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Photonic generation of BFSK RF signals based on optical pulse shaping*

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A novel method to generate binary frequency shift-keying (BFSK) radio frequency (RF) signals in optical domain is proposed. In the proposed system, an optical short pulse train is converted into super-Gaussian RF pulses with high frequency based on optical pulse shaping by two Mach-Zehnder fiber interferometers (MZIs). And the generated RF signals are coded using a fast electro-optic switch. By properly designing the MZIs, BFSK RF signals with desired code pattern and modulation index can be generated. A theoretical model for describing the system is developed, and the generation of BFSK RF signals in millimeter-wave regime is demonstrated via simulations.

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Binary frequency shift-keying (BFSK) is one of the common digital modulation schemes in wireless communications, which simply means sending binary data with a sinusoidal carrier at two frequencies, representing logic “0” (space) and logic “1” (mark), respectively. Traditionally, BFSK radio frequency (RF) signals are usually generated in the electrical domain by using a voltage-controlled oscillator (VCO) or digital electronic circuits[1]. The major difficulty associated with these techniques is that the frequency of the generated signals is limited to a few gigahertzs. However, with the increasing demand for higher communication capacity, high frequency digitally modulated RF signals in millimeter-wave regime are required for the emerging applications, such as millimeter-wave video transmission, indoor wireless systems and deep-space communications[2-4]. An effective alternative is to generate high frequency RF signals in the optical domain[5]. Various techniques have been proposed to generate binary digitally modulated RF signals using photonic methods[6-14]. Among the existing techniques, optical pulse shaping followed by frequency-to-time mapping (FTTM) has been demonstrated to be a promising technique to generate microwave signals[10]. Photonic generation of BPSK RF signals based on optical pulse shaping using a spatial light modulator (SLM) was demonstrated[7]. The major difficulty of the SLM-based technique is that the pulse shaping is usually implemented in free space, making the system bulky and costly. On the other hand, the photonic generation of BPSK RF signals can also be implemented using pure fiber-optic components[8-11]. In the last few years, the generation of BASK RF signals based on pulse shaping using fiber-optic device has also been proposed[12]. However, few efforts have been dedicated to the generation of BFSK RF signals in the optical domain.

In this paper, a method to photonically generate BFSK RF signals based on optical pulse shaping is proposed. In the proposed system, an optical pulse train from a short pulse laser source (SPLS) is split into two branches by a fast electro-optic switch consisting of a polarization modulator (PolM) followed by a polarization beam splitter (PBS). In each branch of the system, the optical pulses are spectrally shaped by two different Mach-Zehnder fiber interferometers (MZIs), respectively. By properly designing the MZIs, BFSK RF signals with different modulation indices can be generated at the output of a high-speed photodetector (PD) thanks to the FTTM in a dispersive device. Theoretical models for describing the signal generation are developed, which are verified via

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simulations. It is the first time, to the best of our knowledge, that the photonic generation of BFSK RF signals in the optical domain is demonstrated.

The schematic diagram of the proposed system is shown in Fig.1. An optical pulse train from an SPLS is sent to a PolM which is connected to a PBS. The PolM is driven by a binary digital data signal. When the linearly polarized incident light is oriented with an angle of 45° to one principal axis of the PolM by the polarization controller (PC), the polarization state of the output lightwave can change between two orthogonal linear polarization states in accordance with the applied data signal. The PBS is connected to the output of the PolM with one of its principal axes oriented at an angle of 45° to that of the PolM. Therefore, when a linearly polarized optical pulse train is sent to the PolM with an angle of 45° to one principal axis of the PolM, the optical pulse train can be split into two branches at the two outputs of the PBS under the control of the binary data signal applied to the PolM. In each branch of the system, the optical pulses are spectrally shaped by different MZIs, respectively. The spectrum-shaped optical pulses from the two branches are then combined by optical coupler (OC) which is connected to a tunable optical filter (TOF), and sent to a dispersive device which is a section of single mode fiber (SMF) in the system, to perform linear FTTM. Finally, BFSK RF signals are generated after the PD detection.

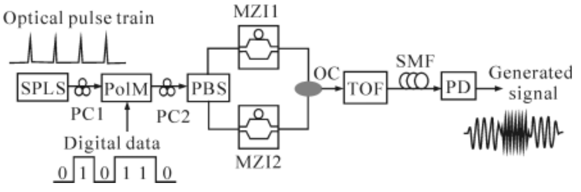


Fig.1 Schematic diagram of the proposed BFSK RF signal generation system

An MZI can be modeled as a two-tap delay-line filter with an impulse response given by

$$h_{\mathrm{M}}(t)=\frac{1}{2}[\delta(t)+\delta(t-\tau)] \ , \tag{1}$$

where τ is the time delay difference between its two arms. And its intensity response can be obtained using the Fourier transform, which can be written as

$$H_{\mathrm{M}}(f)=1+\cos(2\pi f\cdot\tau) \ . \tag{2}$$

The free spectral range (FSR) of the filter response, which is defined as the frequency separation between two adjacent fringes, can be expressed as $FSR_f=1/\tau$.

The TOF can be modeled as an m-order super-Gaussian filter with the full width at half maximum (FWHM) bandwidth of B_{W}, and its intensity response can be expressed as:

$$H_{\mathrm{T}}(f)=\exp[-(\ln 2)\cdot(\frac{2f}{B_{\mathrm{W}}})^{2m}] \ . \tag{3}$$

Therefore, in each branch of the system, the intensity transfer function of an MZI incorporated with a TOF can be expressed as:

$$H(f)=H_{\mathrm{M}}(f)\cdot H_{\mathrm{T}}(f) \ . \tag{4}$$

An optical pulse from the SPLS can be modeled as a transform-limited Gaussian pulse, which can be expressed as

$$x(t)=\exp(-t^2/t_0^2) \ , \tag{5}$$

where t_0 corresponds to the half pulse width at 1/e of the maximum. After propagating through the pulse shaper consisting of an MZI incorporated with a TOF, the output pulse $y(t)$ is given by calculating the convolution of $y(t)=x(t)*h(t)$, where * denotes convolution operation, and $h(t)$ is the inverse Fourier transform of $H(f)$ in Eq.(4). It is well-known that the output optical pulse can be also expressed as $Y(f)=X(f)\cdot H(f)$ in frequency domain. Therefore, the spectra of the input optical pulse from the SPLS are shaped by the pulse shaper.

After the pulse shaping, the spectrum-shaped optical pulse is sent to a section of SMF with the dispersion of Φ_v(ps^2). Then the output pulse from the SMF can be expressed as[5]

$$\begin{aligned}z(t)&=y(t)*\exp(\mathrm{j}t^2/2\Phi_v)=\\&\int_{-\infty}^{\infty}y(\tau)\cdot\exp[\mathrm{j}(t-\tau)^2/2\Phi_v]\mathrm{d}\tau=\\&\exp(\mathrm{j}t^2/2\Phi_v)\cdot\int_{-\infty}^{\infty}y(\tau)\cdot\exp(\mathrm{j}\tau^2/2\Phi_v)\cdot\\&\exp(-\mathrm{j}t\tau/\Phi_v)\mathrm{d}\tau\approx\\&\exp(\mathrm{j}t^2/2\Phi_v)\cdot\int_{-\infty}^{\infty}y(\tau)\cdot\exp(-\mathrm{j}t\tau/\Phi_v)\mathrm{d}\tau=\\&\exp(\mathrm{j}t^2/2\Phi_v)\cdot Y(f)|_{f=t/\Phi_v} \ .\end{aligned} \tag{6}$$

As can be seen from Eq.(6), after the FTTM in SMF, the envelope of the output signal is proportional to the shaped optical pulse spectrum. Note that Eq.(6) is obtained if the duration of the input ultrashort pulse Δt and the second order dispersion Φ_v can satisfy $|\Delta t/\Phi_v|<<1$, which means that the pulse duration before the SMF is much smaller than that after dispersion. This assumption is always true for picosecond optical pulses propagating in a few kilometers of SMF[13]. Therefore, after pulse shaping and the dispersion-induced FTTM, the optical short pulse is converted into time-domain RF pulse at the output of a PD, which can be expressed as

$$\begin{aligned}&s(t)\propto|z(t)|^2=\\&g(t)\cdot[1+\cos(\frac{2\pi\cdot\tau}{\Phi_v}\cdot t)]\cdot\exp[-(\ln 2)\cdot(\frac{2t}{B_{\mathrm{W}}\cdot\Phi_v})^{2m}] \ ,\end{aligned} \tag{7}$$

where $g(t)$ is the envelope of the input optical pulse $x(t)$ after passing through the SMF, which maintains the Gaussian shape. As can be clearly seen from Eq.(7), after pulse shaping and FTTM, an optical pulse is converted to super-Gaussian RF pulses with a sinusoidal carrier. And the center frequency of the generated microwave signal can be expressed as

$$f=\frac{\tau}{\Phi_v}=\frac{1}{FSR_f\cdot\Phi_v}\ . \tag{8}$$

Therefore, if two MZIs with different time delay differences of τ_0 and τ_1 are used in each branch of the system, respectively, RF signals with different center frequencies of f_0 and f_1 can be generated. And by properly designing the MZIs, BFSK RF signals with different modulation indices can be generated.

Additionally, based on the mapping relationship of the FTTM, the time-domain duration ΔT of each RF pulse can be calculated by

$$\Delta T=B_{\mathrm{W}}\cdot\Phi_v\ . \tag{9}$$

If ΔT is adjusted properly to match the bit period of the generated BFSK RF signals, the generated BFSK RF signals can have a duty cycle of 100%.

Fig.2 presents the simulation model of the proposed BFSK RF signal generation system using a commercial software package of virtual photonic incorporation (VPI) transmission maker. The SPLS generates transform-limited Gaussian optical pulse with the FMHM of 1 ps, the central wavelength of 1550 nm and the repetition rate of 4 GHz. The center wavelength of the TOF is adjusted to 1550 nm, and the bandwidth B_{W} is set as 300 GHz, which corresponds to the bandwidth of 2.4 nm described in wavelength. The time delay differences τ_0 and τ_1 of the two MZIs are set as 40 ps and 25 ps, respectively. The SMF has a standard dispersion coefficient of 16 ps/(nm·km), and its length is set as 6.5 km. The bit rate of the digital data applied to the PolM is set as 4 Gbit/s, which is synchronized with the optical pulse train from the SPLS.

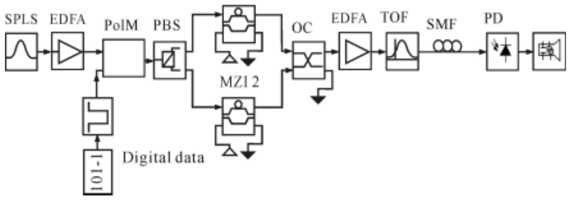
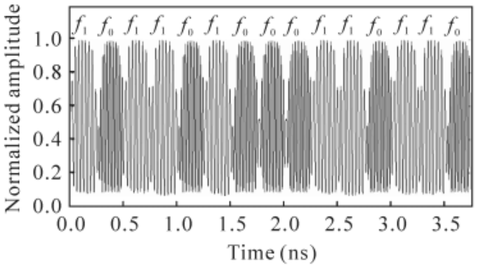


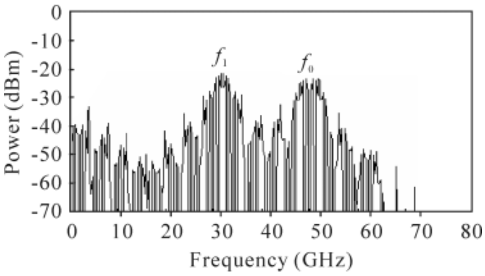
Fig.2 Simulation model for the proposed system

In the simulation, 15-bit pseudo-random binary sequence (PRBS) code is used for demonstrating the generation of BFSK RF signals. The generated signals and their power spectra are shown in Fig.3.

As seen from Fig.3(a), the BFSK RF signals are successfully generated. And the mark and space frequencies of f_1 and f_0 are estimated to be around 30 GHz and 48 GHz, respectively, which verifies the theoretical analysis based on Eq. (8). The modulation index of the generated BFSK RF signals, which is defined as the difference between f_0 and f_1 divided by the signal bit rate, is calculated as m = 4.5. According to Eq.(8), if the dispersion is fixed, the mark and space frequencies of the generated BFSK signals can be varied by changing τ_0 and τ_1 of the two MZIs. Therefore, BFSK RF signals with different modulation indices can be obtained by properly designing the MZIs in the system.



(a) Signal waveform

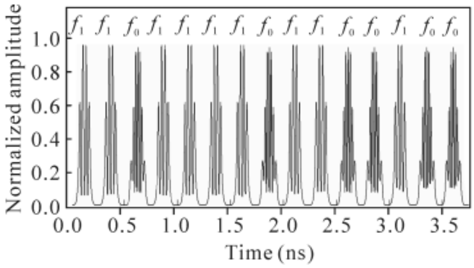


(b) Power spectrum

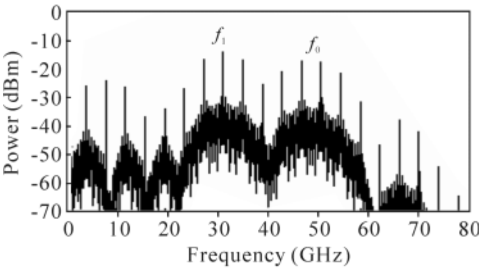
Fig.3 Simulation results of the generated BFSK RF signals

In the proposed system, each input optical pulse is converted into an RF pulse with a time-domain duration of ΔT determined by Eq.(9). When ΔT equals the bit period (namely the reciprocal bit rate), the generated BFSK signals have a duty cycle of 100%, which is consistent with the simulation results shown in Fig.3. If ΔT is smaller than the bit period, BFSK RF signals with different duty cycles can be generated. According to Eq.(9), if the dispersion is fixed, ΔT can be reduced by tuning the bandwidth of the TOF. Fig.4 shows the simulation results when the bandwidth of the TOF is reduced by half, while keeping all the other parameters unchanged.

As seen from Fig.4(a), the generated BFSK RF signals have a duty cycle of 50%, which verifies the theoretical prediction based on Eq.(8). Fig.4(b) shows the power spectrum of the generated signals. As can be seen, the center frequencies of f_0 and f_1 remain the same with those in Fig.3(b). However, the power spectrum is broadened with spectrum spikes on the top. It can be explained by the spectral characteristics of the return-to-zero (RZ) codes.



(a) Signal waveform



(b) Power spectrum

Fig.4 Generated BFSK RF signals with duty cycle of 50%

In the proposed system, the generated RF signals are encoded under the control of the digital data sequence. It can be seen from the simulations that the bit rate of the system is determined by the repetition rate of the SPLS. By adjusting the repetition rate of the SPLS and the bit rate of the digital data signal, the bit rate of the generated BFSK RF signals can be adjusted. However, it should be noted that ΔT should always be kept smaller than the bit period of the generated BFSK signals to avoid inter symbol interference (ISI).

A novel approach to photonically generate BFSK RF signals based on optical pulse shaping and FTTM is proposed and demonstrated via simulations. In the proposed system, microwave signals in millimetre regime are generated in the optical domain without microwave sources. Therefore, the proposed approach can break the electronic bottleneck and take the advantages such as small size, low loss and immunity to magnetic interference. Additionally, the proposed method offers some flexibility, as the modulation index, duty cycle and bit rate of the generated BFSK RF signals can be easily tuned to suit specific application. The proposed method provides a simple and effective solution for the generation of high frequency BFSK RF signals, which could find applications in future wireless communications systems. An experimental study will be implemented to further investigate the proposed method. Since the PolM is an integrated waveguide device, the stable operation of the electro-optic switch in the proposed system can be guaranteed.

References

[1] John Proakis, Digital Communications, Principles of Optics, 4th Edition, New York: McGraw-Hill Press, 2003.

[2] HONG Lei, SU Jue, YANG Li and QIAN Jing-ren, Journal of Optoelectronics • Laser **22**, 64 (2011). (in Chinese)

[3] SUN Guo-dan, WANG Rong, PU Tao and ZHAO Zhi-shuang, Journal of Optoelectronics • Laser **22**, 1633 (2011). (in Chinese)

[4] A. J. Beasley, R. Murowinski and M. Tarenghi, Astrophysics and Space Science **1**, 313 (2008).

[5] J. P. Yao, Optics Communication **284**, 3723 (2011).

[6] J. D. McKinney, D. E. Leaird and A. M. Weiner, Optics Letters **27**, 1345 (2002).

[7] J. Chou, Y. Han and B. Jalali, Photonic Technology Letters **15**, 581 (2003).

[8] C. Wang and J. P. Yao, Journal of Lightwave Technology **28**, 1652 (2010).

[9] H. Chi and J. P. Yao, Photonic Technology Letters **19**, 768 (2007).

[10] C. Wang and J. P. Yao, Microwave and Millimeter-Wave Arbitrary Waveform Generation and Processing Using Fiber-Optics-Based Techniques, 2nd IEEE International Conference on Broadband Network & Multimedia Technology, 909 (2009).

[11] C. Wang and J. P. Yao, Journal of Lightwave Technology **28**, 1652 (2010).

[12] H. Chi, F. Zeng and J. P. Yao, Photonic Technology Letters **19**, 668 (2007).

[13] H. Chi and J. P. Yao, Microwave and Wireless Components Letters **18**, 371 (2008).

[14] Z. Li, W. Li, H. Chi, X. Zhang and J. P. Yao, Photonic Technology Letters **23**, 712 (2011).