A Photonic UWB Generator Reconfigurable for Multiple Modulation Formats

Shilong Pan and Jianping Yao, *Senior Member, IEEE*

***Abstract*—In this letter, we propose and demonstrate a simple and flexible optical ultra-wideband (UWB) pulse generator that can be reconfigured for pulse-position modulation, biphase modulation, and pulse-shape modulation. The system is implemented using a dual-drive Mach–Zehnder modulator and an electrically reconfigurable asymmetric Mach–Zehnder interferometer (AMZI). The AMZI consists of a polarization modulator (PolM), a polarization controller (PC), a section of polarization-maintaining fiber, and an optical polarizer. By adjusting the PC and the drive voltage to the PolM, the system is reconfigured to generate UWB signals with different modulation formats. An experiment is performed, which verifies the proposed technique.**

***Index Terms*—Biphase modulation (BPM), polarization modulator (PolM), pulse-position modulation (PPM), pulse-shape modulation (PSM), ultra-wideband (UWB).**

I. Introduction

ULTRA-WIDEBAND (UWB) impulse radio is gaining increasing interest from industry, government, and academia for its potential applications in short-range high-data-rate wireless communications and sensor networks [1]–[4]. By wireless transmission, UWB communication systems can only operate within a short distance of a few meters to tens of meters. To increase the area of coverage, a new technology called UWB over fiber has been considered an effective solution [4]. To distribute UWB signals over the optical fiber, it is also desirable that the UWB signals can be generated in the optical domain without the need for extra electrical-to-optical conversion. For a practical UWB communication system, the information must be encoded using different pulse modulation schemes. Till now, many modulation schemes have been demonstrated in the electrical domain, such as pulse-position modulation (PPM), biphase modulation (BPM, also known as pulse-polarity modulation), and pulse-shape modulation (PSM). For UWB over fiber communications, it is interesting that the modulation schemes are implemented in the optical domain [5]. To implement PSM, BPM, or PPM, the position, polarity, or shape of a UWB pulse sequence from a UWB pulse generator should be switchable at a high speed. Previously, various optical UWB pulse generation techniques have been reported [5]–[12], but only few modulation schemes were demonstrated.

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The authors are with the Microwave Photonics Research Laboratory, School of Information Technology and Engineering, University of Ottawa, Ottawa, ON K1N 6N5, Canada (e-mail: span@site.uottawa.ca; jpyao@site.uOttawa.ca).

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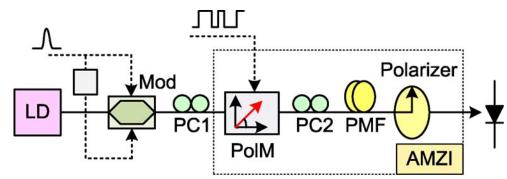

Fig. 1. Schematic of the optical UWB generator using a dual-drive intensity modulator and an asymmetric Mach–Zehnder interferometer. LD: laser diode; Mod: dual-drive Mach–Zehnder modulator; PC: polarization controller; PolM: polarization modulator; PMF: polarization-maintained fiber; and PD: photodetector.

In this letter, we propose a simple and novel optical UWB generator using a dual-drive Mach–Zehnder modulator (MZM) and an asymmetric Mach–Zehnder interferometer (AMZI) that can be reconfigured to implement PPM, BPM, and PSM. The AMZI consists of a polarization modulator (PolM), a section of polarization maintaining fiber (PMF), and an optical polarizer. By simply adjusting the drive voltage to the PolM, a position-switchable UWB monocycle and a polarity-inverted UWB doublet are generated. UWB signals with PPM, BPM, or PSM are thus realized with a data signal sent to the PolM.

II. Principle

Fig. 1 shows the schematic diagram of the proposed UWB pulse generator. A light wave from a laser diode is fiber coupled to a dual-drive MZM, which is driven by a Gaussian pulse train. A proper time delay difference between the signals to the two ports of the MZM is introduced by an electrical delay line. The modulated optical signal is then sent to an AMZI. The AMZI is formed by a section of PMF with the fast axis oriented at an angle of 45° to the transmission axis of a polarizer. A PolM is incorporated between the MZM and the PMF to modulate the polarization direction of the incident light wave. Two polarization controllers (PCs), PC1 and PC2, are incorporated at the input and the output of the PolM, with PC1 being used to adjust the polarization direction of the incident light wave to have an angle of 45° with respect to one principal axis of the PolM, and PC2 being used to adjust the angle between the polarization direction of the polarization-modulated light wave and the fast axis of the PMF, which can also introduce a static phase difference between the two orthogonal optical components along the directions of the fast and the slow axes of the PMF. A photodetector (PD) is connected at the output of the polarizer. A UWB monocycle or doublet pulse train is generated at the output of the PD.

Assume that the electrical drive signals applied to the dual-drive MZM via the two ports are $V_1(t) = V_0\varphi(t)$ and $V_2(t) = V_0\varphi(t+\tau_1)$, where $\varphi(t)$ is a normalized Gaussian pulse, V_0 is the amplitude, and τ_1 is the time delay difference introduced by the electrical delay line. With an optical field of $E_i = \exp(j\omega_c t)$ is injected, where ω_c is the angular frequency of the optical carrier, the optical field at the output of the MZM can be expressed as

$$E_o = \frac{E_i}{2}\left[\exp\left(j\pi\frac{V_1(t)}{V_\pi} + j\frac{\pi}{2}\right) + \exp\left(j\pi\frac{V_2(t)}{V_\pi}\right)\right] \quad (1)$$

where V_π is the half-wave voltage of the MZM. In writing (1), the MZM is assumed to be biased at the quadrature transmission point.

In the AMZI, the incident light is split into two signals traveling along the two principle axes of the PMF, which undergo a time delay difference of τ_2 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

$$\begin{aligned} E_o' = {} & \frac{E_i}{2}\sin\alpha\left[\exp\left(j\pi\frac{V_1(t)}{V_\pi} + j\frac{\pi}{2}\right) + \exp\left(j\pi\frac{V_2(t)}{V_\pi}\right)\right] \\ & + \frac{E_i}{2}\cos\alpha\left[\exp\left(j\pi\frac{V_1(t+\tau_2)}{V_\pi} + j\frac{\pi}{2} + j\theta_0\right)\right. \\ & \left. + \exp\left(j\pi\frac{V_2(t+\tau_2)}{V_\pi} + j\theta_0\right)\right] \end{aligned} \quad (2)$$

where α is an angle between the polarization direction of the incident light wave and the fast axis of the PMF, and $\theta_0 = \omega_c\tau_2 + \phi_0$. If the optical signal expressed in (2) is sent to a PD for square-law detection, the ac term of the photocurrent is

$$\begin{aligned} i(t) \propto {} & (1-\cos 2\alpha)\sin\beta\left[\varphi(t+\tau_1) - \varphi(t)\right] \\ & + \sin 2\alpha\cos\left\{\beta\left[\varphi(t+\tau_2) - \varphi(t)\right] + \theta_0\right\} \\ & + \sin 2\alpha\sin\left\{\beta\left[\varphi(t+\tau_1+\tau_2) - \varphi(t)\right] + \theta_0\right\} \\ & + \sin 2\alpha\sin\left\{\beta\left[\varphi(t+\tau_1) - \varphi(t+\tau_2)\right] - \theta_0\right\} \\ & + \sin 2\alpha\cos\left\{\beta\left[\varphi(t+\tau_1+\tau_2) - \varphi(t+\tau_1)\right] + \theta_0\right\} \\ & + (1+\cos 2\alpha)\sin\beta\left[\varphi(t+\tau_1+\tau_2) - \varphi(t+\tau_2)\right] \end{aligned} \quad (3)$$

where $\beta = \pi V_0/V_\pi$ is the phase modulation index of the MZM.

When the polarization direction of the modulated light wave is aligned with one principle axis of the PMF (i.e., $\alpha = 0$ or $\pi/2$), (3) is simplified to

$$i(t) \propto \begin{cases} \sin\beta\left[\varphi(t+\tau_1) - \varphi(t)\right], & \alpha = \pi/2 \\ \sin\beta\left[\varphi(t+\tau_1+\tau_2) - \varphi(t+\tau_2)\right], & \alpha = 0. \end{cases} \quad (4)$$

For small-signal modulation, β is small, we have $\sin\beta \approx \beta$, then (4) is approximated as

$$i(t) \propto \begin{cases} \beta\left[\varphi(t+\tau_1) - \varphi(t)\right], & \alpha = \pi/2 \\ \beta\left[\varphi(t+\tau_1+\tau_2) - \varphi(t+\tau_2)\right], & \alpha = 0. \end{cases} \quad (5)$$

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 drive signal is a Gaussian pulse [4]. By simply alternating α between 0 and $\pi/2$ via tuning the drive voltage to the PolM, the position of the generated monocycle is changed. The time shift is determined by the differential group delay (DGD) of the PMF.

To generate a UWB doublet, we let $\theta_0 = \pi$ and $\alpha = \pi/4 - \delta$, where δ is very small as compared with $\pi/4$. Again, if small-signal modulation is assumed, the six terms on the right-hand side of (3) can be expanded in Taylor series. By neglecting the second- and higher order terms, (3) is simplified to

$$i(t) \propto 2\delta\beta\left[\varphi(t+\tau_1+\tau_2) - \varphi(t+\tau_2) - \varphi(t+\tau_1) + \varphi(t)\right]. \quad (6)$$

As can be seen, the output current is 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 drive signal is a Gaussian pulse [4]. Since the sign of δ is easily changed from positive to negative via adjusting the drive voltage to the PolM, a pair of polarity-inverted Gaussian doublet pulses can be generated. In addition, considering that α can be easily switched from 0 (or $\pi/2$) to $\pi/4 - \delta$ by the PolM, and PC2 can be adjusted to guarantee $\theta_0 = \pi$, the shape of the UWB pulses is also switchable between a monocycle and a doublet.

III. Experimental Verification

An experiment is performed based on the experimental setup shown in Fig. 1 to verify the UWB pulse generation and the implementation of PPM, BPM, and PSM schemes. A lightwwave from a tunable laser source is sent to a dual-drive $LiNbO_3$ MZM. A Gaussian-like pulse train generated by a bit-error-rate tester [(BERT), Agilent 4901B] with a fixed pattern "1000 0000 0000 0000 " (one "1" every 16 bits) and a bit rate of 10 Gb/s, which is equivalent to a pulse train with a repetition rate of 625 MHz and a duty cycle of about 1/16, is split into two channels, and then, applied to the MZM via the two RF ports. A time delay difference of ~30 ps between the two signals is introduced by an electrical delay line. The pulse shape is close to a Gaussian with a full-width at half-maximum (FWHM) of about 85 ps. The AMZI consists of a PolM (Versawave Technologies), a section of PMF (Corning PM1550) of 29.1 m, and a polarization beam splitter. The DGD 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).

Fig. 2 shows the waveforms and the spectra of the generated UWB Gaussian monocycle and doublet pulses. As can be seen from Fig. 2(a) and (b), the monocycle pulse has an FWHM of 56.8 ps, and the spectrum has a central frequency of 5.3 GHz and a 10-dB bandwidth of about 8.2 GHz, which indicates that the generated UWB monocycle has a fractional bandwidth of about 155%. Fig. 2(c) shows the waveform of a generated UWB

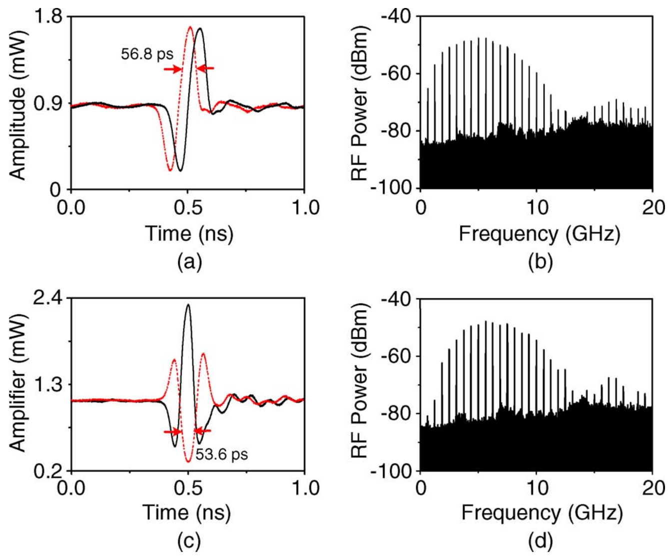

Fig. 2. Waveforms and spectra of the generated UWB pulses. (a) Generated UWB monocycle. (b) Corresponding electrical spectrum. (c) Generated UWB doublet. (d) Corresponding electrical spectrum.

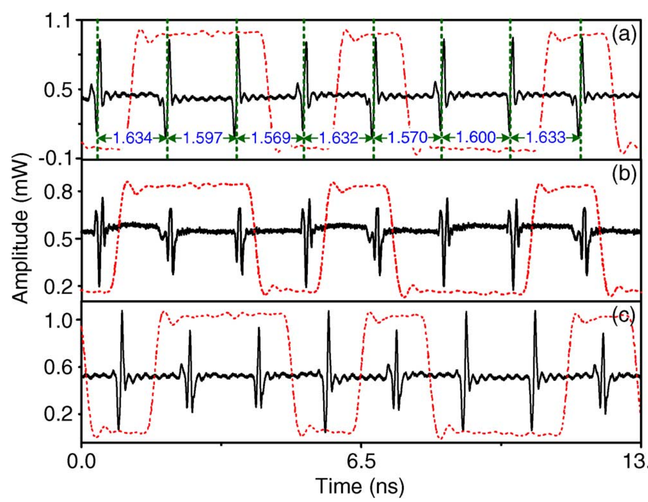

Fig. 3. Waveforms of the (a) pulse-position-modulated, (b) biphase-modulated, and (c) pulse-shape-modulated UWB signals.

doublet pulse, which has an FWHM of about 53.6 ps. Fig. 2(d) shows the corresponding spectrum, which gives a central frequency of 6.55 GHz and a 10-dB bandwidth of about 8.1 GHz, corresponding to a fractional bandwidth of about 123%. The position switchability of the generated monocycle is achieved by simply adjusting the drive voltage to the PolM. As shown in Fig. 2(a), the time difference between the two positions is about 38.5 ps, very close to the DGD of the PMF. The polarity-switchability of the Gaussian doublet is also investigated with the waveforms shown in Fig. 2(c).

To verify the implementation of PPM, BPM, and PSM schemes, a data signal with a bit rate of 625-Mb/s having a fixed pattern "01101001" generated by a second BERT (Anritsu ME522A) is applied to the PolM. By carefully adjusting PC2 and the amplitude of the data signal to the PolM, excellent PPM, BPM, and PSM are realized. Fig. 3 shows the waveforms of the pulse-position-modulated, biphase-modulated, and pulse-shape-modulated UWB signals. Some undesirable parasitic pulses are also observed, which are produced by the transient state between "0" and "1" or "1" and "0" in the data signal. The presence of the parasitic pulses may deteriorate the performance of a UWB transmission system. Methods to eliminate the parasitic pulses are under investigation.

Note that for UWB monocycle pulses, only PPM is achievable; for UWB doublet pulses, only BPM is achievable. However, the entire system can be reconfigured to achieve all three different modulations schemes by using either monocycle or doublet pluses. To enable the system to generate the three modulation scheme for a particular pulse shape, one more AMZI may be added in the configuration [11]

IV. Conclusion

A photonic UWB pulse generator reconfigurable for different modulation formats was proposed and experimentally demonstrated. The reconfigurability was achieved by adjusting the drive voltage to the PolM and PC2. A position-switchable UWB monocycle or polarity-switchable doublet pulse with a fractional bandwidth of about 155% or 123% was generated by simply adjusting the drive voltage to a PolM in the AMZI. By sending a data signal to the PolM, UWB signals with PPM, BPM, and PSM were realized experimentally. The proposed optical UWB pulse generator is simple and compact, which may find applications in UWB over fiber systems.

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