Approach to all-optical bipolar direct-sequence ultrawideband coding

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An approach to all-optical bipolar direct-sequence ultrawideband (UWB) encoding for multiple access communications is proposed and demonstrated. The bipolar coding is performed based on electro-optic phase modulation and phase modulation to intensity modulation (PM-IM) conversion in a fiber Bragg grating (FBG) array that serves as a multichannel frequency discriminator. The chip number and the chip period of the code are determined by the number of FBGs and their physical separation. By locating the optical carriers that carry a Gaussian pulse at the left or right slopes of the FBG reflection spectra, bipolar direct-sequence UWB codes are generated. A bipolar UWB coding system with a code length of 4 is experimentally demonstrated.

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Ultrawideband (UWB) has been considered a prime technology for short-range high data-rate wireless communications, thanks to the advantages such as low power consumption, high immunity to multipath fading, enhanced capability to penetrate through obstacles, and coexisting with other conventional radios [1]. In 2002, the U.S. Federal Communications Commission (FCC) approved the unlicensed use of the UWB band from 3.1 to 10.6 GHz with a power density lower than −41.3 dBm/MHz (FCC: part 15). Until now, most of the work has been focused on the use of UWB for short-range wireless communications, in which electrical circuits are commonly used to generate and process UWB signals [2,3]. Recently, UWB signal generation and distribution in the optical domain has been a topic of interest. Most of these techniques are proposed and demonstrated for the generation of UWB pulses based on optics, to take advantage of the broad bandwidth and low loss offered by optics [4–11]. On the other hand, owing to its low power spectral density (PSD) regulated by the FCC, the UWB communications distance is limited to a few to tens of meters. Such short-range wireless networks can operate mainly in an indoor environment in a stand-alone mode, with a nearly nonexistent integration into the existing network infrastructures. To offer availability of undisrupted service across different networks and eventually achieve high-speed data access at any time and from any place, UWB combined with fiber distribution or UWB over fiber, to take advantage of the low loss of the state-of-the-art optical fiber, may provide an effective solution [12,13]. To distribute UWB signals over optical fiber, it is also desirable that the UWB signals can be generated and encoded in the optical domain without the need for an extra electrical to optical conversion.

For a UWB communication system that supports multiple users, the UWB signals must be encoded with each user represented by a specific code. Time-hopping ultrawideband (TH-UWB) has been extensively studied for multiple access UWB systems. Recently, it was demonstrated that a direct-sequence ultrawideband (DS-UWB) system outperforms a TH-UWB system in terms of the bit-error-rate performance [14]. Moreover, a DS-UWB system is more convenient to realize in the optical domain than a TH-UWB system. In this Letter, we propose a technique to implement all-optical bipolar DS-UWB coding for multiaccess UWB communications. In the proposed system, the encoding is implemented using an electro-optic phase modulator (EOPM) to perform phase modulation and a fiber Bragg grating (FBG) array as a multichannel frequency discriminator to perform phase-modulation to intensity-modulation (PM-IM) conversion [11]. By locating the phase-modulated light waves at the opposite slopes of the FBG reflection spectra, PM-IM conversion leading to the generation of UWB pulses with opposite polarities would be realized. The chip number and the chip period of the code are determined by the number of FBGs in the array and the physical separation between two adjacent FBGs. By tuning the optical carriers at the left or right slopes of the FBGs, a bipolar DS-UWB code with a predefined code pattern is generated. The proposed scheme is experimentally verified; bipolar DS-UWB codes with a code length of 4 are experimentally demonstrated.

The schematic of the proposed bipolar DS-UWB encoding system is shown in Fig. 1. The encoding operation is to map a low bit-rate electrical data sequence to a high bit-rate optical data sequence with a specific code for each user. In our proposed encoding system, the light waves from a laser array with N wavelengths are phase modulated by a low bit-rate electrical data sequence at an EOPM and then sent to an FBG array that consists of N cascaded uniform FBGs, with each wavelength being located at the left or right slope of the corresponding FBG. The FBG array in the system has two functions: (1) to serve as a multichannel frequency discriminator to perform PM-IM conversion, and (2) to serve as an optical delay-line to spread each data symbol into N pulses.

Mathematically, a phase-modulated light wave can be expressed as

$$A(t) = \exp[j\omega_c t + j\beta_{PM} m(t)], \qquad (1)$$

where $m(t)$ is the electrical modulation signal, β_{PM} is the phase-modulation index, and ω_c is the angular frequency of the optical carrier. When the phase-modulated light is sent to an FBG with the optical carrier located at one slope of the reflection spectrum of the FBG, PM-IM conversion is performed. At the output of a photodetector (PD), an electrical signal is obtained, which is given by [15]

$$I_0(t) \approx 2\Re K^2(\omega_c - \omega_0)\beta_{PM} m'(t), \qquad (2)$$

where $\Re$ is the responsivity of the PD, K is the steepness factor of the filter slope, and ω_0 is the angular frequency at which $H_d(\omega)=0$. Note that Eq. (2) is obtained by neglecting the dc and higher-order terms, which is valid for small signal modulation [15]. From Eq. (2), it is clearly seen that the photocurrent at the output of the PD is proportional to the first-order derivative of the applied electrical modulating signal. Therefore, if the modulation signal is a Gaussian pulse, a Gaussian monocycle would be generated at the output of the system. In addition, the sign of $I_0(t)$ is dependent on the sign of $(\omega_c - \omega_0)$, which can be adjusted by changing the location of the optical carrier at the left $(\omega_c < \omega_0)$ or right $(\omega_c > \omega_0)$ slope of the reflection spectrum of the corresponding FBG. Therefore, a Gaussian monocycle with either a positive or negative sign is generated by locating the optical carrier at the right or left slope of the FBG reflection spectrum. In the proposed DS-UWB encoding system, this important feature is used to generate bipolar UWB codes with a Gaussian monocycle and its inverted version representing a "+1" and a "–1," respectively, in the code sequence. At the output of the system, each Gaussian pulse is mapped to N Gaussian monocycle pulses with binary codes (+1 and −1). The optical intensity of the coded sequence is

$$I(t) = \sum_{n=1}^{N} a_n I_0(t - nT), \qquad (3)$$

where T denotes the time-delay difference between two adjacent chips in the code sequence, which is determined by the physical spacing between two adjacent FBGs, and $a_n \in \{1,-1\}$ is determined by the locations of the nth wavelength with respect to the slopes of the FBG reflection spectrum.

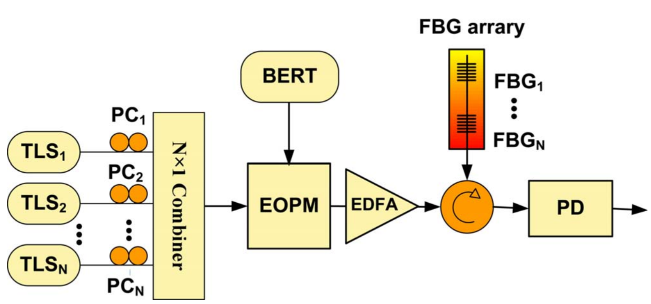

Fig. 1. (Color online) Diagram of the proposed bipolar DS-UWB encoding system. TLS, tunable laser source; PC, polarization controller; EOPM, electro-optic phase modulator; FBG, fiber Bragg grating; PD, photodetector; EDFA, erbium-doped fiber amplifier; BERT, bit-error-rate tester.

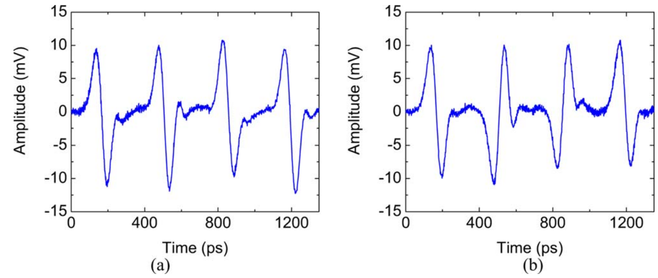

Fig. 2. (Color online) Bipolar DS-UWB codes realized by tuning the wavelengths of the input light waves at the opposite slopes of the FBG reflection spectra, (a) C1 =(M,M,M,M), (b) C2=(M,–M,–M,M).

The proposed approach is experimentally investigated. Based on the theory of direct-sequence communications, to accommodate N users the code length should be at least N [16]. To demonstrate the concept, an all-optical bipolar UWB encoding system with a code length of 4 to provide multiple access for four users is experimentally investigated. In the experiment, four tunable laser sources (TLSs) are used as the laser array. The data sequence applied to the EOPM is generated by a bit-error-rate tester, with a bit rate of 13.5 Gbits/s, and a fixed pattern of "10⋯0" (one "1" with 31 "0"), which is equivalent to a pulse train with a bit rate of about 420 Mbits/s and a duty cycle of 1/32. The pulse shape is close to Gaussian, with a FWHM of about 72 ps. The FBG array consists of four uniform FBGs, fabricated using a frequency-doubled argon-ion laser operating at 244 nm. The center reflection wavelengths of the four FBGs are 1549.53, 1550.38, 1551.36, and 1552.31 nm, each with a reflectivity higher than 90%. In the FBG writing process, a high-precision translation stage is used to scan the laser beam along the fiber, so that the physical spacing between two adjacent FBGs can be accurately controlled. In the experiment, the physical spacing between two adjacent FBGs is 35 mm, which corresponds to a time-delay difference of about 350 ps.

Bipolar encoding is realized by locating the wavelength of each TLS at the right or left slope of the corresponding FBG, to generate a positive or a negative monocycle pulse that represents a +1 or −1 in the code sequence. In the experiment, Walsh–Hadamard codes are selected as the orthogonal codes [16]. For a code length of 4, the four orthogonal codes are

$$\{(1,1,1,1),(1,-1,-1,1),(1,-1,1,-1),(1,1,-1,-1)\}.$$

Therefore, the corresponding UWB codes are

$$\{C1,C2,C3,C4\} = \{(M,M,M,M),(M,-M,-M,M),(M,-M,M,-M),(M,M,-M,-M)\},$$

where M denotes a single Gaussian monocycle pulse. In the experiment, the UWB code C1 is generated by tuning the wavelengths of the four TLSs to the right slopes of the four FBGs; another UWB code C2 is generated by tuning the wavelengths of TLS_2 and TLS_3 to the left slopes of FBG_2 and FBG_3. The waveforms of the two codes are shown in Figs. 2(a) and 2(b).

To demonstrate the feasibility, an example is given by considering two users, User1 and User2, with codes C1 and C2 as their signature codes. Two data sequences, D1="011001" and D2="010111," are encoded by using the signature codes C1 and C2. The waveforms of the two coded sequences (CS1 and CS2) are shown in Figs. 3(a) and 3(b). At the receiver, UWB decoding is realized by implementing the correlation between the received signals and the signature codes that are prestored at the receiver. For simplicity, in our demonstration we consider only back-to-back transmission, which means that the coded sequences at the transmitter end are directly used as the received signals for decoding. In this example, we show that a data sequence can be recovered through correlation with the same signature code that is used to make encoding. Figure 4(a) shows the correlation between CS2 and C2. As can be seen, the original data sequence D2=010111 is successfully recovered. The interference from CS1 is also studied by calculating the cross-correlation between CS1 and C2, as shown in Fig. 4(b). Comparing Fig. 4(b) with Fig. 4(a), it can be seen that the interference from CS1 is trivial, which demonstrates that there is little interference between User1 and User2 thanks to the orthogonality of the codes. Therefore, the feasibility of the proposed bipolar DS-UWB encoding scheme is verified.

The correlation results can be improved by extending the code length with the use of more wavelengths and FBGs. In the experiment, the light sources are tunable lasers with narrow linewidth. The use of lasers may cause instability owing to the optical interferences. This problem can be solved by replacing the laser array with a low-coherence multiwavelength light source such as a sliced amplified spontaneous emission (ASE) source.

In conclusion, an approach to all-optical bipolar direct-sequence coding for multiple access UWB communications was proposed. The bipolar encoding was realized based on optical phase modulation and PM-IM conversion in an FBG-based multichannel frequency discriminator, to generate complementary UWB monocycle pulses, with the code pattern determined by the locations of the optical wavelengths at the left or right slopes of the FBG reflection spectra. Bipolar encoding with a code length of 4 was experimentally demonstrated. For practical applications with more users, the code length should be extended, which requires more laser sources. A simple solution is to a use sliced amplified-spontaneous-emission (ASE) source. The use of a sliced ASE source will also solve the interference problem.

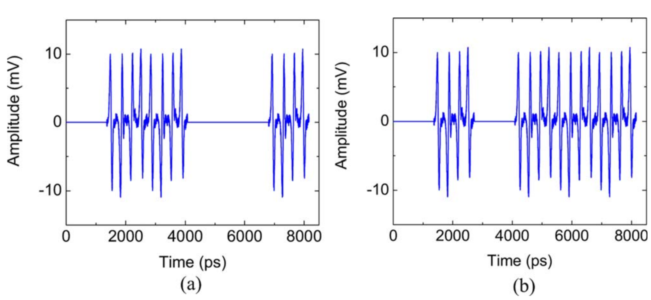

Fig. 3. (Color online) Waveforms of the bipolar direct-sequence coded sequences (a) CS1, (b) CS2.

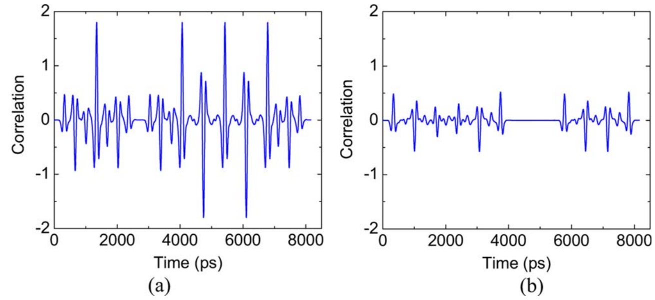

Fig. 4. (Color online) Correlation results between (a) C2 and CS2, (b) C2 and CS1.

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