

Photonic generation of phase-coded microwave signals based on optical pulse shaping and time delay

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A novel approach to photonic generation of phase-coded microwave signals based on optical pulse shaping and time delay is proposed. In the proposed approach, an optical short pulse train is inserted with a specified amount of time-delay to certain pulses, and then converted into super-Gaussian microwave pulses based on the optical pulse shaping technique. By properly adjusting the time-delay, phased-coded microwave signals with a desired code pattern can be generated. A model to describe the signal generation is developed, and the generations of phase-coded microwave signals with frequencies up to 50 GHz are demonstrated.

Keywords: microwave photonics, microwave signal generation, pulse shaping.

1. Introduction

Pulse compression based on matched filtering using frequency-chirped or phase-coded microwave signals has been widely used in modern radar systems to improve the range resolution [1]. Chirped or phase-coded microwave signals can be generated using photonic techniques to take the advantage of broad bandwidth, low loss and immunity to electromagnetic interference offered by modern optics. Various techniques have been proposed to generate frequency-chirped or phase-coded signals using photonic methods [2–13]. Frequency-chirped or phase-coded microwave signals can be generated using spatial light modulator (SLM)-based pulse shaping techniques [2, 3]. An SLM can be updated in real time, making the system reconfigurable. However, since an SLM-based system involves the use of free-space optics, the system is usually bulky and complicated. On the other hand, frequency-chirped or phase-coded microwave signals can also be generated using fiber-optics components. In [4], a frequency-chirped microwave pulse is generated by beating two chromatically dispersed optical

pulses obtained by passing a broadband ultrashort pulse through two chirped fiber Bragg gratings (CFBGs) with different chirp rates in a Mach–Zehnder interferometer geometry. In [5–10], optical pulse shaping followed by frequency-to-time mapping (FTTM) using fiber-optics components has been demonstrated, which features much smaller size, lower loss, better stability and higher potential for integration. The generation of phase-coded microwave signals using a specially designed CFBG was suggested in [6]. However an additional fiber shift function is required to implement the phase modulation of the generated microwave signals. Recently, phase-coded microwave signal generation using an optical phase modulator (PM) or polarization modulator (PolM) has been demonstrated [11–13]. Using these techniques, phase-coded microwave signals with a required code pattern can be generated. However, a microwave signal source is required in [12] and [13], which may cause great inconvenience to the signal generation at high center frequency due to the electronic bottleneck. And the stability in [11] was poor due to its sensitivity to environmental variations.

In this paper, a novel approach to realizing phase-coded microwave signal generation based on optical pulse shaping and time delay is proposed. In the proposed approach, an optical pulse train from a short pulse laser source (SPLS) is inserted with a specified amount of time-delay to certain pulses using a tunable optical delay line (TODL), and then those optical pulses are converted into super-Gaussian microwave pulses based on the optical pulse shaping technique. By properly adjusting the time delay, phased-coded microwave signals with desired code pattern can be generated due to a time-delay-induced phase shift. The main advantage of the proposed method is that the microwave signal is generated in the optical domain, therefore, a high frequency microwave signal can be generated without the need of microwave sources. Besides, the phase coding of the generated microwave signal is implemented using a polarization modulator, which is an integrated waveguide device and stable operation can be ensured [12], and no additional fiber shift function is needed. A theoretical mode describing the proposed approach is presented, and the generation of phase-coded microwave signals with a required code pattern with central frequencies up to 50 GHz is demonstrated via simulations.

2. Principle and theoretical analysis

The schematic diagram of the proposed system is shown in Fig. 1. An optical pulse train from a short pulse laser source (SPLS) is sent to a polarization modulator (PolM) that is connected to a polarization beam splitter (PBS). The PolM is driven by a binary digital data signal. When a linearly polarized incident light is oriented with an angle of 45° to one principal axis of the PolM, the polarization state of the output light wave will 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

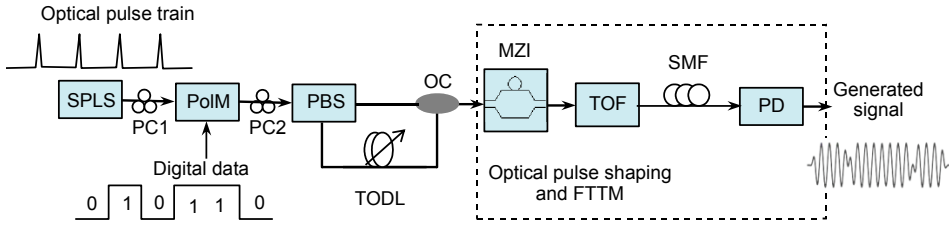


Fig. 1. Schematic diagram of the proposed phase-coded microwave signal generation system. SPLS – short pulse laser source, PolM – polarization modulator, PBS – polarization beam splitter, PC – polarization controller, OC – optical coupler, MZI – Mach-Zehnder interferometer, TOF – tunable optical filter, SMF – single mode fiber, PD – photodetector.

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 will be split into two branches and switched to the two outputs of the PBS according to the binary data signal applied to the PolM. The two outputs of the PBS are combined by an optical coupler (OC) with one output delayed by a TODL. Therefore, certain optical pulses in the optical pulse train will pass through the TODL under the control of the binary data signal. By adjusting the TODL, a proper amount of time delay will be inserted to the optical pulse train. Then the optical pulse train is sent to an optical pulse shaping module consisting of a Mach-Zehnder fiber interferometer (MZI), a tunable optical filter (TOF) to perform pulse shaping. Microwave pulses with the shape identical to the shaped spectrum can be obtained at the output of a photodiode (PD) after the FTTM in a length of a single mode fiber (SMF). And the desired phase coding is realized due to the time-delay-induced phase shift.

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

$$h_M(t) = \frac{1}{2} [\delta(t) + \delta(t - \tau)] \tag{1}$$

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

$$H_M(f) = 1 + \cos(f\tau) \tag{2}$$

The free spectral range (FSR) of the filter response, 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 a full-width at half-maxim (FWHM) bandwidth of B_W , and its intensity response can be expressed as

$$H_T(f) = \exp \left\{ -\ln(2) \left(\frac{2f}{B_W} \right)^{2m} \right\} \tag{3}$$

Therefore, the intensity transfer function of the pulse shaping module, consisted of an MZI incorporated with a TOF, can be expressed as:

$$H(f) = H_M(f) H_T(f) \quad (4)$$

It is known that the mapping relationship of the FTTM in a length of SMF is given by $f = t/\Phi_v$, where Φ_v (ps²) is the first-order dispersion of the SMF [9], which can also be described as Φ_λ (ps/nm), where $\Phi_\lambda = (c/\lambda^2)\Phi_v$ and c is the speed of light. If an optical short pulse is spectrally shaped by the pulse shaping module with an intensity response described in (4), then after the dispersion-induced linear FTTM in the SMF, the temporal pulse would have an envelope that is a scaled version of the spectrum profile of the spectrum-shaped pulse. For simplicity, the input optical short pulse is assumed to be a Dirac delta function $\delta(t)$, then after pulse shaping and FTTM, the optical short pulse is converted into a time-domain microwave pulse at the output of a PD, which can be expressed as

$$s(t) \propto H(f)|_{f=t/\Phi_v} = \left[1 + \cos\left(\frac{\tau}{\Phi_v}t\right) \right] \exp\left\{-\ln(2)\left(\frac{2t}{B_W\Phi_v}\right)^{2m}\right\} \quad (5)$$

Considering that the input optical short pulse actually has a nonzero width, the generated microwave pulse envelope should be modified by an envelope $g(t)$

$$s(t) \propto g(t) \left[1 + \cos\left(\frac{\tau}{\Phi_v}t\right) \right] \exp\left\{-\ln(2)\left(\frac{2t}{B_W\Phi_v}\right)^{2m}\right\} \quad (6)$$

where $g(t)$ is the pulse envelope after the input pulse passing through the SMF. Assuming the input optical pulse has a Gaussian envelope as $p(t) \propto \exp(-t^2/t_0^2)$, where t_0 is the half pulsewidth at $1/e$ maximum, then, the envelope of the output pulse from a length of SMF will maintain the Gaussian shape but with a broadened pulsewidth of $|\Phi_v/t_0|$. Actually, the envelope $g(t)$ is a scaled version of the spectrum envelope of the input pulse, which is mapped to the time-domain, thanks to the dispersion-induced FTTM in the SMF. As can be clearly seen from Eq. (6), after pulse shaping and FTTM, an optical pulse is converted to super-Gaussian microwave pulses with a sinusoidal carrier. The time-domain pulse duration of the generated microwave pulse is calculated by $\Delta T = B_W\Phi_v = B_W(\lambda^2/c)\Phi_\lambda$. And the center frequency of the generated microwave signals can be expressed as

$$f = \frac{\tau}{2\pi\Phi_v} = \frac{1}{2\pi\text{FSR}_f\Phi_v} \quad (7)$$

The period of the microwave carrier is calculated by $T = 2\pi\text{FSR}_f\Phi_v = 2\pi\text{FSR}_f(\lambda^2/c)\Phi_\lambda$. When we adjust ΔT to be the repetition period of the optical pulse sequence from the SPLS, the converted microwave pulses can form a quasi-continuous microwave signal. And if the time delay T_D between two consecutive microwave pulses

is $T/2$, a π phase shift can be introduced to the generated microwave signal due to the time-delay-induced phase shift [14]. Therefore, by properly adjusting the time delay induced by the TODL, a desired phase coding can be implemented.

3. Simulation model and results

Figure 2 presents the simulation model of the proposed phase-coded microwave signal generation system using a commercial software package Virtual Photonic Incorporation (VPI) Transmission maker. The SPLS generates transform-limited Gaussian pulse with an FWHM pulsewidth of 550 fs, a central wavelength of 1550 nm, and a repetition rate of 4 GHz, which corresponds to a repetition period of 0.25 ns. The center wavelength of the TOF is adjusted to 1550 nm, and the bandwidth is set as 300 GHz, which corresponds to a bandwidth of 2.4 nm described in wavelength. The FSR of the MZI is set as 50 GHz, which corresponds to $\tau = 20$ ps. The SMF has a standard dispersion coefficient of 16 ps/nm/km, and its length is set as 6.5 km. After FTTM, the time-domain duration of the generated microwave pulse is calculated to be $\Delta T = 0.25$ ns, and the period of its microwave carrier is calculated to be $T = 41.6$ ps. The TODL is set to induce a time delay of $T_D = 20.8$ ps. The bit rate of the digital data applied to the PolM is set as 4 Gbps which is synchronized with the optical pulse train from the SPLS.

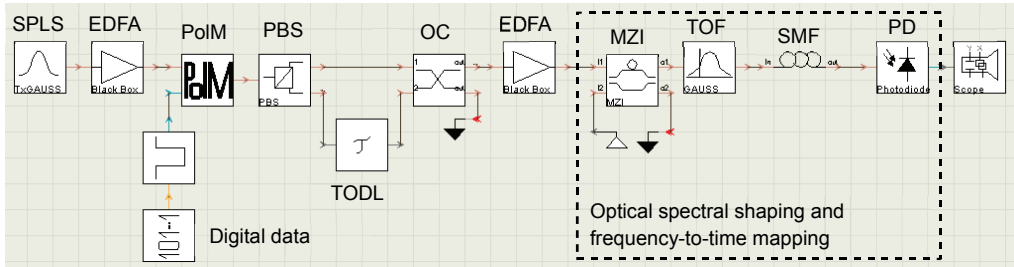


Fig. 2. Simulation model for the proposed system.

In the simulation, three code patterns are used to demonstrate the generation of phase-code microwave signals: Code 1 = $\{0, 0, 0, 0, 0, 0, 0\}$, Code 2 = $\{0, \pi, 0, \pi, 0, \pi, 0\}$, Code 3 = $\{\pi, \pi, \pi, 0, \pi, 0, 0\}$, where Code 1 corresponds to the generation of microwave signals without phase coding, Code 2 is an alternating sequence, and Code 3 is an M -sequence of 7 bits. The generated microwave signals are shown in Figs. 3a–3c, respectively.

As can be seen from Fig. 3a, without phase-coding, a quasi-continuous microwave signal is generated. The central frequency of the signal is estimated to be around 25 GHz, which verifies the theoretical analysis. As can be seen from Figs. 3b and 3c, the phase-coded microwave signals with desired code patterns are successfully generated. The phase coding is realized by time-delay, which is introduced to the input

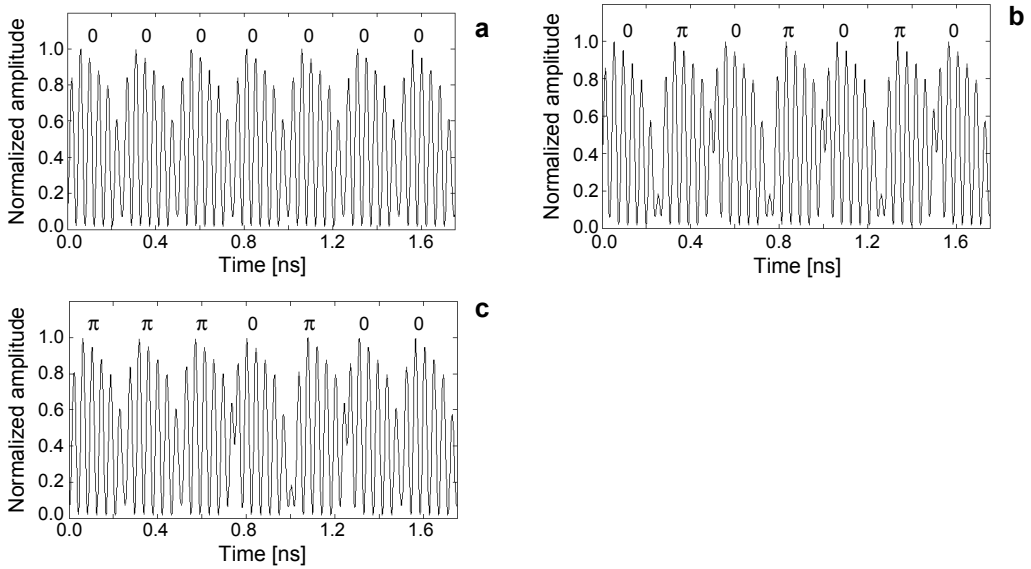


Fig. 3. Simulation results. The generated phase-coded microwave signals using Code 1 (a), Code 2 (b), and Code 3 (c).

optical short pulse sequence by the TODL in collaboration with PolM and PBS, under the control of the digital data applied to the PolM.

Phase-coded microwave signals can find applications in pulse compression radar or code-division multiple access (CDMA) systems, where the code identification is usually performed based on matched filtering at the radar or CDMA receiver. Mathematically, the operation of matched filtering is equivalent to an autocorrelation. Figures 4a and 4b show the autocorrelation waveforms of the generated phase-coded microwave signals using Code 2 and Code 3, respectively. As can be seen from Figs. 4a and 4b, the microwave signals are significantly compressed, with a peak at the center of their autocorrelation waveforms. However, the autocorrelation waveform in Fig. 4b shows a better suppression of the sidelobes, which can be explained by the better

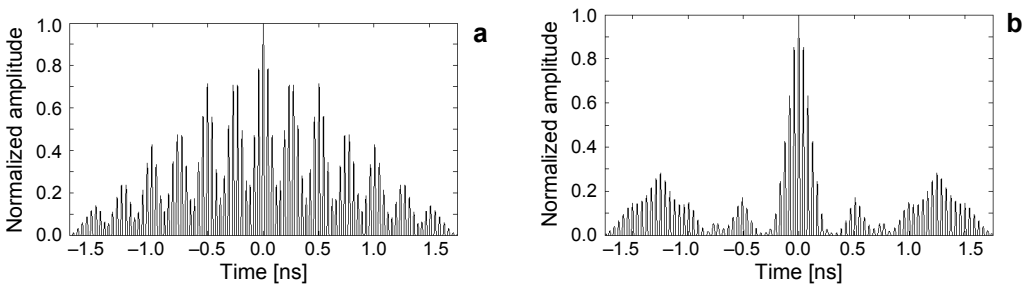


Fig. 4. The autocorrelation waveforms of the generated phase-coded microwave signals with Code 2 (a) and with Code 3 (b).

autocorrelation function of M -sequence in terms of maximum nontrivial correlation magnitude. The FWHM of the autocorrelation waveform shown in Fig. 4b is 0.17 ns, and the total time-domain duration of the generated microwave signal shown in Fig. 3c is 1.73 ns, therefore the signal compression ratio of the phase-coded microwave signal is estimated to be 10.2.

The compression ratio can be improved by using M -sequence code of more bits. For example, phase-coded microwave signal generation using 15-bit M -sequence code $\{\pi, \pi, \pi, \pi, 0, \pi, 0, \pi, \pi, 0, 0, \pi, 0, 0, 0\}$ is also performed in the simulation. Simulation results show that the total time-domain duration of the generated microwave signals increases to about 3.75 ns, and the FWHM of the corresponding autocorrelation waveform is around 0.17 ns, therefore the compression ratio increases to 21.9. On the other hand, the frequency of the generated microwave signal is dependent on the FSR and the total dispersion of the SMF, as predicted by Eq. (7). Therefore the center frequency of the generated phase-coded microwave signals can be tuned by adjusting the time delay difference τ between the two arms of the MZI. For example, the FSR of the MZI is reduced to 25 GHz, while keeping the SMF length unchanged. And the carrier period of the generated microwave signal is calculated to be 20.8 ps. Therefore, in order to realize a π phase-shift in the generated microwave signal, the TODL is set to induce a time delay of $T_D = 10.4$ ps. The microwave signal is generated using the code pattern of Code 3, as shown in Fig. 5a. As can be seen,

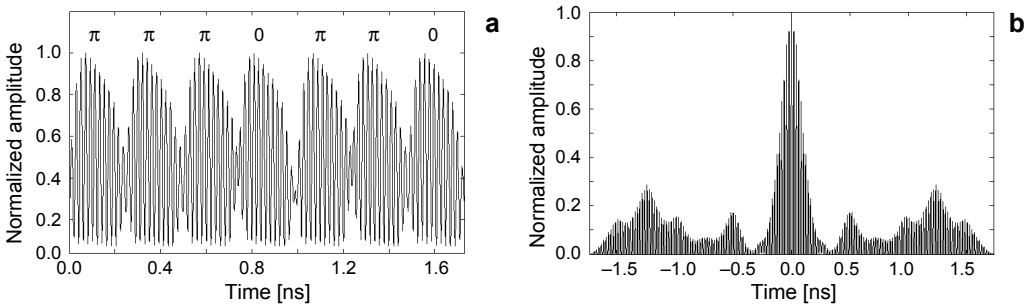


Fig. 5. Simulation results of the generated 50 GHz phase-coded microwave signal: time-domain waveform (a) and its autocorrelation waveform (b).

the central frequency of the generated microwave signal is estimated to be around 50 GHz. Figure 5b shows the autocorrelation waveform of the generated phase-coded microwave signal. The total time-domain duration of the generated microwave signal is about 1.75 ns, while the FWHM of its autocorrelation waveform is 0.164 ns, which leads to the signal compression ratio of 10.67. The signal compression ratio is slightly improved because more cycles within the pulse envelope are generated.

Additionally, the bit rate of the phase-coded signal generation system can be tuned by using SPLS with a tunable repetition rate. At the same, ΔT may also need to be adjusted with the increase of the bit rate because ΔT should always be kept smaller than the bit period (of the generated phase-coded namely the reciprocal of the bit rate)

signals to avoid inter-symbol-interference (ISI). An experimental study is needed to further investigate the proposed method, which will be the focus of our future work when the tunable mode locked pulsed laser is available to us.

4. Conclusions

A novel approach to photonic generation of phase-coded microwave signals based on optical pulse shaping and time delay was proposed and demonstrated via simulations. In the proposed system, an optical short pulse train is converted into microwave signals based on optical pulse shaping technique using a MZI and a TOF, and followed by FTTM in a length of SMF. Phase-coding is realized by introduced time delay using a TODL in cooperation with a PolM and a PBS. By properly adjusting the time delay, binary phase-coded signals were generated with a required code pattern. The phase-coded microwave signals can find application in modern radar systems to increase the range resolutions, and it can also find application in CDMA systems to support multi-user communications.

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References

- [1] RIHACZEK A.W., *Principles of High-Resolution Radar*, Artech House, Norwood, MA, 1996.
- [2] MCKINNEY J.D., LEAIRD D.E., WEINER A.M., *Millimeter-wave arbitrary waveform generation with a direct space-to-time pulse shaper*, *Optics Letters* **27**(15), 2002, pp. 1345–1347.
- [3] CHOU J., HAN Y., JALALI B., *Adaptive RF-photonic arbitrary waveform generator*, *IEEE Photonics Technology Letters* **15**(4), 2003, pp. 581–583.
- [4] ZEITOUNY A., STEPANOV S., LEVINSON O., HOROWITZ M., *Optical generation of linearly chirped microwave pulses using fiber Bragg gratings*, *IEEE Photonics Technology Letters* **17**(3), 2005, pp. 660–662.
- [5] HAO CHI, JIANPING YAO, *All-fiber chirped microwave pulse generation based on spectral shaping and wavelength-to-time conversion*, *IEEE Transactions on Microwave Theory and Techniques* **55**(9), 2007, pp. 1958–1963.
- [6] CHAO WANG; JIANPING YAO, *Photonic generation of chirped millimeter-wave pulses based on nonlinear frequency-to-time mapping in a nonlinearly chirped fiber Bragg grating*, *IEEE Transactions on Microwave Theory and Techniques* **56**(2), 2008, pp. 542–553.
- [7] HAO CHI, JIANPING YAO, *Chirped RF pulse generation based on optical spectral shaping and wavelength-to-time mapping using a nonlinearly chirped fiber Bragg grating*, *Journal of Lightwave Technology* **26**(10), 2008, pp. 1282–1287.
- [8] CHAO WANG, JIANPING YAO, *Photonic generation of chirped microwave pulses using superimposed chirped fiber Bragg gratings*, *IEEE Photonics Technology Letters* **20**(11), 2008, pp. 882–884.
- [9] CHAO WANG, JIANPING YAO, *Chirped microwave pulse generation based on optical spectral shaping and wavelength-to-time mapping using a Sagnac loop mirror incorporating a chirped fiber Bragg grating*, *Journal of Lightwave Technology* **27**(16), 2009, pp. 3336–3341.
- [10] CHAO WANG, JIANPING YAO, *Large time-bandwidth product microwave arbitrary waveform generation using a spatially discrete chirped fiber Bragg grating*, *Journal of Lightwave Technology* **28**(11), 2010, pp. 1652–1660.

- [11] HAO CHI, JIANPING YAO, *An approach to photonic generation of high-frequency phase-coded RF pulses*, IEEE Photonics Technology Letters **19**(10), 2007, pp. 768–770.
- [12] HAO CHI, JIANPING YAO, *Photonic generation of phase-coded millimeter-wave signal using a polarization modulator*, Microwave and Wireless Components Letters **18**(5), 2008, pp. 371–373.
- [13] ZE LI, WANGZHE LI, HAO CHI, XIANMIN ZHANG, JIANPING YAO, *Photonic generation of phase-coded microwave signal with large frequency tunability*, IEEE Photonics Technology Letters **23**(11), 2011, pp. 712–714.
- [14] YITANG DAI, JIANPING YAO, *Microwave pulse phase encoding using a photonic microwave delay-line filter*, Optics Letters **32**(24), 2007, pp. 3486–3488.

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