100-GHz-Resolution Dynamic Holographic Channel Management for WDM

A. D. Cohen, M. C. Parker, *Associate Member, IEEE,* and R. J. Mears, *Associate Member, IEEE*

***Abstract*— We present results that demonstrate the active management of eight ~100-GHz-spaced wavelength-division-multiplexed (WDM) channels using a polarization-insensitive spatial-light-modulator-based holographic filter. The filter has a fundamental stepping resolution close to 25 GHz and 3-dB width of each individual passband equal to 42 GHz. Arbitrary permutations of dropped and passed channels are possible. Additionally, passed channels can be transmitted according to an equal-amplitude comb filter function or be transmitted with weighted-amplitude passbands to effect power equalization where necessary. The holographic technique is further extendable to passband spectral engineering, yielding near-rectangular "top hat" passbands. Suppression of the dropped channels, which is consistently >15 dB in these experiments, can be straightforwardly improved by deploying a spatial light modulator of greater resolution and higher pixel number. The technology has potential application as the key element in both an optical add–drop multiplexer and a dynamic multichannel equalizer. The passband 3-dB width can be straightforwardly reduced to allow processing of multiple channels at the 50-GHz spacing of future WDM systems.**

***Index Terms*—Equalizers, holographic optical components, liquid crystals, optical amplifiers, optical communication, optical filters, spatial light modulators, wavelength-divison multiplexing.**

I. INTRODUCTION

THE APPLICATION of liquid-crystal (LC) based etalon devices to wavelength filtering is well established [1]. The combination of a pixellated LC element with a bulk diffraction grating, allowing on device assembly the separate processing of each member of a fixed set of wavelengths, has also been extensively studied [2]. In the technique of [2] each LC pixel operates to rotate the polarization of light at a single given wavelength. By contrast, the work reported in this letter concerns recent developments of a technique in which a diffraction grating and an LC spatial light modulator (SLM) combine to form a wavelength filter by virtue of the holographic Fourier replay of the SLM's binary phase array [3]. In this technique, an arbitrary set of WDM channels—arbitrary in both number and individual channel wavelengths—are processed collectively.

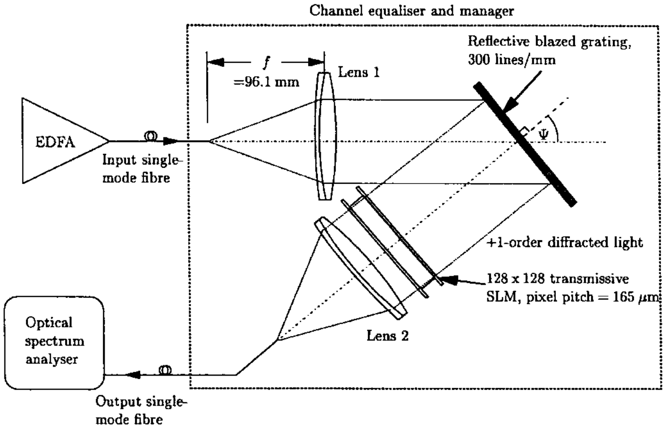


Fig. 1. Schematic diagram of experimental architecture.

Dynamically reconfigurable multichannel equalizing add–drop wavelength-division-multiplexed (WDM) filter elements have been identified as key components in future generation wavelength-switched networks [4]. Prototyping of such devices is typically based on the acoustooptic tunable filter (AOTF) [5]; although the AOTF-based technology is relatively well developed, the achievement of 100-GHz resolution requires a design of increased complexity [6]. By contrast, the holographic technique attains such resolution by means of straightforward modifications to filter design parameters, as described in this letter. The facility to provide dynamic holographic spectral equalization of WDM channels (for instance, to compensate for erbium-doped fiber amplifier (EDFA) gain tilt and fluctuations in individual channel powers) has already been demonstrated in proof-of-principle experiments [7]. The in-line holographic filter is based on a pixellated programmable binary phase diffractive element—a ferroelectric LC SLM (FLC–SLM) of relatively coarse spatial resolution—which provides wavelength dispersion in conjunction with a higher resolution fixed diffraction grating. Both the dispersive elements are located in the collimated beam of a 4-f relay extending between input and output single mode fibers. This technique is polarization-insensitive [8], robust (owing to the inherent redundancy of displayed holograms) and scalable to many more channels. With an optimized electronic drive scheme the fast FLC response can be exploited to yield device reconfiguration as fast as 20 μs [9].

II. EXPERIMENT

The experimental configuration is similar to that described in detail in a previous publication [7]. The key modification

Manuscript received November 17, 1998; revised March 2, 1999.

A. D. Cohen was with the Department of Engineering, Cambridge University, Cambridge CB2 1PZ, U.K. He is now with JDS FITEL Inc., Nepean, ON, K2G 5W8, Canada.

M. C. Parker was with the Department of Engineering, Cambridge University, Cambridge CB2 1PZ, U.K. He is now with Fujitsu Telecommunications Europe Ltd., Northgate House, Colchester CO1 1HH, U.K.

R. J. Mears is with the Department of Engineering, Cambridge University, Cambridge CB2 1PZ, U.K.

Publisher Item Identifier S 1041-1135(99)05134-4.

is the adoption of a folded architecture to accommodate the reflective blazed grating (see Fig. 1). In the experiments reported in this letter, the fixed diffractive element was a 300 line-pairs/mm reflective-blazed grating. The resultant filter stepping resolution of ~27.5 GHz lies well within the current 100-GHz ITU channel spacing standard. Since the blazed grating used was optimized for a wavelength of 1 μm, its deployment reduced the basic filter insertion loss by only 1.1 dB; a further ~2-dB improvement should be achieved by using a grating optimized for high efficiency 1.55-μm operation at the design angle of incidence. The SLM consists of a two-dimensional array of 128 × 128 pixels on a 165-μm pitch with interpixel dead space of 15 μm. However, in this application the device is simply used to display one-dimensional (1-D) binary phase holograms.

Hologram Design

Design calculations were based on numerical solutions to the following equation, which is derived by consideration of summed diffraction angles:

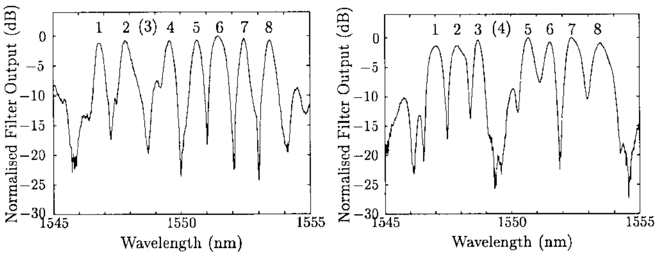
$$\tan^{-1}\left(\frac{x}{f}\right) \simeq \sin^{-1}\left(\frac{\lambda}{d}\right) + \frac{n\lambda}{ND} - \Psi. \tag{1}$$

In (1), λ is the filter wavelength, x is the displacement of the output fiber from the optical axis, $f = 96.1$ mm is the focal length of the lens, $N = 128$ is the number of pixels in the 1-D hologram, $D = 165$ μm is the SLM pixel pitch and $d \simeq 3.3$ μm is the period of the fixed grating. Ψ is the angle made by the normal of the fixed grating to the input optical axis. Within the physical constraints of the arrangement the value of this angle was optimized for maximum blazed grating diffraction efficiency and minimum x (to reduce output spot aberration). Use of a standard simulated annealing (SA) algorithm generally yields optimum results when the design spatial frequency parameter n is an integer in the range 0–$N/2$, i.e., 0–64 in this particular case. However, fractional values of n can be input to a modified algorithm that, despite a tendency to produce holograms of ~10%–20% lower diffraction efficiency, allows quasicontinuous filter tuning [10].

With the SLM displaying a hologram designed to filter a single channel, the individual filter passband is near-Gaussian in form having a 3-dB width, determined by the overlap integral of the dispersed input spectrum over the output fiber core, of 42 GHz. This filter function results in adjacent channel isolation (defined at 30 GHz from adjacent channel center) of −32 dB. The filter stepping resolution is given approximately by differentiating (1) with respect to n to yield

$$\frac{\partial\lambda}{\partial n} \simeq \frac{-\lambda\sqrt{d^2-\lambda^2}}{ND} \tag{2}$$

which, for the parameters in question, implies $\Delta\lambda \simeq 0.215$ nm, i.e., a frequency resolution $\Delta\nu \simeq 26.9$ GHz, for integer increments in n. This agrees well with the experimentally observed mean $\Delta\nu \simeq 27.5$ GHz. To achieve $\Delta\nu = 25$ GHz, which would yield conformance to the ITU grid by setting $\Delta n = 4$, the fixed grating pitch d must simply be reduced to



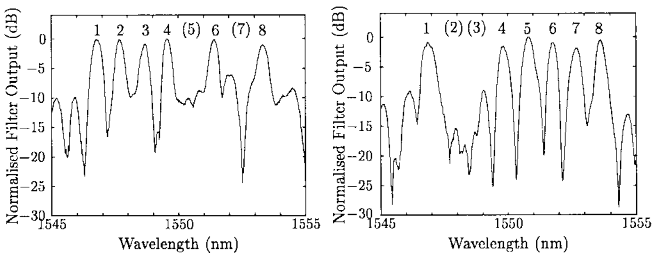
(a) (b)

Fig. 2. (a) Normalized output of equalizer with channel #3 dropped. (b) Normalized output of equalizer with channel #4 dropped.

Holograms have been designed by a version of the SA algorithm adapted to give multiple, arbitrary-amplitude passbands [7], [10] to demonstrate various pass/drop and equalization permutations of eight channels. By setting $\Delta n = 4$ between channels, a mean spacing of ~110 GHz is achieved. The modified SA algorithm allows holograms to be designed for equal transmission of passed channels (i.e., a flat filter function) or to obtain equalized outputs, i.e., in this case compensating for the spectral variation of the EDFA ASE. The equalization technique can also be straightforwardly extended to compensate for dynamic input channel power variation [7]. A further possibility presented by the modified design algorithm is the control of passband shape; near-rectangular flat-topped composite passbands can be obtained by ensuring overlap of three individual passbands. Control of C channels incurs an excess filter loss of $10\log_{10} C$, or $10\log_{10} 3C$ for flattened passbands, but at the high-channel counts anticipated in future systems the incremental penalty will be small.

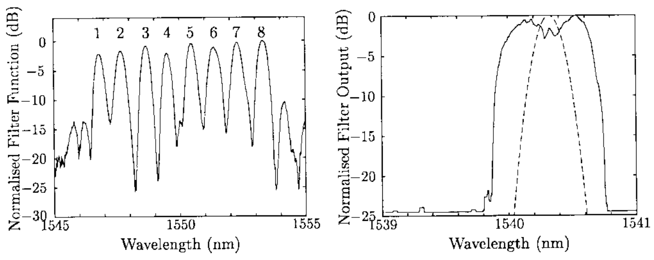
III. RESULTS

All results were recorded using an optical spectrum analyzer. Fig. 2(a) and (b) shows a single channel dropped in two different spectral locations, channels #3 and #4, respectively, with the other seven passed and equalized. The dynamic range of equalization over the ~7-nm wavelength range is about 3 dB, corresponding to the range of EDFA ASE levels in this portion of the spectrum. Previous experiments have demonstrated that a dynamic range of the order of 10 dB is within the capabilities of this system [7] and simulations show that the use of a higher resolution SLM would yield a commensurately greater dynamic range of operation. In addition to providing attenuation at the dropped channel frequency, the filter also provides suppression of the accumulated EDFA ASE between passed channels; this additional functionality is particularly beneficial in systems containing concatenated optical amplifiers. For hologram 1, interchannel ASE suppression is consistently greater than 15 dB and the dropped channel #3 is suppressed by approximately 19 dB. Hologram 2, however, while similarly yielding ~19-dB suppression of the dropped channel #4, has binary phase quantization noise peaks that cause the poorest interchannel suppression to fall to ~6 dB. While this result demonstrates the flexibility of the channel management technique, the hologram performance is suboptimal. Further hologram design iterations would reduce



(a) (b)

Fig. 3. (a) Normalized output of equalizer, channels #5 and #7 dropped. (b) Normalized output of equalizer, channels #2 and #3 dropped.



(a) (b)

Fig. 4. (a) Normalized filter function of eight-channel equalizer operating at 100-GHz channel spacing. (b) Spectral shaping of the holographic filter passband. Single Gaussian passband shown overlaid (broken line) for comparison.

the majority of the residual noise to peripheral regions of the spectrum, such that the performance would match that of hologram 1. The hologram design process would also be improved by the use of an *in situ* feedback loop to compensate for system aberrations.

Fig. 3(a) and (b) demonstrates the facility to drop two channels: In Fig. 3(a) channels #5 and #7 are dropped. In this case, the interchannel ASE suppression is at least ∼9 dB and while the suppression of channel #5 is only ∼10 dB, that of channel #7 approaches 20 dB. Again, further design iterations would yield improved performance. Fig. 3(b) shows channels #2 and #3 dropped, with suppression greater than 12–15 dB in both cases and passed channels uniform to within 1.8 dB following equalization. Fig. 4(a) illustrates a filter function with transmission equalized from ∼3 dB to within 1.5 dB for all eight channels passed; interchannel ASE suppression ranges from 12 to 23 dB.

Holograms designed to produce ‘top hat’ passbands yielded, in the previous filter configuration, responses having significantly improved −20 dB :−3 dB-width merit functions [11]. The reduced effective Gaussian width was achieved by designing a hologram to yield three overlapping passbands. In the new, higher resolution reflective configuration, a passband top that is flat to within 3 dB over >0.7 nm (>88 GHz) has been demonstrated [see Fig. 4(b)] together with a −20-dB width of ∼0.9 nm (∼112 GHz). The merit function derived in the new configuration is approximately 1.35, a considerable improvement on the −20-dB:−3-dB-width ratio of 2.25 typically demonstrated in previous experiments. Some further physical redesign of the filter, including further scale reductions in pixel size and fixed grating period, would be necessary for the composite “top hat” passband to conform to the ITU grid with acceptable isolation performance.

IV. CONCLUSION

This letter has reported 27.5-GHz resolution active holographic management of eight WDM channels spaced by ∼100 GHz. The flexibility of the computer-based hologram design algorithm allows arbitrary add/drop permutations in which the filter passbands have arbitrary relative transmission. Dropped channels are consistently suppressed by >15 dB and the filter also provides commensurate ASE suppression between passed channels. The suppression and adjacent channel crosstalk can be straightforwardly improved by deploying a spatial light modulator of greater resolution and higher pixel number. The holographic technique can be extended to facilitate spectral engineering of the passband, yielding a near-rectangular “top hat” shape. The FLC-SLM-based holographic filter is robust and can incorporate an SLM capable of reconfiguration as fast as ∼20 μs. The technology is based upon elements which are low cost in volume production; it could form the key component in optical add–drop and equalization nodes of future WDM networks.

REFERENCES

[1] A. Sneh and K. M. Johnson, “High-speed continuously tunable liquid crystal filter for WDM networks,” *J. Lightwave Technol.*, vol. 14, pp. 1067–1080, June 1996.

[2] J. S. Patel and Y. Silberberg, “Liquid crystal and grating-based multiple-wavelength cross-connect switch,” *IEEE Photon. Technol. Lett.*, vol. 7, pp. 514–516, May 1995.

[3] S. T. Warr, M. C. Parker, and R. J. Mears, “Optically transparent digitally tunable wavelength filter,” *Electron. Lett.*, vol. 31, no. 2, pp. 129–130, 1995.

[4] A. E. Willner, “Systems issues for WDM components,” in *IEEE LEOS Summer Topical Meeting WDM Components Technology* Montréal, Québec, Canada, 1997, pp. 5–6, paper WB1.

[5] S. H. Huang, A. E. Willner, Z. Bao, and D. A. Smith, “Experimental demonstration of active equalization and ASE suppression of three 2.5-Gb/s WDM-network channels over 2500 km using AOTF as transmission filters,” *IEEE Photon. Technol. Lett.*, vol. 9, pp. 389–391, Mar. 1997.

[6] T. Nakazawa, M. Doi, S. Taniguchi, Y. Takasu, and M. Seino, “Ti:LiNbO$_3$ AOTF for 0.8 nm channel-spaced WDM,” in *OSA Conf. Optical Fiber Communication*, San Jose, CA, Feb. 22–27, 1998, postdeadline paper.

[7] M. C. Parker, A. D. Cohen, and R. J. Mears, “Dynamic holographic spectral equalization for WDM,” *IEEE Photon. Technol. Lett.*, vol. 9, pp. 529–531, Apr. 1997.

[8] S. T. Warr and R. J. Mears, “Polarization-insensitive operation of ferroelectric liquid crystal devices,” *Electron. Lett.*, vol. 31, no. 9, pp. 714–716, 1995.

[9] H. J. White, G. M. Proudley, C. Stace, N. A. Brownjohn, R. Dawkins, A. C. Walker, M. R. Taghizadeh, C. P. Barrett, D. T. Neilson, W. A. Crossland, J. R. Brocklehurst, and M. J. Birch, “The OCPM demonstrator system,” in *OSA Topical Meeting Photonics in Switching*, Salt Lake City, Utah, 1995, page PPd1.

[10] A. D. Cohen, “Spatial light modulator technologies for WDM,” Ph.D. dissertation, Univ. of Cambridge, Cambridge, U.K., 1998.

[11] A. D. Cohen and R. J. Mears, “Dynamic holographic eight-channel spectral equlalizer for WDM,” in *IEEE LEOS Summer Topical Meeting WDM Components Technology*, Montréal, PQ, Canada, 1997, pp. 46–47, paper ThC2.