Ultrawideband Impulse Radio Signal Generation Using a High-Speed Electrooptic Phase Modulator and a Fiber-Bragg-Grating-Based Frequency Discriminator

Fei Zeng, *Student Member, IEEE*, and Jianping Yao, *Senior Member, IEEE*

Abstract—**We propose a novel approach to generating ultrawideband impulse radio signals in the optical domain. The proposed system consists of a laser source, an electrooptic phase modulator (EOPM), a fiber Bragg grating (FBG), and a photodetector (PD). The light source is phase modulated by an electrical Gaussian pulse train via the EOPM. The optical phase modulation to intensity modulation conversion is achieved by reflecting the phase modulated light at the slopes of the FBG that serves as a frequency discriminator. Electrical monocycle or doublet pulses are obtained at the output of the PD by locating the wavelength of the optical carrier at the linear or the quadrature slopes of the FBG reflection spectrum. The use of the proposed configuration to implement pulse polarity and pulse shape modulation in the optical domain is discussed. Experimental measurements in both temporal and frequency domains are presented.**

Index Terms—**All-optical signal processing, fiber Bragg grating (FBG), frequency discriminator, microwave photonics, radio-over-fiber, ultrawideband (UWB)-over-fiber.**

I. INTRODUCTION

ULTRAWIDEBAND (UWB) impulse technology has been known for a few decades, but its applications for broadband wireless communications have been explored only recently. Much research effort is being directed to the enhancement of the operational capabilities and the cost-effectiveness of UWB systems for high-throughput wireless communications and sensor networks. Basically, the impulse signal in a UWB wireless system needs to achieve a fractional bandwidth larger than 20% or a 10-dB bandwidth of at least 500 MHz in the frequency range from 3.1 to 10.6 GHz, as defined in Part 15 of the Federal Communications Commission (FCC) regulations [1]–[3]. However, by wireless transmission, UWB signals are only limited in short distance of a few to tens of meters. To avoid such short-range networks operating only in a stand-alone mode, UWB-over-fiber technology can provide a very promising solution to integrate local UWB environment into the fixed wired networks or wireless wide-area infrastructures [4], [5].

Therefore, to fully exploit the advantages provided by optics, it is highly desirable that the distributed UWB pulse signals can be generated directly in the optical domain without the need of extra optical–electrical and electrical–optical conversions. In addition, using optical techniques to generate UWB pulses has many other advantages, such as light weight, small size, large tunability, and the immunity to electromagnetic interference. Recently, we have proposed a method to generate and distribute UWB doublet pulses over a single-mode fiber (SMF) link [6]. In the system, electrical Gaussian pulses were modulated on an optical carrier using an electrooptic phase modulator (EOPM). The optical phase modulation to intensity modulation (PM-IM) conversion was realized by changing the phase relationships among all the frequency components of the optical phase-modulated signal. The chromatic dispersion of the fiber link of a length of 25 km is used to achieve the desired phase changes. The PM-IM conversion has a transfer function equivalent to a microwave bandpass filter, by which the input Gaussian pulses were converted to UWB doublet pulses [6].

In this letter, we propose an approach to generating monocycle or doublet pulses in a structure without using a long optical fiber. In the proposed system, an optical carrier is phase modulated by a Gaussian pulse train via an EOPM. The PM-IM conversion is achieved here by use of a fiber Bragg grating (FBG) that serves as a frequency discriminator [7]. By locating the optical carrier at the linear or the quadrature slope of the FBG reflection spectrum, monocycle or doublet pulses can be obtained at the output of a photodetector (PD). In addition, UWB pulses with opposite polarities can be generated by locating the optical carrier at the right or the left side of the FBG reflection spectrum. This property is important, because the proposed system can be used to implement two different UWB pulse modulation schemes by shifting the optical carrier, the pulse shape modulation (PSM) (monocycle–doublet), and the pulse polarity modulation (PPM). Experiments are carried out to investigate the proposed UWB pulse generation system. Experimental measurements in both temporal and frequency domains are presented, which have good agreement with theoretical analysis.

II. PRINCIPLE

The block diagram of the proposed UWB pulse generator is shown in Fig. 1. Light from a laser diode is fiber coupled to an EOPM which is driven by a sequence of Gaussian pulses. The phase-modulated optical signal is then applied to an FBG

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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: jpyao@site.uottawa.ca).

Color versions of Figs. 1–5 are available online at http://ieeexplore.ieee.org.

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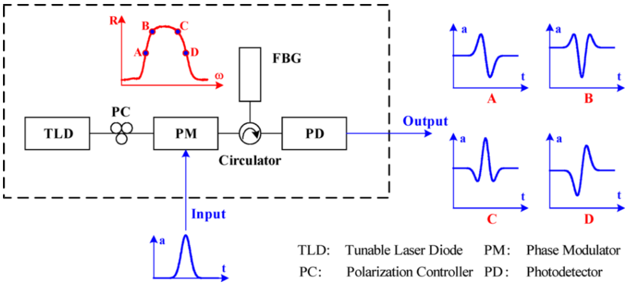

Fig. 1. Block diagram of the proposed UWB pulse generator.

via an optical circulator. The PM-IM conversion is achieved by using the FBG serving as a frequency discriminator. The PM-IM converted signal is then detected at a PD, which serves as an envelope detector.

The normalized optical field being phase-modulated by the Gaussian pulse train can be expressed in the form of

$$E_{\mathrm{PM}}(t) = \exp[j\omega_c t + \beta_{\mathrm{PM}} \cdot s(t)] \tag{1}$$

where ω_c is the angular frequency of the optical carrier, β_{PM} is the phase modulation index, and $s(t)$ is the pulse train represented by

$$s(t) = \sum_{n=-\infty}^{+\infty} \Omega(t - nT_r) \tag{2}$$

where T_r is the pulse repetition interval, and $\Omega(t)$ represents an ideal Gaussian pulse waveform. It is known that the energy spectral density of $\Omega(t)$ is large at dc and low-frequency region, which makes wireless transmission of such a signal impractical. Monocycle and doublet pulses that can be generated by performing the first-order and second-order derivatives of Gaussian pulses have a spectrum profile that can satisfy the FCC specified spectrum mask. Pulse waveforms for UWB applications can also be created by employing a high-pass filter to modify the spectrum of the Gaussian pulse, which is similar to the implementation of different orders of derivative of $\Omega(t)$ [1], [9]. For example, a Gaussian monocycle and a Gaussian doublet, that have very low spectral power at low-frequency region, can be respectively generated by performing the first-order and second-order derivatives of $\Omega(t)$. The approach proposed in this letter is to convert the Gaussian pulses into UWB pulses in the optical domain, which can be employed as UWB pulse source in a UWB-over-fiber network. In addition, in the proposed approach since the UWB signal is already modulated on optical carriers, optically controlled true time-delay beamforming structures [8] can be directly applied at the receiver front-end to improve the operational capabilities of the UWB impulse systems.

Based on the configuration shown in Fig. 1, when the phase modulated light is located at the linear region of the FBG reflection slopes, as shown in Fig. 1 at A, the ac part of the recovered signal at the output of the PD can be written as [7]

$$r(t) \sim \Re P \beta_{\mathrm{PM}} K \cdot s'(t) \tag{3}$$

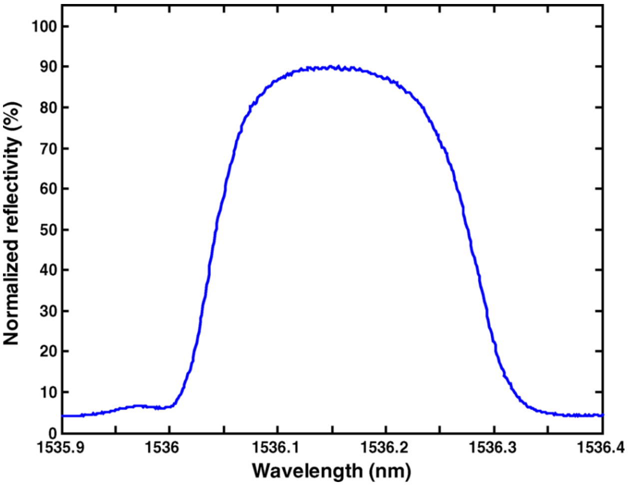

Fig. 2. Measured power reflection spectrum of the FBG used in the experiment.

where $\Re$ is the responsivity of the PD, P is the optical power reflected from the FBG, K is the slope steepness factor of the FBG power spectrum, and $s'(t)$ is the first-order derivative of the modulating signal $s(t)$. Then the UWB monocycle pulses are obtained, which is denoted as $\Omega'(t)$.

Furthermore, when the optical carrier is located at the opposite slope of the FBG reflection spectrum, as shown in Fig. 1 at D, the output pulse will have a π phase difference. This property is important, which has the potential to realize PPM when two optical carriers corresponding to these two out-of-phase pulses are employed and switched by the data sequence to be transmitted. More interestingly, if the optical carrier is located at the quadrature slopes of the FBG reflection response, as shown in Fig. 1 at B and C, doublet pulses will be generated. Therefore, by locating the optical carrier at different locations, UWB pulses with different shapes can be generated in the same configuration, and eventually the implementation of another pulse modulation scheme, i.e., PSM, is possible.

III. EXPERIMENT

The proposed UWB pulse generation system is experimentally implemented based on the configuration shown in Fig. 1. A tunable laser source with typical linewidth of 150 kHz is employed as the light source. The Gaussian-like pulse train is generated by a bit-error-rate tester (BERT). The temporal waveform representing a single input pulse can be found in [6, Fig. 3(a)], which has a full-width at half-maximum (FWHM) amplitude of about 63 ps. Phase modulation is performed by using a $\mathrm{LiNbO_3}$ straight-line phase modulator. An FBG with a length of 10 mm and a peak power reflectivity of 90% is fabricated and used as the frequency discriminator in the experiment. A proper Gaussian apodization is applied during the FBG fabrication process to suppress the reflection sidelobes. Its reflection spectrum is shown in Fig. 2, which has a central wavelength of 1536.12 nm and a 3-dB bandwidth of 0.23 nm.

First, the carrier wavelength λ_c is tuned at 1536.032 nm, which is located at the left linear slope of the FBG. The signal at the output of the PD is then measured in both temporal and frequency domains by use of a high-speed sampling oscilloscope and an electrical spectrum analyzer, respectively. Fig. 3(a)

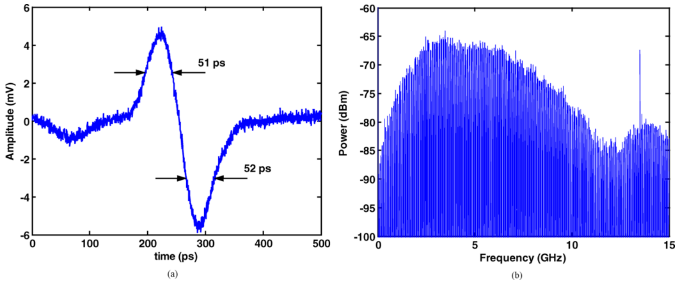

Fig. 3. When a 13.5-Gb/s pseudorandom binary sequence (PRBS) $2^{10}-1$ signal (generated by the BERT) is applied to the EOPM, the wavelength of the optical carrier $\lambda_c = 1536.032$ nm, (a) the waveform showing a monocycle pulse, and (b) the power spectrum measured at the output of the PD.

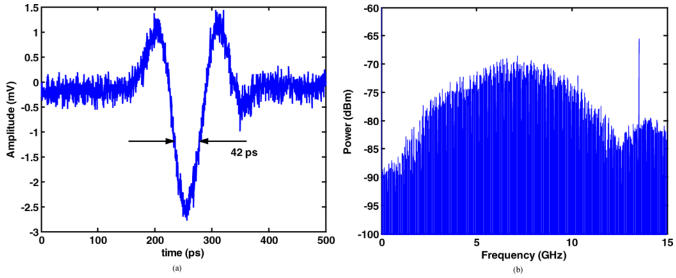

Fig. 4. (a) Waveform of the Gaussian doublet pulse, and (b) power spectrum of the shaped 13.5-Gb/s PRBS $2^{10}-1$ signal obtained at the output of the PD. The wavelength of the optical carrier is $\lambda_c = 1536.098$ nm.

shows the generated Gaussian monocycle pulse, which has an FWHM of about 52 ps. Fig. 3(b) shows the power spectrum of the Gaussian monocycle pulse signal, which has a central frequency of about 3.45 GHz, and a 10-dB bandwidth of about 7.94 GHz.

Then, the carrier wavelength is tuned at 1536.098 nm, which is located at the left turning corner (quadrature slope) of the FBG reflection spectrum, the output pulse turns to be a doublet with a negative mainlobe and two equal-time sidelobes having positive values, as shown in Fig. 4(a). Its FWHM is about 42 ps. From its power spectrum shown in Fig. 4(b), we can see that the central frequency is increased to be about 7.14 GHz and the 10-dB bandwidth is about 8.8 GHz. These results are expected according to the mathematical definition of a Gaussian pulse with different orders of derivatives [9]. We then further tune the carrier wavelength and make it be reflected at the right linear slope and the right turning corner, respectively. As can be seen from Fig. 5, the generated pulses are actually the inverted versions of the ones shown in Figs. 3(a) and 4(a), respectively. These interesting results agree well with the theoretical analysis in Section II.

The stability of the output electrical pulses depends mainly on the wavelength stability of the laser source and the stability of the FBG. In the proposed approach, since the FBG is used as a frequency discriminator, if the relative wavelength shifts of the laser source are within the linear or quadrature region, only the dc level of the output waveforms will be affected. In the experiment, the generated monocycle and doublet pulses are stable at room temperature without any extra temperature control.

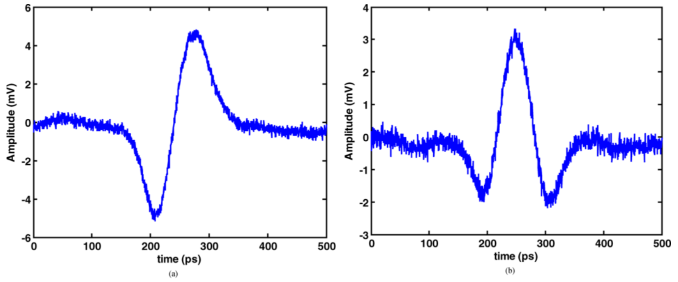

Fig. 5. Waveforms of the output pulses when the optical carrier is located at the opposite slope of the FBG: (a) $\lambda_c = 1536.272$ nm, (b) $\lambda_c = 1536.210$ nm.

IV. CONCLUSION

An optical UWB pulse generator that can shape the input Gaussian pulses into monocycle or doublet pulses has been proposed and experimentally demonstrated. The proposed system was based on the optical PM-IM conversion that was realized by use of an EOPM and an FBG serving as an optical frequency discriminator. By locating the optical carrier at different locations of the FBG reflection spectrum, UWB pulses with inverted polarity or different shapes were obtained. This feature makes PPM and PSM schemes possible. In addition, since the UWB pulse signals were obtained directly in optical domain, the proposed approach can be well incorporated into UWB-over-fiber networks and eventually simplify the entire networks by centralizing the operations at the central offices. In the proposed system, an electrical pulse source was needed. The system can be made all-optical, if the electrical pulse source is replaced by an optical pulse source, such as a mode-locked laser source.

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