Generation of ultra-wideband triplet pulses based on four-wave mixing and phase-to-intensity modulation conversion

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Abstract: We propose and demonstrate a novel scheme to generate ultra-wideband (UWB) triplet pulses based on four-wave mixing and phase-to-intensity modulation conversion. First a phase-modulated Gaussian doublet pulse is generated by four-wave mixing in a highly nonlinear fiber. Then an UWB triplet pulse is generated by generating the first-order derivative of the phase-modulated Gaussian doublet pulse using an optical filter serving as a frequency discriminator. By locating the optical signal at the linear slope of the optical filter, the phase modulated Gaussian doublet pulse is converted to an intensity-modulated UWB triplet pulse which well satisfies the Federal Communications Commission spectral mask requirements, even in the extremely power-restricted global positioning system band.

OCIS codes: (060.5625) Radio frequency photonics; (190.4380) Nonlinear optics, four-wave mixing.

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1. Introduction

Ultra-wideband (UWB) has been considered as a promising radio technology for future short-range high-capacity wireless communication and sensor networks due to its numerous advantages, such as low power consumption, immunity to multipath fading, and high data rate [1,2]. The U.S. Federal Communications Commission (FCC) has approved the unlicensed use of spectral band from 3.1 to 10.6 GHz with power density lower than –41.3 dBm/MHz [1]. Such low spectral density in a wide spectral range leads to a limited propagation distance (typically <10 m) of the UWB links. Therefore, UWB-over-fiber systems have emerged to increase the transmission distance and take advantage of the low loss and wide bandwidth of the optical fiber. In this context, there is a strong demand to generate, modulate, and transmit UWB pulses directly in the optical domain.

Many efforts have been made to generate UWB pulses that meet the requirements specified by the FCC spectral mask. The main challenge is to avoid the –75 dBm dip in the FCC spectral mask for noninterference operation with other wireless communications, especially in the global positioning system (GPS) band (0.96–1.61 GHz). In the past few years, various techniques [3–11] have been proposed to generate UWB monocycle and doublet pulses using e.g. cross-gain modulation in a semiconductor optical amplifier (SOA) [3,12], phase-to-intensity modulation conversion [2], and nonlinear modulation in a Mach-Zehnder modulator [10]. However, it has been demonstrated that the frequency spectra of both UWB monocycle and doublet pulses have significant components in the low frequency range (<2 GHz) and thus violate the dip in the FCC spectral mask [8,9]. As a result, the signal power has to be attenuated to avoid the dip, which might make the UWB signals too weak to be detected. Recently, it was reported that an UWB triplet, i.e. the third-order derivative of a Gaussian pulse, can well meet the FCC spectral mask [13]. UWB triplet generation has been proposed e.g. based on an N tap microwave photonic filter [14] or the incoherent summation of two asymmetric monocycle pulses [15]. On the other hand, it is noted that the UWB triplet pulses reported in [14,15] consist of more than one optical wavelengths. As a result, these UWB pulses suffer from the fiber dispersion significantly. Hence, after a long-distance transmission these pulses are distorted [16] and no longer fulfill the FCC mask. Therefore, it is much more promising to generate UWB triplet pulses at a single wavelength to meet the FCC spectral mask and to alleviate the dispersion-induced distortion.

This paper presents a FCC-compliant UWB triplet pulse generation technique using four-wave mixing (FWM) and phase-to-intensity modulation (PM-IM) conversion. In previous work [15,17], PM-IM conversion was usually used to create the first-order derivative of a phase-modulated Gaussian pulse to generate a Gaussian monocycle pulse. Higher-order Gaussian pulses were obtained by combining time-delayed UWB monocycles at different wavelengths with inverted polarities [15,17]. In our scheme, the high-order Gaussian triplet pulse is directly generated by performing the first-order derivative of a phase-modulated Gaussian doublet pulse. The key novelty of our work lies in the generation of a phase-modulated Gaussian doublet pulse using FWM. After PM-IM conversion, an UWB triplet pulse is generated at a single wavelength to alleviate the fiber dispersion-induced distortion,

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which is FCC-compliant, even in the highly power-restricted GPS band. In addition, our UWB generator can be easily extended to generate arbitrary order UWB Gaussian pulses.

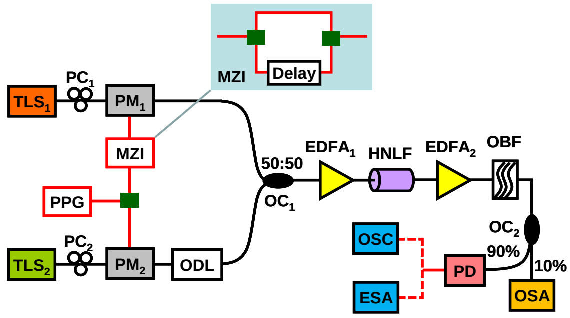

Fig. 1. UWB triplet pulse generator.

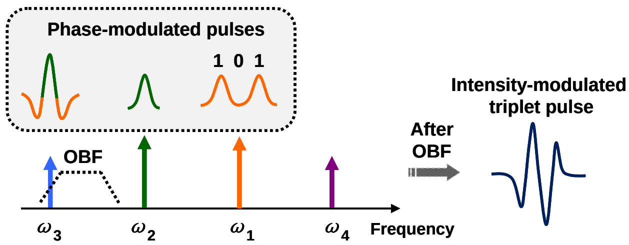

Fig. 2. Principle of the UWB triplet pulse generator (OBF: optical bandpass filter).

2. Principle

The schematic configuration of the proposed UWB triplet pulse generator is shown in Fig. 1. Two light waves emitted from two tunable laser sources (TLSs) are fiber coupled to two phase modulators (PMs) via two polarization controllers (PCs), respectively. An electrical Gaussian pulse from a pulse pattern generator (PPG) is split into two parts and then applied to the PMs. For the upper PM_1, the Gaussian pulse is sent to an electrical Mach-Zehnder interferometer (MZI) before driving to the PM_1. The inset of Fig. 1 shows the structure of the MZI. An optical delay line (ODL) is added after PM_2 to introduce a delay between the two light waves. The two light waves are then combined together using an optical coupler (OC_1) and amplified by an erbium-doped fiber amplifier ($EDFA_1$). A highly nonlinear fiber (HNLF) is used to perform the FWM. The output signal from the HNLF is boosted by the other $EDFA_2$ and then filtered by an optical bandpass filter (OBF) which performs the PM-IM conversion. An UWB triplet is generated at the output of the photodetector (PD).

Mathematically, the electrical fields of the phase-modulated light waves E_1(t) and E_2(t) can be expressed as

$$E_1(t) = E_1 \exp(j\omega_1 t)\exp[j\beta_1 s(t) + j\beta_1 s(t-2T_0)] \tag{1}$$

$$E_2(t) = E_2 \exp(j\omega_2 t)\exp[j\beta_2 s(t-T_0)] \tag{2}$$

where E_1 and E_2 are the amplitudes of the light waves, ω_1 and ω_2 are the angular frequencies of the light waves, respectively. $\beta_1 = \pi V_{s1}/V_{\pi 1}$, $\beta_2 = \pi V_{s2}/V_{\pi 2}$ is the phase modulation index of PM_1 and PM_2, respectively. V_{s1} and V_{s2} are the amplitudes of the electrical signals applied to the PM_1 and PM_2, respectively. $V_{\pi 1}$ and $V_{\pi 2}$ are the half-wave voltages of PM_1 and PM_2, respectively. $s(t)$ is the normalized electrical Gaussian pulse and T_0 is the full width at half-maximum (FWHM) of the Gaussian pulse. The time delay, $2T_0$, in Eq. (1) is introduced by the electrical MZI as shown in Fig. 1 and the time delay, T_0, in Eq. (2) is adjusted by the ODL.

Figure 2 shows the principle of the UWB triplet generator. In the HNLF idlers at frequencies of ω_3 and ω_4 are generated due to the FWM. The electrical field of the idler at ω_3 is proportional to

$$\begin{aligned} E_3(t) &\propto E_2^2(t)E_1^*(t) \\ &= E_2^2 E_1 \exp[j(2\omega_2-\omega_1)t]\cdot\exp\{j\beta[2s(t-T_0)-s(t)-s(t-2T_0)]\} \\ &= E_3\exp(j\omega_3 t)\exp[j\beta\cdot f(t)] \end{aligned} \tag{3}$$

where we assume $E_3 = E_1\cdot E_2^2$, $\omega_3 = 2\omega_2-\omega_1$, $\beta_1 = \beta_2 = \beta$, and $f(t) = 2s(t-T_0)-s(t)-s(t-2T_0)$. It can be seen that $f(t)$ is a Gaussian doublet pulse where the inverted pulses are contributed by the phase conjugate term. In this way, a Gaussian doublet pulse is phase modulated onto the idler at ω_3 via the FWM as shown in Fig. 2. The phase modulated Gaussian doublet pulse is sent to the OBF, which performs two functions: 1) PM-IM conversion and 2) rejecting the undesired optical components and the amplified spontaneous emission noise from EDFAs. When the phase modulated idler is located at the linear slope of the OBF, the OBF serves as a linear frequency discriminator [2]. The linear frequency discriminator has a linear frequency and phase responses which can be expressed as

$$H(\omega) = K\omega\cdot\exp(-j\omega\tau_f) \tag{4}$$

where K is the slope of the frequency response and τ_f denotes the time delay introduced by the OBF. The output from the OBF is given by

$$E_{out}(\omega) = H(\omega)\cdot E_3(\omega) \tag{5}$$

where $E_3(\omega)$ is the Fourier transform of $E_3(t)$. Applying the inverse Fourier transform to Eq. (5), we have

$$E_{out}(t) = K\{\omega_3+\beta\frac{d[f(t-\tau_f)]}{dt}\}\cdot E_3(t-\tau_f). \tag{6}$$

Then, the photocurrent after the PD is proportional to [5]

$$i(t) \propto K^2\beta\omega_3\frac{d[f(t-\tau_f)]}{dt}. \tag{7}$$

It is apparent that the photocurrent is equivalent to the first-order derivative of the Gaussian doublet pulse. Therefore, an UWB Gaussian triplet pulse is generated at a single wavelength as shown in Fig. 2. We note that the UWB triplet pulse with inverted polarity can be generated by locating the idler ω_3 at the opposite slope of the OBF. Since the transfer spectrum of a microring resonator [18] based optical filter can be shifted by adjusting the driving voltage, it is possible to realize bi-phase modulation [19] of the UWB triplet pulse.

3. Experiment and result

An experiment was designed based on the experimental setup shown in Fig. 1. Two light waves at wavelengths of 1549.77 (TLS_1) and 1552.03 nm (TLS_2) were sent to the PM_1 and PM_2, respectively. A Gaussian-like pulse train generated by a PPG (Anritsu MP1800A) was applied to PMs. The electrical MZI used in the setup had a free spectral range (FSR) of 5.85 GHz, corresponding to a time difference of ~171 ps between the two arms. Therefore, the PPG was set at a bit rate of 11.7 Gbit/s (2 × 5.85), according to Eq. (1), with a fixed pattern “1000 0000 0000 0000” (one “1” every 16 bits). This is equivalent to a pulse train with a repetition rate of 731.25 MHz and a duty cycle of about 1/16. As a result, electrical pulses with fixed patterns of “1010 0000 0000 0000” and “1000 0000 0000 0000” were applied to PM_1 and PM_2 via two gain-tunable electrical amplifiers (Photoline DR-AN-20-HO), respectively. An ODL was added in the lower path to introduce one bit time-delay between the two light waves.

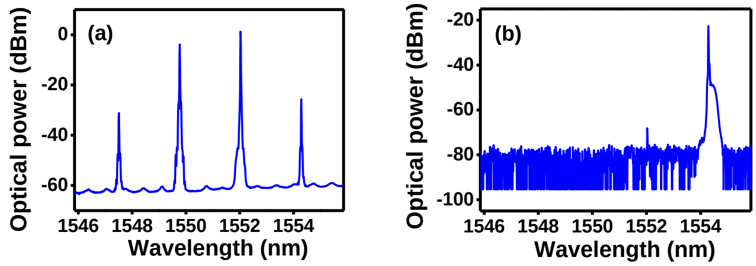

Fig. 3. Measured optical spectra at (a) the output of the HNLF and (b) the 10% branch of the OC_2 as shown in Fig. 1.

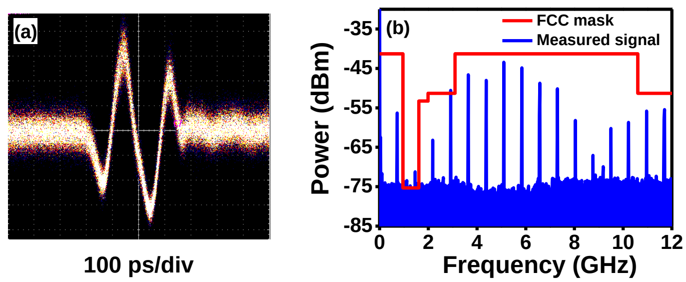

Fig. 4. Measured (a) waveform of the UWB triplet and (b) the corresponding electrical spectrum.

The two light waves were coupled by a 50:50 OC_1 and amplified by the $EDFA_1$ to a total optical power of 13 dBm. The combined light waves were transmitted along a 1 km HNLF with zero-dispersion wavelength of 1551 nm and a nonlinear coefficient of 10 $W^{-1} \cdot km^{-1}$. The optical spectrum was measured at the output of the HNLF, as shown in Fig. 3(a), using an optical spectrum analyzer (OSA, Advantest Q8384). Due to the FWM in the HNLF, two idlers were generated at wavelengths of 1547.51 and 1554.29 nm. An OBF with 3–dB bandwidth of 0.2 nm was used to filter out the idler at 1554.29 nm and perform the PM-IM conversion. Figure 3(b) shows the measured optical spectrum of the remaining idler after filtering. It can be seen that the optical signal consists of only one wavelength and is therefore resistant to distortion. The UWB triplet pulse was detected by a PD (Agilent 11982A) with the waveform measured by a high-speed sampling oscilloscope (OSC, Tektronix CSA8000). The electrical spectrum was recorded by an electrical spectrum analyzer (ESA, Advantest R382). The measured waveform of the generated UWB triplet pulse and the corresponding electrical spectrum are presented in Fig. 4(a) and (b), respectively. The UWB triplet pulse is generated from the idler. Therefore, a low FWM efficiency will result in a low signal-to-noise ratio of the idler, which degrades the quality of the generated pulses. The electrical spectrum is centered at 5.1 GHz with a fractional bandwidth of about 100% which is larger than the minimal requirement of 20% defined by the FCC. It can be seen that the electrical spectrum has a dip around GPS band and matches the FCC spectral mask well. Actually, the proposed UWB generator can also be regarded as a multi-tap bandpass microwave filter [14]. The envelope of the electrical spectrum shown in Fig. 4(b) is the frequency response of the microwave filter. The mainlobe locates in the frequency range from ~1.5 to ~9 GHz with the second dip at ~9 GHz.

4. Discussion and outlook

It should be noted that the proposed UWB generator is not tunable since it is actually a direct-sequence impulse radio UWB generator that operates in a single UWB band. For multiband

UWB generator, subband tuning and switching can be achieved [2]. For the proposed scheme, arbitrary order UWB Gaussian pulses, in principle, can be optically generated by simply modifying the experimental configuration as illustrated in Fig. 5, where PMs are cascaded at the outputs of the two TLSs. The time delays between pulses are adjusted by ODLs instead of the electrical and optical hybrid delay lines used in Fig. 1. As a result, the bit rate of the PPG is no longer restricted by the FSR of the electrical MZI, which cannot be changed easily. An example of generating the UWB quadruplet pulse by performing the first order derivative of a phase-modulated Gaussian triplet pulse is shown in Fig. 5, where four PMs are used. In addition, the proposed technique can be also used as a multi-tap microwave filter since it shares the same operational principle with the UWB generator [14,20].

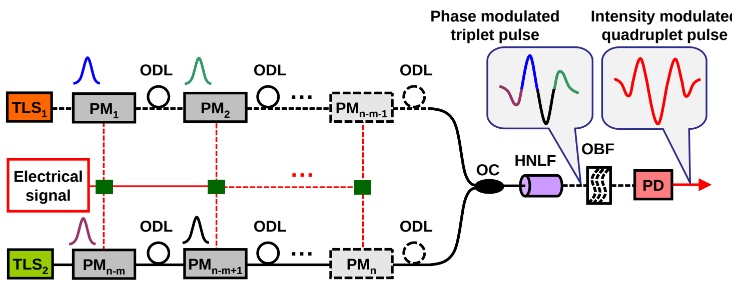

Fig. 5. Arbitrary order UWB pulse generator (*m* and *n* are integers).

5. Conclusion

We have demonstrated a FCC-compliant UWB triplet generation technique using FWM and PM-IM conversion. The proposed scheme is basically a two-step process. First a phase-modulated Gaussian doublet pulse is generated by FWM in the HNLF. Then a FCC-compliant UWB triplet pulse is generated by performing PM-IM conversion of the phase-modulated Gaussian doublet pulse using an OBF serving as the frequency discriminator. The triplet pulses are generated at a single wavelength to alleviate dispersion-induced distortion. In addition, it is easy to extend our scheme to generate arbitrary order UWB Gaussian pulses by cascading PMs.

Acknowledgments

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