Switchable UWB pulse generation using a phase modulator and a reconfigurable asymmetric Mach–Zehnder interferometer

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We propose a new scheme to generate polarity-switchable ultrawideband (UWB) Gaussian pulses in the optical domain by use of a phase modulator and a reconfigurable asymmetric Mach–Zehnder interferometer (AMZI). In the proposed system, an optical carrier is phase modulated by a Gaussian pulse train and then sent to a first-or second-order AMZI. The system is equivalent to a first- or second-order differentiator for the production of Gaussian UWB monocycle or doublet pulses. The polarity of the generated UWB pulses can be switched by adjusting the phase difference between the two interference components in the AMZI. An experiment is performed. Gaussian monocycle and doublet pulses with fractional bandwidths of about 177% and 140% are generated. The polarity switchability of generated UWB pulses is also experimentally confirmed.

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Ultrawideband (UWB) technology is considered promising for short-distance, high-speed wireless communication systems, thanks to numerous advantages such as immunity to multipath fading, wide bandwidth, and low-power spectral density [1,2]. For UWB communications, one of the key challenges is the generation of UWB pulses [2] that meet the requirement specified by the Federal Communications Commission (FCC). In addition, to implement pulse-polarity modulation (PPM) [3,4], the polarity of the generated UWB pulses should be switchable at a high speed. Recently, several UWB pulse generators with switchable polarity have been proposed. Wang *et al.* suggested an optical UWB pulse generator based on polarization modulation followed by a polarization-dependent time delay [5]. By adjusting the polarization state of the incident lightwave, the polarity and the shape of the generated UWB pulses could be switched electrically. The major limitation of the technique in [5] is that an undesirable time shift is presented between the two polarity-switched monocycle pulses, which is not desirable for a system using a PPM scheme. Utilizing a phase modulator and a fiber-Bragg-grating-based frequency discriminator, Zeng *et al.* obtained polarity-switchable UWB pulses [6] by locating the wavelength of the optical carrier at different locations of the fiber Bragg grating (FBG) reflection spectrum, but a time shift between the two polarity-switched pulses was also inevitable owing to the wavelength-dependent group delay in the FBG. Recently, Li *et al.* proposed a flexible UWB source using a Sagnac-interferometer-based intensity modulator [7]. By turning on and off a light source and alternating the two output ports in the scheme, the shape and the polarity of the UWB pulses are changed. However, synchronizing and switching the UWB pulses from two output ports will require a high-speed optical switch, which would complicate the system.

In this Letter, we propose an efficient method to generate polarity-switchable UWB monocycle and doublet pulses using a phase modulator and a reconfigurable asymmetric Mach–Zehnder interferometer (AMZI). In the proposed system, an optical carrier is phase modulated by a Gaussian pulse train in the phase modulator and then launched into the AMZI. The entire system is equivalent to a first- or second-order differentiator. As a result, a UWB monocycle or doublet pulse is generated based on the context that a first- or second-order derivative of a Gaussian pulse achieves a Gaussian monocycle or doublet pulse [1]. Because the phase difference between the two interference components in the AMZI determines the polarity of the generated UWB pulses, the switching operation will not cause an undesirable time shift. An experiment based on the proposed approach is carried out. Gaussian monocycle and doublet pulses with fractional bandwidths of about 177% and 140% are experimentally generated. The polarity switchability is also demonstrated. Since both the phase modulator and the AMZI are integrable [8,9], the proposed system has the potential for integration using photonic integrated circuit technology and possesses the desirable properties of small size, low cost, and stable operation for UWB communications.

The schematic diagram of the proposed UWB pulse generator is shown in Fig. 1. The system consists of a laser diode, a phase modulator, an AMZI, and a pho-

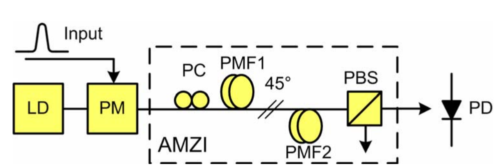

Fig. 1. (Color online) Schematic diagram of the UWB pulse generator. LD, laser diode; PM, phase modulator; PC, polarization controller; PMF, polarization-maintaining fiber; PBS, polarization beam splitter; PD, photodetector.

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todetector (PD). A lightwave from the laser diode is fiber-coupled to the phase modulator, which is driven by a Gaussian pulse train. The phase-modulated optical signal is then sent to the AMZI. A UWB monocycle or doublet pulse train is generated at the output of the PD. The AMZI is formed using two sections of PMF with their fast axes aligned with an angle of 45° followed by a PBS. A PC is connected at the input of the PMF to adjust the polarization direction of the incident lightwave to have an angle of 0° or 45° to one principle axis of the PMF. The PC can also introduce a static phase difference between the two orthogonal polarization components along the directions of the fast and the slow axes of the PMF.

The normalized optical field after phase modulation can be expressed as $E_{\mathrm{PM}}(t)=\exp[j\omega_c t+j\beta_{\mathrm{PM}}\varphi(t)]$, where ω_c is the angular frequency of the optical carrier, β_{PM} is the phase modulation index, and $\varphi(t)$ is the modulating signal.

To generate a UWB monocycle, the AMZI should operate as a first-order interferometer, which can be realized by aligning the polarization direction of the phase-modulated lightwave with one principal axis of the first PMF section. The phased-modulated light is divided equally into two signals at the second PMF section along the two principal axes, with a time delay difference of τ_1 induced by the birefringence of the PMF and a phase difference of φ_1 introduced by the PC, and then recombined by a 2×2 coupler. The output signals at the two output ports can be expressed as

$$\begin{bmatrix} E_1 \\ E_2 \end{bmatrix} = e^{j\omega_c t}\begin{bmatrix} e^{j[\beta_{\mathrm{PM}}\varphi(t)+\varphi_1]} + e^{j[\beta_{\mathrm{PM}}\varphi(t-\tau_1)-\omega_c\tau_1+\pi/2]} \\ e^{j[\beta_{\mathrm{PM}}\varphi(t)+\varphi_1+\pi/2]} + e^{j[\beta_{\mathrm{PM}}\varphi(t-\tau_1)-\omega_c\tau_1]} \end{bmatrix}. \quad (1)$$

If these signals are detected by a PD, the obtained ac terms of the photocurrents are

$$\begin{bmatrix} i_1(t) \\ i_2(t) \end{bmatrix} \sim \begin{bmatrix} -\sin\{\beta_{\mathrm{PM}}[\varphi(t)-\varphi(t-\tau_1)]+\omega_c\tau_1+\varphi_1\} \\ \sin\{\beta_{\mathrm{PM}}[\varphi(t)-\varphi(t-\tau_1)]+\omega_c\tau_1+\varphi_1\} \end{bmatrix}. \quad (2)$$

By choosing a proper φ_1 via tuning the PC to let $(\omega_c\tau_1+\varphi_1)$ equal $N\pi$ (N is an integer) and considering that $\beta_{\mathrm{PM}}[\varphi(t)-\varphi(t-\tau_1)]$ is small, we obtain the approximated form of Eq. (3), given by

$$\begin{bmatrix} i_1(t) \\ i_2(t) \end{bmatrix} \sim \begin{bmatrix} \pm\beta_{\mathrm{PM}}[\varphi(t)-\varphi(t-\tau_1)] \\ \mp\beta_{\mathrm{PM}}[\varphi(t)-\varphi(t-\tau_1)] \end{bmatrix}. \quad (3)$$

As can be seen, the output current is proportional to the first-order difference of the input Gaussian signal. If τ_1 is sufficiently small, the first-order difference can be approximated as the first-order derivative; therefore, the entire system is equivalent to a first-order differentiator, and a Gaussian monocycle is generated if the input is a Gaussian pulse.

To generate a Gaussian doublet, a second-order difference should be achieved. To do so, the AMZI should be reconfigured as a second-order interferometer, which is implemented by aligning the polarization direction of the phase-modulated lightwave to have an angle of 45° with respect to the principal axes of the first PMF section. By properly adjusting φ_1 via tuning the PC to let $[\omega_c(\tau_1+\tau_2)+\varphi_1+\varphi_2]$ equal $K\pi$ (K is an integer) and using a similar mathematical manipulation as used in deriving Eq. (3), we can obtain the ac terms of the photocurrents at the outputs of the PDs,

$$\begin{bmatrix} i_1(t) \\ i_2(t) \end{bmatrix} \sim \begin{bmatrix} \pm\beta_{\mathrm{PM}}[\varphi(t)-\varphi(t-\tau_1)-\varphi(t-\tau_2)+\varphi(t-\tau_1-\tau_2)] \\ \mp\beta_{\mathrm{PM}}[\varphi(t)-\varphi(t-\tau_1)-\varphi(t-\tau_2)+\varphi(t-\tau_1-\tau_2)] \end{bmatrix}. \quad (4)$$

As can be seen, the output currents are proportional to the second-order difference of the input Gaussian signal. Again, if τ_1 and τ_2 are sufficiently small, the second-order difference can be approximated as the second-order derivative; therefore, the entire system is equivalent to a second-order differentiator and a Gaussian doublet is generated if the input is a Gaussian pulse. The "±" or "∓" on the right sides of Eq. (3) and Eq. (4) represents the polarity of the UWB pulses, indicating that a pair of UWB pulses with inverted polarity are simultaneously generated at the two output ports. In addition, adjusting φ_1 will change the polarity of the UWB pulses at each output port. Considering that a π phase shift at the frequency of the optical carrier (>190 THz) cannot bring obvious time shift (<3 fs) as compared with the bit period of a UWB pulse (>1 ns), a switching operation of the polarity of the UWB pulses without time shift can be achieved.

An experiment is performed based on the experimental setup shown in Fig. 1. A light wave from a tunable laser source is sent to a $LiNbO_3$ straight-line phase modulator. A Gaussian-like pulse train generated by a bit error rate tester (Agilent 4901B) with a fixed pattern of 1000 0000 0000 0000 0000 0000 0000 0000 (one 1 every 32 bits) and a bit rate of 13.5 Gbit/s, which is equivalent to a pulse train with a repetition rate of 0.42 GHz and a duty cycle of about 1/32, is applied to the phase modulator to phase modulate the lightwave. The pulse shape is close to Gaussian with FWHM of about 63 ps. The reconfigurable AMZI consists of two sections of PMF (Corning PM1550, with a beat length of 3.75 mm) with their fast axes aligned with an angle of 45°, followed by a PBS. The lengths of the two sections of PMF are 14.6 and 29.1 m, giving differential group delays (DGDs) of about 20.1 and 40.1 ps, respectively. A PC is connected at the input of the PMF to adjust the polarization state of the incident lightwave. The output UWB pulses are detected by a PD, with the waveforms observed by a high-speed sampling oscilloscope (Agilent 86116A) and the spectra measured by an electrical spectrum analyzer (Agilent E4448A).

Figure 2 shows the waveforms and the spectra of the generated UWB monocycle and doublet pulses. As can be seen from Figs. 2(a) and 2(b) the monocycle pulse has an FWHM of 54 ps, the spectrum has a central frequency of 6.1 GHz, and the 10 dB bandwidth is about 10.8 GHz, indicating that the gener-

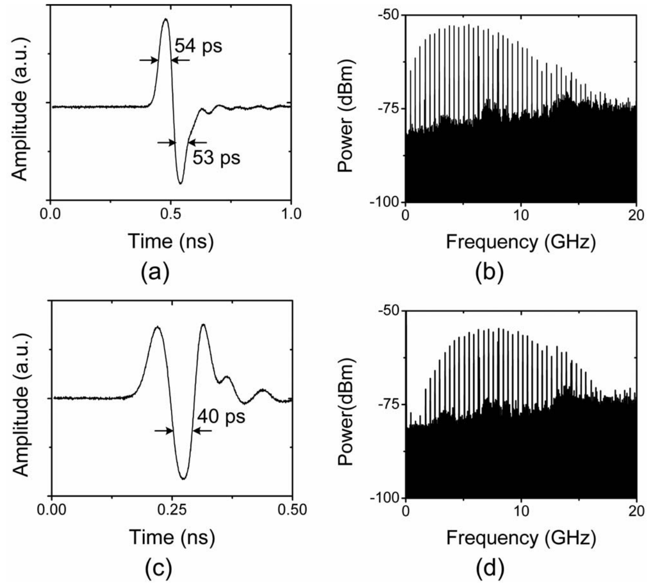

Fig. 2. Waveforms and spectra of the Gaussian UWB pulses obtained at the output of the AMZI. (a) Generated UWB monocycle, (b) corresponding electrical spectrum, (c) generated UWB doublet, (d) corresponding electrical spectrum.

ated UWB monocycle has a fractional bandwidth of about 177%. Figures 2(c) and 2(d) show the doublet pulse and the corresponding spectrum. The doublet has an FWHM of about 40 ps, the spectrum has a central frequency of 8.8 GHz, and the 10 dB bandwidth is about 12.3 GHz, indicating a fractional bandwidth of about 140%. The polarity switchability is also observed by adjusting the PC. The temporal relationship between the polarity-switched pulses is also studied. Figure 3 shows the polarity-inverted monocycle and doublet pulses observed at one output of the PBS. The centers of the two pulses are located at the same position, with no significant time shift being observed. This feature makes the proposed approach suitable for a PPM scheme.

It should be noted that if the PC is replaced by a polarization modulator [10], both the polarity and the shape of the UWB pulses would be electrically switchable at a high speed. The integration of an AMZI in $LiNbO_3$ waveguides has been demonstrated in [9], indicating that a monolithic integration of the AMZI and a $LiNbO_3$ phase modulator is possible. As a result, the performance of the proposed system with smaller size, lower cost, and more stable operation can be achieved via integration. In addition, a UWB pulse that satisfies the FCC spectral mask can be generated by passing a Gaussian pulse through an N-tap microwave delay-line filter [11]. Considering that an AMZI implemented using N sections of PMF followed by a PBS is equivalent to an N-tap microwave delay-line filter, the proposed system is capable of generating FCC-compliant, polarity-switchable UWB pulses if more sections of PMF are used.

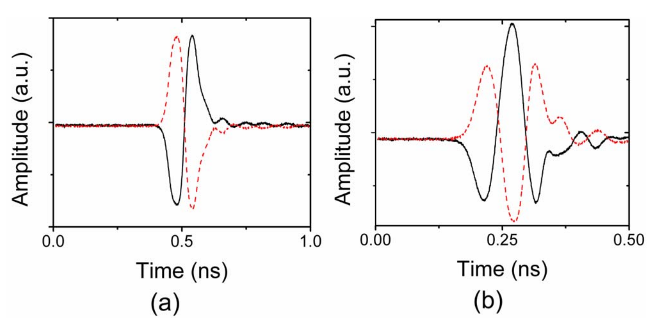

Fig. 3. (Color online) Temporal relationship between the polarity-switched pulses. (a) Polarity-inverted monocycle pulses. (b) Polarity-inverted doublet pulses.

In conclusion, an optical UWB pulse generator that could shape an input Gaussian pulse into a UWB monocycle or doublet pulse has been proposed and experimentally demonstrated. The proposed system consisted of an optical phase modulator and a first- or second-order AMZI. A UWB monocycle or doublet pulse with a fractional bandwidth of about 177% or 140% was generated if a Gaussian pulse with a FWHM of 63 ps was applied to the input. The polarity switchability was also demonstrated. It was shown that the polarity of the generated UWB pulses was switched without introducing a time shift, making the proposed scheme suitable for a PPM scheme. The proposed system is potentially integrable, which would meet the practical requirements of small size, low cost, and stable operation for UWB communications.

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