Optical generation of polarity- and shape-switchable ultrawideband pulses using a chirped intensity modulator and a first-order asymmetric Mach–Zehnder interferometer

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Received February 2, 2009; revised March 17, 2009; accepted March 18, 2009; posted March 26, 2009 (Doc. ID 107045); published April 20, 2009

We propose and demonstrate a simple method to generate ultrawideband (UWB) pulses in the optical domain using a chirped intensity modulator and an asymmetric Mach–Zehnder interferometer (AMZI). Polarity- and shape-switchable UWB Gaussian monocycle, doublet, and triplet pulses with fractional bandwidths of 158%, 134%, and 100% and center frequencies of 6.52, 9.78, and 10.1 GHz are experimentally generated by controlling the dc bias of the intensity modulator and adjusting the polarization controller in the AMZI. © 2009 Optical Society of America

OCIS codes: 060.2310, 060.5625, 070.1170, 350.4010.

Ultrawideband (UWB) impulse radio is attracting increasing interest from industry, government, and academia for its potential applications in high-throughput wireless communications and sensor works [1,2]. By wireless transmission, UWB communication distance is limited to a few meters to tens of meters. To increase the area of coverage, UWB signals should be transmitted over wired lines, such as optical fiber: a technology called UWB over fiber [2]. In a UWB over-fiber system, it is also highly desirable to generate UWB signals in the optical domain without the need for extra electrical-to-optical conversion.

In the past few years, a few techniques for photonic UWB pulse generation have been proposed, in which an electro-optical modulator, such as a phase modulator (PM) [3–6], a polarization modulator (PolM) [6,7], or an intensity modulator (IM) [8,9], was employed. UWB pulse generation based on optical pulse shaping [10,11] and optical cross-phase modulation without using an electro-optical modulator were also proposed [12]. Considering that intensity modulation is widely used in commercial communications systems, the use of an IM for UWB generation is most cost effective. In [8], we suggested a very simple method to generate polarity-switchable UWB doublet pulses using an IM by switching the bias point from near the maximum transmission point to near the minimum transmission point. A UWB monocycle can also be generated with a $LiNbO_3$ IM by using the wavelength-dependent nature of the transfer functions of the IM [9]. The major limitation of the approaches in [8,9] is that only a single fixed UWB pulse is obtained, which may limit the potential for many applications. In addition, two wavelengths are needed in [9], which makes the system complicated and costly. To use a single wavelength and to generate UWB pulses with polarity and shape switchabilities, we reported recently a novel method in which a PM and a reconfigurable asymmetric Mach–Zehnder interferometer (AMZI) were employed [5]. With the high flexibility provided by the AMZI, both polarity- and shape-switchable UWB Gaussian monocycle and doublet pulses were generated. However, two first-order AMZIs must be cascaded to form the reconfigurable AMZI, which would increase the difficulty for stable operation. In this Letter, we propose and demonstrate a simpler and more flexible method to generate UWB pulses with polarity and shape switchabilities using only a chirped IM and a single first-order AMZI.

The schematic of the proposed UWB pulse generator is shown in Fig. 1. A light wave from a laser diode is fiber coupled to a chirped IM via a polarization controller (PC1). The modulated optical signal is then sent to an AMZI. The AMZI is formed by a section of polarization-maintaining fiber (PMF) followed by a polarizer. A second PC (PC2) is connected at the input of the PMF to adjust the polarization direction of the incident light wave with respect to the principal axis of the PMF, which can also introduce a static phase difference between the two orthogonal optical components along the fast and the slow axes of the PMF. A UWB monocycle, doublet, or triplet pulse train is generated at the output of a photodetector.

Mathematically, the normalized optical field at the output of the chirped IM can be expressed as

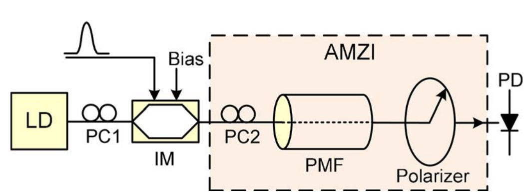

Fig. 1. (Color online) UWB pulse generator using an IM and an asymmetric AMZI. LD, laser diode; PC, polarization controller; PMF, polarization-maintaining fiber; and PD, photodetector.

0146-9592/09/091312-3/$15.00

$$E_{\mathrm{IM}} = e^{j\omega_c t}[1 + e^{j[\beta\phi(t)+\phi_{\mathrm{B}}]}], \tag{1}$$

where ω_c is the angular frequency of the optical carrier, β is the phase modulation index, $\phi(t)$ is the modulating signal, and ϕ_{B} is a constant phase shift determined by the dc bias voltage. In the AMZI, the intensity-modulated light is split into two signals traveling along the two principal axes of the PMF, which undergo a time delay difference of τ and a phase difference of ϕ_0, and then recombined at the polarizer. The optical field at the output of the polarizer can be expressed as

$$E_{\mathrm{o}} \propto \cos\alpha + (\cos\alpha)e^{j[\beta\phi(t)+\phi_{\mathrm{B}}]} + (\sin\alpha)e^{-j\varphi} + (\sin\alpha)e^{j[\beta\phi(t-\tau)+\phi_{\mathrm{B}}-\varphi]}, \tag{2}$$

where α is the polarization angle of the incident light wave with respect to the fast axis of the PMF and $\varphi = \omega\tau + \phi_0$. If this signal is sent to a photodetector (PD) for square-law detection, we obtain the ac term of the photocurrent given by

$$\begin{aligned} i \propto {} & |\cos\alpha|\sqrt{1+\sin 2\alpha\cos\varphi}\,\cos[\beta\phi(t)+\phi_{\mathrm{B}}+\theta_1] \\ & + |\sin\alpha|\sqrt{1+\sin 2\alpha\cos\varphi}\,\cos[\beta\phi(t-\tau)+\phi_{\mathrm{B}}-\theta_2] \\ & + \tfrac{1}{2}\sin 2\alpha\cos\{\beta[\phi(t)-\phi(t-\tau)]+\varphi\}, \end{aligned} \tag{3}$$

where

$$\theta_1 = \tan^{-1}\left(\frac{\sin\alpha\sin\varphi}{\cos\alpha+\sin\alpha\cos\varphi}\right), \tag{4}$$

$$\theta_2 = \tan^{-1}\left(\frac{\cos\alpha\sin\varphi}{\sin\alpha+\cos\alpha\cos\varphi}\right). \tag{5}$$

To generate a UWB monocycle, we set $\varphi = \pi/2$, $\phi_{\mathrm{B}} = 0$, and $\alpha = \pi/4$. Equation (3) can be then rewritten as

$$\begin{aligned} I_{\mathrm{o}} \propto {} & \cos[\beta\phi(t)] + \cos[\beta\phi(t-\tau)] + \sin[\beta\phi(t-\tau)] \\ & - \sin[\beta\phi(t)] - \sin\{\beta[\phi(t)-\phi(t-\tau)]\}. \end{aligned} \tag{6}$$

If β is small, the five terms on the right-hand side can be expanded in Taylor series. By neglecting the second- and higher-order terms, Eq. (6) is approximated as

$$I_{\mathrm{o}} \propto -2\beta[\phi(t)-\phi(t-\tau)]. \tag{7}$$

As can be seen the output current is proportional to the first-order difference of the input signal. If τ is sufficiently small, the first-order difference can be approximated as the first-order derivative [2]; therefore, the entire system is equivalent to a first-order differentiator and a Gaussian monocycle is generated if the input is a Gaussian pulse. On the other hand, when $\alpha = -\pi/4$, the polarity of the UWB monocycle pulse will be changed, indicating that a pair of polarity-inverted Gaussian monocycle pulses can be generated simply by adjusting PC2. If PC2 is replaced with a PolM, the polarity of the UWB monocycle pulse would be electrically switchable at a high speed.

To get a UWB doublet, we let $\varphi = \pi$, $\phi_{\mathrm{B}} = 0$, and $\alpha = \pi/4 + \delta$, where δ is very small as compared with $\pi/4$. Then Eq. (3) can be approximated as

$$\begin{aligned} I_{\mathrm{o}} \propto {} & \sqrt{\delta}\{\cos[\beta\phi(t)] + \cos[\beta\phi(t-\tau)]\} - \cos\{\beta[\phi(t) \\ & - \phi(t-\tau)]\}. \end{aligned} \tag{8}$$

On the right-hand side of Eq. (8), the first term is a dark pulse, while the second term corresponds to a W-shape pulse. The subtraction of the two terms will lead to the generation of a doublet pulse. In a simulation, we let $\delta = \pi/60$ and $\beta = \pi/3$; a Gaussian doublet pulse is obtained, as shown in Fig. 2(a). Considering that φ can be controlled by PC2, and α and ϕ_{B} are almost the same as those for monocycle pulse generation, the shape of the UWB pulses is electrically switchable if PC2 is replaced with a PolM.

In addition, the doublet pulses can be obtained using the method reported in [8], in which the IM is biased near the maximum or minimum transmission point. If the amplitude of the modulation is large enough, the pedestal part and the peak part of the modulation pulse would lie in the positive and negative slopes or the negative and positive slopes, depending on the bias point on the transfer function curve. Therefore, the pedestal or the peak part of the Gaussian pulse is inverted and a UWB doublet is obtained at the output port of the IM. Then, we set $\alpha = \pi/4$, where the AMZI is again acting as a first-order differentiator. As a result, a Gaussian triplet will be generated. In a simulation, we let $\alpha = \pi/4$, $\varphi = 2\pi/9$, $\phi_{\mathrm{B}} = 13\pi/16$, and $\beta = \pi/3$; a quasi-triplet pulse shape is achieved, shown as the solid curve in Fig. 2(b). By simply setting $\varphi = -2\pi/9$, the polarity of the UWB triplet pulse is inverted, shown as the dashed curve in Fig. 2(b). Again, if PC2 is replaced with a PolM, the polarity of the UWB triplet pulse would be electrically switchable.

An experiment is performed based on the experimental setup shown in Fig. 1. A light wave from a tunable laser source (TLS) is sent to a $LiNbO_3$ chirped IM. A Gaussian-type pulse train generated by a bit-error-rate tester (BERT, Agilent 4901B) with a fixed pattern "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 422 MHz and a duty cycle of about 1/32, is applied to the IM to modulate the light wave. The pulse shape is close to a Gaussian with a FWHM of about 63 ps. The AMZI consists of a PC (PC2), a section of PMF (Corning PM1550), and a polarization

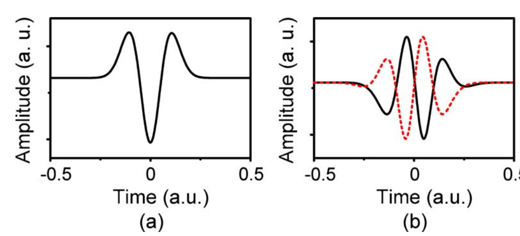

Fig. 2. (Color online) Simulation results for the UWB Gaussian doublet and triplet generated using an IM and an AMZI. (a) Doublet, (b) triplet.

beam splitter. The differential group delay of the PMF is about 40.1 ps. 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 3 shows the waveforms and the spectra of the generated UWB monocycle, doublet, and triplet pulses. As can be seen from Figs. 3(a) and 3(b) the monocycle pulse has an FWHM of 39 ps, and the spectrum is centered at 6.52 GHz with a 10 dB bandwidth of about 10.33 GHz, which indicates that the generated UWB monocycle has a fractional bandwidth of about 158%. Figure 3(c) shows the waveform of a generated UWB doublet pulse, which has an FWHM of about 40 ps. Figure 3(d) shows the corresponding spectrum, which is centered at 9.78 GHz with a 10 dB bandwidth of about 13.1 GHz, indicating a fractional bandwidth of about 134%. The waveforms and the spectra of the generated UWB triplet are shown in Figs. 3(e) and 3(f). The spectrum is centered at 10.1 GHz with a 10 dB bandwidth of about 10.1 GHz, corresponding to a fractional bandwidth of about 100%. The polarity switchability of the generated monocycle pulse and triplet pulse is demonstrated by adjusting PC2, with the waveforms shown as dashed lines in Figs. 3(a) and 3(e). By tuning PC2, the monocycle pulse can also be switched to a doublet pulse. Furthermore, if the dc bias of the IM is tuned to be near the maximum or minimum transmission point, and the polarization direction of the intensity-modulated light wave is aligned with one principal axis of the PMF, a polarity-inverted doublet pulse would be generated, as shown as dashed curve in Fig. 3(c). The entire system is operated in a room environment for a period of 30 min; no significant changes in the temporal waveforms and electrical spectra are observed.

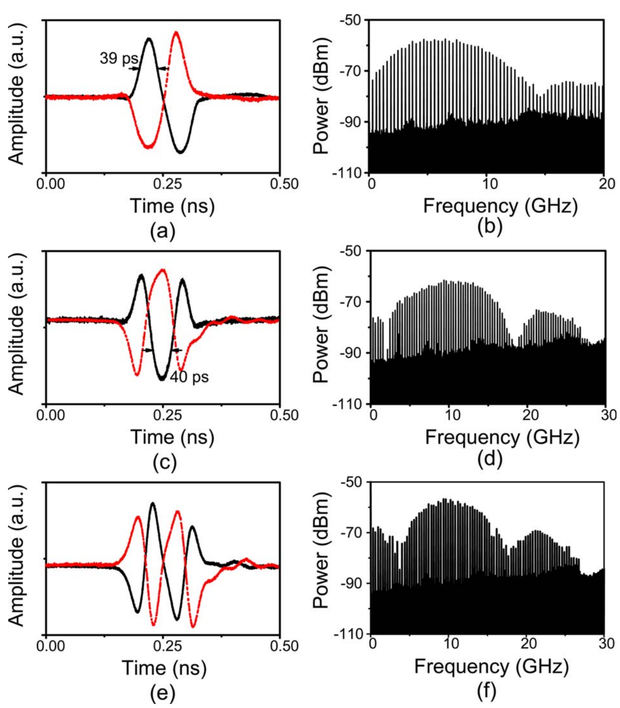

Fig. 3. (Color online) Waveforms and spectra of the generated Gaussian UWB pulses. (a) Generated UWB monocycle and (b) the corresponding electrical spectrum. (c) Generated UWB doublet and (d) the corresponding electrical spectrum. (e) Generated UWB triplet and (f) the corresponding electrical spectrum.

In conclusion, a simple optical UWB pulse generator capable of generating Gaussian monocycle, doublet, or triplet using a chirped IM and an AMZI was proposed and experimentally demonstrated. A UWB monocycle, doublet, or triplet pulse with a fractional bandwidth of about 158%, 134%, or 100% was generated when a Gaussian pulse with a FWHM of 63 ps was applied to the input. The switchability was also demonstrated. The proposed system is potentially integratable, which would meet the practical requirements of small size, low cost, and stable operation for UWB communications.

This work was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC).

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