Photonic generation of pulsed microwave signals with tunable frequency and phase based on spectral-shaping and frequency-to-time mapping

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Photonic generation of pulsed microwave signals with tunable frequency and phase based on spectral-shaping and frequency-to-time mapping

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A scheme for photonic generation of pulsed microwave signals with tunable frequency and phase based on optical spectral-shaping and frequency-to-time mapping is proposed and experimentally demonstrated. The spectral shaping is realized by a tunable optical comb filter consisting of a differential group delay (DGD) element, a polarization modulator (PolM), and a polarizer. By passing a short optical pulse through the tunable comb filter and a dispersive element (DE), a pulsed microwave signal is generated after optical-to-electrical conversion. The phase of the generated microwave signal can be continuously tuned by tuning the voltage applied to the PolM. The frequency of the microwave signal can be tuned by changing the DGD and/or the dispersion of the DE. An experiment is performed. The generation of a pulsed microwave signal with tunable frequency and phase is demonstrated.

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Photonic generation of microwave signals has been a topic of interest and has been intensively investigated. It can find applications such as in broadband wireless access networks, software-defined radio, radar, and warfare systems [1,2]. Numerous schemes have been proposed and demonstrated [2–9]. Among the techniques, the one based on optical spectral-shaping and frequency-to-time (SS-FTT) mapping has been demonstrated to be an effective solution for the generation of pulsed microwave signals [6–9]. The key component in a SS-FTT mapping system is the spectral shaper, which can be implemented based on free-space optics [6] or fiber optics [7–9]. In [6], a spatial light modulator (SLM) is used to implement optical spectral shaping. The advantage of using an SLM for spectral shaping is that the spectral response of an SLM can be updated in real time, making the generation of an arbitrary waveform possible. The main limitation of a free-space-optics-based spectral shaper is the large size and high loss. In addition, the coupling between fiber to free-space and free-space to fiber makes the system complicated. On the other hand, a spectral shaper can be implemented based on fiber optics [7–9]. A fiber-optic spectral shaper has the advantages of smaller size, lower loss, and better compatibility with other fiber-optic components. The main limitation is poor flexibility. Once fabricated, the spectral response is fixed. The frequency of the generated microwave signal may be tuned by changing the free-spectral range (FSR) of the spectral shaper [7,8], but the phase of the microwave signals cannot be tuned due to the fixed phase response in the optical power transfer function. For many applications, such as phased array beam forming and arrayed signal processing, the phase of the microwave signal must be tunable.

In this Letter, we propose and demonstrate a scheme for photonic generation of a pulsed microwave signal with tunable frequency and phase based on optical SS-FTT mapping using fiber-optic devices. The key component in the system is the spectral shaper implemented using a differential group delay (DGD) element, a polarization modulator (PolM), and a polarizer. The phase of the generated microwave signal can be continuously tuned by tuning the voltage applied to the PolM. The frequency of the microwave signal can also be tuned by changing the DGD and/or the dispersion of a dispersive element (DE). An experiment is performed. The generation of a pulsed microwave signal with tunable frequency and phase is demonstrated.

Figure 1 shows the schematic diagram of the proposed microwave signal generator. It consists of a mode-locked laser (MLL), a DGD element (DGDE), a PolM, a polarizer, a polarization controller (PC), a DE, and a photodetector (PD). The DGDE, the PolM, and the polarizer operate jointly as an optical comb filter with both the FSR and the phase of the power transfer function tunable. In Fig. 1,

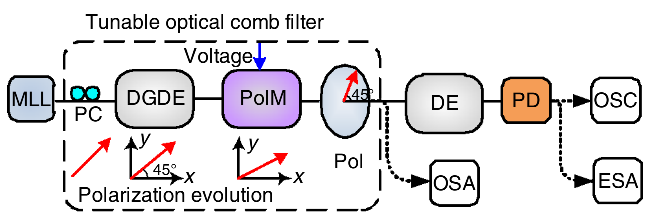

Fig. 1. Schematic diagram of the proposed microwave signal generator. MLL, mode-locked laser; PolM, polarization modulator; DGDE, DGD element; DE, dispersion element; PC, polarization controller; Pol, polarizer; PD, photodetector; OSC, oscilloscope; ESA, electrical spectrum analyzer; OSA, optical spectrum analyzer.

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the polarization direction of the incident light fed into the DGDE is aligned by the PC to have an angle of 45° relative to one principal axis of the DGDE. The DGDE introduces a DGD of $\Delta\tau$ between the TM and TE modes along its two principal axes (x and y). Then, the light is sent into the PolM. The PolM is a special phase modulator that supports phase modulation along its two principal axes with opposite phase modulation indices [10]. In the proposed scheme, the two principal axes of the PolM are aligned with those of the DGDE; thus, a phase difference of $\Delta\varphi$ between TM and TE modes of the transmitted light is achieved at the output of the PolM. If the field of the optical signal injected into the DGDE is $E = \exp(j\omega t)$, where ω is the angular frequency of the optical signal, the optical fields at the output of the PolM along its two principal axes are

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \frac{\sqrt{2}}{2}\begin{bmatrix} \exp[j\omega(t+\Delta\tau)] \\ \exp[j(\omega t - \Delta\varphi)] \end{bmatrix}. \quad (1)$$

After the PolM, a polarizer is inserted with its polarization direction aligned to have an angle of 45° to one principal axis of the DGDE. The optical field after the polarizer is

$$\begin{aligned} E_{\text{out}} &= \frac{\sqrt{2}}{2}(E_x + E_y) \\ &= \frac{1}{2}\exp(j\omega t)[\exp(j\omega\Delta\tau) + \exp(-j\Delta\varphi)]. \end{aligned} \quad (2)$$

Based on Eq. (2), the optical power transfer function of the comb filter can be calculated, which is a cosine function given by

$$T = \frac{E_{\text{out}} \cdot E^*_{\text{out}}}{E \cdot E^*} = \frac{1}{2}[1 + \cos(\omega\Delta\tau + \Delta\varphi)]. \quad (3)$$

The FSR of the comb filter is $1/\Delta\tau$, which can be tuned by changing the DGD value. The phase term $\Delta\varphi$ in Eq. (3) can be changed by applying a tunable voltage to the PolM.

When a short optical pulse from the MLL is sent to the optical comb filter, as shown in Fig. 1, the power spectrum of the optical pulse will be shaped by the comb filter with a cosine transfer function. By using a DE to perform FTT mapping [11], the optical power spectrum is mapped to the time domain, and a microwave signal with a shape that is a scaled version of the shaped power spectrum is generated at the output of the PD.

If the group velocity dispersion (GVD) of the DE is D (in ps/nm), the frequency of the obtained microwave signal is

$$f_{\text{RF}} = \frac{1}{\Delta\lambda D} = \frac{c\Delta\tau}{n\lambda^2 D}, \quad (4)$$

where $\Delta\lambda$ is the wavelength spacing corresponding to the FSR of the comb filter, λ is the central wavelength, c is the speed of light in vacuum, and n is the refractive index of the fiber. It is known from Eq. (4) that the frequency of the obtained microwave signal is a function of $\Delta\tau$ and D; thus, it can be tuned by changing the DGD and/or GVD values. According to Eq. (3), the phase of the temporal cosine waveform after the FTT mapping is determined by $\Delta\varphi$. As a result, by changing the voltage applied to the PolM, the phase of the generated microwave signal can be continuously tuned.

The proposed scheme is experimentally demonstrated based on the setup shown in Fig. 1. An optical pulse generated by the MLL (Calmar Laser) with a full width at half-maximum (FWHM) of 0.6 ps and a repetition rate of 10 MHz is sent to the DGDE. Due to the lack of a tunable DGD or GVD device, a polarization maintaining fiber (PMF) and a single-mode fiber (SMF) are used, respectively, to produce the DGD and GVD. The PolM has a bandwidth of 40 GHz and a half-wave voltage of 3.7 V (at 10 GHz). The polarizer is realized by a PC and a polarization beam splitter (PBS). A 50 GHz PD is utilized to perform the optical-to-electrical conversion. The optical spectra before and after the comb filter are monitored by an optical spectrum analyzer (OSA). The waveform and spectrum of the generated microwave signal are observed by an oscilloscope (OSC) and an electrical spectral analyzer (ESA), respectively.

The optical power spectrum before the comb filter is shown in Fig. 2(a), where the 3 dB spectral width is about 6 nm. A 6.5 m length of PMF is used as the DGDE ($\Delta\tau = 13.3$ ps) to implement the comb filter. The optical spectrum after the comb filter is shaped by the cosine transfer function, as shown in Fig. 2(b). In Fig. 2(b), a cosine profile is successfully imposed on the power spectrum and the wavelength spacing between the adjacent peaks is 0.6 nm, corresponding to the FSR of the comb filter. When a 5.25 km SMF serves as the DE ($D \approx 90$ ps/nm), the shaped optical spectrum is mapped to the time domain, and a temporal waveform that is a scaled version of the shaped power spectrum is generated, as shown in Fig. 3(a). The temporal period of the waveform is 54 ps. The measured electrical spectrum of the microwave signal is given in Fig. 3(e), where high frequency components centered at 18.5 GHz are clearly observed. According to Eq. (4), the frequency of the generated microwave signal is calculated to be 18.51 GHz, which means that the experimental result complies well with the theoretical result.

The most distinctive feature of the proposed scheme is that, by applying a tunable voltage to the PolM, the phase

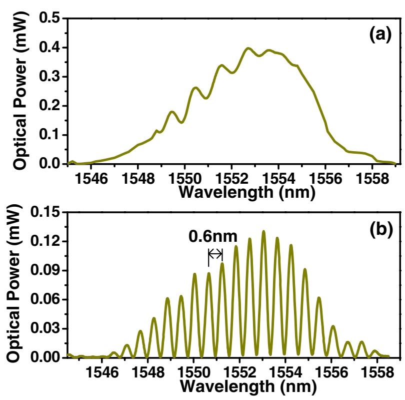

Fig. 2. Measured optical spectra (a) before the optical comb filter and (b) after the optical comb filter.

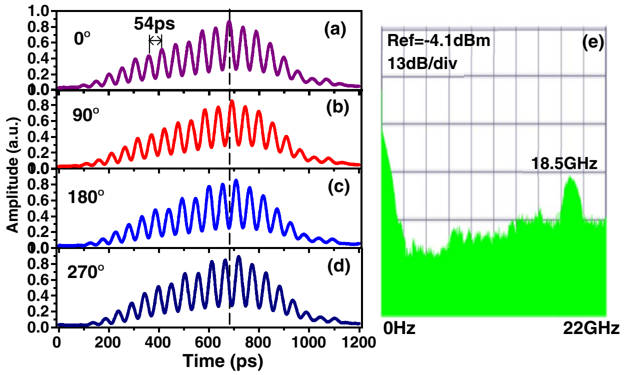

Fig. 3. Measured waveform and spectrum of the generated microwave signal when the lengths of the PMF and the SMF are 6.5 m and 5.25 km: (a) waveform without phase shift, (b) waveform with a 90° phase shift, (c) waveform with a 180° phase shift, (d) waveform with a 270° phase shift, and (e) electrical spectrum of the microwave signal.

of the microwave signal can be continuously tuned. To illustrate this property, we manually change the bias voltage to the PolM, and the waveforms with a phase shift of 90°, 180°, and 270° are thus observed, as shown in Figs. 3(b)–3(d).

The PolM has a bandwidth as large as 40 GHz; thus, high-speed phase modulation of the microwave signal can also be achieved if a control signal is applied to the PolM through the RF port. Figure 4(a) shows the waveform when the 10 MHz microwave signal pulse train is binary phase modulated by a 10 Mb/s control signal with a fixed pattern of "1010." The waveforms of adjacent pulses are complementary to each other with a precise 180° phase difference, as shown in Fig. 4(b).

If a DGDE with a variable DGD and/or a DE with a continuously tunable dispersion are used, the frequency of the generated microwave signal can also be tuned continuously. In our experiment, due to the lack of a continuously tunable DGDE or DE, the frequency tuning is demonstrated by changing the length of the PMF and the SMF. First, the length of the SMF is changed from 5.25 to 10.2 km ($D \approx 173.4$ ps/nm) while maintaining the length of the PMF to be 6.5 m. The measured waveform and spectrum of the generated microwave signal are shown in Figs. 5(a) and 5(b), respectively. The temporal period of the waveform in Fig. 5(a) is increased to 104 ps due to the increased GVD, and the central frequency of the microwave signal is reduced to 9.62 GHz. Then, the length of the PMF is changed to 12.4 m ($\Delta\tau = 25.4$ ps) to obtain a smaller FSR (0.32 nm) of the comb filter, and the SMF is still 10.2 km long; the waveform and spectrum of the generated microwave signal are measured and shown in Figs. 5(c) and 5(d), respectively. The temporal period is measured to be 55.5 ps, and the corresponding central frequency is now 18 GHz, as shown in Fig. 5(d).

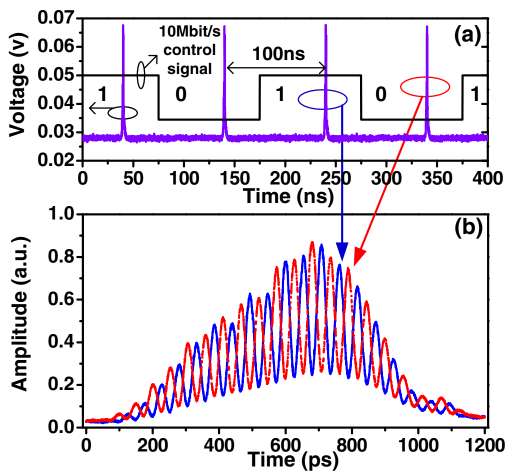

Fig. 4. (a) Waveforms of the 10 Mb/s binary phase modulated pulse train and the control signal and (b) measured waveforms with a 180° phase difference.

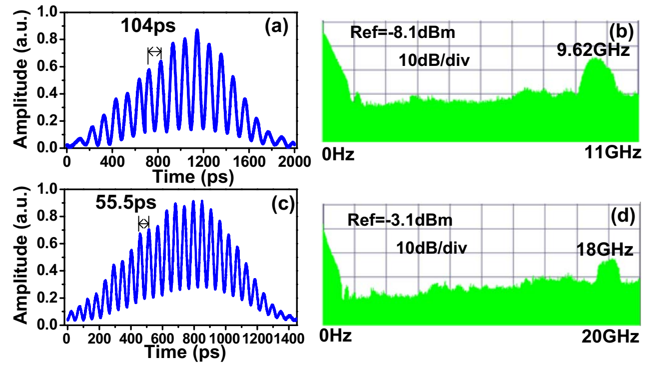

Fig. 5. Waveform and electrical spectrum of the generated microwave signal pulse. (a),(b) when PMF = 6.5 m and SMF = 10.2 km; (c),(d) when PMF = 12.4 m and SMF = 10.2 km.

In conclusion, we have proposed and experimentally demonstrated a pulsed microwave signal generation scheme based on SS-FTT mapping using fiber-optic components. Thanks to the use of an optical comb filter that is composed by a DGDE, a PolM, and a polarizer, the phase of the generated microwave signal could be continuously tuned by tuning the voltage applied to the PolM. The frequency of the microwave signal could also be tuned by changing the DGD and/or the dispersion of the DE. The proposed scheme was verified by an experiment. The generation of a pulsed microwave signal with tunable frequency and phase shift was demonstrated.

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