Arbitrary Phase-Modulated RF Signal Generation Based on Optical Pulse Position Modulation

Yitang Dai and Jianping Yao, *Senior Member, IEEE, Member, OSA*

***Abstract*—In this paper, the generation of an arbitrary band-limited phase-modulated RF signal from a pulse-position-modulated (PPM) optical pulse train is investigated. We show that a specifically designed PPM pulse train would have a multichannel spectral response, with one channel having the spectrum corresponding to a phase-modulated RF signal. By using a microwave bandpass filter to select the channel of interest, a phase-modulated RF signal is obtained. The relationship between the pulse position modulation and the phase modulation is derived and analyzed. Two design examples are presented, with one for the generation of a chirped RF signal, and the other for the generation of a binary phase-coded RF signal. The chirped pulse has a central frequency of 50 GHz and a 3-dB bandwidth of 12.5 GHz. The binary phase-coded RF pulse has 15 chips with a central frequency of 5.34 GHz. The proposed approach provides a simple and effective solution for the generation of high-speed arbitrary phase-modulated RF waveforms for applications in modern radar, communications, and imaging systems.**

***Index Terms*—Microwave photonics, phase modulation, pulse position modulation (PPM).**

I. Introduction

MICROWAVE and millimeter-wave waveforms with arbitrary pulse shape could find many important applications in civil and defense systems. For example, in a modern radar system, to increase the radar range resolution, the generated electrical pulses should have a large time-bandwidth product (TBWP), which can be realized through frequency chirping or phase coding [1]. Due to the limited sampling speed of the state-of-the-art digital electronics, the speed of currently available electronic arbitrary waveform generation (AWG) systems is limited to 10 Gb/s [2]. To generate ultrafast arbitrary waveforms, great efforts have been directed to the arbitrary waveform generation in the optical domain based on the optical pulse shaping. In a Fourier-domain-based system, the spectrum of the input pulse is usually altered using a spatial light modulator (SLM) [3]–[5]. The major advantage of using an SLM for ultrashort pulse shaping is that an SLM can be updated in real time, which provides a high flexibility and reconfigurability. Optical arbitrary pulse shaping can also be implemented in the time domain based on temporal pulse shaping (TPS). A TPS system usually consists of two conjugate dispersive elements and an optical modulator that is placed between the two dispersive elements [6]–[9]. In the system, an ultrashort optical pulse is temporally stretched and spectrally dispersed by passing through the first dispersive element, and then the dispersed pulse is spectrum shaped by modulating its spectrum with a RF signal at the optical modulator; the temporal compression is realized by passing the spectrum-shaped pulse through the second dispersive element. At the output of the system, a waveform that is the Fourier transform of the RF signal is obtained. The two approaches are both based on the manipulation of the spectrum of the input ultrashort pulse, which have been well studied both theoretically and experimentally [3]. Another approach for arbitrary waveform generation is based on wavelength-to-time mapping [10]–[14]. In such a system, the spectrum of a super-continuum optical source is shaped by an optical filter; at the output of the system, an electrical pulse that has a shape that is a scaled version of the spectrum would be generated thanks to the wavelength-to-time mapping. The theory for wavelength-to-time mapping has also been well developed [13].

Arbitrary waveform generation can also be realized based on direct space-to-time (DST) mapping [15]–[19], in which an arbitrary optical pulse sequence is used to drive a high-speed optical-to-electrical converter to generate microwave waveforms. By this technique, reprogrammable cycle-by-cycle synthesis of an arbitrarily shaped phase- and frequency-modulated waveform has been demonstrated experimentally. In the system, a bandwidth-limited optical-to-electrical conversion system is usually used to convert an optical pulse train into a smooth microwave or millimeter-wave sinusoid.

In this paper, we propose and demonstrate that an arbitrary band-limited phase-modulated RF signal can be generated from a pulse-position-modulated (PPM) optical pulse train with the help of a microwave bandpass filter. In theory, a specifically designed PPM pulse train would have a multichannel spectral response, with one channel having a spectrum corresponding to the desired phase modulated RF signal. By using a microwave bandpass filter to select the channel of interest, a phase-modulated RF signal would be generated. It is demonstrated, based on the developed theory, within the channel of interest, the PPM pulse train has the same spectrum as the desired phase-modulated RF signal. The relationship between the pulse position modulation and the desired phase modulation is developed, which is verified by numerical simulations and experiments. To the best of our knowledge, this is the first time a technique is proposed to implement arbitrary phase-modulated RF signal generation based on pulse position modulation and pulse

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The authors are with the Microwave Photonics Research Laboratory, School of Information Technology and Engineering, University of Ottawa, Ottawa, ON, K1N 6N5, Canada (e-mail: jpyao@site.uOttawa.ca).

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position modulation to phase modulation conversion using a microwave bandpass filter. Two design examples are presented. In the first example, a chirped RF pulse is generated from a PPM pulse train which is designed based on the developed theory. A comparison of generated chirped RF signal with a theoretical chirped signal in both the time and the frequency domains is made, and excellent agreement is reached. Then, as a practical example, we experimentally generate a binary phase-coded RF signal with a PPM pulse train designed again based on the developed theory. The selection of the channel of interest is performed using a photonic microwave bandpass filter implemented based on a polarization modulator (PolM). A 15-chip binary phase-coded RF signal with a central frequency 5.34 GHz is generated.

The paper is organized as follows. In Section II, the theory that describes the conversion of a PPM pulse train to a phase-modulated RF signal is analyzed. The mathematical derivation begins with a uniformly spaced pulse train which has a spectrum with multichannel responses. We show that by modulating the pulse train with pulse position modulation, a multichannel spectral response with one channel having a spectrum corresponding to the desired phase-modulated RF signal can be obtained. By using a microwave bandpass filter to select the channel of interest, a phase-modulated RF signal is generated. In Section III, the generation of a chirped RF signal based on a specially designed PPM pulse train is studied. A chirped RF pulse with a central frequency of 50 GHz and 3-dB bandwidth of 12.5 GHz is obtained. The results are compared with a theoretical chirped RF signal in both the time and the frequency domains, excellent agreement is reached. Some issues related to the chirped RF signal generation are also discussed in this section. In Section IV, an experiment is performed to generate a binary phase-coded RF signal from a PPM pulse train. A 15-chip binary phase-coded signal with a central frequency at 5.34 GHz is experimentally generated. Finally, a conclusion is drawn in Section V.

II. Principle

The technique to use a short pulse to generate a PPM pulse train and the use of the PPM pulse train to generate a phase-modulated RF signal is illustrated in Fig. 1. As can be seen a short pulse is sent to N time-delay modules with different time delays to generate a PPM pulse train with N chips. By properly designing the pulse position modulation of the pulse train, a multichannel spectral response with one channel having a spectrum corresponding to the desired phase modulated RF signal is obtained. By using a microwave bandpass filter with its passband located at the spectral channel of interest, a phase-modulated RF signal is thus generated.

In the following, we will provide a detailed theoretical analysis on the generation of a phase-modulated RF signal from a PPM pulse train through microwave bandpass filtering. The theory starts with a uniformly spaced pulse train, in which the kth pulse has a time delay of $\tau_k = kT$, where T is the time delay difference between two adjacent pulses.

Since the phase of the optical pulse train is not involved in the conversion process, in the theoretical treatment we are only concerned with the intensity of the pulse train. Mathematically, a uniformly spaced pulse train, $p_T(t)$, can be expressed as

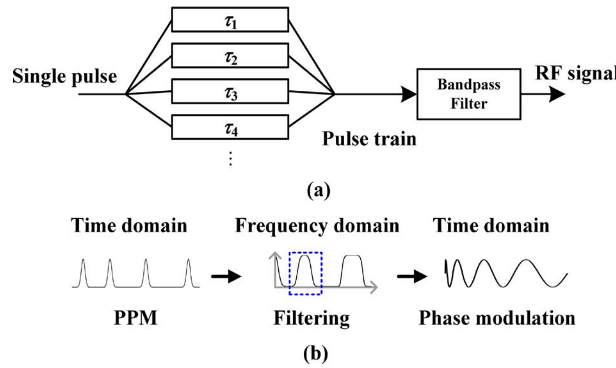

Fig. 1. Generation of a phase-modulated RF signal from a PPM pulse train. (a) Short pulse is time delayed by N time-delay modules to generate a PPM pulse train with N chips. (b) Phase-modulated RF signal is obtained by selecting the spectral channel of interest using a microwave bandpass filter.

$$p_T(t) = \sum_{k=1}^{N} \alpha_k q(t - kT) \tag{1}$$

where $q(t)$ is a single short pulse, α_k is the coefficient weighted on the kth pulse, and N is the number of the pulses in the pulse train. The pulse train can be expressed in another form

$$\begin{aligned} p_T(t) &= q(t) * \sum_{k=1}^{N} \alpha_k \delta(t - kT) \\ &= q(t) * [a(t) \times s(t)] \end{aligned} \tag{2}$$

where $a(t)$ is the weight profile which is given as $a(kT) = \alpha_k$ for $1 \le k \le N$, otherwise $a(t) = 0$; $s(t)$ is an unit impulse train given by $s(t) = \sum_k \delta(t - kT)$, and $*$ denotes convolution operation.

The spectrum of the pulse train, $P_T(\omega)$, can be calculated by the Fourier transform

$$\begin{aligned} P_T(\omega) &= Q(\omega) \times \left[\frac{1}{2\pi} A(\omega) * \sum_m \Omega \delta(\omega - m\Omega)\right] \\ &= \sum_m \frac{1}{T} Q(\omega) A(\omega - m\Omega) \end{aligned} \tag{3}$$

where $\Omega = 2\pi/T$, $Q(\omega)$ is the spectrum of the short pulse $q(t)$, and $A(\omega)$ is the Fourier transform of $a(t)$. It is clearly seen that the pulse train has a multichannel spectral response, with all channels having the same spectral profile $A(\omega)$ and the mth channel being located at $m\Omega$. Note that the multichannel spectral response is modulated by a spectral profile given by $Q(\omega)$.

If a microwave bandpass filter with its bandpass located at $\omega = m\Omega$ is used in the system, the spectrum of the mth channel of the pulse train is selected. Note that since the pulse $q(t)$ is usually ultrashort, its spectrum $Q(\omega)$ changes much slower compared with $A(\omega - m\Omega)$ within the bandwidth at Ω. Therefore, the change of $Q(\omega)$ within the mth channel could be ignored, and $Q(\omega)$ can be approximated as $Q(m\Omega)$. As a result, the signal at the output of the microwave bandpass filter is given by

$$P(\omega) \approx \frac{1}{T} Q(m\Omega) A(\omega - m\Omega) \tag{4}$$

where the responsibility of the photodetector (PD) is assumed to be 1.

In the time domain, the output RF signal, $p(t)$, is the inverse Fourier transform of (4), which is given by

$$\begin{aligned} p(t) &= \frac{1}{T} Q(m\Omega) a(t) \times \exp(jm\Omega t) \\ &= \frac{1}{T} Q(m\Omega) |a(t)| \times \exp\{j[\varphi(t) + m\Omega t]\} \end{aligned} \tag{5}$$

where $\varphi(t)$ is the phase of $a(t)$. From (5) we can clearly see that the output signal is an RF signal with a central frequency located at $m\Omega$. The generated phase modulation is just the phase of the weight profile, $\varphi(t)$.

In an optical arbitrary RF signal generation system, to avoid optical interference which is extremely sensitive to environmental changes, the time-delayed pulses should be added incoherently at a PD. For incoherent detection, the coefficients, α_k, are always positive. Based on (5), we can conclude that a desired phase modulation cannot be introduced to the generated RF signal if the short pulse train is uniformly spaced, since $a(t)$ is always positive. To achieve the desired phase modulation, a solution is to use a pulse train with nonuniform spacing.

To establish the relationship between the nonuniform time spacing and the desired phase modulation, we build a new optical pulse train following (2), which is given by

$$\tilde{p}_T(t) = q(t) * \{|a(t)| \times s[t + f(t)]\}. \tag{6}$$

The function $f(t)$ is introduced to describe the pulse position modulation. With the introduction of $f(t)$, the time spacing of the pulse train is no longer uniform. Same as the uniform case, however, the coefficients are all positive. Although it is hard to obtain analytically the spectrum of the new pulse train in (6), it is still possible to expand the signal as the sum of many bandpass signals with different central frequencies. Note that

$$s(t) = \sum_m \frac{1}{T} \exp(jm\Omega t). \tag{7}$$

Based on (6) and (7), we have

$$\tilde{p}_T(t) = q(t) * \sum_m \frac{1}{T} |a(t)| \exp[jm\Omega f(t)] \times \exp(jm\Omega t). \tag{8}$$

Considering the approximation used in (4), i.e., the variation of $Q(\omega)$ is negligible within the bandwidth at Ω, (8) can be approximated as

$$\tilde{p}_T(t) \approx \sum_m \frac{1}{T} Q(m\Omega) |a(t)| \exp[jm\Omega f(t)] \times \exp(jm\Omega t). \tag{9}$$

It is clearly seen from (9) that the nonuniformly spaced pulse train is expressed as the sum of multiple bandpass RF signals with different central frequencies. If the mth channel is not interfered by its adjacent channels, the spectral component at $m\Omega$ can be filtered out by a microwave bandpass filter with its central frequency at $m\Omega$. Then the output RF signal is now given by

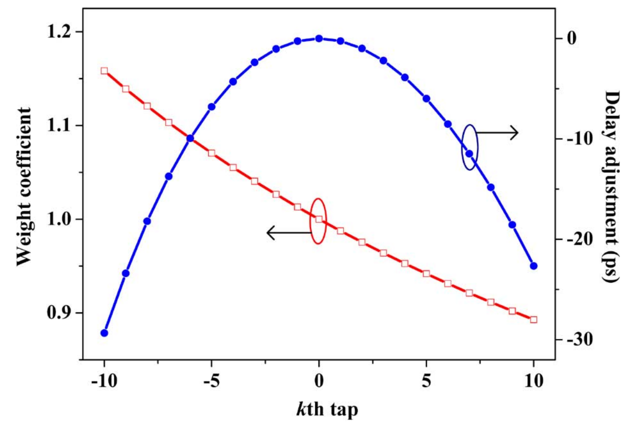

Fig. 2. Time delay adjustment ($\Delta\tau_k = \tau_k - kT$) and the coefficient of each pulse in the pulse train.

$$\tilde{p}(t) = \frac{1}{T} Q(m\Omega) |a(t)| \exp[jm\Omega f(t)] \times \exp(jm\Omega t). \tag{10}$$

Comparing (10) with (5), one can see that an additional phase modulation is introduced to the RF signal due to the pulse position modulation introduced by $f(t)$. Therefore, although the weight coefficients are all positive, by using a specially designed PPM pulse train, a phase modulated RF signal can be obtained.

The relationship between the pulse position modulation function $f(t)$ and the desired phase modulation can be obtained by comparing (10) and (5)

$$f(t) = \frac{\varphi(t)}{m\Omega}. \tag{11}$$

Substituting (11) into (6), and considering the definition of $s(t)$, one gets the time delay of each pulse in the pulse train

$$\tau_k + \frac{\varphi(\tau_k)}{m\Omega} = kT. \tag{12}$$

The coefficients can also be obtained, which is given by

$$|\alpha_k| = \left| \frac{a(\tau_k)}{1 + \frac{\varphi'(\tau_k)}{m\Omega}} \right|. \tag{13}$$

Based on the analysis, we conclude that if a pulse train with a pulse position modulation described by (12) with the coefficients given by (13), a RF signal with a central frequency located at $m\Omega$ and a phase modulation of $|a(t)| \exp[j\varphi(t)]$ is then obtained at the output of a microwave bandpass filter with its central frequency located at $m\Omega$.

III. Chirped RF Pulse Generation

In this section, the synthesis of a chirped RF pulse using the proposed technique is investigated numerically. Chirped RF pulses have been widely used for many important applications such as in a modern radar system to increase the range resolution and in a broadband communications system to increase the signal-to-noise ratio (SNR). In the design, we assume that the

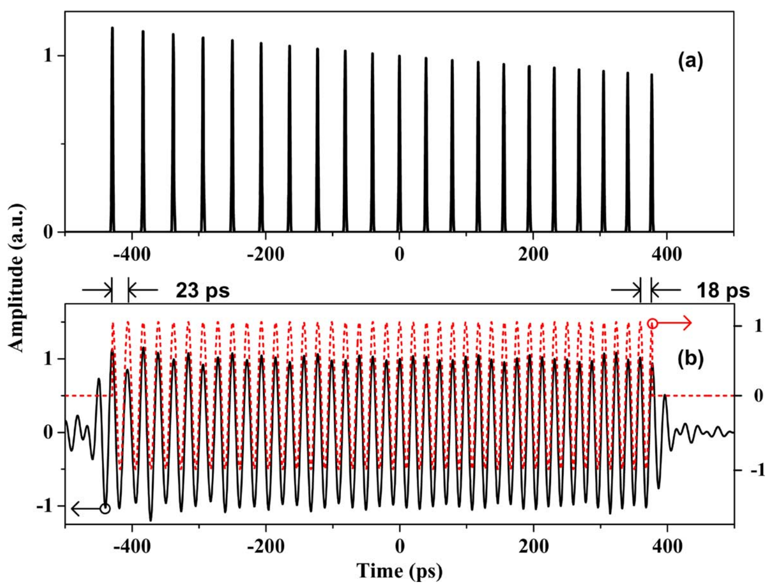

Fig. 3. (a) Nonuniformly spaced pulse train in the time domain. (b) Solid line: the generated chirped RF signal from the nonuniformly spaced pulse train after filtering using an ideal microwave bandpass filter. Dotted line: the desired chirped RF signal. Chirped RF signal obtained from the nonuniformly spaced pulse train agrees well with the desired chirped RF signal.

desired RF chirped pulse has a central frequency of ω_0 and a phase modulation given by

$$\varphi(t) = C\left(\frac{t}{t_0}\right)^2 \tag{14}$$

where C is the chirp coefficient and $t_0 = 2\pi/\omega_0$ is the mean period of the chirped RF signal. In our numerical study, we choose $\omega_0 = m\Omega$ which means that the desired central frequency of the chirped RF signal is m times the mean frequency of the pulse train. Based on (12) and (13), we can get the time delay and the coefficient of each pulse in the pulse train

$$\tau_k = \frac{2kT}{1+\sqrt{1+k\frac{2mC}{\pi}}} \tag{15a}$$

$$\alpha_k = \frac{1}{1+\frac{mC\tau_k}{\pi T}}. \tag{15b}$$

In the simulations, the parameters are selected as follows: $\omega_0 = 2\pi \times 50$ GHz, and $m = 2$. Then the repetition rate of the pulse train is 25 GHz. The number of the pulse in the pulse train is 21, and $C = 0.02$. Based on (15), the structure of the pulse train can be calculated, which is plotted in Fig. 2. Note that in order to illustrate the nonuniformly spaced time delay, the time delay adjustment, i.e., $\Delta\tau_k = \tau_k - kT$ rather than τ_k, is plotted.

For simplicity, the pulses in the pulse train are assumed to have a Gaussian shape with a full-width-at-half-maximum (FWHM) of 2 ps. The nonuniformly spaced pulse train is shown in Fig. 3(a) and the output chirped RF pulse obtained by using a microwave bandpass filter is shown in Fig. 3(b).

To demonstrate the theory clearly, the spectrum of the pulse train is also studied. Fig. 4(a) shows the calculated spectrum based on the Fourier transform. For comparison, the spectrum of a uniformly spaced pulse train is also plotted in Fig. 4(b). Obviously, one can see that although the spectra of the both pulse trains have multichannel spectral response, the spectral profile for different channels of the nonuniformly spaced train are, however, not identical. The bandwidth of each channel of the uniformly spaced train is the same, while the bandwidth increases with the increase of m for the nonuniformly spaced pulse train. The above observation shows that the phase modulation corresponding to each channel is different, which has been predicted by our theory in (9) and (10).

We now focus on the spectrum of the channel of interest, which is the second channel in this example since $m = 2$ is selected in our design. The spectrum of the desired chirped RF signal, which is illustrated as the dotted line in Fig. 3(b), is calculated and plotted in Fig. 4(a). One can see that within the channel of interest, the spectrum of the PPM pulse train agrees well with the desired spectrum. If the second channel is selected by an ideal microwave bandpass filter having a bandwidth of 25 GHz and a central frequency at 50 GHz, we then obtain the desired signal shown in Fig. 3(b). Since the spectra of the pulse train and the desired RF signal are the same in Fig. 4(a), in the time domain they should have the same waveforms, which can be seen from Fig. 3(b). The generated chirped RF signal has an instantaneous period decreasing from 23 to 18 ps, which agrees well with the chirp rate of the desired chirped signal. As a result, the nonuniformly spaced pulse train designed based on the developed theory can be used to generate the desired chirped RF signal with the help of a microwave bandpass filter.

Some issues should be discussed when implementing the proposed technique for chirped RF pulse generation. First, for $m = 0$, no phase modulation is imposed on the filtered signal, as can be seen from (10), which is also confirmed by the simulation results shown in Fig. 4(a). As can bee seen from Fig. 4, the 0th spectral channel of the nonuniformly spaced train is the same as

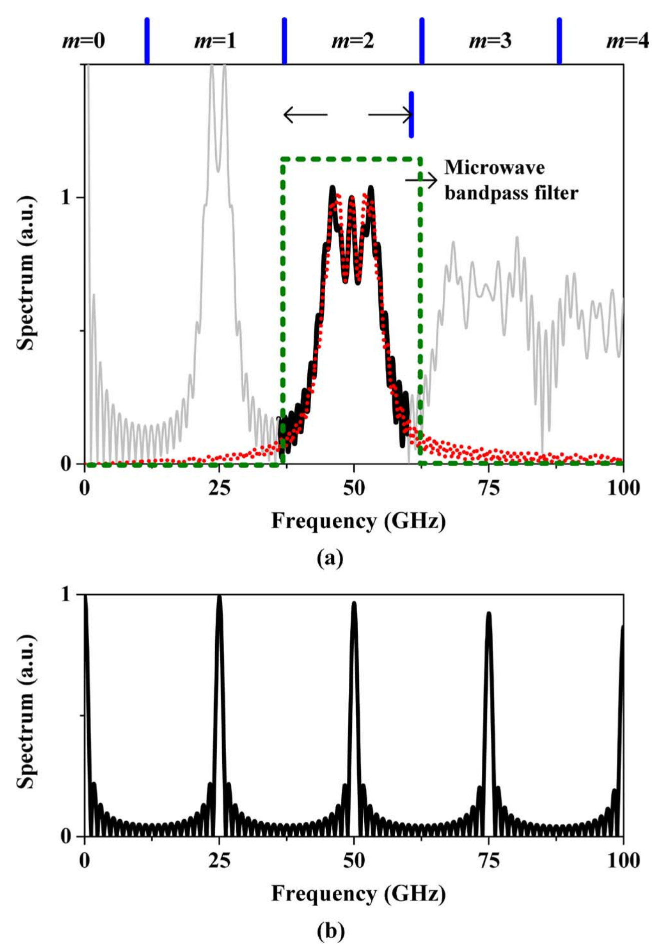

Fig. 4. (a) Spectrum of the nonuniformly spaced pulse train illustrated in Fig. 3(a). Dotted line: the spectrum of the desired chirped RF signal illustrated as dotted line in Fig. 3(b). Clearly, within the second spectral channel, the spectrum of the pulse train agrees well with the desired spectrum. (b) Spectrum of the uniformly spaced pulse train. Parameters of the uniformly spaced pulse train are: the pulse number is 21, period is 40 ps (corresponding to a repetition rate of 25 GHz), and the pulses are Gaussian shaped with a FWHM of 2 ps.

that of the uniformly spaced pulse train; no spectrum expansion due to phase modulation is resulted.

Second, other than the 0th channel, all other channels would experience phase modulations. In addition, with the increase of the pulse position modulation depth, i.e., with the increase of the magnitude of $f(t)$, the bandwidths of the channels would be increased. If the bandwidths are larger than Ω, then the spectrum of the channel of interest would be affected by the spectra of the adjacent channels, such as the third channel in Fig. 4(a). To avoid the impact from the adjacent channels, in the design of the pulse position modulation, we should choose a small $f(t)$, or a large Ω. In fact, in our theoretical treatment, to obtain (10) from (9), we assume that there is no or little interference from the adjacent $(m\pm1)$ channels. Therefore, in the proposed technique to generate a phase-modulated RF signal from a PPM pulse train, the available bandwidth of the phase-modulated RF signal is limited by the mean repetition rate of the pulse train, Ω. In the example for the chirped RF pulse generation, the upper limit of the bandwidth is about Ω, that is, the fractional bandwidth is limited within 0.5. Generally, in terms of fractional bandwidth,

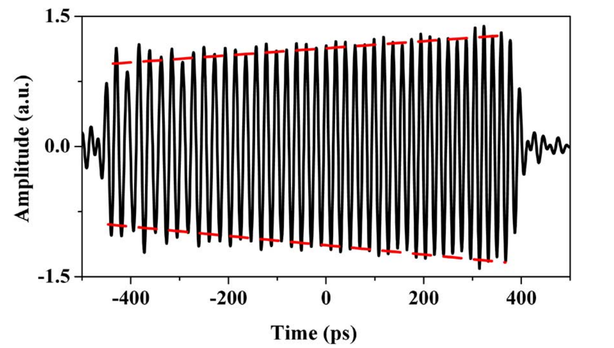

Fig. 5. Uniform coefficients would generate a chirped RF signal with nonconstant amplitude.

if the mth-order channel is used, the fractional bandwidth will be limited to within $1/m$.

Third, to get a chirped RF pulse with a constant amplitude in the time domain, as shown in Fig. 3(b), nonuniform coefficients should be used. As shown in Fig. 5, when the coefficients are uniform, i.e., $\alpha_k = 1$, the generated chirped RF signal will have a nonconstant amplitude. This phenomenon can be easily explained by considering the chirp nature of the PPM pulse train. For uniform coefficients, the PPM pulse train would have higher average power at higher repetition rate. To ensure that the generated chirped RF pulse has constant amplitude, the weight coefficients should be reduced for pulses at higher repetition rate, which can be calculated using (15).

The optical pulse train with the required pulse position modulation can be realized by the DST technology which has been demonstrated in [17]. The output RF signal can be updated in real time if a programmable mask in the DST system is employed. Compared with the microwave arbitrary pulse generation based on optical pulse shaping such as the approach in [3], the proposed PPM to PM conversion has the key advantage that the conversion process is incoherent, making the process insensitive to the optical phase fluctuations.

IV. Phase-Coded RF Pulse Generation

The use of the proposed technique for phase-coded RF pulse generation is also investigated. In the experiment, a binary phase-coded RF signal is generated from a PPM pulse train using a microwave bandpass filter to select the spectrum of the channel of interest. The microwave bandpass filter in our experimental demonstration is a photonic microwave delay line filter implemented in the optical domain using a polarization modulator [21].

Phase-coded RF signals have been widely used in radar and code division multiple access (CDMA) systems. Assume that the phase-coded RF pulse has M chips with the time duration of each chip being T_{chip}. The central frequency is $t_0 = 2\pi/\omega_0$ with a corresponding period of $t_0 = 2\pi/\omega_0$. The phase introduced to the kth chip is then given by

$$\varphi(t) = \varphi_k, \quad k < \frac{t}{T_{\text{chip}}} \le k+1. \tag{16}$$

We also assume that each chip contains r RF cycles, then $T_{\text{chip}} = rt_0$. In our design, $m = 1$ is selected, i.e., $T = t_0$.

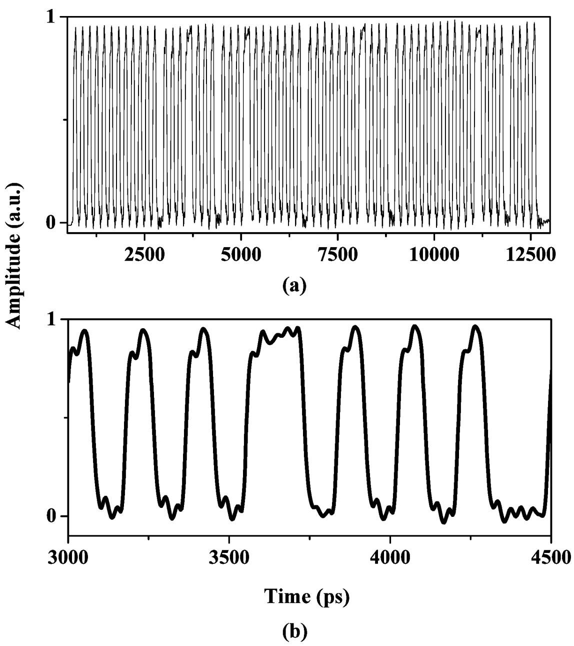

Fig. 6. (a) Designed PPM pulse train for the generation of phase-coded RF pulse. (b) Zoom-in view of the PPM pulse train.

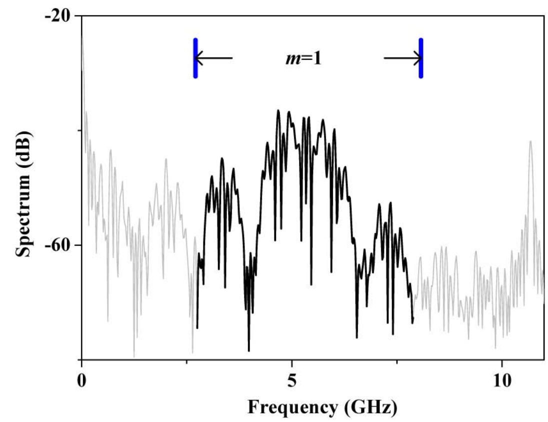

Fig. 7. Spectrum of the PPM pulse train. The band corresponding to the desired phase-coded RF signal is highlighted.

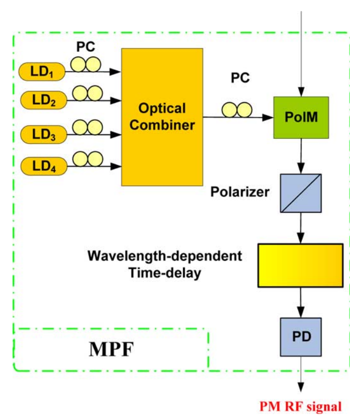

Fig. 8. Photonic microwave bandpass filter with negative coefficients implemented based on a PolM. PC: polarizer controller. MPF: microwave photonics filter. PM: phase modulated, PolM: polarization modulator.

Since the phase-coded RF signal contains M chips, the pulse trains should have rM pulses. Based on (16), the phase is φ_k around $t = (kr + l)T$ where $0 \leq k < M$ and $0 \leq l < r$. Then for the $(kr + l)$th optical pulse in the pulse train, the time delay is obtained based on (12)

$$\tau_{kr+l} = \left(kr + l + \frac{\varphi_k}{2\pi}\right)T. \tag{17}$$

The weight coefficients can be calculated based on (13). It is different from the example discussed in the previous section, to generate a chirped RF pulse with constant amplitude; the coefficients should be reduced for pulses at higher repetition rate. To generate a phase-coded RF pulse, however, based on (13), the coefficients are uniform.

In the experiment, the PPM pulse train is generated by a pattern generator. The time delay difference between two adjacent pulses for a uniformly spaced pulse train is $T = 187.2$ ps, corresponding to a repetition rate of the pulse train of 5.34 GHz. In the design, we select $m = 1$, the central frequency of the generated RF signal is then equal to Ω. The chip number of the generated pulse, M, is 15, and the desired binary code pattern is $\{1, 1, 1, -1, 1, -1, 1, 1, -1, -1, 1, -1, -1, -1, 1\}$, which is a pseudo-random binary sequence (PRBS) with a good correlation property. In the design, we choose that each chip contains $r = 4$ RF cycles. The output pulse train from the pattern generator is shown in Fig. 6 with its spectrum shown in Fig. 7. In our design, the spectrum of the first-order channel is selected to generate the desired phase-coded RF signal by using a microwave bandpass filter.

The PPM pulse train is filtered in the experiment by a microwave bandpass filter implemented in the optical domain. To avoid optical interference, a photonic microwave filter is usually designed to operate in the incoherent regime. A photonic microwave filter operating in the incoherent regime usually has all positive coefficients. It is known that a photonic microwave filter with all-positive coefficients can only function as a low-pass filter. To design a photonic microwave filter with bandpass functionality, the filter should have negative coefficients [20], [21]. In the experiment, a photonic microwave filter with negative coefficients is implemented based on a PolM, which was reported recently by us in [21]. The configuration of the filter is shown in Fig. 8.

As can be seen from Fig. 8, the outputs from four laser diodes (LDs) are combined by an optical combiner and then sent to a PolM, which is modulated by a PPM pulse train generated by a pattern generator. The output signal from the PolM is sent to a polarizer to perform polarization modulation to intensity modulation conversion. Depending on the polarization states of the input lightwaves from the LDs with an angle of 45° or 135° with respect to the principal axis of the PolM, positive or negative coefficients are generated. The time delays for the different wavelengths are generated by a wavelength-dependent time delay module, which is a length of fiber in the experiment. In the experiment, we adjust the polarization states of the four wavelengths by tuning the four PCs connected at the outputs of the LDs to make the incident angles to be 45°, 135°, 45° and 135° with respect to the principal axis of the PolM, leading to the generation of four coefficients of $[1, -1, 1, -1]$. The fiber is 10-km

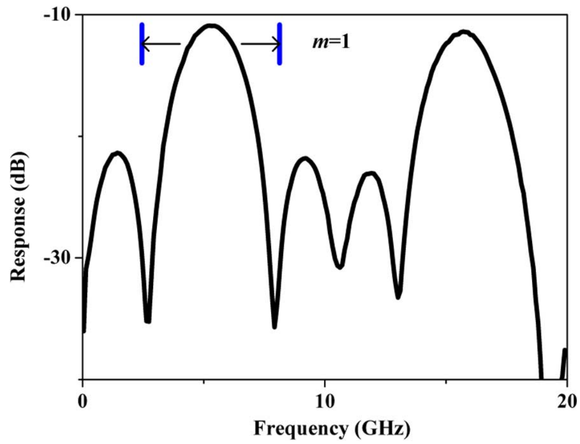

Fig. 9. Frequency response of the photonic microwave bandpass filter. Filter is used to convert the PPM pulse train shown in Fig. 6 to the desired phase-coded RF signal.

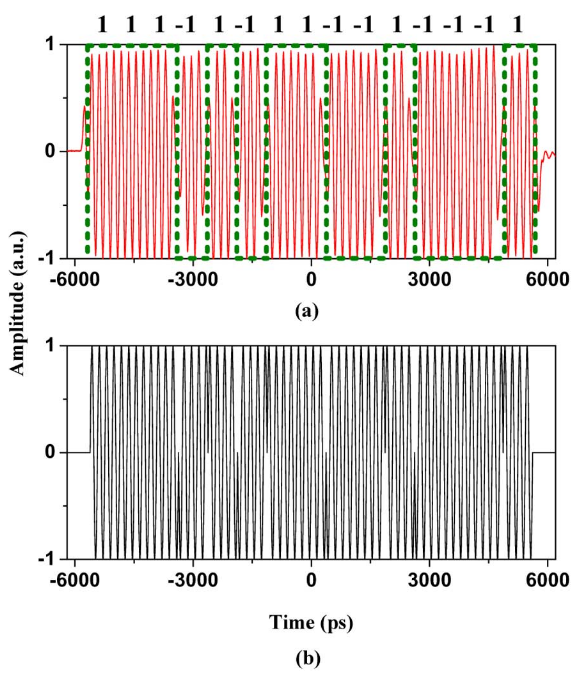

Fig. 10. (a) Generated phase-coded RF signal in the experiment. (b) Ideal phase-coded RF signal with the same code pattern.

standard single mode fiber with a chromatic dispersion parameter of 17 ps/nm/km. The four wavelengths have an identical wavelength spacing of 0.6 nm. The time delay difference between adjacent channels is 102 ps, corresponding to a free spectral range (FSR) of 10.68 GHz, i.e., $2\,\Omega$. The frequency response of the microwave filter is measured using a vector network analyzer (VNA, Agilent E8364A), which is shown in Fig. 9. As can be seen the microwave filter has a passband located at 5.34 GHz, which is used to select the spectrum of the channel concerned to get a phase-coded RF signal at the output of the PD. The generated phase-coded RF signal is monitored by a high-speed oscilloscope (Agilent 86100C), as shown in Fig. 10.

The code pattern used to encode the RF signal is a PRBS, which has a good correlation property. To verify the quality of the generated phase-coded RF pulse, we calculate two correlations, the first one is a correlation between the ideal RF pulse with the generated RF pulse, and the other is a correlation between the ideal RF pulse with itself. The results are shown in Fig. 11(a) and (b). It is clearly seen that the phase-coded RF pulse is significantly compressed. The excellent auto-correlation property demonstrates the effectiveness of the proposed technique for phase-coded RF signal generation.

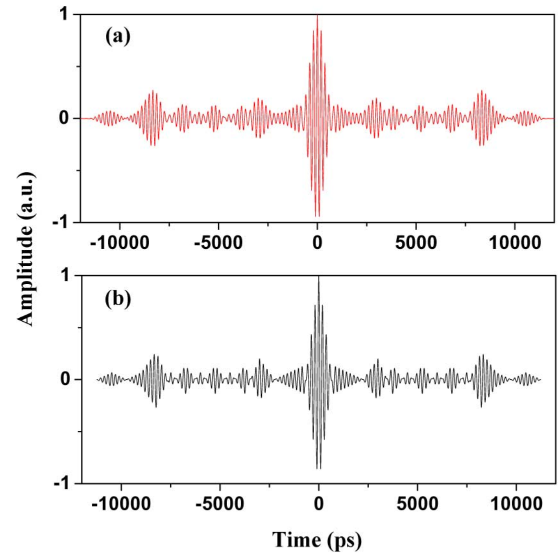

Fig. 11. (a) Calculated auto-correlation of the experimentally generated phase-coded RF signal. (b) Auto-correlation of the ideal phase-coded signal in Fig. 10(b).

V. Conclusion

In conclusion, we have demonstrated the generation of an arbitrary band-limited phase modulated RF signal by using a PPM optical pulse train with the help of a microwave bandpass filter. A detailed theoretical analysis was presented. We have shown that a specially designed PPM pulse train has a multi-channel spectral response, with one channel having the spectrum corresponding to the desired phase modulated RF signal. The relationship between the pulse train structure, including the pulse position modulation and the weight coefficients, and the desired phase modulation, was mathematically derived. Two design examples to generate a chirped RF signal with a central frequency of 50 GHz and a 3-dB bandwidth of 12.5 GHz and a 15-chip binary phase-coded RF signal with a central frequency of 5.34 GHz were presented. The proposed technique provides a simple and effective solution to high-speed arbitrary phase-modulated RF waveform generation based on pulse position modulation and pulse position modulation to phase modulation conversion using a microwave bandpass filter.

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Yitang Dai received the B.Sc. and Ph.D. degrees in electronic engineering from the Tsinghua University, Beijing, China, in 2002 and 2006, respectively.

Since June 2007, he has been a Postdoctoral Research Fellow with the Microwave Photonics Research Laboratory, School of Information Technology and Engineering, University of Ottawa, Ottawa, ON, Canada. His research interests include fiber Bragg grating, optical CDMA, fiber lasers, microwave photonics, optical pulse shaping, semiconductor lasers, and optical sensors.

Jianping Yao (M'99–SM'01) received the Ph.D. degree in electrical engineering from the Université de Toulon, France, in 1997.

He joined the School of Information Technology and Engineering, University of Ottawa, ON, Canada, in 2001, where he is a Professor and University Research Chair, Director of the Microwave Photonics Research Laboratory, and Director of the Ottawa-Carleton Institute for Electrical and Computer Engineering. He holds a Yongqian Endowed Chair Professorship of Zhejiang University since May 2008, China. From 1999 to 2001, he held a faculty position in the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore. He spent three months as an Invited Professor in the Institut National Polytechnique de Grenoble, France, in 2005. He established the Microwave Photonics Research Laboratory at the University of Ottawa in 2002. His research has focused on microwave photonics, which includes photonic processing of microwave signals, photonic generation of microwave, mm-wave and THz, radio over fiber, UWB over fiber, and optically controlled phased array antenna. His research also covers fiber optics, which includes fiber lasers, fiber and waveguide Bragg gratings, fiber-optic sensors and bio-photonics. He has authored or co-authored 200 papers in refereed journals and in conference proceedings.

Dr. Yao is an Associate Editor of the *International Journal of Microwave and Optical Technology*. He is on the Editorial Board of IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES. He is a chair or committee member of numerous international conferences, symposia, and workshops. He received the 2005 International Creative Research Award of the University of Ottawa. He was the recipient of the 2007 George S. Glinski Award for Excellence in Research. He was named University Research Chair in Microwave Photonics in 2007. He was a recipient of a Discovery Accelerator Supplements award of The Natural Sciences and Engineering Research Council of Canada in 2008. He is a registered professional engineer of Ontario. He is a Member of SPIE and OSA.