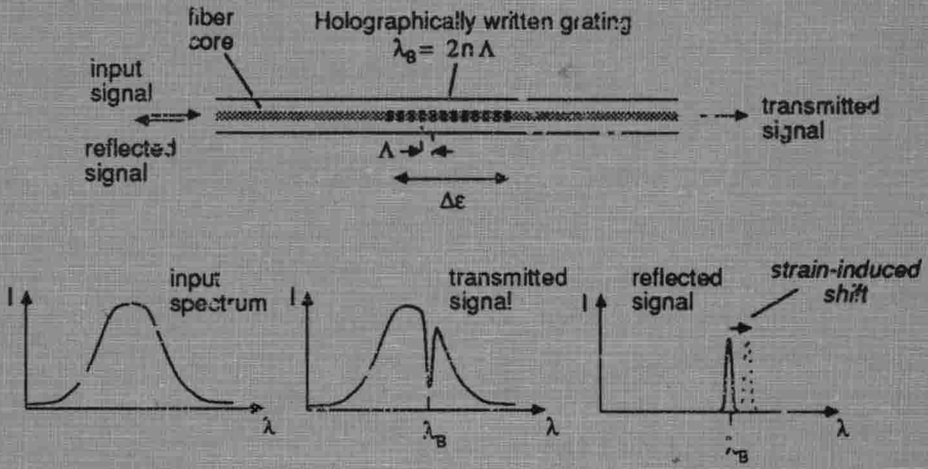

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Fiber Optic Sensors

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Cover illustration: *Diagram of a fiber Bragg grating sensor system, from the paper "Multiplexed fiber optic sensors" by A. D. Kersey, p. 202.*

Contents

APPLICATIONS OF FIBER OPTIC SENSORS

MULTIPLEXED FIBER OPTIC SENSORS

Alan D. Kersey

Optical Techniques Branch, Code 5670
Naval Research Laboratory
Washington, D.C. 20375

ABSTRACT

A wide range of multiplexing techniques for fiber optic sensors have been proposed and demonstrated over the past 10 years. In many cases, systems utilizing multiplexed sensors have under gone field trails which have successfully proven the technology. This paper reviews this technology, and discusses recent research efforts in the area.

1. INTRODUCTION

The ability to multiplex sensors is an important issue in many of the proposed application areas for fiber optic sensors. Whether the application involves high sensitivity military sensor systems, industrial process control sensors, chemical sensing, or environmental and structural sensing, the use of multiplexing techniques can be beneficial in regard of a number of system aspects including reduced component costs, lower fiber count in telemetry cables, ease of E/O interfacing, and overall system immunity to EMI. The development of efficient multiplexing techniques can thus be expected to lead to general improvements in the competitiveness of fiber sensors compared with conventional technologies in a broad range of application areas.

This paper reviews the development of multiplexing techniques for fiber sensors, including simple serial arrays of sensors based on optical time domain reflectometry (OTDR) processing concepts, to highly sophisticated interferometric fiber sensors. Recent developments in the area are also discussed.

2. SERIAL POINT SENSOR (QUASI-DISTRIBUTED) NETWORKS

The simplest form of multiplexed sensor system involves the serial concatenation of point or 'quasi-point' fiber sensors in a linear array. This type of system can be interrogated using OTDR signal processing [1], and is an extension of fully distributed fiber sensing techniques (Dakin [2], these proceedings) to the interrogation of a finite number of discrete sensors. Figure 1 shows such an implementation of a quasi-DFOS (QDFOS) system. Various sensing methods and addressing techniques have been used to implement quasi-distributed sensor systems. For example, modified fiber sections with sensitized optical properties

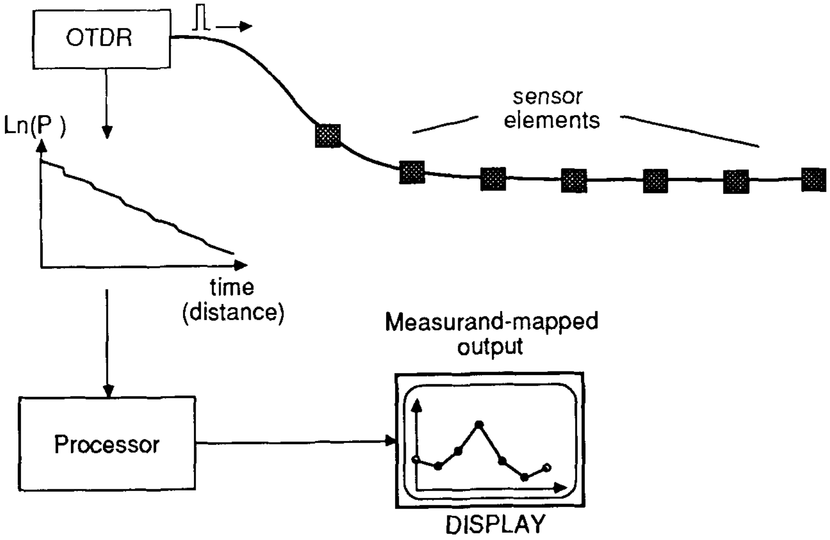


Figure 1. Quasi-distributed serial array using OTDR processing

can be spliced into a long fiber at certain intervals to provide localized variations in the loss, backscatter intensity, polarization, fluorescence intensity, etc. This is different from intrinsic-distributed fiber sensing in that the measurand can be determined at a finite number of locations only, and not continuously along the fiber path. Alternatively, discrete non-fiber sensor elements which vary in transmittance or reflectance with the measurand field can be incorporated into the fiber line. Such an arrangement for distributed temperature sensing was demonstrated at a early stage in the development of QDFOS technology [3]. This system used ruby glass sensor elements, the attenuation of which increase with temperature for light of wavelength ~ 600 to 620 nm (absorption edge shift rate ~ 1.2 Å/°C). OTDR type interrogation of the system was used to determine the loss at each sensor element, and a second wavelength removed from the absorption edge was used to provide a temperature independent reference output. Other materials, such as semiconductors are also suitable for this approach, as are fibers doped with certain elements, e.g. Hollium, Neodymium. The major limitations of this system, and similar approaches [4,5] is the fact that the attenuation is accumulative; the light levels at the most distal sensor thus depends on the measurand at each sensor along the fiber. This places demanding requirements on the dynamic range of the detection system and limits the number of sensors which could be used in a practical system. This is also true, but to a lesser extent, for systems based on reflective sensing elements [6].

3. FIBER BRAGG-GRATING BASED SENSORS

Intra-core fiber Bragg grating (FBG) sensors have attracted considerable interest over the past few years because of their intrinsic nature and wavelength-encoded operation. The gratings are holographically written into Ge-doped fiber by side-exposure to UV interference patterns [7-9]. Other means for producing such gratings also exist, and other fiber dopants may be used to improve efficiency, or

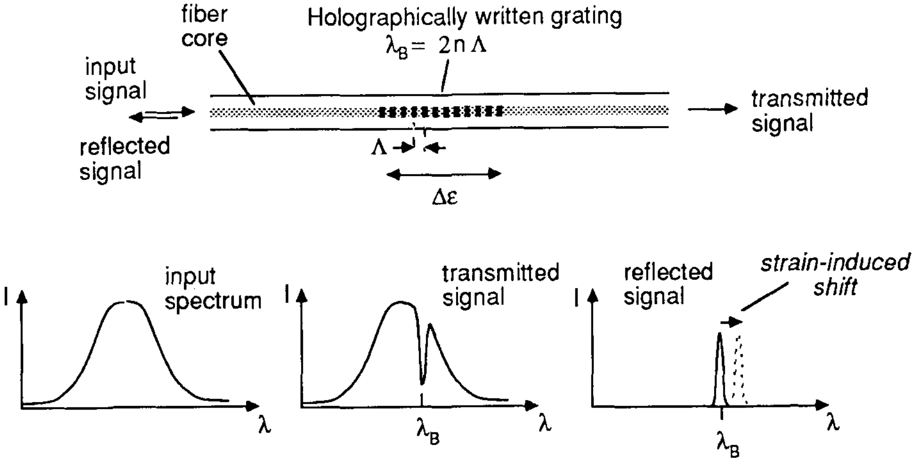


Figure 2. Fiber Bragg grating sensor system

alter the required writing wavelength. These sensors will prove to be useful in a variety of applications, in particular, in the area of advanced composite materials, or 'smart structures' where fibers can be embedded into the materials to allow real time evaluation of load, strain, temperature, vibration etc. Figure 2 shows the generic sensing concept involved for a single sensor element. The fiber Bragg grating (FBG) sensor is illuminated using a broadband source (BBS), such as an edge-emitting LED, superluminescent diode, or superfluorescent fiber source. The narrow wavelength component reflected by the sensor is determined by the Bragg wavelength;

$$\lambda_B = 2n\Lambda, \qquad (1)$$

where n is the effective index of the core, and Λ is the period in the index modulation of the core induced by the UV exposure. Measurand-induced perturbation of the grating sensor changes the wavelength returned, which can be detected and related to the measurand field (e.g. strain) at the sensor position. The wavelength-encoded nature of the output has a number of distinct advantages over other direct intensity based sensing schemes, most importantly, the self-referencing nature of the output; the sensed information is encoded directly into wavelength, which is an absolute parameter and does not depend on the total light levels, losses in the connecting fibers and couplers or source power. The reported dependence of the (normalized) shift in Bragg wavelength with fiber strain, ε, is $(1/\lambda_B)(d\lambda_B/d\varepsilon) \approx 0.74 \times 10^{-6}/\mu$strain, where 1 µstrain is a strain of 1 part in 10^6, and a temperature dependence $(1/\lambda_B)(d\lambda_B/dT)$ of $\approx 8.9 \times 10^{-6}/°C$.

These FBG elements are ideal for multiplexed networks, and a variety of configurations have been proposed [9,10]. Figure 3 shows a generalized concept for multiplexing based on wavelength division addressing. Here, the gratings are asigned a particular wavelength range, or 'domain' for operation which do not overlap. The Bragg wavelengths of the individual grating can thus be determined

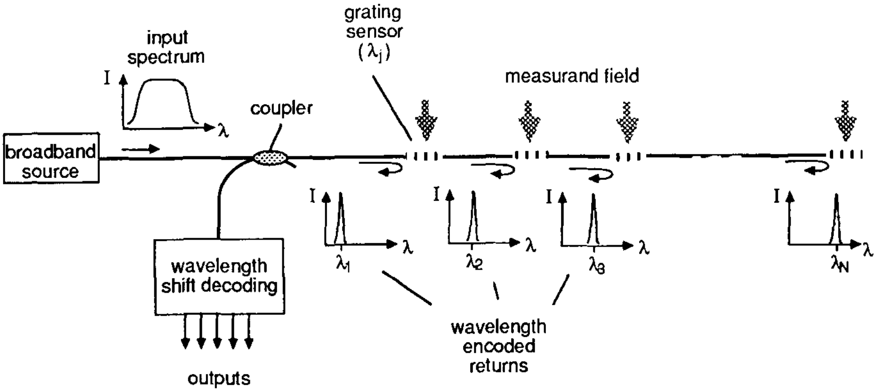


Figure 3. FBG sensor array

by illuminating the system with a broadband source and using an optical spectrum analyzer (spectrometer) to analyze the return signal. This simplest approach is practical for only a limited number of devices, simply due to the fact that the bandwidth of sources are limited, and can thus only accommodate a specific number of grating operational wavelength bands.

A means to overcome this limitation is to adopt some form of time division multiplexing (TDM) in conjunction with the inherent wavelength division multiplexing (WDM) capability of the grating sensors. Figure 4 shows a

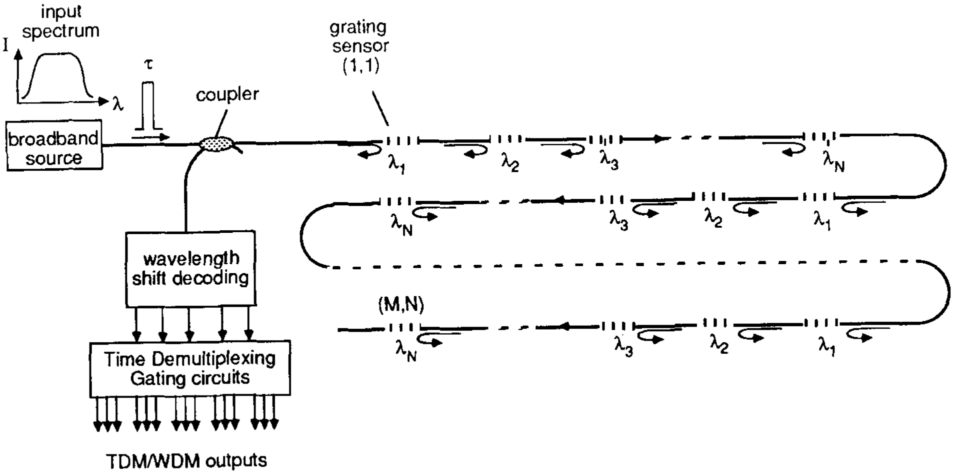


Figure 4. FBG array based on time and wavelength division addressing.

proposed concept using both TDM and WDM for addressing a large number of elements [10,11]. This type of signal processing may allow a large number of grating sensors to be interrogated in a serial array which would be of interest in applications such as embedded sensor systems for smart structures.

4. INTENSITY-SENSOR BASED NETWORKS

4.1 General

The term 'intensity based sensor' is used to describe a generic class of sensors which depend on monitoring changes some characteristic related to the detected intensity at the sensor output. Examples include sensors based on attenuation, reflectance, fluorescence signal, and modal modulation. A number of different types of branching networks have been investigated for use with intensity-based sensors, particularly those based on simple concepts such as attenuation. Sensors can be addressed using schemes based on optical analogs of conventional electronic time- and frequency- division multiplexing (TDM and FDM respectively) techniques, or by using schemes devised for use in optical communications systems such as wavelength-division multiplexing (WDM).

4.2 Time-division multiplexing

The first passive discrete-sensor network was proposed by Nelson et. al. [12] and used TDM to address a number of reflective intensity-based sensors. These sensors were spaced at different distances from the source and detector, such that a single pulse, of appropriate duration at the input to the network produced a series of distinct pulses at the output. These pulses represent time samples of the sensor outputs interleaved in time sequence, as shown in Figure 5. The required duration of the input pulse is determined by the effective optical delay of the fiber connecting the sensor elements, and repetitive pulsing of the system allows each sensor to be addressed by simple time-selective gating of the detector

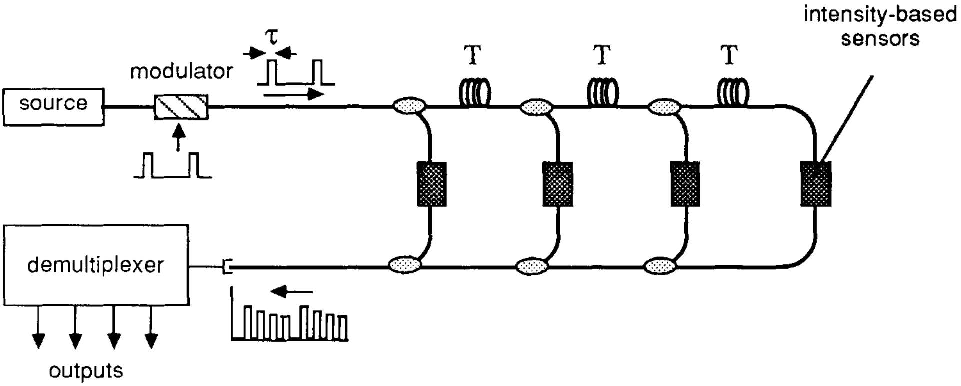


Figure 5. Time division multiplexed intensity sensor array

Network configurations for both transmissive and reflective intensity based sensors were described. Spillman and Lord have reported a self-referencing TDM intensity sensor network based on recirculating fiber loops [13]. This work has also been extended to use frequency division addressing [14].

4.3 Frequency-division multiplexing

A number of novel concepts for frequency-domain-based multiplexing schemes for intensity sensors have also been reported. Mlodzianowski et.al. [15] described a scheme in which the individual sensor information is carried not by separate beat or carrier frequencies, but by the phase and amplitude of an RF sub-carrier amplitude modulation of source light returned from a number of sensor elements. Interrogation of the system at a number of discrete modulation frequencies allows the status of each sensor to be interpreted. A system comprising three sensors has been demonstrated using this technique, and showed particularly good crosstalk performance (~ -40 dB). In another approach, the radar-based FMCW technique has also been used to allow frequency division addressing with a network of intensity based sensors [16]. In this case a chirped RF intensity modulated source is used to interrogate a number of simple reflective intensity sensors, and the detector output is electrically mixed with a 'reference' chirp signal. This produces a beat frequency associated with each sensor element, allowing frequency demultiplexing of the outputs.

4.4 Wavelength-division multiplexing

Demonstrations of wavelength division multiplexing in fiber communications systems have been reported for many years [17-19]. The use of this technique in sensor application has not, however, received much practical attention. Figure 6 shows the type of arrangement possible using WDM. The scheme, which is

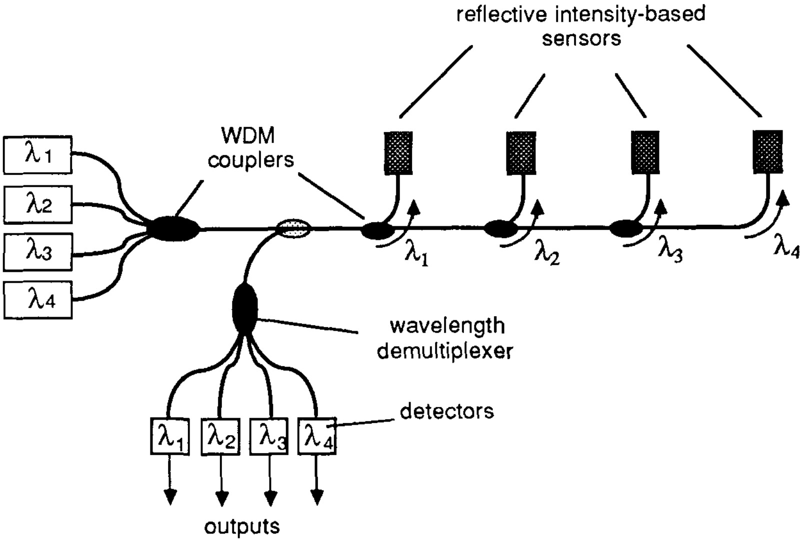


Figure 6. Wavelength division multiplexed sensor array

essentially applicable to both intensity and interferometric sensor types, is theoretically the most efficient technique possible, as all the light from a particular source could in principle be directed to a particular sensor element and then onto a corresponding photodetector with minimal excess loss. The reason for the lack of practical demonstrations of this technique is due to the limited availability of wavelength-selective couplers (splitters and recombiners) which are required to implement the technique. This combined with the complexity of the WDM fiber components (e.g. N x N star and 1 xN tree couplers) needed to build systems based on a number of sensors and the limited wavelength-selectivity of such devices are the major drawbacks of the approach. Consequently, apart from the obvious use of WDM techniques in FBG systems (Section 3), wavelength division multiplexing of large numbers of discrete intensity-based (or interferometric) sensors utilizing common servicing fibers may not prove to be viable, in terms of both cost and performance.

4.5 Subcarrier based multiplexing

Another technique for the multiplexing of fiber sensors which is based on subcarrier signal processing has been demonstrated. In this case, each sensor in the network is a transversal filter which consists of two fibers of unequal length connected in parallel. In response to an RF intensity-modulated source the recombined light at the output of such a filter exhibits a series of minima when the differential delay in the two fiber paths corresponds to a half-integral number of cycles of the modulation frequency. The normalized frequency response of a single sensor is given by [20,21]

$$g_i(f) = |\cos(\pi\Delta\tau_i f)|, \tag{2}$$

where f is the frequency of the modulation and $\Delta\tau_i$ is the differential delay of sensor i. For a linear array of sensors the frequency response of the combination is given by $G(f) = \Pi g_i(f)$; i.e., the product of the frequency response functions of the individual elements in the array [22]. A system of three fiber-optic differential-delay filters configured as temperature sensors based on this approach has been experimentally demonstrated. The experimental arrangement used is shown in Figure 7. Light from a SLD source, which was modulated by a voltage-controlled oscillator (VCO), was input to a series of three differential delay sensor elements. In Figure 8, curves (a) , (b) and (c) show the frequency response from 0 to 20 MHz for each sensor independently operated with the source and detection system, whereas the measured frequency response of the three-sensor network is shown in curve (d) of Figure 2 from 0 to 20 MHz and in curve (e) from 10 to 16 MHz. In order to monitor temperature-induced shifts in the null frequencies corresponding to each sensor, the null-tracking technique detailed in [23] was used.

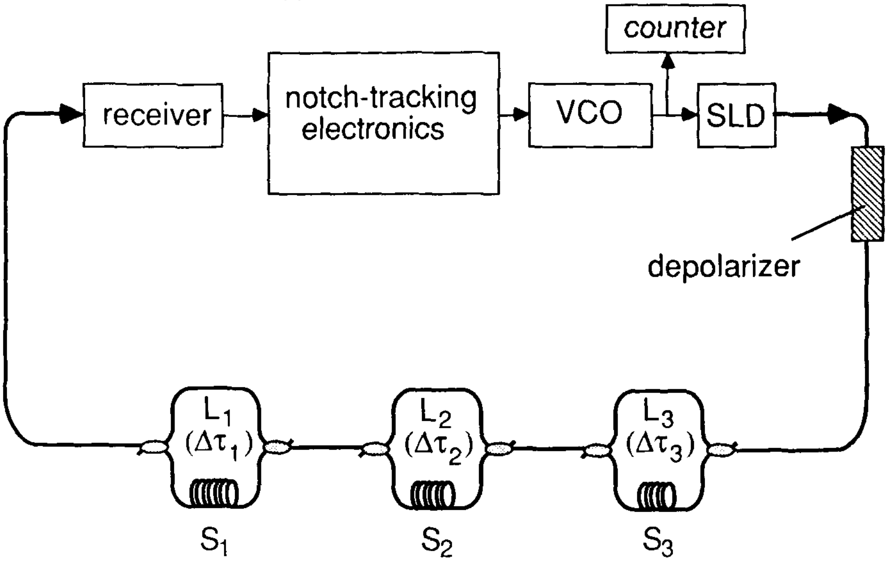
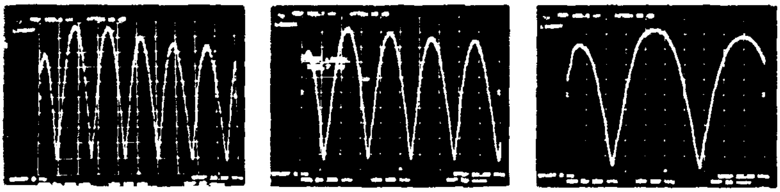
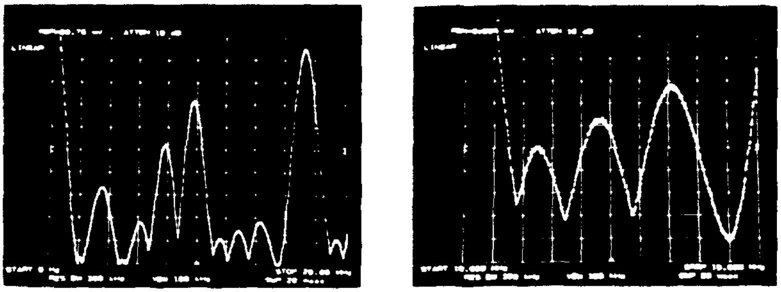


Figure 7. Subcarrier multiplexed sensor system



(a) SENSOR S1 (b) SENSOR S2 (c) SENSOR S3



(d) S1 + S2 + S3 (e) S1 + S2 + S3

Figure 8. Response curves for the sensor arrangement of Figure 7:
a - c individual sensors; d and e, combined transfer function.

5. INTERFEROMETRIC SENSOR MULTIPLEXING

5.1 General

Interferometric fiber sensors are being widely researched for use in a range of application areas including acoustic pressure, and magnetic and electric fields [24]. A number of different multiplexing topologies have been devised and tested by research groups working in this field. Early work during the mid to late 1980s concentrated on demonstrating the principle of operation of various multiplexing approaches such as time-division (TDM), frequency-division (FDM) and coherence multiplexing (Coh.M) using a relatively low number of sensors. In more recent years, however, arrays with up to 10 sensors [25] multiplexed on a common input/output fiber pair have been reported in the literature, representing the first demonstrations of significant multiplexing gain achieved in practical systems. Additionally, a system utilizing a hybrid TDM/WDM approach was demonstrated with 14 sensor elements supported on a single input/output fiber pair. Systems have also been taken beyond the laboratory environment: An array comprising a total of 48 networked sensors based on a FDM scheme was tested at sea in 1990.

A range of different multiplexing topologies continue to be investigated and tested by research groups working in this field. Developments in the areas of frequency, time, coherence, and code-division based systems continue to be made. The following sections discuss these developments, and recent experimental results.

5.2 Frequency division multiplexing

One of the earliest approaches developed for the multiplexing of interferometric sensors was based on the FMCW concept [26-28]. This scheme relies on the use of unbalanced interferometers arranged in a serial (see Figure 9) or parallel network illuminated by a frequency chirped optical source. Due to the inherent

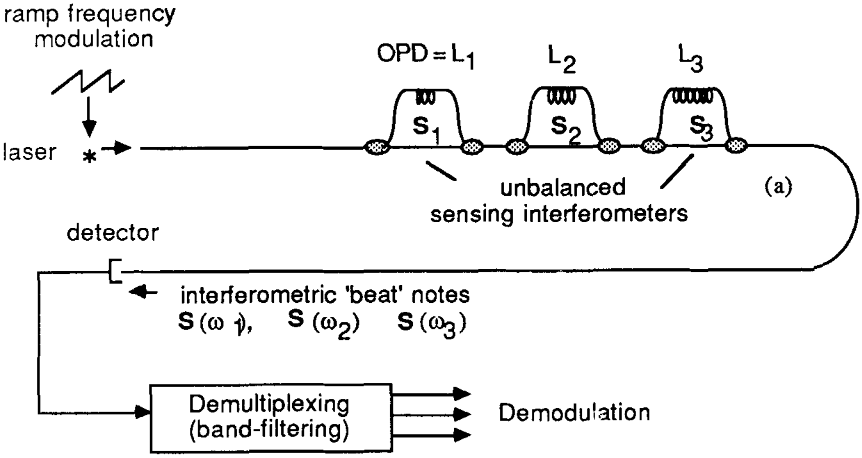


Figure 9. FMCW interferometric sensor multiplexing

sensitivity of an unbalanced sensor to input optical frequency, a beat frequency is generated at each interferometer output, the period of which depends on the frequency excursion of the chirp, the chirp rate, and the interferometer optical path difference (OPD). Assigning a different OPD to each interferometer allows the beat-frequencies associated with each sensor element to be distinct, and thus separable using band filtering. One major problem which arises with this type of multiplexing technique is cross-terms due to unwanted interferometric components arising differentially or additively between sensors, or 'ghost' interferometers arising from connecting fiber paths in conjunction with the interferometers. These cross-terms lead to sensor-to-sensor interference, or crosstalk which is a problem in most applications where the full capability of an interferometric sensor, in terms of the detection sensitivity and dynamic range, are important. These 'stray' components can be minimized using certain topologies, but cause significant design complexity for an array involving an appreciable number of sensors elements. Little experimental work has been reported on this approach since the demonstration of a three-sensor multiplexed system in 1986 [28].

A preferred FDM approach utilizes the spatial and frequency domain separation of sensor signals shown in Figures 10. In Figure 10.a., the outputs from K sensor elements all powered from a common source are 'spatially-multiplexed' onto separate fibers. In Figure 10.b. the outputs from J sensors, which are independently illuminated by separate sources, are combined onto a single output fiber. Using phase-generated-carrier (PGC) interrogation [29], with each laser

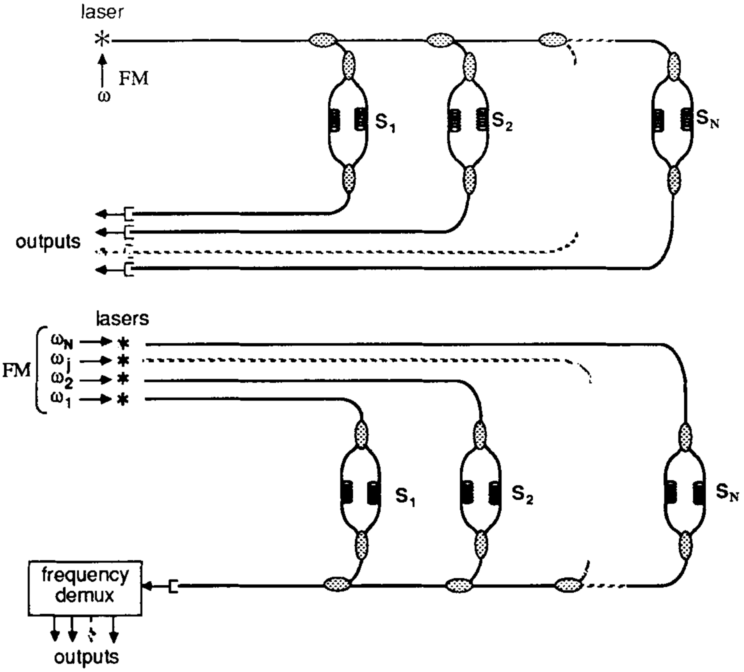


Figure 10. a) 'Spatial' and b) frequency domain addressing of interferometers

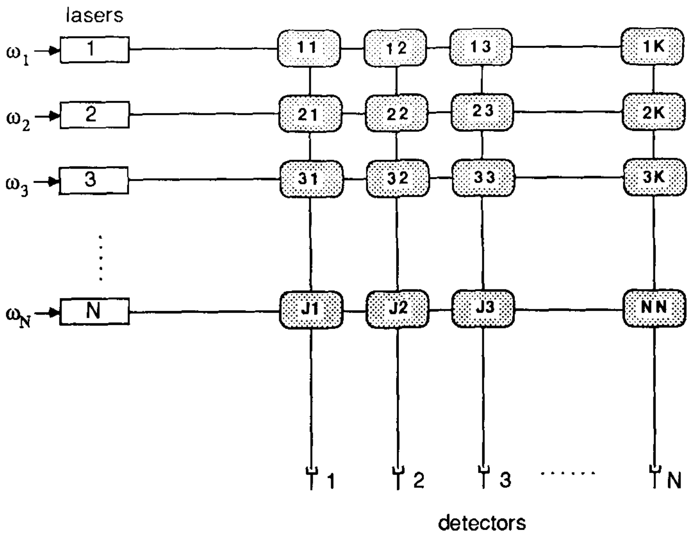


Figure 11. JxK matrix array configuration based on the spatial and frequency domain multiplexing concepts of Figure 10.

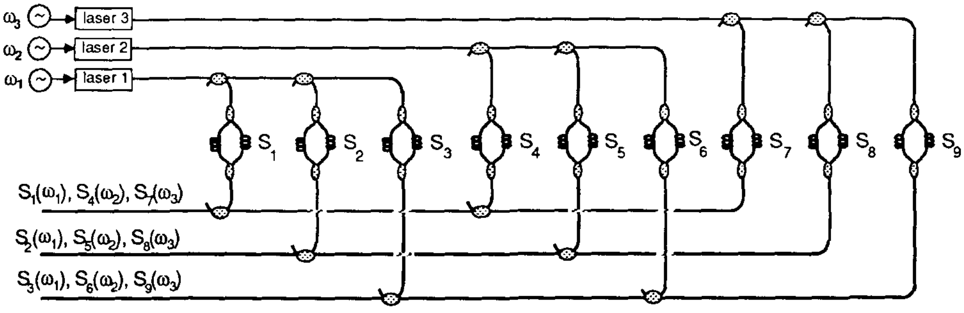


Figure 12. Practical implementation of the JxK FDM matrix array system

operated at a different 'carrier' frequency, the sensor outputs in Fig 10.b can be separated using synchronous detection or band-filtering. Combining these techniques allows a matrix-type array [30] to be configured, which contains N = JxK sensor elements, as schematically represented in Figure 11. This system is somewhat unique in that the operation of the remote PGC interrogation (demodulation) scheme automatically provides both the demodulation and demultiplexing functions, provided the sources are modulated at different carrier frequencies. Figure 12 shows a practical implementation of this type of array for a 3x3 (9 sensor) system. This type of array has been shown to be capable of providing good phase detection sensitivity and low crosstalk for systems involving up to eight sensor outputs combined onto a single output fiber.

This type of array is the most highly developed topology demonstrated to-date; an array comprising 48 acoustic sensors was successfully demonstrated in a sea test under a joint NUSC/NRL advanced technology demonstration program in 1990 [31].

5.3 Coherence multiplexing

The basic principle of the coherence multiplexing concept for interferometric sensors is shown in Figure 13. Although there was initially significant interest in coherence multiplexing [32-34], problems associated with crosstalk, excess phase noise and poor power budget have limited the practical use of this approach with interferometric sensors. Nevertheless, strong interest in the use of this approach remains for other less demanding applications; for example, for use with interferometric sensors configured to detected quasi-static (DC) measurands. A two-element multiplexed temperature sensor system based on a wavelength-modulation scheme for monitoring interferometric OPD [35] has been reported. In this case the ultra-high phase detection sensitivity normally attainable in interferometric sensor systems is not required, and crosstalk levels of ~ –40 dB maybe tolerable. The coherence-addressing and multiplexing of polarimetric sensors has also been recently reported [36,37].

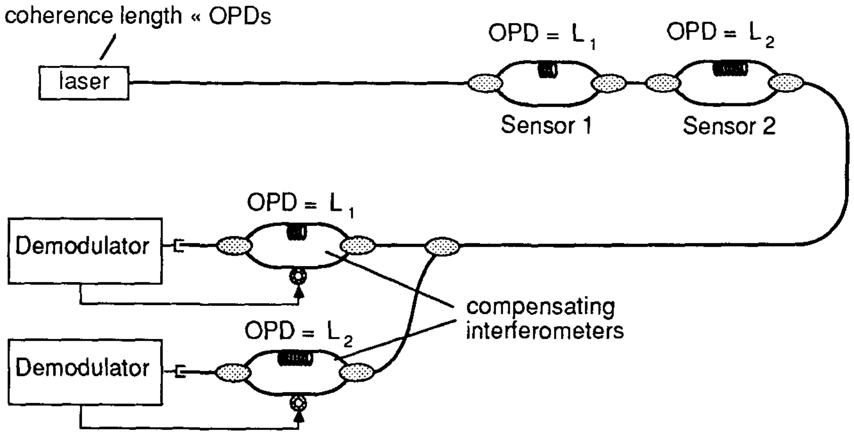


Figure 13. Coherence multiplexed interferometric array

5.4 Time division multiplexing (TDM)

Considerable interest has been directed towards the experimental demonstration and evaluation of multiplexing topologies based on time division addressing [38-45]. This work led to the development of a number of array architectures based on serial and parallel topologies, of the type shown in Figures 14 and 15 respectively. The system of Figure 14.a, referred to as a reflectometric sensor array, was the first interferometric TDM array to be demonstrated. This configuration utilized in-line partially-reflective fiber-splices, or in-fiber reflectors [38], between fiber sensing coils each of length L, to form in-line interferometric elements, which can be interrogated with pulsed operation of the source and a compensating interferometer of delay equal to the round trip delay ($T_d = 2L/nc$) between reflectors. Providing the width of the input pulse, τ, is less than T_d, an interferometric signal from each element in the array can be generated in time sequence at the compensator output. The initial demonstration of this concept utilized a differential delay heterodyne interrogation approach, where two pulses of differing optical frequencies and separated in time by T_d were launched into the array, such that at the output pulses reflected from consecutive partial reflectors in the array overlapped to produce heterodyne beat signals associated with each sensing element, without the need for a compensating interferometer. An array of six acoustic sensors based on this approach has been field tested [39].

A similar type of operation, but configured in a transmissive , was achieved using the tapped serial array (TSA) [40,41] topology shown schematically in Figure 14.b. The system is based on the use of low-coupling ratio couplers which tap off a fraction of the light in the input fiber to an output bus as shown. Fiber coils in the input fiber serve both as delay and sensing elements. Pulses obtained from the series of N+1 (for N sensors) tap points are separated in time if the delay in each sensor coil is longer than the width of the input pulse (τ) to the system. These output pulses are then coupled to a compensating interferometer which splits the

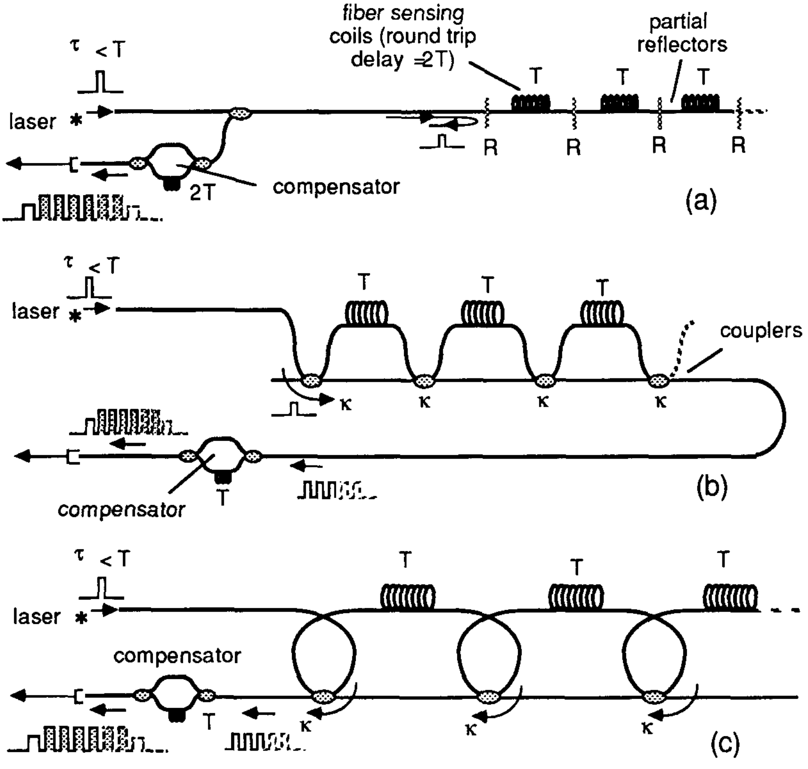


Figure 14. Time division multiplexed serial arrays

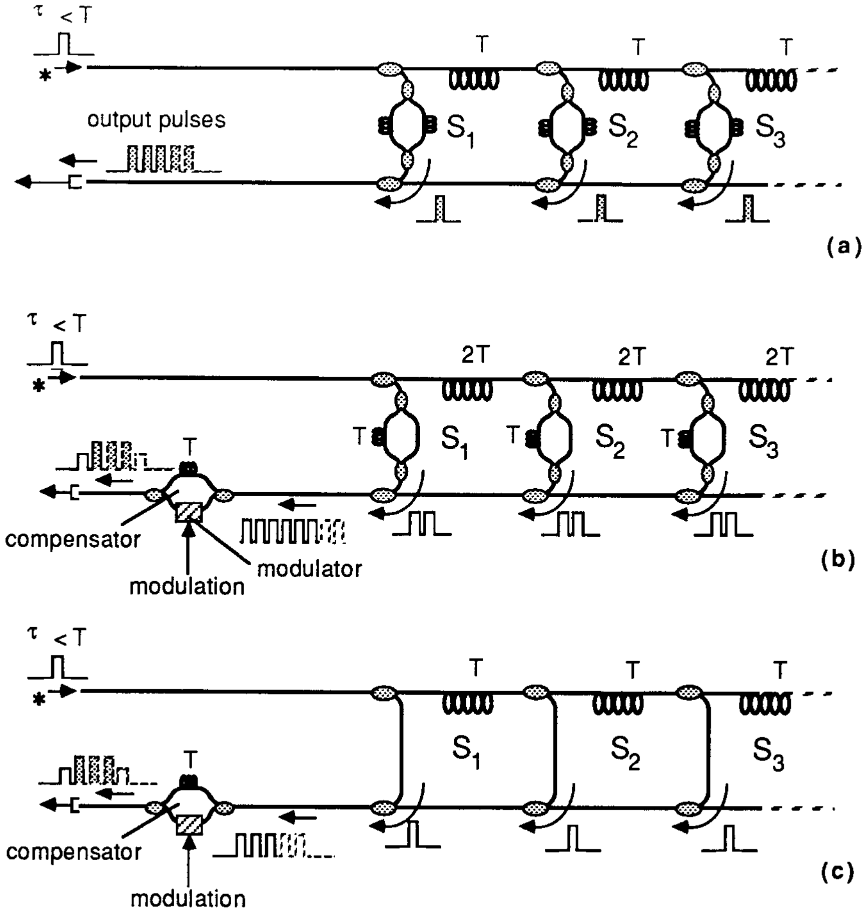


Figure 15. Time division multiplexed parallel (ladder) arrays

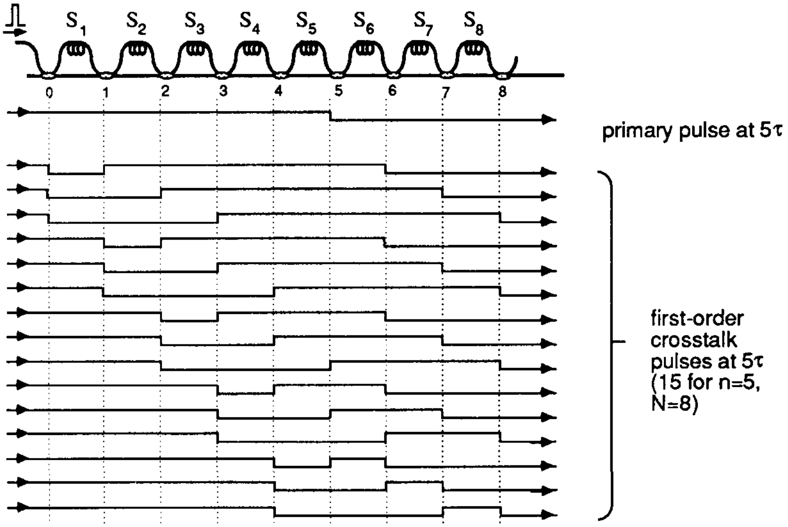


Figure 16. Origin of the multi-coupling crosstalk paths in the TSA system

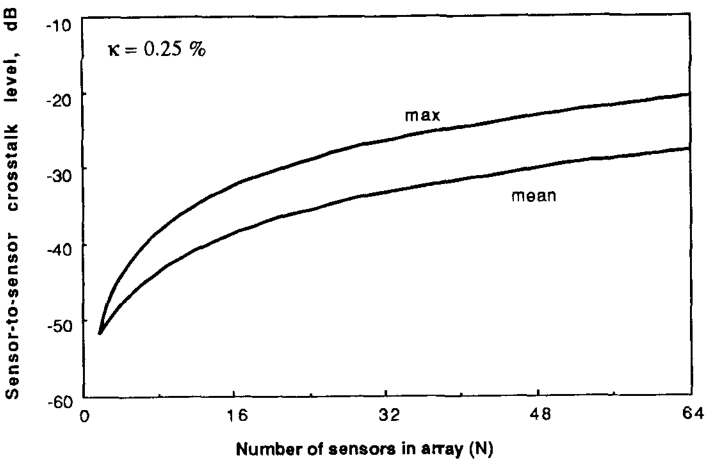


Figure 17. Crosstalk in the TSA

pulse stream into two components, delays one by a period equal to the sensor coil delay T, and subsequently recombines the signals. This forces components of adjacent pulses to overlap, resulting in interference signals which can be monitored at the detector. An array of eight sensors has been experimentally demonstrated using this approach [41].

Due to the possibility of multiple pulse reflections between partial reflectors, and coupling between the input and output fibers at the tap points, both the reflectometric and TSA array topologies give rise to multiple pulse interactions which leads to crosstalk. Figure 16 shows an example of the origin if the type of effect in the TSA system. This problem has been addressed both experimentally and theoretically at NRL. We have found excellent agreement between predicted and observed crosstalk levels between sensor elements in an eight sensor array [41,42]. As shown in Figure 17, the results of this type of analysis shows that time-average sensor-sensor crosstalk levels can be < 30 dB for an array of 25 sensors using couplers with a 0.25 % coupling ratio.

The 'recursive lattice' [43] array topology of Figure 14.c is functionally identical to the reflectometric array, giving rise to the same crosstalk effects. This array has not been experimentally tested to date.

More recent work in TDM systems has concentrated on 'ladder' array configurations [25,44,45] of the form shown in Figure 15. A ten-element array based on the topology of Figure 15.a has been successfully demonstrated. This topology does not lead to direct optical crosstalk between the sensor elements, and phase detection sensitivities comparable to those obtained in single sensor systems have been achieved. Interferometers which are slightly unbalanced to allow for passive demodulation via frequency modulated laser based phase generated carrier or synthetic heterodyne techniques are used. Phase detection sensitivities obtained with the array ranged from 12 to 18 μrad/√Hz at 1 kHz. Crosstalk

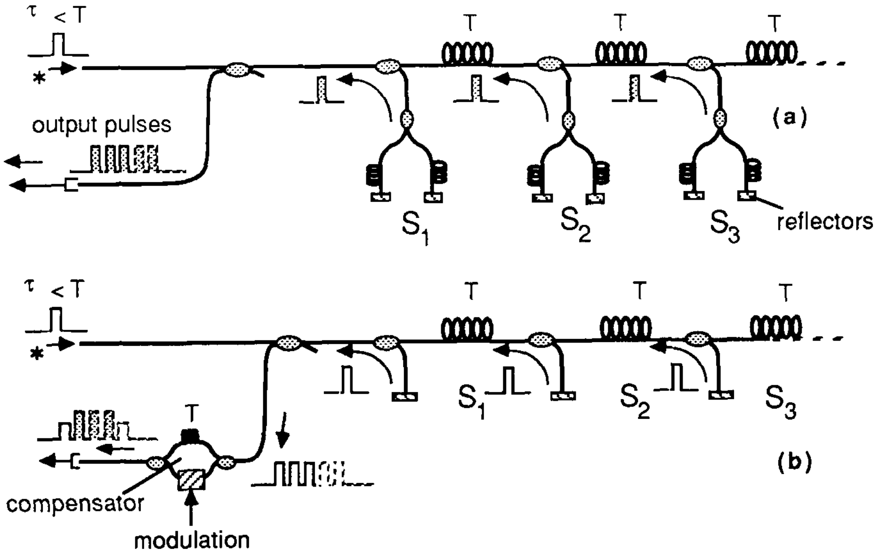


Figure 18. Time division multiplexed serial arrays based on Michelson interfeometer sensor elements

levels for the array were measured to be in the range -50 to -65 dB.

Naturally, Mach-Zehnder arrays are not the only possible system topologies which can be used. Arrays based on Michelson interferometers have, for instance, been proposed and demonstrated. Figure 18 shows two Michelson configurations based on discrete and non-discrete interferometer elements, which are analogous to the Mach-Zehnder systems of Figures 15.a and 15.c.

Other developments in the area of TDM interferometric arrays include systems based on the reflectometric system of Figure 14.a, but using low-reflectivity fiber Bragg gratings as the partial reflectors [10]

5.5 Code-division multiplexing

Spread spectrum (SS) and code division multiplexed (CDM) techniques [46] have been applied to a variety of communications applications, including optical fiber systems [47]. This type of signal processing has also been previously investigated for optical time-domain reflectometry (OTDR) based sensing [48], and more recently, has been proposed and tested as a means for multiplexing interferometric sensors [49]. In this work, the interrogating laser source is modulated using a pseudo-random bit sequence (PRBS) of length 2^m -1 (maximal length sequence, or m-sequence), and correlation is used to provide synchronous detection to identify specific sensor positions. A delay equal to an integer multiple of the bit (or 'chip') period separate the sensors. The received signals from the array are then encoded by delayed versions of the PRBS, and correlation techniques can be used to extract the individual signals.

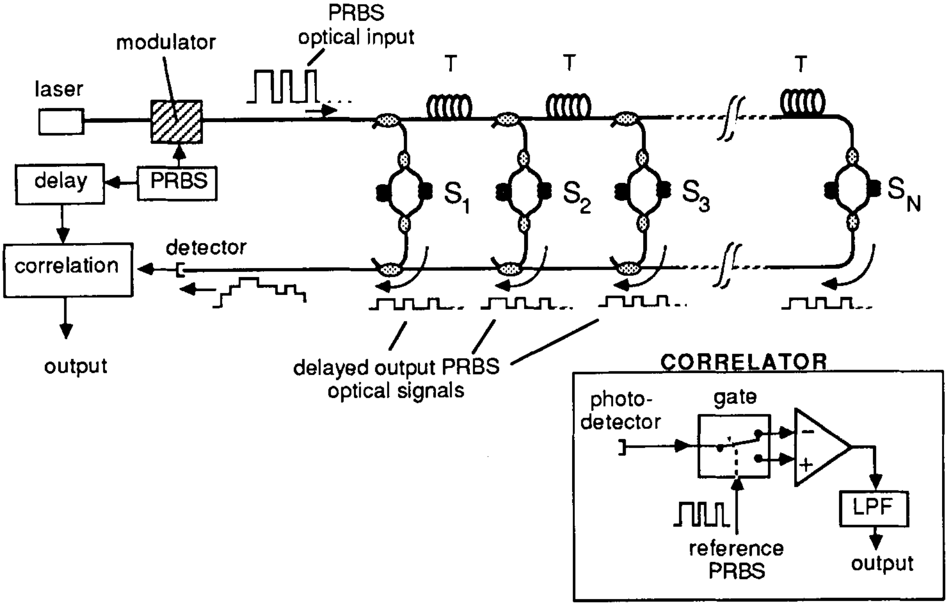


Figure 19. Code-division multiplexed array using Spread-Spectrum techniques

Figure 19 diagrammatically represents the principle of operation of the CDM approach applied to an interferometric sensor array. The PRBS input optical signal is fed to each the N sensors, delayed by a multiple, n_j, of the bit period T, where j denotes a specific sensor ($1 \leq j \leq N$). The total output signal comprises the intensity sum of the overlapping delayed PBS sequences (each modified by the appropriate sensor transfer function). This results in a complex up-down staircase-like function at the optical detector which can be decoded using synchronous correlation-detection involving multiplication of the received signal with an appropriately delayed reference PRBS.

Although this method may provide advantages in terms of power budget for time-division multiplexed systems, it would also seem to be limited by excess phase noise effects arising due to mixing of time co-incident pulses from different sensors, and relatively high crosstalk between sensors. Recent work addressed these limitations of the technique, using a detection/signal processing approach which yields improved crosstalk and noise performance [50]. In this work, crosstalk levels lower than those expected from consideration of the code length were obtained using a mix of bipolar and unipolar codes which produces an improvement in the channel/channel isolation. This arises due to the correlation function of a bipolar with unipolar m-sequence PRBS, shown in Figure 20, which has a value $2^{(m-1)}$ for an aligned code, but is zero for any asynchronous alignment of the codes (this is in contrast to the conventional bipolar-bipolar auto-correlation which has a value of $(2^m -1)$ for code alignment, but a value of -1 for asynchronous alignment). This feature ensures good crosstalk can be obtained without the need to utilize excessively long PRBS codes: indeed, low crosstalk can be obtained providing the code length $(2^m -1) \geq N$, where N is the number of

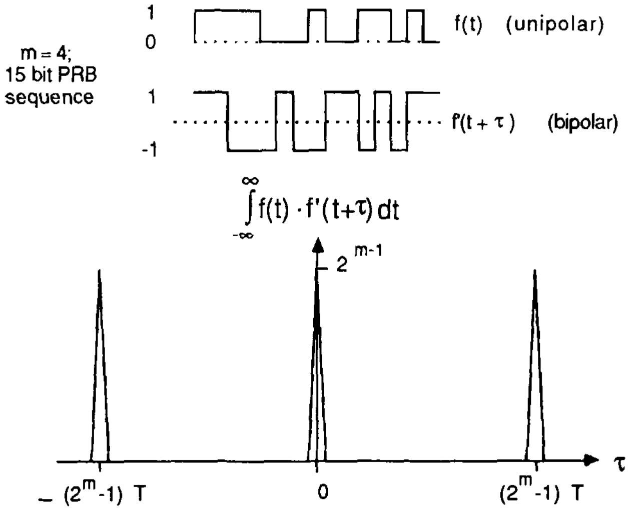


Figure 20. Correlation function between a bipolar and uniploar PRBS of length 2^m-1, with m = 4.

sensors in the array (assuming a one-bit time delay between sensors). Reduction of the excess phase noise by modulation of the laser source was also demonstrated in this work [50]

5.6 Power budget

Analysis shows that the power budget is a major factor determining the number of sensors which may be multiplexed using time-division and frequency-division schemes [51]. Calculations based on array loss models and input optical powers of 10 mW suggest that ~ 25 to 30 sensors may be supported per laser source with shot-noise equivalent phase detection sensitivities ~ 3 to 10 μrad./√Hz. This limitation to the multiplexing gain (number of sensors supported per input/output fiber) is due primarily to the relatively severe power recombinational losses associated with the use of conventional singlemode directional couplers in star or branching configurations. Generally, in a multiplexed fiber sensor array based on discrete sensor elements, light from a source is equally divided into the N sensors. On recombination of the sensor outputs onto a single monomode fiber, the optical throughput per channel is 1/N (effective loss of -10log[N] dB). A further effective power reduction factor of 1/N is encountered in time-division multiplexed (TDM) systems due to the duty-cycle of the pulsed source. In frequency division multiplexed (FDM) systems, a similar deleterious effect is encountered due to the fact that each channel is measured against a background of (N-1) other channels.

A novel singlemode/multimode (S/M) optical power combiner in multiplexed fiber sensor applications [52] has been demonstrated for improved power budget performance. This device allows a number of sensor outputs on single mode fibers to be efficiently recombined onto a single multimode output fiber with minimal effective insertion and excess loss.

5.7 Hybrid TDM/WDM system

An alternative means of improving the multiplexing gain is to utilize a system based on a hybrid of addressing approaches. A possible means for this is combining time or frequency division addressing with wavelength division multiplexing. Wavelength division multiplexing (WDM) has primarily been considered for use in communications systems. Its extension to the field of fiber sensors is obvious, and in principle the technique has the capability to allow a number of sensors to be remotely addressed in a very efficient manner. However, as discussed earlier, due to the complexity of the components, i.e.tree- or star-type WDM-couplers, required to selectively tap certain wavelengths from a fiber bus to sensors and recombine them onto a single output fiber, this approach has received little experimental attention. Furthermore, the crosstalk between sensors will be determined directly by the degree of wavelength isolation which can be achieved with the WDM-couplers, which is typically only ~ 15 to 20 dB. Consequently, WDM may not prove to be viable for the multiplexing of a significant number of sensors. However, combining wavelength division multiplexing concepts with time or frequency division addressing has the potential to allow a several-fold improvement in the number of multiplexed sensors in an array.

This type of system has been experimentally demonstrated [53]. The system, which is shown schematically in Figure 21, is based on two time division multiplexed systems which are addressed via common input and output fibers using wavelength division multiplexing to produce an array of 14 sensor elements. The source wavelengths are 835 nm and 790 nm, and the fiber WDM couplers used were manufactured by Aster Inc. The two sub-arrays comprised a ten-sensor system operating at 835 nm, and a four-sensor system designed for operation at 790 nm.

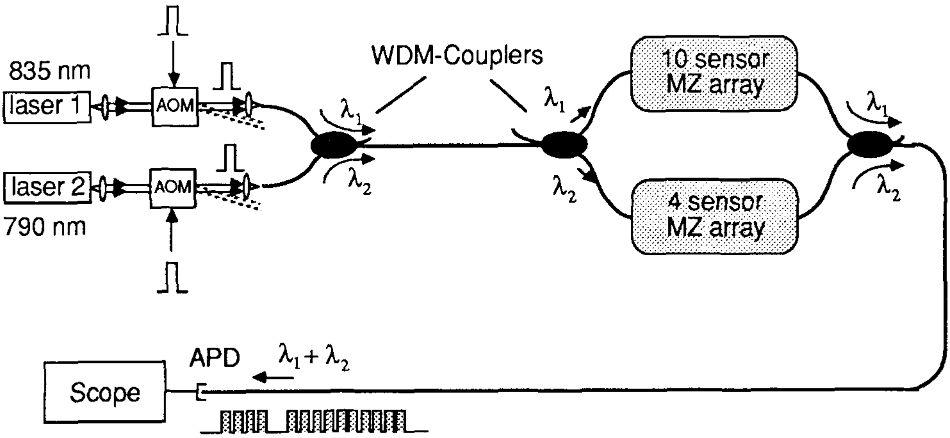
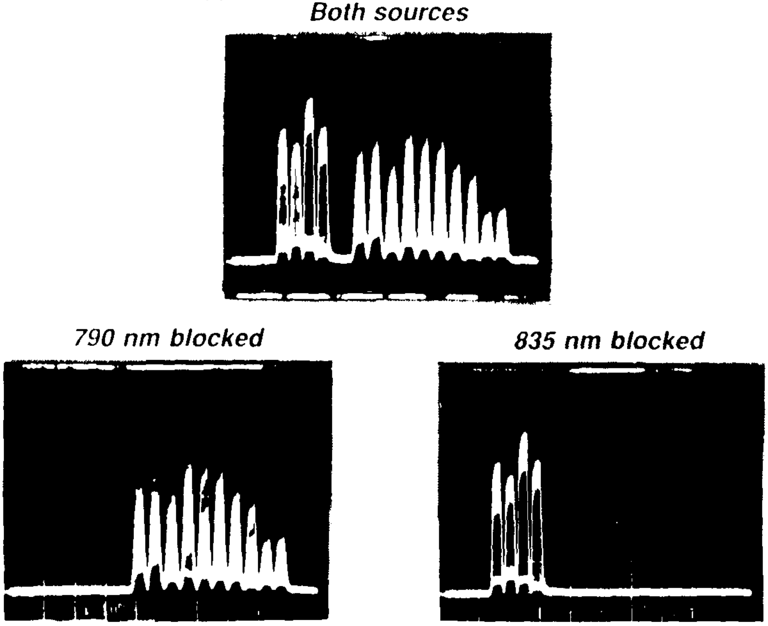


Figure 21. Hybrid TDM/WDM array



Both sources

790 nm blocked

835 nm blocked

Figure 22. Outputs from the array configuration of Figure 20

Figure 21 shows the output pulse train observed with the system. Here, the top trace shows the detector (APD) output with both sources in operation. To provide a clearer visualization of the operation of the scheme, in this demonstration the input pulses from the two lasers were delayed relative to each other in order to separate in time the pulse trains produced by the two sub-arrays. In the two lower traces in Figure 21, the 835 nm and 790 nm lasers were blocked in turn to show the correct routing of the wavelengths in the system. Under normal operation, further wavelength de-multiplexing of the signals prior to detection would be utilized. Optical crosstalk levels < -25 dB (equivalent to < -50 dB electrical) between the two arrays were achieved with the components used.

5.8 Polarization fading

In recent years, considerable effort has been directed towards the development of techniques which provide compensation for the effects of polarization fading in interferometric sensor systems. Techniques based on the selection of a particular output state of polarization (SOP) or set of SOPs [54,55] have been demonstrated, which perform with limited success.

Very recently, a birefringence compensation approach has been used to develop a polarization independent Michelson interferometer [56]. An array based on this concept has also be demonstrated [57]. The birefringence compensation method is based on use of the "orthoconjugate reflector" of Edge and Stewart [58] which consists of a 45^{O} Faraday rotator followed by a plane mirror. For an optical beam which retraces its path in a fiber, Pistoni and Martinelli [59] demonstrated that the insertion of a Faraday rotator and mirror (FRM) results in a state of polarization (SOP) at the exit which is orthogonal to the SOP at the input to the fiber. As

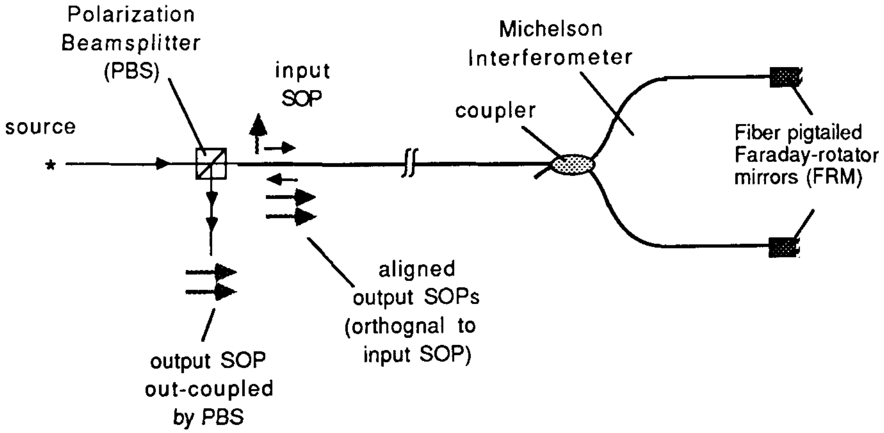


Figure 23. Polarization independent Michelson interferometer configuration

depicted in Figure 23, when employed in a Michelson interferometer the SOP from each of the device is returned orthogonal to the common input SOP. Consequently they are aligned with each other and insure maximum fringe visibility is obtained at the interferometer output. A four-sensor array configuration based on the configuration of Figure 18.b with miniaturized pigtailed FRMs as the reflectors has been built and tested. The fringe visibility was estimated to be > 0.95 (fading < 0.5 dB) simultaneously for all of the sensors under birefringence perturbations induced manually in the fiber leads [60].

6. TRANSDUCER MULTIPLEXING

The multiplexing techniques described in the foregoing section involve the networking of interferometric sensors. It is also possible to multiplex the transducer elements within a single interferometric sensor. Several fiber transducers have been developed in which the strain imparted to a fiber in an interferometer is proportional to the square to the applied measurand field. Examples include magnetostrictive [61] and electrostrictive materials [62], and a displacement sensing geometry [63] based on the lateral displacement of a fiber supported at two fixed points.

In general, the fiber strain can be expressed as

$$\varepsilon = C M^2, \tag{3}$$

where C is a constant which depends on the material parameters, or the exact geometrical arrangement of the transducer, and M is the measurand field (i.e. H, E or z in the cases of magnetic, electric fields and displacement respectively). If M comprises two components , $M_o + \Delta M \sin \omega_d t$, where M_o is proportional to the measurand field amplitude, and $\Delta M \sin \omega_d t$ is a 'dither' signal, the component of

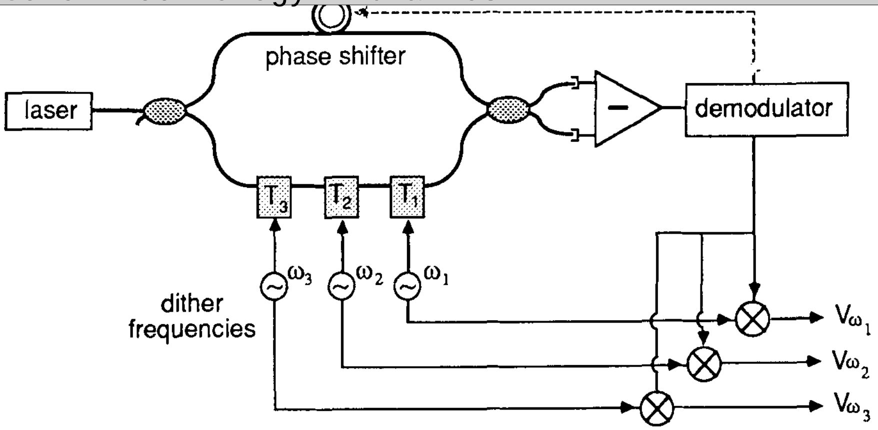


Figure 24. Interferometer configuration with transducer multiplexing

the strain induced in the fiber at the fundamental (ω_d) of the dither is

$$\varepsilon\,(\omega_d) \;=\; 2C\Delta M\, M_o, \qquad (4)$$

which is linearly proportional to M_o and thus the measurand field of interest. This strain can be detected using a fiber interferometer, and a number of such non-linear transduction elements can be incorporated in a single interferometer system by using different dither frequencies for each sensor, as shown schematically in Figure 24. Using this basic concept, the multiplexing of transducers for pressure, displacement and magnetic field [64] using a single interferometer has been demonstrated. Other measurands such as acceleration, and remote optical dithering have been demonstrated [65].

7. CONCLUSIONS

Work in the area of multiplexed fiber optic sensors has been reviewed. A key area of interest has been in the development of multiplexing techniques for high performance interferometric fiber sensor arrays, and the detailed coverage in this paper reflects this interest.

8. REFERENCES

1. A. D. Kersey and A. Dandridge," Distributed and Multiplexed Fiber Optic Sensor Systems," J. IERE, 58, p. S99, 1988.
2. J. P. Dakin, “Distributed fiber optic sensors”, these proceedings.
3. E. Theochorous, " Distributed sensors based on differential absorption," Proc. of the IEE Colloquium on Distributed Optical Fiber Sensors (Digest 1986/74), paper #13, London, 1986.
4. S. A. Kingsley," Distributed Fiber-Optic Sensors: an Overview," Proc. SPIE Vol. 566, Fiber Optic and Laser Sensors III, p. 234, San Diego, CA, 1985.
5. A. J. Rogers," Intrinsic and Extrinsic Distributed Optical-Fiber Sensors," Proc. SPIE Vol. 566, Fiber Optic and Laser Sensors III, p. 234, 1985.

6. F. X. Desforges *et. al.*," Progress in OTDR Optical Fiber Sensor Networks," Proc SPIE Vol. 718, Fiber Optic and Laser Sensors IV, p. 225, Cambridge, MA, 1986.
7. G. Meltz et al., " Formation of Bragg Gratings in Optical Fiber by a Transverse Holographic Method", Optics Lett., 14,
8. W. W. Morey et al., " Bragg-Grating Temperature and Strain Sensors", Proc. OFS'89, p. 526, Paris, 1989 (Springer Verlag).
9. A. D. Kersey et al., " High Resolution Fiber Grating Based Strain Sensor With Interferometric Wavelength Shift Detection", Electron. Lett., 28, p. 236, 1992.
10. W. W. Morey et al., "Multiplexing Fiber Bragg Grating Sensors", Proc. 'Distributed and Multiplexed Fiber Sensors I', SPIE Proc. Vol. 1586, p. 216, 1991.
11. A. D. Kersey, " Multiplexing Options for Quasi-Distributed Sensing in Smart Structures Using Fiber Interferometry", Proc. Va Tech. Workshop on Optical Fiber Sensor Based Smart Materials and Structures, p. 6, Blacksburg, Va, April 1991 (Technomic).
12. A. R. Nelson *et. al.* ," Passive Multiplexing System for Fiber-Optic Sensors," Appl. Optics, 19, p. 2917, 1980.
13. W. B. Spillman and J. R. Lord," Self -Referencing Multiplexing Technique for Fiber-Optic Intensity Sensors," J. Lightwave Technol., LT-5, p. 865, 1987.
14. W. B. Spillman and J. R. Lord," Self -Referencing Multiplexing Technique for Fiber-Optic Intensity Sensors, SPIE Proc. Fiber Optic and Laser sensors V, San Diego, CA, 1987.
15. J. Mlodzianowski *et. al.*," A Simple Frequency Domain Multiplexing System for Optical Point Sensors," IEEE J. Lightwave Technol., LT-5, p.1002, 1987.
16. K. I. Mallalieu *et. al.*," FMCW of Optical Source Envelope Modulation for Passive Multiplexing of Frequency-Based Fiber-Optic Sensors," Electron. Lett., 22, p.809, 1986.
17. K. Fassgaenger et. al. "4 x 560 MBit/s WDM System using 3 Wavelength Selective Fused Single-mode Fiber Couplers as Multiplexer" Proc. ECOC '86, Barcelonia, Spain, Sept 1986.
18. H. Ishio, J. Minowa and K. Nosu, "Review and Status of Wavelength-Division Multiplexing Technology and its Application", J. Lightwave Technology, LT-2, pp. 448-463, 1984.
19. G. Winzer, "Wavelength Multiplexing Components - A Review of Single-mode Devices and their Applications", J. Lightwave Technology, LT-2, pp. 369–378, 1984.
20. C. A. Wade et al., " Optical Fiber Displacement Sensor Based on Electrical Subcarrier Interferometry Using a Mach-Zehnder Configuration", Proc. 'Fiber Optic Sensors', SPIE Conf. Proc Vol. 586, p. 223, Cannes, 1985.
21. C. A. Wade, A. D. Kersey and A. Dandridge, "Temperature Sensor Based on a Fiber-Optic Differential Delay RF Filter", Electron. Lett., 24, p.1305, 1988.
22. C. A. Wade, M. J. Marrone, A. D. Kersey and A. Dandridge, "Multiplexing of Sensors Based on Fiber-Optic Differential Delay RF Filters", Electron. Lett., 24, p.1557, 1988.
23. M. J. Marrone et al., " Quasi-Distributed Fiber optic Sensor System with Subcarrier Filtering", Proc. OFS'89, p. 519, Paris, 1989 (Springer Verlag).
24. A. D. Kersey, "Recent Progress in Interferometric Fiber Sensor Technology", Proc. 'Fiber Optic and Laser Sensors VIII', SPIE Proc. Vol. 1367, p. 2, 1990.

25. A.D. Kersey and A. Dandridge, "Multiplexed Mach-Zehnder Ladder Array with Ten Sensor Elements, Electron. Lett. 25, p.1298, 1989.
26. I.P. Giles, D. Uttam, B. Culshaw and D.E.N. Davies, "Coherent Optical-Fiber Sensors with Modulated Laser Sources", Electron. Lett., 19, p. 14, 1983.
27. S. Al Chalabi *et. al.* ," Multiplexed Optical Interferometers - An Analysis Based on Radar Systems," Proc. IEE Part J, 132, p. 150, 1985.
28. I. Sakai *et. al.*," Multiplexing of Optical Fiber Sensors Using a Frequency-Modulated Source and Gated Output," IEEE J. Lightwave Technol., LT-5, p.932, 1987.
29. A. Dandridge, A.B. Tveten and T.G. Giallorenzi, "Homodyne Demodulation Scheme for Fiber-Optic Sensor Using Phase Generated Carrier", IEEE J. Quantum Electron., 18, p. 647, 1982.
30. A. Dandridge, A.B. Tveten, A.D. Kersey and A.M. Yurek, "Multiplexing of Interferometric Sensors using Phase Generated Carrier Techniques", IEEE J. Lightwave Technology, LT-5, p. 947, 1987.
31 A. Dandridge et al., "AOTA Tow test results", Proc. AFCEA/DoD Conf. on Fiber Optics '90, p. 104, McLean, 1990.
32. S.A. Al -Chalabi, B. Culshaw, and D.E.N. Davies, "Partially Coherent Sources in Interferometric Sensors",Proceedings of the First International Conference on Optical Fibre Sensors (IEE), pp. 132-135, 1983.
33. J. L. Brooks e. al., " Coherence Multiplexing of Fiber Optic Interferometric Sensors", IEEE J. Lightwave Technol., 3, p. 1062, 1985.
34. A.D. Kersey and A. Dandridge, "Phase Noise Reduction in Coherence Multiplexed Interferometric Fiber sensors", Electron. Lett., Vol. 22, No. 11, pp. 616-618, 1986.
35. D. O'Connell, A. D. Kersey, A. Dandridge, and C. A. Wade, "Coherence Multiplexed Fiber Optic Temperature Sensor using a Wavelength Dithered Source", Proc. OFC '89, p. 145, Houston, Feb. 1989. (OSA)
36. A. D. Kersey et al., " Differential polarimetric Fiber Optic Sensor Configuration with Dual Wavelength Operation", Appl. Optics, 28, p. 204, 1989.
37. V. Gusmeroli et al., " A Coherence Multiplexed Quasi-Distributed Polarimetric Sensor Suitable for Structural Monitoring", Proc. OFS'89, p. 513, Paris, 1989 (Springer Verlag).
38. J.P. Dakin, C.A. Wade and M.L. Henning, "Novel Optical Fibre Hydrophone Array Using a Single Laser Source and Detector", Electron. Lett., 20, p. 53, 1984.
39. M.L. Henning and C. Lamb, "At-Sea Deployment of a Multiplexed Fiber Optic Hydrophone Array," Proc. 5 th Int. Conf. on Optical Fiber Sensors, p. 84, New Orleans, Jan. *1988 (OSA technical digest).*
40. A. D. Kersey, K. L. Dorsey and A. Dandridge, "Demonstration of an eight-element Time-Division Multiplexed Interferometric Fiber Sensor Array," Electron. Lett., 24, p. 689, 1988.
41. A. D. Kersey, A. Dandridge and K. L. Dorsey, "Transmissive Serial Interferometric Fiber Sensor Array," J. Lightwave Technol., 7, p. 846, 1989.
42. A. D. Kersey et al., " Analysis of Intrinsic Crosstalk in Tapped Serial and Fabry-Perot Interferometric Fiber Sensor Arrays",, Proc. 'Fiber Optic and Laser Sensors VI', SPIE Proc. Vol. 985, p. 113, Boston, 1988.

43. B. Moslehi et al., “Efficient Fiber Optic structure with Applications to Sensor Arrays, IEEE J. Lightwave Technol., 7, p. 236, 1989.
44. Brooks et al.,” Fiber Optic Interferometric Sensor Arrays with Freedom From Source Induced Phase Noise”, Opt. Lett., p.473, 1986.
45. A.D. Kersey, A. Dandridge and A.B. Tveten,"Multiplexing of Interferometric Fiber Sensors Using Time Division Addressing and Phase Generated Carrier Demodulation", Optics Letters, 12, p. 775, 1987.
46. R. C. Dixon, “Spread Spectrum Systems”, Wiley, 1984.
47. P. R. Prucnal et al., “Spread Spectrum Fiber Optic Local Area Network using Optical Processing”, J. Lightwave Technol., LT-4, p. 547, 1986.
48. J. K. A. Everard, “ Novel Signal Processing Techniques for Enhanced OTDR Sensors”, Proc. Fiber Optic Sensors II, SPIE vol. 798, p. 42, The Hague, 1987.
49. H. S. Al-Raweshidy and D. Uttamchandani, “ Spread Spectrum Technique for Passive Multiplexing of Interferometric Fiber Optic Sensors”, Proc. Fiber Optics’90, SPIE vol. 1314, p. 342, London, 1990.
50. A.D. Kersey and A. Dandridge, “Low Crosstalk Code division Multiplexed Interferometric Array”, Electron. Lett., 28, p.351, 1992.
51. A. D. Kersey and A. Dandridge, “Comparative Analysis of Multiplexing Techniques for Interferometric Fiber Sensors”, Proc. ‘Fiber Optics 89, SPIE Conf. Proc. Vol 1120, p. 236, London, 1989
52. A. Dandridge et. al., “ Increasing Multiplexed Fiber Sensor Array Performance by Use of a Singlemode/Multimode Recombiner”, Proc. 6th In. Conf. on Optical Fiber Sensors, OFS’89, Post deadline paper # 5, p. 40, 1989.
53. A.D. Kersey and A. Dandridge, “Demonstration of a Hybrid Time/Wavelength Division Multiplexed Interferometric Fiber Sensor Array”, Electron. Lett., 2, p.554, 1991.
54. N. J. Frigo, A. Dandridge and A. B. Tveten, "Technique for elimination of polarization fading in fiber interferometers," Electron. Lett., 20, p. 319, 1984.
55. A. D. Kersey, M. J. Marrone, A. Dandridge and A. B. Tveten, "Optimization and Stabilization of Visibility in Interferometric Fiber-Optic Sensors Using Input-Polarization Control", J. Lightwave Technol. 6, p. 1599, 1988.
56. A. D. Kersey, M. J. Marrone and M. A. Davis, "Polarization-Insensitive Fiber Optic Michelson Interferometer", Electron. Lett. 26, p. 518, 1991.
57. M. J. Marrone et al., "Fiber Michelson Array with Passive Elimination of Polarization Fading and Source Feedback Isolation", Proc. OFS’92, p. 69, Monterey, 1992 (IEEE).
58. C. Edge and W. J. Stewart, "Measurement of Nonreciprocity in Single-Mode Optical Fibers", Tech. Dig. IEE Colloq. on Optical Fiber Measurements, No. 1987/55, 1987.
59. N. C. Pistoni and M. Martinelli, "Birefringence Effects Suppression in Optical Fiber Sensor Circuits", Proc. 7th Int. Conf. on Optical Fiber Sensors, p. 125, 1990.
60. M. J. Marrone et al., "Polarization Independent Interferometric Array Configurations", Proc. ‘Distributed and Multiplexed Fiber Optic Sensors II”, SPIE vol 1797, 1992.
61. A. D. Kersey et al., “Detection of DC and Low Frequency AC Magnetic Fields Using an All Single-Mode Fiber Magnetometer”, Electron. Lett., 19, p. 469, 1983., and K. P. Koo et al., “A Fiber Optic DC Magnetometer, IEEE J. Lightwave Technol., LT-1, p. 524, 1983.

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62. S. T. Vohra et al., “Fiber Optic DC and Low Frequency Electric Field Sensor”, Optics Lett., 16, p. 1445, 1991.
63. A. D. Kersey et al., “ New Nonlinear Phase Transduction Method for DC Measurand Interferometric Fiber Sensors”, Electron. Lett., 22, p. 75, 1986.
64. F. Bucholtz, A. D. Kersey and A. Dandridge, “ Multiplexing of Nonlinear Fiber Optic Interferometric Sensors”, IEE J. Lightwave Technol., 7, p. 514, 1989.
65. A. D. Kersey, F. Bucholtz, K. Sinansky and A. Dandridge," Interferometric Sensors for DC Measurands - A New Class of Fiber Sensors," SPIE Proc. vol. 718., ' Fiber Optic and Laser Sensors IV', Cambridge, MA, p. 198, 1986.

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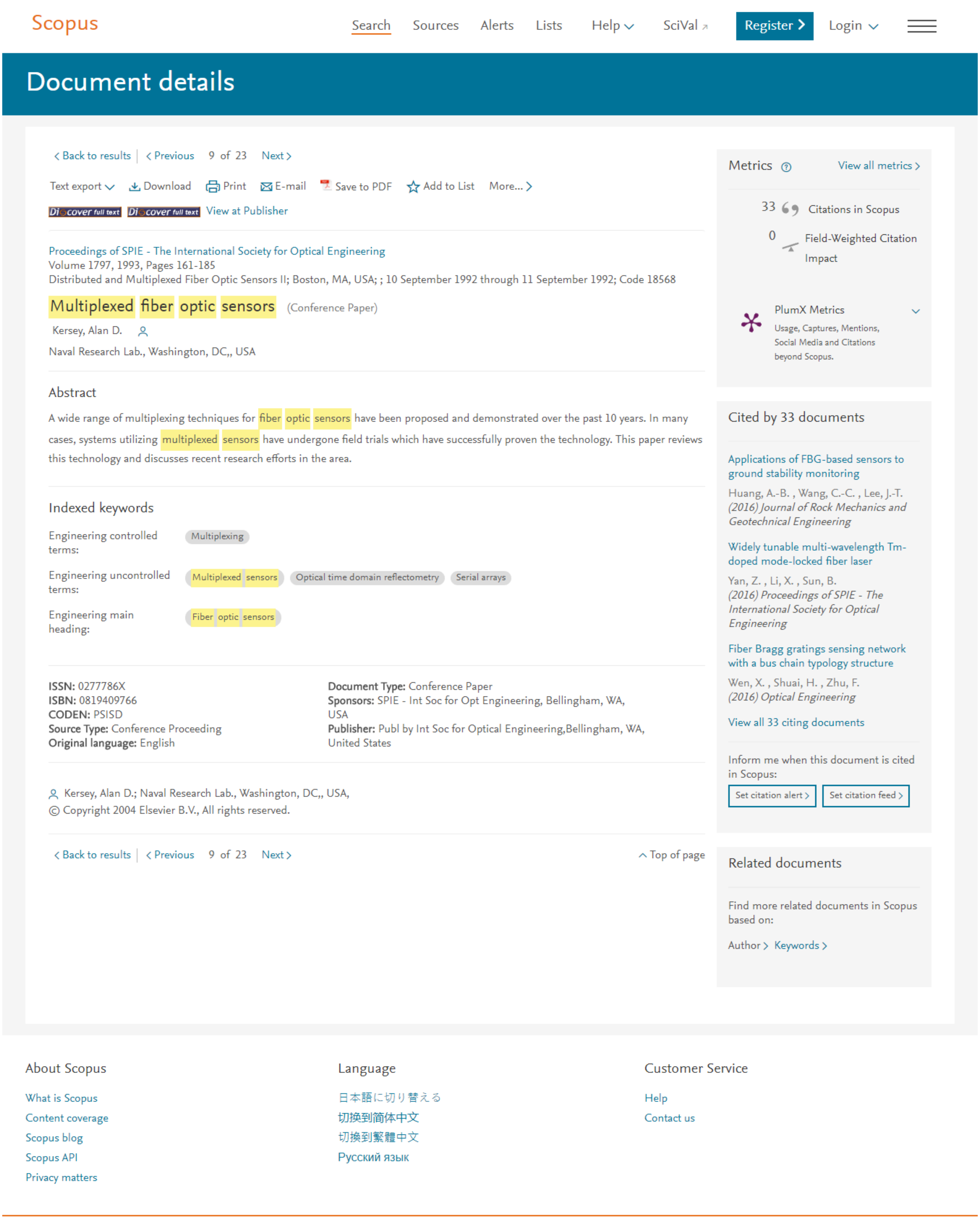

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Multiplexed fiber optic sensors (Conference Paper)

Kersey, Alan D.
Naval Research Lab., Washington, DC,, USA

Abstract

A wide range of multiplexing techniques for fiber optic sensors have been proposed and demonstrated over the past 10 years. In many cases, systems utilizing multiplexed sensors have undergone field trials which have successfully proven the technology. This paper reviews this technology and discusses recent research efforts in the area.

Indexed keywords

Engineering controlled terms: Multiplexing
Engineering uncontrolled terms: Multiplexed sensors; Optical time domain reflectometry; Serial arrays
Engineering main heading: Fiber optic sensors

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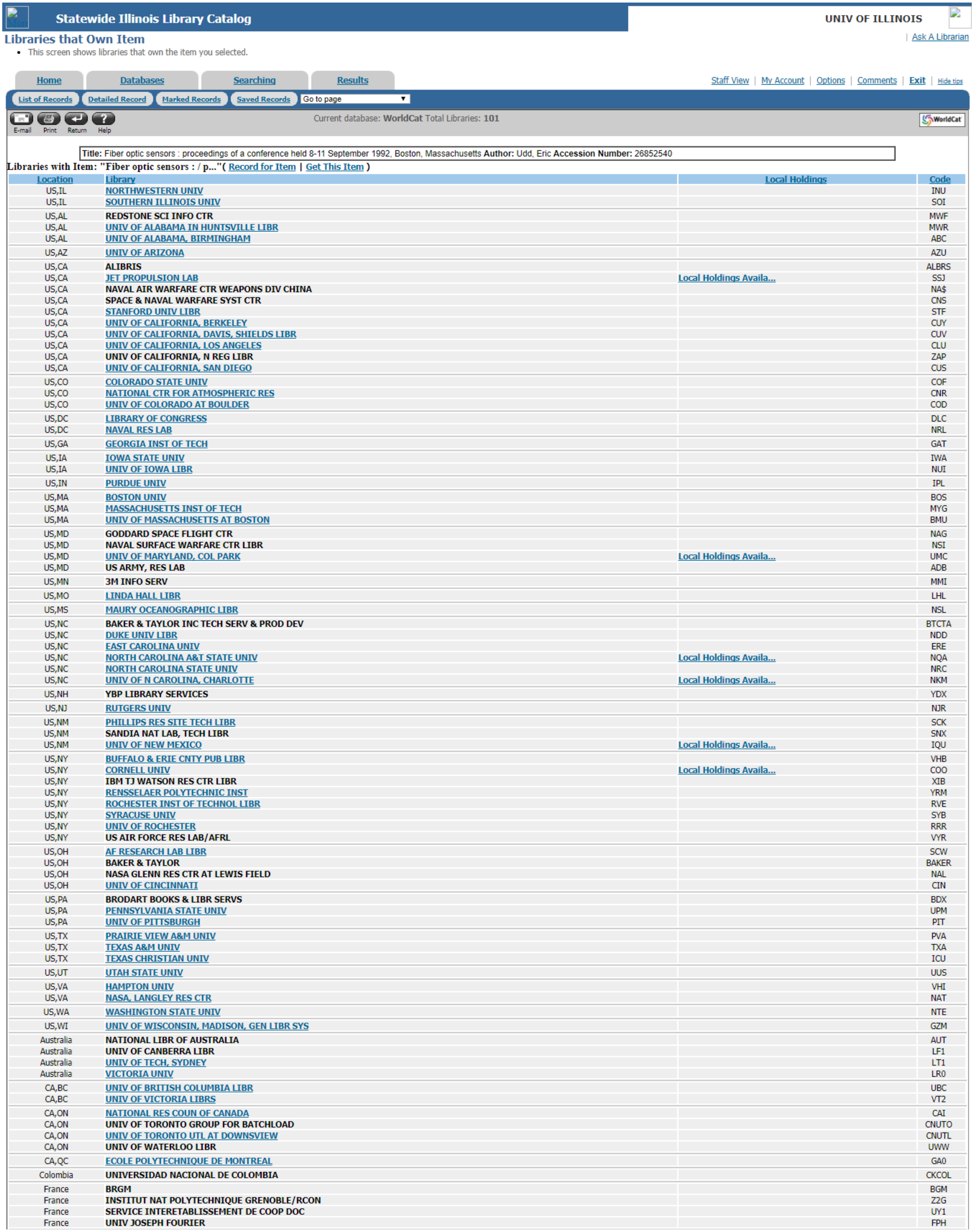

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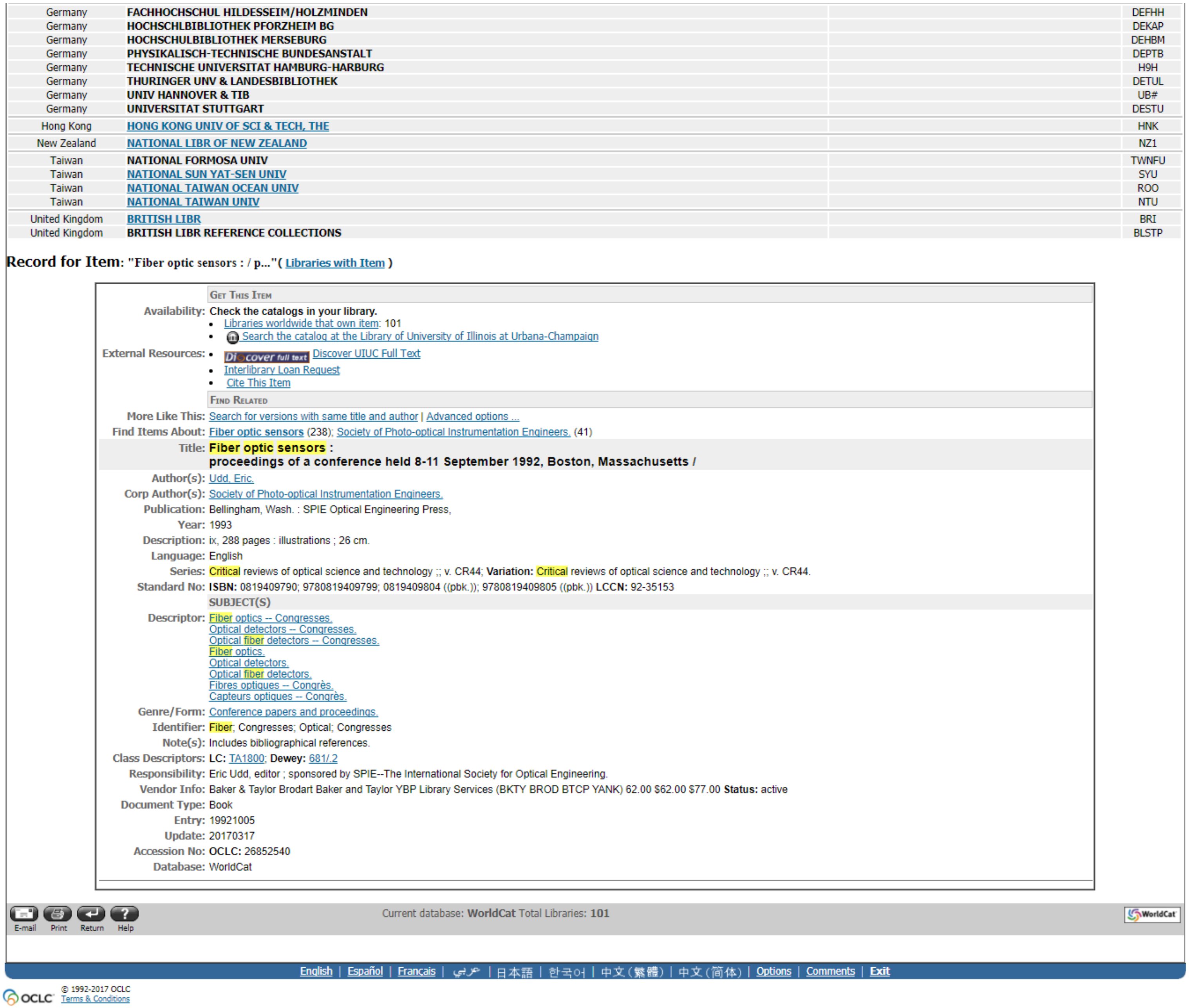

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Author(s): Udd, Eric.

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Publication: Bellingham, Wash. : SPIE Optical Engineering Press,

Year: 1993

Description: ix, 288 pages : illustrations ; 26 cm.

Language: English

Series: Critical reviews of optical science and technology ;; v. CR44; **Variation:** Critical reviews of optical science and technology ;; v. CR44.

Standard No: **ISBN:** 0819409790; 9780819409799; 0819409804 ((pbk.)); 9780819409805 ((pbk.)) **LCCN:** 92-35153

SUBJECT(S)

Descriptor: Fiber optics -- Congresses.
Optical detectors -- Congresses.
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Genre/Form: Conference papers and proceedings.

Identifier: Fiber; Congresses; Optical; Congresses

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Class Descriptors: **LC:** TA1800; **Dewey:** 681/.2

Responsibility: Eric Udd, editor ; sponsored by SPIE--The International Society for Optical Engineering.

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Title: Fiber optic sensors : proceedings of a conference held 8-11 September 1992, Boston, Massachusetts / Eric Udd, editor.
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Date of Creation: 1993
Date of Publication: 1993-05-12
Other Title: Critical reviews of optical science and technology ; vol. CR44
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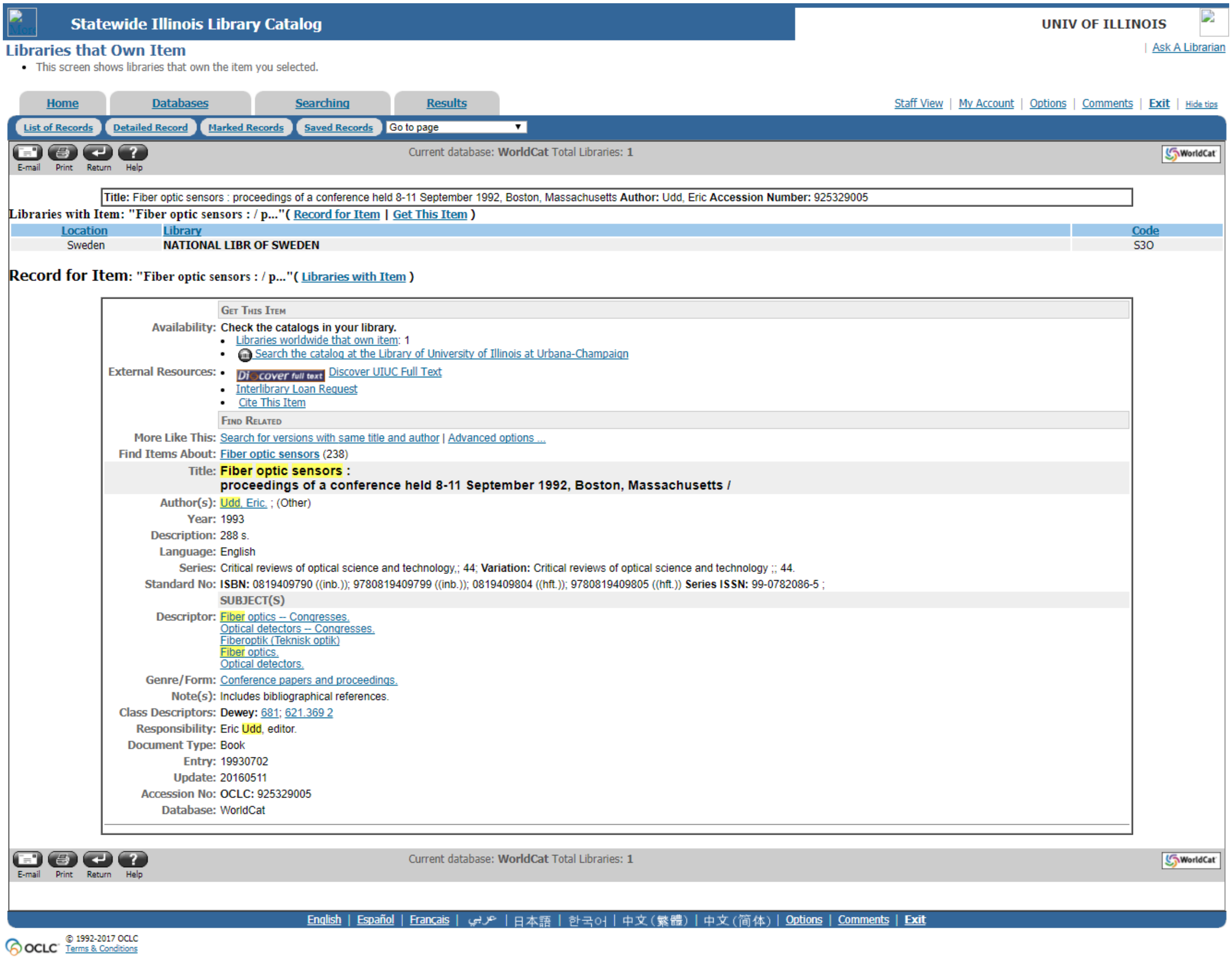

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Author(s): Udd, Eric. ; (Other)

Year: 1993

Description: 288 s.

Language: English

Series: Critical reviews of optical science and technology,; 44; **Variation:** Critical reviews of optical science and technology ;; 44.

Standard No: **ISBN:** 0819409790 ((inb.)); 9780819409799 ((inb.)); 0819409804 ((hft.)); 9780819409805 ((hft.)) **Series ISSN:** 99-0782086-5 ;

SUBJECT(S)

Descriptor: Fiber optics -- Congresses.
Optical detectors -- Congresses.
Fiberoptik (Teknisk optik)
Fiber optics.
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Genre/Form: Conference papers and proceedings.

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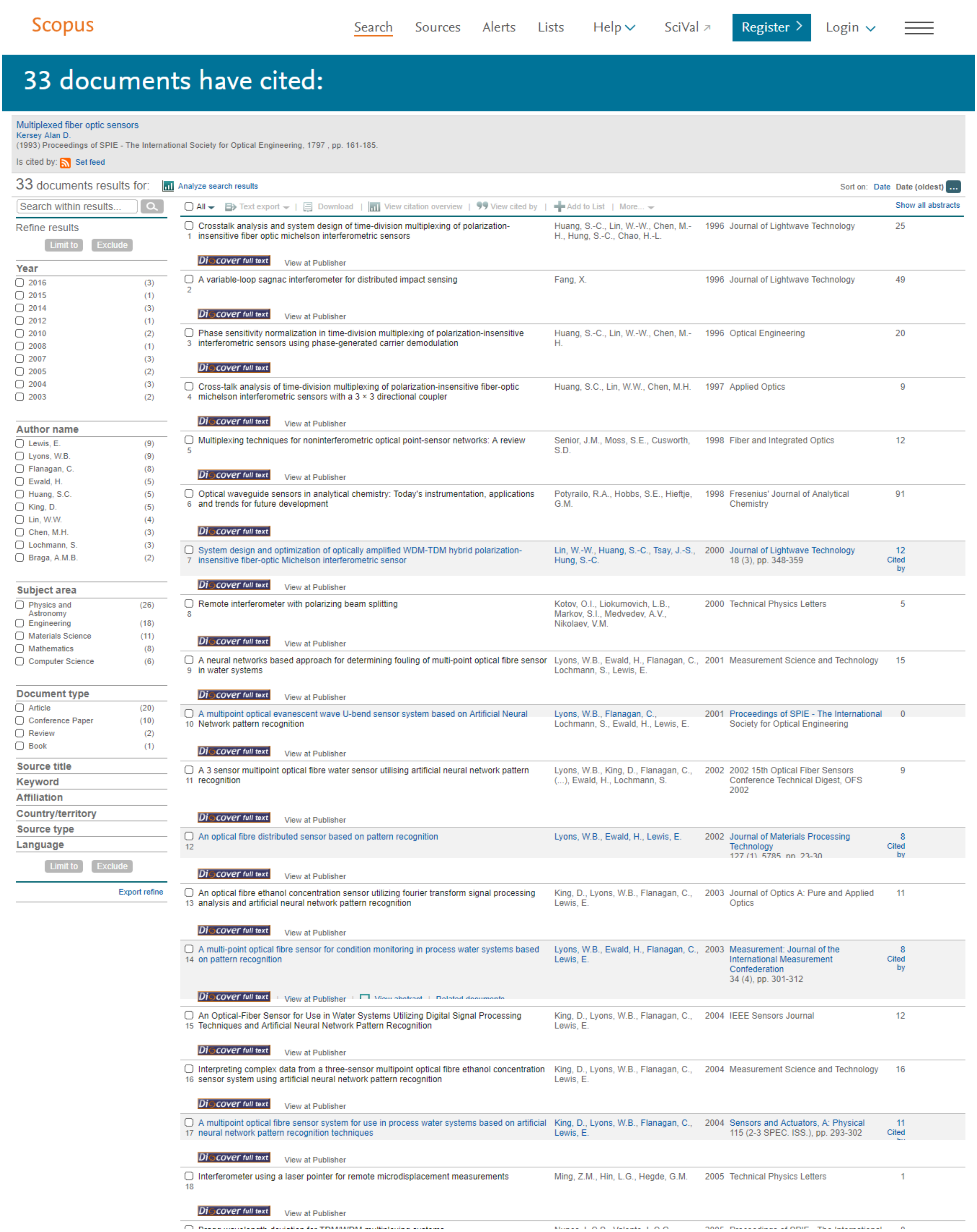

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Author name

☐ Lewis, E.	(9)
☐ Lyons, W.B.	(9)
☐ Flanagan, C.	(8)
☐ Ewald, H.	(5)
☐ Huang, S.C.	(5)
☐ King, D.	(5)
☐ Lin, W.W.	(4)
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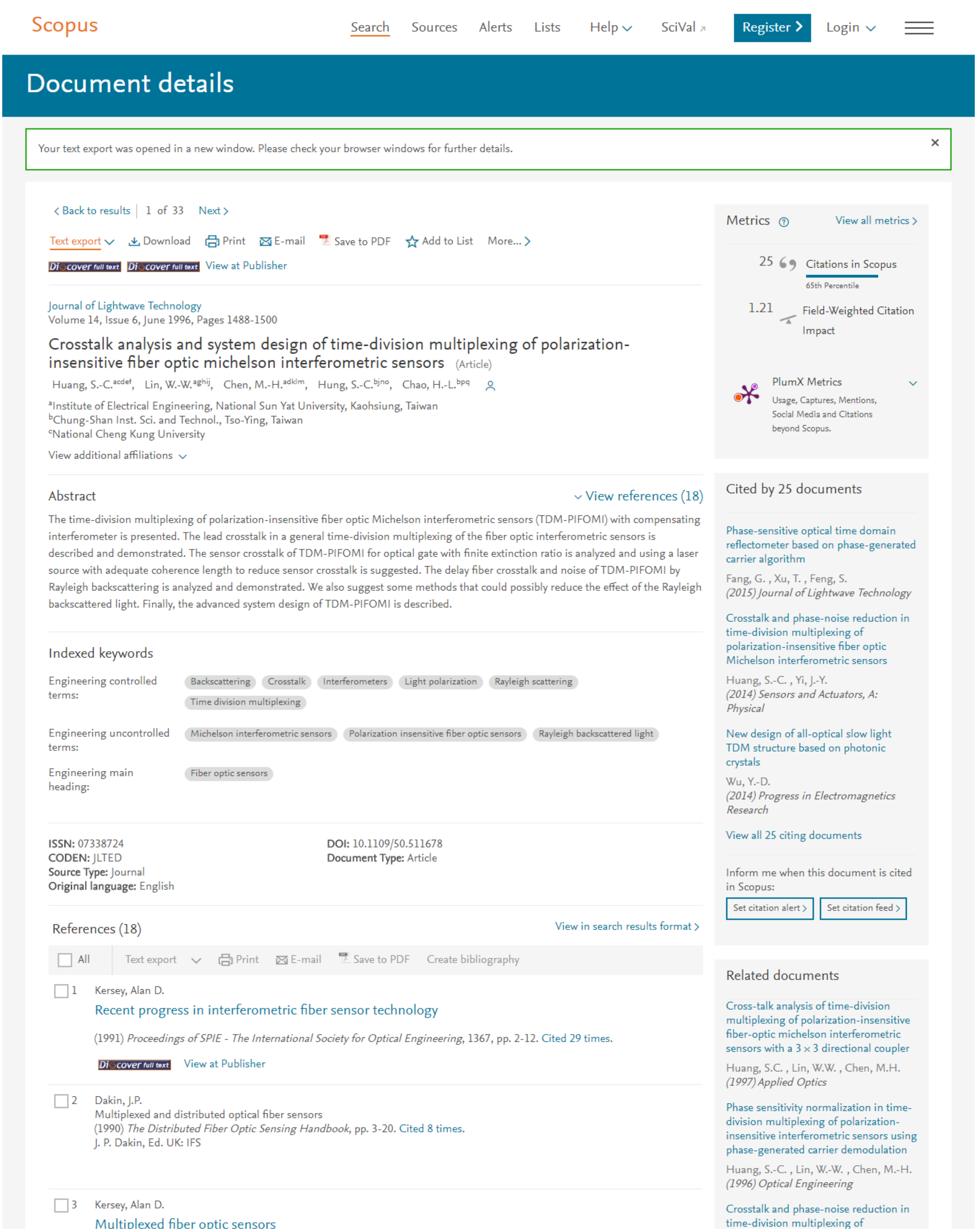

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Journal of Lightwave Technology
Volume 14, Issue 6, June 1996, Pages 1488-1500

Crosstalk analysis and system design of time-division multiplexing of polarization-insensitive fiber optic michelson interferometric sensors (Article)

Huang, S.-C.[acdef], Lin, W.-W.[aghij], Chen, M.-H.[adklm], Hung, S.-C.[bjno], Chao, H.-L.[bpq]

[a]Institute of Electrical Engineering, National Sun Yat University, Kaohsiung, Taiwan
[b]Chung-Shan Inst. Sci. and Technol., Tso-Ying, Taiwan
[c]National Cheng Kung University

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Abstract

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The time-division multiplexing of polarization-insensitive fiber optic Michelson interferometric sensors (TDM-PIFOMI) with compensating interferometer is presented. The lead crosstalk in a general time-division multiplexing of the fiber optic interferometric sensors is described and demonstrated. The sensor crosstalk of TDM-PIFOMI for optical gate with finite extinction ratio is analyzed and using a laser source with adequate coherence length to reduce sensor crosstalk is suggested. The delay fiber crosstalk and noise of TDM-PIFOMI by Rayleigh backscattering is analyzed and demonstrated. We also suggest some methods that could possibly reduce the effect of the Rayleigh backscattered light. Finally, the advanced system design of TDM-PIFOMI is described.

Indexed keywords

Engineering controlled terms:	Backscattering Crosstalk Interferometers Light polarization Rayleigh scattering Time division multiplexing
Engineering uncontrolled terms:	Michelson interferometric sensors Polarization insensitive fiber optic sensors Rayleigh backscattered light
Engineering main heading:	Fiber optic sensors

ISSN: 07338724
CODEN: JLTED
Source Type: Journal
Original language: English

DOI: 10.1109/50.511678
Document Type: Article

References (18)

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☐ 1 Kersey, Alan D.
Recent progress in interferometric fiber sensor technology
(1991) *Proceedings of SPIE - The International Society for Optical Engineering*, 1367, pp. 2-12. Cited 29 times.
Discover full text View at Publisher

☐ 2 Dakin, J.P.
Multiplexed and distributed optical fiber sensors
(1990) *The Distributed Fiber Optic Sensing Handbook*, pp. 3-20. Cited 8 times.
J. P. Dakin, Ed. UK: IFS

☐ 3 Kersey, Alan D.
Multiplexed fiber optic sensors

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(2015) Journal of Lightwave Technology

Crosstalk and phase-noise reduction in time-division multiplexing of polarization-insensitive fiber optic Michelson interferometric sensors
Huang, S.-C. , Yi, J.-Y.
(2014) Sensors and Actuators, A: Physical

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(2014) Progress in Electromagnetics Research

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Phase sensitivity normalization in time-division multiplexing of polarization-insensitive interferometric sensors using phase-generated carrier demodulation
Huang, S.-C. , Lin, W.-W. , Chen, M.-H.
(1996) Optical Engineering

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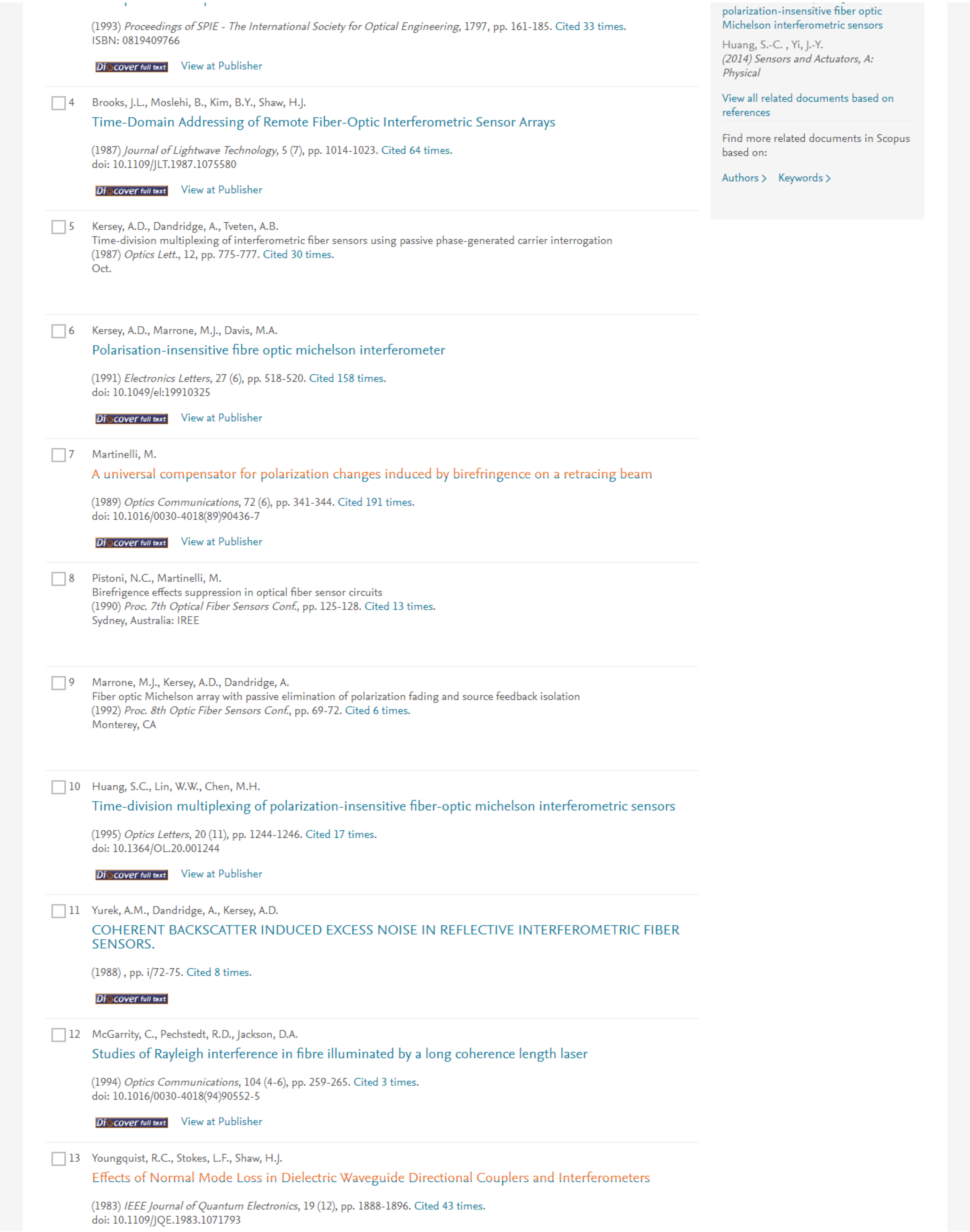

(1993) *Proceedings of SPIE - The International Society for Optical Engineering*, 1797, pp. 161-185. Cited 33 times.
ISBN: 0819409766

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☐ 4 Brooks, J.L., Moslehi, B., Kim, B.Y., Shaw, H.J.
Time-Domain Addressing of Remote Fiber-Optic Interferometric Sensor Arrays

(1987) *Journal of Lightwave Technology*, 5 (7), pp. 1014-1023. Cited 64 times.
doi: 10.1109/JLT.1987.1075580

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☐ 5 Kersey, A.D., Dandridge, A., Tveten, A.B.
Time-division multiplexing of interferometric fiber sensors using passive phase-generated carrier interrogation
(1987) *Optics Lett.*, 12, pp. 775-777. Cited 30 times.
Oct.

☐ 6 Kersey, A.D., Marrone, M.J., Davis, M.A.
Polarisation-insensitive fibre optic michelson interferometer

(1991) *Electronics Letters*, 27 (6), pp. 518-520. Cited 158 times.
doi: 10.1049/el:19910325

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☐ 7 Martinelli, M.
A universal compensator for polarization changes induced by birefringence on a retracing beam

(1989) *Optics Communications*, 72 (6), pp. 341-344. Cited 191 times.
doi: 10.1016/0030-4018(89)90436-7

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☐ 8 Pistoni, N.C., Martinelli, M.
Birefrigence effects suppression in optical fiber sensor circuits
(1990) *Proc. 7th Optical Fiber Sensors Conf.*, pp. 125-128. Cited 13 times.
Sydney, Australia: IREE

☐ 9 Marrone, M.J., Kersey, A.D., Dandridge, A.
Fiber optic Michelson array with passive elimination of polarization fading and source feedback isolation
(1992) *Proc. 8th Optic Fiber Sensors Conf.*, pp. 69-72. Cited 6 times.
Monterey, CA

☐ 10 Huang, S.C., Lin, W.W., Chen, M.H.
Time-division multiplexing of polarization-insensitive fiber-optic michelson interferometric sensors

(1995) *Optics Letters*, 20 (11), pp. 1244-1246. Cited 17 times.
doi: 10.1364/OL.20.001244

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☐ 11 Yurek, A.M., Dandridge, A., Kersey, A.D.
COHERENT BACKSCATTER INDUCED EXCESS NOISE IN REFLECTIVE INTERFEROMETRIC FIBER SENSORS.

(1988) , pp. i/72-75. Cited 8 times.

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☐ 12 McGarrity, C., Pechstedt, R.D., Jackson, D.A.
Studies of Rayleigh interference in fibre illuminated by a long coherence length laser

(1994) *Optics Communications*, 104 (4-6), pp. 259-265. Cited 3 times.
doi: 10.1016/0030-4018(94)90552-5

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☐ 13 Youngquist, R.C., Stokes, L.F., Shaw, H.J.
Effects of Normal Mode Loss in Dielectric Waveguide Directional Couplers and Interferometers

(1983) *IEEE Journal of Quantum Electronics*, 19 (12), pp. 1888-1896. Cited 43 times.
doi: 10.1109/JQE.1983.1071793

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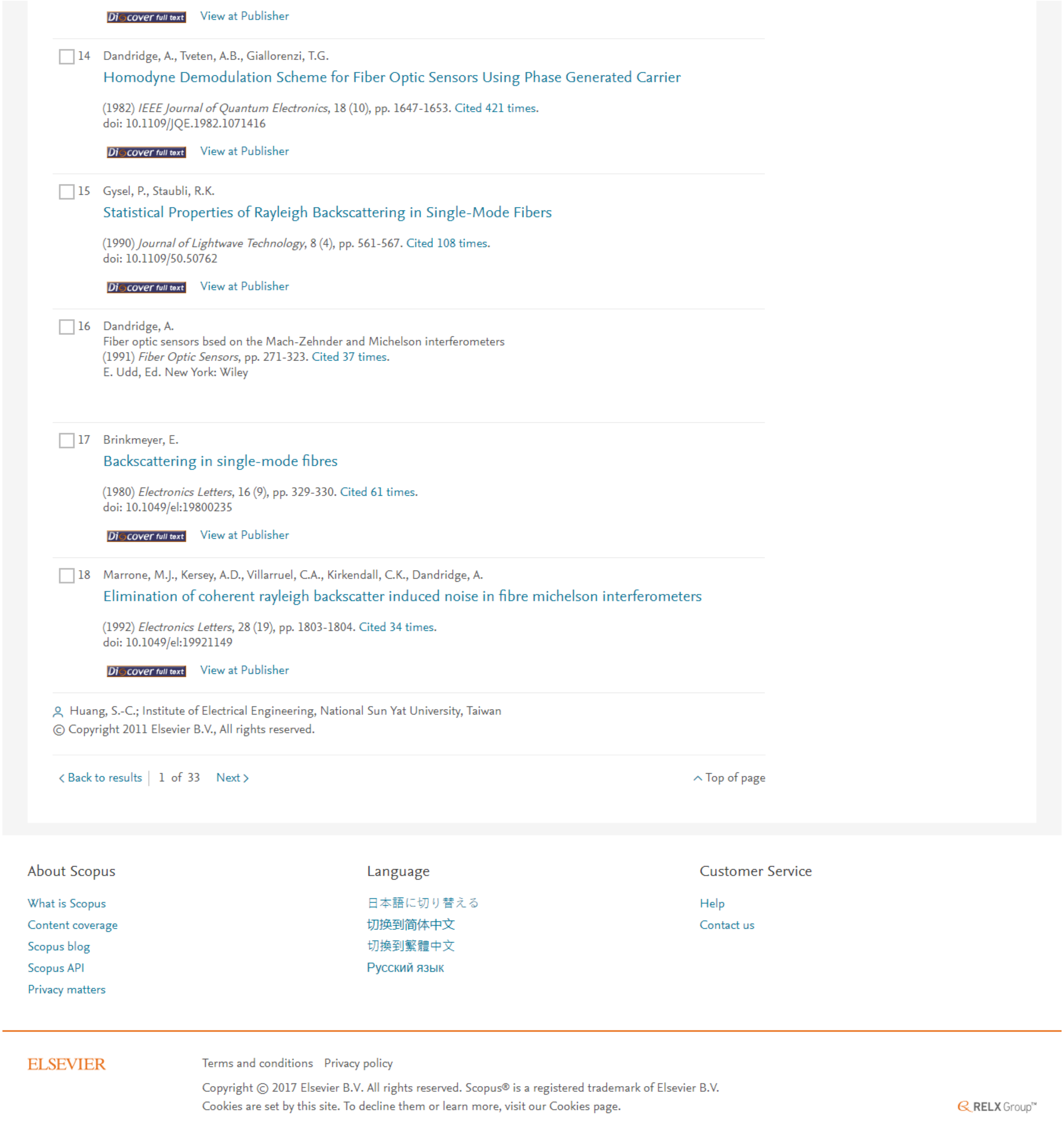

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Homodyne Demodulation Scheme for Fiber Optic Sensors Using Phase Generated Carrier

(1982) *IEEE Journal of Quantum Electronics*, 18 (10), pp. 1647-1653. Cited 421 times.
doi: 10.1109/JQE.1982.1071416

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☐ 15 Gysel, P., Staubli, R.K.
Statistical Properties of Rayleigh Backscattering in Single-Mode Fibers

(1990) *Journal of Lightwave Technology*, 8 (4), pp. 561-567. Cited 108 times.
doi: 10.1109/50.50762

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☐ 16 Dandridge, A.
Fiber optic sensors bsed on the Mach-Zehnder and Michelson interferometers
(1991) *Fiber Optic Sensors*, pp. 271-323. Cited 37 times.
E. Udd, Ed. New York: Wiley

☐ 17 Brinkmeyer, E.
Backscattering in single-mode fibres

(1980) *Electronics Letters*, 16 (9), pp. 329-330. Cited 61 times.
doi: 10.1049/el:19800235

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☐ 18 Marrone, M.J., Kersey, A.D., Villarruel, C.A., Kirkendall, C.K., Dandridge, A.
Elimination of coherent rayleigh backscatter induced noise in fibre michelson interferometers

(1992) *Electronics Letters*, 28 (19), pp. 1803-1804. Cited 34 times.
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