An Approach to Ultrawideband Pulse Generation and Distribution Over Optical Fiber

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***Abstract*—We propose a novel approach to generating and distributing ultrawideband (UWB) pulse signals over optical fiber. The proposed system consists of a single-wavelength laser source, an electrooptic phase modulator (EOPM), a length of single-mode fiber (SMF), and a photodetector (PD). The combination of the EOPM, the SMF link, and the PD forms an all-optical microwave bandpass filter, which is used to generate a UWB signal with a spectrum meeting the regulation of the Federal Communication Commission. Gaussian doublet pulses are obtained at the receiver front-end, which can provide several gigahertz bandwidths for applications in high-bit-rate UWB wireless communications. Experimental results measured in both temporal and frequency domains are presented.**

***Index Terms*—Bandpass filter, chromatic dispersion, direct sequence impulse radio, electrooptic phase modulation, radio-over-fiber, ultrawideband (UWB).**

I. Introduction

ULTRAWIDEBAND (UWB) wireless systems have recently attracted considerable interest for short-range high-throughput wireless communication and sensor networks thanks to their intrinsic properties, such as the immunity to multipath fading, extremely short time duration, carrier free, low duty cycle, wide occupied bandwidth, and low power spectral density [1], [2]. Specifically, the indoor and hand-held UWB systems must operate in the frequency range from 3.1 to 10.6 GHz with an effective isotropic radiated power level of less than −41 dBm/MHz, as required by the U.S. Federal Communication Commission (FCC) [3].

However, by wireless transmission, UWB signals are only limited in short distance of a few to tens of meters. Such short-range wireless networks can operate mainly in indoor environments in stand-alone mode, with a nearly nonexistent integration into the fixed wired networks or wireless wide-area infrastructures. To offer availability of undisrupted service across different networks and eventually achieve high-rate data access at any time and from any place, UWB-over-fiber technology combined with fiber-to-the-home topology may provide an effective solution [4].

On the other hand, one of the most attractive technologies to generate UWB signals is based on direct-sequence impulse radio technology. It is a carrier-free modulation scheme that does not use the complicated frequency mixer and intermediate frequency; hence, the cost can be greatly reduced compared to that of multiband orthogonal frequency multiplexing scheme. The selection of the impulse signal types is one of the fundamental considerations in designing UWB circuits and systems because the impulse types determine the performance of the UWB systems. As described in [5], Gaussian mono-cycle pulses and doublets can provide a better bit-error rate and multipath performance among different impulse signals. Basically, these desired waveforms can be created by a sort of bandpass filtering of a Gaussian pulse, i.e., the filtering acts in a manner similar to taking the derivation of the Gaussian waveform. For instance, a Gaussian mono-cycle is the first-order derivative of a Gaussian pulse and has a single zero crossing, while a Gaussian doublet with an additional zero crossing is the second-order derivative of a Gaussian pulse [2]. However, with the current stage of technology, it is rather expensive and difficult to make such a pulse with a fractional bandwidth even greater than 100% at the central frequency of around 7 GHz [6]–[8].

In fact, since UWB-over-fiber is essential to integrate the local UWB environment into the fixed networks or other wireless wide-area infrastructures, it is highly desirable that the distributed UWB signals can be created directly in the fiber link and are ready to radiate at the receiver front-end, which can simplify the system by centralizing the operation. In this letter, we propose a novel approach to achieving both UWB pulse generation and distribution in a simple and efficient way. By using an electrooptic phase modulator (EOPM), an optical carrier is phase modulated by a Gaussian pulse train representing the data sequence to be transmitted. A length of single-mode fiber (SMF) is then employed as transmission medium to send the information to a remote site. Thanks to the SMF-induced chromatic dispersion, which is usually considered a negative effect in traditional intensity-modulation and direct-detection (IM-DD) systems, in our approach, the combination of the EOPM and the SMF link forms an all-optical microwave bandpass filter [9] that can be designed to shape the input Gaussian pulses into UWB pulses that meet the UWB spectral requirement. In this letter, a point-to-point UWB-over-fiber connection is experimentally implemented. The experimental result shows that Gaussian doublet pulses are obtained at the end of the fiber link with a spectrum meeting the FCC regulation.

II. Principle and Experiment

The block diagram of the proposed UWB-over-fiber system connecting a central station (CS) and an access point (AP) is shown in Fig. 1. At the CS, light from a laser diode (LD) is fiber coupled to an EOPM which is driven by the data sequence to be transmitted. The phase-modulated optical signal is then applied to a length of SMF that serves as a transmission medium as well as a dispersive device. In our approach, the information is carried by the optical phase, if the phase-modulated optical signal

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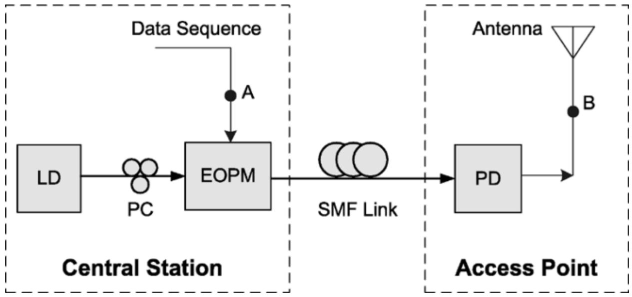

Fig. 1. Block diagram of the proposed UWB-over-fiber system.

is directly fed to a power-detection device, e.g., a photodetector (PD), no information but a dc can be detected. Thanks to the chromatic dispersion induced by the SMF, at the AP the phase information is converted to the optical intensity, and the modulating electrical signal is then obtained at the output of the PD [9], [10], which is ready to radiate via an antenna.

Under small-signal condition, the frequency response of the proposed system with respect to the modulating signal (between Point A and B) can be written as [10]

$$H(\omega) = \cos\left(\frac{\pi\chi\lambda_0^2 f_m^2}{c} + \frac{\pi}{2}\right) \cdot H_{\mathrm{EOPM}}(\omega) \cdot H_{\mathrm{PD}}(\omega) \quad (1)$$

where the first term on the right side represents the dispersion-based phase-modulation to intensity-modulation conversion, c is the optical wave propagation velocity in free space, χ is the accumulated dispersion of the SMF link, λ_0 denotes the wavelength of the optical carrier, and f_m is the frequency of the modulating signal; $H_{\mathrm{EOPM}}(\omega)$ and $H_{\mathrm{PD}}(\omega)$ represent the radio-frequency responses of the EOPM and PD, respectively. Based on (1), some unique properties can be concluded [10]. First, a quasi-periodic change of the response with a notch at the dc frequency is expected. Second, radio-frequency responses of the EOPM and PD are usually bandwidth limited, which have a significant degradation at high frequency. Therefore, only the first null-to-null frequency range need to be considered and higher frequency response can be ignored, and eventually bandpass filtering is achieved. Furthermore, since the proposed frequency response is the function of the optical carrier wavelength λ_0 and the dispersion of the transmission medium, e.g., the peak and the second null are obtained by letting $\pi\chi\lambda_0^2 f_m^2/c = \pi/2$ and π, respectively, it indicates that by varying λ_0 or χ, the bandwidth and shape of the proposed bandpass filter can be tuned and, hence, the spectrum of the generated UWB signals can be optimized.

The proposed UWB bandpass filter in an optical link is experimentally implemented based on the configuration shown in Fig. 1. An LD with a wavelength of 1550 nm is used as the light source. A 25-km standard SMF-28 fiber is employed to transmit UWB signal from the CS to the AP. The SMF-28 fiber has a chromatic dispersion of 17 ps/nm · km at 1550 nm. 25 km of this fiber has a accumulated dispersion of $\chi = 425$ ps/nm. The frequency response between Points A and B, as shown in Fig. 2, is measured via a vector network analyzer (Agilent E8364A) by sweeping the modulating frequency from 45 MHz to 20 GHz while keeping the same output power of 3 dBm. From Fig. 2, we can see that a notch at the dc is observed. The passband peak, the lower and higher -10-dB cutoff frequencies are of 10.5, 4.1, and 15.9 GHz, respectively, which provide a fractional bandwidth of about 112%. It should be noted that this frequency response does not need to meet the spectral mask authorized by the FCC, but the spectrum of the shaped pulses should meet that regulation.

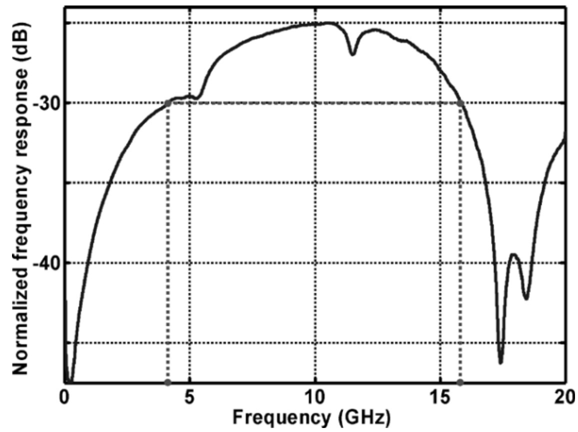

Fig. 2. Measured frequency response of the proposed UWB-over-fiber system.

To further verify the pulse shaping function of our proposed system, at the CS, a 13.5-Gb/s pseudorandom bit sequence (PRBS) $2^7 - 1$ signal is applied to the EOPM, which is generated by use of a bit-error tester (Agilent N4901B). The temporal waveform representing a single bit is measured by use of a high-speed sampling oscilloscope (Agilent 86116A), as shown in Fig. 3(a). We can see that it has a Gaussian-like shape and a full-width at half-maximum (FWHM) of about 63 ps. The spectrum of the pulse train is also measured by use of an electrical spectrum analyzer (Agilent E4448A), as shown in Fig. 3(b).

After passing through the 25-km SMF-28 fiber link, the phase-modulated optical signal is then fed to the PD located at the AP. The output of the PD is then measured in both temporal and frequency domain as we did at the CS. Fig. 4(a) shows that a Gaussian doublet pulse is obtained at the receiver front-end, which has an FWHM of about 40 ps. From Fig. 4(b), we can see that the measured spectrum has a central frequency of about 7 GHz, and the lower and higher frequencies at -10-dB points are around 3.0 and 10.9 GHz, respectively, which indicates that the generated UWB signal achieves a fractional bandwidth of about 113%. In particular, the FCC assigned bandwidth and spectral mask for indoor communications is also illustrated in Fig. 4(b). We can see that the resulting pulses in our approach not only meet the FCC's mask, but also optimally exploit the allowable bandwidth and power. A spectral line at 13.5 GHz is observed in the spectrum, which is due to the use of a short code-length of the PRBS pattern, i.e., $2^7 - 1$. By employing longer code-length PRBS patterns or by using pulse position modulation or pulse polarity modulation, this spectral line can be significantly reduced.

III. Conclusion

A novel and simple UWB-over-fiber system to generate and distribute UWB signals has been proposed and experimentally implemented. In the proposed approach, an all-optical microwave passband filter realized by use of an EOPM, a length of SMF, and a PD was implemented to generate a UWB signal with a spectrum meeting the regulation of the FCC. The

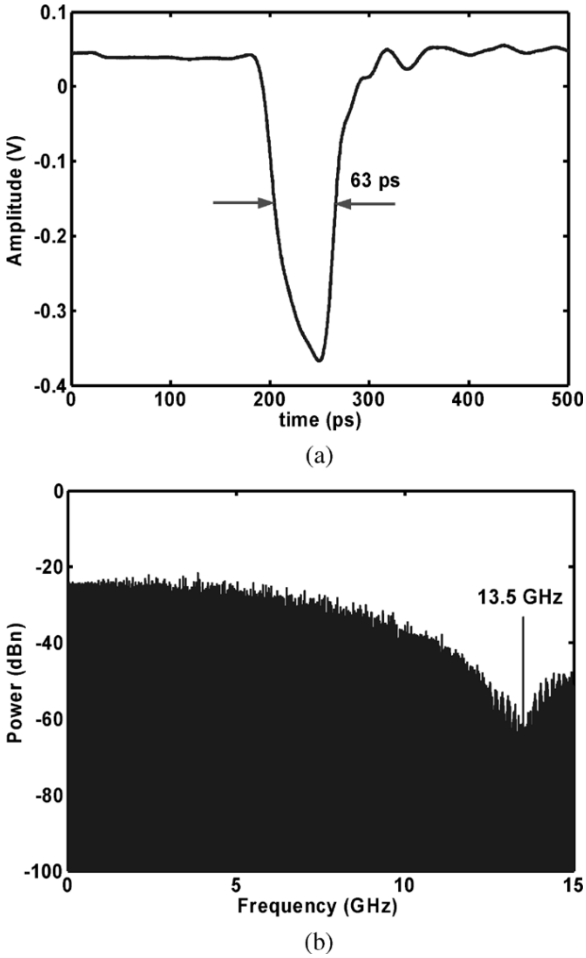

Fig. 3. When a 13.5-Gb/s PBRS $2^7 - 1$ signal is applied to the EOPM, (a) the waveform of a single bit, and (b) the power spectrum of the modulating signal are measured at Point A.

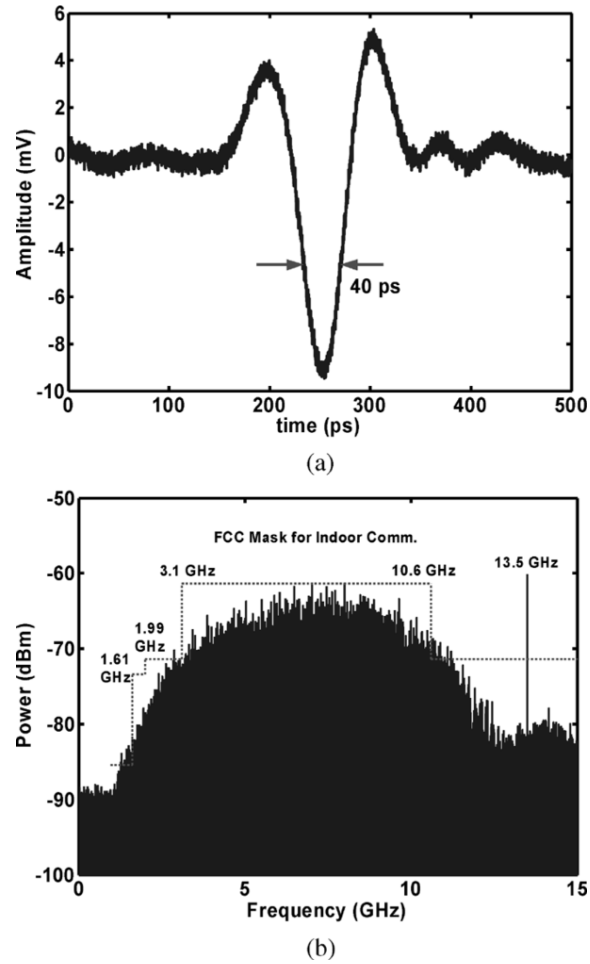

Fig. 4. (a) Waveform of the Gaussian doublet pulse, and (b) power spectrum of the shaped 13.5-Gb/s PRBS $2^7 - 1$ signal obtained at the end of the fiber link (Point B in Fig. 1). Dashed line: FCC spectral mask for indoor applications.

SMF in the system has two functions, as a dispersive device for all-optical bandpass filtering and transmission medium to connect a CS to an AP. Therefore, UWB signals were not only generated but also distributed to a remote site. Owing to the use of the EOPM, the chromatic-dispersion-induced power penalty existing in traditional IM-DD systems does not exist in the proposed system. On the contrary, it is a positive effect that contributes to the generation of UWB pulse signals. In addition, the use of the EOPM has some other advantages over an intensity modulator, which include a lower insertion loss, no bias control, and simpler system design. The experimental results showed that the doublet pulses generated by the proposed system had a central frequency of about 7 GHz with the lower and higher frequencies at -10-dB points of 3.0 and 10.9 GHz, which meets well the FCC regulation.

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