Ultra-Wideband Waveform Generator Based on Optical Pulse-Shaping and FBG Tuning

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***Abstract*—We propose and demonstrate experimentally a prototype for ultra-wideband (UWB) waveform generator based on optical pulse shaping. The time-domain pulse shape is written in the frequency domain, and a single-mode fiber performs frequency-to-time conversion. A U.S. Federal Communications Commission (FCC)-compliant power efficient pulse shape is inscribed in the frequency domain by a fiber Bragg grating (FBG) with an excellent match between optimized and measured pulses. Two other popular UWB pulse shapes (Gaussian monocycle and doublet pulses) are achieved by proper tuning of two FBG-based variable optical filters. A balanced photodetector removes an unwanted rectangular pulse superimposed on the desired waveform, assuring compliance at low frequency.**

***Index Terms*—Balanced detection, fiber Bragg grating (FBG), spectral pulse shaping, ultra-wideband (UWB).**

I. Introduction

RESEARCH into design and generation of the appropriate ultra-wideband (UWB) pulses supports applications to consumer indoor wireless communications, medical and military communications, etc. [1]–[4]. UWB systems are highly power-limited, and pulse-shaping techniques that eke out the greatest transmission power legally allowed by the U.S. Federal Communications Commission (FCC) [5] are critical to enhancing performance. Expert pulse shaping increases the total transmit power by exploiting all available bandwidth from near dc to 14 GHz (to the limits of the antenna bandwidth) that can be used for range extension or power margin.

Pulse generation techniques in general and electronic techniques in particular, mainly focus on the widely adopted Gaussian monocycle and doublet pulses [1]. Optical pulse generation techniques for UWB have been proposed based on optical spectral shaping and frequency-to-time conversion using a dispersive medium [3], [4], [6]–[8], a principle first established in [9]. The pulse shaping device in [3] consists of a bulky free-space grating, a large focal length lens to angularly disperse the frequency components, and a liquid crystal modulator to modulate the amplitude of frequency components. Although this arbitrary waveform generator can be used to generate any desired UWB pulse, it cannot be used in many applications due to its large size and high optical loss. Based on the general concept provided in [3], an all-fiber pulse shaper was recently proposed in [6] in which two optical filters with complementary spectra are placed in two arms of an interferometer to shape the power spectrum as the shape of the Gaussian monocycle or doublet pulses. However, the generated pulses do not resemble the desired waveform and the RF spectrums contain a non-FCC-compliant baseband spectral component below 1 GHz due to the wide Gaussian pedestal of the source. In addition, its interferometric structure leads to sensitivity to environmental changes such as temperature or vibration.

In another approach [7], a femtosecond pulse laser is spectrum sliced to the required pulsewidth and the optical pulse train is then injected into a nonlinear fiber together with a continuous-wave probe laser to create cross-phase modulation (XPM). A fiber Bragg grating (FBG) is used as a frequency discriminator. By locating the probe laser at the linear or the quadrature slopes of the FBG reflection spectrum, UWB monocycle or doublet pulses are generated. The two laser sources used in this technique make it complex and costly.

The Gaussian, monocycle, and doublet pulses are poorly adapted to the FCC spectral mask. For instance, the doublet pulse optically generated in [7] violates the FCC mask at low frequency (especially the GPS band around 1575.42 MHz), and additional processing to cut the signal at low frequency is required if these pulses are to be power efficient. Nonetheless, these pulses are widely used in the literature.

In this letter, we propose a prototype for a UWB waveform generator based on the concept proposed in [8] to generate Gaussian, monocycle, and doublet pulses, as well as a simple FCC-compliant and power efficient pulse. Similar to the approach in [6], this technique exploits spectral pulse shaping using an FBG, a length of single-mode fiber (SMF) as a dispersive medium to perform the frequency-to-time conversion. However, instead of an interferometric structure [6], we use a two-branch structure and balanced photodetector (BPD); due to this structure, unlike [6], we can completely remove the unwanted rectangular pedestal and achieve a desired signal that has both positive and negative going parts. The rectangular pedestal has frequency components in the band of interest that distorts the resulting pulse. We use two tunable optical filters to cut the lower and upper sides of the FBG spectrum. By appropriately positioning the cutoff wavelengths of the filters, we can easily generate the Gaussian monocycle and doublet pulses, as well as the power-efficient FCC-compliant pulse. We avoid the use of an interferometeric setup and take advantage of all-fiber components that are less sensitive to environmental perturbations. Moreover, the proposed structure is less sensitive

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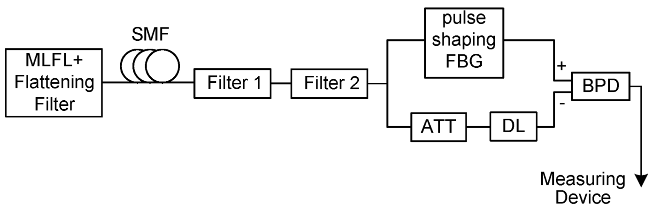

Fig. 1. Schematic diagram of the UWB waveform generator.

to the environmental fluctuations than an interferometric structure: ours involves optical intensity-to-voltage conversion by the BPD before electronic subtraction, while an interferometric structure combines optical fields and is thus sensitive to optical phase variations easily induced by environmental changes.

II. Principle and Experiment

A Gaussian pulse is defined by $g(t) = A\exp(-2(t/\tau)^2)$, where A is a scaling constant and the pulse duration is related to τ. The first and the second derivative of the Gaussian pulse are known as the monocycle and doublet pulses, respectively. All of these pulses do not exploit the FCC mask efficiently: transmit power must be severely reduced to prevent violation of the mask, especially around 1.57 GHz to protect the GPS band. An optimization method is provided in [2] to design the FCC-compliant UWB pulses while maximizing the transmitted power by efficient utilization of the area under FCC spectral mask. In this technique, the shifted versions of a basic function are added together with different tap coefficients to design the UWB pulse. They used a Gaussian monocycle as the basic function, and the coefficients are obtained by numerical optimization. The larger the number of taps, the higher the spectral efficiency; on the other hand, the longer the pulse is, the more complex is the shape.

To generate the optimized UWB pulse, we shape the spectrum of a passive mode-locked fiber laser (MLFL) using a cascade of FBG filters. The spectrum of the laser is first flattened over the desired bandwidth by an appropriately designed FBG. Then a pulse-shaping filter modifies the spectrum according to the desired time-domain pulse. The spectrally shaped pulse is sent to a dispersive medium (e.g., SMF) to perform frequency-to-time mapping. The SMF may be placed anywhere along the generator; placing it before spectral shaping avoids requiring SMF in both arms of the BPD. The pulse generated is the summation of the desired pulse shape and a rectangular pulse with the same width; the rectangular pulse will be removed by a BPD.

The setup block diagram is shown in Fig. 1. An MLFL generates 270-fs sech^2 pulses with a repetition rate of 31.25 MHz. The spectrum is then flattened and the optical pulse travels 5.46 km of SMF with total dispersion of 88.9 ps/nm in order to map 4.5-nm source bandwidth to 0.4 ns. Filters 1 and 2 are chirped gratings (phase mask chirp $=$ 2.5 nm/cm) used to cut off the lower and upper band of the spectrum. The FBGs are mounted on stretchers for wavelength tuning.

The optical signal is then divided into two arms. In the first arm, a chirped grating (0.498 nm/cm) with a complex apodization profile imprints the optimized pulse shape on the spectrum of the source. The chirped grating's spectral response

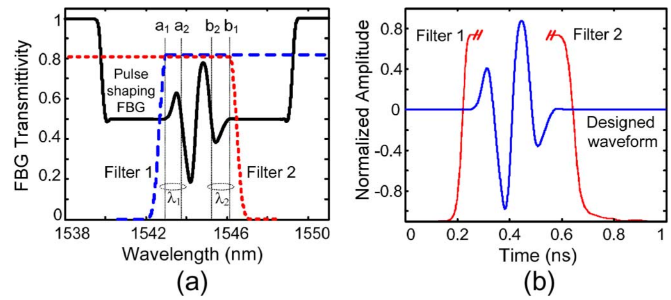

Fig. 2. (a) Transmittivity of the pulse shaping FBG, tunable Filters 1 and 2; (b) designed UWB waveform and filters' shapes.

TABLE I
Cutoff Wavelengths of the Filters for Different UWB Waveforms

Waveform	λ_1	λ_2
Monocycle pulse	a_2	b_2
Doublet pulse	a_1	b_2
FCC-compliant pulse	a_1	b_1

$T(\lambda)$ and the index modulation amplitude $\Delta n_{ac}(\lambda)$ are typically related by $\Delta n_{ac}(\lambda) \propto \sqrt{\alpha \ln(T(\lambda))}$ [10], where α is a constant depending on the index modulation chirp. Once the apodization profile is obtained, the gratings are written via a UV beam scanning technique. The apodization profiles are applied by dithering the phase mask with an estimated resolution of 300 μm. All FBGs are 14 cm long and act in transmission.

In the second arm, the optical delay line and the variable attenuator are used to balance the amplitude and the delay of the two arms. The two arms are connected to a 10-GHz DSC-710 BPD. The detected UWB pulse shape is then viewed on a 40-GHz sampling scope (Agilent 86100A) and the corresponding electrical power spectrum is measured by a high-speed RF spectrum analyzer (HP 8565E).

In this letter, we use the method in [2] to design a simple waveform that respects the FCC mask at all frequencies. This waveform, shown in Fig. 2, contains two large positive and negative peaks confined between two smaller peaks with a total duration of ~0.4 ns. By appropriate windowing of this FCC-compliant pulse, a very good approximation of monocycle and doublet pulses can be obtained. Fig. 2(a) shows the transmittivity of the pulse-shaping FBG (solid line), as well as those of two filters (dashed and dotted lines). The cutoff wavelengths of Filter 1, λ_1, and Filter 2, λ_2, are varied between a_1 to a_2 and b_1 to b_2, respectively. By stretching the FBGs, the cutoff wavelengths are located at the appropriate positions (based on the Table I) to generate the monocycle, doublet, and the FCC-compliant waveforms. The generated waveforms depend on the transition shape of the filters taking into account the effects of the limited bandwidth of the BPD. Fig. 2(b) shows the optimized FCC-compliant pulse and the measured shape of the filters around the cutoff wavelengths. The optical filtering of the pulse shaping FBG's spectrum is equivalent to the time windowing of the designed pulse.

Experimental results are shown in Fig. 3. The left column gives the targeted time-domain pulse (dashed) and the measured pulse (solid). The right column gives the measured RF spectrum superimposed on the FCC mask (dashed) and Fourier transform

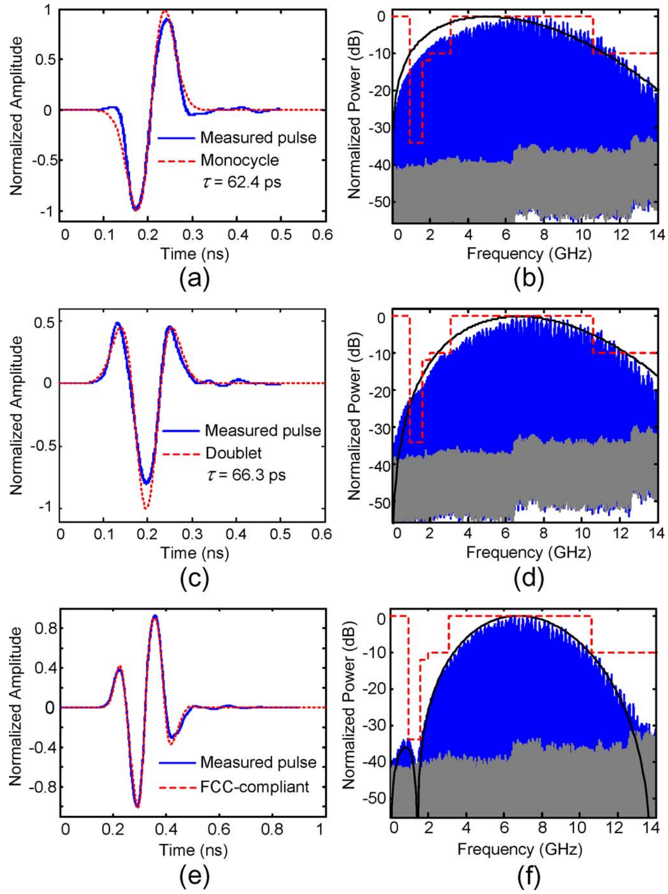

Fig. 3. Generated and target waveforms and their spectrum: (a), (b) monocycle, (c), (d) doublet, and (e), (f) FCC-compliant power-efficient pulses.

of the targeted pulse (solid). The gray portion of the spectrum is the measurement noise floor (BPD and RF spectrum analyzer).

Fig. 3(a) shows the measured monocycle pulse when λ_1 and λ_2 are adjusted to a_2 and b_2. The monocycle is approximated by extracting the large peaks of the optimized pulse [see Fig. 2(b)]. This pulse well approximates the first derivative of the Gaussian waveform with $\tau = 62.4$ ps. The spectrum, given in Fig. 3(b), violates the mask in the frequencies less than 1.6 GHz. The transmit power should be reduced by at least 25 dB to respect the mask, or additionally filtering must be used.

The doublet waveform, Fig. 3(c), is generated by locating the filter cutoff wavelengths at a_1 and b_2; it approximates the second derivative of a Gaussian waveform with $\tau = 66.3$ ps. A good fit is achieved at the two side peaks, but the central peak is shallow. However, from Fig. 3(d), the spectrum of the generated doublet pulse represents a good match to the spectrum of the targeted curve (solid line). In this case, the transmit power should be reduced by about 15 dB to be completely below the FCC mask.

Finally, when the cutoff wavelengths of the filters are located at a_1 and b_1, we can obtain the full optimized pulse, as shown in Fig. 3(e), where an excellent match between the designed and the generated pulses is observed. The measured spectrum of the pulse in Fig. 3(f) optimally exploits and scrupulously respects the FCC spectral mask (dashed line) and follows our design (solid line). There is no need for reduction in the transmitted power.

As we can see, the proposed UWB waveform generator is able to generate not only the Gaussian monocycle and doublet pulses, but also an FCC-compliant power optimized pulse by simply stretching two FBG filters. If only the FCC-compliant power-efficient pulse is of interest, the two filters can be combined in a single FBG to reduce system complexity.

III. Conclusion

In this letter, we proposed and experimentally demonstrated a UWB waveform generator based on spectral pulse shaping of coherent light and frequency-to-time conversion. Our design is based on a simple FCC-compliant power-efficient UWB pulse. The monocycle and doublet pulses can also be easily generated by stretching two FBGs responsible for the filtering of the lower and upper sides of the flattened source spectrum. A BPD removes the undesired rectangular-shaped pulse superimposed on the desired pulse, which exists in all techniques involving frequency-to-time conversion. The system is quite stable and insensitive to environmental changes such as temperature or vibration.

Although the Gaussian monocycles and doublet pulses do not efficiently exploit the spectral mask imposed by the FCC, they can be useful for less power-critical applications.

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References

[1] C. F. Liang, S. T. Liu, and S. I. Liu, "A calibrated pulse generator for impulse-radio UWB applications," *IEEE J. Solid-State Circuits*, vol. 41, no. 11, pp. 2401–2407, Nov. 2006.

[2] X. Wu, Z. Tian, T. N. Davidson, and G. B. Giannakis, "Optimal waveform design for UWB radios," *IEEE Trans. Signal Process.*, vol. 45, no. 6, pt. 1, pp. 2009–2021, Jun. 2006.

[3] I. S. Lin, J. D. McKinney, and A. M. Weiner, "Photonic synthesis of broadband microwave arbitrary waveforms applicable to ultra-wideband communications," *IEEE Microw. Wireless Compon. Lett.*, vol. 5, no. 4, pp. 226–228, Apr. 2005.

[4] B. Bortnik, I. Y. Poberezhskiy, J. Chou, B. Jalali, and H. R. Fetterman, "Predistortion technique for RF-photonic generation of high-power ultrawideband arbitrary waveforms," *J. Lightw. Technol.*, vol. 24, no. 7, pp. 2752–2759, Jul. 2006.

[5] FCC, Report and Order FCC 02-48 2002.

[6] C. Wang, F. Zeng, and J. Yao, "All-Fiber ultrawideband pulse generation based on spectral shaping and dispersion-induced frequency-to-time conversion," *IEEE Photon. Technol. Lett.*, vol. 19, no. 3, pp. 137–139, Feb. 1, 2007.

[7] F. Zeng, Q. Wang, and J. Yao, "All-optical ultrawideband impulse generation based on cross-phase modulation and frequency discrimination," *Electron. Lett.*, vol. 43, no. 2, pp. 119–121, Jan. 2007.

[8] M. Abtahi, J. Magné, M. Mirshafiei, S. Doucet, L. A. Rusch, and S. LaRoch-elle, "Experimental generation of FCC-compliant UWB pulse using FBGs," in *Eur. Conf. Opt. Commun. (ECOC)*, Germany, Sep. 2007.

[9] P. V. Kelkar, F. Coppinger, A. S. Bhushan, and B. Jalali, "Time-domain optical sensing," *Electron. Lett.*, vol. 35, no. 19, pp. 1661–1662, Sep. 1999.

[10] S. Pereira and S. LaRochelle, "Field profiles and spectral properties of chirped Bragg grating Fabry–Perot interferometers," *Opt. Express*, vol. 13, no. 6, pp. 1906–1915, Mar. 2005.