Broadband Microwave Photonic Phase Shifter Based on Heterodyne frequency conversion

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***Abstract*—A broadband microwave photonic phase shift scheme based on LO signal heterodyne frequency conversion is proposed, with the benefits of the 360° phase shift transferred from simple- frequency LO signal to ultra-wideband RF signal.**

Keywords—microwave photonics, heterodyne frequency conversion, phase shifter, DPMZM modulator

I. INTRODUCTION

Microwave phase shifters have many applications, such as phased array radar [1] and broadband wireless communication [2]. With the rapid development of radar and communication systems, the carrier frequency of signals is getting higher and higher, and the signal bandwidth is also getting larger and larger. The traditional microwave phase shifter is limited in terms of operating bandwidth, tuning speed and phase shift range. In recent years, microwave photonic phase shifters have attracted much attention due to their wide bandwidth, low loss, fast tuning and anti-electromagnetic interference [3]. So far, many different methods have been reported to realize microwave phase shifters. One method is to use stimulated Brillouin scattering (SBS) effect [4, 5], however the use of the SBS effect makes the phase shifter too complex, which also an requires accurate pump signal. The other method is to tune the phase of the microwave signal by properly controlling the amplitude of two microwave signals with a 90° phase difference based on the principle of vector sum [6]. The main disadvantage of this method is that the configuration of the phase shifter is too complex. Another method to realize photonic microwave phase shifter is the photonic microwave phase shifter based on modulator and optical bandpass filter (OBPF) [7]. However, the use of OBPF limits the frequency tunable range and affects the stability of the phase shifter.

In this paper, we propose a microwave photon frequency conversion phase shifter for broadband signals. The proposed variable frequency phase shifter is based on dual-parallel Mach–Zehnder modulator (DPMZM) and variable frequency local oscillator (LO) signal. In DPMZM, the broadband signal and RF signal through the 90° hybrid coupler (HC) are respectively loaded into the upper and lower arms of DPMZM, where DMZM1 and DMZM2 are both biased at the quadrature transmission point (QTP) to achieve single-sideband (SSB) modulation. By adjusting the main offset point of the DPMZM, the optical carriers of the upper and lower arms cancel each other, so as to obtain the required optical signal, while avoiding the use of OBPF. The frequency of the output broadband signal after the beat of the optical signal depends on the frequency difference between the local oscillator signal and the input signal, which can realize the adjustable frequency conversion function. The phase of the output broadband signal changes with the phase of the local oscillator signal, which can achieve a full 360° phase shift without bandwidth limitation.

II. TOPOLOGY AND OPERATION PRINCIPLE

Fig. 1 shows the structure of the broadband microwave photonic phase shifter. The system consists of a laser diode (LD), two 90° HCs, a DPMZM, an Erbium-doped-fiber-amplifier (EDFA) and a photodetector (PD). The sub-MZMs of the DPMZM in our system are dual-drive. In the system, continuous-wave (CW) light generated by the LD is injected into the DPMZM , which can be expressed as $E_{in}(t) = E_{in} \bullet e^{j\omega_c t}$.

Three direct-current voltages are used to control the bias points of the DPMZM. A broadband signal that can be expressed as $V_{RF} \bullet g(t) \bullet \cos(\omega_{RF} t)$ is loaded at the two arms of the DMZM1 after going the 90° HC. By controlling DC1, we can set $\varphi_1 = \pi/2$ in the DMZM1, and we can get

$$E_1(t) = \frac{E_{in}(t)}{2}\left[e^{j(\beta_1 \cdot g(t)\cdot \cos\omega_{RF}t)} + e^{j(\beta_1 \cdot g(t)\cdot \sin\omega_{RF}t+\pi/2)}\right] = \frac{E_{in}(t)}{2}\left[(1+j)J_0(\beta_1) + 2jJ_1(\beta_1)\cdot g(t)\cdot e^{j\omega_{RF}t}\right] \tag{1}$$

Where $J_n(\bullet)$ is the nth-order Bessel function of the first kind, and $\beta_1 = \pi V_{RF}/V_{\pi 1}$ is the modulation depth of the broadband signal. The DMZM1 can realize the Single-sideband modulation (SSB).

A phase-controlled LO signal expressed as $V_{LO}\cos(\omega_{LO}t+\theta)$ is loaded at the two arms of the DMZM2 after going the 90° HC. By controlling DC2, we can set $\varphi_2 = \pi/2$ in the DMZM2, and we can get

$$E_2(t) = \frac{E_{in}(t)}{2}\left[e^{j(\beta_2 \cos(\omega_{LO}t+\theta))} + e^{j(\beta_2 \sin(\omega_{LO}t+\theta)+\pi/2)}\right] = \frac{E_{in}(t)}{2}\left[(1+j)J_0(\beta_2) + 2jJ_1(\beta_2)e^{j(\omega_{LO}t+\theta)}\right] \tag{2}$$

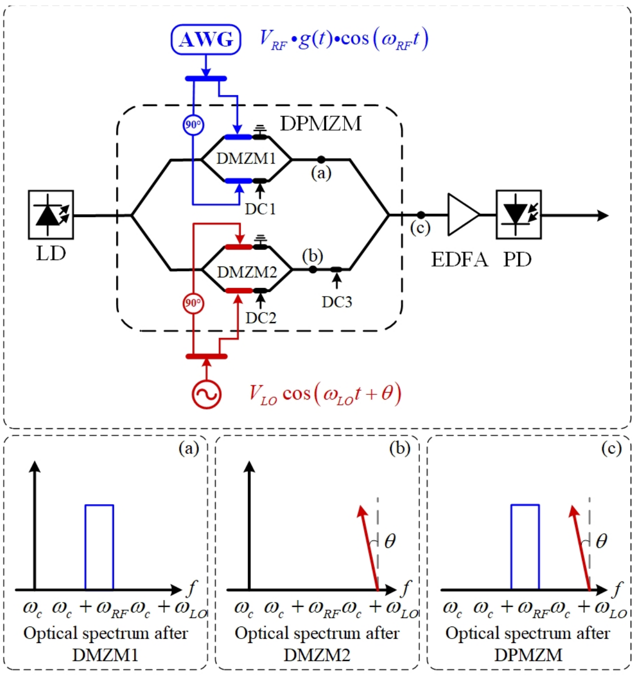

Fig. 1. Schematic of the broadband microwave photonic phase shifter. (a) and (b) the illustration of the optical spectrum in the DMZM1 and DMZM2. (c) The optical spectrums output form the DPMZM

Where $\beta_2 = \pi V_{LO}/V_{\pi 2}$ is the modulation depth of the LO signal. We can see from (2) that the DMZM2 also realizes SSB. Two optical signals are modulated by the parent-MZM of the DPMZM, and the output can be expressed as

$$E_{out}(t) = \frac{1}{2}\left[E_1(t) + E_2(t)e^{j\varphi_3}\right] = \frac{E_{in}(t)}{4}\begin{bmatrix}(1+j)\left(J_0(\beta_1)+J_0(\beta_2)e^{j\varphi_3}\right) \\ +2jJ_1(\beta_1)\cdot g(t)\cdot e^{j\omega_{RF}t} \\ +2jJ_1(\beta_2)e^{j(\omega_{LO}t+\theta+\varphi_3)}\end{bmatrix} \tag{3}$$

Where $\varphi_3 = \pi V_{DC3}/V_{\pi DC3}$ is the phase shift of the parent-MZM. By adjusting DC3, the optical carrier can be suppressed, that is $J_0(\beta_1)+J_0(\beta_2)e^{j\varphi_3}=0$, and expression (3) can be simplified as

$$E_{out}(t) = \frac{E_{in}(t)}{4}\begin{bmatrix}2jJ_1(\beta_1)\cdot g(t)\cdot e^{j\omega_{RF}t} \\ +2jJ_1(\beta_2)e^{j(\omega_{LO}t+\theta+\varphi_3)}\end{bmatrix} \tag{4}$$

The optical signals are amplified by the EDFA，and then beat by the PD, the output signals can be given as

$$i_{PD} = E_{out}\cdot E_{out}^{*} \propto E_{in}^2 \cdot J_1(\beta_1)\cdot J_1(\beta_2)\cdot g(t)\cdot \cos\left[(\omega_{LO}-\omega_{RF})t+\theta+\varphi_3\right] \tag{5}$$

It can be seen from formula (5) that the frequency of the output signal is determined by $\omega_{LO}-\omega_{RF}$. By reasonably setting the value of ω_{LO}, a broadband output signal with up/down conversion or constant frequency can be obtained. The phase of the output signal is determined by the phase θ carried by the local oscillator signal, and the phase of the output broadband signal can be shifted by adjusting θ.

III. Simulation Results

To investigate the performance of the broadband microwave photonic phase shifter, a simulation based on the setup shown in Fig. 1 is conducted.

A. RF Signal Verification Simulation

First, in order to verify the 360° fully tunable phase-shift performance of the system, the RF signal is used to replace the broadband signal for simulation. 10GHz LO signal and 5GHz RF signal are applied to the modulator after passing through 90° HC respectively.

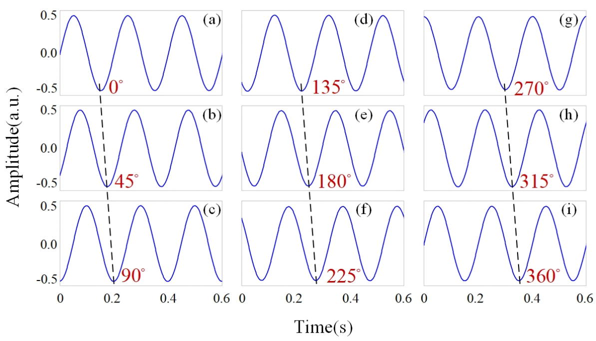

Fig. 2. (a)-(i) are the waveforms of RF signal with phase shifts of 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315° and 360°.

In the simulation, the phase of LO signal is adjusted in 45 ° steps. The waveforms of the RF signals from the PD are shown in Fig. 2. It can be seen that the output signal is still a 5GHz RF signal, and phase shift of the RF signals in Fig. 2 (b)-(i) are shifted linearly with a step of 45° relative to the waveform in Fig. 2(a). The phase shift of the output RF signal is the same as that of the LO signal, and 360° fully tunable phase shift can be achieved.

B. Broadband Signal Verification Simulation

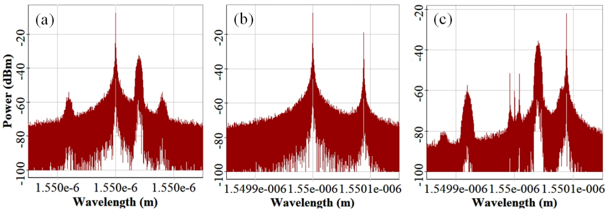

Fig. 3. (a) The optical spectrums of the QPSK signal with a 2GHz bandwidth and a 5GHz center frequency modulated by SSB. (b) The optical spectrums of the LO signal modulated by SSB. (c) The optical spectrums output from the DPMZM

Based on the structure designed in Fig. 1, the broadband frequency conversion and phase shift performance of the system is simulated and tested using broadband signals. The broadband signal is a Quadrature Phase Shift Keying (QPSK) signal with a 2GHz bandwidth and a 5GHz center frequency, and the LO signal is an 11GHz cosine signal. The broadband signal and LO signal are applied to the DPMZM after 90 °HC. The both arms of the modulator are subjected to SSB, and the optical carrier is eliminated through the main bias of the modulator. Fig. 3 shows the optical spectrum of this process. There are second-order optical sidebands in Fig. 3 (a) and (c). However, the second order that is 20dB lower than the first-order optical sideband does not affect the desired signal.

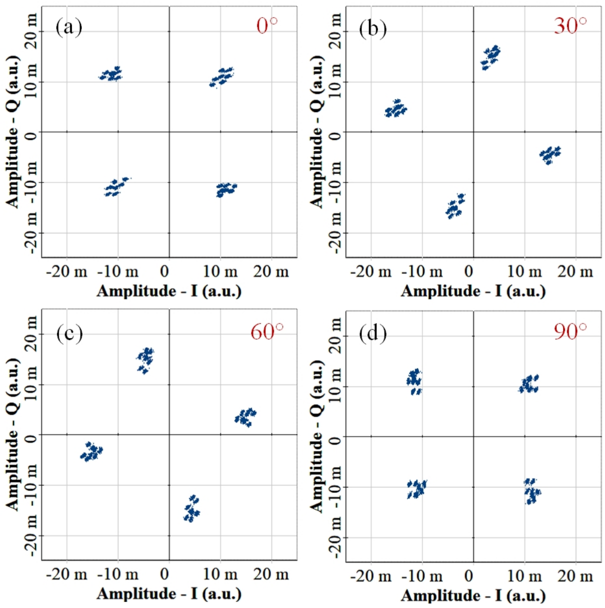

Fig. 4. Constellation after output QPSK signal demodulation with phase shifts of 0°, 30°, 60°and 90°.

After the DPMZM output optical signal is amplified by EDFA, a QPSK signal with a bandwidth of 2GHz and a center frequency of 6GHz is generated from PD. Demodulate the converted QPSK signal and observe the phase shift of the broadband signal through the constellation diagram, as shown in Fig. 4. In the simulation, the phase of the LO signal is changed in steps of 30 ° . By comparing Fig. 4 (a) to Fig. 4 (d), we can see that with the phase shift of the LO signal, the constellation of the broadband signal rotates, and the rotation angle of the constellation corresponds to the phase shift of the LO signal. As the LO signal generates a 90° phase shift, the wideband signal constellation rotates to the orthogonal position again. The center frequency of the output signal depends on the difference between the LO signal and the QPSK signal. By selecting the appropriate frequency of the LO signal, the up/down conversion of the broadband signal can be achieved, or a broadband signal with a constant center frequency can be obtained. Simulation results show that the proposed system can realize the function of frequency conversion and phase shift of broadband signal.

IV. Conclusion

We propose a microwave photonic broadband phase shifter based on heterodyne frequency conversion of phase-tuned LO signals. By changing the phase of the LO signal, the phase shift of the broadband signal without bandwidth limitation can be realized. According to the simulation, this scheme can realize 360° fully tunable phase shift of broadband signal, and has great potential in the future broadband wireless communication system.

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