© DIGITAL STOCK

Jianping Yao

Photonics for Ultrawideband Communications

Ultrawideband (UWB) for applications such as broadband wireless communications have been a topic of interest recently. Due to the low power density regulated by the Federal Communications Commission (FCC), the communication distances are limited, typically extending less than 100 meters. To increase the area of coverage, UWB signals should be distributed over wired lines such as coaxial cable or optical fiber. Thanks to the low loss and broad bandwidth of state-of-the-art fiber, the distribution of UWB signals over optical fiber, or UWB-over-fiber, is considered a promising solution. In this article, the concept of UWB-over-fiber is briefly introduced, and different techniques for generating and encoding impulse UWB signals in the optical domain is discussed. The challenges of implementing UWB-over-fiber systems is also examined.

UWB impulse technology has been around for a few decades and has been applied mainly to radar systems. Its application to broadband wireless communications has only recently been explored. As defined in Part 15 of the FCC regulations [1]–[4], a UWB impulse signal should have a fractional bandwidth larger than 20% or a 10-dB bandwidth of at least

Jianping Yao (jpyao@site.uOttawa.ca) is with the Microwave Photonics Research Laboratory, School of Information Technology and Engineering, University of Ottawa, Ottawa, Ontario, Canada.

Digital Object Identifier 10.1109/MMM.2009.932287

500 MHz. The UWB frequency mask defined by the FCC is shown in Figure 1. As can be seen, the frequency band assigned to UWB indoor communications systems extends from 3.1 GHz to 10.6 GHz, with a bandwidth of 7.5 GHz centered around 7 GHz. The power density is limited to −41.3 dBm/MHz.

Due to the low power density regulated by the FCC, the wireless transmission distance for UWB communications is limited to a few meters to tens of meters. Such a short-range communications network can only operate in a stand-alone mode. To increase the coverage area and integrate the local UWB environment into fixed wired networks or wireless wide-area infrastructures, UWB signals can be distributed using wired lines made of coaxial cable or optical fiber. Thanks to the low loss and broad bandwidth of state-of-the-art fiber, the distribution of UWB signals over fiber, a new technology, termed *UWB-over-fiber* [5], is considered a promising solution. Figure 2 shows a UWB-over-fiber system for broadband indoor wireless access. In the system, UWB signals are generated and encoded in the central office and distributed over optical fiber to the access points. At the access points, the UWB signals in the optical domain are converted to the electrical domain and then radiate to free space. For upstream signal transmission, considering the low-data-rate nature of upstream transmission, a simple and mature wireless communication technique (such as a wireless local-area network) would be used. Therefore, the entire UWB-over-fiber system would be operating in a hybrid mode to take advantage of the high-data-rate feature of UWB for downstream signal distribution and the low cost of a mature wireless communication technology for upstream transmission.

In addition to the distribution of UWB signals over optical fiber, it is also desirable that UWB signals be generated and encoded directly in the optical domain, without the need for extra optical-electrical and electro-optical conversions, to fully exploit the advantages provided by optics. Moreover, using optical techniques to generate UWB signals has many other advantages, such as light weight, small size, large tunability, and immunity to electromagnetic interference.

There are, in general, two types of UWB technologies, direct-sequence UWB [6] and multiband UWB [7]. Direct-sequence impulse radio is one of the most attractive techniques for UWB communications since it is carrier-free, and there is thus no need for complicated frequency mixing and bandpass filtering to down- or up-convert to the carrier frequency. The selection of the impulse types is one of the fundamental considerations in designing impulse UWB systems, because the impulse types determine the performance of a UWB communications system. As discussed in [8], Gaussian monocycle and doublet pulses can provide better bit error rate (BER) and multipath performance among different impulse signals.

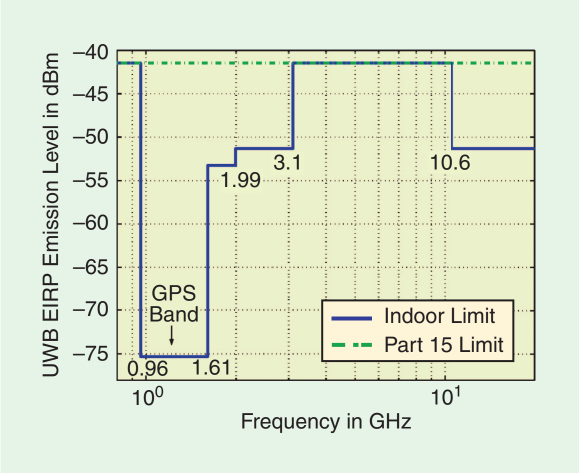

Figure 1. *The ultrawideband frequency mask defined by the FCC for ultrawideband indoor communications (from [4]).*

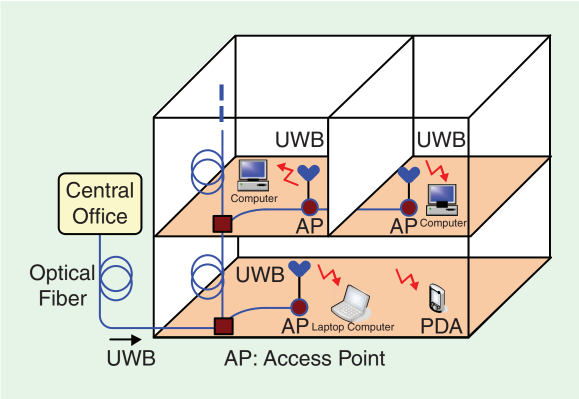

Figure 2. *Ultrawideband-over-fiber system for broadband indoor wireless access (from [5]).*

These waveforms can be created by bandpass filtering a Gaussian pulse, which is equivalent to the implementation of different orders of differentiation of a Gaussian pulse. For instance, a Gaussian monocycle can be generated by performing the first-order derivative of a Gaussian pulse, and a Gaussian doublet can be generated by performing the second-order derivative of a Gaussian pulse [1]. With the current stage of technology, however, it is rather expensive and difficult to generate such a pulse with a fractional bandwidth even greater than 100% at the center frequency of around 7 GHz [9]–[11]. An effective solution for generating impulse UWB signals is to use optical technology so as to take advantage of the broadband and low-loss nature of modern optics.

Optical generation of impulse UWB signals has been summarized recently [5], with all techniques classified into three categories. Here we summarize these techniques for the general reader. To support multiuser UWB communications, impulse UWB signals must be encoded, with specific codes representing specific users. At a receiver, UWB signals can then be decoded based on correlation.

Photonic Generation of Impulse UWB Signals

Several approaches have been proposed for generating impulse UWB signals in the optical domain. These approaches can be classified into three categories [5]:

1) *UWB pulse generation based on first- or second-order differentiation of a Gaussian pulse.* A simple solution for realizing first- or second-order differentiation is to implement optical phase modulation and phase modulation to intensity-modulation (PM-IM) conversion [12].
2) *UWB pulse generation based on first- or second-order differencing of a Gaussian pulse.* Since a first- or second-order differentiation can be approximated by a first- or second-order difference, a UWB pulse can be generated based on first- or second-order differencing of a Gaussian pulse. This can be achieved by using a photonic microwave delay-line filter [13]. To generate a UWB monocycle, a two-tap microwave delay-line filter with two coefficients of [1, -1] is needed, while to generate a UWB doublet, a three-tap microwave delay-line filter with three coefficient of [1, -2, 1] is needed.
3) *UWB pulse generation based on optical spectral shaping and frequency-to-time mapping [14], [15].* Usually, the spectrum of an ultrashort pulse is shaped by an optical filter to give the spectrum a shape identical to that of a UWB monocycle or doublet. The conversion of the spectrum-shaped pulse from the spectral domain to the temporal domain is realized from wavelength-to-time mapping using a dispersive element. Each of these three techniques is described in more detail in the following.

Impulse UWB Signal Generation Based on First- or Second-Order Differentiator

In addition to simplicity and achievability, the use of Gaussian monocycle and doublet pulses in an impulse UWB communications system can also provide better BER and multipath performance. Mathematically, a Gaussian monocycle or doublet can be generated by performing a first- or second-order differentiation of a Gaussian pulse. Figure 3 shows the generation of a Gaussian monocycle or doublet pulse using a first- or second-order differentiator. To implement the differentiation in the optical domain, an electrical Gaussian pulse should be first converted to the optical domain using an intensity modulator.

Various techniques have been proposed for realizing an optical differentiator. In this article, we will discuss a simple technique based on optical phase modulation and PM-IM conversion, as shown in Figure 4.

Assume the input to the phase modulator is an electrical Gaussian pulse $s(t)$. As a result, the phase of the input light wave is modulated. The electrical field of the phase-modulated light wave can be expressed [16] as

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

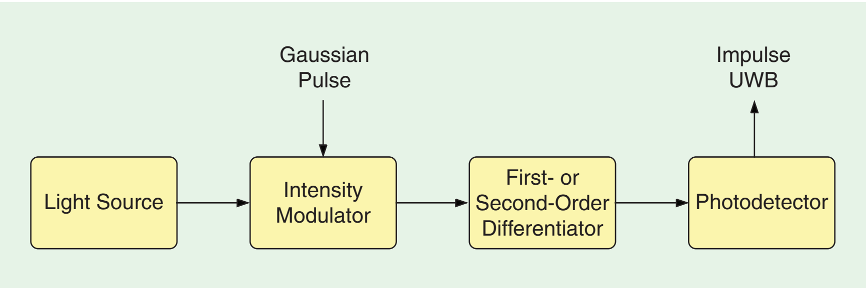

Figure 3. *Generation of an ultrawideband monocycle or doublet pulse using a first- or second-order differentiator.*

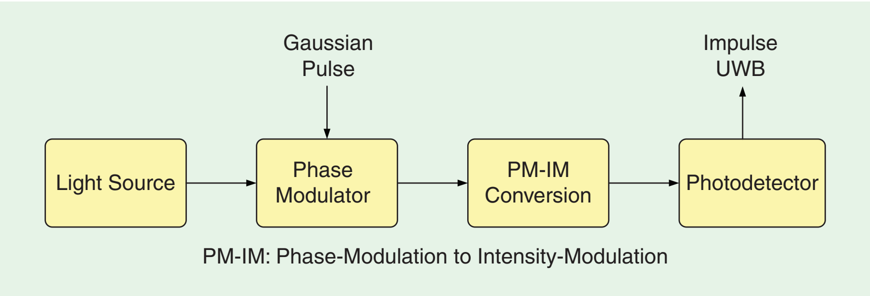

Figure 4. *Ultrawideband pulse generation based on phase modulation and phase-modulation to intensity-modulation conversion.*

where β_{PM} is the phase-modulation index and ω_c is the angular frequency of the optical carrier. The phase-modulated light wave is then fed to an optical frequency discriminator, which is usually an optical filter with a transfer function having two opposite linear slopes. When the optical carrier is located at one of the two opposite linear slopes, PM-IM conversion is realized.

It is known that a linear frequency discriminator has a frequency response given by

$$H_d(\omega) = K(\omega - \omega_0), \quad (2)$$

where K denotes the slope of the frequency response and ω_0 is the angular frequency for $H_d(\omega) = 0$. When the phase-modulated light is sent to the linear frequency discriminator, the output signal in the frequency domain is given by

$$A_{\mathrm{out}}(\omega) = K(\omega - \omega_0)A(\omega), \quad (3)$$

where $A(\omega)$ is the Fourier transform of $A(t)$. We obtain (3) based on the convolution property. For a linear time-invariant system, in the frequency domain the output is a multiplication of the Fourier transform of the input signal and the frequency response of the system.

Applying the inverse Fourier transform to (3), we obtain the signal in the time domain

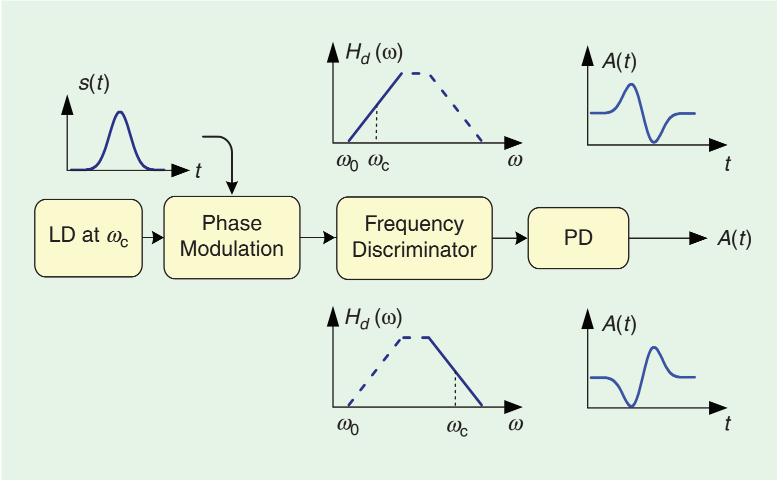

Figure 5. *Gaussian monocycle pulse generation based on frequency discrimination.*

$$A_{\mathrm{out}}(t) = [K(\omega_c - \omega_0) + K\beta_{PM}s'(t)]\,A(t), \quad (4)$$

where $s'(t)$ is the first-order derivative of $s(t)$. After photodetection at the photodetector, we obtain the photocurrent, given by

$$i_{PD}(t) = K^2(\omega_c - \omega_0)^2 + K^2\beta_{PM}^2[s'(t)]^2 + 2K^2(\omega_c - \omega_0)\beta_{PM}s'(t) \quad (5)$$

The first term on the right-hand side in (5) is a dc term. For a small phase-modulation index, we usually have $2K^2(\omega_c - \omega_0)\beta_{PM}s'(t) \gg K^2\beta_{PM}^2[s'(t)]^2$, so the term $K^2\beta_{PM}^2[f'(t)]^2$ can be neglected and the ac term of the photocurrent at the output of the photodetector is

$$i_{\mathrm{sig}}(t) = 2K^2(\omega_0 - \omega_1)\beta_{PM}s'(t). \quad (6)$$

From (6), we can see that the detected signal after the photodetector is proportional to the first-order derivative of the applied modulating signal. Therefore, if the phase-modulating signal is a Gaussian pulse, a Gaussian monocycle would be generated, as shown in Figure 5. In addition, the sign of $i_{sig}(t)$ in (6) is determined by $(\omega_c - \omega_0)$. If $(\omega_c - \omega_0) > 0$, $i_{sig}(t)$ has the same waveform as $s'(t)$, while if $(\omega_c - \omega_0) < 0$, $i_{sig}(t)$ is an inverted version of $s'(t)$.

If the optical carrier is located at the left slope of the transfer function, as shown in Figure 5, we have $(\omega_c - \omega_0) > 0$. If it is located at the right slope, we have $(\omega_c - \omega_0) < 0$. Therefore, by locating the optical carrier at either slope of the optical bandpass filter, UWB pulses with inverted polarities can be generated, as shown in Figure 5.

The approach to generating UWB monocycle or doublet based on optical phase modulation and PM-IM conversion has been experimentally demonstrated. As shown in Figure 6, a light wave from a laser diode is fed to an optical phase modulator driven by a Gaussian pulse. The phase-modulated optical signal is then applied to a fiber Bragg grating (see "Fiber Bragg Grating") via an optical circulator. The PM-IM conversion is achieved at the fiber Bragg grating, which serves as a frequency discriminator. The converted signal is then detected at a photodetector.

When the optical carrier is located at A, as shown in Figure 6, a positive monocycle will be generated. If the optical carrier is located at the opposite slope of the fiber Bragg grating reflection spectrum, as shown in Figure 6 at D, the output pulses will be a monocycle with opposite polarity. This feature

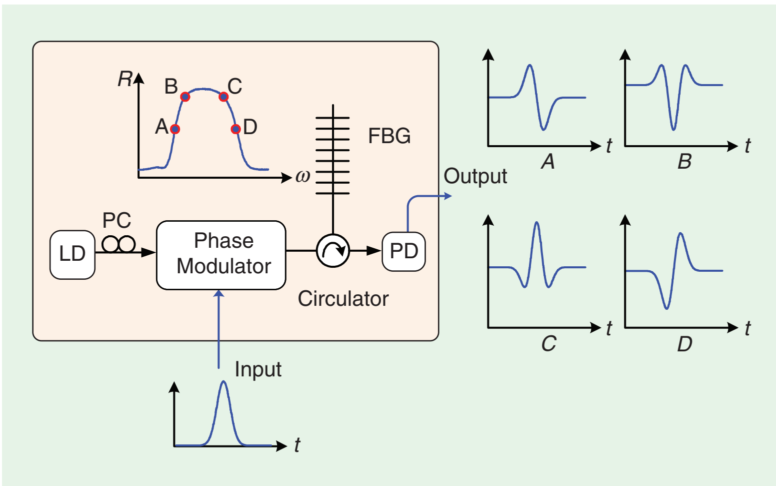

Figure 6. *Experimental setup for ultrawideband pulse generation based on phase modulation and phase-modulation to intensity-modulation conversion.*

Fiber Bragg Grating

A fiber Bragg grating is a fiber-optic device that is produced by ultraviolet illumination of a fiber core in order to periodically change the refractive index. If the grating period is Λ and the effective refractive index of the fiber core is n_{eff}, then we have $2n_{eff}\Lambda = \lambda_B$, which is called the *Bragg condition*; λ_B is called the Bragg wavelength. If a broadband light source is sent to the grating, the wavelength component at the Bragg wavelength will be reflected, and the wavelength components at other wavelengths will be transmitted. Due to this wavelength-selective property, a fiber Bragg grating is used for narrow-band filtering in fiber-optic systems. If the grating period is a constant over the entire grating, then the grating is called a uniform fiber Bragg grating, as shown in Figure S1. If the grating period is not constant, then the grating is a chirped Bragg grating. The simplest type of chirped Bragg grating is one where the variation in the grating period is linear; the grating is called a linearly chirped grating, as shown in Figure S2. A chirped Bragg grating has a broader bandwidth, which can be used for broadband filtering. In addition, a linearly chirped Bragg grating has a linear group delay response, which can be used for dispersion compensation in an optical transmission system.

Cross gain modulation: In an active optical device, for example, a semiconductor optical amplifier, when an input optical signal is sent along with a continuous-wave probe into the semiconductor optical amplifier, cross gain modulation results. The probe will be amplified when the input signal is at low level, and the

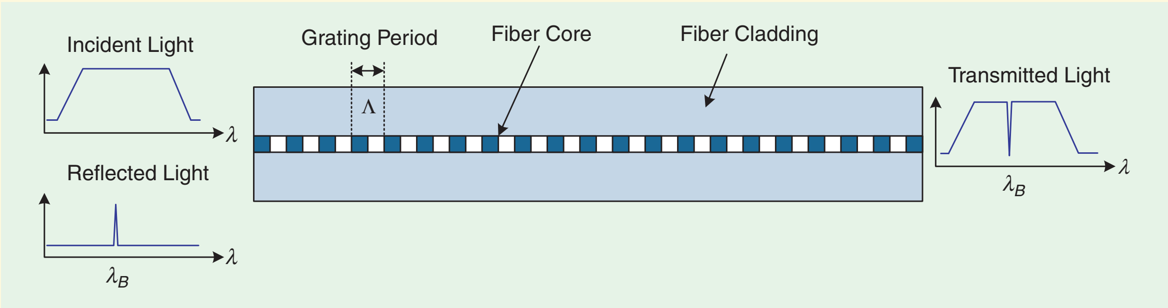

Figure S1. *A uniform fiber Bragg grating.*

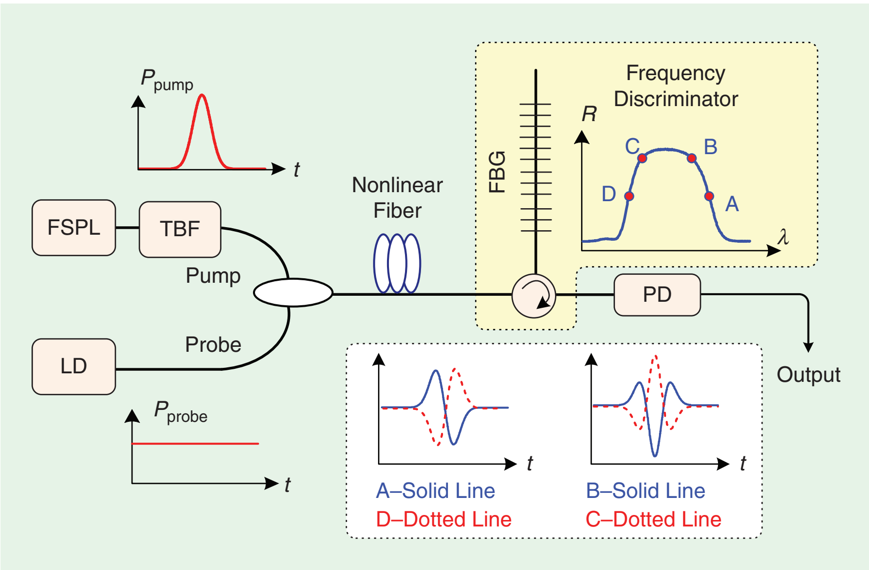

Figure 7. *An all-optical ultrawideband pulse generator. The Gaussian pulse is generated by a femtosecond pulse laser with its spectrum sliced by a tunable bandpass filter to control the pulse width. Phase modulation is achieved in the 400-m dispersion-shifted fiber due to cross-phase modulation. LD: laser diode. PD: photodetector. FBG: fiber Bragg grating. FSPL: femtosecond pulsed laser. TBF: tunable bandpass filter.*

enables the realization of pulse polarity modulation when two optical carriers corresponding to these two complementary pulses are employed and switched by a data sequence. In addition, if the optical carrier is located at the quadrature slopes of the fiber Bragg grating reflection spectrum, as shown in Figure 6 at B and C, two complementary UWB doublets are generated. Therefore, by placing the optical carrier at different locations, UWB pulses with different shapes can be generated, and eventually the implementation of pulse shape modulation is possible.

We should note that in the systems shown in Figure 6, the input Gaussian pulse

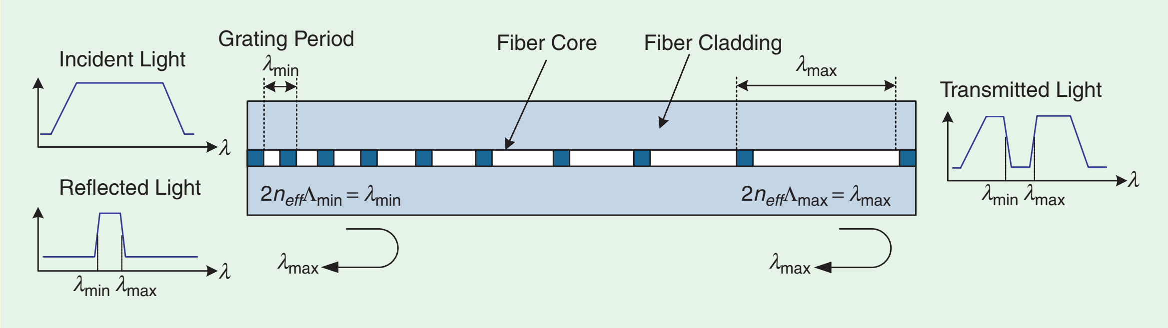

Figure S2. *A chirped fiber Bragg grating.*

probe will get little or no amplification when the input signal is at higher level due to the gain saturation of the amplifier. Figure S2 shows a setup to generate a 180°-phase-shifted microwave signal based on cross gain modulation in a semiconductor optical amplifier. As can be seen, a microwave signal carried by an optical carrier at λ_1 is sent to the amplifier with a continuous-wave probe at λ_2. Due to the cross gain modulation in the semiconductor optical amplifier, the microwave signal carried by λ_1 will be transferred to λ_2 with a π phase shift.

Cross phase modulation is a nonlinear phenomenon in which the phase of one optical wave is modulated by another optical wave due to the change of refractive index of the optical medium by the modulating optical wave.

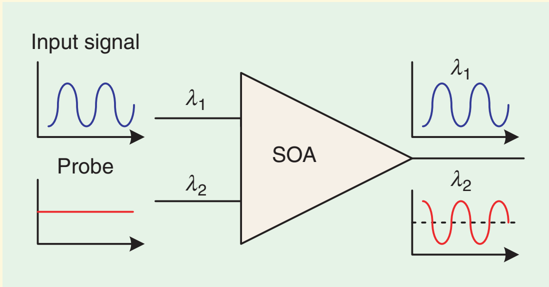

Figure S3. *Cross gain modulation in a semiconductor optical amplifier (SOA). The input signal is carried by an optical carrier at a wavelength of λ_1. A continuous-wave optical probe at a wavelength of λ_2 is sent to the semiconductor optical amplifier. At the output of the semiconductor optical amplifier, two complementary microwave signals carried by the optical carriers at λ_1 and λ_2 are obtained.*

is generated electrically using a pulse generator, and the phase modulation is implemented using an optical phase modulator. Therefore the system is not entirely optical. To implement all-optical impulse UWB signal generation, the Gaussian pulse should be generated in the optical domain. One solution is to use a mode-locked pulsed-laser source. In addition, the optical phase modulation should also be implemented in the optical domain. This can be accomplished using optical cross-phase modulation (see sidebar) in a nonlinear element such as a length of nonlinear fiber.

Figure 7 shows an all-optical UWB pulse generation system [17]. The optical Gaussian pulse is generated using a femtosecond pulse laser and the phase modulation is implemented based on cross-phase modulation in a length of nonlinear fiber. To control the pulse width, a tunable bandpass filter is incorporated after the femtosecond pulse laser. The generated optical pulse is then injected together with a continuous-wave probe into a length of dispersion-shifted fiber serving as a nonlinear element to achieve optical cross-phase modulation. The phase-modulated signal carried by the probe is then converted to an intensity-modulated signal at a fiber Bragg grating–based frequency discriminator. Note that the fiber Bragg grating also serves as an optical bandpass filter to remove the residual pump signal and the amplified spontaneous emission noise from the erbium-doped fiber amplifier. Depending on the location of the probe at the left or right (linear or quadrature) slope of the fiber Bragg grating reflection spectrum, a UWB monocycle or doublet, with or without polarity inversion, is generated.

Impulse UWB Signal Generation Based on a Photonic Microwave Delay-Line Filter

A Gaussian monocycle or doublet can also be generated by performing the first- or second-order derivative of a Gaussian pulse [8]. Mathematically, the first- or second-order derivative can be approximated by the first- or second-order difference, which can be implemented using a two- or three-tap photonic microwave delay-line filter with coefficients of [1, –1] or [1, –2, 1].

Figure 8 shows a two-tap photonic microwave filter for the generation of a UWB monocycle. To implement the filter, a negative coefficient must be generated. A variety of approaches have been proposed for the

UWB impulse technology has been around for a few decades, but its application to broadband wireless communications has only recently been explored.

generation of negative coefficients. Figure 9 shows a technique to generate a negative coefficient based on cross-gain modulation (defined in "Fiber Bragg Grating") in a semiconductor optical amplifier [18]. The function of the semiconductor optical amplifier in the system is to generate a negative coefficient based on cross-gain modulation. As can be seen in Figure 9, two light waves, one a high-power pulsed light wave (the pump, modulated by a Gaussian pulse) and the other a low-power CW light wave (the probe), are injected into the semiconductor optical amplifier.

Due to the cross-gain modulation, the power of the probe varies inversely with the pump power. A pair of complementary optical pulses is thus generated, with one at the pump wavelength and the other at the probe wavelength. By introducing a proper time-delay difference between the two pulses, a UWB monocycle is generated. The system shown in Figure 9 is one of the many photonic microwave delay-line filters that can be used for UWB pulse generation. The pulse width of the monocycle can be adjusted by adjusting the time-delay difference so as to make its spectrum meet the FCC spectrum mask. Figure 10(a) shows a UWB monocycle pulse generated based on a photonic microwave delay-line filter with one negative tap. The spectrum of the monocycle pulse is shown in Figure 10(b).

Similarly, a UWB doublet can be generated using a three-tap photonic microwave filter with three coefficients [1, −2, 1], as shown in Figure 11. Again, the negative tap can also be generated using a semiconductor optical amplifier, as shown in Figure 12. Due to the cross-gain modulation in the semiconductor optical amplifier, the pulse carried by the pump is cross-gain-modulated on the two probes with polarity inversion. The three pulses are then reflected by three fiber Bragg gratings that are physically separated to

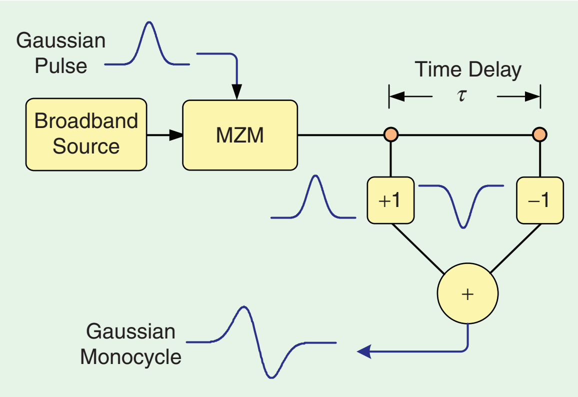

Figure 8. *Ultrawideband monocycle generation based on a two-tap microwave delay-line filter with one negative coefficient. MZM: Mach-Zehnder modulator.*

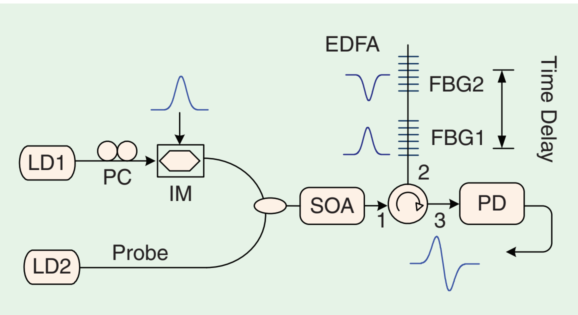

Figure 9. *Ultrawideband monocycle generation based on a two-tap photonic microwave delay-line filter using a semiconductor optical amplifier. PC: polarization controller. IM: intensity modulator. EDFA: erbium-doped fiber amplifier. SOA: semiconductor optical amplifier.*

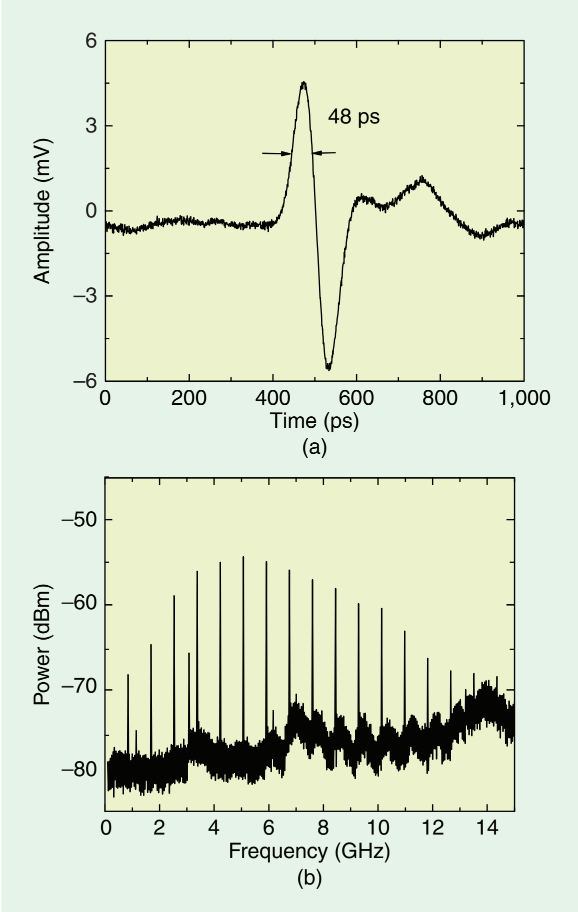

Figure 10. *Ultrawideband monocycle pulse generated using a two-tap photonic microwave filter with one negative coefficient generated based on cross-gain modulation in a semiconductor optical amplifier; (a) the temporal waveform and (b) its spectrum.*

introduce a proper time-delay difference. The power ratio of 1:2:1 of the three powers can be achieved by either tuning the power of the three laser diodes or designing the fiber Bragg gratings to have reflectivities with a ratio of 1:2:1.

Impulse UWB Signal Generation Based on Optical Spectral Shaping and Frequency-to-Time Mapping

UWB pulses can also be generated based on spectral shaping and frequency-to-time mapping [14], [15]. Similar to an optical lens that can perform real-time spatial Fourier transformation, an optical dispersive element can perform real-time temporal Fourier transformation, and the dispersive element is called a time lens. If a pulse with a specific spectrum shape is sent to the time lens, a temporal waveform with a shape that is a scaled version of the shape of the spectrum is generated. Based on this concept, a UWB monocycle or doublet can be generated by shaping the spectrum of an ultrashort pulse so it has a shape identical to a monocycle or doublet. With a time lens—a dispersive element such as a dispersive fiber—a temporal UWB monocycle or doublet can thus be generated.

As shown in Figure 13(a), the spectrum of an ultrashort pulse is shaped by a spectrum shaper, which is an optical filter or a combination of several optical filters. The shaped spectrum is then converted to a temporal pulse with a shape identical to the shaped spectrum. The approach can be implemented in the optical domain based on free-space optics [14] or fiber optics [15].

Figure 13(b) shows an all-fiber UWB pulse generation system, in which the optical power spectrum of an ultrashort pulse is shaped by two parallel optical filters to obtain a spectral shape corresponding to a UWB monocycle or doublet. A length of single-mode fiber acting as a dispersive device is used to perform the wavelength-to-time mapping; at the same time it acts as a transmission medium for distributing the UWB pulse to a remote site. A UWB monocycle or doublet pulse is then obtained at the output of a high-speed photodetector.

To simplify the system, the two operations of spectrum shaping and wavelength-to-time mapping can be implemented simultaneously in a single optical device, such as a linearly chirped fiber Bragg grating [19]. The magnitude response of the linearly chirped fiber Bragg grating can be designed to have a shape identical to a UWB monocycle or doublet, and the linear group delay response is used to perform the wavelength-to-time mapping.

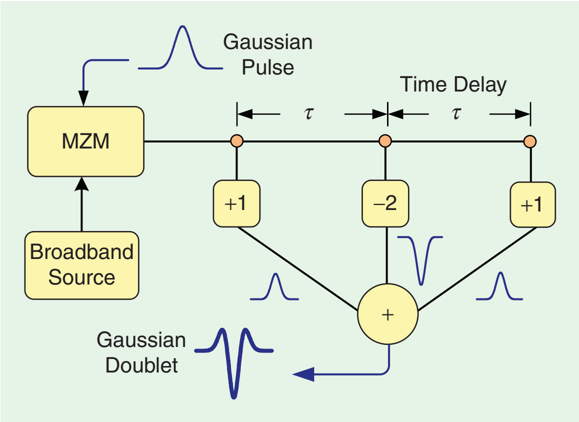

Figure 11. *Ultrawideband doublet generation based on a three-tap photonic microwave delay-line filter with [1, –2, 1] as the three coefficients. MZM: Mach-Zehnder modulator.*

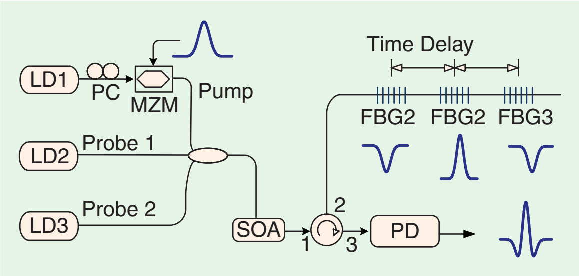

Figure 12. *Ultrawideband doublet generation using a three-tap photonic microwave delay-line filter with one negative coefficient, generated using cross-gain modulation in a semiconductor optical amplifier. PC: polarization controller. SOA: semiconductor optical amplifier.*

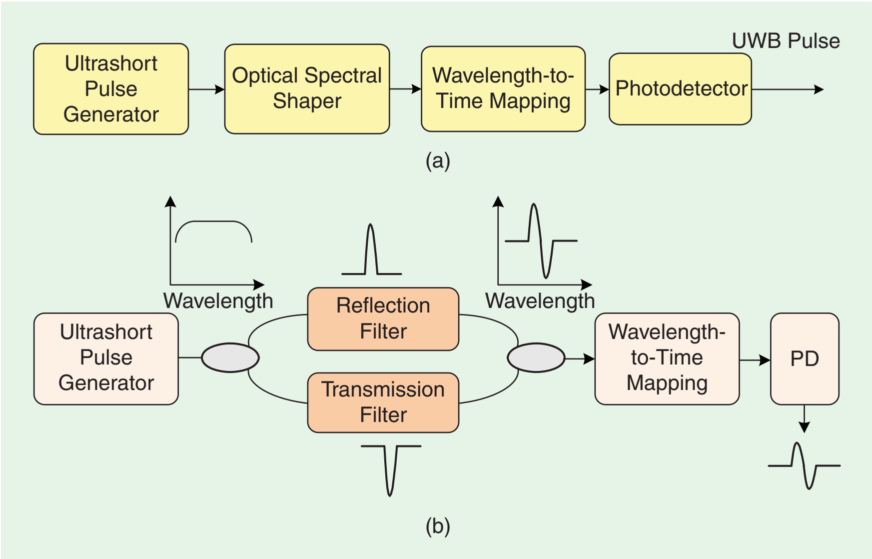

Figure 13. *(a) Ultrawideband pulse generation based on spectral shaping and frequency-to-time mapping. (b) An all-fiber ultrawideband generation system. PD: photodetector.*

There are, in general, two types of UWB technologies, direct-sequence UWB and multiband UWB.

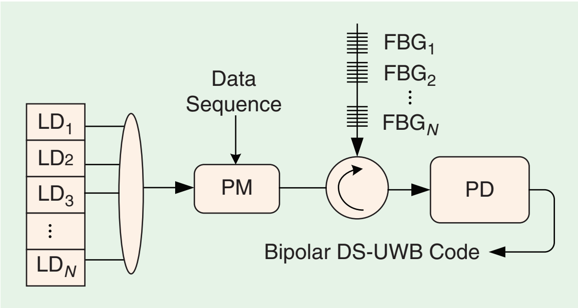

Figure 14. *Bipolar ultrawideband coding using an array of fiber Bragg gratings. LD: laser diode. PD: photodetector.*

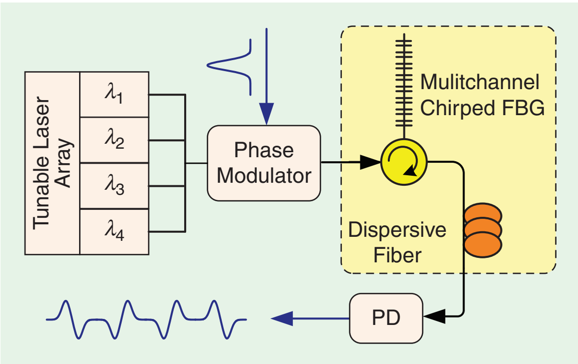

Figure 15. *Ultrawideband coding using a multichannel fiber Bragg grating (from [22]).*

A comparison of the techniques described above (numbered in order of presentation in this article) is given in Table 1. The comparison is made in terms of complexity in system implementation, flexibility in generation of different types of UWB signals, and system cost.

Photonic Coding of Impulse UWB Signals

For a UWB communication system that supports multiple users, impulse UWB signals must be encoded, with each user represented by specific codes. Time-hopping UWB (TH-UWB) has been extensively studied for multiple-access UWB systems. It was

TABLE 1. A comparison of the three UWB generation techniques discussed above.

Category	Complexity	Flexibility	Cost
I	Low	Low	Low
II	High	High	Medium
III	Medium	High	High

demonstrated that a direct-sequence UWB (DS-UWB) system outperforms a TH-UWB system in terms of BER performance [20]. Moreover, a DS-UWB system is more convenient to realize in the optical domain than a TH-UWB system. In this section, three approaches to performing impulse UWB encoding will be presented.

In the first approach, UWB coding is implemented using a fiber Bragg grating array. By locating the optical carriers at the left or right slope of the fiber Bragg grating spectral responses, a bipolar UWB signal is generated with a code length determined by the number of wavelengths. To avoid using a fiber Bragg grating array, which is usually large in size, in the second approach the fiber Bragg grating array is replaced by a multichannel fiber Bragg grating. For both approaches, the number of optical wavelengths determines the code lengths. To avoid using many optical wavelengths, in the third approach UWB coding is achieved using a polarization modulator and a polarization-dependent frequency discriminator. A single wavelength is required for one user, and thus the number of wavelengths is greatly reduced. A significant aspect of this third approach is that a high-chip-count biphase UWB signal can be generated.

UWB Coding Using a Fiber Bragg Grating Array

A simple technique for implementing all-optical bipolar DS-UWB coding for multiaccess UWB communications is to use a fiber Bragg grating array [21]. Figure 14 shows a UWB coding system in which the encoding operation is performed using a phase modulator and a fiber Bragg grating array. The fiber Bragg grating array serves as a multichannel frequency discriminator to perform PM-IM conversion. By locating the phase-modulated light waves at the opposite slopes of the fiber Bragg grating reflection spectral responses, the phase-modulated signal is converted to a UWB impulse sequence, with the polarity of each impulse determined by the location of the carrier frequency within the spectrum of the fiber Bragg grating. The chip number and the chip period of the code are determined by the number of fiber Bragg gratings in the array and the physical separation between two adjacent fiber Bragg gratings. By tuning the optical carriers at the left or right slopes of the fiber Bragg gratings' reflection spectral response, a bipolar DS-UWB code with a predefined code pattern can be generated.

The system shown in Figure 14 was experimentally demonstrated with a code length of four to provide multiple access for four users [21]. In the experiment, Walsh-Hadamard codes were selected as the orthogonal codes. For a code length of four, 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. Two users, U1 and U2, with codes C1 and C2 as their signature codes are considered. Two data sequences, D1 = 011001 and D2 = 010111, are encoded by using the signature codes C1 and C2. The decoding of the modulated UWB signal in a receiver is realized by implementing correlation between the received signals and the signature codes that are prestored at the receiver. Excellent autocorrelation and cross-correlation performance was achieved [21].

UWB Coding Using a Multichannel Fiber Bragg Grating

The system shown in Figure 14 can be simplified by replacing the fiber Bragg grating array with a single multichannel fiber Bragg grating [22], as shown in Figure 15. Similar to the fiber Bragg grating array in Figure 14, the multichannel chirped fiber Bragg grating functions as a multichannel frequency discriminator, fabricated by sampling a chirped fiber Bragg grating. To ensure that the optical carriers on the left or right slope of the reflection spectrum of a specific fiber Bragg grating have identical time delays, the group delay response within the spectrum of a specific fiber Bragg grating must be a constant. This is achieved by connecting the multichannel chirped fiber Bragg grating with a length of dispersive fiber that has an opposite dispersion to cancel the in-channel dispersion, leading to a step-increasing group delay response, as shown in Figure 16.

The system shown in Figure 15 was experimentally verified. In this test, phase-encoded UWB sequences with four chips were generated. Figure 17 shows the coded monocycle and doublet sequences corresponding to different code patterns measured in the time domain.

In the configuration shown in Figure 15, different phase-coding patterns were generated by tuning the wavelengths of the laser array. To avoiding using tunable laser sources, the system shown in Figure 15 can be modified by replacing the

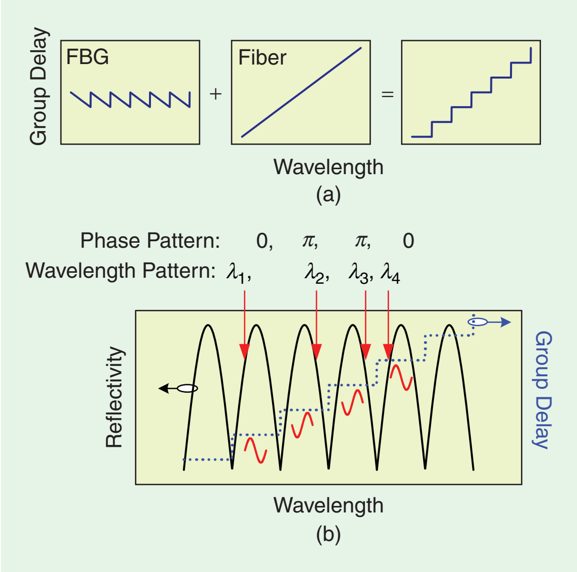

Figure 16. *(a) Step-increasing group delay response generated by a multichannel chirped fiber Bragg grating in combination with a length of dispersive fiber. (b) Frequency response of the multichannel frequency discriminator (from [22]).*

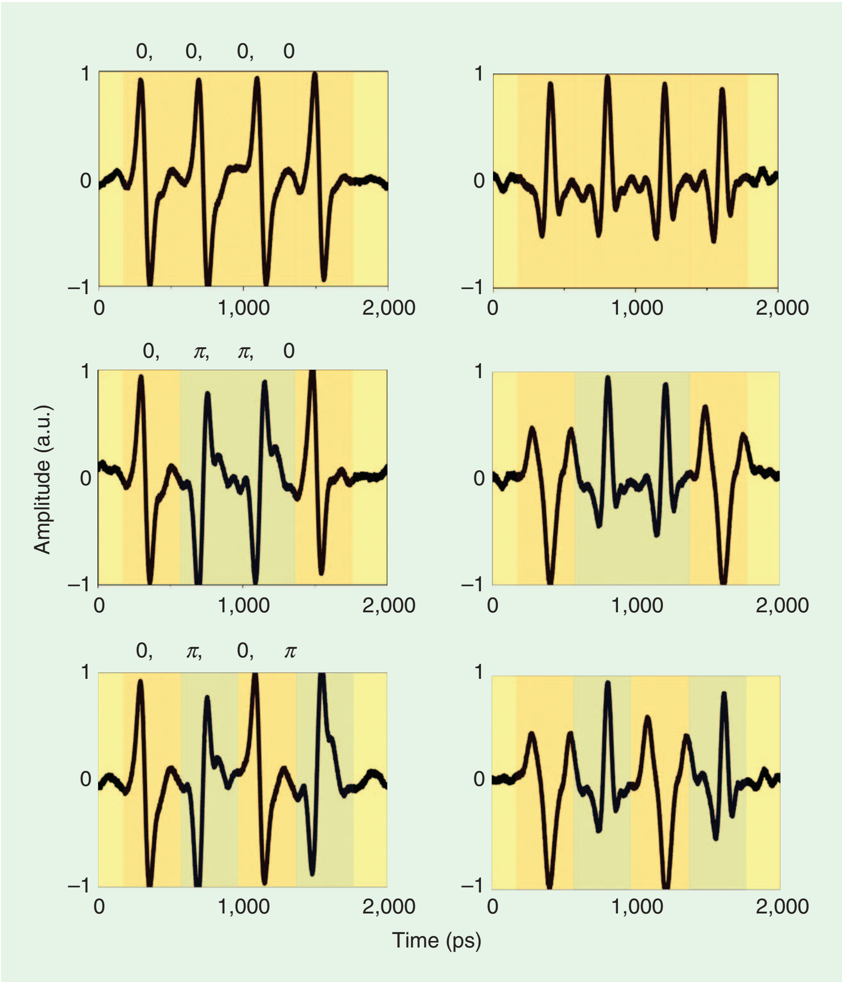

Figure 17. *Phase-coded monocycle and doublet sequences corresponding to different code patterns measured in the time domain (from [22]).*

Thanks to the low loss and broad bandwith of state-of-the-art fiber, the distribution of UWB signals over fiber, a new technology, termed UWB-over-fiber, is considered a promising solution.

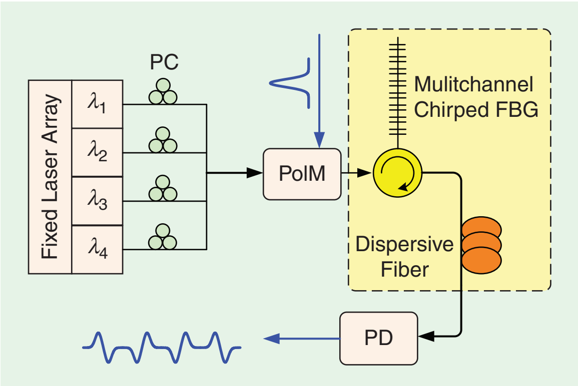

Figure 18. *The ultrawideband phase-coding system, based on a polarization modulator with fixed optical wavelengths. PC: polarization controller. PolM: polarization modulator. PD: photodetector (from [22]).*

phase modulator with a polarization modulator. The new system configuration is shown in Figure 18. The key difference between a phase modulator and a polarization modulator is that a polarization modulator supports both transverse electric (TE) and transverse magnetic (TM) modes while a conventional phase modulator only supports a single polarization mode. In addition, for the TE and TM modes, a polarization modulator acts as a phase modulator with complementary modulation index. Therefore, by adjusting the states of polarization of the optical waves to the polarization modulator, we could achieve the desired phase-coding pattern at the output of the multichannel frequency discriminator.

UWB Coding Using a Polarization Modulator

The encoding system using a fiber Bragg grating array or a single multichannel fiber Bragg grating can perform UWB encoding but with a code length determined by the number of optical wavelengths. This can be complicated and costly, especially for a UWB system with a long code length. A scheme shown in Figure 19 was proposed to solve the problem [23]. The light wave from a laser diode is phase-modulated by a Gaussian pulse train at a phase modulator. The phase-modulated light wave is then sent to a polarization modulator, with its polarization state being modulated by a non-return-to-zero (NRZ) data sequence. The NRZ data sequence is a BPSK code pattern, which is synchronized with the Gaussian pulse train. A polarization-dependent frequency discriminator is connected at the output of the polarization modulator. Depending on the polarization state of the light wave, a UWB pulse with or without polarity inversion is generated due 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 have a frequency response that depends on the input light wave polarization state, as shown in the inset of Figure 19.

In the system, the polarization-dependent frequency discriminator was implemented using a length of polarization maintaining fiber and a polarizer. The polarization axis of the polarizer should be oriented at an angle of 45º with respect to the output principal axis of the polarization-maintaining fiber. The transmission spectrum of the polarization-dependent frequency discriminator is shown in Figure 20. When the frequency of the input light is located at one of the cross points of the two transmission spectra, depending on the polarization angle of the incident light wave to the polarization-maintaining fiber, a UWB pulse with or without polarity inversion is generated.

The polarization modulator used in the system is a special phase modulator that supports both TE and TM modes but with opposite phase modulation indices. The

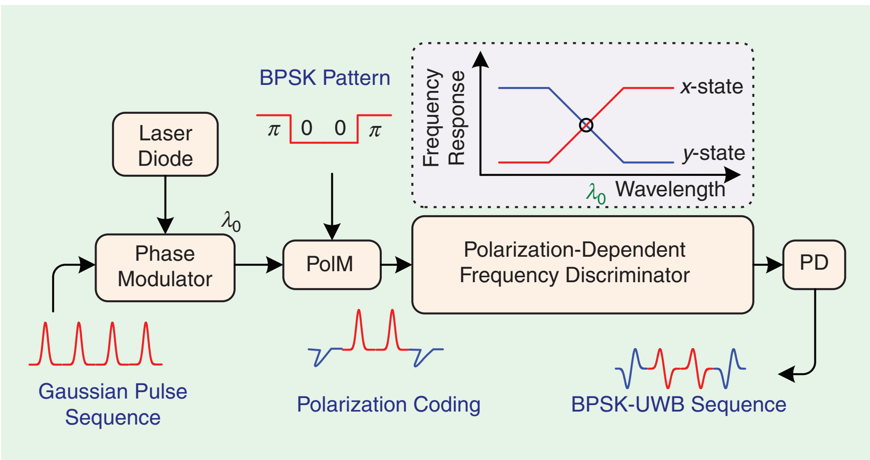

Figure 19. *Generation of biphase coding ultrawideband signals using a polarization modulator and a polarization-dependent frequency discriminator. Inset: The frequency response of the required polarization-dependent frequency discriminator. PolM: polarization modulator. PD: photodetector.*

polarization state of the input light wave to the polarization modulator is oriented at an angle of 45º to one principal axis of the polarization modulator by means of a polarization controller. If the polarization modulator is driven by zero voltage or a half-wave voltage V_π, a light wave with either of the two orthogonal polarization states will then be obtained. If the polarization modulator is driven by a binary sequence with voltages of zero 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.

Long-chip-count phase coding can be easily achieved by inputting an NRZ data stream into the polarization modulator. Figure 21 shows a binary phase-coded monocycle sequence when the NRZ code is a 127-chip *m*-sequence. The decoding can be implemented in a UWB receiver by performing correlation between the encoded signal and a signature sequence.

The key challenge in implementing UWB-over-fiber systems for practical applications at present is the large size and high cost of the systems.

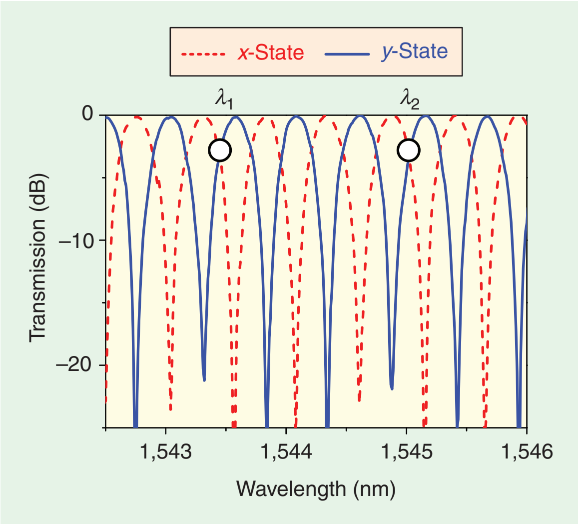

Figure 20. *The transmission spectrum of a polarization-dependent frequency discriminator, consisting of a length of polarization-maintaining fiber and a polarizer (from [23]).*

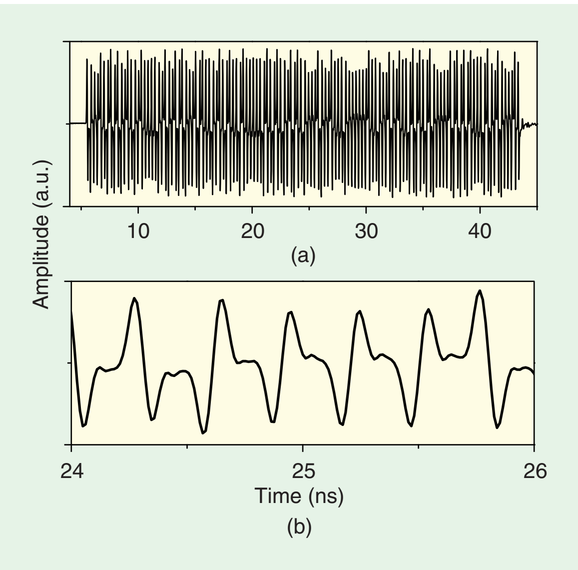

Figure 21. *(a) The measured 127-chip binary phase-coded monocycle sequence and (b) a zoomed-in display (from [23]).*

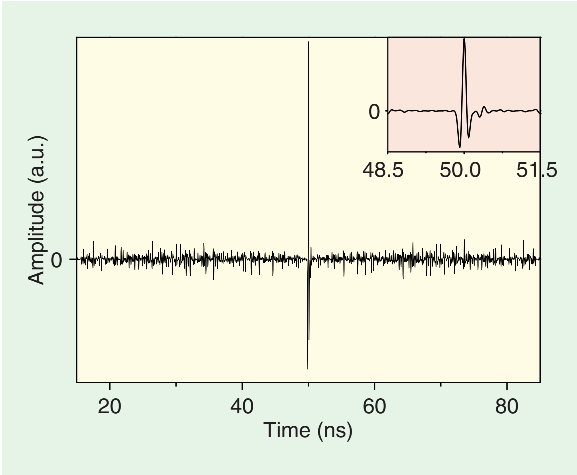

Figure 22. *The signal is decoded by calculating the correlation between the measured signal and the signature sequence; the insert gives a zoom-in display of the correlation peak (from [23]).*

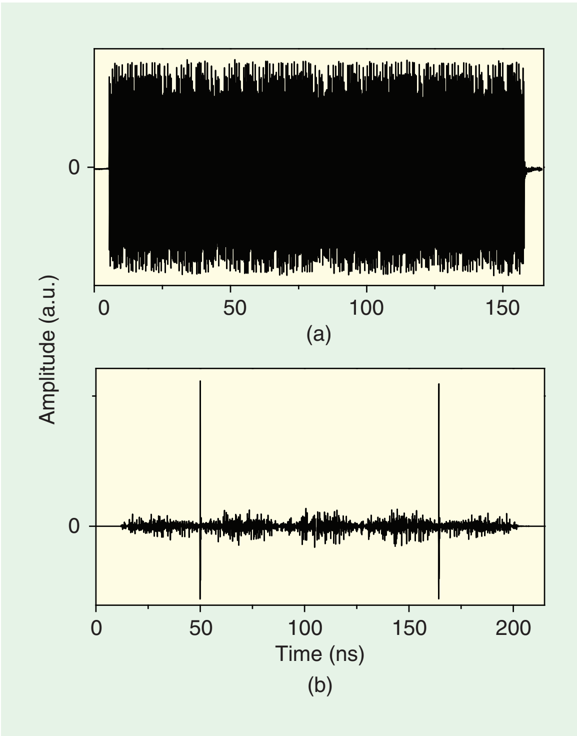

Figure 23. *(a) The encoded signal when the code switch scheme is used. (b) The signal recovered by the correlator (from [23]).*

Figure 22 shows the autocorrelation between the encoded signal and its signature sequence. A high autocorrelation peak is observed.

For multiuser applications, the data sequence should be encoded. This can be done by loading both the data sequence and the code pattern through the polarization modulator. The digital information (the *1*s and *0*s) can be represented by two orthogonal code patterns C_1 and C_0, respectively. Since the two codes have good orthogonality, the digital information can be recognized simply by performing correlation at the receiver. Then the phase modulator is only driven by a periodic Gaussian pulse train.

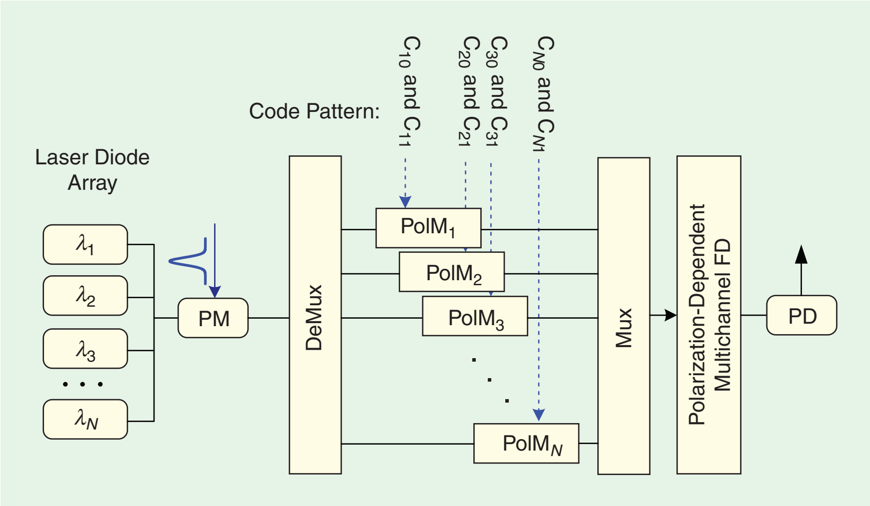

Figure 24. *A multiuser ultrawideband-over-fiber system using a polarization modulator and a polarization-dependent multichannel frequency discriminator. PM: phase modulator. DeMux: demultiplexer. PolM: polarization modulator. Mux: multiplexer. PD: photodetector (from [23]).*

As an example, a signal of four bits (1, 0, 0, 1), encoded by the two code patterns, C_1 and C_0, was transmitted. The measured encoded signal is plotted in Figure 23(a). At the receiver, the encoded signal was decoded by calculating the correlation between the received signal and the signature sequence corresponding to C_1. The decoded signal is shown in Figure 23(b). Obviously, the signal $(1, 0, 0, 1)$ was recognized successfully.

Since only one wavelength is required for each user, a multiple-user UWB-over-fiber system could easily be achieved using this technique, as shown in Figure 24. For a system with N users, an N-wavelength source, N polarization modulators, and a multiplexer-demultiplexer pair are required. Both the code pattern and the user information can be loaded through the polarization modulator, and the only input into the phase modulator is a periodic Gaussian train. Therefore, only one phase modulator is required in the whole system.

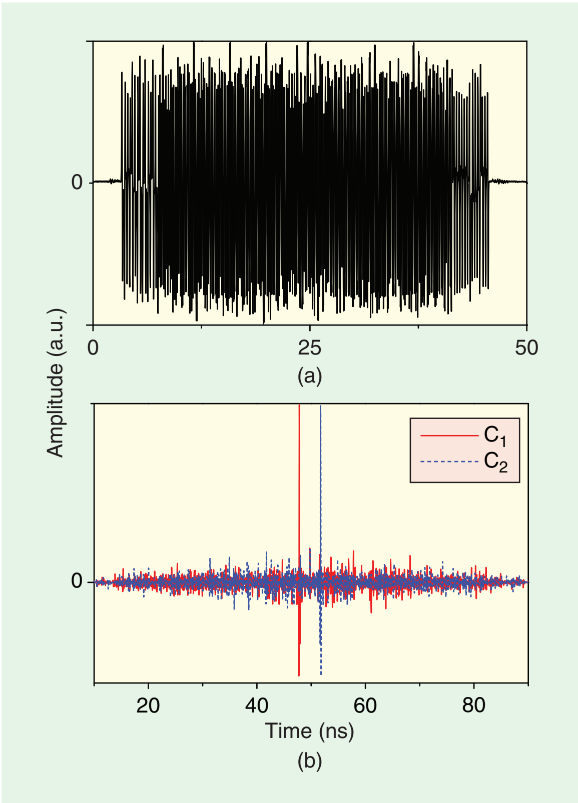

Figure 25. *(a) The encoded output signal of a two-user ultrawideband-over-fiber system. (b) The signals are decoded by calculating the correlation between the measured encoding signal in (a) and the signature sequences corresponding to C_{11} and C_{21} (from [23]).*

As an example, assume a UWB-over-fiber system that supports two users and that the transmitted data are all *1*s for each user. As shown in Figure 25, light waves having two wavelengths λ_1 and λ_2 are combined and phase-modulated by a Gaussian pulse train, then demultiplexed and encoded at the polarization modulators, which are driven by two 127-chip *m*-sequences, C_{11} and C_{21}. Then the two light waves are combined at the multiplexer and pulse-shaped by the multichannel frequency discriminator. The output is the sum of the signals of the two users, measured by a high-speed sampling oscilloscope, as plotted in Figure 25(a).

Since the code patterns of the two users are orthogonal, the UWB receiver can then recognize the data of a specific user by correlation using the corresponding signature sequence. For the two-user case, the signature sequences are the simulated monocycle sequences corresponding to patterns C_{11} and C_{21}. The decoded signals are shown in Figure 25(b).

Clearly, the signal of each user was well recognized. An effective dual-user UWB-over-fiber system based on the DS-UWB technology was then demonstrated.

Discussion and Conclusion

Techniques for generating and encoding impulse UWB signals in the optical domain for UWB-over-fiber applications were discussed. Because of their simplicity and realizability, Gaussian monocycles and doublet pulses are usually employed in impulse UWB communications systems. In this article, three types of techniques for generating impulse UWB signals were described. For UWB-over-fiber systems that support multiple-user communications, the UWB signal for each user must be encoded. Three such techniques developed recently for UWB encoding were reviewed.

The key challenge in implementing UWB-over-fiber systems for practical applications at present is the large size and high cost of the systems. The UWB-over-fiber systems reported recently have been based on discrete photonic and microwave components, which make the systems very bulky and costly. To reduce the cost, the distribution of UWB signals using vertical-cavity surface-emitting lasers has recently been proposed [24]. Since the fabrication of a vertical-cavity surface-emitting laser is completed and tested at the wafer level, the cost of a vertical-cavity surface-emitting laser is much lower than a DFB laser diode. An ultimate solution for reducing size and lowering costs is to use photonic integrated circuits. Current activities in silicon photonics are expected to have an important impact on the development and implementation of future UWB-over-fiber systems, if practical silicon lasers can be successfully developed in the near future [25]. In addition to application for broadband wireless communications, photonic generation and encoding of UWB signals can also find application in broadband sensor networks, imaging, and modern instrumentation.

References

[1] M. Ghavami, L. B. Michael, and R. Kohno, *Ultra Wideband Signals and Systems in Communication Engineering.* Hoboken, NJ: Wiley, 2004.

[2] D. Porcine, P. Research, and W. Hirt, "Ultra-wideband radio technology: Potential and challenges ahead," *IEEE Commun. Mag.*, vol. 41, no. 7, pp. 66–74, July 2003.

[3] G. R. Aiello and G. D. Rogerson, "Ultra-wideband wireless systems," *IEEE Microw. Mag.*, vol. 4, no. 2, pp. 36–47, June 2003.

[4] L. Yang and G. B. Giannakis, "Ultra-wideband communications: An idea whose time has come," *IEEE Signal Processing Mag.*, vol. 21, no. 6, pp. 26–54, Nov. 2004.

[5] J. P. Yao, F. Zeng, and Q. Wang, "Photonic generation of ultra-wideband signals," *J. Lightwave Technol.*, vol. 25, no. 11, pp. 3219–3235, Nov. 2007.

[6] C. R. Nassar, F. Zhu, and Z. Wu, "Direct sequence spreading UWB systems: Frequency domain processing for enhanced performance and throughput," in *Proc. IEEE Int. Conf. on Communications*, May 2003, vol. 3, pp. 2180–2186.

[7] J. Balakrishnan, A. Batra, and A. Dabak, "A multi-band OFDM system for UWB communication," in *Proc. 2003 IEEE Conf. on Ultra Wideband Systems and Technologies*, 16–19 Nov. 2003, pp. 354–358.

[8] X. Chen and S. Kiaei, "Monocycle shapes for ultra wide-band system," in *Proc. IEEE Int. Symp. Circuits and Systems*, 2002, vol. 1, pp. 26–29.

[9] H. Ishida and K. Araki, "Design and analysis of UWB bandpass filter with ring filter," in *IEEE MTT-S Int. Dig.*, June 2004, vol. 3, pp. 1307–1310.

[10] L. Zhu, S. Sun, and W. Menzel, "Ultra-wideband (UWB) bandpass filters using multi-mode resonator," *IEEE Micow. Wireless Compon. Lett.*, vol. 15, no. 11, pp. 796–798, Nov. 2005.

[11] W. P. Lin and J. Y. Chen, "Implementation of a new ultrawideband impulse system," *IEEE Photon. Technol. Lett.*, vol. 17, no. 11, pp. 2418–2420, Nov. 2005.

[12] F. Zeng and J. P. Yao, "Ultrawideband impulse radio signal generation using a high-speed electrooptic phase modulator and a fiber-Bragg-grating-based frequency discriminator," *IEEE Photon. Technol. Lett.*, vol. 18, no. 19, pp. 2062–2064, Oct. 2006.

[13] Q. Wang and J. P. Yao, "Optically switchable UWB monocycle and doublet generation using a reconfigurable photonic microwave delay-line filter," *Opt. Express*, vol. 15, no. 22, pp. 14667–14672, Oct. 2007.

[14] I. Lin, J. D. McKinney, and A. M. Weiner, "Photonic synthesis of broadband microwave arbitrary waveforms applicable to ultra-wideband communication," *IEEE Microw. Wireless Compon. Lett.*, vol. 15, no. 4, pp. 226–228, Apr. 2005.

[15] C. Wang, F. Zeng, and J. P. Yao, "All-fiber ultrawideband pulse generation based on spectral shaping and dispersion-induced frequency-to-time conversion," *IEEE Photon. Technol. Lett.*, vol. 19, no. 3, pp. 137–139, Feb. 2007.

[16] Q. Wang and J. P. Yao, "Theoretical analysis of UWB pulse generation based on phase modulation to intensity modulation conversion," in *Proc. 2007 IASTED Antennas, Radar, and Wave Propagation*, pp. 1–3.

[17] F. Zeng, Q. Wang, and J. P. Yao, "All-optical UWB impulse generation based on cross-phase modulation and frequency discrimination," *Electron. Lett.*, vol. 43, no. 2, pp. 121–122, Jan. 2007.

[18] Q. Wang, F. Zeng, S. Blais, and J. P. Yao, "Optical Ultrawideband monocycle pulse generation based on cross-gain modulation in a semiconductor optical amplifier," *Opt. Lett.*, vol. 31, no. 21, pp. 3083–3085, Nov. 2006.

[19] C. Wang and J. P. Yao, "Simultaneous optical spectral shaping and wavelength-to-time mapping for photonic microwave arbitrary waveform generation," *IEEE Photon. Technol. Lett.*, to be published.

[20] B. Hu and N. C. Beaulieu, "Accurate performance evaluation of time-hopping and direct-sequence UWB systems in multi-user interference," *IEEE Trans. Commun.*, vol. 53, no. 6, pp. 1053–1062, June 2005.

[21] Q. Wang and J. P. Yao, "An approach to all-optical bipolar direct-sequence UWB coding," *Opt. Lett.*, vol. 33, no. 9, pp. 1017–1019, May 2008.

[22] Y. Dai and J. P. Yao, "Optical generation of binary phase-coded direct-sequence UWB signals using a multi-channel chirped fiber Bragg grating," *IEEE/OSA J. Lightwave Technol.*, vol. 26, no. 15, pp. 2513–2520, Aug. 2008.

[23] Y. Dai and J. P. Yao, "High-chip-count UWB bi-phase coding for multi-user UWB-over-fiber system," *IEEE/OSA J. Lightwave Technol.*, to be published.

[24] S. B. Constant, Y. Le Guennec, G. Maury, N. Corrao, and B. Cabon, "Low-cost all-optical up-conversion of digital radio signals using a directly modulated 1550-nm emitting VCSEL," *IEEE Photon. Technol. Lett.*, vol. 20, no. 2, pp. 120–122, Jan. 2008.

[25] B. Jalali and S. Fathpour, "Silicon photonics," *J. Lightwave Technol.*, vol. 24, no. 12, pp. 4600–4615, Dec. 2006.