Microwave Photonic Phase Shifter with frequency up-/down-conversion

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Abstract: In this paper, we propose a microwave photonic phase shifter with frequency conversion (MPSFC) without optically filtering to realize both frequency up- and down-conversion and a full 360° phase-shift for the microwave signal based on an integrated dual-polarization dual-parallel Mach-Zehnder modulator (DP-DPMZM). As the radio frequency (RF) signal is frequency down-converted to intermediate frequency (IF) signal or the IF signal can be frequency up-converted to RF signal, the phase of the output IF or RF signals can be shifted by adjusting the DC bias voltage of PolM. Simulation results demonstrate that both 360° continuously tunable phase shift and frequency conversion can be implemented simultaneously.

1. Introduction
In many applications including millimeter-wave phased-array beamforming networks, phase noise measurement, phase-coded radar systems, and automatic phase control, both frequency conversion and phase shifting are required. On one hand, microwave photonic phase shifter plays a key role in phased-array antennas [1] and analog signal processing [2]. On the other hand, intermediate frequency (IF) signals should be up-converted into radio frequency (RF) signals at the transmitter, and vice versa at the receiver [3]. In fact, combining these two functions into a simple configuration can not only simplify the system structure, but also improve its performance. Recently, microwave photonic frequency down-converters with phase-shift capability have been reported [4–6]. However, the narrow bandwidth of the optical filter limits their frequency tunability. In [7], a frequency converter with phase shift over 360° is reported, while wavelength-division demultiplexer, time delay lines (TDLs), polarizer, and a polarization controller are required to realize the phase shifting, which increase the complexity of the system.

In this paper, we propose an MPSFC which can realize frequency down- and up-conversion of the microwave signal with a full 360° phase-shift capability. In the technology proposed here, an SSB-CS modulated signal with two orthogonally polarized tones is generated by a DP-DPMZM. Then a PolM is used to introduce the opposite phase shift between the two modes by applying a DC bias voltage. Then the orthogonally polarized signal goes through the Pol and is aligned into one polarization state. After detection by a photodiode (PD), a frequency-converted and phase-shifted microwave signal can be obtained. Since the proposed MPSFC doesn't use optical filter, it possesses better frequency tunability. Moreover, a full 360° continuously adjustable phase shift can be achieved using only one DC bias voltage, and the phase shift has a linear relationship with the DC bias voltage.
2. Topology and principle of operation

Fig. 1. System diagram of the microwave photonic phase-tunable frequency converter.

The schematic diagram of our proposed MPSFC is shown in Fig.1, which consists of a laser diode (LD), a DP-DPMZM, two polarization controllers (PCs), a polarization modulator (PolM), a polarizer (Pol) and a photodiode (PD). The DP-DPMZM [6] consists of two DPMZMs (DPMZM1 and DPMZM2) connected in parallel with a 90° polarization rotator after the DPMZM2. When the lightwave emitted from the LD and indicated as $E_{in}(t)=E_0 \exp(i \omega_c t)$ is injected into the DP-DPMZM. One beam is SSB-CS modulated by the RF signal via DPMZM1 and the other beam is SSB-CS modulated by the LO signal via DPMZM2. So the output lightwave field of the DP-DPMZM can be expressed in Jones matrix as

$$E_{DP-DPMZM}(t) = \begin{bmatrix} E_x \\ E_y \end{bmatrix} = -\frac{\sqrt{2}}{2} j E_0 \exp(j \omega_c t) \begin{bmatrix} J_1(\beta_{RF}) \exp(j (\omega_c t)) \\ J_1(\beta_{LO}) \exp(\pm j \omega_c t) \end{bmatrix}$$

where $J_n(\cdot)$ is the $n$th-order Bessel function of the first kind, $E_0$ and $\omega_c$ are the amplitude and angular frequency of the optical carrier. $\beta_n$ is the modulation index of the DPMZMn and is defined as $\beta_n(t)=\pi V_{in}/V_{x1}$, $V_{x1}$ is the half-wave voltage of the DP-DPMZM. $V_{in}$ and $\omega_n$ are, respectively, the amplitude and angular frequency of the driving RF/LO signal. Then, the lightwaves $E_x$ and $E_y$ at the output of the DP-DPMZM are injected into PolM via PC1. The DC bias voltage of the PolM introduces the opposite optical phase shift between the two tones, and so the lightwave field output of the PolM can be expressed as

$$E_{Pol}(t) = \begin{bmatrix} E_x \\ E_y \end{bmatrix} = -\frac{\sqrt{2}}{2} j E_0 \exp(j \omega_c t) \begin{bmatrix} J_1(\beta_{RF}(t)) \exp(j (\omega_n t)) \exp(\frac{\pi}{V_{x2}}u) \\ J_1(\beta_{LO}) \exp(\pm j \omega_n t) \exp(-j \frac{\pi}{V_{x2}}u) \end{bmatrix}$$

where, $V_{x2}$ is the half-wave voltage of the PolM; and $u$ is the DC bias voltage being applied to the PolM. Then, a Pol with its principal axis oriented by an angle of 45° to one principal axis of the PolM is used to assign $E_x$ and $E_y$ into one polarization state. So the output lightwave field of the Pol can be expressed as

$$E_{Pol}(t) = -\frac{1}{2} j E_0 \exp(j \omega_c t) \begin{bmatrix} J_1(\beta_{RF}) \exp(j (\omega_n t)) \exp(\frac{\pi}{V_{x2}}u) \\ J_1(\beta_{LO}) \exp(\pm j \omega_n t) \exp(-j \frac{\pi}{V_{x2}}u) \end{bmatrix}$$

The phase-shifted dual-tone optical signal is then injected into the square-law PD for photodetection. The RF signal from the PD can be expressed as
\[ i_n(t) = \frac{1}{4} E_0^2 J_1(\beta_{RF}) J_1(\beta_{LO}) \cos \left[ (\omega_{RF} - \omega_{LO}) t + \theta \right] \quad (4) \]

It can be seen from Eq. (4) that the RF signal is frequency up- and down-converted with the frequency shift of \( \omega_{LO} \) by the RF local oscillator and is phase shifted with a phase of \( \theta (\theta = 2\pi u/V_{CC}) \) by the DC bias voltage of the PoL. The frequency shift of \( \omega_{LO} \) depends on the local oscillator; the phase shift is linearly proportional to the DC voltage of \( u \) and can be tuned over 360° range. As the relationship between the phase shift and the DC bias voltage of the PoL, \( \theta = 2\pi u/V_{CC} \), is linear, the phase of the frequency-converted signal can easily be shifted by adjusting the DC voltage. Note that, in our proposed MPSFC, adjusting the DC bias voltage of the PoL only changes the phase of the frequency-converted signal while maintaining its amplitude constant.

3. Simulation Results and Discussion

A simulation is conducted to demonstrate the proposed MPSFC, as shown in Fig. 1. In the simulation, the wavelength, optical power and linewidth of the lightwave emitted from the LD are 193.1 THz, 16 dBm and 10 MHz, respectively. The lightwave is injected into a DP-DPMZM. In the DP-DPMZM, the lightwave is split equally and fed into two parallel DPMZMs. For each DPMZM, the half-wave voltage of each sub-modulator is 3.5 V.

Firstly, we demonstrate the performance of frequency down conversion. The RF signal with the frequency of 20 GHz is applied to the DPMZM1 and the bias voltages of DPMZM1 are set as \( V_{b1}=V_{b2}=V_{x1}, V_{b3}=V_{x1}/2 \). The LO signals with the frequencies of 2/4/6/8/10 GHz are applied to the DPMZM2, respectively. The bias voltages of DPMZM2 are set as \( V_{b4}=V_{b5}=V_{x1}, V_{b6}=V_{x1}/2 \). The optical spectra of the DP-DPMZM output with the different LO frequencies, is shown in Fig. 2(a). It can be seen that both the lower sideband and the carrier of the RF and LO modulation signals are suppressed, leaving only the upper sidebands. After going through a Pol, the optical signal is photodetected by a high-speed PD with a sensitivity of 1 A/W, and the RF spectra are given in Fig. 2(b). The frequency spacing between the two optical tones is equal to the frequency difference of the RF and the LO signals, which means the RF signal is frequency down-converted. From Fig. 2(a) and (b), as the LO frequency is tuned from 2 GHz to 4, 6, 8, 10 GHz, the frequency spacing is varied from 18 GHz to 16, 14, 12, 10 GHz, in turn, and the 20 GHz RF signal is down-converted to 18/16/14/12/10 GHz, while the down-converted RF signals keep almost constant magnitude.

\[
\begin{align*}
(a) & \\
(b) & 
\end{align*}
\]

Fig. 2. (a) Optical spectra at the output of DP-DPMZM with the resolution of 0.001 nm; (b) Electrical spectra for frequency down-conversion in the proposed scheme.

For the up-conversion case, the bias voltage of DPMZM2 is set as \( V_{b6}=V_{x1}/2 \), but not \( V_{b6}=V_{x1}/2 \). The optical spectra of the DP-DPMZM output with the different LO frequencies are shown in Fig. 3(a). We can see that the RF signal generates the same optical sideband as the down-conversion cases but the LO generates the lower sidebands. Different from the frequency down-conversion case, the frequency spacing between the two optical tones is equal to the frequency addition of the RF and LO signals, which means a frequency up-conversion for the RF signal. As the LO frequency is tuned, the frequency spacing
varies correspondingly. Then the two optical tones go through a Pol and are aligned into one polarization state. After detecting by a photodiode (PD), the up-converted RF signals are generated, as spectra shown in Fig. 3(b). Fig. 3(a) and (b) show the spectra of the DP-DPMZM output with the LO frequencies of 2, 4, 6, 8 10GHz, the output two optical tones have the frequency spacing of 22, 24, 26, 28, 30 GHz in turn, and the 20 GHz RF signal is up-converted to 22/24/26/28/30 GHz while the amplitude of up-converted RF signals maintains stable.

![Graph](image1)

**Fig. 3.** (a) Optical spectra at the output of DP-DPMZM with the resolution of 0.001nm; (b) Electrical spectra for frequency up-conversion in the proposed scheme.

To verify the 360° fully tunable phase shift capability of the proposed MPPTCF besides the frequency conversion, a 15 GHz RF sinusoidal-signal is down-converted to 10 GHz signal by mixing it with a 5 GHz LO signal. The waveforms of the down-converted RF signals from the PD are shown in Fig. 4 where the DC bias voltage of the PolM with a half-wave voltage of 4.0V is adjusted from 0 to 4.0V with a step of 0.5V. It can be seen that the phase shift of the generated down-converted RF signal in Fig. 4(b)–(i) is shifted linearly with a step of 45° relative to the waveform in Fig. 4(a) where the bias voltage is 0V. It can be seen from Fig. 4(j) that the phase shift is proportional to the DC bias voltage of the PolM. If the DC bias voltage of the PolM is adjusted continuously, we can realize the frequency down-converted RF signal with continuous phase shift. In the real system, since the commercial DC power supplies have a voltage resolution of < 10 mV and a fast response time (< 50μs), the RF signal phase shifter can reach a 1° phase shift resolution and a tuning speed similar to [6].

![Graph](image2)

**Fig. 4.** (a)–(j) are the waveforms of phase-shifted down-converted signal at 10 GHz with phase shifts of 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315° and 360°; (j) the relationships between RF signal phase shift and DC bias voltage of PolM.

So does for the frequency up-conversion case, as shown in Fig. 5(a)–(i) show the waveforms of the 20 GHz up-converted signal at different DC bias voltage of the PolM, and Fig. 5(j) shows that when the DC bias voltage of the PolM is adjusted from 0 to 4.0V in steps of 0.5V, the phase of the down-converted RF signal linearly shifts in steps of 45°. It can be seen that the MPSFC can realize frequency up-conversion with linear continuous phase shift within 360°. It can be seen from Fig. 4(j) and Fig. 5(j) that
the scopes of the lines are identical which means that, the RF converted signals at different frequencies have the same phase shift if the DC bias voltages of PolM are equal.

Fig. 5. (a)–(i) are the waveforms of phase-shifted up-converted signal at 20 GHz with phase shifts of 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315° and 360°; (j) the relationships between RF signal phase shift and DC bias voltage of PolM.

4. Conclusion
This paper has proposed an MPSFC based on a dual-polarization dual-parallel Mach-Zehnder modulator (DP-DPMZM) for both frequency up-/down-conversion and linear phase shift. The proposed MPSFC can realize the frequency up-/down-converted of the RF signals with a tunable phase by a LO signal and a DC bias voltage of the PolM. Simulation results show that the 20GHz RF signal is up (down)-converted to 30 (10) GHz by a 10 GHz LO signal, and the up-/down-converted RF signals keep almost constant magnitude. At same time, the phase shift of the up-/down-converted RF signal has a linear relationship with the DC bias voltage of the PolM, and can be tuned over 360° range.

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