Ultrawideband RF Photonic Phase Shifter Using Two Cascaded Polarization Modulators

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***Abstract*— An ultrawideband RF photonic phase shifter implemented using two cascaded polarization modulators (PolMs) is proposed and experimentally demonstrated. The first PolM (PolM1) is employed to generate an optical carrier and two first-order sidebands that are orthogonally polarized. By aligning the polarization directions of the optical carrier and the two first-order sidebands from the first PolM with the two principal axes of the second PolM (PolM2), complementary phase modulation on the optical carrier and the first-order sidebands is produced if a DC voltage is applied to the second PolM. By selecting the optical carrier and one sideband using an optical filter and beating them at a photodetector, an RF signal with its phase that is tunable by tuning the applied DC voltage is generated. The proposed phase shifter has the advantages of fast tuning and an ultrawide frequency tunable range. An experiment is performed. A full 360° phase shift over an ultrawide frequency range from 5 to 40 GHz is demonstrated. The spurious free dynamic range of the phase shifter is also studied.**

***Index Terms*— Microwave photonics, microwave phase shifters, phased-array beamforming, analog signal processing.**

I. INTRODUCTION

RF PHASE shifters play a key role in phased-array antennas [1], and analog signal processing [2]. Compared with conventional RF phase shifters implemented based on ferrite materials [3], p-i-n diodes [4], or monolithic microwave integrated circuits [5], RF photonic phase shifters have some distinct advantages, such as wider bandwidth and larger tunable range. In the past few years, several photonic-assisted RF phase shifters have been proposed and demonstrated [6]–[10]. Based on stimulated Brillouin scattering in an optical fiber [6], an RF phase shifter with a tunable phase shift of 360° realized by tuning the frequency of an external microwave signal at around 10 GHz was demonstrated. Slow- and fast-light effects either in a tilted erbium-ytterbium (Er/Yb) co-doped fiber Bragg grating (FBG) pumped by a 980-nm laser diode [7] or in a semiconductor optical amplifier (SOA) [8] have also been studied for the implementation of an RF phase shifter over a large bandwidth of tens of GHz. For a phase shifter based on a tilted FBG, the phase can be continuously tuned by pumping the tilted FBG, but the tuning speed is relatively slow in the range of milliseconds [7]. For an SOA-based phase shifter, the tuning speed can be ultra-high (<ns). To achieve a large phase shift, however, multiple SOAs should be used, which may make the system complicated [8]. In addition, for the techniques in [7] and [8], when the phase is tuned, the power at the output of the phase shifter is changed, a phenomenon that is not expected for many applications. By jointly using a polarization modulator and an edge filter to realize single sideband (SSB) modulation [9], [10], a 360° RF phase shifter with a bandwidth of tens of GHz has been demonstrated. The phase shift is introduced by changing the polarization direction of the SSB-modulated light wave. However, to achieve fast phase tuning, an additional high-speed polarization controller is required. Using a polarization modulator (PolM) and a polarization-maintaining fiber Bragg grating (PM-FBG), a wideband microwave photonic phase shifter can also be implemented [11]. Although the system is simple due to the reuse of the PolM in its backward direction, the tunable range is small due to the limited bandwidth of the PM-FBG.

In this letter, we propose and experimentally demonstrate an approach to implementing a fast tuning RF photonic phase shifter with a full 360° phase shift over an ultrawide band using two cascaded PolMs. A PolM is a special phase modulator that supports phase modulation along the two principal axes with opposite phase modulation indices [12]. The fundamental principle of the approach is to use the first PolM (PolM1) to generate an optical carrier and two first-order sidebands that are orthogonally polarized. By aligning the polarization directions of the optical carrier and the two first-order sidebands with the two principal axes of the second PolM (PolM2), complementary phase shifts to the optical carrier and the two first-order sidebands will be introduced if a DC voltage is applied to PolM2. By selecting the optical carrier and one sideband using an optical bandpass filter and beat them at a photodetector (PD), an RF signal with its phase that is tunable by tuning the applied DC voltage is generated. The proposed RF phase shifter is experimentally demonstrated. An RF signal with a phase shift in a full 360° range over an ultra-wide frequency range of 5-40 GHz is generated. The spurious free dynamic range (SFDR) of the phase shifter is also studied. For a noise floor of −166 dBm/Hz, the SFDR is measure to be 82 dB· $Hz^{2/3}$.

II. PRINCIPLE

The schematic of the proposed ultra-wideband RF photonic phase shifter is shown in Fig. 1(a). A continuous-wave (CW)

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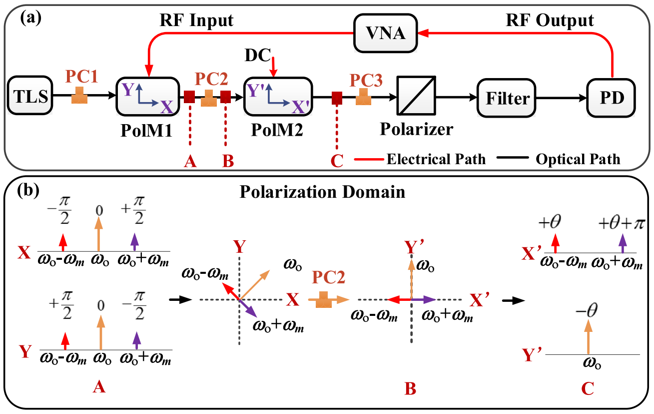

Fig. 1. (a) Schematic of the proposed ultra-wideband RF photonic phase shifter. (b) Evolution of the polarization directions of the optical signal through the cascaded PolMs. TLS: tunable laser source; PolM: polarization modulator; PD: photodetector; VNA: vector network analyzer; PC: polarization controller.

light wave from a tunable laser source (TLS) is sent to PolM1 at an angle of 45° relative to one principal axis of PolM1 via a polarization controller (PC1). A microwave signal from a vector network analyzer (VNA) is applied to PolM1 via the RF port. Due to the opposite phase modulation along the two principal axes of PolM1, two complementarily phase-modulated optical signals are generated at the output of PolM1. The combination of the two phase-modulated signals corresponds to a single optical signal with the carrier and the first-order sidebands orientated at an angle of 45° and 135° relative, respectively, to the horizontal axis of PolM1, as shown in Fig. 1(b). Then, a second PC (PC2) is used to align the polarization directions of the optical carrier and the first-order sidebands with the two principle axes of PolM2. A DC voltage is applied to PolM2. Again, due to the complementary nature of phase modulation, the optical carrier and the sidebands are phase-modulated at PolM2 with opposite phase shifts. The optical carrier and the sidebands that are orthogonally-polarized and complementarily phase-shifted are sent to a polarizer via a third PC (PC3). By using an optical bandpass filter to filter out the upper sideband and apply the carrier and the lower sideband to a PD, a microwave signal with a tunable phase shift is generated.

Mathematically, the optical signal at the output of PolM1 can be expressed as

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \frac{\sqrt{2}}{2} \begin{Bmatrix} \exp j\left[\omega_0 t + \gamma \cos(\omega_m t)\right] \\ \exp j\left[\omega_0 t - \gamma \cos(\omega_m t)\right] \end{Bmatrix} \tag{1}$$

where E_x and E_y are the optical fields of the incident light waves along the X- and the Y-axes (the two orthogonal principal axes) of PolM1, ω_o and ω_m are, respectively, the angular frequencies of the optical carrier and the RF signal applied to PolM1, and γ is the phase modulation index.

Based on the Jacobi-Anger expansion, the optical signal in (1) can be expanded as

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} \propto \exp(j\omega_0 t) \begin{bmatrix} J_0(\gamma) + jJ_1(\gamma)\exp(j\omega_m t) \\ \quad - jJ_{-1}(\gamma)\exp(-j\omega_m t) \\ J_0(\gamma) - jJ_1(\gamma)\exp(j\omega_m t) \\ \quad + jJ_{-1}(\gamma)\exp(-j\omega_m t) \end{bmatrix} \tag{2}$$

where J_n is the Bessel function of the first kind of an order n. In (2), small-signal modulation is assumed, so that the higher order ($\geq$2) sidebands are ignored.

As can be seen the two optical carriers in the two orthogonally polarized phase-modulated signals have identical phase, the combination of the two optical carriers corresponds to a single optical carrier with its polarization direction oriented at an angle of 45° relative to the horizontal principal axis of PolM1, as shown in Fig. 1(b). For the upper or lower sidebands, due to the initial phase terms of $\pi/2$ and $-\pi/2$ or $-\pi/2$ and $\pi/2$, the combination of the upper or lower sidebands corresponds to a single upper or lower sideband with an angle of 135° relative to the horizontal principal axis of PolM1, as also shown in Fig. 1(b). After passing PC2, the polarization directions of the combined carrier, the upper and lower sidebands are aligned with the two principle axes of PolM2. If a DC voltage, V_{DC}, is applied to PolM2, the optical carrier and the sidebands will experience complementary phase shifts. The optical signal at the output of PolM2 is given

$$\begin{bmatrix} E'_x \\ E'_y \end{bmatrix} \propto \exp(j\omega_0 t) \begin{bmatrix} -jJ_1(\gamma)\exp\left\{j\left[\omega_m t + \pi\left(\frac{V_{DC}}{V_\pi}\right)\right]\right\} \\ +jJ_{-1}(\gamma)\exp\left\{-j\left[\omega_m t + \pi\left(\frac{V_{DC}}{V_\pi}\right)\right]\right\} \\ J_0(\gamma)\exp\left[-j\pi\left(\frac{V_{DC}}{V_\pi}\right)\right] \end{bmatrix} \tag{3}$$

where E'_x and E'_y are the optical fields of the incident light waves along the X'- and the Y'-axes corresponding to the two orthogonal principal axes of PolM2, and V_π is the half-wave voltage of PolM2.

The optical signal is then sent to the polarizer via PC3. By using an optical bandpass filter to filter out the upper sideband, we have an optical signal consisting of the carrier and the lower sideband, given by

$$\begin{aligned} E(t) &\propto \exp\left\{j\left[\omega_0 t + \pi\left(\frac{V_{DC}}{V_\pi}\right)\right]\right\} \\ &+ \exp\left\{j\left[(\omega_0 + \omega_m)t - \pi\left(\frac{V_{DC}}{V_\pi}\right)\right]\right\} \end{aligned} \tag{4}$$

By beating the carrier and the lower sideband at the PD, an RF signal with a tunable phase shift is generated,

$$i(t) \propto \Re \cdot \cos\left[\omega_m t + 2\pi\left(\frac{V_{DC}}{V_\pi}\right)\right] \tag{5}$$

where $\Re$ is the responsivity of the PD. As can be seen from (5), an RF signal with its phase term as a function of the DC voltage is generated. When the DC voltage changes from 0 to V_π, the phase of the generated microwave signal is tuned from 0° to 360°.

III. Experiment

We first demonstrate the generation of an optical carrier and two first-order sidebands at the output of PolM1 that are orthogonally polarized, which is the key technique of this approach that is able to introduce two complementary phase shifts to the optical carrier and the two first-order sidebands. To do so, we connect a polarizer at the output of PolM1 via a PC (PC2), as shown in Fig. 2(a). We tune PC2 to rotate the polarization direction of the optical carrier to align at an angle

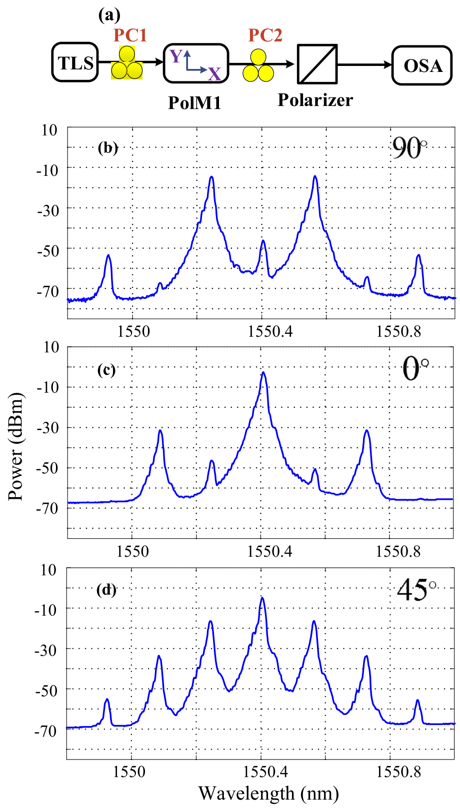

Fig. 2. (a) Setup to demonstrate the polarization orthogonality of the optical carrier and the first-order sidebands at the output of PolM1. The optical spectrum at the output of the polarizer with the polarization direction of the incident optical carrier oriented at an angle of (b) 90°, (c) 0°, and (d) 45° to the principle axis of the polarizer.

of 90°, 0°, or 45° relative to the principle axis of the polarizer, and monitor the optical spectrum at the output of the polarizer using an optical spectrum analyzer (OSA). As can be seen from Fig. 2(b), when the optical signal is aligned at an angle of 90° relative to the principle axis of the polarizer, only the two first-order sidebands are transmitted and the optical carrier is fully suppressed (46 dB). When the optical carrier is aligned at an angle of 0° relative to the principle axis of the polarizer, only the optical carrier is transmitted and the two first-order sidebands are fully suppressed (33 dB), as shown in Fig. 2(c). When the optical carrier is aligned at an angle of 45° relative to the principle axis of the polarizer, both the optical carrier and the two first-order sidebands are transmitted, as shown in Fig. 2(d). This demonstration confirms that the optical carrier and the two first-order sidebands at the output of PolM1 are orthogonally polarized.

Then, we generate an RF signal with a full 360° phase shift based on the setup shown in Fig. 1. At the output of PolM1, the polarization directions of the optical carrier and the first-order sidebands are aligned by PC2 to the two principle axes of PolM2. A DC voltage is applied to PolM2 to introduce complementary phase shifts to the optical carrier and the first-order sidebands. The optical signal at the output of PolM2 is sent to the polarizer via PC3, to project the two orthogonally polarized optical carrier and the sidebands to the principal axis of the polarizer. An optical bandpass filter (one channel of a

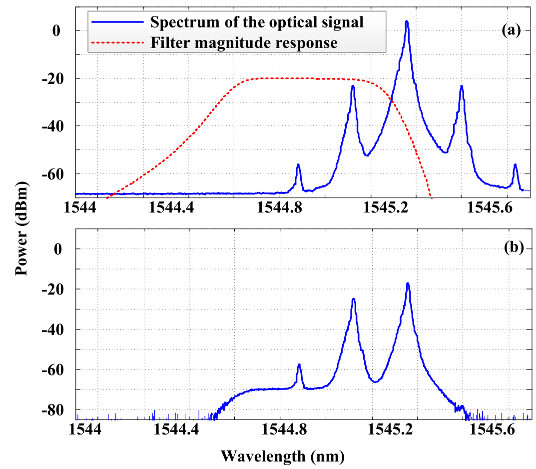

Fig. 3. The measured spectra of the optical signal before and after the optical bandpass filtering. (a) The optical spectrum at the output of the polarizer (blue-solid) and the magnitude response of the optical bandpass filter (red-dashed); (b) the optical spectrum after the optical bandpass filter.

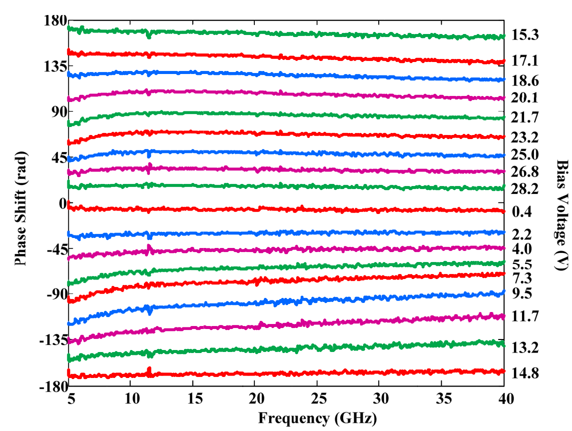

Fig. 4. Measured phase shifts at different DC voltages over a microwave frequency range from 5 to 40 GHz.

WDM) is used to select the carrier and the lower first-order sideband. In Fig. 3(a), the blue-solid line shows the spectrum of the optical signal before the optical bandpass filter, and the red-dashed line shows the transmission spectrum of the bandpass filter. Note that the modulated optical signals shown in Figs. 2 and 3 have different modulation indices. Fig. 3(b) shows the spectrum of the optical signal at the output of the optical bandpass filter. As can be seen the upper sideband is fully suppressed. Note that the optical carrier is also partially suppressed, which is done intentionally to increase the dynamic range of the RF phase shifter. It is known that if the optical power to the PD is maintained constant, the suppression of the optical carrier will increase the dynamic range [13].

The optical carrier and the lower sideband after the optical bandpass filter are then sent to the PD to generate a beat signal with the complementary phase shifts translated directly to the RF signal. The phase-shifted RF signal is then sent back to the VNA to measure the phase response. The tuning of the phase shift is performed by adjusting the DC voltage applied to PolM2. The results are shown in Fig. 4. As can be seen from Fig. 4, for a given DC voltage a constant phase

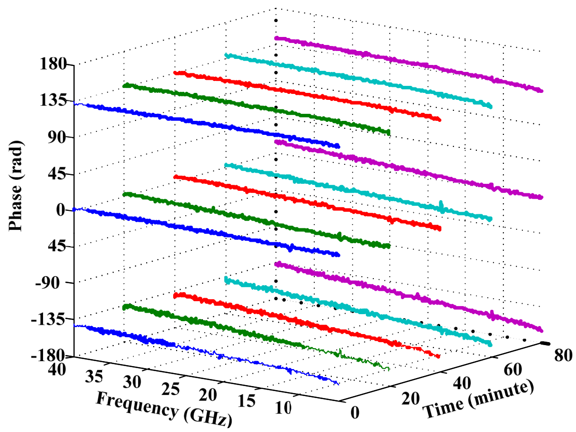

Fig. 5. Stability test for the proposed RF phase shifter. Measurements of phase shifts over a time interval of 20-minute for an 80-minute duration.

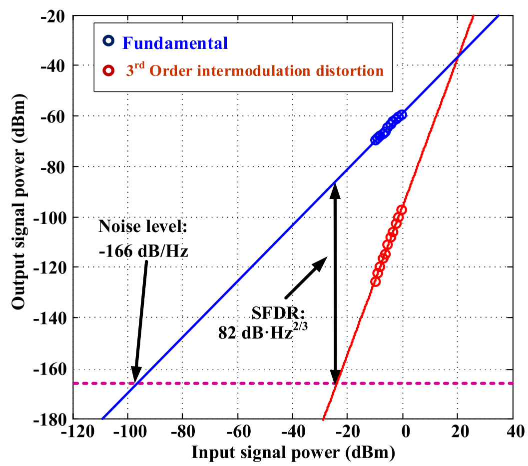

Fig. 6. Measured SFDR of the RF phase shifter.

shift over a frequency range from 5 to 40 GHz is achieved. The uneven phase response near the lower frequency end is due to the insufficient upper sideband suppression by the optical bandpass filter. For the proposed microwave phase shifter, a full 360° phase shift is achieved.

To study the stability of the phase shifter, we let the system operate at a laboratory environment at room temperature with the phase shifts measured over for 80 minutes at a 20-minute interval. Fig. 5 shows five sets of phase shift measurements. As can be seen, no evident phase variations are observed, which indicates an excellent stability of the proposed microwave phase shifter.

For many applications, such as in a radar receiver, RF phase shifters should have a large dynamic range [14]. To evaluate the dynamic range performance of the proposed RF phase shifter, a two-tone test is performed to measure the SFDR. In the experiment, a two-tone microwave signal at 10 and 10.001 GHz is applied to PolM1, and the output microwave powers of the fundamental signal and the third-order intermodulation distortion (IMD3) term are measured, with the results shown in Fig. 6. It can be seen that the SFDR of the microwave phase shifter is about 82 $\mathrm{dB} \cdot \mathrm{Hz}^{2/3}$ for a noise floor of −166 dBm/Hz. The SFDR is relatively small. In the setup, PolM1 is operating with the two PCs (PC2 and PC3) and the polarizer as an equivalent Mach-Zehnder modulator (MZM). If the equivalent MZM is biased precisely at the quadrature point, the SFDR could be increased.

IV. Conclusion

A novel approach to implementing an RF photonic phase shifter was proposed and experimentally demonstrated. The key features of the RF phase shifter included: 1) the phase of an RF signal could be fast tuned by simply tuning a DC voltage; 2) thanks to the large bandwidth of the PolMs and the PD, the RF phase shifter could operate over a large bandwidth; 3) when the phase was tuned, the amplitude of the RF signal was maintained constant. In the experiment, a tunable phase shift of 360° over a frequency range from 5 to 40 GHz was demonstrated. The SFDR of the RF phase shifter was also evaluated. For a noise floor of −166 dBm/Hz, the SFDR was measure to be 82 $\mathrm{dB} \cdot \mathrm{Hz}^{2/3}$.

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