Photonic Synthesis of Triangular-Shaped Pulses and Its Tunability Utilizing Frequency to Time Mapping

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Abstract: A synthesis scheme to generate microwave triangular-shaped pulses based on spectral shaping and frequency-to-time mapping is proposed. Triangular-shaped signals with periods of 0.2ns, 0.4ns, 1.6ns and pulse widths of 0.13ns, 0.35ns are demonstrated.

OCIS codes: (060.5625) Radio frequency photonics; (350.4010) Microwaves;

1. Introduction

Microwave signals with special waveforms are widely used in modern radar or antenna, sensor network, radio frequency (RF) communication systems, and so on [1-4]. Indeed, compared with electrical ones, microwave signal generation approaches in the optical domain offer many prominent advantages, such as high bandwidth, immunity to electromagnetic interference, and reconfigurability.

Currently, there exist various solutions to generate microwave signals based on spectral shaping and frequency to time mapping (FTTM) [5-9]. Among these solutions, the methods employing spatial light modulator (SLM) as the spectral shaper can achieve arbitrary waveform generation and supply an obvious advantage in terms of reconfigurability. Furthermore, pure fiber-optic methods are competitive candidates with relatively simple system configuration. However, waveforms generated by using all-fiber components are mostly limited to sinusoidal pulse envelope. For certain applications, it would be desirable to generate special waveforms, such as triangle, sawtooth and so on based on all-fiber approaches. In particular, triangle waveforms have applications mainly in the fields of test equipment and data display [10].

In this paper, we propose a synthesis scheme to generate microwave triangle waveforms using all-fiber components. The pulse signals from a mode-locked laser (MLL) are sent to an external modulator. The modulator is modulated with a pulse gate longer than the signal width to decrease the frequency of the pulse train, therefore the pulse can accommodate larger width and flatten the optical spectrum within the signal bandwidth. Consequently, the period of the generated waveform can be electrically tuned by adjusting the RF signals' rate. Furthermore, as the final pulses are generated based on frequency-to-time conversion in the dispersive fiber, the pulse width of the triangle-shaped waveform is also adjustable by selecting the value of the fiber length. To demonstrate the effectiveness of the approach, we have generated triangle waveforms with periods of 0.2-ns, 0.4-ns, 1.6-ns and pulse width of 0.13-ns, 0.35ns.

2. Concept of photonic regenerator of triangular-shaped microwave pulses

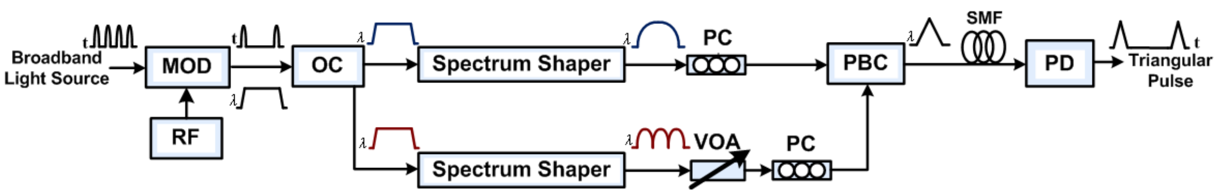

Fig.1 Conceptual diagram of triangular pulse generator: OC: optical coupler; PC: polarization controller; VOA: variable optical attenuator; PBC: polarization beam combiner; PD: photodetector.

It is well known that periodic waveforms can be synthesized by a series of sinusoidal functions with different frequencies. For example, the expansion equation of a periodic triangle waveform can be described as

$$f(t)=\frac{E}{2}+\frac{4E}{\pi^2}(\cos\omega_1 t+\frac{1}{9}\cos 3\omega_1 t+\frac{1}{25}\cos 5\omega_1 t+\cdots) \quad (1)$$

where E denotes the amplitude of the triangle waveform and ω is the waveform frequency. It can be seen from Eq.(1) that the high-order harmonic components have small effects in the synthesis function. For this reason, we can just select the first and third harmonic components to synthesize an approximate triangle waveform.

Fig. 1 shows the conceptual diagram of the triangular pulse generator utilizing frequency to time mapping. The broadband light is firstly sent to an external modulator to adjust the pulse period, and then separated by an optical coupler into two beams. After spectrum shapers with different free-spectral ranges (FSRs), the optical spectrum of one light beam has a sinusoidal envelope with three times the frequency of another one. The variable optical attenuator (VOA) adjusts the amplitude of the three-times frequency component to be one ninth of another. Then a PBC is used to combine two light beams to form the triangular-shaped spectrum without interference. After that, a spool of standard dispersive fiber is used so that the temporal waveform detected through the photodetector (PD) can have the same shape as the optical spectrum defined by the shaper according to the FTTM theory. Note that the period of the generated waveform can be electrical tuned by adjusting the modulation rate (the modulator is driven by a frequency-tunable periodic RF signal). Furthermore, by altering the fiber length the pulse width of the triangle-shaped waveform is also tunable, or using certain tunable dispersive modules.

3. Experimental setup and results

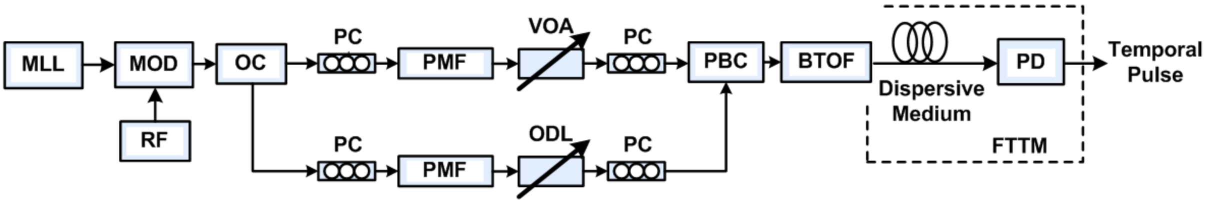

Fig. 2 Experimental setup: MLLD: mode-locked semiconductor laser; MOD: modulator; PMF: polarization maintaining fiber; BTOF: bandwidth-tunable optical filter; ODL: optical delay line

Fig. 2 is the experimental setup. A semiconductor mode-locked laser with a pulse width of ~ 2-ps and a repetition rate of 10-GHz acts as a braodband light source with the center wavelength ~1550nm. The ultrashort pulse sequence is sent to an electro-optic Mach-Zehnder modulator, which is driven by a frequency-tunable periodic signal, to decrease the frequency of the pulse train for accommodating larger pulse width and flattening the optical spectrum within the signal bandwidth. Then the pulse train from the modulator output is separated by a 3-dB coupler into two branches. In each branch, the first polarization controller (PC) is used to align the input light at 45° angle with respect to the principal states of polarization (PSP) of the PMF, and a second PC is used to adjust the polarization rotation of the light with respect to the input port of the PBC. In one branch, we insert a variable optical delay line (ODL) to synchronize two light beams. The whole configuration of each branch works as an optical comb filter which FSR is determined by the length of the PMF. Here we set the FSR of two filters at 0.25-nm and 0.75-nm (i.e. the shaped optical spectra from two filters have sinusoidal envelopes with period of 0.25-nm and 0.75-nm respectively). At the output of the PBC, the two light beams are combined to form triangular-shaped spectra without interference, as they have orthogonal polarizations with each other. The bandwidth of a bandwidth-tunable optical filter (BTOF) is set to 0.75-nm to filter out an individual triangle spectrum. The FTTM module is composed of a standard single-mode-fiber (SMF) and a high-speed photodetector. In our experiment, we use a high-speed oscilloscope (Agilent 86116C with 65-GHz optical bandwidth) as the PD. Note that the length of the SMF determines the width of the generated triangular-shaped pulses.

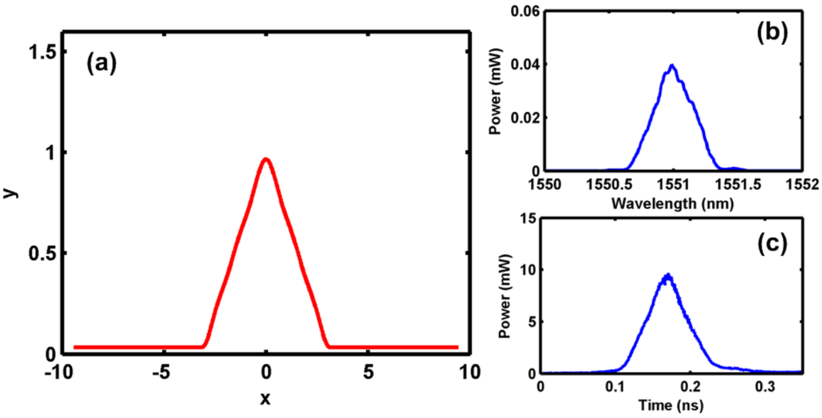

Fig.3 (a) Simulation result and the corresponding measured results of (b) optical spectrum; (c) generated triangular-shaped pulses when the SMF length is 10-km.

Firstly we verify the effectiveness of the triangle waveform synthesis concept. The synthesis function of triangle waveform as shown in Eq.(1) is simulated in Fig. 3(a). The high-order harmonic components over the third harmonic are omitted and we just filter out one period of the triangle waveforms as an example to keep consistency with the experimental results. It can be proved that only the first and third harmonic components are necessary to obtain approximate triangle waveforms. Fig. 3(b) and (c) are the measured optical spectrum and generated triangular-shaped pulse when we employ a 10-km standard SMF. The group delay dispersion (GDD) coefficient of the SMF is about 210-ps^2. There are minor differences between the shape of the spectrum and the temporal waveform for we have to use an ODL to adjust the synchronization of the two harmonic components in time domain. As shown in Fig. 3(c), the temporal width of the triangle-shaped pulse is ~0.13-ns, which matches well with the calculated results 0.123-ns (the relative calculated equation can be found in Ref. [11]). Note that the temporal width is defined as the nonzero value range of the temporal waveform.

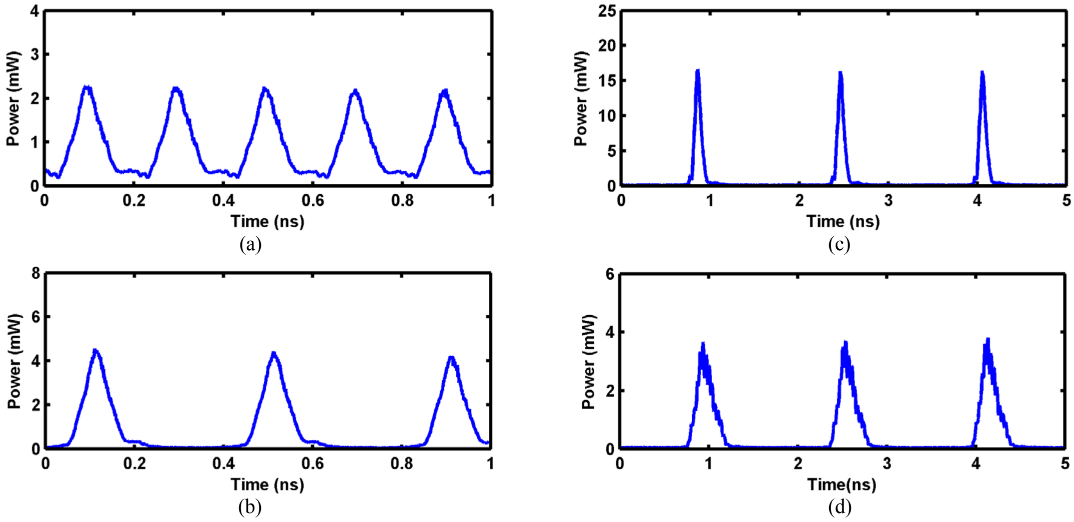

Fig. 4 Generated periodic triangular-shaped pulses with different modulation frequencies and SMF lengths: (a) 5-Gb/s and 10-km; (b) 2.5-Gb/s and 10-km; (c) 625-Mb/s and 10-km; (d) 625-Mb/s and 25-km.

In order to demonstrate the tunability of the triangular-shaped pulse generator, we change the modulation rate and the SMF length to generated triangle waveforms with different periods and pulse widths. At first, we set the SMF length at 10-km and the modulation rate at 5-Gb/s (i.e. the modulator is driven by a 5-Gbit/s data stream with alternate "1"-bit and "0"-bit). Fig. 4(a) shows the generated pulses with temporal period of 0.2-ns and temporal width of 0.13-ns. Then we change the modulation rate to 2.5-Gb/s (the modulator is now driven by a 2.5-Gbit/s data stream with a single "1"-bit following by three "0"-bit). The result is shown in Fig. 4(b). It can be seen that the period of the triangular-shaped pulses turn to be 0.4-ns. To illustrate the tunability of pulse width, we set the modulation rate at 625-Mb/s and employ two pieces of SMF with the lengths of 10-km and 25-km respectively. Fig. 4(c) and (d) show the obtained results. The pulse temporal widths have obvious changes from 0.13-ns to 0.35-ns. In conclusion, we have proposed and demonstrated an all-fiber approach to generate periodic triangular-shaped pulses with tunable period and pulse width.

4. Reference

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