UNITED STATES PATENT AND TRADEMARK OFFICE

BEFORE THE PATENT TRIAL AND APPEAL BOARD

Halliburton Energy Services, Inc.
Petitioner,

v.

Adelos, Inc.
Patent Owner.

Patent 7,030,971

DECLARATION OF SCOTT BENNETT, Ph.D.
31 August 2017

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I, Scott Bennett, hereby declare under penalty of perjury:

I. INTRODUCTION

1. I have personal knowledge of the facts and opinions set forth in this declaration, I believe them to be true, and if called upon to do so, I would testify competently to them. I have been warned that willful false statements and the like are punishable by fine or imprisonment, or both.

2. I am a retired academic librarian working as a Managing Partner of the firm Prior Art Documentation Services LLC at 711 South Race Street, Urbana, IL, 61801-4132. Attached as Appendix A is a true and correct copy of my Curriculum Vitae describing my background and experience. Further information about my firm, Prior Art Documentation Services LLC, is available at www.priorartdocumentation.com.

3. I have been retained by Baker Botts L.L.P. to authenticate and establish the dates of public accessibility of certain documents in an *inter partes* review proceeding for U.S. Patent No. 7,030,971. For this service, I am being paid my usual hourly fee of $91/hour. My compensation in no way depends on the substance of my testimony or the outcome of this proceeding.

II. BACKGROUND AND QUALIFICATIONS

4. I was previously employed as follows:

- University Librarian, Yale University, New Haven, CT, 1994-2001;

- Director, The Milton S. Eisenhower Library, The Johns Hopkins University, Baltimore, MD, 1989-1994;
- Assistant University Librarian for Collection Management, Northwestern University, Evanston, IL, 1981-1989;
- Instructor, Assistant, and Associate Professor of Library Administration, University of Illinois at Urbana-Champaign, Urbana, IL, 1974-1981; and
- Assistant Professor of English, University of Illinois at Urbana-Champaign, 1967-1974.

5. Over the course of my work as a librarian, professor of English, researcher, and author of nearly fifty scholarly papers and other publications, I have had extensive experience with catalog records and online library management systems built around Machine-Readable Cataloging (MARC) standards. I also have substantial experience in authenticating printed documents and establishing the date when they were accessible to researchers.

6. In the course of more than fifty years of academic life, I have myself been an active researcher. I have collaborated with many individual researchers and, as a librarian, worked in the services of thousands of researchers at four prominent research universities. Over the years, I have read some of the voluminous professional literature on the information seeking behaviors of academic

researchers. And as an educator, I have a broad knowledge of the ways in which students in a variety of disciplines learn to master the bibliographic resources used in their disciplines. In all of these ways, I have a general knowledge of how researchers work.

III. PRELIMINARIES

7. *Scope of this declaration*. I am not a lawyer and I am not rendering an opinion on the legal question of whether any particular document is, or is not, a "printed publication" under the law.

8. I am, however, rendering my expert opinion on the authenticity of the documents referenced herein and on when and how each of these documents was disseminated or otherwise made available to the extent that persons interested and ordinarily skilled in the subject matter or art, exercising reasonable diligence, could have located the documents before 5 August 2003.

9. I am informed by counsel that an item is considered authentic if there is sufficient evidence to support a finding that the item is what it is claims to be. I am also informed that authenticity can be established based on the contents of the documents themselves, such as the appearance, contents, substance, internal patterns, or other distinctive characteristics of the item, taken together with all of the circumstances. I am further informed that an item is considered authentic if it is at

least 20 years old, in a condition that creates no suspicion of its authenticity, and in a place where, if authentic, it would likely be.

10. I am informed by counsel that a given reference is publicly accessible upon a satisfactory showing that such document has been disseminated or otherwise made available to the extent that persons interested and ordinarily skilled in the subject matter or art exercising reasonable diligence, can locate it. I have also been informed by counsel that materials available in a library constitute printed publications if they are cataloged and indexed (such as by subject) according to general library practices that make the references available to members of the interested public.

11. *Materials considered*. In forming the opinions expressed in this declaration, I have reviewed the documents and attachments referenced herein. These materials are records created in the ordinary course of business by publishers, libraries, indexing services, and others. From my years of experience, I am familiar with the process for creating many of these records, and I know these records are created by people with knowledge of the information in the record. Further, these records are created with the expectation that researchers and other members of the public will use them. All materials cited in this declaration and its attachments are of a type that experts in my field would reasonably rely upon and refer to in forming their opinions.

12. *Persons of ordinary skill in the art*. I am told by counsel that the subject matter of this proceeding generally relates to the field of time-domain reflectometers and more specifically to reflectometers that are part of photonic system applications in which the object of the reflectometry is a span of optical fiber.

13. I have been informed by counsel that a "person of ordinary skill in the art at the time of the invention" is a hypothetical person who is presumed to be familiar with the relevant field and its literature at the time of the invention. This hypothetical person is also a person of ordinary creativity, capable of understanding the scientific principles applicable to the pertinent field.

14. I am told by counsel that persons of ordinary skill in this subject matter or art would have (1) a Bachelor of Science in Physics or a relevant Engineering field and 4 years of fiber optics industry experience, or (2) a Masters or Doctorate in Physics or a relevant Engineering field and 2 years of fiber optics industry experience.

15. It is my opinion that such a person would have been engaged in academic research, learning though study and practice in the field and possibly through formal instruction the bibliographic resources relevant to his or her research. In the 1980s, 1990s, and 2000s, such a person would have had access to a vast array of long-established print resources in physics and engineering topics relevant to fiber

optics as well as to a rich and fast changing set of online resources providing indexing information, abstracts, and full text services for physics and engineering topics relevant to fiber optics.

16. *Library catalog records*. Some background on MARC formatted records, OCLC, WorldCat, and OCLC's Connexion is needed to understand the library catalog records discussed in this declaration.

17. Libraries world-wide use the MARC format for catalog records; this machine readable format was developed at the Library of Congress in the 1960s.

18. MARC formatted records provide a variety of subject access points based on the content of the document being cataloged. All may be found in the MARC Fields 6XX. For example, MARC Field 600 identifies personal names used as subjects and the MARC Field 650 identifies topical terms. A researcher might discover material relevant to his or her topic by a search using the terms employed in the MARC Fields 6XX.

19. The MARC Field 040, subfield a, identifies the library or other entity that created the original catalog record for a given document and transcribed it into machine readable form. The MARC Field 008 identifies the date when this first catalog record was entered on the file. This date persists in all subsequent uses of the first catalog record, although newly-created records for the same document,

separate from the original record, will show a new date. It is not unusual to find multiple catalog records for the same document.

20. WorldCat is the world's largest public online catalog, maintained by the Online Computer Library Center, Inc., or OCLC, and built with the records created by the thousands of libraries that are members of OCLC. WorldCat provides a user-friendly interface for the public to use MARC records; it requires no knowledge of MARC tags and codes. WorldCat records appear in many different catalogs, including the Statewide Illinois Library Catalog. The date a given catalog record was created (corresponding to the MARC Field 008) appears in some detailed WorldCat records as the Date of Entry.

21. Whereas WorldCat records are very widely available, the availability of MARC formatted records varies from library to library.

22. When an OCLC participating institution acquires a document for which it finds no previously created record in OCLC, or when the institution chooses not to use an existing record, it creates a record for the document using OCLC's Connexion, the bibliographic system used by catalogers to create MARC records. Connexion automatically supplies the date of record creation in the MARC Field 008.

23. Once the MARC record is created by a cataloger at an OCLC participating member institution, it becomes available to other OCLC participating

members in Connexion and also in WorldCat, where persons interested and ordinarily skilled in the subject matter or art, exercising reasonable diligence, can locate it.

24. When a book has been cataloged, it will normally be made available to readers soon thereafter—normally within a few days or (at most) within a few weeks of cataloging.

25. *Publications in series*. A library typically creates a MARC catalog record for a series of closely related publications, such as the proceedings of an annual conference, when the library receives its first issue. When the institution receives subsequent issues/volumes of the series, the issues/volumes are checked in (sometimes using a date stamp), added to the institution's holdings records, and made available very soon thereafter—normally within a few days of receipt or (at most) within a few weeks of receipt.

26. The initial series record will often not reflect all of the subsequent changes in publication details (including minor variations in title, etc.).

27. When a library does not intend systematically to acquire all publications in a given series, but adds individual volumes of the series to its collections, the library will typically treat each such volume as an individual book, or monograph. In this case, the 008 Field MARC will record the date when the record for that individual volume, not the series, was created.

28. It is sometimes possible to find both a series and a monograph library catalog record for the same publication.

29. *Periodical publications*. A library typically creates a catalog record for a periodical publication when the library receives its first issue. When the institution receives subsequent issues/volumes of the periodical, the issues/volumes are checked in (often using a date stamp), added to the institution's holdings records, and made available very soon thereafter—normally within a few days of receipt or (at most) within a few weeks of receipt.

30. The initial periodicals record will sometimes not reflect all of the subsequent changes in publication details (including minor variations in title, etc.).

31. *Indexing*. A researcher may discover material relevant to his or her topic in a variety of ways. One common means of discovery is to search for relevant information in an index of periodical and other publications. Having found relevant material, the researcher will then normally obtain it online, look for it in libraries, or purchase it from the publisher, a bookstore, a document delivery service, or other provider. Sometimes, the date of a document's public accessibility will involve both indexing and library date information. Date information for indexing entries is, however, often unavailable. This is especially true for online indices.

32. Indexing services use a wide variety of controlled vocabularies to provide subject access and other means of discovering the content of documents. The formats in which these access terms are presented vary from service to service.

33. Online indexing services commonly provide bibliographic information, abstracts, and full-text copies of the indexed publications, along with a list of the documents cited in the indexed publication. These services also often provide lists of publications that cite a given document. A citation of a document is evidence that the document was publicly available and in use by researchers no later than the publication date of the citing document.

34. Prominent indexing services include:

35. SPIE Digital Library. Produced by the International Society for Optical Engineering (originally the Society of Photographic Instrumentation Engineers), this data base includes the newsletters, journals, and conference proceedings of the organization. More than 400,000 articles make up the database with 18,000 new research papers added each year.

36. Scopus. Produced by Elsevier, a major publisher, Scopus is the largest database of abstracts and citations of peer-reviewed literature. Its scope includes the social sciences, science, technology, medicine, and the arts. It includes 60 million records from more than 21,500 titles from some 5,000 international

publishers. Coverage includes 360 trade publications, over 530 book series, more than 7.2 million conference papers, and 116,000 books. Records date from 1823.

37. Google Scholar. Google Scholar indexes the texts and metadata of scholarly publications across a wide range of disciplines. It includes most peer-reviewed online academic journals, conference papers, theses, technical reports, and other material. Google does not publish the size of the Google Scholar database, but researchers have estimated that it contained approximately 160 million items in 2014 (Enrique Oduña-Malea, et al., "About the size of Google Scholar: playing the numbers," Granada: EC3 Working Papers, 1B: 23 July 2014, available at https://arxiv.org/ftp/arxiv/papers/1407/1407.6239.pdf).

IV. OPINIONS REGARDING INDIVIDUAL DOCUMENTS

Document 1. Toshihiko Yoshino et al., "Common Path Heterodyne Optical Fiber Sensors," Journal of Lightwave Technology. 10,4 (April 1992): 503-513.

Authentication

38. Document 1 is a research paper by Toshihiko Yoshinto and others published in the April 1992 issue of the Journal of Lightwave Technology.

39. Attachment 1a is a true and accurate copy of Document 1 (along with the issue cover and publication information page) from the University of Illinois at Urbana-Champaign Library. Attachment 1b is a true and accurate copy of the University of Illinois at Urbana-Champaign Library catalog record for the

Journal of Lightwave Technology, showing holdings that include Volume 10, No 4 of this periodical.

40. Attachment 1a is in a condition that creates no suspicion about its authenticity. Specifically, Document 1 is not missing any intermediate pages of the article's text, the text on each page appears to flow seamlessly from one page to the next, and there are no visible alterations to the document. Attachment 1a was found within the custody of a library – a place where, if authentic, it would likely be found.

41. Document 1 is also readily available online. Attachment 1c is a true and accurate copy of the IEEE Xplore Digital Library index record for Document 1. Attachment 1d is a true and accurate copy of Document 1 from the IEEE Xplore Digital Library—a place where, if authentic, Document 1 would likely be found.

42. I conclude, based on finding Document 1 in a library and online and on finding library catalog records and online records for Document 1, that Document 1 is an authentic document and that Attachment 1a is an authentic copy of Document 1.

Public Accessibility

43. Attachment 1e is a true and accurate copy of the Statewide Illinois Library Catalog record for the Journal of Lightwave Technology, showing this periodical was first published in 1983 and is held by 384 libraries world-wide.

Attachment 1e also indicates that the Journal of Lightwave Technology was cataloged or indexed in a meaningful way—including being cataloged by subject. Thus, in my opinion, the Journal of Lightwave Technology was sufficiently accessible to the public interested in the art. An ordinarily skilled researcher, exercising reasonable diligence, would have had no difficulty finding copies of the Journal of Lightwave Technology.

44. Attachment 1a, from the University of Illinois at Urbana-Champaign Library, includes a library date stamp indicating that the April 1992 issue of the Journal of Lightwave Technology was processed on 5 May 1992. Based on my experience, I affirm this date stamp has the general appearance of date stamps that libraries have long affixed to periodicals in processing them. I do not see any indications or have any reason to believe this date stamp was affixed by anyone other than library personnel on or about the date indicated by the stamp.

45. Allowing for some time between the date stamp on the April 1992 issue of the Journal of Lightwave Technology and its appearance on library shelves, where it would be publicly available, it is my opinion that Document 1 was publicly available at least by June 1992.

46. Attachment 1f is a true and accurate copy of the IEEE Xplore Digital Library index record identifying 19 documents citing Document 1. One citing document is by Ti-ing Su and Likarn Wang, "A cutback method for measuring

low linear fibre birefringence using an electro-optical modulator," Optical and Quantum Electronics, 28,1 (October 1996): 1395-1405. Attachment 1g is a true and accurate copy of the SpringerLink index record for the Su and Wang paper, showing Document 1 as the 4th item in its list of references.

Conclusion

47. Based on the evidence presented here—publication in the widely held periodical, online indexing and publication, library processing, and citation—it is my opinion that Document 1 is an authentic document that was publicly available to researchers at least by June 1992. The citation evidence presented here indicates that Document 1 was in actual use by researchers at least by October 1996.

Document 2. J. K. A. Everard, "Novel Signal Processing Techniques for Enhanced OTDR Sensors," Proceedings, Fiber Optic Sensors II, 31 March – 3 April 1987, The Hague, The Netherlands, A. M. Scheggi, ed. SPIE Volume 798 (Bellingham, WA: SPIE – The International Society for Optical Engineering, 1987): 42-46.

Authentication

48. Document 2 is a paper given by J. K. A. Everard at the 1987 Fourth International Symposium on Optical and Optoelectronic Applied Science and Engineering, 30 March - 3 April 1987, at The Hague, and published in 1987 in the proceedings of that symposium.

49. Attachment 2a is a true and accurate copy of Document 2, along with the title page and other front matter, contents pages, and symposium information pages of the conference proceedings in which Document 2 was

published. Attachment 2 is from the University of Illinois at Urbana-Champaign Library. Attachment 2b is a true and accurate copy of that library's catalog record, in MARC format, for the proceedings of Fiber Optic Sensors II, in which Document 4 was published.

50. Attachment 2a is in a condition that creates no suspicion about its authenticity. Specifically, the text of Document 2 is not missing any intermediate pages, the text on each page appears to flow seamlessly from one page to the next, and there are no visible alterations to the document. Attachment 2a was found within the custody of a library – a place where, if authentic, it would likely be found.

51. Document 2 is also readily identified online. Attachment 2c is a true and accurate copy of the SPIE Digital Library index record for Document 2. Document 2 is available for purchase from the SPIE Digital Library.

52. Based on finding Document 2 in a library and online and on finding library catalog and online index records for Document 2, I conclude that Document 2 is an authentic document and that Attachment 2a is an authentic copy of Document 2.

Public Accessibility

53. Document 1 entered the realm of public discourse when it was presented at Session 1 on Distributed Sensors at the Fourth International Symposium on Optical and Optoelectronic Applied Science and Engineering, 30 March - 3 April

1987, at The Hague. The scope of the conference is suggested by the 44 papers and 19 posters presented there, as indicated by the contents pages in Attachment 2a.

54. Attachment 2d is a true and accurate copy of the Statewide Illinois Library Catalog record for Fiber Optic Sensors II, in which Document 2 was published, showing this conference proceedings is held by 92 libraries world-wide. Attachment 2d also indicates that the Fiber Optic Sensors II conference proceedings was cataloged or indexed in a meaningful way—including being cataloged by subject. Thus, in my opinion, the Fiber Optic Sensors II conference proceedings, in which Document 2 was published, was sufficiently accessible to the public interested in the art. An ordinarily skilled researcher, exercising reasonable diligence, would have had no difficulty finding copies of the Fiber Optic Sensors II conference proceedings.

55. In Attachment 2b, the University of Illinois at Urbana-Champaign Library catalog record for Document 2, the MARC Field 008 indicates this catalog record was created on 10 November 1987. Allowing for some time between cataloging Document 2 and its appearance on library shelves, where it would be publicly available, it is my opinion that Document 2 was publicly available at least by December 1987.

56. Attachment 2e is a true and accurate copy of a Google Scholar list of 26 publications citing Document 2. One citing document is by A. D. Kersey and

A. Dandridge, "Distributed and multiplexed fibre-optic sensor systems," Journal of the Institution of Electric and Radio Engineers 58,5S (July-August 1988): S99-S111. Attachment 2f is a true and accurate copy of the IET [Institute of Engineering Technology] Digital Library index record for the Kersey and Dandridge paper, showing Document 2 as the 51st item in its list of references.

Conclusion

57. Based on the evidence presented here—presentation at prominent conference and publication in the conference proceedings, library cataloging, online indexing and publication, library processing, and citation—it is my opinion that Document 2 was available to the public in at least one library by December 1987. The citation evidence presented here indicates that Document 2 was in actual use by researchers by August 1988.

Document 3. D. E. N. Davies, "Method of Phase-Modulating Signals in Optical Fibres: Application to Optical-Telemetry Systems," Electronics Letters, 10,2 (24 January 1974): 21-22.

Authentication

58. Document 3 is a research paper by D. E. N. Davies published in the 24 January 1974 issue of Electronics Letters.

59. Attachment 3a is a true and accurate copy of Document 3 (along with the issue cover and publication information page) from the Linda Hall Library. Attachment 3b is a true and accurate copy of the Linda Hall Library catalog record

for Electronics Letters, showing holdings for Volumes 1-34, including therefore Volume 10, No 2 of this periodical, in which Document 3 was published.

60. Attachment 3a is in a condition that creates no suspicion about its authenticity. Specifically, Document 3 is not missing any intermediate pages of the article's text, the text on each page appears to flow seamlessly from one page to the next, and there are no visible alterations to the document. Attachment 3a was found within the custody of a library – a place where, if authentic, it would likely be found.

61. Document 3 is also readily available online. Attachment 3c is a true and accurate copy of the Scopus index record for Document 3. Attachment 3d is a true and accurate copy of Document 3 from the IEEE Xplore Digital Library—a place where, if authentic, Document 3 would likely be found.

62. I conclude, based on finding Document 3 in a library and online and on finding library catalog records and online records for Document 3, that Document 3 is an authentic document and that Attachment 3a is an authentic copy of Document 3.

Public Accessibility

63. Attachment 3e is a true and accurate copy of the Statewide Illinois Library Catalog record for Electronics Letters, showing this periodical was first published in 1965 and is held by 482 libraries world-wide. Attachment 3e also indicates that Electronics Letters was cataloged or indexed in a meaningful way—

including being cataloged by subject. Thus, in my opinion, Electronics Letters was sufficiently accessible to the public interested in the art. An ordinarily skilled researcher, exercising reasonable diligence, would have had no difficulty finding copies of Electronics Letters.

64. Attachment 3a, from the Linda Hall Library, includes a library date stamp indicating that the 24 January 1974 issue of Electronics Letters was processed on 4 March 1974. Based on my experience, I affirm this date stamp has the general appearance of date stamps that libraries have long affixed to periodicals in processing them. I do not see any indications or have any reason to believe this date stamp was affixed by anyone other than library personnel on or about the date indicated by the stamp.

65. Allowing for some time between the date stamp on the 24 January 1974 issue of Electronics Letters and its appearance on library shelves, where it would be publicly available, it is my opinion that Document 3 was publicly available at least by April 1974.

66. Attachment 3f is a true and accurate copy of the first page of a Scopus list identifying 55 documents citing Document 3. One citing document is by D. F. Nelson et al., "Vibration-induced modulation of fiberguide transmission," Applied Physics Letters, 30,2 (15 January 1977): 94-96. Attachment 3g is a true

and accurate copy of the Scopus index record for the Nelson et al. paper, showing Document 3 as the 8th item in its list of references.

Conclusion

67. Based on the evidence presented here—publication in the widely held periodical, online indexing and publication, library processing, and citation—it is my opinion that Document 3 is an authentic document that was publicly available to researchers at least by April 1974. The citation evidence presented here indicates that Document 3 was in actual use by researchers at least by January 1977.

Document 4. A. Dandridge and A. D. Kersey, "Signal Processing for Optical Fiber Sensors," Proceedings, Fiber Optic Sensors II, 31 March – 3 April 1987, The Hague, The Netherlands, A. M. Scheggi, ed. SPIE Volume 798 (Bellingham, WA: SPIE – The International Society for Optical Engineering, 1987): 158-165.

Authentication

68. Document 4 is a paper given by A. Dandridge and A. D. Kersey at the 1987 Fourth International Symposium on Optical and Optoelectronic Applied Science and Engineering, 30 March - 3 April 1987, at The Hague, and published in 1987 in the proceedings of that symposium.

69. Attachment 4a is a true and accurate copy of Document 4, along with the title page and other front matter, contents pages, and symposium information pages of the conference proceedings in which Document 4 was published. Attachment 4 is from the University of Illinois at Urbana-Champaign Library. Attachment 4b is a true and accurate copy of that library's catalog record,

in MARC format, for the proceedings of Fiber Optic Sensors II, in which Document 4 was published.

70. Attachment 4a is in a condition that creates no suspicion about its authenticity. Specifically, the text of Document 4 is not missing any intermediate pages, the text on each page appears to flow seamlessly from one page to the next, and there are no visible alterations to the document. Attachment 4a was found within the custody of a library – a place where, if authentic, it would likely be found.

71. Document 4 is also readily identified online. Attachment 4c is a true and accurate copy of the Scopus index record for Document 4.

72. Based on finding Document 4 in a library and on finding library catalog and online index records for Document 4, I conclude that Document 4 is an authentic document and that Attachment 4a is an authentic .copy of Document 4.

Public Accessibility

73. Document 4 entered the realm of public discourse when it was presented at Session 4 on Signal Processing and Detection Techniques at the Fourth International Symposium on Optical and Optoelectronic Applied Science and Engineering, 30 March - 3 April 1987, at The Hague. The scope of the conference is suggested by the 44 papers and 19 posters presented there, as indicated by the contents pages in Attachment 4a.

74. Attachment 4d is a true and accurate copy of the Statewide Illinois Library Catalog record for Fiber Optic Sensors II, in which Document 4 was published, showing this conference proceedings is held by 92 libraries world-wide. Attachment 4d also indicates that the Fiber Optic Sensors II conference proceedings was cataloged or indexed in a meaningful way—including being cataloged by subject. Thus, in my opinion, the Fiber Optic Sensors II conference proceedings, in which Document 4 was published, was sufficiently accessible to the public interested in the art. An ordinarily skilled researcher, exercising reasonable diligence, would have had no difficulty finding copies of the Fiber Optic Sensors II conference proceedings.

75. In Attachment 4b, the University of Illinois at Urbana-Champaign Library catalog record for Document 4, the MARC Field 008 indicates this catalog record was created on 10 November 1987. Allowing for some time between cataloging Document 4 and its appearance on library shelves, where it would be publicly available, it is my opinion that Document 4 was publicly available at least by December 1987.

76. Attachment 4e is a true and accurate copy of a Scopus list of 10 publications citing Document 4. One citing document is by L. Grochowski, "Fiber optic geophysics sensor array," Proceedings of SPIE, 954 (16 January 1989): 634-

639. Attachment 4f is a true and accurate copy of the Scopus index record for the Grochowski paper, showing Document 4 as the 2nd item in its list of references.

Conclusion

77. Based on the evidence presented here—presentation at prominent conference and publication in the conference proceedings, library cataloging, online indexing, library processing, and citation—it is my opinion that Document 4 was available to the public in at least one library by December 1987. The citation evidence presented here indicates that Document 4 was in actual use by researchers by January 1989.

Document 5. Sally M. Maughan et al., "Simultaneous distributed fibre temperature and strain sensor using microwave coherent detection of spontaneous Brillouin backscatter," Measurement Science and Technology, 12,7 (July 2001): 834-843

Authentication

78. Document 5 is a research paper by Sally Maughan and others published in the July 2001 issue of Measurement Science and Technology.

79. Attachment 5a is a true and accurate copy of Document 1 (along with the issue cover, publication information pages, and contents pages) from the University of Illinois at Urbana-Champaign Library. Attachment 5b is a true and accurate copy of the University of Illinois at Urbana-Champaign Library catalog record for Measurement Science and Technology, showing holdings that include Volume 12, No 7 of this periodical.

80. Attachment 5a1a is in a condition that creates no suspicion about its authenticity. Specifically, Document 5 is not missing any intermediate pages of the article's text, the text on each page appears to flow seamlessly from one page to the next, and there are no visible alterations to the document. Attachment 5a was found within the custody of a library – a place where, if authentic, it would likely be found.

81. Document 5 is also readily available online. Attachment 5c is a true and accurate copy of the Scopus index record for Document 5. Attachment 5d is a true and accurate copy of Document 5 from IOPscience, the publisher of Measurement Science and Technology—a place where, if authentic, Document 5 would likely be found.

82. I conclude, based on finding Document 5 in a library and online and on finding library catalog records and online records for Document 5, that Document 5 is an authentic document and that Attachment 5a is an authentic copy of Document 5.

Public Accessibility

83. Attachment 5e is a true and accurate copy of the Statewide Illinois Library Catalog record for Measurement Science and Technology, showing this periodical was first published in 1990 and is held by 439 libraries world-wide. Attachment 5e also indicates that Measurement Science and Technology was

cataloged or indexed in a meaningful way—including being cataloged by subject. Thus, in my opinion, Measurement Science and Technology was sufficiently accessible to the public interested in the art. An ordinarily skilled researcher, exercising reasonable diligence, would have had no difficulty finding copies of Measurement Science and Technology.

84. Attachment 5a, from the University of Illinois at Urbana-Champaign Library, includes a library date stamp indicating that the July 2001 issue of Measurement Science and Technology was processed on 17 July 2001. Based on my experience, I affirm this date stamp has the general appearance of date stamps that libraries have long affixed to periodicals in processing them. I do not see any indications or have any reason to believe this date stamp was affixed by anyone other than library personnel on or about the date indicated by the stamp.

85. Allowing for some time between the date stamp on the July 2001 issue of Measurement Science and Technology and its appearance on library shelves, where it would be publicly available, it is my opinion that Document 5 was publicly available at least by August 2001.

86. Attachment 5f is a true and accurate copy of the first page of the Scopus record identifying 95 documents citing Document 5. One citing document is by Y. Li et al., "Wide temperature-range brillouin and rayleigh optical-time-domain reflectometry in a dispersion-shifted fiber," Applied Optics, 42,19 (1 January 2003):

3772-3775. Attachment 5g is a true and accurate copy of the Scopus index record for the Li et al. paper, showing Document 5 as the 5th item in its list of references.

Conclusion

87. Based on the evidence presented here—publication in the widely held periodical, online indexing and publication, library processing, and citation—it is my opinion that Document 5 is an authentic document that was publicly available to researchers at least by August 2001. The citation evidence presented here indicates that Document 5 was in actual use by researchers at least by January 2003.

Document 6. Alan D. Kersey, "Multiplexed Fiber Optic Sensors," in Fiber Optic Sensors, Eric Udd, ed., Proceedings of a conference held 8-11 September 1992, Boston Massachusetts, Critical Reviews of Optical Science and Technology, Vol. CR44 (Bellingham, WA: SPIE Optical Engineering Press, 1993): 161-185.

Authentication

88. Document 6 is a paper given by Alan Kersey at conference sponsored by SPIE, the International Society for Optical Engineering, held in Boston, MA, on 8-11 September 1992, and published in 1993 in the proceedings of that conference.

89. Attachment 6a is a true and accurate copy of Document 6, along with the cover, title page and title page verso, and contents pages, from the Massachusetts Institute of Technology Libraries. Attachment 6b is a true and accurate copy of that library's catalog record, in MARC format, for the proceedings of the 1992 Fiber Optic Sensors conference.

90. Attachment 6a is in a condition that creates no suspicion about its authenticity. Specifically, the text of Document 6 is not missing any intermediate pages, the text on each page appears to flow seamlessly from one page to the next, and there are no visible alterations to the document. Attachment 6a was found within the custody of a library – a place where, if authentic, it would likely be found.

91. Document 6 is also readily identified online. Attachment 6c is a true and accurate copy of the Scopus index record for Document 6.

92. Based on finding Document 6 in a library and on finding library catalog and online index records for Document 6, I conclude that Document 6 is an authentic document and that Attachment 6a is an authentic copy of Document 6.

Public Accessibility

93. Document 6 entered the realm of public discourse when it was presented at a conference on 8-11 September 1992 in Boston, MA. The scope of the conference is suggested by the 12 papers presented there, as indicated by the contents pages in Attachment 6a.

94. Attachment 6d is a true and accurate copy of the Statewide Illinois Library Catalog record for the proceedings of the 1992 Fiber Optic Sensors conference, in which Document 6 was published, showing this conference proceedings is held by 101 libraries world-wide. Attachment 6d also indicates that the proceedings of the 1992 Fiber Optic Sensors conference was cataloged or

indexed in a meaningful way—including being cataloged by subject. Thus, in my opinion, the proceedings of the 1992 Fiber Optic Sensors conference, in which Document 6 was published, was sufficiently accessible to the public interested in the art. An ordinarily skilled researcher, exercising reasonable diligence, would have had no difficulty finding copies of the proceedings of the 1992 Fiber Optic Sensors conference.

95. Attachment 6e is a true and accurate copy of the United States Copyright Office record for the proceedings of the 1992 Fiber Optic Sensors conference, showing that the proceedings were published on 12 May 1993. The proceedings were registered for copyright on 8 June 1993. I conclude that the proceedings of the 1992 Fiber Optic Sensors conference was publicly available from its publisher on or about 8 June 1993.

96. In Attachment 6b, the Massachusetts Institution of Technology Libraries catalog record for the proceedings of the 1992 Fiber Optic Sensors conference, the MARC Field 008 indicates this catalog record was created on 5 October 1992. The date of entry in the Attachment 6d catalog record is the same. That these are cataloging-in-publication (CIP) records, created before the publication of Document 6 (discussed above), is indicated by the presence of CIP information on the verso of the title page in Attachment 6a.

97. Attachment 6a is a copy of Document 6 from the Massachusetts Institute of Technology Libraries. It has a library date stamp on the verso of the title page indicating that the proceedings of the 1992 Fiber Optic Sensors conference was processed on 14 July 1993. Based on my experience, I affirm this date stamp has the general appearance of date stamps that libraries have long affixed to periodicals in processing them. I do not see any indications or have any reason to believe this date stamp was affixed by anyone other than library personnel on or about the date indicated by the stamp. Allowing for some time between cataloging Document 6 and its appearance on library shelves, where it would be publicly available, it is my opinion that Document 6 was publicly available in a second at least by August 1993.

98. Attachment 6f is a true and accurate copy of a second Statewide Illinois Library Catalog record for the proceedings of the 1992 Fiber Optic Sensors conference, in which Document 6 was published, showing this conference proceedings is also held by the National Library of Sweden. The date of entry in the Attachment 6f catalog record is 2 July 1993. Allowing for some time between cataloging Document 6 and its appearance on library shelves, where it available in a second library at least by August 1993.

99. Attachment 6g is a true and accurate copy of a Scopus list of 33 publications citing Document 6. One citing document is by S. –C. Huang et al., “Crosstalk analysis and system design of time-division multiplexing of polarization-

intensive fiber optic michelson interferometric sensors," Journal of Lightwave Technology, 14,6 (June 1996): 1488-1500. Attachment 6h is a true and accurate copy of the Scopus index record for the Huang et al. paper, showing Document 6 as the 3rd item in its list of references.

Conclusion

100. Based on the evidence presented here—presentation at conference and publication in the conference proceedings, library cataloging, online indexing, library processing, and citation—it is my opinion that Document 6 was bibliographically identifiable by 5 October 1992 and subsequently available to the public in at least two libraries by August 1993. The citation evidence presented here indicates that Document 6 was in actual use by researchers by June 1996.

V. ATTACHMENTS

101. The attachments attached hereto are true and correct copies of the materials identified above. Helen Sullivan is a Managing Partner in Prior Art Documentation Services LLC (see http://www.priorartdocumentation.com/hellen-sullivan/ **)**. One of her primary responsibilities in our partnership is to secure the bibliographic documentation used in attachments to our declarations.

102. Ms. Sullivan and I work in close collaboration on the bibliographic documentation needed in each declaration. I will sometimes request specific

bibliographic documents or, more rarely, secure them myself. In all cases, I have carefully reviewed the bibliographic documentation used in my declaration. My signature on the declaration indicates my full confidence in the authenticity, accuracy, and reliability of the bibliographic documentation used.

103. Each Attachment has been marked with an identifying label on the top of each page. However, no alterations other than these noted labels appear in these attachments, unless otherwise noted. All attachments were created on 18-22 August 2017 and all URLs referenced in this declaration were available 30 August 2017.

VI. CONCLUSION

104. In summary, I have concluded that Documents 1 through 6, discussed above, are all authentic documents that were all publicly accessible before 13 April 2003.

105. I reserve the right to supplement my opinions in the future to respond to any arguments that Patent Owner or its expert(s) may raise and to take into account new information as it becomes available to me.

106. I declare that all statements made herein of my knowledge are true, and that all statements made on information and belief are believed to be true, and that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code.

Executed this 31st day of August, 2017 in Urbana, Illinois.

____

Scott Bennett

Appendix A

SCOTT BENNETT
Yale University Librarian Emeritus

711 South Race
Urbana, Illinois 61801-4132
2scottbb@gmail.com
217-367-9896

EMPLOYMENT

Retired, 2001. Retirement activities include:

- Managing Partner in Prior Art Documentation Services, LLC, 2015-. This firm provides documentation services to patent attorneys; more information is available at http://www.priorartdocumentation.com
- Consultant on library space design, 2004-2017 . This consulting practice was rooted in a research, publication, and public speaking program conducted since I retired from Yale University in 2001. I served more than 50 colleges and universities in the United States and abroad with projects ranging in likely cost from under $50,000 to over $100 million. More information is available at http://www.libraryspaceplanning.com/
- Senior Advisor for the library program of the **Council of Independent Colleges**, 2001-2009
- Member of the Wartburg College Library Advisory Board, 2004-
- Visiting Professor, Graduate School of Library and Information Science, **University of Illinois at Urbana-Champaign**, Fall 2003

University Librarian, **Yale University**, 1994-2001

Director, The Milton S. Eisenhower Library, **The Johns Hopkins University**, Baltimore, Maryland, 1989-1994

Assistant University Librarian for Collection Management, **Northwestern University**, Evanston, Illinois, 1981-1989

Instructor, Assistant and Associate Professor of Library Administration**, University of Illinois at Urbana-Champaign**, 1974-1981

Assistant Professor of English, **University of Illinois at Urbana-Champaign**, 1967-1974

Woodrow Wilson Teaching Intern, **St. Paul's College**, Lawrenceville, Virginia, 1964-1965

EDUCATION

University of Illinois, M.S., 1976 (Library Science)
Indiana University, M.A., 1966; Ph.D., 1967 (English)
Oberlin College, A.B. magna cum laude, 1960 (English)

HONORS AND AWARDS

Morningside College (Sioux City, IA) Doctor of Humane Letters, 2010

American Council of Learned Societies Fellowship, 1978-1979; Honorary Visiting Research Fellow, Victorian Studies Centre**, University of Leicester**, 1979; **University of Illinois** Summer Faculty Fellowship, 1969

Indiana University Dissertation Year Fellowship and an **Oberlin College** Haskell Fellowship, 1966-1967; **Woodrow Wilson** National Fellow, 1960-1961

PROFESSIONAL ACTIVITIES

American Association for the Advancement of Science: Project on Intellectual Property and Electronic Publishing in Science, 1999-2001

American Association of University Professors: University of Illinois at Urbana-Champaign Chapter Secretary and President, 1975-1978; Illinois Conference Vice President and President, 1978-1984; national Council, 1982-1985, Committee F, 1982-1986, Assembly of State Conferences Executive Committee, 1983-1986, and Committee H, 1997-2001 ; Northwestern University Chapter Secretary/Treasurer, 1985-1986

Association of American Universities: Member of the Research Libraries Task Force on Intellectual Property Rights in an Electronic Environment, 1993-1994, 1995-1996

Association of Research Libraries: Member of the Preservation Committee, 1990-1993; member of the Information Policy Committee, 1993-1995; member of the Working Group on Copyright, 1994-2001; member of the Research Library Leadership and Management Committee, 1999-2001; member of the Board of Directors, 1998-2000

Carnegie Mellon University: Member of the University Libraries Advisory Board, 1994

Center for Research Libraries: Program Committee, 1998-2000

Johns Hopkins University Press: Ex-officio member of the Editorial Board, 1990-1994; Co-director of Project Muse, 1994

Library Administration and Management Association, Public Relations Section, Friends of the Library Committee, 1977-1978

Oberlin College: Member of the Library Visiting Committee, 1990, and of the Steering Committee for the library's capital campaign, 1992-1993; President of the Library Friends, 1992-1993, 2004-2005; member, Friends of the Library Council, 2003-

Research Society for Victorian Periodicals: Executive Board, 1971-1983; Co-chairperson of the Executive Committee on Serials Bibliography, 1976-1982; President, 1977-1982

A Selected Edition of W.D. Howells (one of several editions sponsored by the MLA Center for Editions of American Authors): Associate Textual Editor, 1965-1970; Center for Editions of American Authors panel of textual experts, 1968-1970

Victorian Studies: Editorial Assistant and Managing Editor, 1962-1964

Wartburg College: member, National Advisory Board for the Vogel Library, 2004-

Some other activities: Member of the **Illinois State Library** Statewide Library and Archival Preservation Advisory Panel; member of the **Illinois State Archives** Advisory Board; member of a committee advising the **Illinois Board of Higher Education** on the cooperative management of research collections; chair of a major collaborative research project conducted by the **Research Libraries Group** with support from Conoco, Inc.; active advisor on behalf of the **Illinois Conference AAUP** to faculty and administrators on academic freedom and tenure matters in northern Illinois.

Delegate to **Maryland Governor's Conference on Libraries and Information Service**; principal in initiating state-wide preservation planning in Maryland; principal in an effort to widen the use of mass deacidification for the preservation of library materials through cooperative action by the **Association of Research Libraries** and the **Committee on Institutional Cooperation**; co-instigator of a campus-wide information service for **Johns Hopkins University**; initiated efforts with the **Enoch Pratt Free Library** to provide information services to Baltimore's Empowerment Zones; speaker or panelist on academic publishing, copyright, scholarly communication, national and regional preservation planning, mass deacidification.

Consultant for the **University of British Columbia** (1995), **Princeton University** (1996), **Modern Language Association**, (1995, 1996), **Library of Congress** (1997), **Center for Jewish History** (1998, 2000-), **National Research Council** (1998); Board of Directors for the **Digital Library Federation**, 1996-2001; accreditation visiting team at **Brandeis University** (1997); mentor for **Northern Exposure to Leadership** (1997); instructor and mentor for ARL's **Leadership and Career Development Program** (1999-2000)

At the **Northwestern University Library**, led in the creation of a preservation department and in the renovation of the renovation, for preservation purposes, of the Deering Library book stacks.

At the **Milton S. Eisenhower Library**, led the refocusing and vitalization of client-centered services; strategic planning and organizational restructuring for the library; building renovation planning. Successfully completed a $5 million endowment campaign for the humanities collections and launched a $27 million capital campaign for the library.

At the **Yale University Library**, participated widely in campus-space planning, university budget planning, information technology development, and the promotion of effective teaching and learning; for the library has exercised leadership in space planning and renovation, retrospective conversion of the card catalog, preservation, organizational development, recruitment of minority librarians, intellectual property and copyright issues, scholarly communication, document delivery services among libraries, and instruction in the use of information resources. Oversaw approximately $70 million of library space renovation and construction. Was co-principal investigator for a grant to plan a digital archive for Elsevier Science.

Numerous to invitations speak at regional, national, and other professional meetings and at alumni meetings. Lectured and presented a series of seminars on library management at the **Yunnan University Library**, 2002. Participated in the 2005 International Roundtable for Library and Information Science sponsored by the **Kanazawa Institute of Technology** Library Center and the Council on Library and Information Resources.

PUBLICATIONS

"Putting Learning into Library Planning," *portal: Libraries and the Academy*, 15, 2 (April 2015), 215-231.

“How librarians (and others!) love silos: Three stories from the field “ available at the Learning Spaces Collaborary Web site, http://www.pkallsc.org/

“Learning Behaviors and Learning Spaces,” *portal: Libraries and the Academy,* 11, 3 (July 2011), 765-789.

“Libraries and Learning: A History of Paradigm Change,” *portal: Libraries and the Academy,* 9, 2 (April 2009), 181-197. Judged as the best article published in the 2009 volume of *portal*.

“The Information or the Learning Commons: Which Will We Have?” *Journal of Academic Librarianship*, 34 (May 2008), 183-185. One of the ten most-cited articles published in JAL, 2007-2011.

“Designing for Uncertainty: Three Approaches,” *Journal of Academic Librarianship*, 33 (2007), 165–179.

“Campus Cultures Fostering Information Literacy,” *portal: Libraries and the Academy*, 7 (2007), 147-167. Included in Library Instruction Round Table Top Twenty library instruction articles published in 2007

“Designing for Uncertainty: Three Approaches,” *Journal of Academic Librarianship*, 33 (2007), 165–179.

“First Questions for Designing Higher Education Learning Spaces,” *Journal of Academic Librarianship*, 33 (2007), 14-26.

“The Choice for Learning,” *Journal of Academic Librarianship*, 32 (2006), 3-13.

With Richard A. O’Connor, “The Power of Place in Learning,” *Planning for Higher Education*, 33 (June-August 2005), 28-30

“Righting the Balance,” in *Library as Place: Rethinking Roles, Rethinking Space* (Washington, DC: Council on Library and Information Resources, 2005), pp. 10-24

Libraries Designed for Learning (Washington, DC: Council on Library and Information Resources, 2003)

“The Golden Age of Libraries,” in *Proceedings of the International Conference on Academic Librarianship in the New Millennium: Roles, Trends, and Global Collaboration*, ed. Haipeng Li (Kunming: Yunnan University Press, 2002), pp. 13-21. This is a slightly different version of the following item.

“The Golden Age of Libraries,” *Journal of Academic Librarianship*, 24 (2001), 256-258

“Second Chances. An address . . . at the annual dinner of the Friends of the Oberlin College Library November 13 1999,” Friends of the Oberlin College Library, February 2000

“Authors’ Rights,” *The Journal of Electronic Publishing* (December 1999), http://www.press.umich.edu/jep/05-02/bennett.html

“Information-Based Productivity,” in *Technology and Scholarly Communication*, ed. Richard Ekman and Richard E. Quandt (Berkeley, 1999), pp. 73-94

“Just-In-Time Scholarly Monographs: or, Is There a Cavalry Bugle Call for Beleaguered Authors and Publishers?” *The Journal of Electronic Publishing* (September 1998), http://www.press.umich.edu/jep/04-01/bennett.html

"Re-engineering Scholarly Communication: Thoughts Addressed to Authors," *Scholarly Publishing*, 27 (1996), 185-196

"The Copyright Challenge: Strengthening the Public Interest in the Digital Age," *Library Journal*, 15 November 1994, pp. 34-37

"The Management of Intellectual Property," *Computers in Libraries*, 14 (May 1994), 18-20

"Repositioning University Presses in Scholarly Communication," *Journal of Scholarly Publishing*, 25 (1994), 243-248. Reprinted in *The Essential JSP. Critical Insights into the World of Scholarly Publishing. Volume 1: University Presses* (Toronto: University of Toronto Press, 2011), pp. 147-153

"Preservation and the Economic Investment Model," in *Preservation Research and Development. Round Table Proceedings, September 28-29, 1992*, ed. Carrie Beyer (Washington, D.C.: Library of Congress, 1993), pp. 17-18

"Copyright and Innovation in Electronic Publishing: A Commentary," *Journal of Academic Librarianship*, 19 (1993), 87-91; reprinted in condensed form in *Library Issues: Briefings for Faculty and Administrators*, 14 (September 1993)

with Nina Matheson, "Scholarly Articles: Valuable Commodities for Universities," *Chronicle of Higher Education*, 27 May 1992, pp. B1-B3

"Strategies for Increasing [Preservation] Productivity*," Minutes of the [119th] Meeting [of the Association of Research Libraries]* (Washington, D.C., 1992), pp. 39-40

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"The Boat that Must Stay Afloat: Academic Libraries in Hard Times," *Scholarly Publishing*, 23 (1992), 131-137

"Buying Time: An Alternative for the Preservation of Library Material," ACLS *Newsletter*, Second Series 3 (Summer, 1991), 10-11

"The Golden Stain of Time: Preserving Victorian Periodicals" in *Investigating Victorian Journalism*, ed. Laurel Brake, Alex Jones, and Lionel Madden (London: Macmillan, 1990), pp. 166-183

"Commentary on the Stephens and Haley Papers" in *Coordinating Cooperative Collection Development: A National Perspective*, an issue of *Resource Sharing and Information Networks*, 2 (1985), 199-201

"The Editorial Character and Readership of *The Penny Magazine*: An Analysis," *Victorian Periodicals Review*, 17 (1984), 127-141

"Current Initiatives and Issues in Collection Management*," Journal of Academic Librarianship*, 10 (1984), 257-261; reprinted in *Library Lit: The Best of 85*

"Revolutions in Thought: Serial Publication and the Mass Market for Reading" in *The Victorian Periodical Press: Samplings and Soundings*, ed. Joanne Shattock and Michael Wolff (Leicester: Leicester University Press, 1982), pp. 225-257

"Victorian Newspaper Advertising: Counting What Counts," *Publishing History*, 8 (1980), 5-18

"Library Friends: A Theoretical History" in *Organizing the Library's Support: Donors, Volunteers, Friends,* ed. D.W. Krummel, Allerton Park Institute Number 25 (Urbana: University of Illinois Graduate School of Library Science, 1980), pp. 23-32

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"Prolegomenon to Serials Bibliography: A Report to the [Research] Society [for Victorian Periodicals]," *Victorian Periodicals Review*, 12 (1979), 3-15

"The Bibliographic Control of Victorian Periodicals" in *Victorian Periodicals: A Guide to Research*, ed. J. Don Vann and Rosemary T. VanArsdel (New York: Modern Language Association, 1978), pp. 21-51

"John Murray's Family Library and the Cheapening of Books in Early Nineteenth Century Britain," *Studies in Bibliography*, 29 (1976), 139-166. Reprinted in Stephen Colclough and Alexis Weedon, eds., *The History of the Book in the West: 1800-1914,* Vol. 4 (Farnham, Surrey: Ashgate, 2010), pp. 307-334.

with Robert Carringer, "Dreiser to Sandburg: Three Unpublished Letters," *Library Chronicle*, 40 (1976), 252-256

"David Douglas and the British Publication of W. D. Howells' Works," *Studies in Bibliography*, 25 (1972), 107-124

as primary editor, W. D. Howells, *Indian Summer* (Bloomington: Indiana University Press, 1971)

"The Profession of Authorship: Some Problems for Descriptive Bibliography" in *Research Methods in Librarianship: Historical and Bibliographic Methods in Library Research*, ed. Rolland E. Stevens (Urbana: University of Illinois Graduate School of Library Science, 1971), pp. 74-85

edited with Ronald Gottesman, *Art and Error: Modern Textual Editing* (Bloomington: Indiana University Press, 1970)--also published in London by Methuen, 1970

"Catholic Emancipation, the *Quarterly Review*, and Britain's Constitutional Revolution," *Victorian Studies*, 12 (1969), 283-304

as textual editor, W. D. Howells, *The Altrurian Romances* (Bloomington: Indiana University Press, 1968); introduction and annotation by Clara and Rudolf Kirk

as associate textual editor, W. D. Howells, *Their Wedding Journey* (Bloomington: Indiana University Press, 1968); introduction by John Reeves

"A Concealed Printing in W. D. Howells," *Papers of the Bibliographic Society of America*, 61 (1967), 56-60

editor, *Non Solus*, A Publication of the University of Illinois Library Friends, 1974-1981

editor, Robert B. Downs Publication Fund, University of Illinois Library, 1975-1981

Reviews, short articles, etc. in *Victorian Studies*, *Journal of English and German Philology*, *Victorian Periodicals Newsletter*, *Collection Management*, *Nineteenth-Century Literature*, *College & Research Libraries*, *Scholarly Publishing Today*, *ARL Newsletter*, *Serials Review*, *Library Issues*, *S[ociety for] S[cholarly] P[ublishing] Newsletter*, and *Victorian Britain: An Encyclopedia*

A JOINT IEEE/OSA PUBLICATION

Journal of LIGHTWAVE TECHNOLOGY

APRIL 1992 VOLUME 10 NUMBER 4 JLTEDG (ISSN 0733-8724)

PAPERS

Fibers

Passive Components

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Common Path Heterodyne Optical Fiber Sensors

Toshihiko Yoshino, Takaharu Hashimoto, Makoto Nara, and Kiyoshi Kurosawa

Abstract—**The common path type of differential heterodyne fiber-optic sensing scheme has been developed which uses a polarization maintaining fiber as either a sensor or an optical lead and a dual-frequency dual-polarization laser beam. The sensing schemes are applied to the measurements of temperature, strain, force, pressure, rotation rate (gyro), magnetic and electric fields, and thin film thickness. The sensing scheme and main performances for each measurand are described. High precision and high stability as well as good linearity for each measurand are demonstrated.**

I. Introduction

By means of optical fiber sensors many physical and chemical quantities can be measured in a flexible and remote manner without undergoing electromagnetic induction noises. However, at the present stage of fiber-optic sensing technology, high stability and reliability are the most required features for practicing fiber sensors. In order to fulfill such requirements, the present authors have developed the common path type of heterodyne optical fiber sensing in which heterodyning two laser beams take a common path in the entire sensing system since 1981. The sensing system can measure various quantities with good linearity and high stability against environmental temperature and pressure variations.

The key devices for the developed fiber sensors are a dual-frequency dual-polarization laser beam and a polarization-maintaining fiber, which are used for a sensor element or an optical lead. The combination of the two devices produces a stable and precise fiber sensing scheme especially suited for polarization based fiber sensors. The developed fiber sensors make it possible to measure various quantities such as temperature, strain, force, pressure, rotation rate (gyroscope), magnetic and electric fields, displacement, and film thickness. The purpose of this paper is to give the detailed descriptions of our previous studies on the in-line heterodyne fiber sensors, partially reported in the several conferences [1]–[7]. The sensing schemes and main performances of the developed fiber sensors are described classifying the use of polarization maintaining fiber (PMF) into a sensor element and an optical lead.

Manuscript received October 31, 1990. This work was partially supported by Grant-in-Aid for Special Project Research for Lightwave Sensing from the Ministry of Education, Science, and Culture of Japan.

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T. Hashimoto is with Tokyo Sokki Kenkyujo Co., Ltd., Aioicho, 4-247, Kiryu, Gunma, Japan.

M. Nara is with Nikon, Nagaodai-machi 4-7-1, Totsuka-ku, Yokohama, Japan.

K. Kurosawa is with the Tokyo Electric Power Inc., Nishi-tutujigaoka 2-4-1, Chohu, Tokyo, Japan.

IEEE Log Number 9106098.

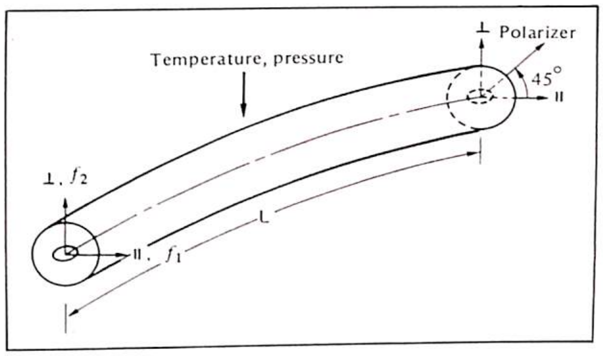


Fig. 1. Optical arrangement of heterodyne fiber-optic sensor using polarization maintaining fiber as sensor element.

II. Use of PMF as Sensor Element

The retardation of highly birefringent single-mode fiber, i.e., polarization maintaining fiber (PMF), depends on temperature and mechanical forces so that it can be used for temperature (e.g., [8]) or mechanical force measurement. Here we present a new sensing scheme to achieve high precision for the retardation measurement.

A laser beam consisting of two frequency components with orthogonal linear polarization is launched into a PMF with the coincidence of polarization axes between the laser and PMF, as shown in Fig. 1. The output beam from PMF is passed through a polarizer oriented at 45° to the fiber polarization axes, ∥ and ⊥, and detected by a photomultiplier. Letting the propagation constants of the orthogonal polarization modes of the fiber be $\beta_{\|}$ and $\beta_{\perp}$ and the laser frequencies be f_1 and f_2, the photoelectric signal is given by

$$I = |A_{\|} \exp i(2\pi f_1 t - \beta_{\|} L) + A_{\|} \exp i(2\pi f_2 t - B_{\perp} L)|^2 \tag{1}$$

where L is the fiber length and $A_{\|}$ and $A_{\perp}$ are real constants. Equation (1) represents a beat signal

$$I = A_{\|}^2 + A_{\perp}^2 + 2A_{\|}A_{\perp} \cos\{2\pi(f_1 - f_2)t - (\beta_{\|} - \beta_{\perp})L\} \tag{2}$$

which can be rewritten as

$$I = A + B\cos(2\pi\Delta f t - \Gamma), \quad (\Delta f = f_1 - f_2;\ A, B \text{ real numbers}) \tag{3}$$

where

$$\Gamma = (\beta_{\|} - \beta_{\perp})L \tag{4}$$

is the retardation of PMF, depending on temperature and applied force besides the initial retardation.

The PMF used in this paper is Hitachi Cable's one having a beat length of 2.5 mm at 20°C and $\lambda = 633$ nm.

The light source used is a home-made frequency stabilized transverse Zeeman He–Ne laser operated at $\lambda = 633$ nm (STZL). The laser emits orthogonally linearly polarized two modes having a frequency separation from 300 to 400 kHz, stabilized within about 1 kHz; the frequency stabilization was achieved by the negative feedback of the beat frequency of the two modes to the cavity length by means of a cooling fan [9].

A. Temperature

Fig. 2(a) shows the temperature sensing system. In order to locate the sensing part at a specified section of the fiber and to eliminate the effect of the surrounding temperature variations, a differential detection scheme using two PMF's is employed. Both a signal fiber and a reference fiber are aligned close to each other except the sensing part, where the sensing fiber was made longer than the reference one by different lengths L of 0–4 m; the entire length of the sensing fiber was 10 m. The sensing part was inserted in a water bath, heated by a nichrome heater inserted in the water. Fig. 2(b) shows the typical beat signals (300 kHz) of the sensing and reference fibers. The phase difference between the two beat signals is detected by a phasemeter. Fig. 2(c) shows the change in phasemeter output measured as a function of the change in water temperature monitored with a mercury thermometer. In the experiment the water bath was heated and natural-cooled many times. Somewhat data variations observed in Fig. 2(c) are most probably due to the temperature inhomogeneity within the bath. The temperature dependence of fiber retardation is given, from the average slope of Fig. 2(c), as

$$d\Gamma / L dT = 114° \,°\mathrm{C}^{-1}\mathrm{m}^{-1}. \tag{5}$$

The temperature resolution ΔT is proportional to the sensing fiber length L and limited by the fluctuation of the phasemeter output, $\Delta\Gamma$, which was about 0.1°. From (5), ΔT is $0.1°/(114°\mathrm{C}^{-1}\mathrm{m}^{-1}L) = 0.009°\mathrm{Cm}/L$, or 0.009°C for $L = 1$ m for example.

Thermal cycling was studied between room temperature and 185°C by inserting a 1-m-long part of PMF into an electric furnace. Fig. 2(d) shows the measured results in which temperature was raised from 30 to 185°C in one hour and fell down in natural cooling. A good reproducibility is shown in Fig. 2(d).

B. Strain and Force Sensors

Fig. 3(a) shows the strain sensing system. In order to reduce the temperature-induced drift, a differential detection scheme using two PMF's is again employed. A 27-mm-long part of a sensing PMF is fixed on an aluminium plate by a scotch tape whereas a reference PMF is aligned close to the sensing one but free from the plate. Axial strain was applied to the fiber by bending the plate and monitored by a metal strain gauge. Fig. 3(b) shows the change in the phasemeter output measured as a function of the monitored strain ε. The strain-induced retardation is proportional to the sensor length L and,

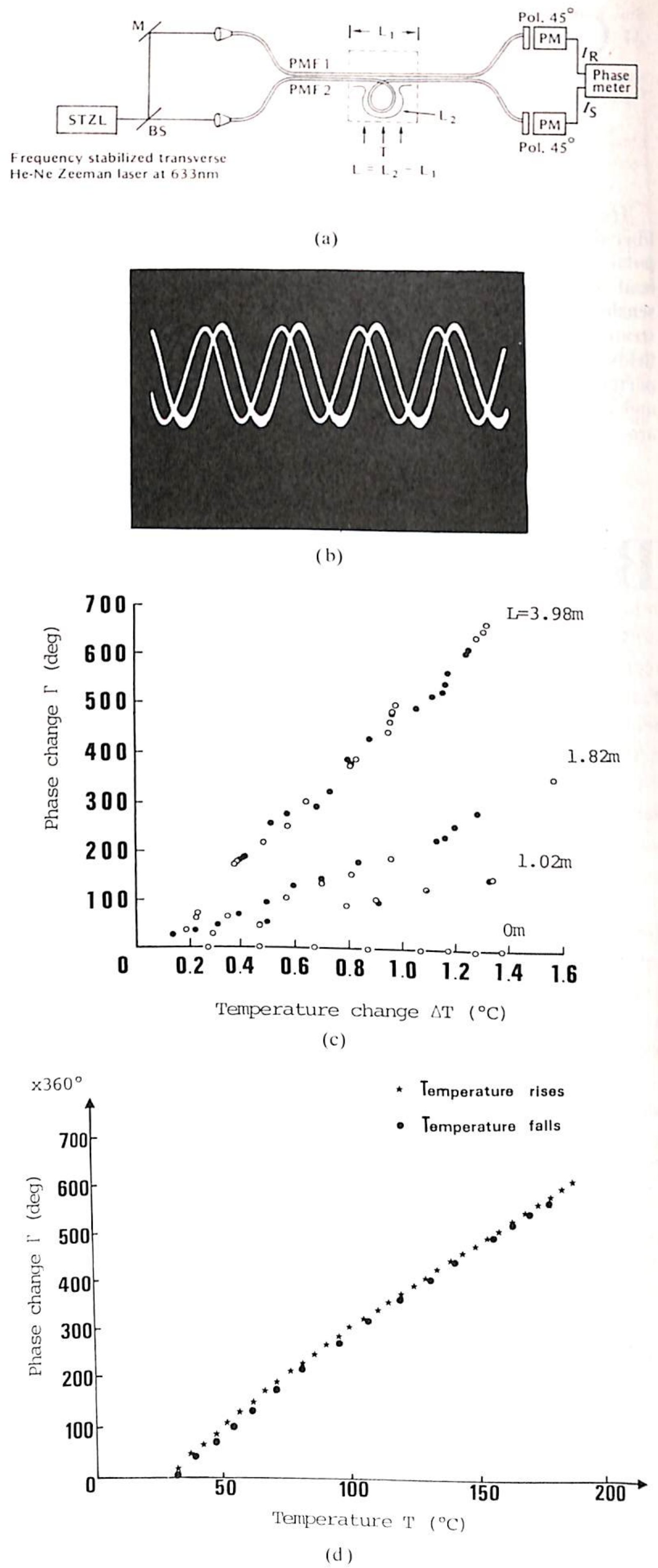


Fig. 2. Heterodyne fiber-optic temperature sensor using polarization maintaining fiber. (a) Measuring system. (b) Beat signals (signal and reference lights; the beat frequency = 300 kHz). (c) Temperature dependence of phasemeter output measured as a parameter of sensor fiber length L. (d) Thermal cycling of 1-m-long polarization maintaining fiber temperature sensor.

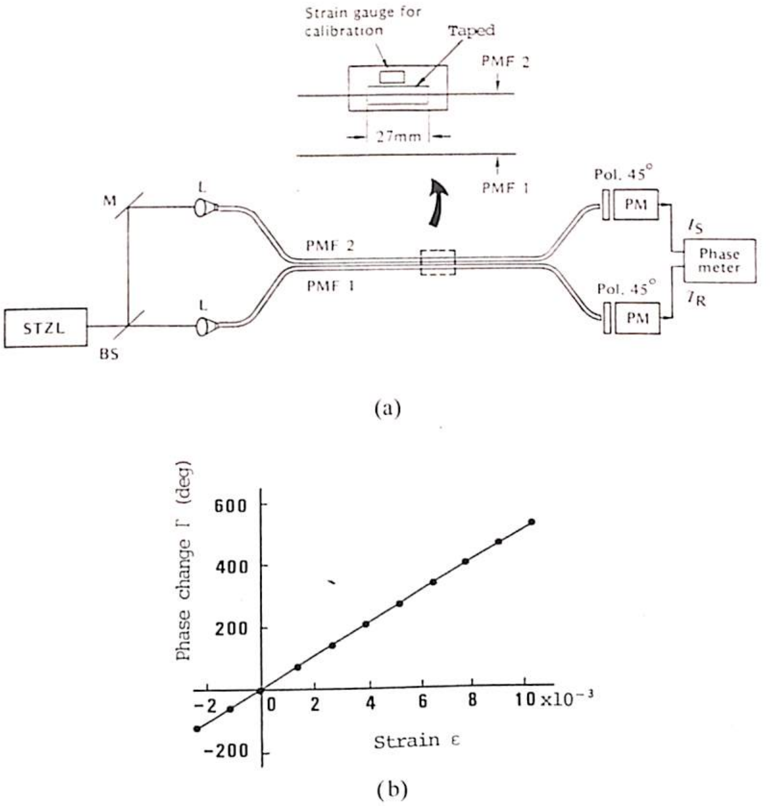


Fig. 3. Heterodyne fiber-optic strain sensor using polarization maintaining fiber. (a) Measuring system. (b) Phasemeter output measured as a function of applied strain.

from Fig. 3(b), is given as

$$\begin{aligned} d\Gamma/Ld\varepsilon &= 500°/(27 \text{ mm} \times 10 \times 10^{-3}\varepsilon) \\ &= 1.9 \times 10^{6°}\varepsilon^{-1}\text{m}^{-1}. \end{aligned} \quad (6)$$

The minimum detectable strain is proportional to the sensor length. As the fluctuation of the phasemeter output was about 0.1°, the strain resolution $\Delta\varepsilon$ is, from (6), $0.1°/(1.9 \times 10^{6°}\varepsilon^{-1}\text{m}^{-1}L) = 5.3 \times 10^{-8}\varepsilon\text{m}/L$, or $0.053 \times 10^{-6}\varepsilon$ for $L = 1$ m for example.

In order to see the temperature compensation effect using two PMF's, the two fibers were inserted in an empire tube and heated over a 1-m-long part by a hair dryer. When the tube temperature was raised by 15°C, the change in the phasemeter output was 100° at worst in contrast with 2500° in the case of a single fiber. The temperature compensation effect is thus better than 1 : 25.

Various types of strain and force sensors can be constructed. Fig. 4(a) shows the measured result for a tension type of force sensor. An 170-mm-long part of PMF was cementized in a glass tube and axial tensile force was applied to the fiber by various weights. The force-induced retardation is proportional to the sensor length L and, from Fig. 4(a), is

$$\begin{aligned} d\Gamma/LdF &= 600°/(0.2 \text{ kgf} \times 170 \text{ mm}) \\ &= 1.8 \times 10^{4°} \text{ kgf}^{-1}\text{m}^{-1}. \end{aligned} \quad (7)$$

From (7), using $\Delta\Gamma = 0.1°$ the minimum detectable force ΔF is $0.1°/(1.8 \times 10^{4°} \text{ kgf}^{-1}\text{m}^{-1}L) = 5.6 \times 10^{-6}$ kgfm$/L$, or 0.0056 grf for $L = 1$ m for example.

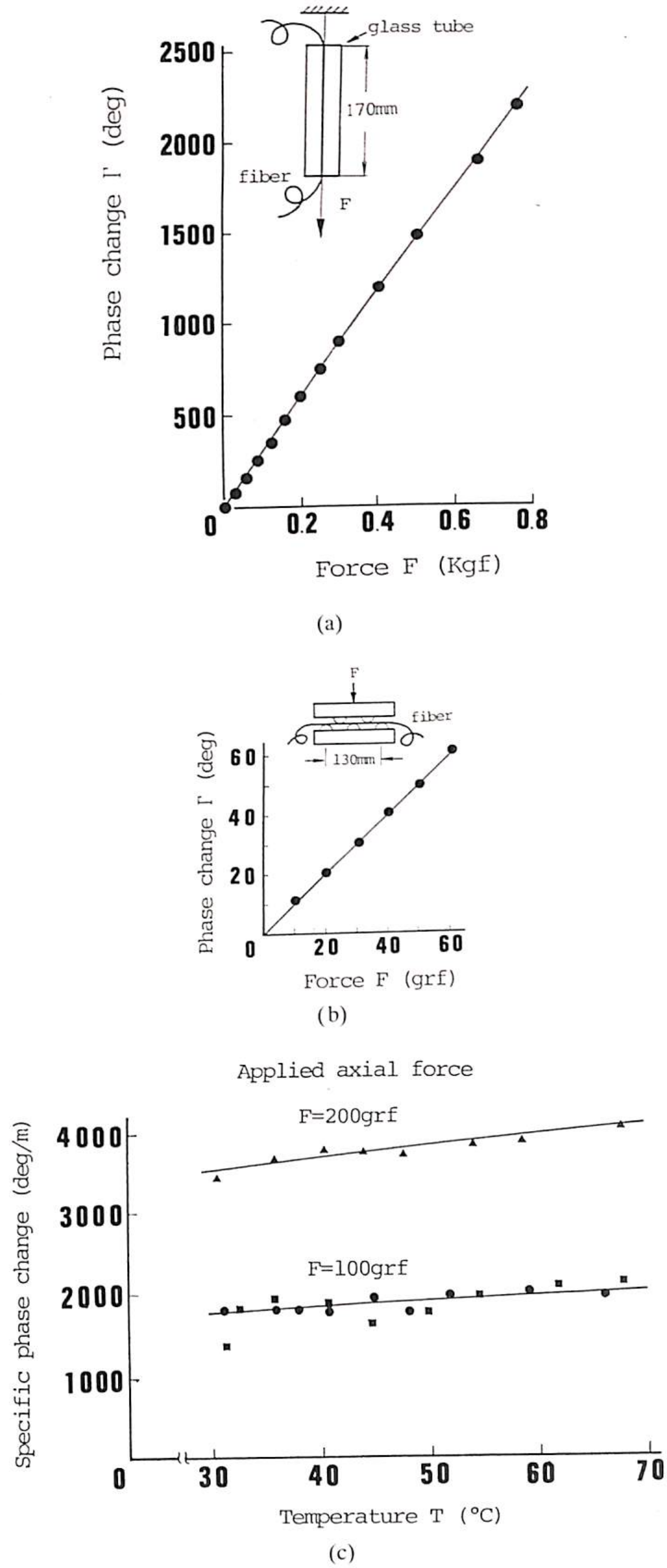


Fig. 4. Heterodyne fiber-optic force sensors using polarization maintaining fiber. (a) Tension type. (b) Microbending type. (c) Temperature dependence of force sensitivity.

Fib. 4(b) shows another type of force sensor using a microbender. An 130-mm-long part of PMF was sandwiched by two wave-form plates having a pitch of 20 mm. Various weights were loaded on the upper plate, causing dominantly axial tensile stress in the fiber. The minimum detectable force was about 1 grf.

The force-induced retardation was found to depend a little on fiber temperature. Fig. 4(c) shows the measured dependence of force-induced retardation on temperature. The force-induced retardation increased with temperature. It follows from Fig. 4(c) that the force sensitivity of PMF increases with temperature in about 0.25%/°C.

C. Fiber Gyro

Fiber gyro is a rotation sensor using the Sagnac effect in the monomode fiber loop. Much work has been done to improve on the gyro performances [10]. Among them, an absolutely constant scale factor for rotation rate detection is one of the most desirable features for practical fiber gyros. Here we present a new type of fiber gyro fulfilling the requirement. The method is based on heterodyne detection, but, unlike the usual heterodyne method [11], the interfering two laser beams take a common path in the entire sensor system so that the gyro system becomes substantially stable against the environmental variations.

Fig. 5(a) shows the entire gyro system. The Sagnac ring interferometer consists of a polarization beam splitter PBS, two Faraday rotators FR1 and FR2, each producing $-45°$ and $+45°$ rotations of polarization plane, and a PMF coil. The orthogonally linearly polarized different frequency f_1 and f_2 components from a STZL are split by PBS into the CW and CCW traveling beams in the ring interferometer. The two beams undergo $\pm 45°$ rotations of polarization plane so that they can travel the PMF along a common polarization axis. The combination of one Faraday rotator and PBS makes an optical isolator so that both the CW and CCW beams going out of the ring interferometer don't return the laser source but go to a photomultiplier PM1.

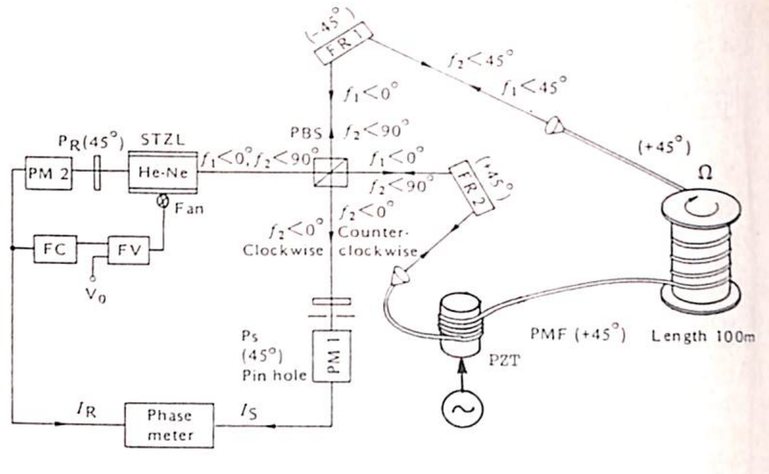
The optical beat I_s generated at PM1 has a phase

$$\Phi = 2\pi \Delta f L/c + \phi_s \qquad (8)$$

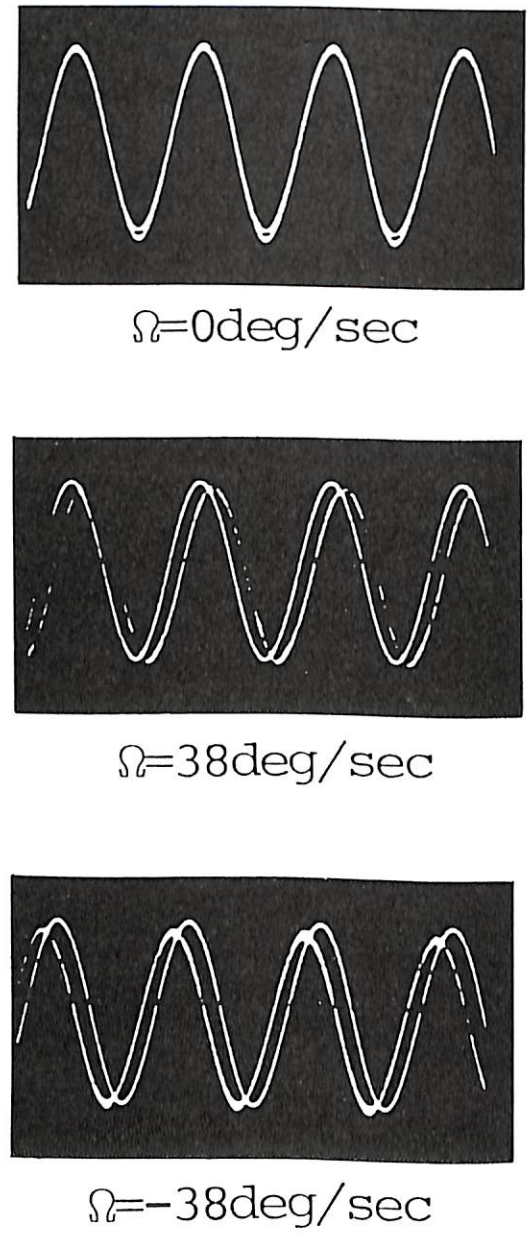
where $\Delta f = f_1 - f_2$, L is the total light path length from the light source to the photodetector, c is the light velocity in vacuum, and

$$\phi_s = (4\pi L_f a/\lambda c)\Omega \qquad (9)$$

is the Sagnac shift [12], where a is the radius of the fiber coil, L_f is the fiber coil length, λ is the light wavelength in vacuum, and Ω is the rotation rate of the fiber coil. In the present experimental conditions, $a = 15$ cm, $L \approx L_f = 100$ m, and $\lambda = 633$ nm so that $\phi_s[\text{deg}] = 1.0\Omega[\text{deg/s}]$. The optical phase of the beat signal I_S was compared with that of the reference beat signal I_R taken from the back side of the laser. Somewhat phase fluctuations were observed in the phasemeter output but they could be reduced down to 0.1° by vibrating a short part of the fiber coil by means of a PZT driven at about 10 kHz. Three pictures of Fig. 5(b) shows the signal and reference beat signals observed when the fiber coil was at rest and rotated at $\Omega = \pm 38°/\text{s}$, respectively; the initial phase bias involved in the phasemeter output was removed; Fig. 5(c) shows the analog output signal of the phasemeter when the fiber coil was rotated by hand; the time constant of the phasemeter was 0.4 s. The minimum detectable rotation rate was then 0.1°/s. The phasemeter output involves a nonreciprocal phase bias due to the first term of (8), which depends on the amount of the



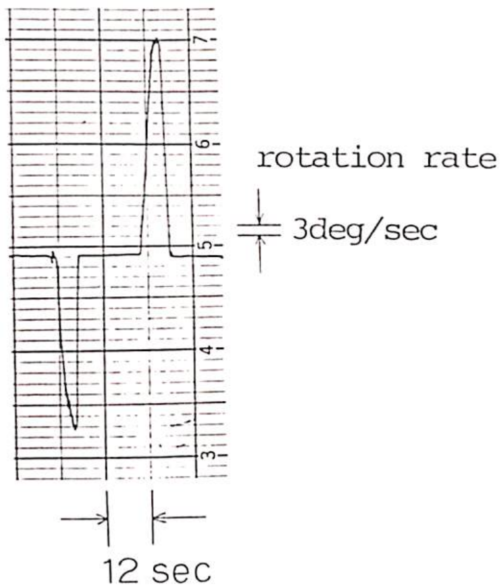
(a)



(b)

Fig. 5. Heterodyne fiber gyroscope. (a) Optical system. (b) Signal and reference optical beats (300 kHz) for different rotation rates of Ω. (c) Phasemeter output when the fiber coil was rotated by hand; the time constant of the phasemeter is 0.4 s.

beat frequency Δf and hence can vary with the beat frequency fluctuation. The associated phase fluctuations, however, can



(c)

Fig. 5. (Continued)

be eliminated by passing the reference light through a fiber having a length equal to L.

III. Use of PMF as Optical Lead

There have been developed lots of types of fiber sensors which use optical fibers as optical leads to connect between optical transducers and light sources or photodetectors in order to realize flexible, *in-situ*, remote measurements. Among many types of such sensors, a polarimetric method is one of the most useful principles. The Faraday effect is used for the measurement of magnetic field [13], [14], the Pockels effect for voltage [14], the photoelastic effect for pressure [15], the natural birefringence for temperature [16] and the oblique light incidence for refractive index or film thickness [17]. In the previous polarization-based fiber sensors, however, optical fiber leads are mostly used to carry the intensity-modulated light signal, therefore being sensitive to light intensity fluctuations associated with fiber transmission, fiber coupling, light source fluctuations and so on. In this paper, intensity-insensitive fiber sensors are developed by the use of PMF as optical leads.

Fig. 6 shows the entire sensing setup for measuring various quantities such as magnetic field, voltage, pressure and temperature. The detection principle is based on the differential heterodyne scheme. The laser beam from a STZL is launched into a PMF (typically 10 m-long) with the mutual coincidence of polarization axes. Some part of the fiber was vibrated at about 5 kHz to reduce the fluctuation of the phasemeter output. The output light from the PMF is collimated by a SELFOC rod lens SL and incident on a polarimetric sensor cell. The laser beam emerging from the cell is, after passing through a polarizer oriented at 45° to the polarization axes of the sensor cell, sent to a photodetector through a fiber bundle. On the other hand, a light beam partially reflected from the entrance of the cell is detected and used for a reference light. Both the signal and reference lights generate the following beat

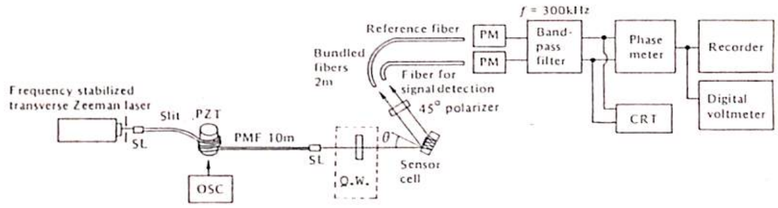


Fig. 6. Schematic diagram for fiber-optic differential heterodyne sensors using polarimetric sensor cell. PMF: polarization maintaining fiber, SL: self-focusing rod lens.

signals:

$$I_S = A_S \cos(2\pi\Delta f - \Phi - \Gamma) \tag{10a}$$

$$I_R = A_R \cos(2\pi\Delta f - \Gamma) \tag{10b}$$

where Φ is the retardation of the sensor cell, Γ is the retardation of PMF, and A_S and A_R are real numbers. The phase difference between the two beat signals is detected by a phasemeter. The minimum detectable retardation $\Delta\Gamma$ was about 0.1°.

A. Magnetic Field

In the measurement system of Fig. 6, the output light from PMF was passed through a quarter-wave plate QW to convert the incident light to the left and right circularly polarized lights. The sensor cell is made of FR5 glass, which has a Verdet constant V of -0.24 min cm^{-1} G^{-1} at $\lambda = 633$ nm. In order to enhance the measurement sensitivity, the multiple reflections of the light beam within a Faraday cell [18] were employed. The upper and lower surfaces of a 3.1-mm-thick 15 mm × 20 mm wide FR5 glass plate were coated with the multilayers of dielectric thin films having $\lambda/4$ optical thicknesses for oblique incidence so that the light beam may perfectly reflect with polarization maintaining. The light beam travels a zigzag path over a lateral region of 12.8 mm in the cell. Under the application of magnetic field, the cell material becomes circularly birefringent, thereby inducing phase retardation between the orthogonal circular polarizations, given by

$$\Phi_H = 2 \cdot 2N \cdot VHd \tag{11}$$

where H is the parallel component of magnetic field to the direction of cell thickness and $2N$ is the number of the multiple passes of light beam within the cell. Fig. 7(a) shows a typical pen recorder chart of the phasemeter output when H was ± 50 Oe; the time constant of the phasemeter was 0.4 s. A very stable and precise measurement of dc magnetic field is achieved, which is very difficult by the conventional intensity modulation Faraday sensor. The minimum detectable dc field is less than 1 Oe. Fig. 7(b) and (c) respectively shows the phase changes measured as a function of relatively small and large dc magnetic fields. The cases of $2N = 40$ and 80 correspond to the angles of incidence on the cell surface 10° and 5°, respectively. The measured results of Fig. 7(a) and (b) agrees quite well with the theoretical ones, which, e.g., for $2N = 40$, $\Phi_H[\text{deg}] = 0.099H[\text{Oe}]$ calculated from (11). The present sensors can be used for ac fields too if the response

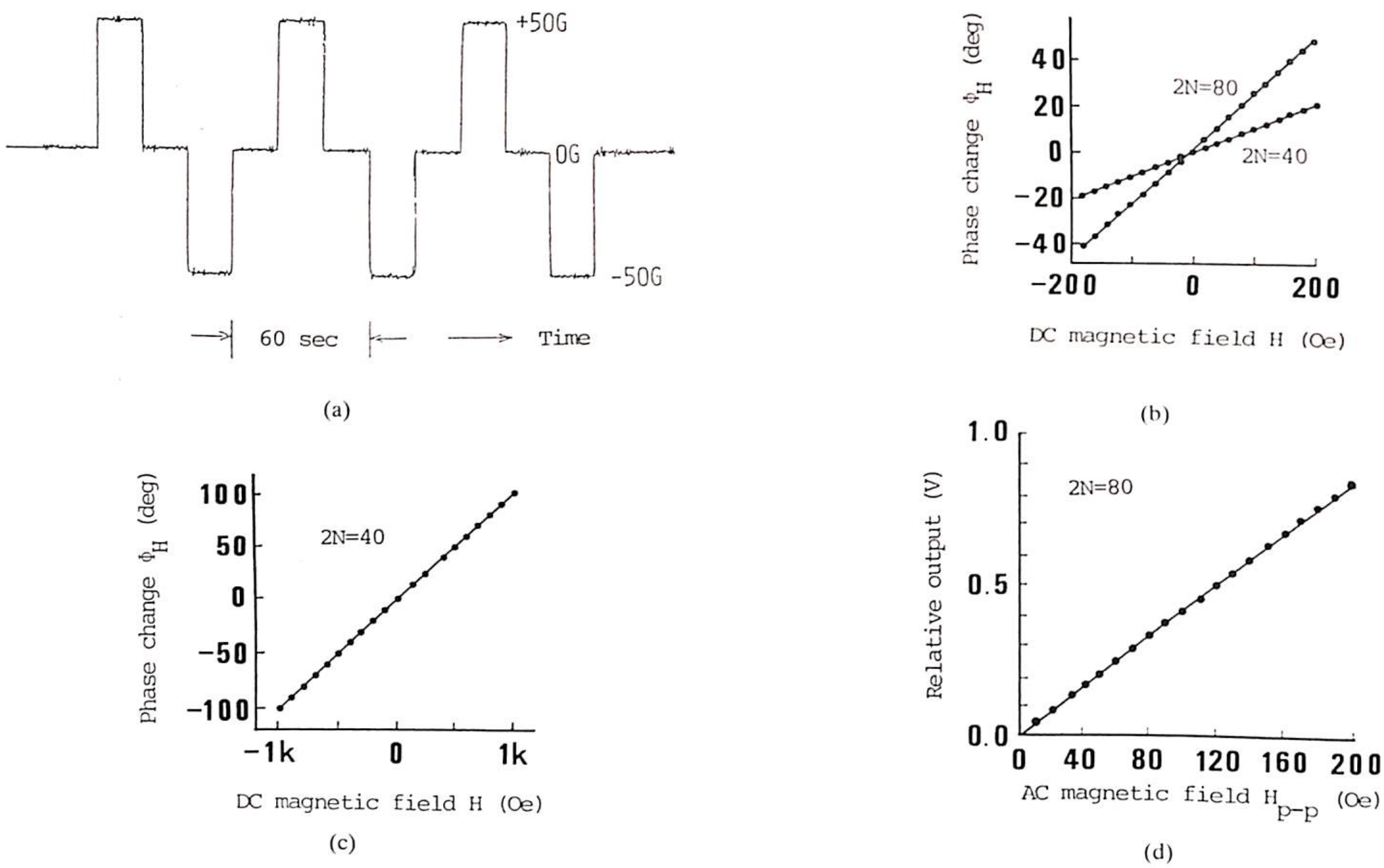


Fig. 7. Phasemeter output of fiber-optic differential heterodyne magnetic field sensor using the multiple reflection FR5 Faraday cell; $2N$ is the number of light passes within the Faraday cell. (a) Recorder trace of phasemeter output; the time constant of the phasemeter is 0.4s and $2N = 40$. (b) Characteristics for small dc magnetic fields. (c) Characteristics for large dc magnetic fields. (d) Characteristics for 50-Hz magnetic fields.

time of the phasemeter is set suitably small. Fig. 7(d) shows the measured results for the commercial frequency of 50 Hz, where $2N$ was made as large as 80 by setting the angle of incidence at as small as 5°.

B. Voltage

As a Pockels material, $Bi_{12}SiO_{20}$ (BSO) is used because of its relatively large and hardly temperature dependent Pockels effect. The material, however, has optical activity, i.e., circular birefringence, which obviously reduces the Pockels effect being linear birefringence. An effective technique for getting rid of such reduction of the Pockels effect is to use two way or in more general multiple light passes within the Pockels cell because then an optical rotary power in an optically active material is cancelled whereas the Pockels effect is accumulated.

1) Theory: We define an eigenstate of polarization that light regenerates the same polarization after one round trip within the Pockels cell as

$$M(-\theta_a)M(\theta_a)\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \sigma \begin{bmatrix} E_x \\ E_y \end{bmatrix} \tag{12}$$

where, referring to [20]

with

$$\phi = \left[\left(\pi \frac{V}{V_\pi}\right)^2 + (2\theta_a d)^2\right]^{1/2} \tag{14}$$

where V_π is the half-wavelength voltage of the Pockels material in the limit of infinitely small thickness, θ_a is the optical activity per unit length, d is the cell thickness, $V = Ed$ is the applied voltage and σ is an eigenvalue [19]. Calculating (12) leads to an eigenvector

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix}_\pm = \begin{bmatrix} -\cos(\phi/2) \pm \sqrt{\cos^2(\phi/2) + (2\theta_a d/\phi)^2 \sin^2(\phi/2)} \\ -(2\theta_a d/\phi)\sin(\phi/2) \end{bmatrix} \tag{15}$$

with an eigenvalue

$$\sigma_\pm = \exp(\pm i\Phi_E) \tag{16}$$

where

$$\Phi_E = 2 \tan^{-1} \frac{((\pi V/V_\pi)/\phi)\sin(\phi/2)}{\sqrt{\cos^2(\phi/2) + (2\theta_a d/\phi)^2 \sin^2(\phi/2)}}. \tag{17}$$

$$M(\theta_a) = \begin{bmatrix} \cos(\phi/2) - i\left(\pi \frac{V}{V_\pi} \,/\, \phi\right)\sin(\phi/2) & -(2\theta_a d/\phi)\sin(\phi/2) \\ (2\theta_a d/\phi)\sin(\phi/2) & \cos(\phi/2) + i\left(\pi \frac{V}{V_\pi} \,/\, \phi\right)\sin(\phi/2) \end{bmatrix} \tag{13}$$

It follows from (15) that

$$(E_Y/E_X)_+ \cdot (E_Y/E_X)_- = -1 \quad (18)$$

implying that the eigenstate of polarization consists of orthogonal linear polarizations. Assuming the applied voltage is relatively low such that $\pi|V|/V_\pi \ll 2|\theta_a|d$, it then follows from (15) that the eigenstates of polarization are, to a good approximation

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix}_+ = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \quad \begin{bmatrix} E_x \\ E_y \end{bmatrix}_- = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \quad (19)$$

independently of applied voltages, implying the azimuths of the principal axes of polarization of the Pockels cell is independent of small applied voltages. Furthermore, for small voltages, $\phi \approx 2\theta_a d$ so that (17) becomes

$$\Phi_E = (\pi V/V_\pi) \cdot 2N \cdot \mathrm{sinc}(\theta_a d) \quad (20a)$$

or

$$\Phi_E = \pi V/V_\pi^*, \quad (20b)$$

where

$$V_\pi^* = V_\pi/\{2N \mathrm{sinc}(\theta_a d)\}, \quad (2N: \text{number of light pass}) \quad (21)$$

which is an effective half-wave voltage, being in inverse proportion to N.

2) Experiment: Both surfaces of a 3-mm-thick BSO crystal plate are dielectric coated to have perfect reflection. A 10-mm-long beam-guiding region is overcoated with ITO transparent electrode films. As BSO has $V_\pi = 3900$ V and $\theta a = 22° \text{ mm}^{-1}$ at $\lambda = 633$ nm, the effective half-wave voltage becomes, from (21)

$$V_\pi^* = 3900 \text{ V}/\{2N \mathrm{sinc}(22° \times 3)\} = 4.91 \times 10^3 \text{ V}/(2N). \quad (22)$$

Using the setup of Fig. 6, the voltage-induced linear birefringence was measured as a function of applied voltages. Fig. 8(a) shows the measured results for dc voltages; the number of multiple passes is $2N = 38$. The experimental curve yields the voltage dependence of retardation as $\Phi_E[\text{deg}] = 1.0$ V[V]. Theoretically, from (22) with $2N = 38$, $V_\pi^* = 129$ V so that, from (20b), $\Phi_E[\text{deg}] = (180/129)$ V[V] = 1.4 V[V]. Both the experimental and theoretical results are in reasonable accordance within the possible discrepancy due to the field inhomogeneity in the cell. The minimum detectable dc voltage is as small as 1 V, which is very difficult to achieve by the use of the conventional intensity modulation scheme. Fig. 8(b) shows the experimental results for ac (50 Hz) voltages.

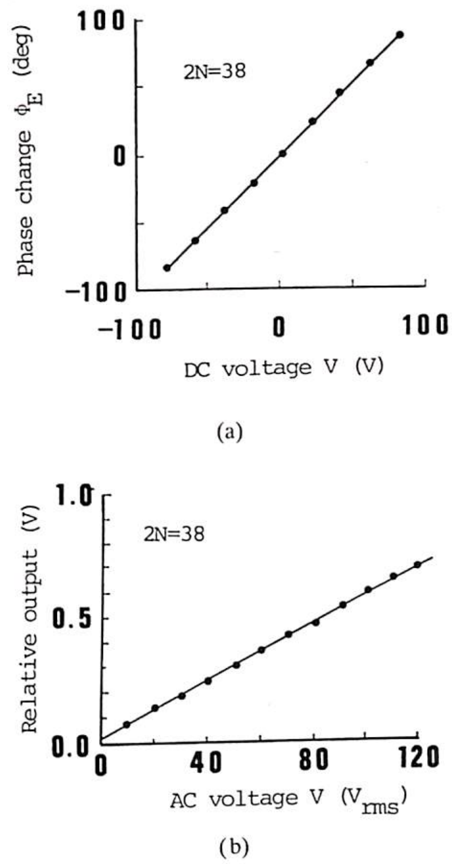


Fig. 8. Phasemeter output of fiber-optic differential heterodyne voltage sensor using the multiple reflection BSO Pockels cell; $2N$ is the number of light passes within the Pockels cell. (a) Characteristics for dc voltages. (b) Characteristics for 50 Hz voltages.

C. Pressure

The multiple-reflection FR5 glass cell described in Section III-A is used for the sensitivity-enhanced photoelastic cell, too. Various weights were loaded on the top surface of the cell so as to generate uniform vertical pressure within the cell. The pressure-induced linear retardation is given by

$$\Phi_P = (2\pi/\lambda) \cdot 2N \cdot C_o P d, \quad (23)$$

where P is the applied pressure, d is the cell thickness and C_o is the photoelastic constant. In the measurement setup of Fig. 6, the polarization azimuth of each of the incident two frequency components was made to coincide with the parallel and perpendicular directions of applied force.

Fig. 9(a) shows a typical pen recorder chart when a weight providing a pressure of 8.29×10^4 Pa was loaded on and off the cell with $2N = 54$; the time constant of the phasemeter was 0.1 s. A rapid response and good reproducibility over a wide dynamic range of 0–5 KPa is observed. The minimum detectable pressure is 350 Pa. Fig. 9(b) shows the phasemeter output measured as a function of applied pressure, representing a pressure dependence of $\Phi_P[\text{deg}] = 2.8 \times 10^{-4} P[\text{Pa}]$. Putting the experimental result into the theoretical relationship (23) of $\Phi_P[\text{deg}] = 9.5 \times 10^7 C_o P[\text{Pa}]$ calculated with $\lambda = 633$ nm, $d = 3.1$ mm and $2N = 54$, the photoelastic constant C_o of FR5 is determined as 2.9×10^{-12} Pa^{-1} or 2.9 Br.

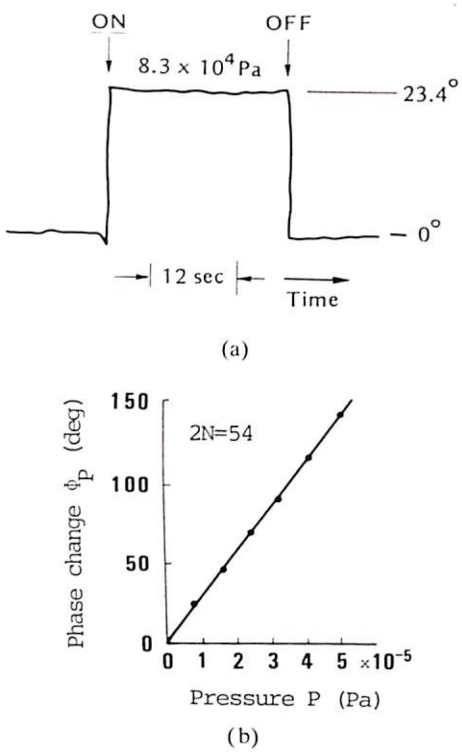


Fig. 9. Phasemeter output of fiber-optic differential heterodyne pressure sensor using the multiple reflection FR5 photoelastic cell; $2N$ is the number of light passes within the photoelastic cell. (a) Dynamic characteristics when a load is on and off the cell; the time constant of the phasemeter is 0.1 s. (b) Characteristics for static pressure.

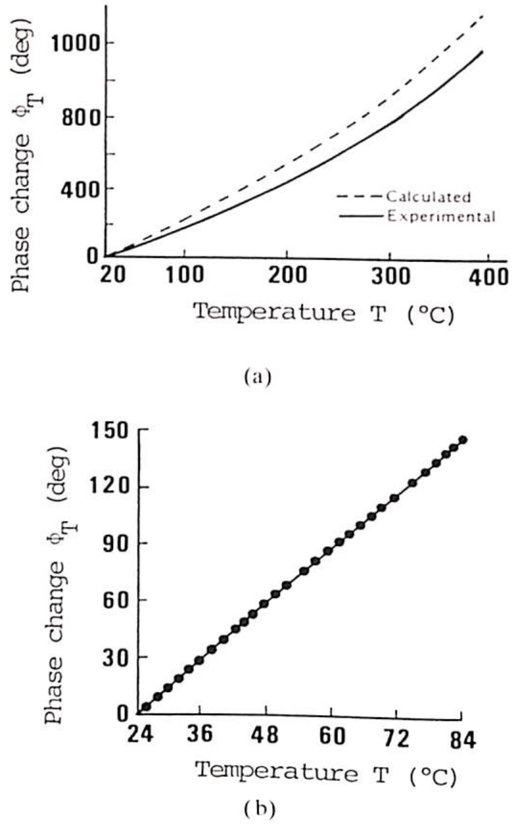


Fig. 10. Phasemeter output of fiber-optic differential heterodyne temperature sensor using the reflection type quartz cell. (a) Comparison between experimental and calculated values. (b) Measured temperature dependence of phasemeter output between room temperature and 84°C.

D. Temperature

An artificial quartz having a 2.09 mm thickness and 10 mm × 10 mm surface area is used for the sensor material. The optic axis (c axis) of the quartz is parallel to the cell surface. In the measurement system of Fig. 6, the dual-frequency dual-polarization components from STZL are incident on the quartz crystal at an angle of incidence of 10° with the mutual coincidence of their polarization axes. The laser beams reflected from the back and front surfaces of the quartz plate are used for the signal and reference lights, respectively. The quartz plate was inserted in a copper block placed on a hot plate. The temperature of the copper block was changed from room temperature to 400°C, monitored by a mercury thermometer. Fig. 10(a) shows changes in retardation measured as a function of the monitored temperature T[°C]. The measured retardation monotonously increased with increasing temperature, showing a good linearity over an interval of about 50°C. For 24°C–84°C in particular, $d\Phi_T/dT = (2.39 \pm 0.01)°/°C$, as shown in Fig. 10(b). The resolution of temperature measurement is 0.04°C; the temperature resolution can be easily increased by the use of the multiple reflection scheme.

The retardation of the quartz plate is

$$\Phi_T = (2\pi/\lambda) \cdot \Delta n \cdot 2d \tag{24}$$

where d is the thickness of the crystal plate and $\Delta n = n_o - n_e$ is the birefringence of quartz. The classical measurement on the variation of Δn with temperature T[°C] for natural quartz [21] at $\lambda = 633$ nm gives

$$10^3 \Delta n = 9.08 - 1.09 \times 10^{-3} T - 1.21 \times 10^{-6} T^2. \tag{25}$$

The thermal expansion of quartz between 50 and 80 K is given by [22] as

$$d = d_o(1 + 1.172 \times 10^{-5} T + 1.168 \times 10^{-8} T^2 + 1.633 \times 10^{-11} T^3). \tag{26}$$

Putting (25) and (26) into (24) results in

$$\Phi_T = (4\pi d_o/\lambda)10^{-3}(9.08 - 9.84 \times 10^{-4} T - 1.12 \times 10^{-6} T^2 + 1.21 \times 10^{-10} T^3). \tag{27a}$$

It then follows from (26) with $d_o = 2.09$ mm and $\lambda = 633$ nm that

$$\Phi_T = \text{const.} - 2.334 \times T(1 + 1.16 \times 10^{-3} T - 1.23 \times 10^{-7} T^2). \tag{27b}$$

The experimental results are compared in Fig. 10(b) with the calculated values of (27b), showing a fairly good agreement between them. Since the present temperature sensor is inherently insensitive to light intensity variations, the sensor cell does not need to be in stable contact with the fiber but can be in remote setting from the fiber, meeting the requirement for most cases of practical temperature measurements.

E. Ellipsometry

Ellipsometry is a powerful tool for the precise measurement of optical constants and/or film thickness. The conventional ellipsometer, however, requires mechanical moving elements such as rotating polarizers and is bulky, thereby being poor at flexible setting. In order to remove such drawbacks, a fiber-optic heterodyne ellipsometer is developed and applied to film thickness measurements.

1) Theory: We consider the case that a transparent thin film of thickness d and refractive index n' is deposited on a substate of complex refractive index n'', as shown in Fig. 11. A collimated light beam is incident on the thin film at an angle of incidence θ. We let the complex amplitude reflection coefficients for $s(\perp)$ and $p(\|)$ polarizations be R_s and R_p, respectively, and define a complex parameter as

$$\rho = R_p/R_s = P\exp(i\psi). \tag{28}$$

Here P and ψ are real ellipsometric parameters related with

$$R_s = \{r_s + r_s' \exp(-i2\delta)\}/\{1 + r_s r_s' \exp(-i2\delta)\} \tag{29a}$$
$$R_p = \{r_p + r_p' \exp(-i2\delta)\}/\{1 + r_p r_p' \exp(-i2\delta)\} \tag{29b}$$

where

$$\begin{aligned} r_s &= -\sin(\theta - \theta')/\sin(\theta + \theta'),\\ r_p &= \tan(\theta - \theta')/\tan(\theta + \theta')\\ r_s' &= -\sin(\theta' - \theta'')/\sin(\theta' + \theta''), \end{aligned} \tag{30a}$$

and

$$r_p' = \tan(\theta' - \theta'')/\tan(\theta' + \theta'') \tag{30b}$$

are the Fresnel reflection coefficients at the film boundaries

$$\sin\theta = n'\sin\theta' = n''\sin\theta'' \tag{31}$$

and

$$\delta = (2\pi/\lambda)n'd\cos\theta' \tag{32}$$

which is the optical phase shift due to the single pass of light in the film [23]. Putting (29) into (28) and solving δ with (32), one obtains the well-known formulas for film thickness [24]

$$d = i(\lambda/4\pi)\cdot ln\eta/\left(n'^2 - \sin^2\theta\right)^{1/2} \tag{33}$$

with

$$\eta = \left\{-B \pm \left(B^2 - 4AC\right)^{1/2}\right\}\Big/(2A) \tag{34}$$

where

$$A = (\rho r_p - r_s)r_s' r_p' \tag{35a}$$
$$B = r_p r_s\left(\rho r_p' - r_s'\right) + \left(\rho r_s' - r_p'\right) \tag{35b}$$
$$C = \rho r_s - r_p. \tag{35c}$$

The ellipsometry parameter ρ is determined by the differential heterodyne method. Letting the s- and p-polarization components of the incident light have frequencies f_1 and f_2, respectively and detecting the reflected light through a polarizer oriented at 45° to the plane of incidence, then the photoelectric signal is proportional to

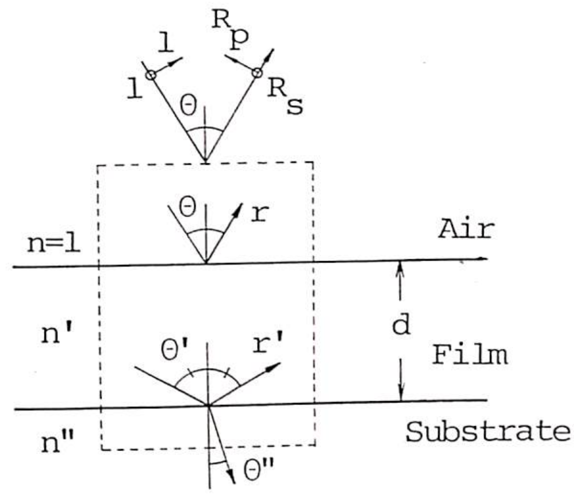


Fig. 11. Thin film configuration under consideration.

$$I = 1 + u^2P^2 + 2uP\cos(2\pi\Delta \text{ft} - \psi - \Gamma) \tag{36}$$

where u is the amplitude ratio of the p to s polarization components of the incident light and Γ is the initial retardation involved in the incident light. The quantity P is related to the modulation depth M of the beat signal (36) by

$$\begin{aligned} M &= (I_{\max} - I_{\min})/(I_{\max} + I_{\min})\\ &= 2uP/\left(1 + u^2P^2\right) \end{aligned} \tag{37}$$

so that

$$P = \left\{1 \pm \left(1 - M^2\right)^{1/2}\right\}\Big/(uM) \tag{38}$$

where the ± signs correspond to whether the reflected intensity of the s-component is larger than that of the p-component or not. The value of u is determined from the modulation depth M_o of the incident beat signal, related by

$$M_o = 2u/\left(1 + u^2\right). \tag{39}$$

2) Experiment: The measurement system is shown in Fig. 12. As the light source, instead of STZL, an acousto-optic modulator system (HOYA model S-21) is used, which converts an He–Ne laser beam to a dual-frequency dual-polarization laser with a frequency separation of 1 MHz beam by means of two AO modulators inserted in a Mach–Zhender interferometer.

For example samples, two SiO_2 thin films deposited on silicon wafer surfaces by the thermal oxidation method were measured. The angle of incidence was set at 60°. The phase shift ψ was detected by the phasemeter. The measured modulation depth M_o of the incident beat signal was 0.987, whence (39) leads to $u = 1.20$. The measured modulation depth M of the reflected beat signal for sample A was between 0.622 and 0.761, depending on the temperature of PMF, and that for sample B is 0.940. Using the corresponding P-values of (38) and assuming $n' = 1.46$ and $n'' = 3.85 - i0.02$ in (29)–(31) and (35), η is determined. Putting the η-values into (33) leads

TABLE I
MEASURED ELLIPSOMETRIC PARAMETERS AND CALCULATED FILM THICKNESS

	Measurement			Calculation	
Sample	$Ip/Is > 1$	M	ψ (deg)	P	d(nm)
A	yes	0.622 ~ 0.761	2.01 ~ 213	2.40 ~ 1.81	139 ~ 144
B	no	0.940	114	0.58	74

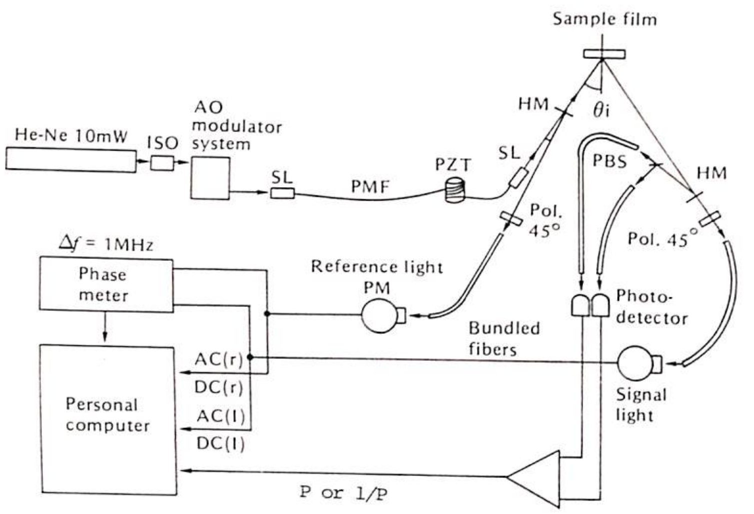


Fig. 12. Measurement system for all-fiber heterodyne ellipsometer. PMF: polarization maintaining fiber, HM: half mirror, PBS: polarization beam splitter.

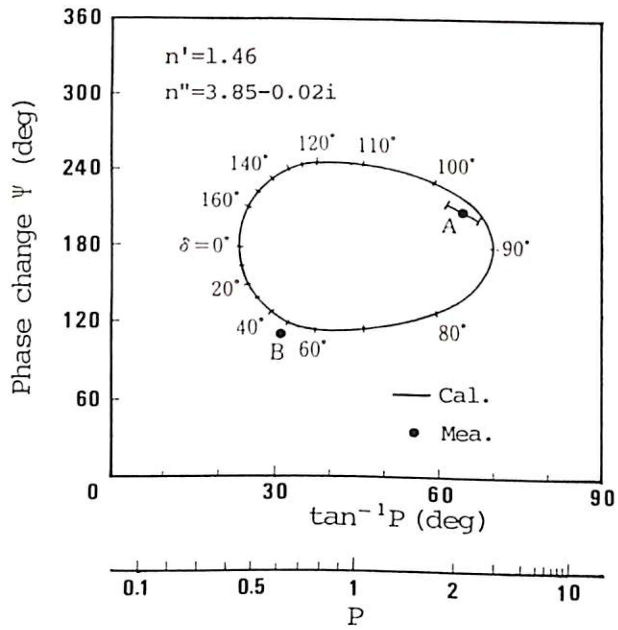


Fig. 13. Experimental and theoretical relationship between amplitude factor P and phase factor ψ of the ellipsometric parameter; δ represents the film phase shift. The solid line of sample A indicates the measurement error.

to a film thickness d between 139 and 144 nm for sample A and 74 nm for sample B, respectively, as shown in Table I.

Experimentally, both the amplitude P and phase ψ of ellipsometry parameter (28) are independently determined, but, theoretically, they are related to each other through (29) if the medium parameters, i.e., n', n'', θ and δ, are given. The theoretical relationship between ψ and $\tan^{-1} P$ (or P) is calculated as a parameter of the film phase shift (32), i.e., $\delta[\text{deg}] = (2\pi/\lambda)n'd \cos\theta' = 0.661d[\text{nm}]$, and the result is shown in Fig. 13 by the solid curve. The experimental points for both samples A and B are located close to the calculated curve, indicating a good accuracy of the present ellipsometer.

IV. Discussion and Conclusion

The single beam ac (optical beat) interferometric fiber sensors which can measure various quantities with high precision and high stability, have been developed. The key devices of the present sensors are the polarization maintaining fiber used as either a sensor itself or an optical lead and the dual-frequency dual-polarization laser source. The present sensing scheme detects the optical phase from the phase shift of the beat signal and the optical amplitude from the modulation depth of the beat signal. As a consequence, both the optical phase and amplitude can be measured independently of light power fluctuations.

The present sensing scheme is easy to construct because of being based on the single beam interferometry and is free from the phase instability due to fiber leads, unlike the usual fiber interferometer, because the sensing scheme is based on the differential phase detection using two fibers. The present sensing scheme can be applied to the measurement of various quantities such as temperature, force, strain, pressure, displacement, magnetic flux, electric field and voltage, film thickness as well as fiber gyroscope.

The measurement errors of the present sensing schemes primarily stem from the polarization crosstalk of the dual frequency components, possibly caused by 1) the misalignment of the polarization axes between the laser light and the polarization maintaining fiber, 2) the polarization cross-talk occurring in polarization maintaining fiber, 3) the initial polarization mixing involved in the laser source or AO modulators. The theoretical and experimental study [25] has shown that, among the possible causes, the first one is the most dominant but can be eliminated simply by suitably orienting the azimuth of the polarizer placed in front of the receiving bundle fiber. In the presence of general polarization mixing, however, additional factors, e.g., a factor proportional to $\cos(2\pi\Delta ft + \psi - \Gamma)$ appears in the beat signal of (36). In that case, even by the use of the differential phase detection scheme, the effect of fiber retardation Γ can't be fully eliminated; moreover the relationship between the phasemeter output and the sensor retardation ψ becomes nonlinear. The polarization mixing is ultimately limited by the crosstalk of polarization maintaining fiber, so that the development of low crosstalk polarization maintaining fiber is desired for the present fiber-optic sensing scheme.

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Common path heterodyne optical fiber sensors

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Abstract:
The common path type of differential heterodyne fiber-optic sensing scheme has been developed. It uses a polarization maintaining fiber as either a sensor or an optical lead and a dual-frequency dual-polarization laser beam. The sensing schemes are applied to the measurements of temperature, strain, force, pressure, rotation rate (gyro), magnetic and electric fields, and thin film thickness. The sensing scheme and main performances for each measurand are described. High precision and high stability as well as good linearity for each measurand are demonstrated.

Published in: Journal of Lightwave Technology (Volume: 10, Issue: 4, Apr 1992)

Page(s): 503 - 513

Date of Publication: Apr 1992

▸ **ISSN Information:**

INSPEC Accession Number: 4179759

DOI: 10.1109/50.134205

Publisher: IEEE

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optical modulation, demodulation, fibre optic sensors, light polarisation

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good linearity, magnetic fields, high precision, accuracy, heterodyne optical fiber sensors, common path, differential heterodyne fiber-optic sensing scheme, polarization maintaining fiber, optical lead, dual-frequency dual-polarization laser beam, temperature, strain, force, pressure, rotation rate, gyro, electric fields, thin film thickness, measurand, high stability

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Common Path Heterodyne Optical Fiber Sensors

Toshihiko Yoshino, Takaharu Hashimoto, Makoto Nara, and Kiyoshi Kurosawa

***Abstract*— The common path type of differential heterodyne fiber-optic sensing scheme has been developed which uses a polarization maintaining fiber as either a sensor or an optical lead and a dual-frequency dual-polarization laser beam. The sensing schemes are applied to the measurements of temperature, strain, force, pressure, rotation rate (gyro), magnetic and electric fields, and thin film thickness. The sensing scheme and main performances for each measurand are described. High precision and high stability as well as good linearity for each measurand are demonstrated.**

I. Introduction

By means of optical fiber sensors many physical and chemical quantities can be measured in a flexible and remote manner without undergoing electromagnetic induction noises. However, at the present stage of fiber-optic sensing technology, high stability and reliability are the most required features for practicing fiber sensors. In order to fulfill such requirements, the present authors have developed the common path type of heterodyne optical fiber sensing in which heterodyning two laser beams take a common path in the entire sensing system since 1981. The sensing system can measure various quantities with good linearity and high stability against environmental temperature and pressure variations.

The key devices for the developed fiber sensors are a dual-frequency dual-polarization laser beam and a polarization-maintaining fiber, which are used for a sensor element or an optical lead. The combination of the two devices produces a stable and precise fiber sensing scheme especially suited for polarization based fiber sensors. The developed fiber sensors make it possible to measure various quantities such as temperature, strain, force, pressure, rotation rate (gyroscope), magnetic and electric fields, displacement, and film thickness. The purpose of this paper is to give the detailed descriptions of our previous studies on the in-line heterodyne fiber sensors, partially reported in the several conferences [1]–[7]. The sensing schemes and main performances of the developed fiber sensors are described classifying the use of polarization maintaining fiber (PMF) into a sensor element and an optical lead.

Manuscript received October 31, 1990. This work was partially supported by Grant-in-Aid for Special Project Research for Lightwave Sensing from the Ministry of Education, Science, and Culture of Japan.

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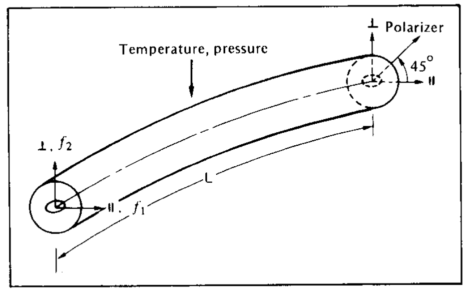

Fig. 1. Optical arrangement of heterodyne fiber-optic sensor using polarization maintaining fiber as sensor element.

II. Use of PMF as Sensor Element

The retardation of highly birefringent single-mode fiber, i.e., polarization maintaining fiber (PMF), depends on temperature and mechanical forces so that it can be used for temperature (e.g., [8]) or mechanical force measurement. Here we present a new sensing scheme to achieve high precision for the retardation measurement.

A laser beam consisting of two frequency components with orthogonal linear polarization is launched into a PMF with the coincidence of polarization axes between the laser and PMF, as shown in Fig. 1. The output beam from PMF is passed through a polarizer oriented at 45° to the fiber polarization axes, || and ⊥, and detected by a photomultiplier. Letting the propagation constants of the orthogonal polarization modes of the fiber be $\beta_{\|}$ and $\beta_{\perp}$ and the laser frequencies be f_1 and f_2, the photoelectric signal is given by

$$I = |A_{\|} \exp i(2\pi f_1 t - \beta_{\|} L) + A_{\|} \exp i(2\pi f_2 t - B_{\perp} L)|^2 \quad (1)$$

where L is the fiber length and $A_{\|}$ and $A_{\perp}$ are real constants. Equation (1) represents a beat signal

$$I = A_{\|}^2 + A_{\perp}^2 + 2A_{\|}A_{\perp} \cos\{2\pi(f_1 - f_2)t - (\beta_{\|} - \beta_{\perp})L\} \quad (2)$$

which can be rewritten as

$$I = A + B\cos(2\pi\Delta f t - \Gamma), \quad (\Delta f = f_1 - f_2;\ A, B \text{ real numbers}) \quad (3)$$

where

$$\Gamma = (\beta_{\|} - \beta_{\perp})L \quad (4)$$

is the retardation of PMF, depending on temperature and applied force besides the initial retardation.

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The PMF used in this paper is Hitachi Cable's one having a beat length of 2.5 mm at 20°C and $\lambda = 633$ nm.

The light source used is a home-made frequency stabilized transverse Zeeman He–Ne laser operated at $\lambda = 633$ nm (STZL). The laser emits orthogonally linearly polarized two modes having a frequency separation from 300 to 400 kHz, stabilized within about 1 kHz; the frequency stabilization was achieved by the negative feedback of the beat frequency of the two modes to the cavity length by means of a cooling fan [9].

A. Temperature

Fig. 2(a) shows the temperature sensing system. In order to locate the sensing part at a specified section of the fiber and to eliminate the effect of the surrounding temperature variations, a differential detection scheme using two PMF's is employed. Both a signal fiber and a reference fiber are aligned close to each other except the sensing part, where the sensing fiber was made longer than the reference one by different lengths L of 0–4 m; the entire length of the sensing fiber was 10 m. The sensing part was inserted in a water bath, heated by a nichrome heater inserted in the water. Fig. 2(b) shows the typical beat signals (300 kHz) of the sensing and reference fibers. The phase difference between the two beat signals is detected by a phasemeter. Fig. 2(c) shows the change in phasemeter output measured as a function of the change in water temperature monitored with a mercury thermometer. In the experiment the water bath was heated and natural-cooled many times. Somewhat data variations observed in Fig. 2(c) are most probably due to the temperature inhomogeneity within the bath. The temperature dependence of fiber retardation is given, from the average slope of Fig. 2(c), as

$$d\Gamma/LdT = 114°\,°\mathrm{C}^{-1}\mathrm{m}^{-1}. \tag{5}$$

The temperature resolution ΔT is proportional to the sensing fiber length L and limited by the fluctuation of the phasemeter output, $\Delta\Gamma$, which was about 0.1°. From (5), ΔT is $0.1°/(114°\mathrm{C}^{-1}\mathrm{m}^{-1}L) = 0.009°\mathrm{Cm}/L$, or 0.009°C for $L = 1$ m for example.

Thermal cycling was studied between room temperature and 185°C by inserting a 1-m-long part of PMF into an electric furnace. Fig. 2(d) shows the measured results in which temperature was raised from 30 to 185°C in one hour and fell down in natural cooling. A good reproducibility is shown in Fig. 2(d).

B. Strain and Force Sensors

Fig. 3(a) shows the strain sensing system. In order to reduce the temperature-induced drift, a differential detection scheme using two PMF's is again employed. A 27-mm-long part of a sensing PMF is fixed on an aluminium plate by a scotch tape whereas a reference PMF is aligned close to the sensing one but free from the plate. Axial strain was applied to the fiber by bending the plate and monitored by a metal strain gauge. Fig. 3(b) shows the change in the phasemeter output measured as a function of the monitored strain ε. The strain-induced retardation is proportional to the sensor length L and,

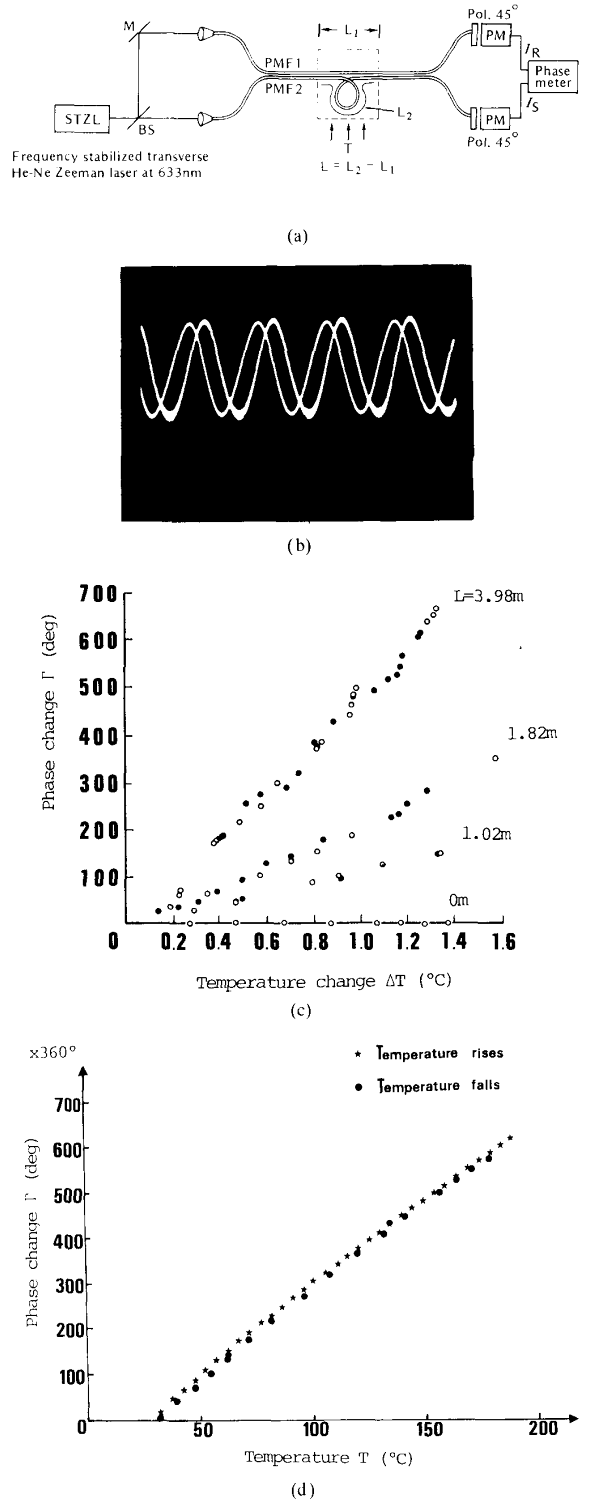


Fig. 2. Heterodyne fiber-optic temperature sensor using polarization maintaining fiber. (a) Measuring system. (b) Beat signals (signal and reference lights; the beat frequency = 300 kHz). (c) Temperature dependence of phasemeter output measured as a parameter of sensor fiber length L. (d) Thermal cycling of 1-m-long polarization maintaining fiber temperature sensor.

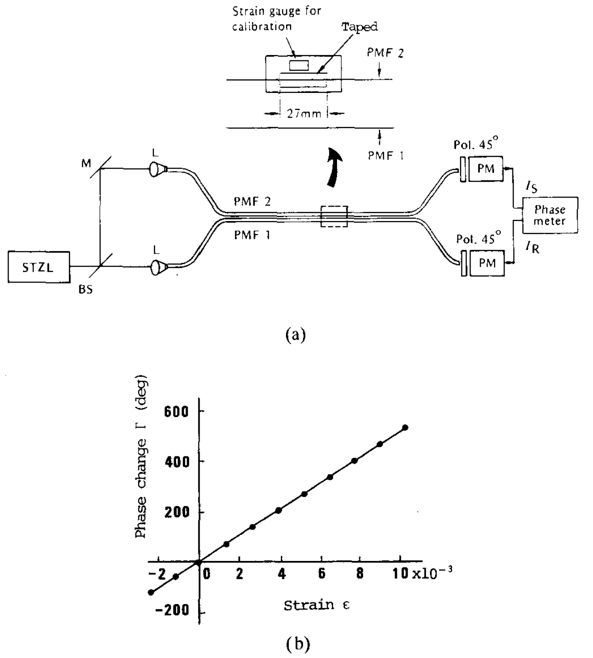


Fig. 3. Heterodyne fiber-optic strain sensor using polarization maintaining fiber. (a) Measuring system. (b) Phasemeter output measured as a function of applied strain.

from Fig. 3(b), is given as

$$\begin{aligned} d\Gamma/Ld\varepsilon &= 500^\circ/(27\text{ mm} \times 10 \times 10^{-3}\varepsilon) \\ &= 1.9 \times 10^{6\circ}\varepsilon^{-1}\text{m}^{-1}. \end{aligned} \quad (6)$$

The minimum detectable strain is proportional to the sensor length. As the fluctuation of the phasemeter output was about 0.1°, the strain resolution $\Delta\varepsilon$ is, from (6), $0.1^\circ/(1.9 \times 10^{6\circ}\varepsilon^{-1}\text{m}^{-1}L) = 5.3 \times 10^{-8}\varepsilon\text{m}/L$, or $0.053 \times 10^{-6}\varepsilon$ for $L = 1$ m for example.

In order to see the temperature compensation effect using two PMF's, the two fibers were inserted in an empire tube and heated over a 1-m-long part by a hair dryer. When the tube temperature was raised by 15°C, the change in the phasemeter output was 100° at worst in contrast with 2500° in the case of a single fiber. The temperature compensation effect is thus better than 1 : 25.

Various types of strain and force sensors can be constructed. Fig. 4(a) shows the measured result for a tension type of force sensor. An 170-mm-long part of PMF was cementized in a glass tube and axial tensile force was applied to the fiber by various weights. The force-induced retardation is proportional to the sensor length L and, from Fig. 4(a), is

$$\begin{aligned} d\Gamma/LdF &= 600^\circ/(0.2\text{ kgf} \times 170\text{ mm}) \\ &= 1.8 \times 10^{4\circ}\text{ kgf}^{-1}\text{m}^{-1}. \end{aligned} \quad (7)$$

From (7), using $\Delta\Gamma = 0.1^\circ$ the minimum detectable force ΔF is $0.1^\circ/(1.8 \times 10^{4\circ}\text{ kgf}^{-1}\text{m}^{-1}L) = 5.6 \times 10^{-6}$ kgfm$/L$, or 0.0056 grf for $L = 1$ m for example.

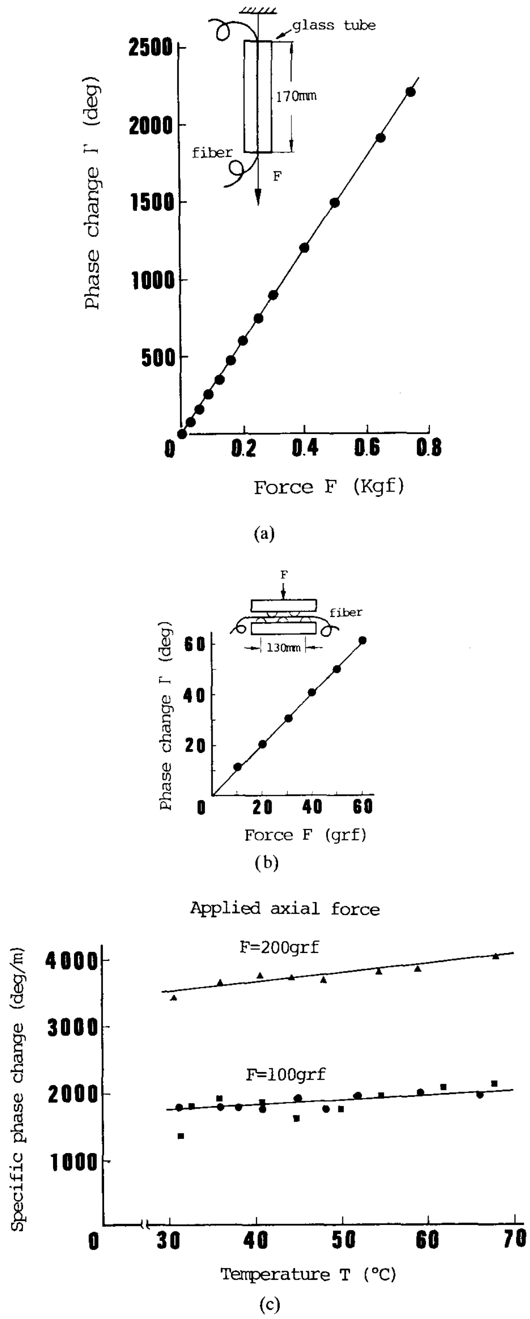


Fig. 4. Heterodyne fiber-optic force sensors using polarization maintaining fiber. (a) Tension type. (b) Microbending type. (c) Temperature dependence of force sensitivity.

Fib. 4(b) shows another type of force sensor using a microbender. An 130-mm-long part of PMF was sandwiched by two wave-form plates having a pitch of 20 mm. Various weights were loaded on the upper plate, causing dominantly axial tensile stress in the fiber. The minimum detectable force was about 1 grf.

The force-induced retardation was found to depend a little on fiber temperature. Fig. 4(c) shows the measured dependence of force-induced retardation on temperature. The force-induced retardation increased with temperature. It follows from Fig. 4(c) that the force sensitivity of PMF increases with temperature in about 0.25%/°C.

C. Fiber Gyro

Fiber gyro is a rotation sensor using the Sagnac effect in the monomode fiber loop. Much work has been done to improve on the gyro performances [10]. Among them, an absolutely constant scale factor for rotation rate detection is one of the most desirable features for practical fiber gyros. Here we present a new type of fiber gyro fulfilling the requirement. The method is based on heterodyne detection, but, unlike the usual heterodyne method [11], the interfering two laser beams take a common path in the entire sensor system so that the gyro system becomes substantially stable against the environmental variations.

Fig. 5(a) shows the entire gyro system. The Sagnac ring interferometer consists of a polarization beam splitter PBS, two Faraday rotators FR1 and FR2, each producing $-45°$ and $+45°$ rotations of polarization plane, and a PMF coil. The orthogonally linearly polarized different frequency f_1 and f_2 components from a STZL are split by PBS into the CW and CCW traveling beams in the ring interferometer. The two beams undergo $\pm 45°$ rotations of polarization plane so that they can travel the PMF along a common polarization axis. The combination of one Faraday rotator and PBS makes an optical isolator so that both the CW and CCW beams going out of the ring interferometer don't return the laser source but go to a photomultiplier PM1.

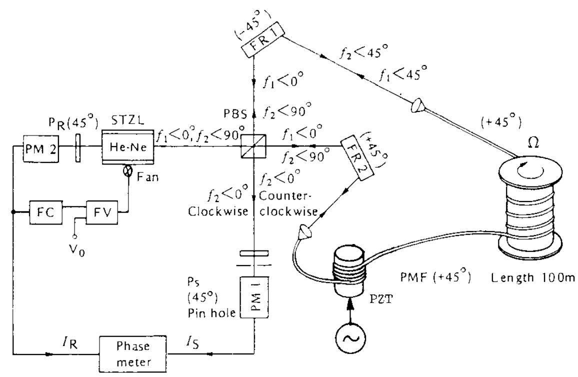
The optical beat I_s generated at PM1 has a phase

$$\Phi = 2\pi \Delta f L/c + \phi_s \tag{8}$$

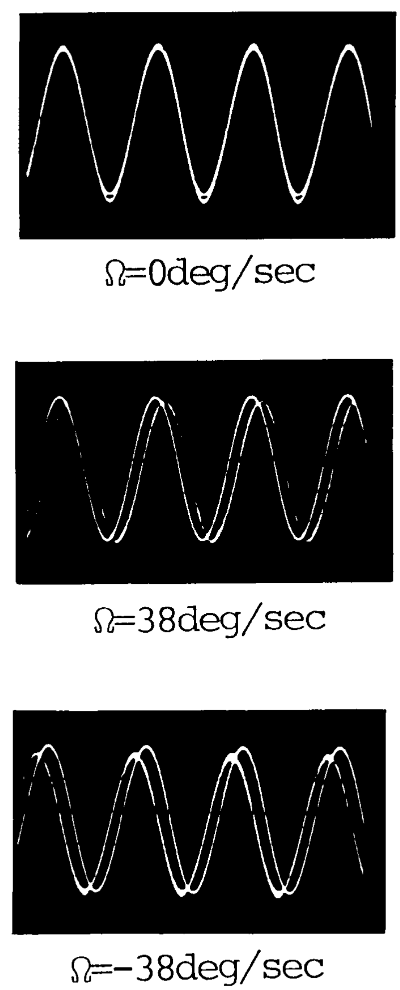
where $\Delta f = f_1 - f_2$, L is the total light path length from the light source to the photodetector, c is the light velocity in vacuum, and

$$\phi_s = (4\pi L_f a/\lambda c)\Omega \tag{9}$$

is the Sagnac shift [12], where a is the radius of the fiber coil, L_f is the fiber coil length, λ is the light wavelength in vacuum, and Ω is the rotation rate of the fiber coil. In the present experimental conditions, $a = 15$ cm, $L \approx L_f = 100$ m, and $\lambda = 633$ nm so that $\phi_s[\text{deg}] = 1.0\Omega[\text{deg/s}]$. The optical phase of the beat signal I_S was compared with that of the reference beat signal I_R taken from the back side of the laser. Somewhat phase fluctuations were observed in the phasemeter output but they could be reduced down to 0.1° by vibrating a short part of the fiber coil by means of a PZT driven at about 10 kHz. Three pictures of Fig. 5(b) shows the signal and reference beat signals observed when the fiber coil was at rest and rotated at $\Omega = \pm 38°/\text{s}$, respectively; the initial phase bias involved in the phasemeter output was removed; Fig. 5(c) shows the analog output signal of the phasemeter when the fiber coil was rotated by hand; the time constant of the phasemeter was 0.4 s. The minimum detectable rotation rate was then $0.1°/\text{s}$. The phasemeter output involves a nonreciprocal phase bias due to the first term of (8), which depends on the amount of the beat frequency Δf and hence can vary with the beat frequency fluctuation. The associated phase fluctuations, however, can

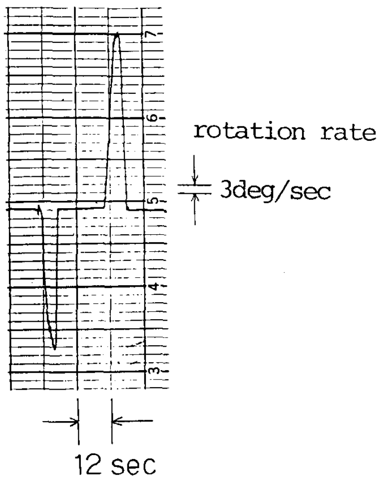


(a)



(b)

Fig. 5. Heterodyne fiber gyroscope. (a) Optical system. (b) Signal and reference optical beats (300 kHz) for different rotation rates of Ω. (c) Phasemeter output when the fiber coil was rotated by hand; the time constant of the phasemeter is 0.4 s.



(c)

Fig. 5. (Continued)

be eliminated by passing the reference light through a fiber having a length equal to L.

III. Use of PMF as Optical Lead

There have been developed lots of types of fiber sensors which use optical fibers as optical leads to connect between optical transducers and light sources or photodetectors in order to realize flexible, *in-situ,* remote measurements. Among many types of such sensors, a polarimetric method is one of the most useful principles. The Faraday effect is used for the measurement of magnetic field [13], [14], the Pockels effect for voltage [14], the photoelastic effect for pressure [15], the natural birefringence for temperature [16] and the oblique light incidence for refractive index or film thickness [17]. In the previous polarization-based fiber sensors, however, optical fiber leads are mostly used to carry the intensity-modulated light signal, therefore being sensitive to light intensity fluctuations associated with fiber transmission, fiber coupling, light source fluctuations and so on. In this paper, intensity-insensitive fiber sensors are developed by the use of PMF as optical leads.

Fig. 6 shows the entire sensing setup for measuring various quantities such as magnetic field, voltage, pressure and temperature. The detection principle is based on the differential heterodyne scheme. The laser beam from a STZL is launched into a PMF (typically 10 m-long) with the mutual coincidence of polarization axes. Some part of the fiber was vibrated at about 5 kHz to reduce the fluctuation of the phasemeter output. The output light from the PMF is collimated by a SELFOC rod lens SL and incident on a polarimetric sensor cell. The laser beam emerging from the cell is, after passing through a polarizer oriented at 45° to the polarization axes of the sensor cell, sent to a photodetector through a fiber bundle. On the other hand, a light beam partially reflected from the entrance of the cell is detected and used for a reference light. Both the signal and reference lights generate the following beat

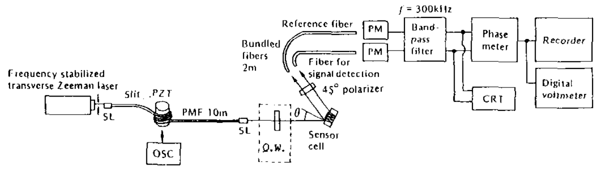


Fig. 6. Schematic diagram for fiber-optic differential heterodyne sensors using polarimetric sensor cell. PMF: polarization maintaining fiber, SL: self-focusing rod lens.

signals:

$$I_S = A_S \cos(2\pi\Delta f - \Phi - \Gamma) \quad (10a)$$

$$I_R = A_R \cos(2\pi\Delta f - \Gamma) \quad (10b)$$

where Φ is the retardation of the sensor cell, Γ is the retardation of PMF, and A_S and A_R are real numbers. The phase difference between the two beat signals is detected by a phasemeter. The minimum detectable retardation $\Delta\Gamma$ was about 0.1°.

A. Magnetic Field

In the measurement system of Fig. 6, the output light from PMF was passed through a quarter-wave plate QW to convert the incident light to the left and right circularly polarized lights. The sensor cell is made of FR5 glass, which has a Verdet constant V of -0.24 min cm^{-1} G^{-1} at $\lambda = 633$ nm. In order to enhance the measurement sensitivity, the multiple reflections of the light beam within a Faraday cell [18] were employed. The upper and lower surfaces of a 3.1-mm-thick 15 mm $\times$ 20 mm wide FR5 glass plate were coated with the multilayers of dielectric thin films having $\lambda/4$ optical thicknesses for oblique incidence so that the light beam may perfectly reflect with polarization maintaining. The light beam travels a zigzag path over a lateral region of 12.8 mm in the cell. Under the application of magnetic field, the cell material becomes circularly birefringent, thereby inducing phase retardation between the orthogonal circular polarizations, given by

$$\Phi_H = 2 \cdot 2N \cdot VHd \quad (11)$$

where H is the parallel component of magnetic field to the direction of cell thickness and $2N$ is the number of the multiple passes of light beam within the cell. Fig. 7(a) shows a typical pen recorder chart of the phasemeter output when H was ± 50 Oe; the time constant of the phasemeter was 0.4 s. A very stable and precise measurement of dc magnetic field is achieved, which is very difficult by the conventional intensity modulation Faraday sensor. The minimum detectable dc field is less than 1 Oe. Fig. 7(b) and (c) respectively shows the phase changes measured as a function of relatively small and large dc magnetic fields. The cases of $2N = 40$ and 80 correspond to the angles of incidence on the cell surface 10° and 5°, respectively. The measured results of Fig. 7(a) and (b) agrees quite well with the theoretical ones, which, e.g., for $2N = 40$, $\Phi_H[\text{deg}] = 0.099H[\text{Oe}]$ calculated from (11). The present sensors can be used for ac fields too if the response

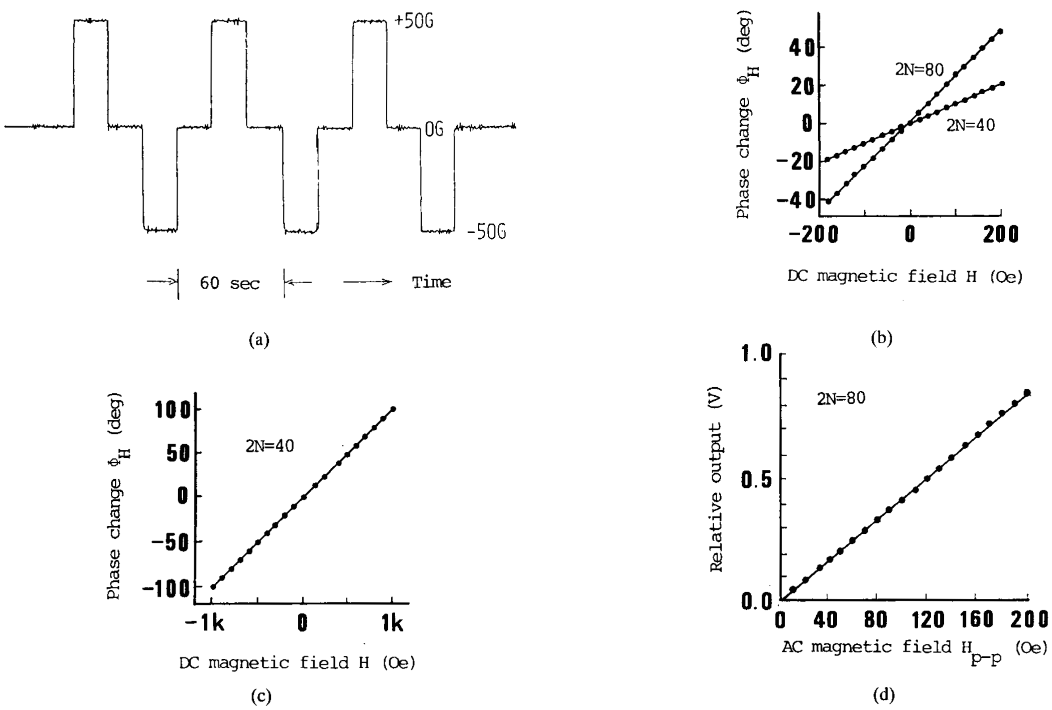


Fig. 7. Phasemeter output of fiber-optic differential heterodyne magnetic field sensor using the multiple reflection FR5 Faraday cell; $2N$ is the number of light passes within the Faraday cell. (a) Recorder trace of phasemeter output; the time constant of the phasemeter is 0.4s and $2N = 40$. (b) Characteristics for small dc magnetic fields. (c) Characteristics for large dc magnetic fields. (d) Characteristics for 50-Hz magnetic fields.

time of the phasemeter is set suitably small. Fig. 7(d) shows the measured results for the commercial frequency of 50 Hz, where $2N$ was made as large as 80 by setting the angle of incidence at as small as 5°.

B. Voltage

As a Pockels material, $Bi_{12}SiO_{20}$ (BSO) is used because of its relatively large and hardly temperature dependent Pockels effect. The material, however, has optical activity, i.e., circular birefringence, which obviously reduces the Pockels effect being linear birefringence. An effective technique for getting rid of such reduction of the Pockels effect is to use two way or in more general multiple light passes within the Pockels cell because then an optical rotary power in an optically active material is cancelled whereas the Pockels effect is accumulated.

1) Theory: We define an eigenstate of polarization that light regenerates the same polarization after one round trip within the Pockels cell as

$$M(-\theta_a)M(\theta_a)\begin{bmatrix}E_x\\E_y\end{bmatrix} = \sigma\begin{bmatrix}E_x\\E_y\end{bmatrix} \tag{12}$$

where, referring to [20]

$$M(\theta_a) = \begin{bmatrix}\cos(\phi/2) - i\left(\pi\frac{V}{V_\pi}\,/\,\phi\right)\sin(\phi/2) & -(2\theta_a d/\phi)\sin(\phi/2)\\ (2\theta_a d/\phi)\sin(\phi/2) & \cos(\phi/2) + i\left(\pi\frac{V}{V_\pi}\,/\,\phi\right)\sin(\phi/2)\end{bmatrix} \tag{13}$$

with

$$\phi = \left[\left(\pi\frac{V}{V_\pi}\right)^2 + (2\theta_a d)^2\right]^{1/2} \tag{14}$$

where V_π is the half-wavelength voltage of the Pockels material in the limit of infinitely small thickness, θ_a is the optical activity per unit length, d is the cell thickness, $V = Ed$ is the applied voltage and σ is an eigenvalue [19]. Calculating (12) leads to an eigenvector

$$\begin{bmatrix}E_x\\E_y\end{bmatrix}_\pm = \begin{bmatrix}-\cos(\phi/2) \pm \sqrt{\cos^2(\phi/2) + (2\theta_a d/\phi)^2\sin^2(\phi/2)}\\ -(2\theta_a d/\phi)\sin(\phi/2)\end{bmatrix} \tag{15}$$

with an eigenvalue

$$\sigma_\pm = \exp(\pm i\Phi_E) \tag{16}$$

where

$$\Phi_E = 2\tan^{-1}\frac{((\pi V/V_\pi)/\phi)\sin(\phi/2)}{\sqrt{\cos^2(\phi/2) + (2\theta_a d/\phi)^2\sin^2(\phi/2)}}. \tag{17}$$

It follows from (15) that

$$(E_Y/E_X)_+ \cdot (E_Y/E_X)_- = -1 \tag{18}$$

implying that the eigenstate of polarization consists of orthogonal linear polarizations. Assuming the applied voltage is relatively low such that $\pi|V|/V_\pi \ll 2|\theta_a|d$, it then follows from (15) that the eigenstates of polarization are, to a good approximation

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix}_+ = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \quad \begin{bmatrix} E_x \\ E_y \end{bmatrix}_- = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \tag{19}$$

independently of applied voltages, implying the azimuths of the principal axes of polarization of the Pockels cell is independent of small applied voltages. Furthermore, for small voltages, $\phi \approx 2\theta_a d$ so that (17) becomes

$$\Phi_E = (\pi V/V_\pi) \cdot 2N \cdot \mathrm{sinc}(\theta_a d) \tag{20a}$$

or

$$\Phi_E = \pi V/V_\pi^*, \tag{20b}$$

where

$$V_\pi^* = V_\pi/\{2N\mathrm{sinc}(\theta_a d)\},$$
$$(2N\text{: number of light pass}) \tag{21}$$

which is an effective half-wave voltage, being in inverse proportion to N.

2) Experiment: Both surfaces of a 3-mm-thick BSO crystal plate are dielectric coated to have perfect reflection. A 10-mm-long beam-guiding region is overcoated with ITO transparent electrode films. As BSO has $V_\pi = 3900$ V and $\theta a = 22° \text{ mm}^{-1}$ at $\lambda = 633$ nm, the effective half-wave voltage becomes, from (21)

$$V_\pi^* = 3900\text{ V}/\{2N\mathrm{sinc}(22° \times 3)\}$$
$$= 4.91 \times 10^3 \text{ V}/(2N). \tag{22}$$

Using the setup of Fig. 6, the voltage-induced linear birefringence was measured as a function of applied voltages. Fig. 8(a) shows the measured results for dc voltages; the number of multiple passes is $2N = 38$. The experimental curve yields the voltage dependence of retardation as $\Phi_E[\text{deg}] = 1.0\text{ V[V]}$. Theoretically, from (22) with $2N = 38$, $V_\pi^* = 129$ V so that, from (20b), $\Phi_E[\text{deg}] = (180/129)\text{ V[V]} = 1.4\text{ V[V]}$. Both the experimental and theoretical results are in reasonable accordance within the possible discrepancy due to the field inhomogeneity in the cell. The minimum detectable dc voltage is as small as 1 V, which is very difficult to achieve by the use of the conventional intensity modulation scheme. Fig. 8(b) shows the experimental results for ac (50 Hz) voltages.

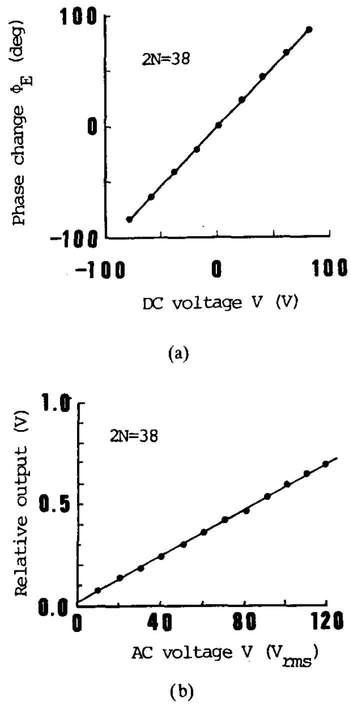


Fig. 8. Phasemeter output of fiber-optic differential heterodyne voltage sensor using the multiple reflection BSO Pockels cell; $2N$ is the number of light passes within the Pockels cell. (a) Characteristics for dc voltages. (b) Characteristics for 50 Hz voltages.

C. Pressure

The multiple-reflection FR5 glass cell described in Section III-A is used for the sensitivity-enhanced photoelastic cell, too. Various weights were loaded on the top surface of the cell so as to generate uniform vertical pressure within the cell. The pressure-induced linear retardation is given by

$$\Phi_P = (2\pi/\lambda) \cdot 2N \cdot C_o P d, \tag{23}$$

where P is the applied pressure, d is the cell thickness and C_o is the photoelastic constant. In the measurement setup of Fig. 6, the polarization azimuth of each of the incident two frequency components was made to coincide with the parallel and perpendicular directions of applied force.

Fig. 9(a) shows a typical pen recorder chart when a weight providing a pressure of 8.29×10^4 Pa was loaded on and off the cell with $2N = 54$; the time constant of the phasemeter was 0.1 s. A rapid response and good reproducibility over a wide dynamic range of 0–5 KPa is observed. The minimum detectable pressure is 350 Pa. Fig. 9(b) shows the phasemeter output measured as a function of applied pressure, representing a pressure dependence of $\Phi_P[\text{deg}] = 2.8 \times 10^{-4} P[\text{Pa}]$. Putting the experimental result into the theoretical relationship (23) of $\Phi_P[\text{deg}] = 9.5 \times 10^7 C_o P[\text{Pa}]$ calculated with $\lambda = 633$ nm, $d = 3.1$ mm and $2N = 54$, the photoelastic constant C_o of FR5 is determined as $2.9 \times 10^{-12}\text{ Pa}^{-1}$ or 2.9 Br.

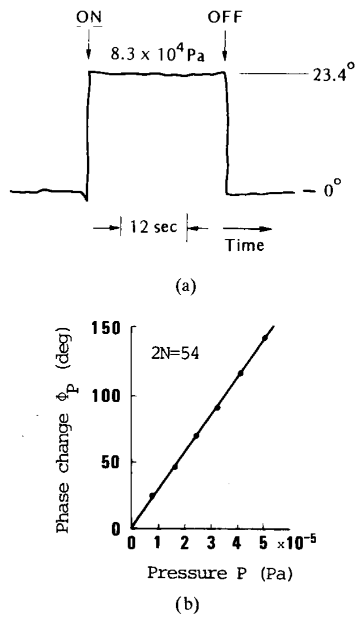


Fig. 9. Phasemeter output of fiber-optic differential heterodyne pressure sensor using the multiple reflection FR5 photoelastic cell; $2N$ is the number of light passes within the photoelastic cell. (a) Dynamic characteristics when a load is on and off the cell; the time constant of the phasemeter is 0.1 s. (b) Characteristics for static pressure.

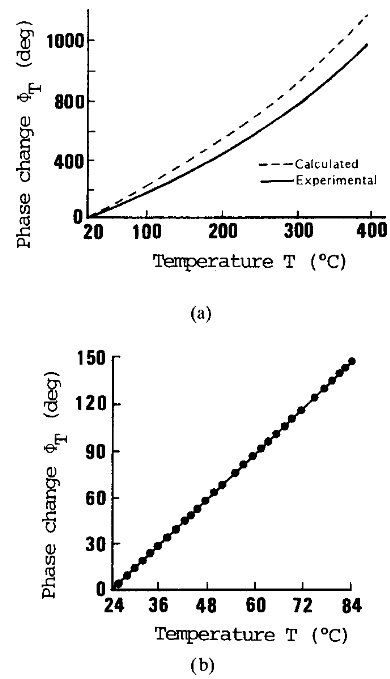


Fig. 10. Phasemeter output of fiber-optic differential heterodyne temperature sensor using the reflection type quartz cell. (a) Comparison between experimental and calculated values. (b) Measured temperature dependence of phasemeter output between room temperature and 84°C.

D. Temperature

An artificial quartz having a 2.09 mm thickness and 10 mm × 10 mm surface area is used for the sensor material. The optic axis (c axis) of the quartz is parallel to the cell surface. In the measurement system of Fig. 6, the dual-frequency dual-polarization components from STZL are incident on the quartz crystal at an angle of incidence of 10° with the mutual coincidence of their polarization axes. The laser beams reflected from the back and front surfaces of the quartz plate are used for the signal and reference lights, respectively. The quartz plate was inserted in a copper block placed on a hot plate. The temperature of the copper block was changed from room temperature to 400°C, monitored by a mercury thermometer. Fig. 10(a) shows changes in retardation measured as a function of the monitored temperature T[°C]. The measured retardation monotonously increased with increasing temperature, showing a good linearity over an interval of about 50°C. For 24°C–84°C in particular, $d\Phi_T/dT = (2.39 \pm 0.01)^\circ/^\circ\mathrm{C}$, as shown in Fig. 10(b). The resolution of temperature measurement is 0.04°C; the temperature resolution can be easily increased by the use of the multiple reflection scheme.

The retardation of the quartz plate is

$$\Phi_T = (2\pi/\lambda)\cdot\Delta n\cdot 2d \tag{24}$$

where d is the thickness of the crystal plate and $\Delta n = n_o - n_e$ is the birefringence of quartz. The classical measurement on the variation of Δn with temperature T[°C] for natural quartz [21] at $\lambda = 633$ nm gives

$$10^3\Delta n = 9.08 - 1.09\times10^{-3}T - 1.21\times10^{-6}T^2. \tag{25}$$

The thermal expansion of quartz between 50 and 80 K is given by [22] as

$$d = d_o(1 + 1.172\times10^{-5}T + 1.168\times10^{-8}T^2 + 1.633\times10^{-11}T^3). \tag{26}$$

Putting (25) and (26) into (24) results in

$$\Phi_T = (4\pi d_o/\lambda)10^{-3}(9.08 - 9.84\times10^{-4}T - 1.12\times10^{-6}T^2 + 1.21\times10^{-10}T^3). \tag{27a}$$

It then follows from (26) with $d_o = 2.09$ mm and $\lambda = 633$ nm that

$$\Phi_T = \text{const.} - 2.334\times T\left(1 + 1.16\times10^{-3}T - 1.23\times10^{-7}T^2\right). \tag{27b}$$

The experimental results are compared in Fig. 10(b) with the calculated values of (27b), showing a fairly good agreement between them. Since the present temperature sensor is inherently insensitive to light intensity variations, the sensor cell does not need to be in stable contact with the fiber but can be in remote setting from the fiber, meeting the requirement for most cases of practical temperature measurements.

E. Ellipsometry

Ellipsometry is a powerful tool for the precise measurement of optical constants and/or film thickness. The conventional ellipsometer, however, requires mechanical moving elements such as rotating polarizers and is bulky, thereby being poor at flexible setting. In order to remove such drawbacks, a fiber-optic heterodyne ellipsometer is developed and applied to film thickness measurements.

1) Theory: We consider the case that a transparent thin film of thickness d and refractive index n' is deposited on a substate of complex refractive index n'', as shown in Fig. 11. A collimated light beam is incident on the thin film at an angle of incidence θ. We let the complex amplitude reflection coefficients for $s(\perp)$ and $p(\|)$ polarizations be R_s and R_p, respectively, and define a complex parameter as

$$\rho = R_p/R_s = P\exp(i\psi). \tag{28}$$

Here P and ψ are real ellipsometric parameters related with

$$R_s = \{r_s + r_s'\exp(-i2\delta)\}/\{1 + r_s r_s'\exp(-i2\delta)\} \tag{29a}$$
$$R_p = \{r_p + r_p'\exp(-i2\delta)\}/\{1 + r_p r_p'\exp(-i2\delta)\} \tag{29b}$$

where

$$\begin{aligned} r_s &= -\sin(\theta - \theta')/\sin(\theta + \theta'), \\ r_p &= \tan(\theta - \theta')/\tan(\theta + \theta') \\ r_s' &= -\sin(\theta' - \theta'')/\sin(\theta' + \theta''), \end{aligned} \tag{30a}$$

and

$$r_p' = \tan(\theta' - \theta'')/\tan(\theta' + \theta'') \tag{30b}$$

are the Fresnel reflection coefficients at the film boundaries

$$\sin\theta = n'\sin\theta' = n''\sin\theta'' \tag{31}$$

and

$$\delta = (2\pi/\lambda)n'd\cos\theta' \tag{32}$$

which is the optical phase shift due to the single pass of light in the film [23]. Putting (29) into (28) and solving δ with (32), one obtains the well-known formulas for film thickness [24]

$$d = i(\lambda/4\pi)\cdot ln\eta/\left(n'^2 - \sin^2\theta\right)^{1/2} \tag{33}$$

with

$$\eta = \left\{-B \pm \left(B^2 - 4AC\right)^{1/2}\right\} \Big/ (2A) \tag{34}$$

where

$$A = (\rho r_p - r_s)r_s' r_p' \tag{35a}$$
$$B = r_p r_s\left(\rho r_p' - r_s'\right) + \left(\rho r_s' - r_p'\right) \tag{35b}$$
$$C = \rho r_s - r_p. \tag{35c}$$

The ellipsometry parameter ρ is determined by the differential heterodyne method. Letting the s- and p-polarization components of the incident light have frequencies f_1 and f_2, respectively and detecting the reflected light through a polarizer oriented at 45° to the plane of incidence, then the photoelectric signal is proportional to

$$I = 1 + u^2P^2 + 2uP\cos(2\pi\Delta\mathrm{ft} - \psi - \Gamma) \tag{36}$$

where u is the amplitude ratio of the p to s polarization components of the incident light and Γ is the initial retardation involved in the incident light. The quantity P is related to the modulation depth M of the beat signal (36) by

$$\begin{aligned} M &= (I_{\max} - I_{\min})/(I_{\max} + I_{\min}) \\ &= 2uP/\left(1 + u^2P^2\right) \end{aligned} \tag{37}$$

so that

$$P = \left\{1 \pm \left(1 - M^2\right)^{1/2}\right\} \Big/ (uM) \tag{38}$$

where the ± signs correspond to whether the reflected intensity of the s-component is larger than that of the p-component or not. The value of u is determined from the modulation depth M_o of the incident beat signal, related by

$$M_o = 2u/\left(1 + u^2\right). \tag{39}$$

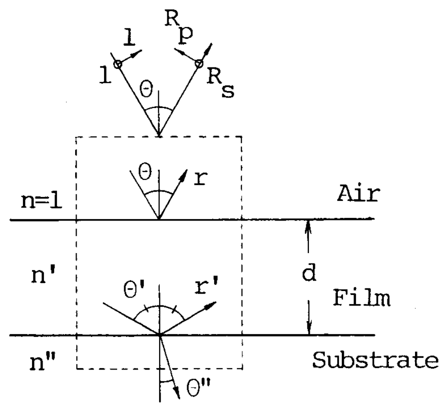


Fig. 11. Thin film configuration under consideration.

2) Experiment: The measurement system is shown in Fig. 12. As the light source, instead of STZL, an acousto-optic modulator system (HOYA model S-21) is used, which converts an He–Ne laser beam to a dual-frequency dual-polarization laser with a frequency separation of 1 MHz beam by means of two AO modulators inserted in a Mach–Zehnder interferometer.

For example samples, two SiO_2 thin films deposited on silicon wafer surfaces by the thermal oxidation method were measured. The angle of incidence was set at 60°. The phase shift ψ was detected by the phasemeter. The measured modulation depth M_o of the incident beat signal was 0.987, whence (39) leads to $u = 1.20$. The measured modulation depth M of the reflected beat signal for sample A was between 0.622 and 0.761, depending on the temperature of PMF, and that for sample B is 0.940. Using the corresponding P-values of (38) and assuming $n' = 1.46$ and $n'' = 3.85 - i0.02$ in (29)–(31) and (35), η is determined. Putting the η-values into (33) leads

TABLE I
MEASURED ELLIPSOMETRIC PARAMETERS AND CALCULATED FILM THICKNESS

	Measurement			Calculation	
Sample	$Ip/Is > 1$	M	ψ (deg)	P	d(nm)
A	yes	$0.622 \sim 0.761$	$2.01 \sim 213$	$2.40 \sim 1.81$	$139 \sim 144$
B	no	0.940	114	0.58	74

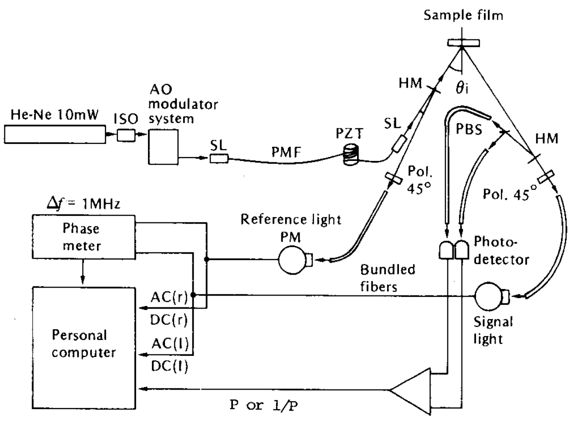


Fig. 12. Measurement system for all-fiber heterodyne ellipsometer. PMF: polarization maintaining fiber, HM: half mirror, PBS: polarization beam splitter.

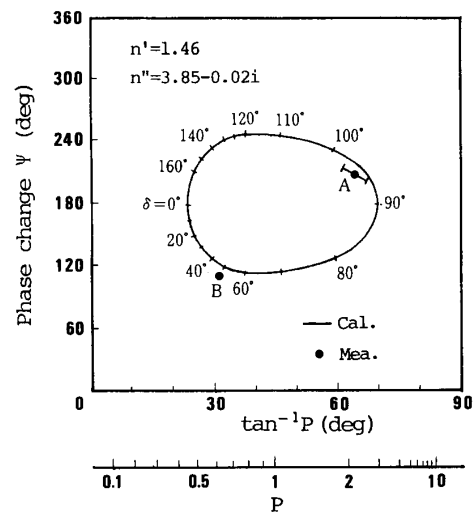


Fig. 13. Experimental and theoretical relationship between amplitude factor P and phase factor ψ of the ellipsometric parameter; δ represents the film phase shift. The solid line of sample A indicates the measurement error.

to a film thickness d between 139 and 144 nm for sample A and 74 nm for sample B, respectively, as shown in Table I.

Experimentally, both the amplitude P and phase ψ of ellipsometry parameter (28) are independently determined, but, theoretically, they are related to each other through (29) if the medium parameters, i.e., n', n'', θ and δ, are given. The theoretical relationship between ψ and $\tan^{-1} P$ (or P) is calculated as a parameter of the film phase shift (32), i.e., $\delta[\text{deg}] = (2\pi/\lambda)n'd \cos\theta' = 0.661d[\text{nm}]$, and the result is shown in Fig. 13 by the solid curve. The experimental points for both samples A and B are located close to the calculated curve, indicating a good accuracy of the present ellipsometer.

IV. Discussion and Conclusion

The single beam ac (optical beat) interferometric fiber sensors which can measure various quantities with high precision and high stability, have been developed. The key devices of the present sensors are the polarization maintaining fiber used as either a sensor itself or an optical lead and the dual-frequency dual-polarization laser source. The present sensing scheme detects the optical phase from the phase shift of the beat signal and the optical amplitude from the modulation depth of the beat signal. As a consequence, both the optical phase and amplitude can be measured independently of light power fluctuations.

The present sensing scheme is easy to construct because of being based on the single beam interferometry and is free from the phase instability due to fiber leads, unlike the usual fiber interferometer, because the sensing scheme is based on the differential phase detection using two fibers. The present sensing scheme can be applied to the measurement of various quantities such as temperature, force, strain, pressure, displacement, magnetic flux, electric field and voltage, film thickness as well as fiber gyroscope.

The measurement errors of the present sensing schemes primarily stem from the polarization crosstalk of the dual frequency components, possibly caused by 1) the misalignment of the polarization axes between the laser light and the polarization maintaining fiber, 2) the polarization cross-talk occurring in polarization maintaining fiber, 3) the initial polarization mixing involved in the laser source or AO modulators. The theoretical and experimental study [25] has shown that, among the possible causes, the first one is the most dominant but can be eliminated simply by suitably orienting the azimuth of the polarizer placed in front of the receiving bundle fiber. In the presence of general polarization mixing, however, additional factors, e.g., a factor proportional to $\cos(2\pi\Delta \text{f}t + \psi - \Gamma)$ appears in the beat signal of (36). In that case, even by the use of the differential phase detection scheme, the effect of fiber retardation Γ can't be fully eliminated; moreover the relationship between the phasemeter output and the sensor retardation ψ becomes nonlinear. The polarization mixing is ultimately limited by the crosstalk of polarization maintaining fiber, so that the development of low crosstalk polarization maintaining fiber is desired for the present fiber-optic sensing scheme.

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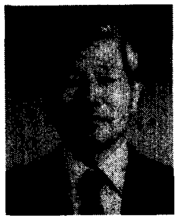

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Description: v. : ill. ; 28 cm. Vol. LT-1, no. 1 (Mar. 1983)-
Language: English
Standard No: **ISSN:** 0733-8724; **Other format's ISSN:** 1558-2213; **CODEN:** JLTEDG; **LCCN:** 83-645426 ; sn 82-5409
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Authors Authors and affiliations

Ti-ing Su, Likarn Wang

Fibre Optics and Integrated Optics Invited Paper
Received: 28 December 1995
Revised: 19 April 1996
Accepted: 22 April 1996

Abstract

A new cutback method based on the use of phase discrimination is proposed for low-linear-fibre-birefringence measurement. In this destructive method, a detection scheme for determining the phase difference between two readily obtained signals is used to give the phase retardation of the test fibre directly. The detection scheme mainly consists of two wave plates, two sections of fibre and an electro-optic modulator. The features of this measurement scheme are two-fold. First, the aforementioned phase difference between two detected signals, and, accordingly, linear fibre birefringence, can be determined in a simple manner, compared with the conventional cutback method. Second, the test fibre can be short in length despite the existence of fibre cladding modes. Experiments show that the proposed method can give a reliable measurement of linear fibre birefringence.

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Printed in the United States of America.

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NOVEL SIGNAL PROCESSING TECHNIQUES FOR ENHANCED OTDR SENSORS

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Abstract

This paper will describe techniques which should greatly reduce the signal averaging times required in conventional distributed Optical Time Domain Reflectometry (OTDR) sensor systems. The technique does not require coherent detection and spectral analysis as is currently used in FMCW or FMAMCW.

A digitally generated pseudo-random noise sequence is modulated on to a light source and transmitted down an optical fibre. The received backscattered signal is then correlated (multiplied) with a delayed version of the transmitted sequence to evaluate the amplitude of the backscattered signal at a given point along the fibre. The average transmitted and received signal power is therefore increased allowing reduced signal averaging times or reduced peak laser powers to be used compared with conventional OTDR systems.

Introduction

Optical fibres offer an ideal medium to produce distributed sensors because they can be used both as the transmission medium as well as the sensor. If their backscatter properties are modified by external measureands then Optical Time Domain Reflectometry techniques (OTDR) can be used to probe these changes at specific points along the fibre.

The detection of the backscattered signal, which is usually very small in magnitude, is often a problem due to the fact that sophisticated detection and time consuming signal averaging techniques are usually required. The use of high power lasers can reduce the amount of signal averaging, however such lasers are usually bulky and very expensive. The development of commercial sensors has therefore been limited by the speed of response of the sensor and the cost of the signal processing circuits required to obtain the result. This paper describes techniques which should reduce this problem.

Time Domain Reflectometry

At present, to measure the spatial properties of the backscatter, Optical Time Domain Reflectometry techniques are used. In these techniques an optical pulse is launched into the fibre and a photodetector, amplifier and sampling gate combination are used to measure the backscatter. The time delay between the transmitted pulse and the sampling gate being fired, defines the slot in the fibre over which the backscatter is measured.

The launched pulse width and sampling aperture define the spatial resolution. The signal is then averaged to improve the signal to noise ratio. The maximum sampling rate is however fixed by the length of the fibre to ensure results free from ambiguity. Thus the backscatter from only one pulse should be sampled. The maximum repetition rate is therefore:

$$rep(max) = 1/2cL$$

where c is the speed of light in the fibre
and L is the length of the fibre.

NB this assumes that multiple reflections from the fibre ends are negligible.

Signal averaging will improve the S/N ratio by a ratio of the square root of the repetition rate. This is because the noise current in the photodetector or the ensuing load amplifier combination is usually proportional to the square root of the bandwidth whereas the signal current is proportional to the optical signal power. Every time the signal is sampled and averaged the rms value of the noise current reduces by $\sqrt{2}$ and the signal remains unaltered. If the signal is integrated the signal component doubles and the noise increases by $\sqrt{2}$.

One way of improving the S/N ratio for a given length of fibre and given resolution using OTDR is to increase the peak power in each pulse.

FMCW can also be used, however, spectral analysis is required in the receiver following the detector. The light source furthermore needs to have a narrow spectral width for good spatial resolution and the linearity of the frequency-swept source is very important. FMAMCW can also be used however this suffers from similar problems to FMCW.

A more satisfactory way of improving the S/N ratio is to increase the number of bits transmitted and hence received without causing ambiguity, thus allowing more effective time integration.

The average transmitted, and hence received, power in the time interval would therefore be increased.

Pseudo-random Noise Modulation

To increase the number of bits transmitted and received a pseudo-random bit sequence is modulated onto the light source. This modulated beam is transmitted down an optical fibre and the backscatted signal is detected using a photo-detector.

Spatial information is obtained by multiplying the detected backscattered signal with a delayed version of the pseudo-random bit sequence, the delay being implemented digitally. By scanning the delay the backscatter from different points can be measured.

Pseudo-random noise sequences are digitally generated binary sequencies which have noise-like properties. For example a pseudo-random binary sequence could be used to mimic tossing a coin many times. The sequences can be arranged to be of any length and they require very few components to electrically implement, even for long sequences. For example a sequence which repeats every 32,767 bits can be generated with 15 shift registers and a feedback network composed of an exclusive-or gate.

If one uses a maximal-length sequence it is possible to produce a sequence with specific auto-correlation properties. These sequences are of length $m = 2^n - 1$ and have $2^{(n-1)}$ ones and $2^{(n-1)} -1$ zeros. The autocorrelation function is shown in Fig.1.

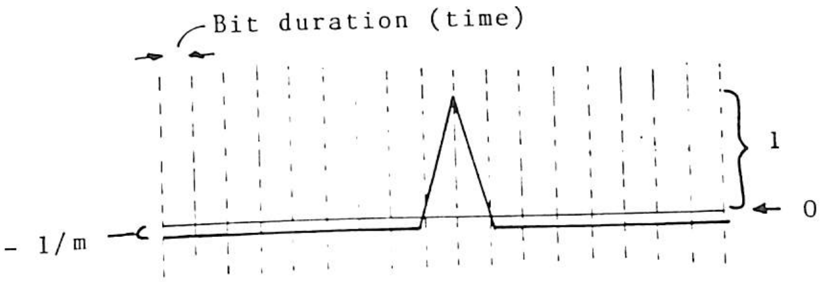


FIGURE 1. AUTO-CORRELATION FUNCTION OF MAXIMAL LENGTH PSEUDO-RANDOM NOISE SEQUENCE

The peak occurs when the delay between the transmitted and received sequence is zero. If this peak is normalised to unity then the correlation between the two pseudo-random sequences when the delay is not zero is constant at -1/m where m is the number of bits before the sequence repeats. This assumes that the integration is performed over one complete sequence of length m.

For the same peak transmitted power, the average power transmitted and received using pseudo-random bit sequences can now be increased to approximately half the peak power transmitted in the OTDR case as the laser is on for half the time. This allows more effective use of signal averaging.

The sampling rate is now therefore increased to the bit rate which is now 1/(bit duration). This allows a S/N improvement γ over conventional OTDR of approximately:

$\gamma = \sqrt{((\text{PRBS Bit rate})/(\text{sampling rate of conventional OTDR}))}$.

The exact improvement in the S/N ratio is dependent on the correlation between the bandwidth limited photo-detector noise and the bandwidth limited pseudo-random bit sequence as well as the detector integration and averaging times. By using Pseudo random bit sequences the sequence repeat time is equivalent to the rep(max) of the OTDR case and the bit length is equivalent to the sampling aperture. The bit length therefore defines the spatial resolution.

This technique can be thought of in terms of sampling in that the ambiguity due to the increase in sampling rate is removed by arranging for the unwanted sampled terms to average out to (approximately) zero by designing the pseudo-random bit sequences to have specific autocorrelation properties.

Experimental Results

An experimental PRBS OTDR system has been built and the block diagram is shown in Fig.2.

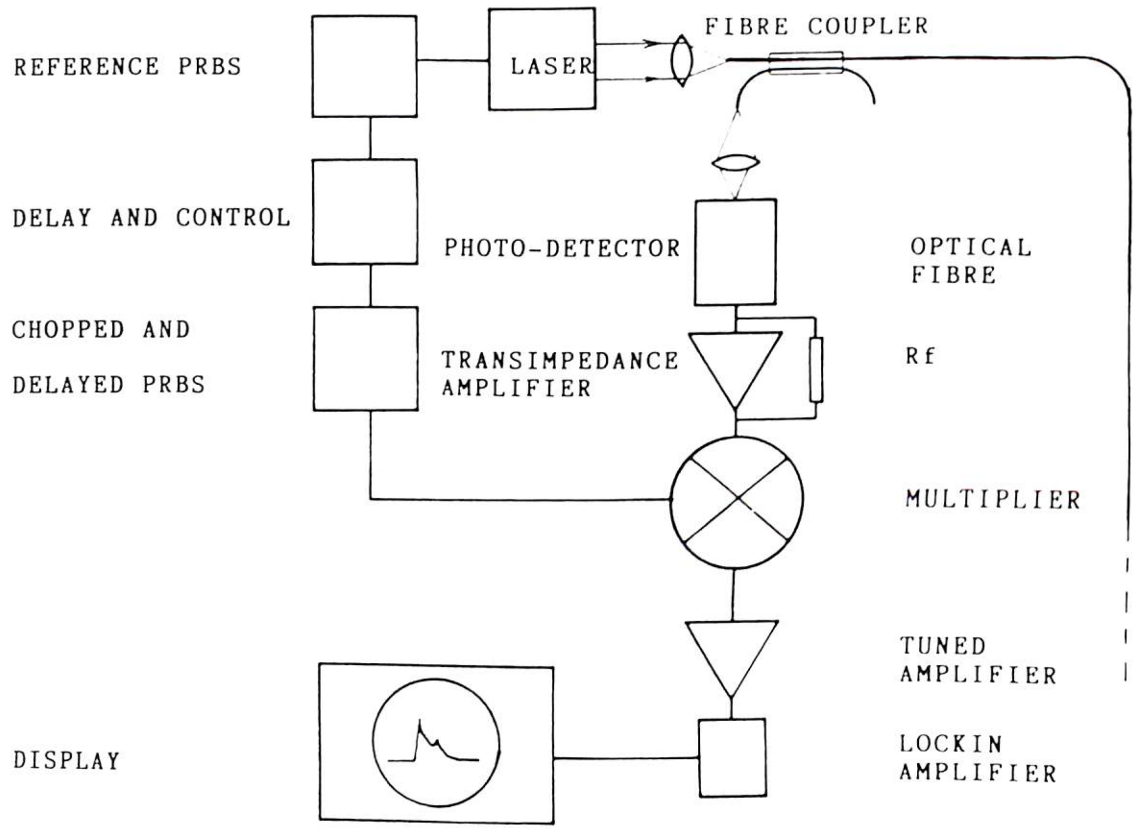


FIGURE 2 PRBS OPTICAL TIME DOMAIN REFLECTOMETER

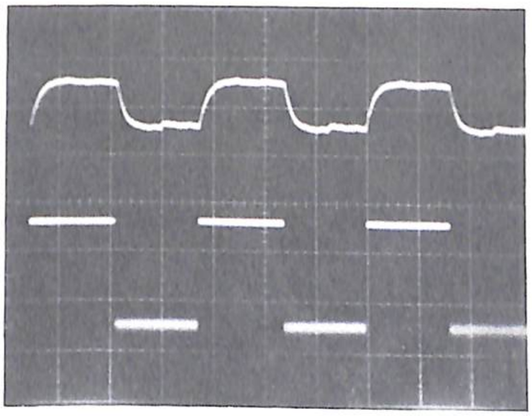
Two digital pseudo-random generators were built using D type edge triggered flip flops and an exclusive-or feedback gate. The output of the reference PRBS generator was amplitude modulated onto a1.3u laser using a high speed laser driver. The laser output was coupled into an optical fibre via a lens and fibre coupler arrangement. The backscattered signal from the fibre was then coupled into a InGaAs transimpedance detector and amplifier with Rf=10Kohms. The electrical output was further amplified and buffered and applied to the RF port of a Schottky barrier double-balanced mixer.

The other PRBS generator was delayed using progammable counter circuits and the signal applied to the LO port of the double-balanced mixer. The delay was loaded into the counters using a small micro-computer.

The delay between the two generators was scanned under computer control and a spatial picture of the fibre properties built up.

It should be noted that the correlated signal (the output of the IF port of the mixer) is a very small DC voltage which is very difficult to measure accurately. This problem is overcome by chopping the signal either optically or electrically. In the system described here the output of the delayed PRBS generator is chopped between a delay where there is never a correlation to the required point to be measured within the fibre. The chopping frequency is arranged to synchronise with the sequence repeat time. This then produces an AC signal with a period of two sequence repeat times. This AC signal is then amplified and detected in a lockin amplifier. This form of electrical chopping also ensures that the drive levels to the mixer do not change. It should be noted that care needs to be taken with the mode of coupling the signals into the laser and the mixer as the spectral components of the PRBS are very broadband.

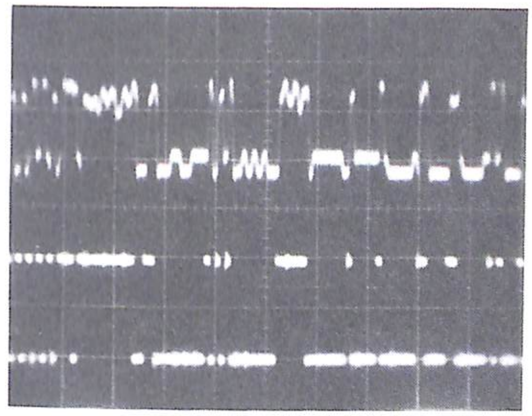
When the delay is set to observe the reflection from the end face of 1 Km of fibre the waveforms into and out of the correlator are shown in figure 3. a and b. The signal also contains a small reflection from the end face of the other coupler arm which is added to the main signal.



Upper = received signal

Lower = reference signal

A) 2 Volts/div 1ms/div



Upper = received signal

Lower = reference signal

B) upper 50mv/div, lower 0.2 Volts/div 1us/div

FIGURE 3 ELECTRICAL WAVEFORMS A) Into Correlator B) Out of correlator

The correlated waveform can be written in the form:

$$F(\tau) = \int_{-m/2}^{+m/2} f(t-\tau) * \left[f_1(t-\tau_1)+\dots + f_x(t-\tau)+\dots + f_n(t-\tau_n)\right] dt$$

where $F(\tau)$ is the output

$f(t-\tau)$ is the delayed reference PRBS

and the remaining terms are backscattered signal.

As the optical backscatter from the fibre is distributed all along the fibre then the wanted term $F_x(t-\tau)$ will be multiplied by unity and each bit not on the peak of the correlation will be effectively multiplied by $-1/m$. All the unwanted bits of backscatter will be summed together causing a large component of signal which could be similar in value to the wanted signal. This large unwanted component can be reduced by arranging for the repeat time of the pseudo-random sequence to be considerably longer than the round trip time of the fibre and also by using the chopping technique described earlier.

This system has been used to measure the discontinuities along a fibre Figure 4 and it shows the end face reflections from the unconnected arm of the coupler and the end face reflection from 1 Km of fibre. When the gain was increased to measure the backscatter along the fibre it was found that the electrical auto-correlation of the two sequences was not flat when the delay was varied. This problem is believed to be due to the fact that the correlation is performed in a linear mixer, however the signals are generated digitally and may therefore contain other switching waveforms due to unwanted coupling between circuits. Furthermore if there is pulse width modulation due to charge storage effects in the switching transistors this could modify the auto-correlation function. Bandwidth limiting of the sequence will also produce sinx/x ripples close to the peak of the auto-correlation function. Techniques to cure these problems are currently being investigated.

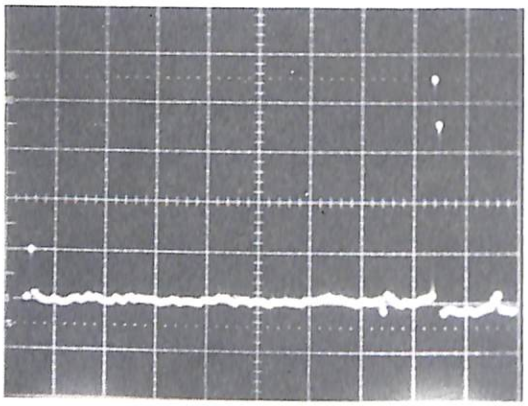


figure 4 PRBS-OTDR SHOWING REFLECTIONS SEPARATED BY 1 Km.

Sensor Applications

When improved, this type of system can be used to enhance any form of OTDR system currently available by reducing the signal averaging time or reducing the optical power. It could reduce the cost of the detectors and could allow the use of other light sources such as LEDs. It can therefore be used to measure any external parameter on which the backscatter is dependent.

Improvements

At present the backscatter is obtained by scanning the delay. Multiple correlators could be used to constantly monitor the signals from each point in the fibre. This could give a further improvement in the signal averaging time. It would also be possible to perform the signal processing completely digitally if high speed components can be built.

The system could also be used in coherent detection systems where other forms of modulation (PSK or FSK) could be used.

Conclusions

A technique has been demonstrated which should improve the signal averaging times and circuit complexity of distributed fibre sensors. Initial results have shown that the system is capable of measuring discontinuities along fibres and it is hoped to demonstrate backscatter and sensor measurements very soon.

Acknowledgements

I would like to thank Mr. A. Baghoomian for building some of the electronic circuits. I would also like to thank the UK Science and Engineering Research Council for supporting this work. I would like to thank Dr. D. Renner and Dr. R. Murison and STC for supplying the lasers.

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Novel Signal Processing Techniques For Enhanced OTDR Sensors

J. K.A. Everard;

Author Affiliations +

Proceedings Volume 0798, Fiber Optic Sensors II; (1987); doi: 10.1117/12.941083
Event: Fourth International Symposium on Optical and Optoelectronic Applied Sciences and Engineering, 1987, The Hague, Netherlands

Abstract

This paper will describe techniques which should greatly reduce the signal averaging times required in conventional distributed Optical Time Domain Reflectometry (OTDR) sensor systems. The technique does not require coherent detection and spectral analysis as is currently used in FMCW or FMAMCW. A digitally generated pseudo-random noise sequence is modulated on to a light source and transmitted down an optical fibre. The received backscattered signal is then correlated (multiplied) with a delayed version of the transmitted sequence to evaluate the amplitude of the backscattered signal at a given point along the fibre. The average transmitted and received signal power is therefore increased allowing reduced signal averaging times or reduced peak laser powers to be used compared with conventional OTDR systems.

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Publication: Bellingham, Wash., USA : SPIE,
Year: 1987
Description: viii, 398 pages : illustrations ; 28 cm.
Language: English
Series: Proceedings / SPIE ;; v. 798; **Variation:** Proceedings of SPIE--the International Society for Optical Engineering ;; v. 798.
Standard No: **ISBN:** 0892528338 ((pbk.)); 9780892528332 ((pbk.)) **LCCN:** 87-61548

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Title: Electronics Letters

Volume: 10

Issue: 2

Date: 1974

Author: Davies DE, Kingsley S

Article Title: Method of phase-modulating signals in optical fibres: application to optical-telemetry systems

Pages: 21-2? P. 21-22

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state of the cycle counter. When the current state of the cycle counter reaches the highest b.c.d. number for the given temperature segment, the reset logic generates a trigger pulse that triggers the m.m.v. The segment decoder has a separate connection with the m.m.v. that triggers the first reset pulse at 120°C, i.e. that starts the first counting cycle of the cycle counter. The specific realisation of the segment decoder and reset logic depends on the thermocouple type used and the permitted error.

The digital lineariser with cycle counter described here can be also used for the linearisation of the outputs of other nonlinear sensors used for the measurement of pressure, flow, humidity etc.

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19th December 1973

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METHOD OF PHASE-MODULATING SIGNALS IN OPTICAL FIBRES: APPLICATION TO OPTICAL-TELEMETRY SYSTEMS

Indexing terms: Fibre optics, Optical communication, Optical modulation, Phase modulation, Piezoelectric transducers, Telemetering systems

By attaching a piezoelectric transducer that modulates the mechanical tension over a short section of fibre, signals in optical fibres are phase modulated. The technique is applicable to a 1-way optical-telemetry system.

Introduction: A method for phase-modulating optical signals in single-mode or multimode optical fibres by dynamic mechanical stressing of the fibre is described. This offers the potential of attaching modulators at various points along a fibre, which can impress phase modulation on the optical carrier within the waveguide without the need to break and join the fibre. If an optical fibre is subjected to longitudinal mechanical tension, there will be three principal effects leading to a change in the phase of the optical carrier, as follows:

(*a*) change of length (strain)

(*b*) change of diameter (Poisson)

(*c*) change of refractive index (photoelastic).

Calculated values for phase retardation due to strain, Poisson and photoelastic effects are shown in Fig. 1. A typical value of $p = 0{\cdot}2$ is assumed, where p is the photoelastic coefficient p_{12}. It can be seen that the change of length predominates. For a multimode fibre, there would also be some 2nd-order effects representing changes of amplitude due to changes in the mode pattern.

Analysis of these three effects indicates that we may neglect the change in diameter of the fibre, as its effect on the optical phase is only 0·2% of the contribution due to longitudinal strain. The relationship between the phase retardation δ and the strain σ/E is

$$\delta = \frac{2\pi L n}{\lambda}(1 - n^2 p/2)\frac{\sigma}{E} \qquad (1)$$

where L is the interaction length, n is the refractive index of core, λ is the free-space optical wavelength, σ is the stress (tensile stress considered as positive) and E is Young's modulus. Eqn. 1 should be a good approximation for both single-mode and low-moded multimode propagation.

Experimental modulator: Fig. 2A shows a diagram of an experimental modulator/demodulator optical-interferometer system based on the above principle. The output of a 0·5 mW helium–neon laser is passed through a polarising beamsplitter, and one of the beams, the signal beam at frequency f_0, is frequency-shifted by f_b, using a Bragg cell. In these experiments, f_b was 23·3 MHz. The signal beam at $f_0 - f_b$ is then launched into a short length of single or multimode fibre. The fibre is wound once round a hollow PZT (lead–zirconate–titanate) ceramic cylinder, and is held under tension. The

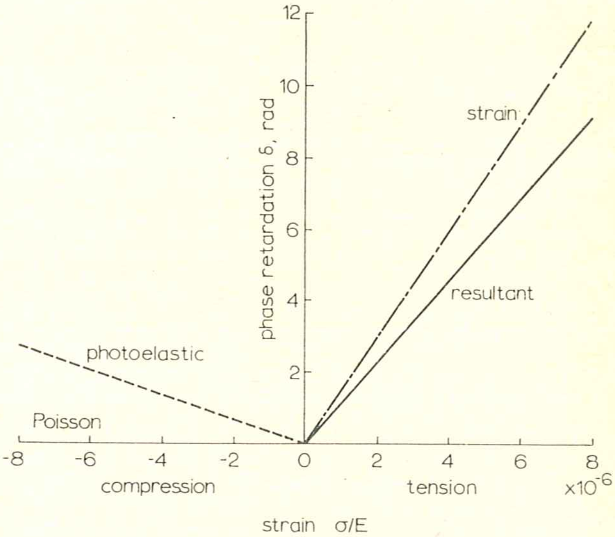

Fig. 1 *Theoretical phase retardation as function of strain*

HE_{11} mode, single-mode fibre
Interaction length = 0·1 m
Refracture index of core = 1·5207
Refractive index of cladding = 1·4995
Core diameter = 1·6 μm
Wavelength = 0·6328 μm
Normalised frequency = 2·01
Breaking strain ≃ 10^{-2}

output from the fibre heterodynes with the reference beam (frequency f_0) on the photodetector to produce a difference i.f. signal at f_b. The $\lambda/2$ plate rotates the plane of polarisation of the reference beam for optimum photomixing. Conventional f.m.-receiver techniques are used for detection. By applying an alternating voltage between the inner and outer

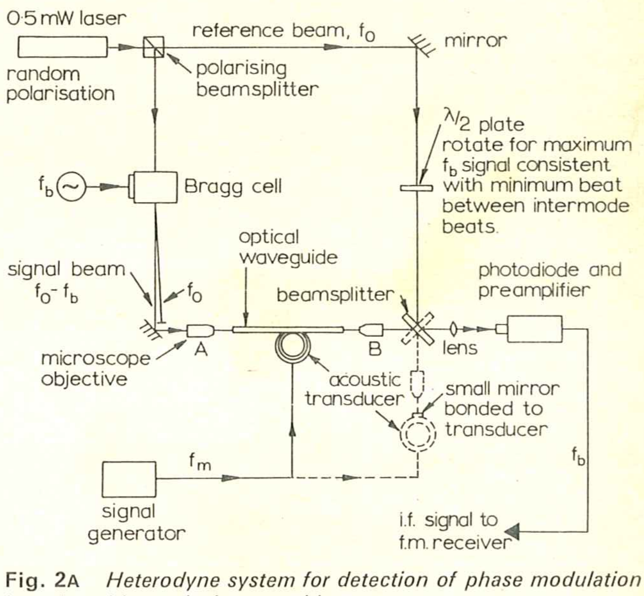

Fig. 2A *Heterodyne system for detection of phase modulation introduced by optical waveguide*

Broken outline shows position of optical components and acoustic transducer for laser-probe measurements of radial displacement. The two microscope objectives and the fibre are removed from arm AB of the interferometer for these measurements

surfaces of the transducers, the cylinder diameter, and hence the tension in the fibre wrapped around the transducer, is modulated at the frequency f_m.

To check the validity of eqn. 1, measurements were made of the radial displacement of the transducer by a laser probe. The laser probe was essentially the same as used for the measurements on the fibre phase modulator, the differences being shown in dotted form in Fig. 2A. The form of the phase-modulated spectrum may be observed on the spectrum analyser, and measurements made of the phase deviation obtained either from the zeros of the Bessel sideband frequencies for large deviations, or from the calibrated f.m. discriminator. Measurements have been made on two different transducer modulators. Fig. 2B shows the measured and theoretical phase deviation produced by these transducers for a single turn of multimode fibre having a core refractive index of 1·518 and a diameter of 16·5 μm with a cladding refractive index of 1·503 and a diameter of 46 μm. The full lines give the phase deviation produced by the optical-fibre phase modulator, and the broken lines give the phase deviation predicted from eqn. 1 by the laser-probe measurements of transducer displacement. Considering the uncertainty in p (a value of 0·2 being assumed for the theoretical line), these results are in good agreement.

It can be seen that even this very simple form of modulator, working away from resonance, can produce substantial linear phase deviations for a single turn of fibre. Such phase deviations can be increased dramatically to over 20 rad/turn

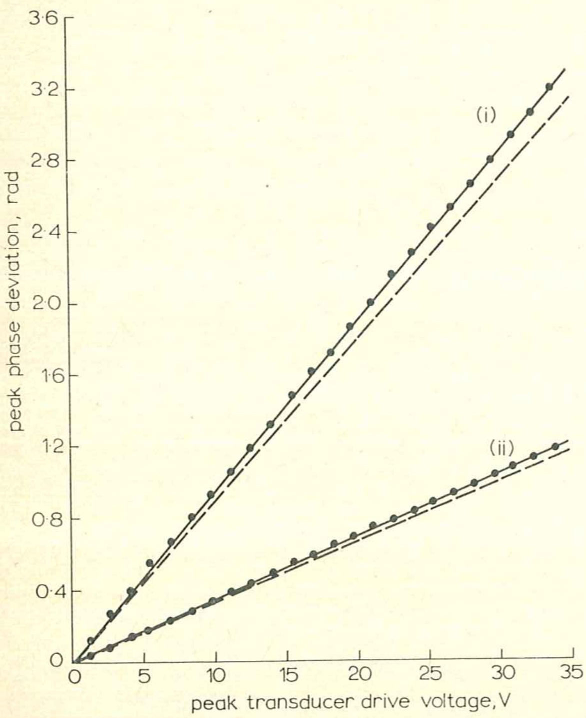

Fig. 2B *Relationship between phase deviation and drive voltage*

——— measured phase deviation at 2 kHz
— — — theoretical phase deviation based on measurements of transducer displacement at 2 kHz by laser probe
(*i*) First transducer:
3·81 cm diameter; 3·81 cm length; 3·81 mm wall thickness; PZT–5H cylinder
Strain in fibre = $2 \cdot 2 \times 10^{-6}$ at 35 V drive
(*ii*) Second transducer:
2·54 cm diameter; 2·54 cm length; 3·81 mm length; PZT-5A cylinder
Strain in fibre = $1 \cdot 3 \times 10^{-6}$ at 35 V drive

of fibre, if the transducer is driven at resonance, which, for the 2·54 cm cylinder, was at 38·6 kHz. The system has been demonstrated with both single-mode and multimode fibres, although the heterodyning efficiency is reduced as the number of modes increases. The particular virtue of using phase modulation for this application is that the total imposed phase shift is the linear summation of the phase shifts imposed on each modulator, so that superposition applies from the modulator input to the discriminator output. This has been demonstrated experimentally using several modulators operating at different frequencies.

Optical-telemetry system: It is evident that a series of transducers could be located at various positions along an optical fibre, and could impress modulation on the optical carrier at different frequencies, thus forming a 1-way telemetry link. It would also enable modulators to be added at any convenient location along the fibre, without having to break or join the fibre. The signals may be demodulated by first employing a reference beam, as in the experimental system, or a second laser (with a.f.c.) used as a local oscillator. The i.f. signal may be then fed to a frequency discriminator prior to filtering the different modulation frequencies. The maximum bandwidth of each channel is set by the corresponding bandwidth of the transducer and fibre interaction-length effects. The number of available channels will be determined by the range of subcarrier frequencies suitable for various designs of transducers (up to about 5 MHz for the types of transducers studied). There is obviously substantial scope for investigating a wide range of different types of modulating transducer. Such an optical-telemetry system system clearly offers many attractive features where the light-weight and interference-free properties of optical links are appropriate.

Acknowledgments: The authors wish to thank Prof. E. A. Ash for valuable comments and the UK Science Research Council for financial support for the project.

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27th December 1973

Reference

1 EBERHARDT, F. J., and ANDREWS, F. A.: 'Laser heterodyne system for measurement and analysis of vibration', *J. Acoust. Soc. Am.*, 1970, **48**, pp. 603–609

PHASE SHIFTER WITH HIGH AMPLITUDE ACCURACY

Indexing term: Phase shifters

A phase shifter for the audio and subaudio range has been built that keeps the amplitude deviation within ±0·4%. The phase angle can be varied between 0 and approximately 180°, with infinite resolution.

In setting up calibration equipment for a highly sensitive search-coil magnetometer, the need arose for a phase shifter in the range of 5 to 5000 Hz that would allow a phase-angle variation from 0 to about 180°, without changing the amplitude of the output voltage. Simple circuits, as in Fig. 1, are well known. The calculation of the input-voltage/output-voltage ratio yields

$$\frac{V_{out}}{V_{in}} = \frac{g_m R_1}{1+g_m R_1} \frac{1-\frac{R_2}{R_1} j\omega C R_3}{1+j\omega C R_3} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where g_m is the transconductance of the transistor. If $R_1 = R_2$, and g_m is sufficiently large,

$$\frac{g_m R_1}{1+g_m R_1} = 1$$

Eqn. 1 shows the transfer function of an allpass filter. In practice, a circuit of this type will not have the required amplitude accuracy. Better results on the same principle can be obtained by the use of an operational amplifier (Fig. 2A). For the ideal case:

open-loop gain $G_0 = \infty$

source resistance $R_s = 0$

load resistance $R_L = \infty$

calibration $R_1 = R_2$

the output-voltage/input-voltage ratio again gives the allpass relation

$$\frac{V_{out}}{V_{in}} = \frac{1-j\omega C R_3}{1+j\omega C R_3}$$

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THE INSTITUTION OF ELECTRICAL ENGINEERS, Savoy Place, London WC2R 0BL
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Additional title:	Electron. lett. Electronics letters IEE electronics letters <Aug. 2006>-Dec. 2006 IET electronics letters Jan. 2007-
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Physical format:	v. : ill. ; 30 cm.
Notes:	Published: Institution of Engineering and Technology, 2007- Description based on: Vol. 42, no. 17 (Aug. 17th, 2006). Latest issue consulted: Vol. 43, no. 1 (Jan. 4th, 2007). V. 25 includes a special issue. Available in microfiche. Vols. 1-7, 1965-71. 1 v.
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Document details

Electronics Letters
Volume 10, Issue 2, 24 January 1974, Pages 21-22

Method of phase-modulating signals in optical fibres: Application to optical-telemetry systems (Article)

Davies, D.E.N., Kingsley, S.

Department of Electronic & Electrical Engineering, University College London, Torrington Place, London WC1E 7JE, United Kingdom

Abstract

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By attaching a piezoelectric transducer that modulates the mechanical tension over a short section of fibre, signals in optical fibres are phase modulated. The technique is applicable to a 1-way optical-telemetry system. © 1974, The Institution of Electrical Engineers. All rights reserved.

Author keywords

Fibre optics | Optical communication | Optical modulation | Phase modulation. Piezoelectric transducers | Telemetering systems

Indexed keywords

Engineering controlled terms: PHASE MODULATION | TELEMETERING SYSTEMS

Engineering main heading: FIBER OPTICS

ISSN: 00135194
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Original language: English

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LASER HETERODYNE SYSTEM FOR MEASUREMENT AND ANALYSIS OF VIBRATION
(1970) *Journal of the Acoustical Society of America*, 48 (3 pt 1), pp. 603-609. Cited 71 times.
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Abdulhalim, I. , Gannot, I. , Pannell, C.N.
(2006) Progress in Biomedical Optics and Imaging - Proceedings of SPIE

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Ueha, S. , Shiota, K. , Okada, T.
(1974) Optics Communications

Interferometry for Underwater Vibrational Measurements
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state of the cycle counter. When the current state of the cycle counter reaches the highest b.c.d. number for the given temperature segment, the reset logic generates a trigger pulse that triggers the m.m.v. The segment decoder has a separate connection with the m.m.v. that triggers the first reset pulse at 120°C, i.e. that starts the first counting cycle of the cycle counter. The specific realisation of the segment decoder and reset logic depends on the thermocouple type used and the permitted error.

The digital lineariser with cycle counter described here can be also used for the linearisation of the outputs of other nonlinear sensors used for the measurement of pressure, flow, humidity etc.

DRAGAN PANTIĆ

19th December 1973

Elektronska Industrija
Division Pionir
Bulevar Revolucije 403
11000 Beograd, Yugoslavia

Reference

1 ZARCADES, P., and HAAS P.: 'Digital thermometry', *Instrum. & Control Syst.*, 1969, p. 102

METHOD OF PHASE-MODULATING SIGNALS IN OPTICAL FIBRES: APPLICATION TO OPTICAL-TELEMETRY SYSTEMS

Indexing terms: Fibre optics, Optical communication, Optical modulation, Phase modulation, Piezoelectric transducers, Telemetering systems

By attaching a piezoelectric transducer that modulates the mechanical tension over a short section of fibre, signals in optical fibres are phase modulated. The technique is applicable to a 1-way optical-telemetry system.

Introduction: A method for phase-modulating optical signals in single-mode or multimode optical fibres by dynamic mechanical stressing of the fibre is described. This offers the potential of attaching modulators at various points along a fibre, which can impress phase modulation on the optical carrier within the waveguide without the need to break and join the fibre. If an optical fibre is subjected to longitudinal mechanical tension, there will be three principal effects leading to a change in the phase of the optical carrier, as follows:

(*a*) change of length (strain)

(*b*) change of diameter (Poisson)

(*c*) change of refractive index (photoelastic).

Calculated values for phase retardation due to strain, Poisson and photoelastic effects are shown in Fig. 1. A typical value of $p = 0{\cdot}2$ is assumed, where p is the photoelastic coefficient p_{12}. It can be seen that the change of length predominates. For a multimode fibre, there would also be some 2nd-order effects representing changes of amplitude due to changes in the mode pattern.

Analysis of these three effects indicates that we may neglect the change in diameter of the fibre, as its effect on the optical phase is only 0·2% of the contribution due to longitudinal strain. The relationship between the phase retardation δ and the strain σ/E is

$$\delta = \frac{2\pi L n}{\lambda}(1 - n^2 p/2)\frac{\sigma}{E} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where L is the interaction length, n is the refractive index of core, λ is the free-space optical wavelength, σ is the stress (tensile stress considered as positive) and E is Young's modulus. Eqn. 1 should be a good approximation for both single-mode and low-moded multimode propagation.

Experimental modulator: Fig. 2A shows a diagram of an experimental modulator/demodulator optical-interferometer system based on the above principle. The output of a 0·5 mW helium–neon laser is passed through a polarising beamsplitter, and one of the beams, the signal beam at frequency f_0, is frequency-shifted by f_b, using a Bragg cell. In these experiments, f_b was 23·3 MHz. The signal beam at $f_0 - f_b$ is then launched into a short length of single or multimode fibre. The fibre is wound once round a hollow PZT (lead–zirconate–titanate) ceramic cylinder, and is held under tension. The

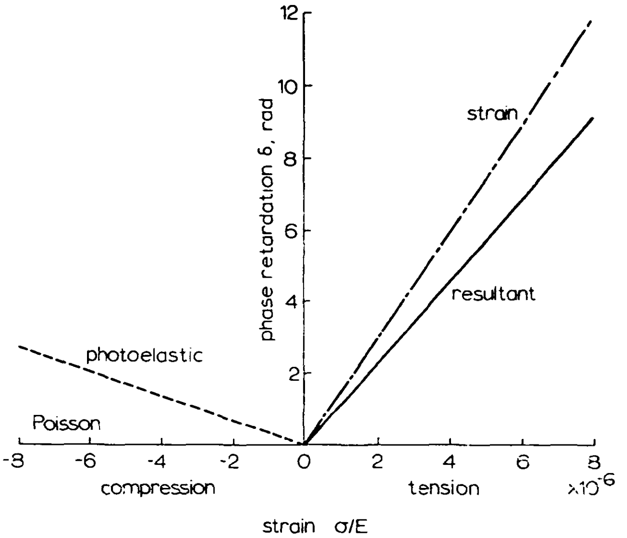

Fig. 1 *Theoretical phase retardation as function of strain*

HE_{11} mode, single-mode fibre
Interaction length = 0·1 m
Refracture index of core = 1·5207
Refractive index of cladding = 1·4995
Core diameter = 1·6 μm
Wavelength = 0·6328 μm
Normalised frequency = 2·01
Breaking strain ≃ 10^{-2}

output from the fibre heterodynes with the reference beam (frequency f_0) on the photodetector to produce a difference i.f. signal at f_b. The $\lambda/2$ plate rotates the plane of polarisation of the reference beam for optimum photomixing. Conventional f.m.-receiver techniques are used for detection. By applying an alternating voltage between the inner and outer

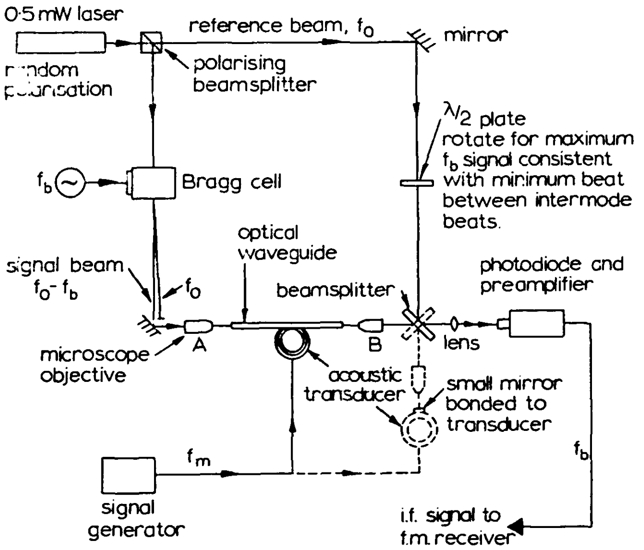

Fig. 2A *Heterodyne system for detection of phase modulation introduced by optical waveguide*

Broken outline shows position of optical components and acoustic transducer for laser-probe measurements of radial displacement. The two microscope objectives and the fibre are removed from arm AB of the interferometer for these measurements

surfaces of the transducers, the cylinder diameter, and hence the tension in the fibre wrapped around the transducer, is modulated at the frequency f_m.

To check the validity of eqn. 1, measurements were made of the radial displacement of the transducer by a laser probe. The laser probe was essentially the same as used for the measurements on the fibre phase modulator, the differences being shown in dotted form in Fig. 2A. The form of the phase-modulated spectrum may be observed on the spectrum analyser, and measurements made of the phase deviation obtained either from the zeros of the Bessel sideband frequencies for large deviations, or from the calibrated f.m. discriminator. Measurements have been made on two different transducer modulators. Fig. 2B shows the measured and theoretical phase deviation produced by these transducers for a single turn of multimode fibre having a core refractive index of 1·518 and a diameter of 16·5 μm with a cladding refractive index of 1·503 and a diameter of 46 μm. The full lines give the phase deviation produced by the optical-fibre phase modulator, and the broken lines give the phase deviation predicted from eqn. 1 by the laser-probe measurements of transducer displacement. Considering the uncertainty in p (a value of 0·2 being assumed for the theoretical line), these results are in good agreement.

It can be seen that even this very simple form of modulator, working away from resonance, can produce substantial linear phase deviations for a single turn of fibre. Such phase deviations can be increased dramatically to over 20 rad/turn

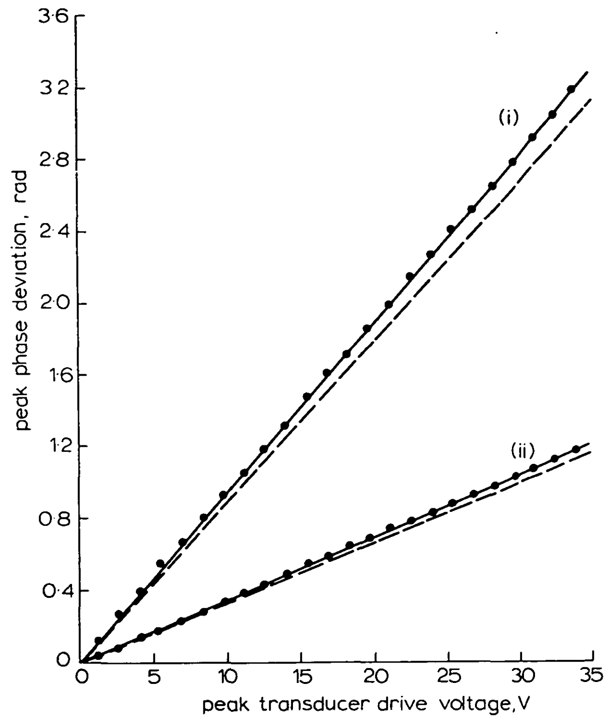

Fig. 2B *Relationship between phase deviation and drive voltage*

——— measured phase deviation at 2 kHz
— — — theoretical phase deviation based on measurements of transducer displacement at 2 kHz by laser probe
(*i*) First transducer:
3·81 cm diameter; 3·81 cm length; 3·81 mm wall thickness; PZT-5H cylinder
Strain in fibre = $2 \cdot 2 \times 10^{-6}$ at 35 V drive
(*ii*) Second transducer:
2·54 cm diameter; 2·54 cm length; 3·81 mm length; PZT-5A cylinder
Strain in fibre = $1 \cdot 3 \times 10^{-6}$ at 35 V drive

of fibre, if the transducer is driven at resonance, which, for the 2·54 cm cylinder, was at 38·6 kHz. The system has been demonstrated with both single-mode and multimode fibres, although the heterodyning efficiency is reduced as the number of modes increases. The particular virtue of using phase modulation for this application is that the total imposed phase shift is the linear summation of the phase shifts imposed on each modulator, so that superposition applies from the modulator input to the discriminator output. This has been demonstrated experimentally using several modulators operating at different frequencies.

Optical-telemetry system: It is evident that a series of transducers could be located at various positions along an optical fibre, and could impress modulation on the optical carrier at different frequencies, thus forming a 1-way telemetry link. It would also enable modulators to be added at any convenient location along the fibre, without having to break or join the fibre. The signals may be demodulated by first employing a reference beam, as in the experimental system, or a second laser (with a.f.c.) used as a local oscillator. The i.f. signal may be then fed to a frequency discriminator prior to filtering the different modulation frequencies. The maximum bandwidth of each channel is set by the corresponding bandwidth of the transducer and fibre interaction-length effects. The number of available channels will be determined by the range of subcarrier frequencies suitable for various designs of transducers (up to about 5 MHz for the types of transducers studied). There is obviously substantial scope for investigating a wide range of different types of modulating transducer. Such an optical-telemetry system system clearly offers many attractive features where the light-weight and interference-free properties of optical links are appropriate.

Acknowledgments: The authors wish to thank Prof. E. A. Ash for valuable comments and the UK Science Research Council for financial support for the project.

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where g_m is the transconductance of the transistor. If $R_1 = R_2$, and g_m is sufficiently large,

$$\frac{g_m R_1}{1+g_m R_1} = 1$$

Eqn. 1 shows the transfer function of an allpass filter. In practice, a circuit of this type will not have the required amplitude accuracy. Better results on the same principle can be obtained by the use of an operational amplifier (Fig. 2A). For the ideal case:

open-loop gain $G_0 = \infty$

source resistance $R_s = 0$

load resistance $R_L = \infty$

calibration $R_1 = R_2$

the output-voltage/input-voltage ratio again gives the allpass relation

$$\frac{V_{out}}{V_{in}} = \frac{1-j\omega C R_3}{1+j\omega C R_3}$$

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3	Single fiber interferometric acoustic sensor	Bucaro, J.A., Carome, E.F.	1978	Applied Optics	35
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7	Fiber optic hydrophone: Improved strain configuration and environmental noise protection	Cielo, P.G.	1979	Applied Optics 18 (17), pp. 2933-2937	49 Cited by
8	Fiber optic sensors	Hughes, R., Priest, R.	1980	Applied Optics	21
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12	Preliminary experiment for optical heterodyne communication with a single-mode optical fiber by using frequency-stabilized He-Ne lasers	Nakazawa, M., Kamimura, J.-I., Musha, T.	1981	Optics Letters 6 (10), pp. 508-510	1 Cited by
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16	Review of fiber optic gyroscopes	Lefevre, H.C., Bourbin, Y., Graindorge, P., Arditty, H.J.	1983	Proceedings of SPIE - The International Society for Optical Engineering	4
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Vibration-induced modulation of fiberguide transmission (Article)

Nelson, D.F., Kleinman, D.A., Wecht, K.W.
Bell Laboratories, Murray Hill, NJ 07974

Abstract

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Linear intensity modulation of several percent in fiberguide transmission caused by flexural vibrations has been observed in bent fiberguides and attributed to modulated bending loss. Measurements of bending loss are presented which support this interpretation.

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SPIE Volume 798

Fiber Optic Sensors II

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31 March - 3 April 1987
The Hague, The Netherlands

Published by
SPIE—The International Society for Optical Engineering
P.O. Box 10, Bellingham, Washington 98227-0010 USA
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Please use the following format to cite material from this book:
Author(s), "Title of Paper," *Fiber Optic Sensors II,* A. M. Scheggi, Editor, Proc. SPIE 798, page numbers (1987).

Library of Congress Catalog Card No. 87-61548
ISBN 0-89252-833-8

Printed in the United States of America.

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