All-Fiber Ultrawideband Pulse Generation Based on Spectral Shaping and Dispersion-Induced Frequency-to-Time Conversion

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***Abstract*—An approach to generating and distributing ultrawideband (UWB) pulses based on optical spectral shaping and frequency-to-time conversion using all-fiber components is proposed and demonstrated. In the system, the spectrum of an ultrashort pulse from a mode-locked fiber laser is spectrally shaped by an all-fiber spectrum shaper, to produce a monocycle- or a doublet-shaped power spectrum. Thanks to the frequency-to-time conversion in a dispersive fiber, time-domain optical pulses exhibiting the user-defined shape of the optical power spectrum are obtained. Experiments based on the proposed approach are carried out. UWB monocycle or doublet pulses are generated.**

***Index Terms*—All-fiber, chromatic dispersion, femtosecond pulse, frequency-to-time conversion, optical spectral shaping, ultrawideband (UWB).**

I. Introduction

ULTRAWIDEBAND (UWB) is an attractive technology for short-range high data-rate wireless communication systems. The key advantages of UWB technology include huge bandwidth, weak spectrum intensity, multipath immunity, high data rates, and low equipment cost [1], [2]. As defined by the U.S. Federal Communications Commission (FCC), UWB signals must occupy a 10-dB bandwidth of 500 MHz or more, or a fractional bandwidth greater than 20% of the center frequency, within the 7.5-GHz spectrum from 3.1 to 10.6 GHz with an effective power level of less than −41.3 dBm/MHz [3].

Due to the extremely low emission power regulated by the FCC, the current UWB systems can operate with a distance limited to 10 m. To integrate such indoor and isolated UWB wireless networks into the existing wired optical access networks, UWB-over-fiber technology is considered a promising solution [4]. In addition, to distribute UWB signals over optical fiber, it is also desirable that the UWB impulse signals can be generated directly in the optical domain to avoid costly electrical to optical conversion.

On the other hand, the choice of the UWB pulse shapes is critical to the performance of the UWB systems. Gaussian monocycle and doublet pulses have been considered promising candidates for UWB communications [5]. Several approaches have been proposed to generating Gaussian monocycle and doublet pulses. Most of them are based on electronics circuits [6]–[8]. Some approaches have been recently proposed to optically generating UWB pulses. In [9], UWB monocycle pulses are generated using a hybrid system, consisting of a gain-switched Fabry–Pérot laser diode and a microwave differentiator. In [10], UWB doublet pulses are generated all-optically by using a specially designed frequency-shift keying modulator. Recently, Zeng and Yao proposed to generate UWB signals using an optical phase modulator in combination with a dispersive fiber [11]. The phase-modulation (PM) signal is converted to intensity-modulation (IM) signal when distributing over the dispersive fiber. The PM-IM conversion has a frequency response corresponding to a bandpass filter, which is used to shape the spectrum profile of a Gaussian pulse, leading to the generation of UWB doublet.

UWB pulses can also be generated based on optical spectral shaping and frequency-to-time conversion using a Fourier transform device. Fourier transform optical spectral shaping and dispersive stretching were implemented to generate adaptive broadband microwave arbitrary waveforms [12], [13]. The technique of spectral-temporal mapping was previously used to measure optical fiber dispersion and to evaluate an optical source spectrum [14]. Dispersion-induced frequency-to-time conversion based on the space–time duality was theoretically analyzed in [15].

In this letter, we proposed a novel approach to generating and distributing Gaussian monocycle and doublet pulses based on all-fiber spectral shaping and frequency-to-time conversion. In our approach, the optical power spectrum of a femtosecond pulse from a passively mode-locked fiber laser (MLFL) is spectrum shaped by an all-fiber optical spectrum shaper, to obtain a spectral shape corresponding to a monocycle or a doublet. A length of single-mode fiber (SMF) is then used to act as a dispersive device to perform the frequency-to-time conversion. A UWB monocycle or doublet pulse is obtained at the output of a high-speed photodetector (PD). Experiments based on the proposed approach are carried out. The key difference between this approach and the approaches in [12] and [13] is that the optical spectral shaping is performed using all-fiber components which has the advantages of smaller size, lower loss, and the potential for integration using the photonic integrated circuit (PIC) technology.

II. Principle

The block diagram of the proposed UWB pulse generation system is illustrated in Fig. 1(a). A transform-limited ultrashort pulse train from the MLFL is spectrally shaped by an all-fiber spectrum shaper. The spectrum shaper is designed such that it shapes the optical power spectrum of the ultrashort pulse to be

Manuscript received August 28, 2006; revised October 19, 2006. This work was supported in part by The Natural Sciences and Engineering Research Council of Canada.

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Digital Object Identifier 10.1109/LPT.2006.888966

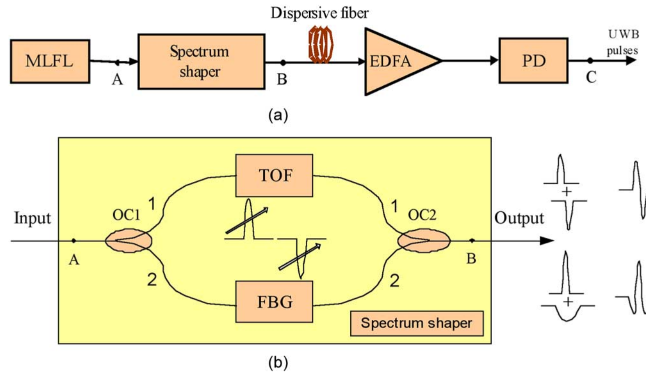

Fig. 1. (a) Block diagram of the proposed all-fiber UWB signal generation system. (b) All-fiber spectrum shaper configuration. EDFA: erbium-doped fiber amplifier. OC: optical coupler.

the user-designed Gaussian monocycle or doublet. The spectrally shaped pulse is then sent to a length of dispersive fiber to perform frequency-to-time mapping. The total chromatic dispersion must be properly determined according to the mapping relationship between the spectrum bandwidth and the temporal pulsewidth [15]. After the optical-to-electrical conversion at a high-speed PD, a temporal electrical monocycle or doublet pulse is obtained. The generated UWB pulse has a shape that is a scaled version of the user-designed optical spectrum.

To obtain a spectrum with a shape corresponding to a Gaussian monocycle or doublet, we use an all-fiber optical spectrum shaper, as shown in Fig. 1(b). The ultrashort pulse train from the MLFL source is divided into two branches by an optical coupler (OC1), with a coupling ratio determined by user-defined spectrum shaping requirement. The spectrum of the ultrashort pulse from Port 1 is shaped by a tunable optical filter (TOF); the spectrum of the ultrashort pulse from Port 2 is spectrally shaped by a fiber Bragg grating (FBG), acting as a transmission filter with a center wavelength that can also be slightly tuned by applying tension. The pulses after spectrum-shaping from the two arms are then recombined by a 3-dB optical coupler (OC2). Since the spectra of the two filters are complementary, the power spectrum of the ultrashort pulse is shaped to have a user-designed Gaussian monocycle or doublet.

This all-fiber optical spectrum shaper can be configured to generate UWB monocycle or doublet pulses by adjusting the spectral widths and the center wavelengths of the two optical filters. To have a power spectrum corresponding to a UWB monocycle, the bandwidths of two optical filters should be controlled to be approximately identical. In addition, a proper wavelength difference between the central wavelengths of the two optical filters is required to ensure a good time separation between the two temporal pulses after frequency-to-time mapping, as shown in Fig. 1(b). For UWB monocycle, the positive and negative spectral peaks at the output of the spectrum shaper should be identical, which is realized in our system by controlling the coupling ratio of OC1 to account for the different insertion losses of the two optical filters. On the other hand, to achieve a power spectrum corresponding to a UWB doublet, the optical spectrum shaper has to be reconfigured by using another FBG with a broader spectral bandwidth. The center wavelength of the TOF is tuned to be identical to that of the FBG, as also shown in Fig. 1(b). Again, the coupling ratio of OC1 is adjusted to ensure that the spectrum meets the UWB doublet requirement [5]. Thus, the combination of the two inversed spectra gives an over power spectrum corresponding to a UWB monocycle or doublet.

In the all-fiber spectrum shaper, the incident ultrashort pulse is spectrally filtered in the two different paths. The optical lengths of the two arms have to be carefully controlled to guarantee a good temporal synchronization of the spectrum-shaped optical pulses from the two paths. In fact, the continuous tuning of the wavelength spacing between the two central wavelengths would lead to the continuous change of the time delay difference between two polarity-reversed pulses thanks to the frequency-time mapping. Therefore, electrical waveforms other than the UWB monocycle or doublet may be generated.

The spectrum shaping operation in the all-fiber spectrum shaper is implemented in an open-loop fiber link without close-loop iterations, which makes the system very simple with high stability. In addition, the spectrum shaper is implemented using all-fiber components, which makes the system compact with low loss and provides the possibility of integration using PIC technology. Although the use of the TOF and the FBG filters would make the system sensitive to environmental changes such as temperature and vibration, an integrated version of the system with temperature control and proper packaging would easily tackle the problem.

III. Experiment

The proposed UWB pulse generation system, as shown in Fig. 1, is experimentally implemented. The MLFL can generate an ultrashort pulse train with a pulsewidth of about 550 fs and a 3-dB spectrum bandwidth of about 9 nm. The ultrashort pulse from the MLFL is spectrally filtered by the all-fiber spectrum shaper. To generate a UWB monocycle, the input pulse spectrum from Port 1 of OC1 is shaped by a TOF, which is a reflection filter with a tunable range of 1460–1575 nm, an average 3-dB bandwidth of 0.2 nm, and a central wavelength set at 1557.71 nm. The input spectrum from Port 2 of OC1 is shaped by an FBG with 0.25-nm bandwidth and a center wavelength at 1558.2 nm. The spectrum-shaped pulses are then combined at OC2. In the experiment, the coupling ratio of OC1 is 70 : 30, that is, 70% of the input power is sent to the upper branch, since TOF has higher insertion loss.

The optical spectrum at the output of the spectrum shaper (Point B) is measured by an optical spectrum analyzer. As shown in Fig. 2(a), the shaped optical spectrum exhibits a monocycle pulse shape, but is superimposed on a broader Gaussian-like pedestal, which is the spectrum of the pulse from the MLFL (as shown in Fig. 2(b) for comparison). The spectrally shaped optical pulse is then applied to a 10-km SMF to perform the frequency-to-time conversion. The total chromatic dispersion of the SMF is about 170 ps/nm. The electrical pulse at point C is obtained at the output of a 45-GHz PD, as shown in Fig. 2(c). We can clearly see that the pulse has the same shape as the optical spectrum at the output of the spectrum shaper. The full-width at half-maximum (FWHM) of the monocycle pulse is about 185 ps. The spectrum of the generated monocycle pulse is also measured by an electrical spectrum analyzer, as illustrated in Fig. 2(d). It can be seen that the spectrum has a central frequency of 6 GHz with a 10-dB bandwidth of 9 GHz, from 1.5 to 10.5 GHz. The fractional

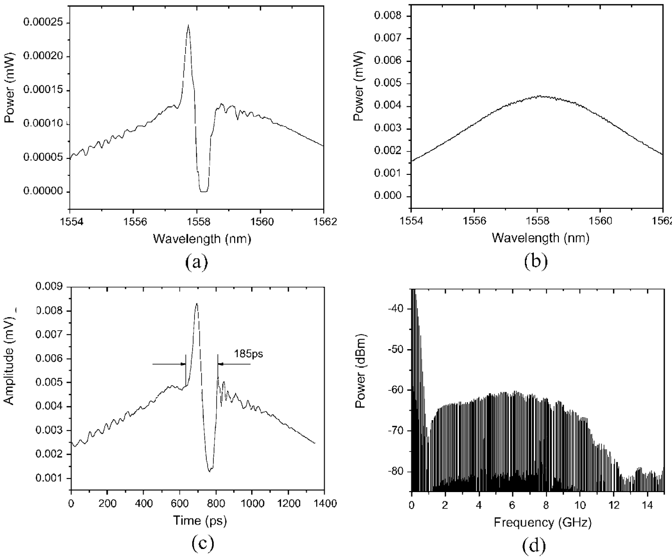

Fig. 2. UWB monocycle pulse generation. (a) Spectrum after spectral shaping. (b) Spectrum of the incident ultrashort pulse. (c) Generated UWB pulse. (d) Power spectrum of the generated monocycle pulse.

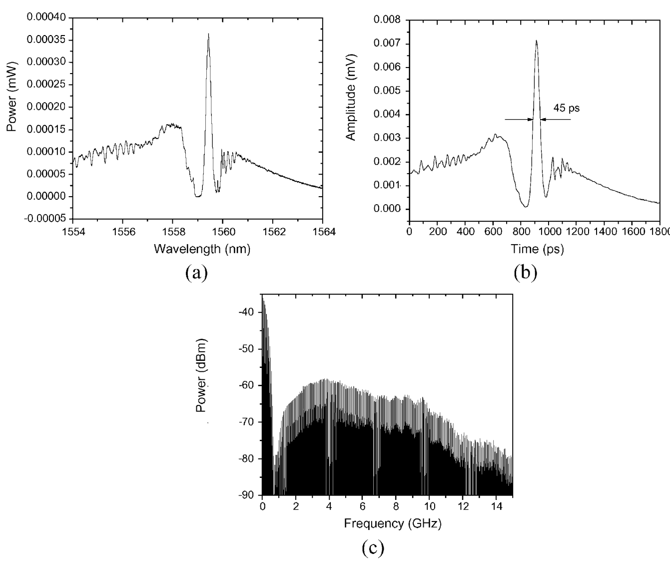

Fig. 3. UWB doublet pulse generation. (a) Spectrum after spectral shaping. (b) UWB doublet pulse. (c) Power spectrum of the generated UWB doublet.

bandwidth is about 150%, which meets the FCC requirement of 20%. One may notice that in addition to the UWB spectrum, there is a baseband spectral component with a bandwidth of less than 1 GHz, which is resulted from the wide Gaussian-like pedestal. One solution to reduce this baseband component is to use an MLFL with a narrower pulsewidth.

To generate a UWB doublet pulse, the spectrum shaper has to be reconfigured. The input pulse from Port 1 of OC1 is spectrally shaped by the TOF, with the center wavelength set at 1559.45 nm. In the other optical path, the input pulse spectrum is shaped by a new FBG with a broader bandwidth of 0.45 nm centered at 1559.4 nm. Again, the coupling ratio of OC1 needs to be adjusted. This is done by using a new optical coupler with a coupling ratio of 80 : 20. Fig. 3(a) shows the optical spectrum after the spectrum shaper. It has a shape corresponding to a doublet. After distribution over 10-km SMF, a UWB doublet pulse is generated thanks to the frequency-to-time conversion. As shown in Fig. 3(b), the generated UWB doublet pulse has an FWHM of about 45 ps, which is again superimposed on a broad Gaussian-like pedestal. Fig. 3(c) illustrates the power spectrum of the generated UWB doublet pulse, which has a 10-dB bandwidth of about 9.5 GHz, from 1.5 to 11 GHz.

IV. Conclusion

An approach to generating UWB monocycle and doublet pulses has been proposed and experimentally demonstrated. The proposed technique was based on spectrum shaping in an all-fiber spectrum shaper and dispersion-induced frequency-to-time conversion in a dispersive fiber. By properly configuring the fiber-optic spectrum shaper, UWB monocycle or doublet pulse was generated. To generate other waveforms, the spectrum shaper has to be reconfigured to produce an optical spectrum corresponding to the required temporal waveform. The frequency-to-time conversion was implemented using a length of SMF, which provides an added advantage: the UWB pulse is not only generated, but also distributed to a remote site, which would find potential applications in UWB over fiber systems.

References

[1] D. Porcine, P. Research, and W. Hirt, “Ultra-wideband radio technology: Potential and challenges ahead,” *IEEE Commun. Mag.*, vol. 41, no. 7, pp. 66–74, Jul. 2003.
[2] M. Ghavami, L. B. Michael, and R. Kohno, *Ultra WideBand Signals and Systems in Communication Engineering*. West Sussex, England: Wiley, 2004.
[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] S. Kim, H. Jang, S. Choi, Y. Kim, and J. Jeong, “Performance evaluation for UWB signal transmission with different modulation schemes in multi-cell environment distributed using ROF technology,” in *Proc. Int. Workshop Ultra WideBand Systems*, May 2004, pp. 187–191.
[5] X. Chen and S. Kiaei, “Monocycle shapes for ultra wideband system,” in *IEEE Int. Symp. Circuits and Systems*, 2002, vol. 1, pp. 26–29.
[6] K. Marsden, H.-J. Lee, D. S. Ha, and H.-S. Lee, “Low power CMOS Re-programmable pulse generator for UWB systems,” in *IEEE Conf. Ultra Wideband Systems and Technologies*, Nov. 2003, pp. 443–337.
[7] Y. Jeong and S. Jung, “A CMOS impulse generator for UWB wireless communication system,” in *Proc. 2004 IEEE Int. Symp. Circuit and Systems*, May 2004, pp. IV-129–IV-132.
[8] B. Jung, Y.-H. Tseng, J. Harvey, and R. Harjani, “Pulse generator design for UWB IR communication system,” in *IEEE Int. Symp. Circuits and Systems*, 2005, pp. 4381–4384.
[9] W. P. Lin and J. Y. Chen, “Implementation of a new ultrawide-band impulse system,” *IEEE Photon. Technol. Lett.*, vol. 17, no. 11, pp. 2418–2420, Nov. 2005.
[10] T. Kawanishi, T. Sakamoto, and M. Izutsu, “Ultra-wide-band signal generation using high-speed optical frequency-shift-keying technique,” in *Proc. IEEE Int. Topical Meeting Microw. Photon.*, Oct. 4–6, 2004, pp. 48–51.
[11] F. Zeng and J. P. Yao, “An approach to ultra-wideband pulse generation and distribution over optical fiber,” *IEEE Photon. Technol. Lett.*, vol. 18, no. 7, pp. 823–825, Apr. 1, 2006.
[12] J. Chou, Y. Han, and B. Jalali, “Adaptive RF-photonic arbitrary waveform generator,” *IEEE Photon. Technol. Lett.*, vol. 15, no. 4, pp. 581–583, Apr. 2003.
[13] I. Lin, J. D. McKinney, and A. M. Weiner, “Photonic synthesis of broadband microwave arbitrary waveforms applicable to ultra-wideband communication,” *IEEE Microw. Wireless Compon. Lett.*, vol. 15, no. 4, pp. 226–228, Apr. 2005.
[14] Y. C. Tong, L. Y. Chan, and H. K. Tsang, “Fiber dispersion or pulse spectrum measurement using a sampling oscilloscope,” *Electron. Lett.*, vol. 33, no. 11, pp. 983–985, 1997.
[15] M. Muriel, J. Azaña, and A. Carballar, “Real-time fourier transformer based on fiber gratings,” *Opt. Lett.*, vol. 24, no. 1, pp. 1–3, Jan. 1999.