Photonic Generation of Microwave Signals Based on Pulse Shaping

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***Abstract*—A novel approach to generating microwave signals based on optical pulse shaping is proposed and experimentally demonstrated. The proposed system consists of a femtosecond pulse laser source, a Sagnac-loop filter (SLF), a dispersive element, and a photodetector. The spectrum of the femtosecond pulse is shaped by the SLF that has a sinusoidal spectral response. Thanks to the frequency-to-time conversion in the dispersive element, time-domain pulse exhibiting the shape of the optical power spectrum is obtained. Depending on the free-spectral range of the SLF and the total dispersion of the dispersive element, signals with frequencies up to terahertz can be generated. A model to describe the signal generation is developed. Experimental results agree well with the theoretical analysis.**

***Index Terms*—Microwave photonics, microwave signal generation, pulse shaping, radio-over-fiber.**

I. Introduction

OPTICAL generation of microwave and millimeter-wave (mm-wave) signals is of great research interest in the last few decades for applications such as broadband wireless access networks, software-defined radio, antenna remoting, phased array antenna, optical sensors, and radar systems [1]–[3]. The key advantage of using optics to generate microwave and mm-wave signals is that very high-frequency signals can be easily generated by beating two optical wavelengths at a high-speed photodetector (PD). To ensure a low phase noise generation, the two optical wavelengths should be phase locked by using either optical injection locking [4] or optical phase lock loop [5]. Microwave signals can also be generated using an external modulation technique, in which the modulation can be done using either an intensity modulator (IM) or a phase modulator [6], [7]. The approaches in [4]–[7] can generate a high-quality microwave signal in the optical domain, but a high-quality reference source is required.

On the other hand, signals can be generated based on the pulse-shaping technique. Spatial light modulator (SLM)-based pulse shaping has been a well-established technology for arbitrary waveform generation. In [8], an mm-wave waveform is generated using an SLM-based direct space-to-time pulse shaper. In [9], the generation of a microwave waveform with arbitrary wideband modulation is realized using an SLM based on wavelength-to-time mapping. The major difficulty related to the SLM-based approaches is that the processing is implemented in free space, which makes the system bulky and complicated. Microwave signals can also be generated in the time domain using pure fiber-optic components. In [10], microwave signals are generated based on dispersive compression or expansion of highly chirped optical pulses that are amplitude-modulated by a microwave signal. A microwave can also be generated based on temporal Talbot self-imaging [11]. The two approaches presented in [10] and [11] can be easily implemented to generate microwave signals at high frequencies, but a reference source is still needed.

In this letter, we propose and demonstrate a novel technique to generate microwave signals based on time-domain-pulse shaping using pure fiber-optic components without the need of a reference source. The proposed system is equivalent to an optical subcarrier system with ON–OFF keying (OOK) modulation. Being different from the techniques in [8] and [9] where the modulated microwave signal is generated using an SLM-based pulse-shaping system, in our approach the microwave carrier is generated based on pulse shaping using pure fiber-optic components and the digital encoding is performed using an optical IM. The proposed approach can find applications such as in radio-over-fiber networks [12] and radar systems. In the proposed system, a pulse train from a short pulse source is encoded by a digital sequence using an optical IM. The encoded pulse sequence is then sent to a pulse-shaping module, which consists of a Sagnac-loop filter (SLF) and a dispersive element. The spectrum of the optical pulse is shaped by the SLF that has a sinusoidal spectral response. Thanks to the frequency-to-time conversion in the dispersive element, a time-domain optical pulse exhibiting the shape of the optical power spectrum is obtained. The frequency of the generated signal is dependent on the free-spectral range (FSR) of the SLF and the total dispersion of the dispersive device, which can be tailored to generate the electrical signals with frequencies up to terahertz.

II. Principle

The proposed microwave signal generation system is shown in Fig. 1. A pulse train from a short pulse source is sent to an optical IM, which is driven by a digital sequence, to perform digital encoding. The encoded pulse train is then sent to a pulse-shaping module to generate the microwave signal. The pulse-shaping module, shown in Fig. 2, consists of an SLF and a dispersive element. The SLF, composed of a length of polarization-maintaining fiber (PMF) and two polarization controllers [13], has a sinusoidal spectral response with an FSR determined by the length of the PMF, as shown in the inset of

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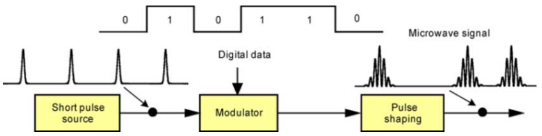

Fig. 1. Schematic diagram of the proposed microwave signal generation based on pulse shaping.

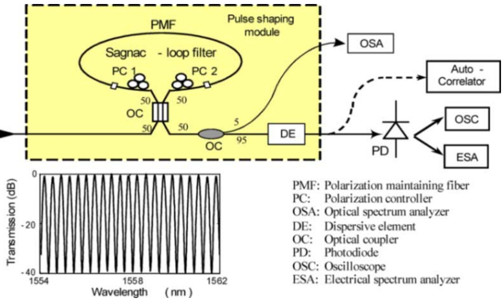

Fig. 2. Pulse-shaping module (inset: spectral response of the SLF).

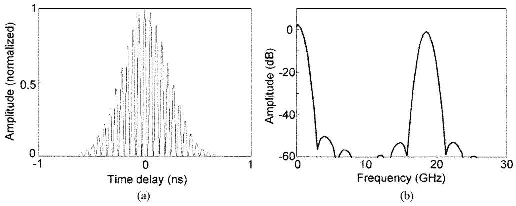

Fig. 3. Theoretical results for the generated mm-wave signal at 18 GHz. (a) Time-domain waveform, and (b) its spectrum.

Fig. 2. The spectrum of the short pulse is shaped by the SLF. Thanks to the frequency-to-time conversion in the dispersive element, the time-domain waveform exhibiting the shape of the power spectrum is generated after the spectrum-shaped pulse propagating in the dispersive element.

In theory, the electrical field of an ultrashort transform-limited Gaussian pulse after propagating through a dispersive element that has only the first-order dispersion can be modeled as [14]

$$E_L(t) = \exp\left(-\frac{t^2}{\tau^2}\right)\exp\left(-j\frac{t^2}{2\ddot{\Phi}}\right) \tag{1}$$

where $\ddot{\Phi}$ is the second-order derivative of the optical phase to the angular frequency, and 2τ is the $1/e$ width of the Gaussian pulse after experiencing the chromatic dispersion. Here, we assume $\left|\ddot{\Phi}/\tau^2\right| \gg 1$, which means that the pulse duration before the dispersive element is much smaller than that after experiencing the chromatic dispersion. This assumption is always true for subpicosecond pulses propagating in a few hundreds of meters of standard single-mode fiber (SSMF) [15].

On the other hand, the SLF with a single section of PMF can be considered as a two-beam interferometer with an impulse response given by

$$h_f(t) = \frac{1}{2}\left[\delta(t) + \delta(t - t_0)\right] \tag{2}$$

where t_0 is the time delay difference between the two polarization modes within the SLF. The SLF can be replaced by other types of two-beam interferometers [16].

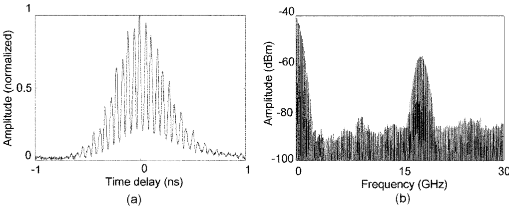

Fig. 4. Experimental results of the generated 18-GHz signal. (a) Time-domain waveform, and (b) the measured electrical spectrum.

After propagating through the dispersive element and the SLF, the output electrical field is

$$\begin{aligned} E_{L,f}(t) = E_L(t) * h_f(t) &= \frac{1}{2}\exp\left(-\frac{t^2}{\tau^2}\right)\exp\left(-j\frac{t^2}{2\ddot{\Phi}}\right) \\ &+ \frac{1}{2}\exp\left(-\frac{(t-t_0)^2}{\tau^2}\right)\exp\left(-j\frac{(t-t_0)^2}{2\ddot{\Phi}}\right) \end{aligned} \tag{3}$$

where $*$ denotes the convolution operation.

The current at the output of the PD is proportional to the intensity of the input electrical field, which is expressed as

$$\begin{aligned} I_{L,f}(t) &= \Re\left|E_{L,f}(t)\right|^2 \\ &= \frac{1}{4}\Re\exp\left[-2\left(\frac{t}{\tau}\right)^2\right] + \frac{1}{4}\Re\exp\left[-2\left(\frac{t-t_0}{\tau}\right)^2\right] \\ &+ \frac{1}{2}\Re\exp\left[\frac{-t^2-(t-t_0)^2}{\tau^2}\right]\cos\left(\frac{t_0 t}{\ddot{\Phi}}\right) \end{aligned} \tag{4}$$

where $\Re$ is the responsivity of the PD.

It can be seen from (4) that the first and the second terms in the right-hand side of the equation are the dc and the low frequency components, and the third term is the high frequency component with a central frequency given by $f = t_0/2\pi\ddot{\Phi}$.

A simulation is performed based on (4); the time-domain waveform of the generated signal and its spectrum are shown in Fig. 3(a) and (b). In the simulation, the FSR of the SLF is 0.8 nm, a 4-km SSMF is used as the dispersion element, and the input optical pulsewidth is 350 fs. As can be seen, the generated signal has a Gaussian envelope with a frequency at 18 GHz determined by the FSR and the length of the SSMF.

III. EXPERIMENT

An experimental setup based on the system shown in Fig. 2 is built. The optical IM is not included in the setup, since the aim of the experiment is to demonstrate the feasibility of the proposed method for microwave waveform generation. A femtosecond pulse laser (FSPL) is used to generate the short pulse train, which has a pulsewidth of 351 fs and a repetition rate of 48.6 MHz. The pulse train from the FSPL is spectrum shaped by the SLF. In the experiment, a length of SSMF is employed as the dispersive element. The spectrum-shaped pulse train is then sent to the dispersive element to perform frequency-to-time conversion. A time-domain signal exhibiting the shape of the optical power spectrum is thus obtained at the output of the PD.

We first generate a microwave signal with a frequency of 18 GHz. Based on (4), to generate an 18-GHz signal the FSR of the SLF is set at 0.8 nm, and the length of the SSMF is 4 km. Fig. 4(a) and (b) shows the time-domain waveform and its corresponding electrical spectrum. As predicted by the model in

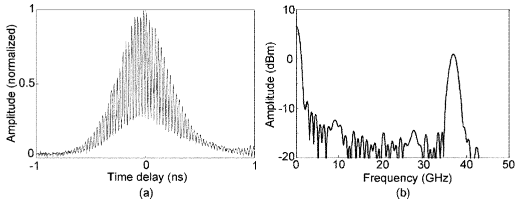

Fig. 5. Experimental result of the generated 36-GHz signal. (a) Time-domain waveform, and (b) the electrical spectrum calculated using FFT.

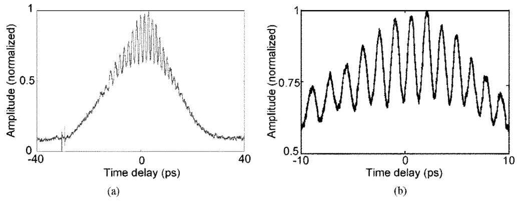

Fig. 6. Experimental results of the generated 0.65-THz waveform. (a) The autocorrelation trace, and (b) the zoom-in display.

(4), the spectrum includes a low-frequency spectral component around the dc and a high-frequency spectral component around 18 GHz. Note that both the dc and the high-frequency spectra have a Gaussian envelope, which is due to the Gaussian-shaped envelope of the input pulse. It is found that the measured time-domain waveform has a poorer visibility compared with that obtained by simulation shown in Fig. 3(a); this is mainly due to the nonflat frequency response of the PD, the gain of which at frequencies higher than 15 GHz is about 2 dB lower than that at around the dc.

Then, the FSR of the filter is reduced to 0.4 nm, while keeping the SSMF length unchanged. The reduction of the FSR leads to an increase in the signal frequency. As shown in Fig. 5(a) and (b), the generated signal has a frequency of 36 GHz. A low-frequency component around dc is also observed. Again, the results are consistent with the theoretical analysis.

Finally, we reduce the length of the SSMF to 100 m, while setting the FSR of the SLF to be 0.8 nm. Based on (4), the generated signal frequency would be 0.65 THz. Since the frequency of the generated signal is too high, the PD cannot respond to such a high frequency. To verify the generation, we use an optical autocorrelator to display the generated signal. The measured autocorrelation trace is shown in Fig. 6(a), with a zoom-in view shown in Fig. 6(b). The period of the autocorrelation trace is 1.54 ps, which corresponds to a frequency of around 0.65 THz. Note that in our experiment, the amplitude of the generated microwave signal is around 15 mV. To generate a microwave signal with a larger amplitude, an RF amplifier may be used. It is worth noting that (3) and (4) are obtained based on the linear dispersion assumption. In a real system, the higher order dispersion in the fiber would inevitably lead to the asymmetry in the generated waveforms, as can be seen in Figs. 4(a) and 5(a)–6(a).

IV. CONCLUSION

A novel approach to generating microwave signals based on pulse shaping was proposed and experimentally demonstrated. A closed-form expression was developed to describe the signal generation. Experiments were performed to generate electrical signals with frequencies of 18 GHz, 36 GHz, and 0.65 THz, by adjusting the FSR of the SLF or the length of the SSMF. The key advantage of the proposed approach is that it can be implemented using all-fiber-optic components without the requirement of a high-quality reference source. In addition, in the proposed system the dispersive element can be a length of SSMF; therefore, the signal cannot only be generated but also be distributed to a remote site. The entire system is equivalent to an optical subcarrier system using the OOK scheme, which can find applications in radio-over-fiber networks and radar systems. The proposed system can also find other applications, such as terahertz generation for imaging, sensing, and terahertz communications [17].

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