High-Chip-Count UWB Biphase Coding for Multiuser UWB-Over-Fiber System

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***Abstract*—In this paper, we propose and demonstrate a novel technique to optically generate high-chip-count, phase-coded direct-sequence (DS) ultrawideband (UWB) signals for multiple-access UWB communications. In the proposed system, a lightwave from a laser source is phase-modulated by a Gaussian pulse train. The phase-modulated lightwave is then sent to a polarization modulator, to modulate the polarization state of the lightwave by a code pattern. The polarization-coded optical signal is then converted into a biphase-coded DS-UWB signal by a polarization-dependent frequency discriminator. The key device in the proposed system is the frequency discriminator, which is implemented using a length of polarization maintaining fiber (PMF) and a polarizer. A 127-chip, biphase-coding DS-UWB that has a data rate of 26.46 Mb/s and a chip rate of 3.36 Gb/s is experimentally generated. A multiuser UWB-over-fiber system is then proposed and a two-user system is demonstrated, in which the encoding is performed experimentally and the decoding is performed by numerically calculating the correlation between the coded UWB signal and the signature sequence. The signal of each user is well recognized. An effective two-user UWB-over-fiber system based on the DS-UWB technology is thus demonstrated.**

***Index Terms*—Code-division multiple access (CDMA), direct sequence (DS), phase coding, ultrawideband (UWB).**

I. Introduction

ULTRAWIDEBAND (UWB) technology has recently attracted considerable interest for short-rang, high-data rate wireless communications due to its unique advantages, such as immunity to multipath fading, extremely short-time duration, carrier-free, low-duty cycle, wide bandwidth, and low-power spectral density [1], [2]. UWB, approved in February 2002 by the U.S. Federal Communications Commission (FCC) for unlicensed use in a frequency band from 3.1 to 10.6 GHz, is considered a promising technology for future wireless communications and sensor networks. Due to the low-power density regulated by the FCC, the UWB communication distance is limited to a few meters to tens of meters. Such a short-range wireless network can operate mainly in indoor environments in a standalone mode, with a nearly nonexistent integration into the fixed wired networks or wireless wide area infrastructures. Therefore, new technologies are highly desirable to offer undisrupted services across different networks and eventually achieve a high-data rate access at any time and from any place. The convergence of optical and UWB technologies, to distribute UWB signals over fiber, or UWB over fiber, would be a promising solution to the above problems, to take advantage of the low loss and broad bandwidth offered by the state-of-the-art fibers. In addition, with the current stage of technology, it is hard and expensive to generate a UWB pulse with a fractional bandwidth even greater that 100% at the central frequency of about 7 GHz [3], [4]. However, optical signal processing technology has been well developed currently to tackle the problem. The generation and processing of UWB signals in the optical domain can benefit from the huge bandwidth offered by modern optics [5]–[11].

There are, in general, two types of UWB, the multiband UWB and the direct-sequence UWB (DS-UWB). DS-UWB is one of the most attractive techniques for UWB communications since it is carrier free, therefore there is no need for complicated frequency mixers and local oscillators to down- or up-convert the carrier frequency [12], [13]. In a DS-UWB system, information is represented by coded short pulses (in the order of a fraction of a nanosecond) with very small duty cycle. The DS-UWB signals can be realized by on–off keying (OOK), pulse position modulation (PPM), or binary phase-shift keying (BPSK). The BPSK is one of the most commonly used modulation schemes found in literature for impulse UWB systems since it offers an additional 3-dB signal-to-noise ratio (SNR) over the PPM and OOK schemes. In addition, the spectrum of a BPSK-modulated signal does not contain any spectral lines, which is advantageous when maximizing transmit power which is limited by the FCC mask. In the PPM or OOK schemes, however, the spectrum contains spectral lines even when modulated with a random data sequence, which requires a PPM or OOK transmitter to have a lower transmitting power compared to a BPSK transmitter [14].

Many optical techniques have been proposed and demonstrated to generate pulsed UWB signals. Among the numerous approaches, the phase modulation to intensity modulation (PM-IM) conversion is a simple and easy-to-realize technique for UWB monocycle and doublet pulse generation [9]. A few optical approaches have been demonstrated to generate biphase-coded UWB sequence for multiuser DS-UWB systems [15]–[18]. In [15], a fiber Bragg grating (FBG) array was used as a multichannel frequency discriminator to perform the PM-IM conversion, leading to the generation of a bipolar UWB code. Since an FBG array usually has a long physical length, especially for a code with a long code length, the system will be bulky and has poor stability. To reduce the size, we proposed to use a multichannel FBG [16], [17]. The UWB

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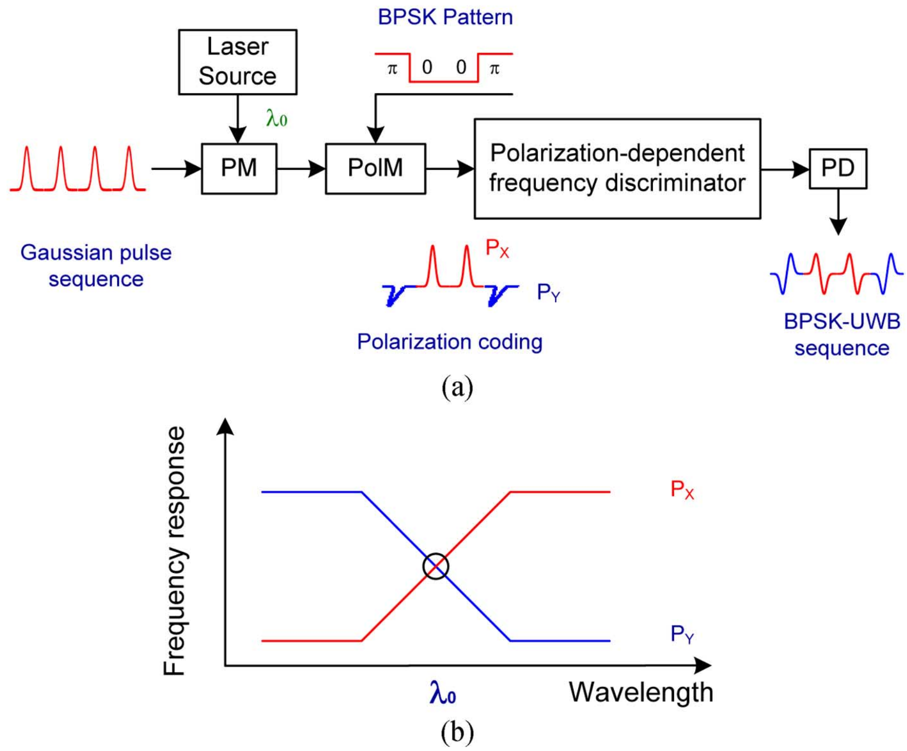

Fig. 1. (a) The proposed scheme for the generation of biphase-coded UWB signals. (b) Frequency response of the required polarization-dependent frequency discriminator.

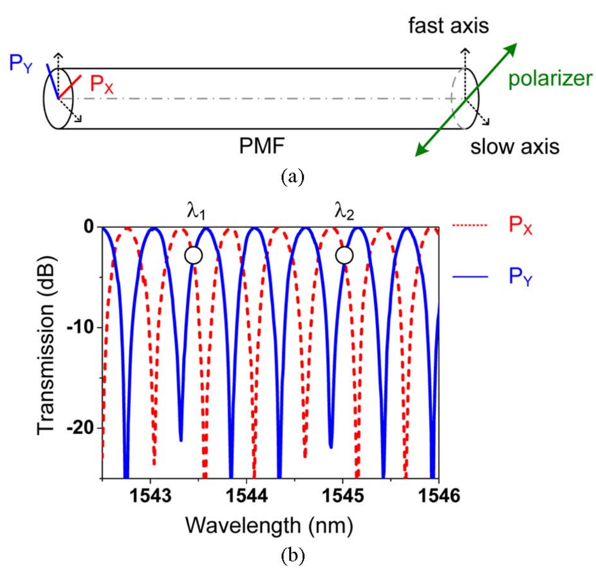

Fig. 2. (a) Polarization-dependent frequency discriminator which consists of a length of PMF and a polarizer. (b) Measured transmission spectrum of the filter.

encoding schemes in [15]–[17] were all implemented based on a multiwavelength source. For a UWB system having a data sequence with a long chip count, the number of wavelengths would be large, which may make it difficulty for practical implementation, since the chip count of the UWB sequence is equal to the number of the used wavelengths. On the other hand, to support more users, the chip count of the DS-USB sequence should be high.

In this paper, we propose and demonstrate a novel approach for optical generation of biphase-coded DS-UWB signals, in which the UWB sequence with arbitrary chip count could be generated with only a single wavelength. In the proposed scheme, a lightwave from a laser source is modulated by a Gaussian pulse train at a phase modulator. The phase-modulated lightwave is then sent to a polarization modulator, to modulate the polarization of the lightwave by a binary code pattern. The Gaussian pulse train is synchronized with the code pattern. Depending on the code that is 1 or 0, the polarization state of the lightwave is rotated by $\pi/2$ or 0. A polarization-dependent frequency discriminator (FD) is then used to perform PM-IM conversion, to generate a biphase UWB pulse sequence [9]. The proposed scheme is experimentally demonstrated. A biphase-coded UWB sequence with a chip length of 127 is generated, which has a data rate of 26.46 Mb/s and a chip rate of 3.36 Gb/s. Based on the encoding technique, a multiple-user system is then proposed, in which different users are represented by different phase code patterns. To prove the concept, a two-user system is demonstrated, in which the generated UWB sequences are decoded by performing correlation with the signature sequence of a specific user using a computer. The correlation results show that each user can be well recognized.

This paper is organized as follows. In Section II, the principle of the proposed UWB coding technique is first discussed. Then, the realization of the polarization-dependent, multichannel frequency discriminator is presented. In Section III, a 127-chip BPSK UWB sequence is generated based on the multichannel frequency discriminator. In Section IV, a multiuser UWB-over-fiber system is proposed based on the encoding scheme with a

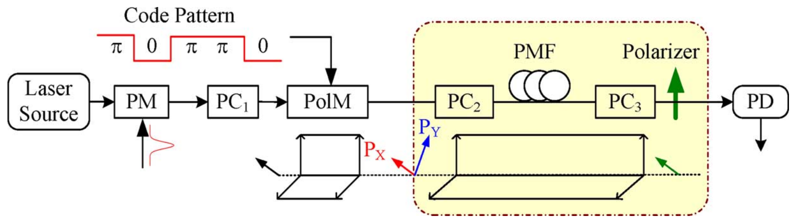

Fig. 3. Experiment setup for a single-user UWB biphase-coding system.

two-user system experimentally demonstrated. A conclusion is drawn in Section V.

II. Principle

The proposed scheme for a long-chip-count UWB biphase coding is illustrated in Fig. 1(a). The lightwave from a laser source is phase modulated by a Gaussian pulse train at a phase modulator. The phase-modulated lightwave is then sent to a polarization modulator (PolM), with its polarization state being modulated by a nonreturn-to-zero (NRZ) data sequence. The NRZ data sequence is the BPSK code pattern, which is synchronized with the Gaussian pulse train. A polarization-dependent frequency discriminator is connected at the output of the PolM. Depending on the polarization state of the lightwave, a UWB pulse with or without polarity inversion is generated thanks to the PM–IM conversion at the polarization-dependent frequency discriminator. The key device in the proposed scheme is the polarization-dependent frequency discriminator, which should be designed to have a frequency response depending on the polarization state of the input lightwave, as shown in Fig. 1(b).

In the proposed system, the polarization-dependent frequency discriminator is implemented using a length of polarization maintaining fiber (PMF) and a polarizer, as illustrated in Fig. 2(a).

The polarization axis of the polarizer should be oriented at an angle of 45° with respect to the output principle axis of the PMF, as shown in Fig. 2(a). In our demonstration, the PMF has a beat length of 3.75 mm. The total length of the PMF is about 11.7 m. If the input polarization state P_X is oriented at an angle of 45° to the input principal axis of the PMF, as shown in Fig. 2(a), the transmission spectrum of the PMF followed by the polarizer corresponds to a multichannel filter, with a free spectral range (FSR) of 0.52 nm, as shown by the dashed line in Fig. 2(b). If the input polarization state is at P_Y, which is oriented at an angle of 135° to the principal axis of the PMF, the transmission spectrum is then shifted by a half FSR, as shown by the solid line in Fig. 2(b). When the wavelength of the input light is located at one of the cross points of the two transmission spectra, e.g., λ_1 and λ_2 in Fig. 2(b), the filter is then the required polarization-dependent frequency discriminator. Obviously, the proposed frequency discriminator has a multichannel response, which is useful when there are multiple users (wavelengths).

III. 127-Chip BPSK UWB Coding

Based on the above principle, the UWB biphase coding for a single user is experimentally demonstrated in this section. The experiment setup is illustrated in Fig. 3.

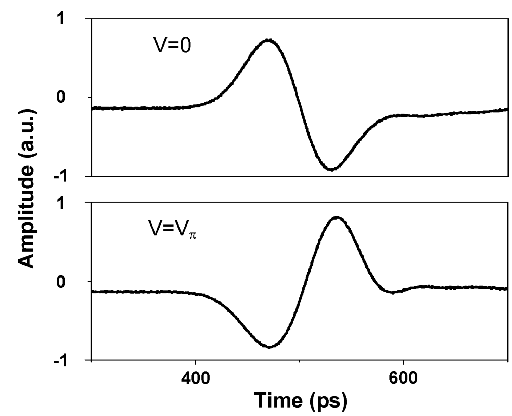

Fig. 4. Generated monocycle pulses with opposite polarities when the input polarization state to the frequency discriminator is switched by the PolM.

The PolM used in the system is a special phase modulator, which supports both TE and TM modes with however opposite phase modulation indices [19]. The polarization state of the input lightwave to the PolM is oriented at an angle of 45° to one principle axis of the PolM by using a polarization controller (PC_1). If the PolM is driven by 0 or a half-wave voltage V_π, a lightwave with either of the two orthogonal polarization states, illustrated as P_X and P_Y in Fig. 1(a), will then be obtained. If the PolM is driven by a binary sequence with voltages of 0 and V_π, corresponding to the desired phase code pattern, the code pattern is then encoded into the polarization state of each phase-modulated pulse.

In our single-user experiment, the wavelength of the laser source is tuned at λ_1, as shown in Fig. 2(b), where the magnitudes of transmission are identical with however opposite slopes for P_X and P_Y. By controlling the voltage applied to the PolM to be 0 or V_π, the spectrum of the frequency discriminator is shifted between the solid and the dashed lines, with positive or negative slope of the frequency discriminator being used for PM–IM conversion. A Gaussian monocycle with opposite polarities is then generated. In our experiment, the electrical Gaussian pulse train driving the PM has a full-width-at-half-maximum (FWHM) of 63 ps and a data rate of 3.36 Gb/s. The PolM is driven by an NRZ code with the same data rate to ensure a good synchronization between the Gaussian pulse train and the NRZ code. Fig. 4 shows the generated Gaussian monocycles with opposite polarities, measured by a high-speed sampling oscilloscope.

The long-chip-count phase coding can be easily achieved by inputting the corresponding NRZ data into the PolM. Fig. 5 shows a binary-phase-coded monocycle sequence when the

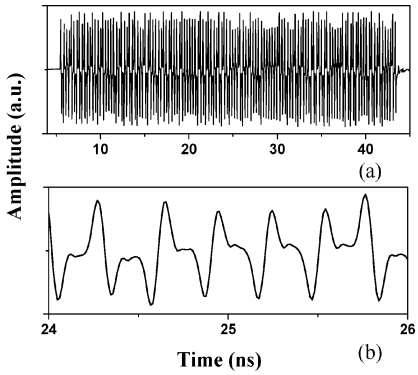

Fig. 5. (a) Measured 127-chip binary-phase-coded monocycle sequence and (b) its zoom-in display.

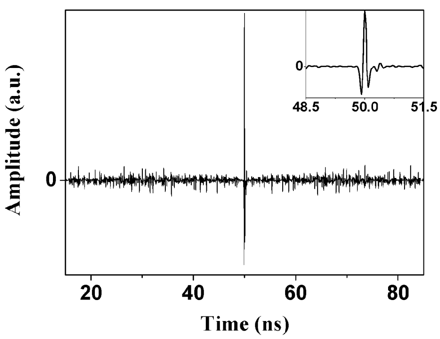

Fig. 6. Decoded signal by calculating the correlation between the measured signal in Fig. 5 and the signature sequence; the insert gives a zoom-in display.

NRZ code is a 127-chip M-sequence (marked as C_0). Since the chip rate is 3.36 Gb/s, a code length of 127 corresponds to a data rate of 26.456 Mb/s. The output RF power is -12 dBm from the PD. In a practical UWB-over-fiber system, a PD with a high output power is required in order to increase the radiation power. The decoding can be implemented in a UWB receiver by performing correlation between the encoded signal and a signature sequence [20], [21], just like in a DS-CDMA system. In this paper, the decoding process is done by calculating the correlation between the measured signal and the signature sequence, which is the theoretical (ideal) monocycle sequence with the same phase code pattern used in the experiment. The autocorrelation is plotted in Fig. 6, and a high autocorrelation peak is observed.

In the previous approaches, the digital data of a user are loaded through the PM [15]–[17]. Here we propose a code switch scheme where a user data sequence and the code pattern are both loaded through the PolM. In our design, the digital information "1" and "0" are represented by two code patterns (M-sequences) C_1 and C_0, respectively, with good autocorrelation and cross-correlation properties. Since the two codes have good orthogonality, the digital information can be recognized simply by performing matched filtering at the receiver. Then the PM is only driven by a periodic Gaussian pulse train, and such a scheme will simplify the system design when multiple users are required, which will be discussed in Section IV.

To demonstrate the use of the proposed code switch scheme in the DS-UWB system, we transmit a signal of four bits $(1, 0, 0, 1)$ by the two code patterns C_1 and C_0. The measured

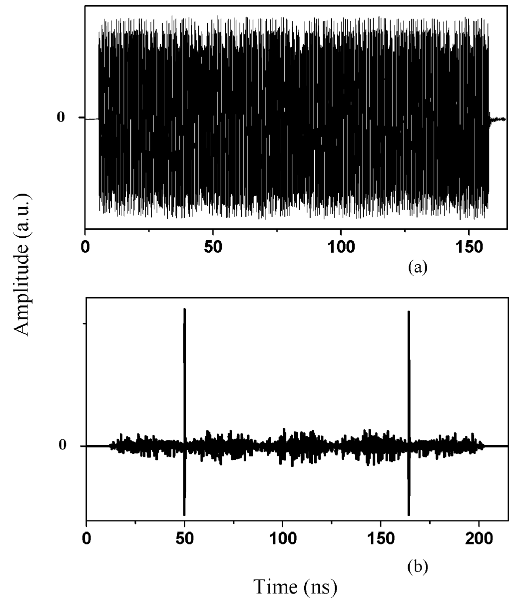

Fig. 7. (a) Encoded signal when the code switch scheme is used. (b) Recovered signal by the correlator.

encoded signal is plotted in Fig. 7(a). At the receiver, the encoded signal can be decoded by a correlator corresponding to C_1. Here we simulate such a process by calculating the cross correlation between the received signal and the signature sequence corresponding to C_1. The decoded signal is plotted in Fig. 7(b). Obviously, the original signal $(1, 0, 0, 1)$ is recognized successfully.

IV. Multiuser UWB-Over-Fiber System

Since only one wavelength is required for one user, a multiple-user UWB-over-fiber system could be easily achieved by this technique with multiple wavelengths, as shown in Fig. 8. For a system with N users, an N-wavelength source, N PolMs, and a pair of Mux and DeMux are required. In addition, N PMs may also be required by which the data of the N users are loaded. However, as we discussed in Section III, if the code switch scheme is used, both the code pattern and the user information are loaded through the PolM, and only a periodic Gaussian pulse train is inputted into the PM. Therefore, only one PM is required in the whole system, which simplifies greatly the system.

To demonstrate a simple multiuser UWB-over-fiber system, we assume that system supports two users and the transmitted data are all "1s" for each user in our experiment. As shown in Fig. 8, two laser sources, with wavelengths of λ_1 and λ_2 as shown in Fig. 2(b), are combined and phase modulated by a Gaussian pulse train, then demultiplexed and encoded at the PolMs which are driven by two 127-chip M-sequences C_{11} and C_{21} with good autocorrelation and cross- correlation properties. Then, the two lightwaves are combined at the multiplexer and pulse shaped by the multichannel FD. The output is the sum of the signals of the two users, and measured by a high-speed sampling oscilloscope, which is plotted in Fig. 9(a).

For practical applications, the output signal from the PD could be radiated to free space by a UWB antenna and then

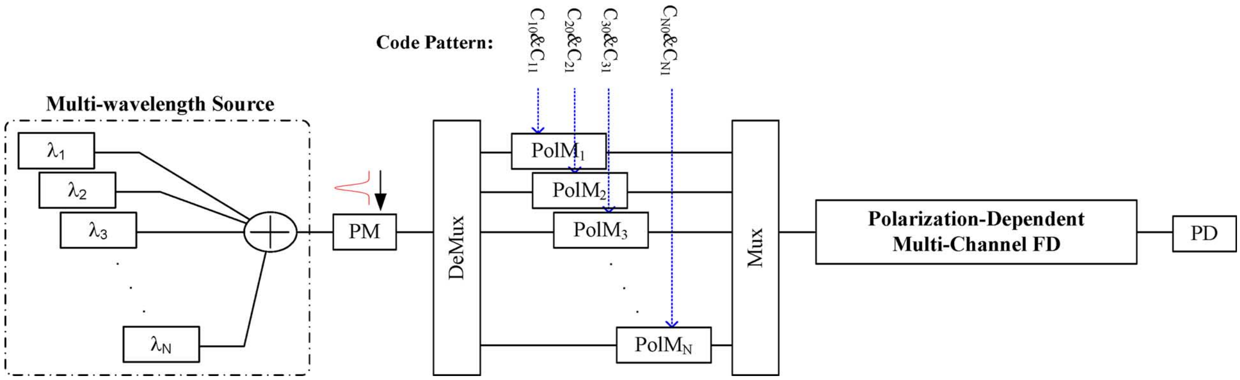

Fig. 8. Multiuser UWB-over-fiber system based on DS-UWB.

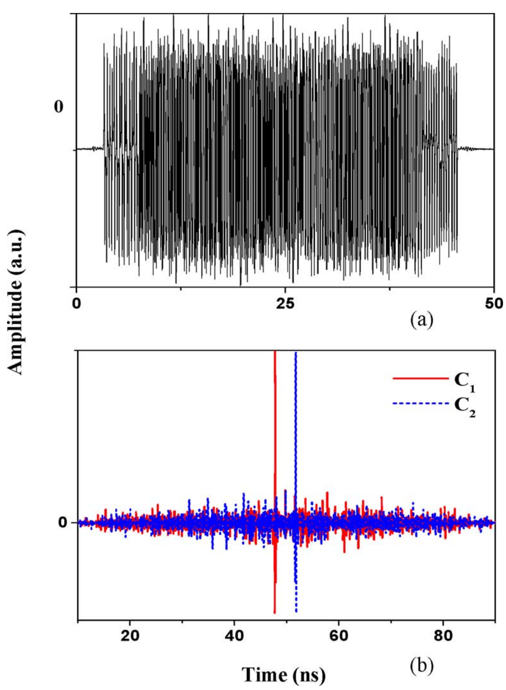

Fig. 9. (a) Output signal of a two-user UWB-over-fiber system. (b) Decoded signals by calculating the correlation between the measured encoding signal in (a) and the signature sequences corresponding to C_{11} and C_{21}.

received by the users. Since the code patterns of the two users are orthogonal, the wireless UWB receiver can then recognize the data of the specific user by matched filtering or correlation using the corresponding signature sequence. For the two-user system, the signature sequences are the simulated monocycle sequences corresponding to patterns C_{11} and C_{21}. The decoded signals are plotted in Fig. 9(b). Clearly, the signal of each user is well recognized. An effective dual-user UWB-over-fiber system based on the DS-UWB technology is thus demonstrated. We should note that in a real system, the free-space propagation will introduce signal distortions due to the varying spectral amplitude response either from the antenna or the fundamental propagation effects or from the varying spectral phase response. Such distortions would degrade the orthogonality of the generated codes, which could be a challenge for a real system implementation [5], [21].

V. Conclusion

In this paper, we proposed and experimentally demonstrated a novel approach for optical generation of DS-UWB signals. Biphase-coded 127-chip UWB sequences were experimentally generated, based on which a dual-user UWB-over-fiber system was implemented. The proposed technology has the following advantages: 1) only a single wavelength is required for one user, and the code pattern could be very long and software defined; 2) the multiuser system has a simple structure and the implementation of the system can benefit from the well-developed wavelength division multiplexing (WDM) technology.

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