Fast Wavelength-Hopping Time-Spreading Encoding/Decoding for Optical CDMA

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***Abstract*—We demonstrate a new technique for implementation of fast wavelength-hopping incoherent optical code-division multiple-access (CDMA). The output pulse from a mode locked laser is spectrally broadened through supercontinuum generation. This pulse is then encoded into fast wavelength-hopped time-spread waveforms through a wavelength-selective time-delay device. At the receiver, matched-filter decoding is used to recover data. We present a 1-Gb/s digital transmission experiment through a 15-km dispersion-shifted (DS) single-mode fiber link. This technique avoids the need for a fast wavelength tunable optical source.**

***Index Terms*—Mode locked laser, optical CDMA, optical processing.**

I. Introduction

OPTICAL code-division multiplexing (OCDM) is an attractive technique that takes advantage of the enormous bandwidth (almost 25 THz) in single-mode fiber to achieve random asynchronous communication access among many users, free of network control [1]–[3]. Every user is assigned a specific code sequence. Through a proper choice of the OCDM codes, the signals from all network nodes can be made mutually noninterfering. In incoherent OCDM, an encoder maps each bit "1" of source information into a high bit rate optical sequence of ultrashort light pulses, while the bit "0" is not encoded. Encoding results in time spreading of the signal. The encoded signal is then broadcast to all node receivers. At the receiver, the optical signal is correlated with the local code in a matched filter thereby reconstructing the signal. A threshold detector is used to detect the autocorrelation peak [4]. This approach to multiplexing allows transmission without delay and handles multiaccess interference (contention) as an integral part of the multiplexing scheme.

In order to improve their cross-correlation property, conventional incoherent OCDM systems employ very sparse codes with a small number of codes in the family [5]. This results in a small number of operating nodes and simultaneous users and, more importantly, a very high chip (signaling) rate for a particular data rate. Recently, in analogy to hybrid systems in electrical code-division multiple-access (CDMA), there has been a proposal to integrate time spreading with a wavelength-hopping pattern to achieve a perfect needle-shaped autocorrelation function with zero sidelobes and a very low cross correlation [6]. Every pulse (chip) within the code sequence is transmitted at a different wavelength according to a hopping algorithm. At the receiver, the original signal is recovered by a matched-filter correlator which is the conjugate of the transmission filter. Since every wavelength occurs only once in every hopping pattern, for a prime-hop sequence of order p the autocorrelation is a maximum of p at zero time-shift and sidelobes are completely absent, while crosscorrelation gives p individual coincidences of at most one. For the worst case cross correlation (when chips are synchronous), the average variance can be shown to be [6]

$$\sigma^2 = \frac{1}{2p}\left(1 - \frac{1}{2p}\right) \tag{1}$$

which is very low. Consequently, the number of stations in the network and the number of simultaneous users is expected to be greatly increased. The number of orthogonal codes in the family is also increased from p in prime codes (time spread only) to $p(p-1)$ for prime-hopped (time-spread plus wavelength-hopped) codes. However, wavelength-hopped OCDM requires an extremely high repetition rate modelocked tunable laser with very fast wavelength tunability to achieve rapid wavelength hopping. Hence, such wavelength-hopping time-spreading OCDM systems remained a concept in paper until recent simultaneous experimental demonstrations by two groups [7], [8].

In this letter, we propose a novel implementation of wavelength-hopped time-spread OCDM, where the ultrafast tuning requirement and extremely high repetition rate for the modelocked laser is eliminated. This is achieved in an optically incoherent system. A fixed-wavelength modelocked laser is used to obtain the entire optical wavelength spectrum through supercontinuum generation [9], [10]. This is followed by parallel optical processing through splitting and recombining on a wavelength basis using wavelength-division multiplexing (WDM) multiplexers and demultiplexers and encoding using optical delay lines [11]. To verify the concept, a 1-Gb/s digital transmission experiment over a 15-km dispersion-shifted (DS) single-mode fiber link using an all-optical three-chip code for wavelength hopping and time spreading is demonstrated.

The experiment setup is shown in Fig. 1. An actively modelocked fiber laser generating 3 ps optical pulses at a 1-GHz repetition rate is used as the light source. To achieve a spectral width of 2 nm (for three chips in spectrum spaced by 0.8 nm) we amplify the pulses and use supercontinuum generation in 4 km of DS fiber followed by a tunable bandpass filter to select a 2-nm band. Fig. 2 shows the spectrum after the laser and after supercontinuum generation. We obtain a 10-nm spectral bandwidth after supercontinuum broadening. While this is sufficient for our experiment, it has been shown that more than 200-nm supercontinuum broadening with relatively flat spectral response

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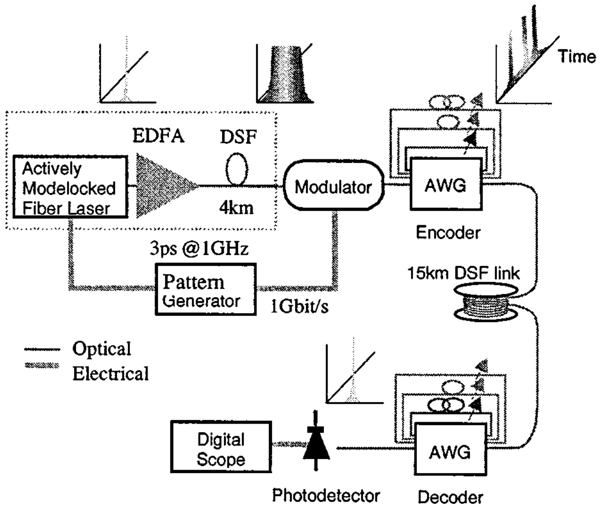

Fig. 1. Experimental setup of the wavelength-hopped time-spread OCDM system.

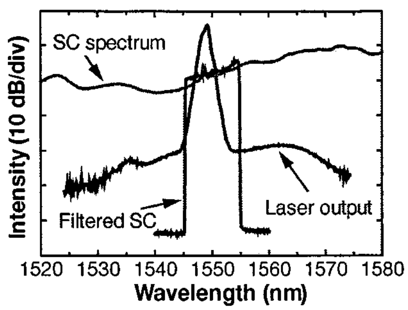

Fig. 2. Spectrum at the output of modelocked laser and after supercontinuum generation.

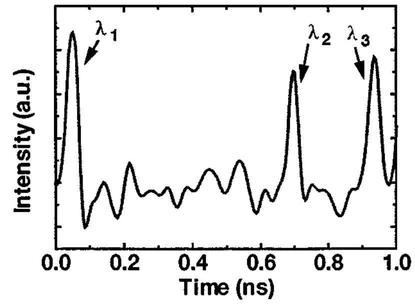

Fig. 3. Time-stretched spectral-coded output of encoder. $\lambda_1 = 1554$ nm, $\lambda_2 = 1554.8$ nm, $\lambda_3 = 1555.6$ nm.

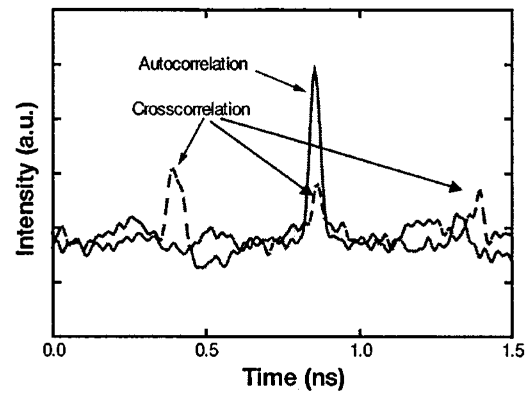

Fig. 4. Autocorrelation and cross-correlation outputs.

can be obtained using a fiber with optimized dispersion profile [10].

Pattern generator data at 1Gb/s is used to modulate the 2-nm 3-ps pulses. The encoder consists of a waveguide grating (AWG) to demultiplex the input spectrum followed by fiber loops of different lengths. The delayed and amplitude weighted spectral components are then recombined using the same waveguide grating in a feedback configuration [11]. The delays and the amplitude of the spectral components are used to define wavelength-hopped and time-spread optical codes. The use of switched delay lengths would enable us to program the encoder to a different prime-hop code. Fig. 3 shows a three-chip time-spread and spectral-coded output of the encoder that was obtained from a 3-ps 2-nm spectral width input optical pulse.

The transmission link consists of 15-km single-mode DS fiber with a total loss of 4 dB. Because the encoded signal is optically broadband, DS fiber is needed to minimize dispersion-induced penalty. The received signal is passed through the decoder which is identical to the encoder with conjugate delay loops. Here, the time-spread and spectral-coded data is collapsed and the original data is recovered.

We performed autocorrelation and cross-correlation measurements of the optical signal with the local code. For a three-chip prime-hop code, when the optical signal and local code words are matched we expect a perfect autocorrelation peak of three and zero sidelobes. When the optical signal and the local code-words are not matched we expect three cross-correlation sub-peaks of amplitude one. As can be seen from Fig. 4, we experimentally observe the expected orthogonality property.

To demonstrate transmission of digital data we use a 1-Gb/s 1101 data pattern. Fig. 5(a) shows a 1101 pattern after transmission through the fiber link. Fig. 5(b) shows the decoded output. As can be seen, encoded data is properly recovered at the receiver.

Conventional time-spread incoherent OCDM systems are limited chiefly by the nonzero multiple-user cross correlation. However, in our case, the time-spreading combined with the wavelength-hopping pattern achieves a perfect needle-shaped autocorrelation function with zero sidelobes and a very low cross correlation, resulting in a very low average variance and hence improved capacity compared to traditional time-spread OCDM system [6]. Nevertheless, since all the code-words share the same optical spectrum, beat noise that occurs between: 1) the signal and the multiple user interference and 2) between the different multiple user interference signals, needs to be considered. Assuming that the phase of the individual spectral components are random variables uniformly distributed over $[-\pi, \pi]$, it has been recently shown that the beat noise due to multiple-user interference in such two-dimensional (2-D) OCDM systems appears as a dominant source of noise and degrades the system performance [12].

In conclusion, we have proposed and successfully demonstrated a novel energy-efficient encoding and decoding technique for OCDM. Each data bit was time-stretched and spectrally coded through fast wavelength hopping. We also demon-

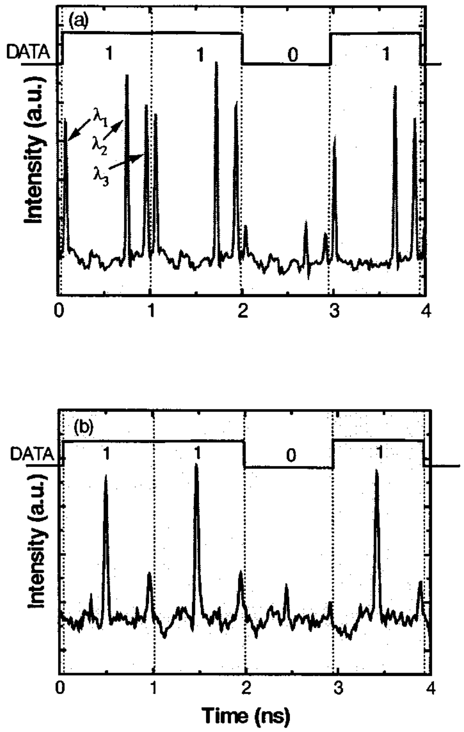

Fig. 5. (a) Encoded digital data at 1 Gb/s transmitted over 15-km DSF link. (b) Recovered data after matched decoder.

strated digital data transmission at 1-Gb/s over a 15-km DS fiber link using this novel OCDM technique. The proposed technique avoids the need for a fast wavelength-tunable optical source.

REFERENCES

[1] J. Y. Hui, "Pattern code modulation and optical decoding—A novel code division multiplexing technique for multifiber networks," *IEEE J. Select. Areas Commun.*, vol. 3, pp. 916–927, June 1985.

[2] P. R. Prucnal, M. A. Santoro, and T. R. Fan, "Spread spectrum fiber-optic local area networks using optical processing," *J. Lightwave Technol.*, vol. 4, no. 5, pp. 547–554, 1986.

[3] J. A. Salehi, "Code-division multi-access techniques in optical fiber networks—Part I: Fundamental principles," *IEEE Trans. Commun.*, vol. 37, pp. 824–833, Aug. 1989.

[4] H. P. Sardesai and A. M. Weiner, "A nonlinear fiber-optic thresholder for spectrally coded ultrashort pulses with 36 dB extinction ratio," *OSA Trends Optics Photonics*, vol. 13, pp. 60–62, 1997.

[5] F. R. K. Chung, J. A. Salehi, and V. K. Wei, "Optical orthogonal codes: Design, analysis, and applications," *IEEE Trans. Inform. Theory*, vol. 35, no. 3, pp. 595–604, 1989.

[6] L. Tancevski, I. Andonovic, M. Tur, and J. Budin, "Hybrid wavelength hopping time spreading code division multiple access systems," *Proc. Inst. Elect. Eng.*, vol. 143, no. 3, pp. 161–166, 1996.

[7] S. Yegnanarayanan, B. Asuri, and B. Jalali, "An incoherent wavelength hopping/time spreading code-division multiple access system," in *Proc. 25th Eur. Conf. Optical Communication, I*, 1999, pp. 188–189.

[8] N. Wada, H. Sotobayashi, and K. Kitayama, "Error-free transmission of 2-channel × 2.5 Gb/s time-spread/wavelength-hop OCDM using fiber Bragg grating with supercontinuum light source," in *Proc. 25th Eur. Conf. Optical Communication—II*, 1999, pp. 230–231.

[9] T. Morioka, K. Uchiyama, S. Kawanishi, S. Suzuki, and M. Saruwatari, "Multiwavelength picosecond pulse source with low jitter and high optical frequency stability based on 200 nm supercontinuum filtering," *Electron. Lett.*, vol. 31, no. 13, pp. 1064–1066, 1995.

[10] T. Okuno, M. Onishi, and M. Nishimura, "Generation of ultra-broad-band supercontinuum by dispersion-flattened and decreasing fiber," *IEEE Photon. Technol. Lett.*, vol. 10, pp. 72–74, Jan. 1998.

[11] S. Yegnanarayanan, P. D. Trinh, and B. Jalali, "Recirculating photonic filter: A wavelength selective time-delay filter for optically-controlled phased-array antennas and wavelength CDMA," *Opt. Lett.*, vol. 21, pp. 740–742, 1996.

[12] L. Tancevski and L. A. Rusch, "Impact of the beat noise on the performance of 2-D optical CDMA systems," *IEEE Commun. Lett.*, to be published.