Photonic Generation and Application of Dual-band Phase-Coded LFM Signals

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Photonic Generation and Application of Dual-band Phase-Coded LFM Signals

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Abstract: A novel photonic method is proposed to generate dual-band phase encoding linearly frequency modulation (LFM) waveforms. In this scheme, two binary sequences are sent into one dual-polarization Mach-Zehnder modulator (DPol-MZM) to perform phase modulation with the optical carrier, while driving LFM signal is sent into another DPol-MZM to generate second and fourth-order optical sidebands. Then, the generated sidebands and the phase modulated optical carrier are combined together to perform optical to electrical conversion. As a result, bandwidth doubled and quadrupled phase coded LFM signals can be produced. The proposed scheme is verified by simulation, dual-band signals of 6~10 GHz & 12~20 GHz, 6~13 GHz & 12~26 GHz and 8~10 GHz & 16~20 GHz are obtained by using 3~5 GHz, 3~6.5 GHz, and 4~5 GHz driving LFM signals, respectively. Furthermore, the applications of the generated dual-band signals on both radar and communication are demonstrated. For radar detection, optical de-chirping operation for the dual-band signals can be simultaneously realized by using a DPol-MZM, on the other hand, the time bandwidth product of the radar waveform can be improved by phase encoding the LFM signal with M sequence. For wireless communication, each band LFM signal can be modulated with a binary sequence, and the two phase-coded LFM signals can be coherently demodulated in the optical domain. The proposed method features multi-functional operation, which can be potentially employed in radar-communication integrated systems.

Keywords: Linearly Frequency Modulation, microwave photonics, dual-band signals, radar communication integration

1. Introduction

Linearly frequency modulation (LFM) signal features excellent pulse compression performance, and it is widely used in modern radar systems [1-2]. On the other hand, LFM signal can be applied in wireless communication through spread spectrum operation to reduce interception probability [3]. LFM signals are conventionally generated with electronic techniques, which have several bottlenecks. For example, the electrical analog and digital circuits have limited operating frequency range and severe interference. In comparison, photonic techniques can overcome these bottlenecks and generate LFM signals with higher frequency, wider bandwidth, enhanced flexibility, and immunity to electromagnetic interference [4-6]. Plenty of efforts have been made for the photonic generation of LFM signals [7-15]. However, most of the reported schemes only generate a LFM signal in a single band, which cannot fulfill the requirements of the multi-band radar system. The multi-band radar system is capable of performing multiple functions (searching, tracking, mapping, etc.) with enhanced sensitivity, resolution, and reliability [16-18]. LFM signal can be adopted in multi-band radar with lower cost and improved detection performance.

Recently, photonic methods to generate LFM signals with multiple bands have been explored [19-23]. In 2015, the first fully coherent dual-band photonic-aid radar system was demonstrated. By using
dual-band LFM signals and data fusion operation, the sensitivity and resolution of the system can be improved [19]. After that, several schemes based on the dual-polarization dual-parallel Mach-Zehnder modulator (DPol-DPMZM) were proposed to generate dual-band LFM signals with high frequency and wide bandwidth [20-23]. However, these schemes are mainly focused on the radar function, the data modulation is not involved to perform communication function or radar-communication integration.

In 2016, a scheme based on optical frequency-to-time mapping to generate LFM signals in binary phase shift keying format (BPSK) was firstly proposed [24]. 250 Mbit/s error-free data transmission was experimentally demonstrated. Since spatially separated structure was used, the scheme has low stability. In [25], an electrical phase-coded parabolic waveform was introduced into an optical orthogonally-polarized wavelength-pair through a PolM, after optical to electrical conversion, phase-coded LFM signal was obtained. A complex driving signal was needed in this method, and the generated signals also had limited bandwidth. In 2019, amplitude shift keying (ASK) was inserted into a photonic LFM signal generation system to achieve radar detection and wireless communication synchronously [26]. But the severe power fluctuation of the ASK signal will shorten the detection range. Another scheme based on swept frequency optoelectronic oscillator (OEO) was proposed to obtain phase-coded LFM signal [27]. However, the complexity of the OEO and the limited oscillating modes hinder the precision of the generated LFM signal. Recently, we proposed a frequency multiplied phase-coded LFM signal generator based on a DPol-DPMZM [28]. Bandwidth doubled or quadrupled LFM waveform can be obtained and be used for radar detection and covert communication. Another method has also been investigated to generate LFM waveform with multiple modulation formats, which may improve the communication rate by using high order modulation [29].

To further improve the performance of target detection and wireless communication, in this paper, we propose a photonic-assisted method to generate dual-band phase-coded LFM waveforms based on two parallel dual-polarization Mach-Zehnder modulators (DPol-MZMs). Each DPol-MZM consists of two parallel sub-MZMs. For the upper DPol-MZM, the optical carriers output from the two sub-MZMs are phase modulated by two binary sequences respectively. While for another DPol-MZM, the sub-MZMs are driven by two electrical LFM signals respectively to obtain second and fourth-order optical sidebands.

Thanks to the polarization controller (PC), the second-order and fourth sidebands can be separated into two polarization states and then combined with phase-modulated optical carriers. After optic-electronic conversion bandwidth doubled and quadrupled, phase encoding LFM waveforms are independently generated. Furthermore, the photonic receiver is also investigated to perform low-speed processing to the received signals. With a local optical signal directly extracted from the generator, optical de-chirping and coherent demodulation can be easily achieved without an independent local oscillator.

2. Theory and Principle
Fig. 1 shows the systematical diagram of the proposed photonic dual-band radar-communication integration system. The system contains two modules, a phonic generator used for dual-band phase-coded LFM signal generation and a photonic receiver to perform de-chirping and coherent demodulation to the received signal. The photonic generator consists of a laser diode (LD), two DPol-MZMs, two pulse pattern generators (PPGs), an arbitrary waveform generator, a PC, an optical coupler (OC), two polarization beam splitters (PBSs), two optical filters (OFs), two photodetectors (PDs), two electrical filters, two electrical amplifiers and two transmitting antennas. While the photonic receiver consists of four receiving antennas, four electrical bandpass filters (BPFs), four electrical amplifiers, a tunable time-delay line (DL), two DPol-MZMs, two PBSs, four PDs, four electrical low pass filters (LPFs).
Fig2. Structure of the DPol-MZM (a) consists of polarization rotator (PR), PBC and dual-drive sub-MZMs, (b) consists of PBS, PBC and single-drive sub-MZMs.

Note that there are two types of DPol-MZM deployed in this scheme, as shown in Fig.2. In the photonic generator, the DPol-MZM consists of two sub-MZMs, a 90° polarization rotator (PR) and a polarization beam combiner (PBC), as shown in Fig.2(a). Fig. 2(b) shows the structure of another type of the DPol-MZM, it consists of two sub-MZMs, a PBC and a PBS, and it is deployed in the photonic receiver.

2.1 Generation of dual-band phase-coded LFM signal

Fig.3 (a) Output optical carrier of DPol-MZM1. Optical sidebands in the output of DPol-MZM2 and PC on polarization state x (b) & (d), and polarization state y (c) & (e).

In the photonic generator, the CW laser output from the LD is firstly split into two paths and then applied into the two DPol-MZMs. In DPol-MZM1, the two sub-MZMs are biased at the maximum transmission point (MATP). For each sub-MZM, the input optical carrier is phase modulated by a binary sequence to introduce a phase difference of $\Delta \phi$, as shown in Fig.3(a). Assume that the light emitted from the LD has an angular frequency of $\omega_c$ and an amplitude of $E_{in}$. The $i$-th symbol of the two binary sequences are respectively $N_{1i}$ and $N_{2i}$. Then the output of DPol-MZM1 in two polarization states can be expressed as,
\[
\begin{bmatrix}
E_{\text{DM1-1}}(t) \\
E_{\text{DM1-2}}(t)
\end{bmatrix} = \frac{\sqrt{2}}{8} \sum_i E_m^i \begin{bmatrix}
e^{j \Delta \phi} (e^{j \theta_1} + e^{j \theta_0}) \\
e^{j \Delta \phi} (e^{j \theta_1} + e^{j \theta_0})
\end{bmatrix} \delta(t - iT)
\]
\[
= \frac{\sqrt{2}}{4} \sum_i E_m^i e^{j \Delta \phi} (e^{j \theta_1} + e^{j \theta_0}) \delta(t - iT)
\]

(1)

Where \(\delta\) denotes the pulse function, \(T\) is the period of each symbol of the binary sequence. \(M_{p1}\) and \(M_{p2}\) are the modulation index of the sub-MZMs in DPol-MZM1. As can be seen in the Equation 1, the phase difference \(\Delta \phi\) is defined by \(M_{p1}\) and \(M_{p2}\).

The electronic LFM signal is firstly split by a 90° hybrid coupler and then sent into two sub-MZMs of DPol-MZM2. The sub-MZMs are biased at the maximum transmission point (MATP) to generate optical carrier and even-order sidebands in the two polarization states, as shown in Figs. 3(b) and (c).

The polarization-multiplexed optical signals are then adjusted by the PC and put into the following PBS. The two principal axes of the PBS have differences of 45° and 135° to one polarization direction of the optical signals. After that, two optical filters (OFs) are used to filter the desired sidebands respectively. As a result, second-order sidebands can be remained in polarization direction \(x\), and fourth-order sidebands in polarization direction \(y\). Assuming the electrical driving signal is a repetitive wave train of \(s_L(t) = V_L \cos(\omega_{IF} t + kt^2/2)\), where \(V_L\) is the amplitude, \(\omega_{IF}\) is the initial angular frequency, and \(k\) is the chirp rate. Then the output of DPol-MZM2 can be given by,

\[
\begin{bmatrix}
E_{\text{DM2-1}}(t) \\
E_{\text{DM2-2}}(t)
\end{bmatrix} = \frac{\sqrt{2}}{4} \sum_i E_m^i e^{j \Delta \phi} \begin{bmatrix}
e^{j \theta_1} e^{j (2 \omega_{OF} + k t^2)} + e^{j (4 \omega_{OF} + 2 k t^2)} \\
e^{j \theta_0} e^{j (2 \omega_{OF} + k t^2)} + e^{j (4 \omega_{OF} + 2 k t^2)}
\end{bmatrix} \delta(t - iT)
\]

(2)

Where \(m_2 = \pi V_L / V_{\pi}\) is the modulation index of the sub-MZMs in DPol-MZM2, and \(V_{\pi}\) is the switch voltage. Note that the driving signal is synchronized with the binary sequences. By applying the Jacob expansion, Equation (2) can be rewritten as,

\[
\begin{bmatrix}
E_{\text{OF1}}(t) \\
E_{\text{OF2}}(t)
\end{bmatrix} = \frac{1}{2} \sum_i E_m^i \begin{bmatrix}
J_4(m_2) e^{j (4 \omega_{OF} + 2 k t^2)} \\
-J_4(m_2) e^{j (2 \omega_{OF} + k t^2)}
\end{bmatrix} \delta(t - iT)
\]

(3)

In which, \(J_n\) is the \(n\)-th order Bessel function of the first kind. Consequently, the output of OF1 and OF2 can be expressed as,

\[
\begin{bmatrix}
E_{\text{OF1}}(t) \\
E_{\text{OF2}}(t)
\end{bmatrix} = \frac{1}{2} \sum_i E_m^i \begin{bmatrix}
J_4(m_2) e^{j (4 \omega_{OF} + 2 k t^2)} \\
-J_4(m_2) e^{j (2 \omega_{OF} + k t^2)}
\end{bmatrix} \delta(t - iT)
\]

(4)

Then, \(E_{\text{OF1}}(t)\) and \(E_{\text{OF2}}(t)\) are respectively combined with \(E_{\text{DM1-x}}(t)\) and \(E_{\text{DM1-y}}(t)\) and sent into two PDs. The input signal of PD1 and PD2 can be expressed as,

\[
\begin{bmatrix}
E_{\text{PD1}}(t) \\
E_{\text{PD2}}(t)
\end{bmatrix} = \frac{1}{2} \sum_i E_m^i \begin{bmatrix}
J_4(m_2) e^{j (4 \omega_{OF} + 2 k t^2)} + \sqrt{2} e^{j \Delta \phi} \\
-J_4(m_2) e^{j (2 \omega_{OF} + k t^2)} + \sqrt{2} e^{j \Delta \phi}
\end{bmatrix} \delta(t - iT)
\]

(5)

The output signal of PD1 and PD2 can be given by,

\[
\begin{bmatrix}
I_{\text{PD1}}(t) \\
I_{\text{PD2}}(t)
\end{bmatrix} \propto \frac{\sqrt{2}}{4} \sum_i \eta E_m^i \begin{bmatrix}
\cos(4 \omega_{OF} t + 2 k t^2 + N_1 \Delta \phi) \\
\cos(2 \omega_{OF} t + k t^2 + N_3 \Delta \phi)
\end{bmatrix} \delta(t - iT)
\]

(6)

Where \(\eta\) is the responsivity of PD.
As shown in Equation 6, frequency-doubled and quadrupled phase-coded LFM waveforms are generated.

2.2 De-chirping of radar detection

\[ \omega_c -(4\omega_{IF}+4kt) \quad \omega_c \quad \omega_c +(4\omega_{IF}+4kt) \]

LPF

\[ \omega_c -(4\omega_{IF}+4kt)+2\omega_{echo} \]

![Fig.4](image)

Fig.4 (a) The local optical sidebands set to the upper brunch of DPol-MZM4 and (b) the optical sidebands modulated by received echo signal.

In the proposed scheme, de-chirping of to the received echo signal with a local optical signal provided by the photonic generator is available. As shown in Fig.1, the output of DPol-MZM2 is split into two branches. One is used to generate a dual-band LFM signal. The other is sent into the receiver as a local signal. Echo signal of each band will be sent into one sub-MZM of DPol-MZM4, both the sub-MZMs are biased at MATP to generate second-order optical sidebands, as shown in Fig. 4. Assume that one echo signal has an instantaneous frequency of \(4\omega_{IF}+4kt\), then one of the generated positive second-order sidebands has a frequency of \(\omega_c + (4\omega_{IF}+4kt - 8kt_0)\). After the PD, the frequency difference between components \(\omega_c + (4\omega_{IF}+4kt)\) and \(\omega_c + (4\omega_{IF}+4kt - 8kt_0)\) can be extracted through the LPF. The output of the LPF can be expressed as,

\[ i_{LPF}(t) \propto \eta E_r^2 \cos(8kt, t) , (0 < t < T) \]  

(7)

Where \(t_0\) represents the propagation time of the detection signal. The relationship between de-chirp signal and the distance to target can be given by,

\[ R = \frac{f_{LPF}}{16k} \]  

(8)

In which \(c\) represents the velocity of light, \(f_{LPF}\) is the frequency of de-chirp signal extracted by LPF.

2.3 Optical coherent demodulation of communication

One advantage of the proposed scheme is that demodulation to the generated phase-coded LFM signal can be achieved without any electrical devices or independent local oscillator source. As shown in Fig.1, the output of DPol-MZM2 is sent into DPol-MZM3 through a tunable time-delay line. On the other hand, the frequency quadrupled and doubled communication signals will be respectively received by receiving antennas. After bandpass filtering and power amplifying, the received signals of two bands are sent into the two sub-MZMs of DPol-MZM3, respectively. The sub-MZMs also biased at the MATP. After PD6, communication information can be recovered at the output of LPF.

Assume that the normalized emitting communication signal is a frequency quadrupled phase-coded LFM waveform train, which can be written as,

\[ i_r(t) = \cos(4\omega_{IF}t + 2kt^2 + N_\text{sig} \Delta \phi) , (0 < t < T) \]  

(9)

So, in the receiver end, the corresponding received signal can be given by,

\[ i_{ri}(t) = i_r(t - \frac{L}{c}) \]  

(10)
Where \( L \) is the propagation distance from the transceiver end to receiver end. The local signal sent into DPol-MZM3 on polarization direction \( x \) can be expressed as,

\[
E_{\text{local}}(t) = \frac{1}{2} \sum_i E_i e^{j\phi_i} \left[ J_0(m_i) + J_2(m_i) e^{j4\pi \phi_i (t - \tau)} \right] \delta(t - iT) \tag{11}
\]

\( \tau \) is the time delay introduced by the tunable delay line. In order to ensure the phase synchronization to the received signal, the time delay should be tuned as,

\[
\tau = \frac{L}{c} \mod T \tag{12}
\]

Where \( \mod \) represents modulus. Then the output of DPolMZM3 on polarization direction \( x \) can be given by,

\[
E_{\text{output}}(t) = \frac{1}{2} \sum_i E_i e^{j\phi_i} \left[ J_0(m_i) + J_2(m_i) e^{j4\pi \phi_i (t - \tau)} \right] \delta(t - iT) \tag{13}
\]

Finally, after the PD and the LPF, the demodulated signal can be expressed as

\[
i_{\text{demod}}(t) \propto \sum_i \cos(2N_i \Delta \phi) \delta(t - iT) \tag{14}
\]

Therefore, the communication information is successfully recovered.

2.4 Functional separation in the receiver end

Since the phase-coded LFM waveform generated in a photonic generator can be simultaneously used for target detection and wireless communication, so in the receiver end, the received signal needs to be functionally separated to perform de-chirping and coherent demodulation. In this scheme, we adopt the method proposed by George N. Saddik [30]. In the emitting end, two right-handed circularly polarized (RHCP) antennas working in different wavebands are used. And in the receiver end, two RHCP antennas are used to receive the communication signals, while two left-handed circularly polarized (LHCP) antennas are deployed to receive the echo waves of the radar detection.

As shown in Fig. 5, the phase-coded LFM signal transmitted by the photonic generator is a right-handed polarized wave, which can be directly received by RHCP receiving antenna as a communication signal. On the other hand, the polarization direction of the reflected wave will be reversed to be a left-handed polarized wave. Consequently, the echo signal can only be received by an LHCP antenna to perform radar detection. The separation of communication and radar functions...
can be achieved in the receiver end.

3. Simulation and Discussion

The feasibility of the proposed scheme is verified by a simulation based on the platform Optisystem. The central frequency and optical power of LD are set to be 191.3 THz and 16 dBm. The extinction ratio of all the sub-MZMs is 30 dB.

3.1 Application on Radar Detection

In this section of simulation, an electrical repetitive LFM wave train with a repetitive period of 10 ns is provided. Each basic LFM waveform is chirped from 3 to 5 GHz. Fig. 7 shows the DC blocked waveforms and time-frequency diagrams of the generated dual-band signals. As shown in Figs. 7(b) and (d), LFM waveform chirped from 6 to 10 GHz, and 12 to 20 GHz is generated, which means that frequency-doubled and quadrupled dual-band radar signals are successfully obtained.

Fig.7 (a)Waveforms of generated 6~10 GHz signal and (b)its instantaneous frequency, (c) waveforms of generated 12~20 GHz signal and (d)its instantaneous frequency.

To further verify the tunability of the proposed generator, we change the chirp range of the driving signal to 3–6.5 GHz and 4–5 GHz. As shown in Figs. 8(b) and (d), 6~13 GHz and 12~26 GHz LFM wave trains are generated. In Figs. 8(f) and (h), 8~10 GHz and 16~20 GHz, LFM signals are obtained. Since the OFs are only used to extract the positive order sidebands, the passbands don’t need to be adjusted to generate the signals of different chirp range. Consequently, the tunability of the proposed generator will not be influenced by the OFs.
Optical de-chirping to the echo signals is also demonstrated. A 2–3 GHz, 10 μs driving signal is used in this section. A time delay of 0.1 μs is introduced to the emitted signal and then sent into the receiving antenna, corresponding an echo signal reflected from a target with distance of 15 m. Figs. 9(a) and (b) show the electrical spectra of the de-chirp results of each band signal. The peak pulses have frequencies of 79.96 MHz and 160.11 MHz, respectively, which are substantially consistent with the theoretical value 80 MHz and 160 MHz. Besides, the RF spurious sidebands suppression ratios (SSRs) are 42.38 dB and 41.78 dB. Thus, low-speed and real-time radar signal processing of dual-band radar are achieved.

To verify the improvement of the time bandwidth product (TBWP) of this proposed scheme,
auto-correlation functions of the 4–6 GHz, 10 ns driving LFM waveform and corresponding generated LFM waveforms are investigated. As can be seen in Figs.10(a), (b), and (c), the full widths at half maximum (FWHM) of the pulses are 0.6 ns, 0.3 ns, and 0.15 ns. The pulse compression ratios (PCRs) of the driving waveform, the generated bandwidth-doubled and quadrupled waveforms are 16.7(10 ns/0.6 ns), 33.3 (10 ns/0.3 ns) and 66.7(10 ns/0.15 ns), respectively. It indicates that the TBWP of the generated waveforms is improved by twice and four times.

![Fig.10 Auto-correlation functions of basic waveforms of (a) driving LFM signal, (b) frequency-doubled, and (c) quadrupled LFM signals.](image)

Then, two binary sequences are set as two M sequences with lengths of 31 and 63 respectively, the sequences are employed to generate phase-coded dual-band LFM signals. Fig.11(a) shows the auto-correlation of bandwidth-doubled phase-coded LFM waveform which is modulated by the 31-length M sequence. The PCR is 1033.33 (310 ns/0.3 ns), and its TBWP is improved by 62 times. The auto-correlation of the bandwidth-quadrupled LFM waveform which is modulated by the 63-length M sequence is shown in Fig.11(b). The PCR of the pulse is 4200 (630 ns/0.15 ns), verifying that the TBWP is improved by 252 times.

![Fig.11 Auto-correlation of (a) bandwidth doubled waveforms modulated by a 31-length M sequence and (b) bandwidth quadrupled waveforms modulated by a 63-length M sequence.](image)

3.4 Wireless Communication for Dual Users
Fig. 12 (a) Waveforms of generated bandwidth-doubled LFM signal and (b) zoom in on it, (c) waveforms of generated bandwidth-quadrupled LFM signal, and (d) zoom in on it.

In this section, the capability of this scheme to generate dual-band phase-coded LFM signals and perform phase demodulation on the optical domain is demonstrated. A 3–5 GHz, 10 ns LFM waveform train is generated by the AWG, binary sequences "1001011010" and "0010001011" with identical bit rate of 0.1 Gbit/s are provided by PPG1 and PPG2, respectively. The modulation index of both sub-MZMs in DPol-MZM1 is set as 1.57. Figs. 12(a) and (c) show the DC-blocked waveforms of the phase-coded LFM signals of two bands. For the generated bandwidth-doubled LFM signal, the zoom-in and overlapped view of two waveforms with time windows from 0 to 1 ns and 10 to 11 ns is shown in Fig 12(b), a 90° phase shift can be observed. Fig. 12(d) shows the zoom-in and overlapped view of two waveforms for the bandwidth-quadrupled phase-coded signal, a 90° phase shift also exists. Consequently, phase modulation is successfully performed.

Fig. 13 (a) Binary signal used to generate bandwidth-doubled waveform and (b) its demodulation result, (c) binary signal used to generate bandwidth-quadrupled waveform, and (d) its demodulation result. Fig. 13(a) and (c) show the normalized binary signals provided by PPG1 and PPG2, while the phase-demodulated waveforms of each band are shown in Fig. 13(b) and (d). Obviously, the phase
information is recovered, and optical demodulation is successfully achieved.

As can be seen, the proposed scheme is capable of achieving wireless communication in two bands, which can support independent communication for two users.

4. Conclusion

A photonic approach to generate a dual-band phase-coded LFM signal is proposed and demonstrated. Bandwidth-doubled and quadrupled LFM waveforms modulated by different binary sequences are simultaneously generated. Optical de-chirping and phase demodulation are also achieved. The proposed scheme is verified by simulation. The results show that 6–10 GHz and 12–20 GHz LFM waveforms are generated with a 3–5 GHz driving signal. Changing the chirp range of the driving signal to 3–6.5 GHz and 4–5 GHz, frequency-doubled and quadrupled LFM signals can also be obtained, which shows the good tunability of the proposed generator. For radar detection, optical de-chirping to an echo signal of a target 15 m away is performed, and the de-chirp results in each band are 79.96 MHz and 160.11 MHz, which are consistent with the theoretical values. By setting the binary sequences as 31-length and 63-length M sequences, the TBWPs of the generated dual-band signals are respectively improved by 62 and 252 times. Application on wireless communication is also demonstrated. Two different binary signals are respectively modulated to the two LFM signals of each band, and the optical demodulation results show that the communication information can be successfully recovered. The proposed method will find wide applications in dual-band radar and covert wireless communication for dual users.

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