# Polarity- and Shape-Switchable UWB Pulse Generation Based on a Photonic Microwave Delay-Line Filter With a Negative Tap Coefficient

Hongqian Mu and Jianping Yao, *Senior Member, IEEE*

***Abstract*—A novel and simple scheme to implement a two- or three-tap photonic microwave filter with one negative coefficient for polarity- and shape-switchable ultrawideband (UWB) pulse generation is proposed and demonstrated. The entire system can be reconfigured as a two- or three-tap microwave delay-line filter with one negative coefficient realized by operating a balanced photodetector (BPD) as a single photodetector or a BPD for the generation of UWB monocycle or doublet pulses. The polarity of the generated UWB pulses can be switched by tuning the transmission axis of the arbitrary wave plate. The proposed scheme is experimentally demonstrated. Gaussian monocycle and doublet pulses with fractional bandwidths of about 174% and 141% are generated.**

***Index Terms*—Microwave photonics, phase modulation, photonic microwave delay-line filter, ultrawideband (UWB).**

## I. INTRODUCTION

ULTRAWIDEBAND (UWB) for wireless communications has numerous advantages over the conventional narrowband communication, such as high data rate, low power consumption, and high resistance to multipath fading [1]–[4]. The U.S. Federal Communications Commission (FCC) in 2002 approved the unlicensed use of a frequency band from 3.1 to 10.6 GHz with a power spectral density lower than −41.3 dBm/MHz for indoor wireless communications [3]. Based on the FCC definition, a UWB signal should have a spectral bandwidth greater than 500 MHz or a fractional bandwidth greater than 20%.

Due to the low power density regulated by the FCC, the communications distance is limited to a few to tens of meters. To increase the area of coverage, a solution is to distribute UWB signals over optical fiber to take advantage of the low loss and broad bandwidth offered by the state-of-the-art optical fiber [4]. To avoid extra electrical to optical conversion, it is also desirable to generate UWB signals in the optical domain. Among the many UWB pulses, Gaussian monocycle and doublet are considered as two excellent candidates for UWB impulse communications due to the simplicity and achievability in generating these pulses. A Gaussian monocycle or doublet can be generated by implementing the first- or the second-order derivative of a Gaussian pulse. Mathematically, a first- or second-order derivative can be approximated by a first- or second-order difference, which can be implemented using a two- or three-tap photonic microwave delay-line filter with tap coefficients of $(1, -1)$ or $(1, -2, 1)$ [4]. Numerous techniques have been proposed to implement a photonic microwave delay-line filter with negative taps [5]–[7]. For example, a photonic microwave delay-line filter with negative tap coefficients can be realized based on cross-gain modulation in a semiconductor optical amplifier (SOA) [8]. By using an SOA-based photonic microwave delay-line filter, Wang *et al.* demonstrated the generation of a Gaussian monocycle pulse [9]. To avoid using two optical sources, Wang *et al.* proposed a system using a polarization modulator (PolM) to generate the Gaussian monocycle [10]. A PolM is a special phase modulator (PM) that supports both transverse electric mode and transverse magnetic mode but with opposite modulation indexes. With the use of a fiber Bragg grating as a frequency discriminator to perform phase-modulation to intensity-modulation conversion, a Gaussian monocycle with switchable polarities was generated. Pan and Yao proposed to generate UWB pulses using a PM and a reconfigurable asymmetric first- or second-order Mach–Zehnder interferometer (AMZI) [11]. The use of an optical interferometer, especially the second-order AMZI that consists of two cascaded first-order AMZIs, makes the system sensitive to environmental changes. Most recently, a flexible UWB pulse generator that uses a multiple-tap microwave photonic filter for the generation of high-order UWB pulses with different pulse modulation formats was proposed [12].

In this letter, we propose a novel and simple scheme to implement a reconfigurable photonic microwave delay-line filter with a negative tap for polarity- and shape-switchable UWB pulse generation. The system consists of a laser diode (LD), a PM, a polarization-maintaining fiber (PMF), an arbitrary wave plate (AWP), and a balanced photodetector (BPD). The entire system is equivalent to a photonic microwave delay-line filter having two or three taps with coefficients of $(1, -1)$ or $(1, -2, 1)$. When a Gaussian pulse is sent as an input to the photonic microwave filter, a Gaussian monocycle or doublet pulse is generated. To meet the spectrum requirement specified by the FCC, the shape of the pulse can be adjusted by changing the time-delay difference between two adjacent taps. Compared with the use of a

---

Manuscript received February 28, 2009; revised May 18, 2009. Current version published August 19, 2009. This work was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC). The work of H. Mu was supported by a scholarship from the China Scholarship Council.

H. Mu is with the Microwave Photonics Research Laboratory, School of Information Technology and Engineering, University of Ottawa, Ottawa, ON K1N 6N5, Canada, and also with the Institute of Optoelectronics Engineering, Beijing University of Aeronautics and Astronautics, Beijing 100083, China.

J. Yao is with the Microwave Photonics Research Laboratory, School of Information Technology and Engineering, University of Ottawa, Ottawa, ON K1N 6N5, Canada (e-mail: jpyao@site.uOttawa.ca).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2009.2024643

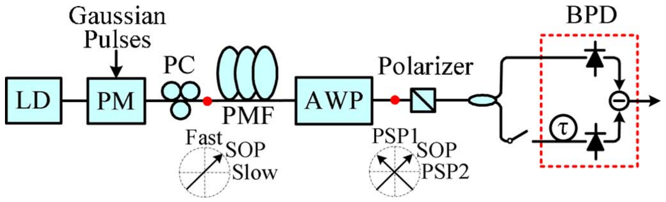


Fig. 1. Schematic diagram of the proposed UWB pulse generator. LD: laser diode. PM: phase modulator. PC: polarization controller. PMF: polarization-maintaining fiber. AWP: arbitrary wave plate. BPD: balanced photodetector. SOP: state of polarization. PSP: principal state of polarization.

PolM in [10], the use of a PM makes the system simplified with a lower cost.

## II. PRINCIPLE

The schematic diagram of the proposed UWB pulse generator is illustrated in Fig. 1. A linearly polarized light wave emitted from the LD is modulated at the PM by a Gaussian pulse, and then launched into the PMF with an incidence angle of 45° with respect to the fast axis by adjusting the polarization controller (PC). In the PMF, the light wave is decomposed equally into two orthogonally polarized components, and then transmits along the fast and slow axes of the PMF at different velocities; therefore, a time-delay difference $\tau_1$ between the two orthogonally polarized components is introduced. The angle from the fast axis of the PMF to the transmission axis of the polarizer can be aligned at 45° or $-45°$, which is realized by adjusting the voltage applied to the AWP. In either case, the two modes in the PMF will be projected to the polarization axis of the polarizer.

The electric field of a phase-modulated optical carrier can be expressed as

$$E_{\mathrm{PM}}(t) = E_0 \exp(j\omega_c t) \exp[j\beta s(t)] \tag{1}$$

where $E_0$ and $\omega_c$ are the amplitude and angular frequency of the optical carrier, $\beta$ is the phase modulation index, and $s(t)$ is the electrical modulation signal applied to the PM. The electric field at the output of the PMF is

$$\begin{aligned} E_{\mathrm{PMF}}(t) =& \{E_0 \exp[j\omega_c t + j\beta s(t)]/\sqrt{2}\}\hat{x} \\ &+ \{E_0 \exp[j\omega_c (t-\tau_1) + j\beta s(t-\tau_1)]/\sqrt{2}\}\hat{y} \end{aligned} \tag{2}$$

where $\hat{x}$ and $\hat{y}$ denote the polarization directions of the fast and slow axes of the PMF, respectively. An optical polarizer is placed after the PMF. The angle between the fast axis of the PMF and the transmission axis of the polarizer is adjusted to be 45° or $-45°$, and the corresponding optical field $E_{\mathrm{pol}}(t)$ at the output of the polarizer is given by

$$\begin{aligned} E_{\mathrm{pol}}(t) =& E_0 \exp[j\omega_c t + j\beta s(t)]/2 \\ &+ (-1)^n E_0 \exp[j\omega_c (t-\tau_1) + j\beta s(t-\tau_1)]/2 \end{aligned} \tag{3}$$

where $n = 0$ or 1 corresponding to the fast axis of the PMF is oriented with an angle of 45° or $-45°$ to the transmission axis of the polarizer.

If the output signal is sent to one photodetector (only one arm of the BPD is connected), under small-signal modulation condition, we have the photocurrent at the output of the photodetector

$$I_1(t) = (-1)^{n+1} \Re \beta E_0^2 (\sin \omega_c \tau_1)[s(t) - s(t-\tau_1)]/4 \tag{4}$$

where $\Re$ is the responsivity of the photodetector. As can be seen, the system is operating as a two-tap microwave delay-line filter with coefficients of $(1, -1)$. If the input modulation signal is a Gaussian pulse, a Gaussian monocycle is thus generated.

When the two arms of the BPD are both connected, at the output of the BPD, we have

$$\begin{aligned} I_2(t) =& I_1(t) - I_1(t-\tau_2) \\ =& (-1)^{n+1} \Re \beta E_0^2 (\sin \omega_c \tau_1) [s(t) - s(t-\tau_1) - s(t-\tau_2) \\ &+ s(t-\tau_1-\tau_2)]/4. \end{aligned} \tag{5}$$

If the time-delay difference $\tau_2$ introduced by the BPD is identical to the time-delay difference $\tau_1$ introduced by the PMF, (5) can then be rewritten as

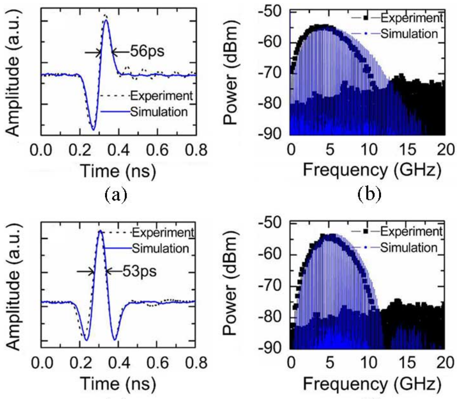
$$\begin{aligned} I_2(t) &= I_1(t) - I_1(t-\tau_1) \\ &= (-1)^{n+1} \Re \beta E_0^2 (\sin \omega_c \tau_1) [s(t) - 2s(t-\tau_1) \\ &\quad + s(t-2\tau_1)]/4. \end{aligned} \tag{6}$$

As can be seen, the system is now operating as a three-tap microwave delay-line filter with coefficients of $(1, -2, 1)$. If the input modulation signal is a Gaussian pulse, a Gaussian doublet is generated.

From (4)–(6), it is clearly seen that by adjusting the orientation of the fast axis of the PMF to have an angle of 45° or $-45°$ to the transmission axis of the polarizer, the polarity of the generated UWB monocycle or doublet can be switched.

## III. EXPERIMENT AND DISCUSSION

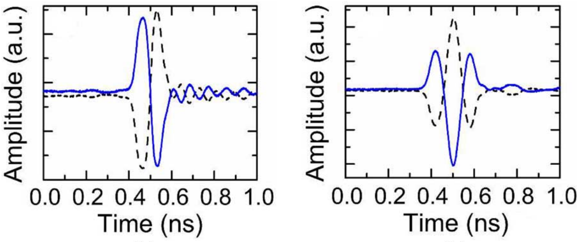
The proposed UWB pulse generator shown in Fig. 1 is experimentally implemented. A tunable laser source with a linewidth of 700 kHz operating at 1550 nm is employed as the light source. The modulator used in the experiment is a $\mathrm{LiNbO_3}$ straight-line PM. The PM is driven by a Gaussian-like pulse train generated by a bit-error-rate tester (BERT, Agilent 4901B) with a fixed pattern of one "1" for every 64 bits at a bit rate of 10 Gb/s, corresponding to a Gaussian pulse train with a repetition rate of 156.25 MHz and a duty cycle of 1/64. The full-width at half-maximum of the Gaussian pulse is about 80 ps. The peak voltage of the Gaussian pulse is 2.5 V and the half-wave voltage of the PM is 11 V, which leads to a phase modulation index of 0.71 rad. The output from the PM is sent to the PMF (Corning PM1550). The PMF is 29.1 m long with a beat length 3.75 mm, corresponding to a time-delay difference between the fast and the slow axes of about 40.1 ps. Since no AWP is available at the time of the experiment, a second PC is used to replace the AWP. The incident polarization angle is adjusted to be 45° with respect to the fast axis of the PMF by the first PC. The angle between the fast axis of the PMF and the transmission axis of the polarizer is tunable by adjusting the second PC. The generated UWB pulses at the output of the BPD are monitored by a high-speed sampling oscilloscope (Agilent 86116A) and an electrical spectrum analyzer (Agilent E4448A).



(a) (b)

(c) (d)

Fig. 2. Generated UWB Gaussian monocycle and doublet pulses in the experiment and simulation. (a) Monocycle, and (b) its corresponding spectrum. (c) Doublet, and (d) its corresponding spectrum.



(a) (b)

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

We first adjust the angle between the fast axis of the PMF and the transmission axis of the polarizer to be 45°. When the optical switch in the BPD is turned off, a UWB monocycle is generated with its temporal waveform and the corresponding spectrum shown in Fig. 2(a) and (b). The pulsewidth of the monocycle pulse is measured to be about 56 ps and the spectrum has a central frequency of 4.85 GHz with a 10-dB bandwidth of about 8.44 GHz, which means that the fractional bandwidth is 174%. Then, the optical switch in the BPD is turned to generate a UWB doublet with the temporal waveform and the corresponding spectrum shown in Fig. 2(c) and (d). The pulsewidth is measured to be 53 ps and the spectrum has a central frequency of 5.34 GHz, a 10-dB bandwidth of about 7.53 GHz, and a fractional bandwidth of 141%.

To demonstrate the polarity switchability, the angle between the fast axis of the PMF and the transmission axis of the polarizer is adjusted from 45° to $-45°$. As can be seen, both UWB Gaussian monocycle and doublet are generated, but with an inverted polarity, as shown by the solid line in Fig. 3.

Since the delay-line filter is operating in the coherent regime, the coherent time $\tau_c$ of the laser source must be greater than the time-delay difference $\tau_1$. To satisfy this coherence condition, the linewidth of the laser source used in the experiment must be narrower than $\Delta\nu = 1/\tau_c \ll 1/\tau_1 = 2.5 \times 10^{10}$ Hz. Since a distributed-feedback (DFB) laser or Fabry–Pérot (FP) laser has a linewidth narrower than 100 MHz or a coherence time greater 10 ns, which is much greater than the time-delay difference of 40.1 ps. Therefore, it is feasible to use a commercially available DFB or FP laser to replace the highly coherent tunable laser source to reduce the system cost. From (4)–(6), we can see that the coefficients of the delay-line filter depend on the term $\omega_c\tau_1$. Considering that the frequency stability of the laser source is 100 MHz/h, the variation of $\omega_c\tau_1$ is calculated to be about 0.0252 rad/h, which is very small and can be neglected.

## IV. CONCLUSION

A novel and simple scheme to implement a two- or three-tap photonic microwave delay-line filter with one negative tap for the generation of polarity- and shape-switchable UWB pulses was proposed and experimentally demonstrated. The polarity switchability of the generated UWB pulses was achieved by adjusting the transmission axis of the AWP. A state-of-the-art electrically tunable AWP can operate at a speed up to 40 Gb/s [13], which is high enough for applications where pulse polarity modulation is needed. The number of taps could be increased to generate higher order UWB pulses to better fit the FCC spectral mask. To do so, $N$ sections of PMF can be cascaded with the principal axes of the adjacent sections being oriented with an angle of 45°; then, the entire system is operating as a delay-line filter with $N+1$ or $N+2$ taps.

## REFERENCES

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

[2] F. Nekoogar, *Ultra-Wideband Communications: Fundamentals and Applications*. Upper Saddle River, NJ: Prentice-Hall, 2006.

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

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

[5] J. Capmany, B. Ortega, and D. Pastor, "A tutorial on microwave photonic filters," *J. Lightw. Technol.*, vol. 24, no. 1, pp. 201–229, Jan. 2006.

[6] R. A. Minasian, "Photonic signal processing of microwave signals," *IEEE Trans. Microw. Theory Tech.*, vol. 54, no. 2, pp. 832–846, Feb. 2006.

[7] J. P. Yao, "Microwave photonics," *J. Lightw. Technol.*, vol. 27, no. 3, pp. 314–335, Feb. 2009.

[8] F. Coppinger, S. Yegnanarayanan, P. D. Trinh, and B. Jalali, "All-optical RF filter using amplitude inversion in a semiconductor optical amplifier," *IEEE Trans. Microw. Theory Tech.*, vol. 45, no. 8, pp. 1473–1477, Aug. 1997.

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

[10] Q. Wang and J. P. Yao, "An electrically switchable optical Ultrawideband pulse generator," *J. Lightw. Technol.*, vol. 25, no. 11, pp. 3626–3633, Nov. 2007.

[11] S. Pan and J. P. Yao, "Switchable UWB pulse generation using a phase modulator and a reconfigurable asymmetric Mach–Zehnder interferometer," *Opt. Lett.*, vol. 34, no. 2, pp. 160–162, Jan. 2009.

[12] M. Bolea, J. Mora, B. Ortega, and J. Capmany, "Optical UWB pulse generator using an N tap microwave photonic filter and phase inversion adaptable to different pulse modulation formats," *Opt. Express*, vol. 17, no. 7, pp. 5023–5032, Mar. 2009.

[13] J. D. Bull, N. A. F. Jaeger, H. Kato, M. Fairburn, A. Reid, and P. Ghanipour, "40 GHz electro-optic polarization modulator for fiber optic communications systems," *Proc. SPIE*, vol. 5577, no. 1, pp. 133–143, Sep. 2004.