Edge-Triggered Bi-Phase Modulation for the Generation and Modulation of UWB Pulses

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***Abstract*—We propose and demonstrate a novel scheme called edge-triggered bi-phase modulation for the generation and modulation of ultra-wideband (UWB) pulses in the optical domain. The proposed system consists of a laser diode, a Mach–Zehnder modulator (MZM), and a photodetector. An input data sequence with either return-to-zero or nonreturn-to-zero format is sent to the MZM via its radio-frequency port. The MZM is biased at the quadrature point; for an input pulse having a pulse amplitude equal to the two times the half-wave voltage of the MZM, a pair of UWB monocycles is generated with opposite polarities corresponding to the rising and falling edges of the input pulse. A proof-of-concept experiment is performed. A UWB monocycle sequence is generated when a square-wave with a frequency of 680 MHz is applied to the MZM. The generated UWB pulse has a 10-dB bandwidth of 5 GHz with a fractional bandwidth of 165%.**

***Index Terms*—Bi-phase modulation, electrooptical Mach–Zehnder modulator (MZM), Gaussian monocycle, microwave photonics, ultra-wideband (UWB) communication.**

I. Introduction

ULTRA-WIDEBAND (UWB), approved by the U.S. Federal Communications Commission (FCC) for unlicensed use in the frequency band from 3.1 to 10.6 GHz, has been considered a promising technology for applications such as in broadband wireless access networks, sensor networks, medical imaging systems, and modern radars [1], [2]. The ultra-short nature of UWB pulses offers several distinct advantages over conventional narrowband communication techniques such as large channel capacity, good immunity to multipath fading, and low power consumption. A number of techniques have been proposed recently to generate and modulate UWB pulses in the electrical domain [3]–[5]. Due to the low power density regulated by the FCC, the communication distance of a UWB system is usually limited to several or tens of meters. To increase the area of coverage, a solution is to distribute UWB signal over optical fiber, a new technology called *UWB over fiber*, to take advantage of the low loss and broad bandwidth offered by the state-of-the-art fiber optics [6], [7]. In a UWB over fiber system, it is also desirable to generate UWB signals in the optical domain, to avoid additional electrical to optical conversion. In addition, the generation of UWB signals in the optical domain would benefit from the huge bandwidth offered by optics. Recently, a few techniques to generate and distribute UWB signals in the optical domain have been proposed [7]–[11]. Thanks to the simplicity and implementability, UWB pulses are usually generated bases on the implementation of the first- or second-order derivative of a Gaussian pulse using a first- or second-order frequency differentiator. In addition to UWB pulse generation, UWB pulse modulation or encoding is also expected to be implemented in the optical domain [12], [13].

In this letter, a novel technique, called edge-triggered bi-phase (ETBP) modulation, to generate and modulate UWB pulses in the optical domain is proposed and demonstrated. In the proposed system, a laser diode (LD), a Mach–Zehnder modulator (MZM), and a photodetector (PD) are used. The MZM is biased at the quadrature point with an input data sequence with either nonreturn-to-zero (NRZ) or return-to-zero (RZ) format applied to the MZM via its radio frequency (RF) port. For an input pulse having a peak-to-peak voltage equal to two times of the half-wave voltage of the MZM, a pair of UWB monocycles with opposite polarities corresponding to the rising and falling edges of the input pulse is generated. It is different from the conventional modulation schemes such as pulse-position modulation (PPM), bi-phase modulation (BPM), or transmitted-reference (TR) modulation [2]; the information is encoded by the pulse polarities and the time duration between two adjacent UWB pulses. A proof-of-concept experiment is performed. To ease the requirement for a large peak-to-peak voltage of the input data sequence, we propose to use two cascaded MZMs, which is equivalent to a single MZM, but has a half-wave voltage that is 50% of the half-wave voltage of a single MZM. A UWB monocycle pulse sequence is generated when a 680-MHz quasi-square wave is applied to the MZMs. The spectrum of the generated UWB pulse has a 10-dB bandwidth of 5 GHz with a fractional bandwidth as large as 165%.

II. Principle of Operation

The principle of the proposed approach is shown in Fig. 1. The system consists of a continuous wave (CW) laser source, an MZM, and a PD, as shown in Fig. 1(a). The lightwave from the CW laser source is launched into the MZM, to which a data sequence, with either NRZ or RZ format, is applied. The PD is connected at the output of the MZM to perform optical to electrical conversion.

Mathematically, the transfer function of the MZM is given by

$$I = I_0 \sin^2\left(\frac{\pi}{2} \times \frac{V(t)+V_B}{V_\pi}\right) \quad (1)$$

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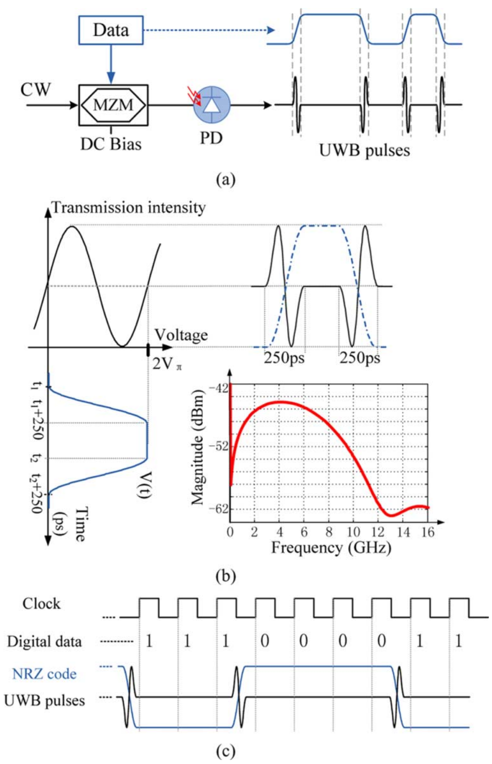

Fig. 1. Diagram showing the principle of the edge-triggered bi-phase modulation. (a) The setup of the system. (b) Generation and modulation of UWB monocycle pulses. (c) The relationship among the clock, the digital data, the NRZ code and the generated UWB pulses.

where I_0 is the maximum output light intensity, $V(t)$ is the data sequence applied to the MZM, V_B is the bias voltage, and V_π is the half-wave voltage of the MZM. As can be seen from Fig. 1(b), the MZM is biased at the quadrature point with $V_B = V_\pi/2$. When an input pulse having a peak-to-peak voltage $V_{\text{pp}} = 2V_\pi$ is applied to the MZM, a pair of monocycles with opposite polarities corresponding to the rising and falling edges of an input pulse is generated.

Mathematically, a pulse of the input data sequence in Fig. 1(b) can be expressed as

$$V(t) = \begin{cases} 0, & t < t_1 \text{ and } t > t_2 + 250 \\ V_\pi\{1+\cos[2\pi(t-t_1)/T]\}, & t_1 < t < t_1 + 250 \\ 2V_\pi, & t_1 + 250 < t < t_2 \\ V_\pi\{1+\cos[2\pi(t-t_2)/T]\}, & t_2 < t < t_2 + 250 \end{cases} \tag{2}$$

where $T = 500$ ps, which is two times the time duration of the rising or falling edge, and $V_{\text{pp}} = 2V_\pi$. The edges of the pulse are modeled as a sinusoidal function, for simplicity. The generated pulses are given by

$$I = I_0 \sin^2\{3\pi/4 + \pi/2 \times \cos[2\pi(t-t_i)/T]\}$$
$$t_i < t < t_i + 250, \quad i = 1, 2 \tag{3}$$

The spectrum of the generated pulse corresponding to a UWB monocycle is shown Fig. 1(b).

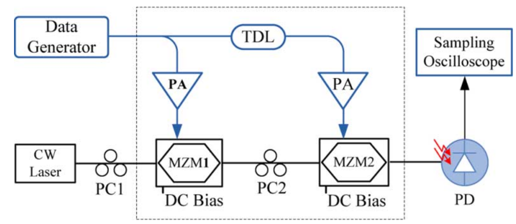

Fig. 2. Block diagram of experimental setup. The dashed lines outline the equivalent MZM. PA: power amplifier and TDL: time delay line.

The generated UWB monocycle pair has opposite polarities. This property is important, since the proposed system cannot only generate, but also modulate, the UWB pulses. The digital information carried by the data sequence is modulated to the UWB sequence by the polarities and the time duration between two adjacent UWB pulses. As shown in Fig. 1(c), the data between the first negative monocycle and the positive monocycle correspond to three "1", and the data between the positive monocycle and the negative monocycle correspond to four "0". The number of "1" or "0" is determined with the help of the timing clock. Therefore, by counting the number of clocks between two adjacent UWB pulses and the polarities of two adjacent monocycles, the original data can be recovered.

III. Experiment

A proof-of-concept experiment is implemented based on the experimental setup shown in Fig. 2. The input data sequence must have a peak-to-peak voltage that is twice the half-wave voltage of the MZM, which is very high for most of the applications. To ease the requirement for a large input voltage, we propose to use two cascaded MZMs. We prove that two cascaded MZMs is equivalent to a single MZM, but with a half-wave voltage that is reduced by half compared to a single MZM.

Mathematically, the transfer function of the two cascaded MZMs is given by

$$I = I_0 \sin^2\left(\frac{\pi}{2} \times \frac{V(t)+V_{B1}}{V_\pi}\right) \times \sin^2\left(\frac{\pi}{2} \times \frac{V(t)+V_{B2}}{V_\pi}\right) \tag{4}$$

where V_{B1} and V_{B2} are the bias voltages applied to MZM1 and MZM2, respectively. By adjusting the bias voltages to make $V_{B1} - V_{B2} = V_\pi$ and $V_{B1} = V_\pi/4$, then (4) becomes

$$I = \frac{I_0}{4} \sin^2\left(\pi \cdot \frac{V(t)}{V_\pi} + \frac{\pi}{4}\right). \tag{5}$$

Comparing (5) and (1), we can see that the two cascaded MZMs is equivalent to a single MZM, but with a half-wave voltage that is $V_\pi/2$. Thus, when the data sequence $V(t)$ with a V_{pp} of V_π is applied to drive the MZMs, a UWB sequence is generated, as shown in Fig. 3(a).

Note that to compensate for the time delay introduced by the lightwave traveling from MZM1 to MZM2, a tunable time delay line (TDL) is introduced between the data generator and MZM2.

In the experiment, to demonstrate the concept, we use a square wave with a frequency of 680 MHz and a duty cycle of 50% generated by a function generator as the data sequence, as

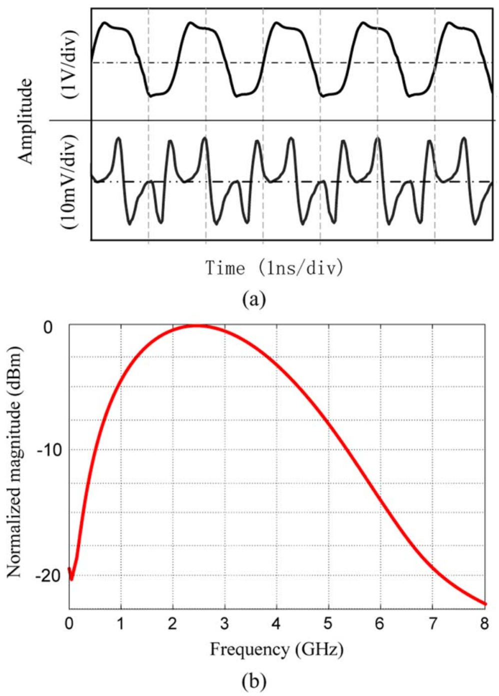

Fig. 3. The experimental results. (a) The data sequence and the generated UWB pulses. (b) The spectrum of a UWB monocycle corresponding to one rising edge of the data waveform, obtained by calculating the Fourier transform of one single monocycle taken from the experimentally generated sequence.

shown in Fig. 3(a). The $V_{\rm pp}$ of the data square wave after the amplifiers is 4 V; the MZMs are biased with V_{B1} being 2.2 V and V_{B2} being 8 V. The difference between V_{B1} and V_{B2} is larger than 4 V because the half-wave voltage of the MZMs at dc is higher than that at a higher frequency. The generated UWB pulses are also shown in Fig. 3(a). As can be seen, a positive UWB monocycle is generated at the rising edge and a negative UWB monocycle is generated at the falling edge. The time duration between two adjacent UWB pulses is approximately 480 ps, which is equal to the time duration of the square wave. The spectrum of the generated UWB monocycle is also evaluated. To do so, we take one single monocycle from the experimentally generated sequence and calculate the Fourier transform of that single monocycle. The spectrum is shown in Fig. 3(b). As can be seen, the UWB monocycle has a spectrum a 10-dB bandwidth of 5 GHz with a fractional bandwidth as large as 165%.

The key advantage of the proposed scheme compared with the existing techniques based on an optical frequency differentiator [7], [8] is that UWB pulses can be generated and modulated at the same time using a simple system with a nonlinearly operated MZM. The information is converted into the polarities of the UWB pulses and the temporal duration between two adjacent UWB pulses.

IV. Conclusion

A novel technique to generate and modulate UWB pulses in the optical domain was proposed and experimentally demonstrated. The key feature of the technique is that a data sequence is converted to a UWB sequence with a positive UWB monocycle representing the rising edge and a negative UWB monocycle representing the falling edge. Therefore, the information, either in RZ or NRZ format, can be converted to the polarities and the time duration of two adjacent UWB monocycles. In the proposed system, the data sequence should have a peak-to-peak voltage of twice the half-wave voltage of the MZM in the system, which is high for most of the applications. To reduce the input voltage, we proposed to use two cascaded MZMs, which are proved to be equivalent to a single MZM, but with half of the half-wave voltage of a single MZM. An experiment was performed to demonstrate the concept. In the experiment, a square wave with a frequency of 680 MHz and a duty cycle 50% was used as the data sequence. A UWB monocycle sequence was generated with a positives monocycle corresponding to the rising edge and a negative monocycle corresponding to the falling edge. The time duration of adjacent UWB pulses was about 480 ps. The monocycle has a spectrum with a 10-dB bandwidth of 5 GHz and a fractional bandwidth of 165%.

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