A tunable cyclic encoder using photopolymer-based holographic grating for optical CDMA application

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ABSTRACT

It is important to have a tunable encoder in optical channel coding for the purpose of coping with varying communication environment. In this paper, a tunable encoder based on the holographic grating (HG) using photopolymer as the holographic medium is described. The system is composed of photopolymer holographic grating as a demultiplexer, spatial light modulator (SLM), and other lens systems. The photopolymer grating acts as a demultiplexer to distribute optical wavelength channels on the SLM through its spatial dispersion property. Then, the SLM produces wavelength-encoded data by its spatial amplitude/phase modulation. The merits of using the holographic grating are that it has relatively easy fabrication process, and that non-uniform grating structure and multiplexing can be exploited. In this setup, we can additionally change demultiplexing wavelengths by inducing strain gradient on the polymer grating, which is attached on the two XYZ linear stages. Hence a different set of wavelengths is incident to SLM and this enables another type of encoding pattern.

Key words: diffraction, grating, polymer, tunability, cyclic property

1. INTRODUCTION

Optical code division multiple access (O-CDMA) system is getting more attention in the field of all-optical communications. O-CDMA system provides multi-access communications asynchronously and simultaneously with good transmission security in optical networks by assigning to each user-pair a channel-specific code sequence [1]. Each user in the network communicates by encoding optical bits with channel specific codes, which are transmitted over a common transport fiber to all users [2]. However, no matter how the system is designed, it will always suffer from a basic limitation. As the number of simultaneous active users is increased, the code length has to be increased to maintain the same performance. One is constrained to use shorter and shorter pulses not to lower the bit rate [3]. Coherent systems are likely to use mode-locked lasers as optical sources to produce transform limited pulses, but that renders the system expensive and possibly not competitive when compared with those using other access schemes. And as the pulses used become very short, the chip duration becomes incompatible with the bandwidth of the photodetector, and the cost and the complexity of the system increase [4]. Early incoherent optical CDMA systems used pseudo orthogonal sequences to encode signals in the time domain, but the codes were long and multiple-access interference (MAI) limited the number of simultaneous users. Theoretical analysis of optical CDMA systems

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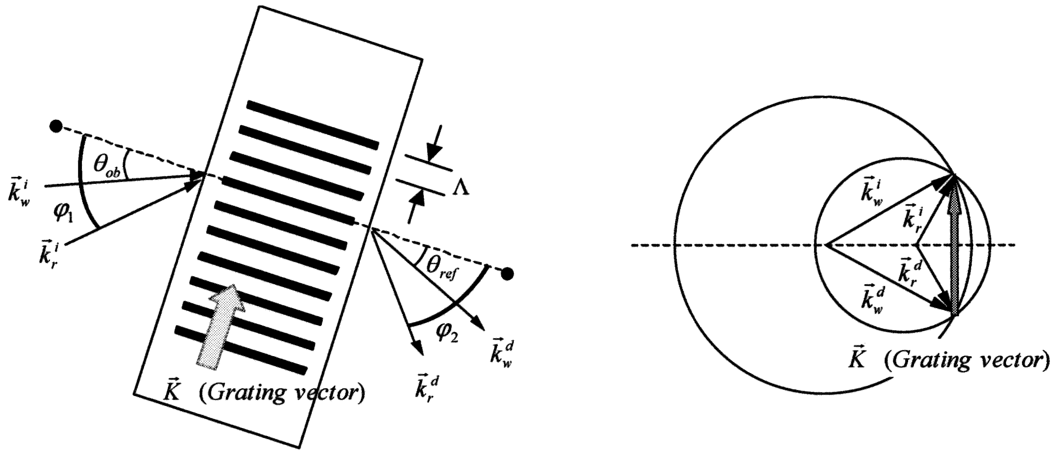
has shown that multi-user interference (MUI) is the main reason for performance degradation, especially when large numbers of users are involved [5].

A number of research groups have proposed various types of encoder/decoder including fiber Bragg gratings, a pair of diffraction gratings, arrayed-waveguide grating (AWG) devices and optical delay lines [6,7]. In the schemes that use fiber Bragg gratings (FBGs) as encoding–decoding devices in O-CDMA networks, the physical size of FBG array can be a disadvantage when the number of total network users becomes large. Or lengthy fiber delay lines are needed to accommodate large numbers of users. And also these are difficult to construct tunable encoder/decoder. In this paper, we propose a tunable encoder with the cyclic property applicable from O-CDMA systems to various optical systems.

2. Polymer Holographic Grating (PHG)

Tunability of the selected wavelength is strongly desired in order to flexibly deal with changes of traffic demand and lightpath troubles in wavelength division multi-access (WDMA) networks. Several different multiplexing and demultiplexing techniques including arrayed-waveguide gratings, MEMS structures, and interferometric filters have been reported. But, the cost of the devices can be lowered by the use of a polymer-based holographic grating as a demultiplexer since polymer devices can potentially offer low-cost processing, ease of integration and good coupling with optical fibres [8]. Another advantage of this device is that it can more precisely and simply tune its transmission wavelength over the WDM channel range compared with conventional methods using thermal wavelength shift. Our group demonstrated the strain tuning method of a polymer-based holographic grating in a previous research. In the present paper we propose a tunable cyclic encoder by the use of the grating in this paper.



(a) (b)

Figure1. (a) Wave vector representation of the two-lambda method, (b) wave vector diagram representation of the two-lambda method

Figure 1 show the wave vector representation and wave vector diagram of the two-lambda method. Two-lambda method which writes holograms with wavelength of 488 nm and read-out them with wavelength of 1550 nm, offers the opportunity of recording holograms in classical photorefractive materials by means of light at maximum sensitivity wavelengths and reading such holograms at 1550 nm wavelengths [9-11]. A hologram is recorded at the writing wavelength λ_w with an incidence angle θ_{ob} for the object beam and θ_{ref} for the reference beam (with respect to the normal to the incidence face). The recorded hologram can be reconstructed by introducing a readout beam at the different wavelength λ_r with a tilted angle with respect to the reference beam. Then Bragg law satisfies the following condition [12].

$$\frac{\lambda_w}{\sin\left(\frac{\theta_{ob}+\theta_{ref}}{2}\right)}=\frac{\lambda_r}{\sin\left(\frac{\varphi_1+\varphi_2}{2}\right)}, \tag{1}$$

where φ_2 defines the direction of the diffracted beam at readout wavelength. The same condition can be easily shown in a wave vector diagram. The satisfaction of the Bragg law is graphically represented by the closing of the triangle formed by the wave vectors of the incident $\vec{k}_w^{\,i}$, $\vec{k}_r^{\,i}$ and diffracted $\vec{k}_w^{\,d}$, $\vec{k}_r^{\,d}$ beams, and the grating vector as shown Fig. 1 (b). In our experiment the read-out light source was a tunable laser with a tunability range from 1400 to 1600 nm.

3. DEVICE DESIGN

The basic configuration of the proposed device is shown in Figure 2. As shown in Fig. 2, the input light coming from a tunable laser source (Ando, AQ 4321D) is collimated by the collimating optics and impinges on a spatial light modulator (SLM). The transmitted light which consists of specific wavelengths selected out of input light according to the SLM amplitude pattern meets a hologram grating recorded on a photopolymer. The photopolymer holographic grating (PHG) is fixed on XYZ stages and meets collimated input beam with a slanted angle. This angle is Bragg matched to the hologram grating so that the –1st order diffraction occurs to the opposite direction of transmitted beam. The diffracted light is then coupled to the output fiber (fiber bundle) by use of an objective lens and is analyzed by lightwave multimeter (HP, 8153A) or optical spectrum analyzer (Anritsu, MS9710B). We note here that, by making the PHG thickness relatively thin (~100um), different wavelength channels could be separated into different output fibers by use of the spatial dispersion characteristics. The different optical wavelengths of different channels are transversely separated at the focusing plane of the coupling lens (i.e., spatial dispersion of the grating). Therefore, by locating a fiber bundle in the spatial dispersion direction, we can separate different wavelength channels to the different fibers for demultiplexer application [13, 14].

The PHG was fabricated using two-beam interference. In the recording process, we use a visible laser source (in experiments, we used 532 nm wavelength laser beam) since most of holographic recording materials do not respond to the optical fiber communication wavelengths in recording. In our experiment, the laser for recording PHG was Nd:YAG (Coherent, DPSS 532). An achromatic microscope objective lens (focal length 18.2 mm, NA 0.25) was used for the out-coupling optics. For a specific channel output of the grating, the spectrum S for a wavelength λ is as follows.

$$S \propto corr\left[\Im\{F\}\otimes\Im\{U^{(i)}\},\Im\{U^{(o)}\}\right] \tag{2}$$

Here, $\Im$ and $\otimes$ express spatial Fourier transform and convolution in the spatial frequency domain, respectively. F is the refractive index perturbation of the hologram grating, $U^{(i)}$ the collimated input beam, and $U^{(o)}$ the out-coupling beam corresponding to the SMF mode [15, 16]. It means that spatial spectra of the incident beam are Bragg diffracted by the hologram grating spatial spectra and then coupled out to the output SMF through overlap with the out-coupling beam spatial profile. We note that by modulating each of these parameters or profiles, channel output characteristics can also be changed. For the demultiplexed channel wavelength tuning, we can efficiently exploit spectra modulation of the holographic grating.

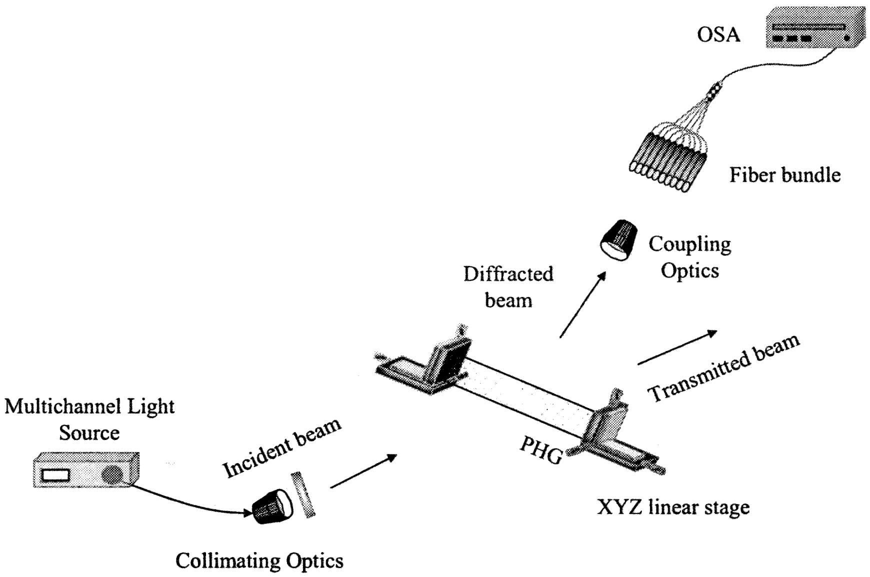


Fig. 2. Basic configuration of the proposed cyclic encoder
(OSA : Optical Spectrum Analyzer, PHG : Polymer Holographic Grating)

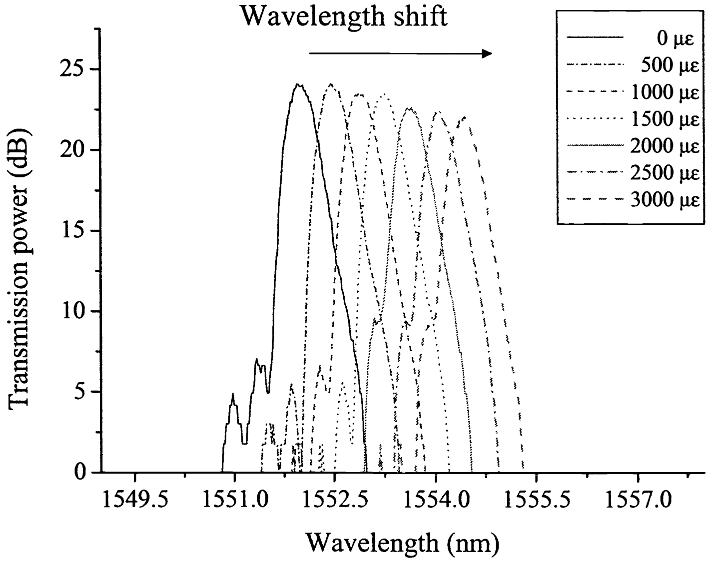


Fig. 3. Center wavelength shift response to the applied strain.

Tuning of this device over a wide wavelength range is based on the large elasticity of photopolymer. In Bragg condition, we can obtain the following equation in Fig. 1 (a).

$$\frac{2\pi}{\Lambda}=\frac{2\pi\sin\varphi_1}{\lambda_i}+\frac{2\pi\sin\varphi_2}{\lambda_i}\ , \tag{3}$$

where Λ , λ_i are grating period and *i*th channel wavelength (Bragg diffracted wavelength). We assumed that readout beam angle φ_1 is fixed for all wavelengths. And the relation between the extended polymer length and grating period is as follows [17].

$$\Delta\Lambda = \frac{\Delta L}{L}\cdot\Lambda \ , \tag{4}$$

where $\Delta\Lambda$, ΔL are the increments in grating period and polymer length. We assumed that a uniform structure grating is used. Figure 3 shows the experimental results with a fixed SMF for the case of polymer hologram extension for wavelength tuning of the demultiplexer. In this experiment, we tuned the center wavelength in the 1552.0 nm to 1554.7 nm range using strain applied by the linear stages. The resulting mean strain sensitivity was $\Delta f / \Delta\varepsilon = 0.1\ GHz / \mu\varepsilon$ as shown in Fig. 3.

4. An application to a Tunable Cyclic Encoder

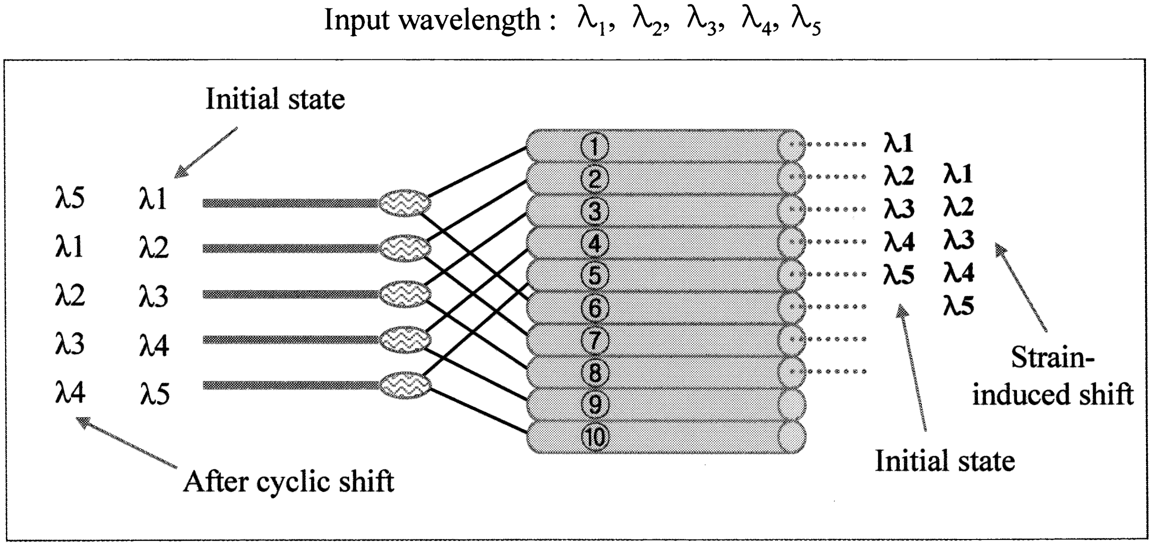


Fig. 4. Basic principle of cyclic shift with the proposed device

The proposed device has the cyclic property which is based on the strain-induced wavelength tuning method proposed by our group [17]. Fig. 4 shows the basic principle of cyclic shift operation. Assuming that input light is composed of 5 wavelengths ($\lambda_1 \sim \lambda_5$), each wavelength component is collimated and coupled to a predetermined fiber. If the number of input wavelengths is N, Mth and (N+M)th fiber (M is arbitrary integer.) are paired by 2×2 couplers as shown in Fig. 4. We made a match ①-⑥ fiber, ②-⑦ fiber, ③-⑧ fiber, ④-⑨ fiber and ⑤-⑩ fiber, respectively. And the sequence of the output light is changed from $\lambda_1 \sim \lambda_5$ to λ_5, $\lambda_1 \sim \lambda_4$ with the applied strain. Performing one channel shift, we have to apply appropriate strain so as to λ_1 will be coupled to fiber 2. Other channels will also shift to right and coupled to next fiber. Though there is no light coupled into fiber 1, but the light coupled into fiber 6 is combined at the coupler. In the end, the wavelength sequence of this device comes to have a cyclic property. By using this, any channel can be shifted to other channel arbitrarily with the cyclic order.

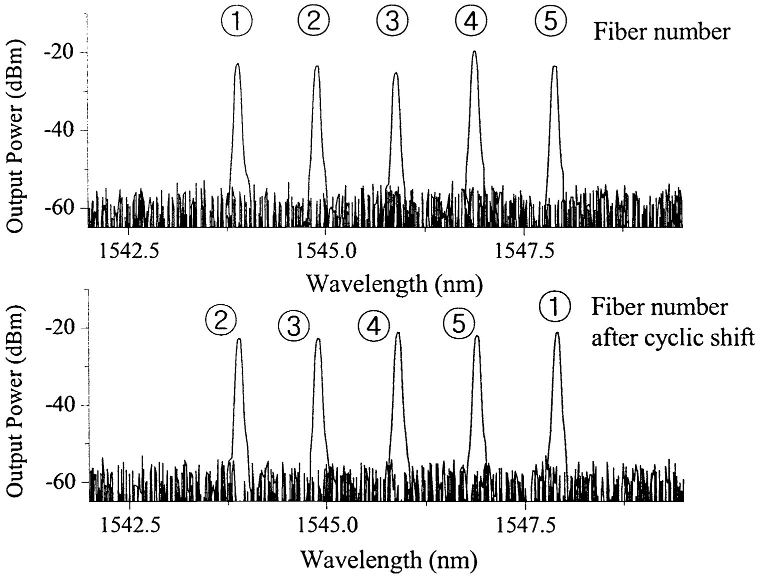


Fig. 5. Experimental result which shows one channel cyclic shift.

5. An application to CDMA system

One of the most prominent features of O-CDMA system is that it can vary encoding and decoding methods in various ways depending on the type of laser and detection scheme used. For the most part, O-CDMA techniques can be categorized into three different schemes. First, a form of spread-spectrum technique, designed for incoherent light sources using optical orthogonal codes (OOC), and on–off keying for data modulation. Second, a form of spread-time technique, designed for mode-locked laser sources whereby each output pulse is optically Fourier transformed and spectrally encoded by pseudorandom sequences and then Fourier inversed before transmission to a common multiple-access optical channel. Third, a form of spread-space technique, designed for spatially coherent laser sources and using spatially two-dimensional (2-D) code masks and free-space optical signal processing techniques to establish its encoding and decoding functions [18-19].

For the OCDMA scheme to be more realistic, it is desired to devise an optical code that can accommodate a larger number of simultaneous users with a low error probability for a given code length. The optical orthogonal code (OOC) is a one-dimensional (1-D) collection of binary sequences. 1-D OCDMA system, one period of transmission clock is divided into a given number of small temporal segments, and bit "1" is encoded with a number of optical pulses spread in the time chips. To overcome the limit of the 1-D optical codes, 2-D system approaches are proposed, in which optical pulses are spread in both space and time domains or in wavelength and time domains. By employing another dimension (space or wavelength), 2-D code with single pulse per row is achieved and the performance of the 2-D OCDMA system is much improved in comparison to the 1-D OCDMA system [21, 22].

Figure 6 shows a possible O-CDMA encoder using PHG. As shown in Fig. 6, the PHG spatially decomposes the spectral components present in the incoming optical signal with a certain resolution. A spatially patterned mask is inserted midway between PHG and the objective lens. After the mask, the spectral components are coupled into a fiber bundle. The mask can modify the frequency components in phase and/or in amplitude, depending on the coherence property of the incident optical source. The number of frequency bands and the number of subscribers in the system will decide the code length. In this setup, the information signal employs ON–OFF keying and the PHG is used to control the amplitude spectra of

REFERENCES

1. J.A. Salehi, "Code division multiple-access techniques in optical fiber networks. I. Fundamental principles," *Commun., IEEE Transactions on,* **37**, pp. 824-833, 1989.
2. M. Kavehrad, and D. Zaccarin, "Optical code-division-multiplexed systems based on spectral encoding of noncoherent sources," *J. Lightwave Technol.,* 13, pp. 534-545, 1995.
3. H.P. Sardesai, C-C. Chang, and A.M. Weiner, "A femtosecond code-division multiple-access communication system testbed," *J. Lightwave Technol.*, 16, pp.1953-1964, 1998.
4. T. Dennis and J. F. Young, "Experimental demonstration of bipolar codes for optical spectral amplitude CDMA communication," *IEEE J. Quantum Electron.*, **35**, pp.287, 1999.
5. M. Abtahi and J. A. Salehi, "Spread-Space Holographic CDMA Technique: Basic Analysis and Applications," *IEEE Trans. Wireless Commun.*, **1**, pp. 311-321, 2002.
6. H. Jaafar, S. LaRochelle, P.-Y. Cortes and H. Fathallah, "1.25 Gbit/s transmission of optical FFH-OCDMA signals over 80 km with 16 users," OFC 2001, **2**, TuV3-1 - TuV3-3
7. S. Kim, "Cyclic Optical Encoders/Decoders for Compact Optical CDMA Networks," *IEEE Photon. Technol. Lett.,* **12**, pp.428-430, 2000.
8. J.-F. Viens, C. L. Callender, J. P. Noad, and L. Eldada, "Compact wide-band polymer wavelength-division multiplexers," *IEEE Photon. Technol. Lett.*, **12**, pp. 1010-1012, 2000.
9. E. Chuang and D. Psaltis, "Storage of 1000 holograms with use of a dual-wavelength method," *Appl. Opt.*, **36**, pp. 8445–8447, 1997.
10. P. Boffi, M. Ubaldi, D. Piccinin, C. Frascolla, and M. Martinelli, "1550-nm Volume Holography for Optical Communication Devices," *IEEE Photon. Technol. Lett.*, **12**, pp. 1355-1357, 2000.
11. M. C. Ubaldi, P. Boffi, D. Piccinin, C. Frascolla, and M. Martinelli, "Volume holography for 1550 nm digital databases," The International Society for Optical Engineering, *Proc. SPIE* **4089**, pp. 625-629, 2000.
12. D. Psaltis, D. Brady and K. Wagner, "Adaptive optical networks using photorefractive crystals," *Appl. Opt.,* **27**, pp. 1752-1754, 1988.
13. S. Han, B.-A. Yu, S. Chung, H. Kim, J. Paek, and B. Lee, "Filter characteristics of a chirped volume holographic grating," *Opt. Lett.*, **29**, pp. 107-109, 2004.
14. S. Han, T. Kim, S. Chung, and B. Lee, "Dispersion Characteristics of Holographic Multiple-Channel Demultiplexers," *IEEE Photon. Technol. Lett.,* **16**, pp. 1879-1881, 2004.
15. B. Lee, S. Han, Y. Jeong, and J. Paek, "Remote multiplexing of holograms with random patterns from multimode fiber bundle," *Optics Letters*, **29**, pp. 107-109, 2004.
16. B. Lee, S. Han, K. Choi, S. Chung, and T. Kim, "Applications of holographic devices for optical communications," in SPIE Annual Meeting, *Proc. SPIE* **5560**, 5560-16, 2004.
17. S. Chung, T. Kim, S. Han, and B. Lee, "A tunable demultiplexer using a polymer-based holographic grating with strain gradient," in SPIE Annual Meeting, *Proc. SPIE* **5560**, 5560-13, 2004.
18. J.-G. Zhang and G. Picchi, "Tunable prime-code encoder-decoder for all-optical CDMA applications," *Electron. Lett.,* **29**, pp. 1211-1212, 1993.
19. J.A. Salehi, E. G. Paek, "Holographic CDMA," *Commun., IEEE Transactions on*, **43**, pp. 2434 – 2438, 1995.
20. L. Nguyen, T. Dennis, B. Aazhang, and J. F. Young, "Experimental Demonstration of Bipolar Codes for Optical Spectral Amplitude CDMA Communication," *J. Lightwave Technol.,* **15**, pp. 1647-1653, 1997.
21. S. Kim, K. Yu, and N. Park, "A New Family of Space/Wavelength/Time Spread Three-Dimensional Optical Code for OCDMA Networks," *J. Lightwave Technol.,* **18**, pp. 502-511, 2000.
22. X. Zhou, H. Shalaby, C. Lu and T. Cheng, "Code for spectral amplitude coding optical CDMA systems," *Electron. Lett.*, **36**, pp. 728-729, 2000.
23. C.-C. Yang, J.-F. Huang, and S.-P. Tseng, "Optical CDMA Network Codecs Structured With M-Sequence Codes Over Waveguide-Grating Routers," *IEEE Photon. Technol. Lett.*, **16**, pp. 641-643, 2004.
24. H.Wang, Z. Zheng, D. E. Leaird, A.M.Weiner, T. A. Dorschner, J. J. Fijol, L. J. Friedman, H. Q. Nguyen, and L. A. Palmaccio, "20-fs Pulse Shaping With a 512-Element Phase-Only Liquid Crystal Modulator,"