Tunable and wideband microwave photonic phase shifter based on a single-sideband polarization modulator and a polarizer

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A novel microwave photonic phase shifter based on a single-sideband (SSB) polarization modulator (PolM) and a polarizer is proposed and demonstrated. In the SSB-PolM, two SSB intensity-modulated signals with a phase difference of π along two orthogonal polarization directions are generated. With the polarizer to combine the two signals, the phase of the optical microwave signal can be tuned from −180 to 180 deg by simply adjusting the polarization direction of the polarizer, whereas the amplitude keeps unchanged. An experiment is carried out. A full-range tunable phase shift in the frequency range of 11–43 GHz is achieved. The flat power response, power independent operation, and high stability of the proposed microwave photonic phase shifter is also confirmed. © 2012 Optical Society of America

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Microwave phase shifter plays a key role in phased-array antennas [1] and analog signal processing [2]. Thanks to the distinct advantages brought by the photonic technology, such as small size, high bandwidth, large tunability, and immunity to electromagnetic interference, it is also of great interests to implement the microwave phase shifter in the optical domain. Previously, photonic microwave shifters based on slow light [3–5], optical-vector-sum technique [6], heterodyne-mixing technique [7], or two-dimensional array of liquid crystal on silicon pixels [8] have been proposed. These methods, however, always suffer from the limited bandwidth, large power variation with phase shifting, high sensitivity to power drift, slow tuning speed, and high system complexity. To overcome these problems, a photonic microwave phase shifter based on a polarization-sensitive phase modulator has been proposed [9,10], which can achieve a linearly tunable 0–2 π phase shift over 40 GHz. The key challenge associated with this approach is that the optical carrier and the sideband must be orthogonally polarized to receive a different phase modulation index in the phase modulator. To do so, Li *et al.* [10] introduced a differential-group-delay element, but this would make the phase shifter effective only around several discrete frequencies.

In this Letter, we propose and demonstrate a novel microwave photonic phase shifter with a principle that is different from previously reported works, which allows for wideband operation, continuous phase tuning ranging from −180 to 180 deg, flat power response, power independent operation, large tuning speed, high linearity, and compact configuration. In the phase shifter, single-sideband (SSB) polarization modulation is performed by a conventional polarization modulator (PolM) and an optical bandpass filter (OBPF). The PolM generates two orthogonally polarized double sideband (DSB) optical signals with complementary phase modulations [11]. The optical filter removes one of the two sidebands, converting the DSB phase-modulated signals into two SSB intensity-modulated signals with a phase difference of π. Therefore, if a polarizer is followed to combine the two signals, the phase shift of the optical microwave signal can be tuned from −180° to 180° by simply adjusting the polarization direction of the polarizer.

Figure 1 shows the schematic diagram of the proposed microwave photonic phase shifter, which consists of a laser diode, a PolM, an OBPF, a polarizer, and a photodetector (PD). The PolM is a special phase modulator that can support both TE and TM modes with opposite phase modulation indices [12]. When a linearly polarized incident light that is oriented at an angle of 45 deg to one principal axis of the PolM is sent to the PolM, two complementary phase-modulated signals are generated along the two principal axes. The normalized optical fields at the output of the PolM along the two principal axes can be expressed as

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \frac{\sqrt{2}}{2} \begin{bmatrix} \exp j(\omega_o t + \gamma\phi(t) + \varphi) \\ \exp j(\omega_o t - \gamma\phi(t)) \end{bmatrix}, \quad (1)$$

where ω_o is the angular frequency of the optical carrier, $\phi(t)$ is the modulating signal, γ is the phase modulation index, and φ is the phase difference between E_x and E_y, which is controlled by the dc bias of the PolM. To analyze the frequency response of the scheme, we let

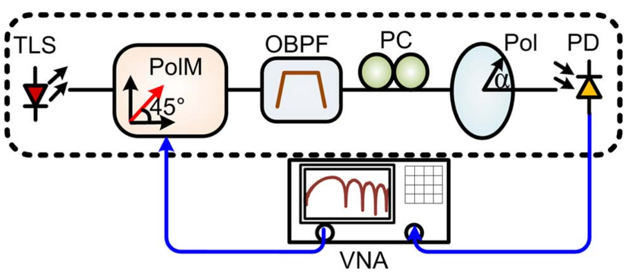

Fig. 1. (Color online) Schematic diagram of the proposed microwave photonic phase shifter. OBPF, optical bandpass filter; TLS, tunable laser source; PC, polarization controller; PolM, polarization modulator; Pol, polarizer; PD, photodetector; VNA, vector network analyzer.

the modulating signal be $\cos \omega_m t$. Based on the Jacobi–Anger expansion, the signal in Eq. (1) can be expanded as

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

where J_n is the Bessel function of the first kind of order n In writing Eq. (2), small-signal modulation is assumed so that the higher order (≥2) sidebands are ignored. If the phase-modulated signals are beat at the PD, only a dc can be generated because the two first-order sidebands are equal in amplitude and out of phase.

Therefore, we apply the OBPF to remove one sideband of the signals, converting the DSB phase-modulated signals into two SSB intensity-modulated signals with a phase difference of π, as follows:

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} \propto \begin{bmatrix} \exp(j\varphi)\left[J_0(\gamma) + J_{-1}(\gamma)\exp\left(-j\left(\omega_m t + \frac{\pi}{2}\right)\right)\right] \\ J_0(\gamma) + J_{-1}(\gamma)\exp\left(-j\left(\omega_m t - \frac{\pi}{2}\right)\right) \end{bmatrix}. \quad (3)$$

Then, the polarizer with its polarization direction aligned by a polarization controller (PC) to have an angle of α to one of the principal axes of the PolM is incorporated to combine the two orthogonally polarized SSB signals, as follows:

$$E_{\text{out}}(t) = \cos \alpha E_x + \sin \alpha E_y. \quad (4)$$

When the signal in Eq. (4) is sent to the PD for square-law detection, the output current can be written as

$$\begin{aligned} I(t) &\propto E_{\text{out}}(t)E^*_{\text{out}}(t) \\ &= (1 + \sin 2\alpha \cos \varphi)J_0^2(\gamma) + (1 - \sin 2\alpha \cos \varphi)J_{-1}^2(\gamma) \\ &\quad -2(\cos 2\alpha \sin \omega_m t + \sin 2\alpha \cos \omega_m t \sin \varphi)J_0(\gamma)J_{-1}(\gamma). \end{aligned} \quad (5)$$

When $\varphi = \pi/2$, Eq. (5) can be simplified to

$$I(t) \propto \cos\left(\omega_m t + 2\alpha + \frac{\pi}{2}\right)J_0(\gamma)J_{-1}(\gamma). \quad (6)$$

As can be seen from Eq. (6), when α changes in the range of $[0, \pi]$, the phase of the signal would be varied in $[0, 2\pi]$ and the amplitude remains unchanged. As a result, a fully tunable microwave photonic phase shifter is achieved. The PC can be an electronically controlled PC, so the microwave photonic phase shifter can be electronically driven at a fast speed.

An experiment based on the setup shown in Fig. 1 is carried out. A lightwave from a tunable laser source (Agilent, N7714A) with a wavelength of 1551.140 nm is sent to a PolM (Versawave Inc.). The PolM has a 3 dB bandwidth of 40 GHz and a half-wave voltage of 3.5 V. The electrically driven signal to the PolM is an RF signal generated by a 50 GHz vector network analyzer (VNA; Agilent N5245A). The power of the RF signal is 10 dBm to ensure small signal modulation. A tunable OBPF (Yenista XTM-50) with an edge slope of more than 500 dB/nm and a top flatness of 0.2 dB is incorporated to remove the positive sidebands of the signals. After the filter, a polarization beam splitter (PBS) with a polarization extinction ratio of more than 35 dB is used as a polarizer. A PC is placed before the PBS to adjust the angle between the polarization direction of the PBS and the principal axis of the PolM. A PD with a bandwidth of 40 GHz and a responsivity of 0.65 A/W is used to perform optical-to-electrical conversion.

Figure 2 shows the transmission response of the OBPF, and the typical optical spectra before and after the OBPF. By locating the optical carrier at the right edge of the OBPF, the +1st and higher order sidebands are effectively removed. Because polarization-independent loss of the OBPF is less than 0.2 dB, the two signals along the two principal axes of the PolM undergo almost the same sideband suppression ratio. Therefore, SSB polarization modulation is successfully implemented.

Figure 3(a) shows the phase responses of the proposed phase shifter. As can be seen, a flat phase within 11–43 GHz is obtained. The uneven phase response below 11 GHz is due to the insufficient sideband suppression in the OBPF, and the large noise above 43 GHz is mainly the result of the limited bandwidth of the PolM and the PD. By adjusting the PC, which changes the angle between the polarization direction of the PBS and the principal axis of the PolM, the phase of the RF signal is tuned from −180 to 180 deg. Figure 3(b) shows the power fluctuations when the phase is swept from −180 to 180 deg. Four curves for 10, 20, 30, and 40 GHz signals are plotted. As can be seen, for all the cases, the power

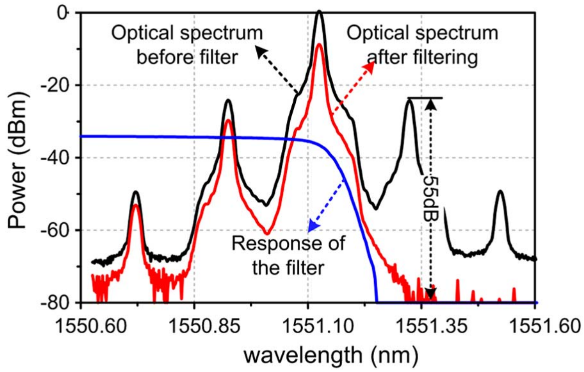

Fig. 2. (Color online) Optical spectra of the signals before and after the OBPF, and the transmission response of the OBPF.

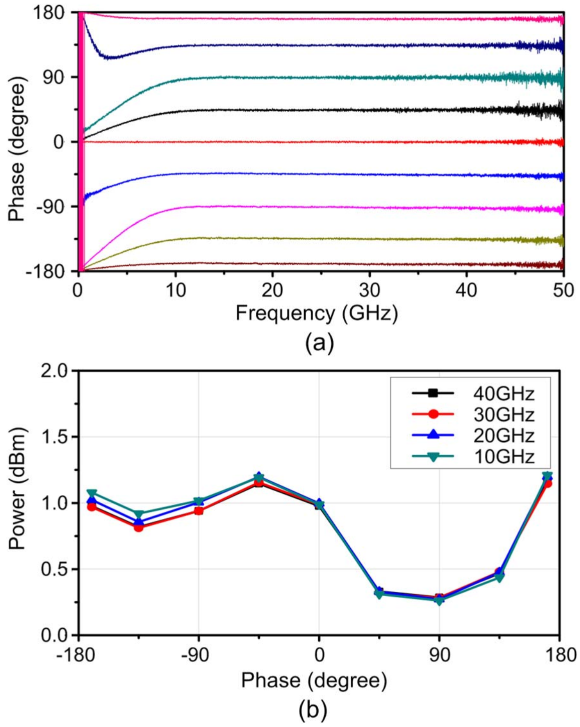

Fig. 3. (Color online) (a) Phase response of the proposed phase shifter at different PC settings. (b) Output power as a function of the phase shift at different frequencies.

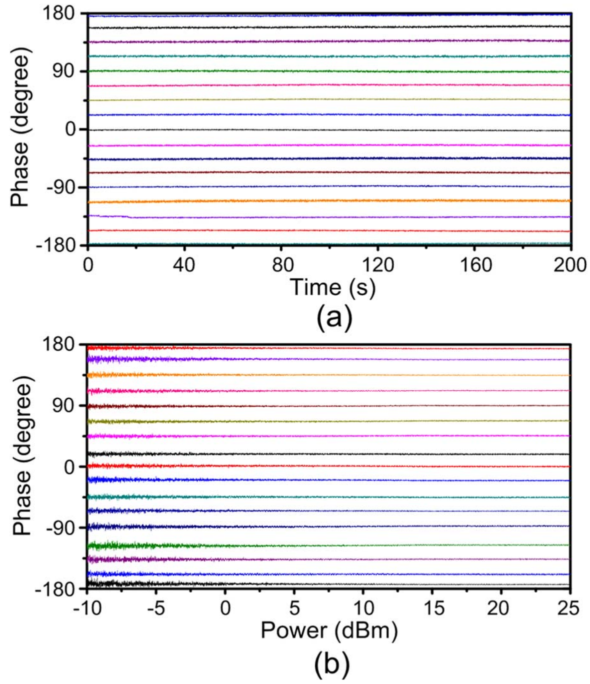

Fig. 4. (Color online) (a) Phase shift when the time is swept from 0–200 s. (b) Phase shift when the electrical input power is swept from −10 to 25 dBm.

variation is within ±0.5 dB, which is preferable compared with that in previous works [1–10].

To study the stability of the phase shifter, we let the scheme operate at the laboratory environment and sweep the time from 0 to 200 s. Figure 4(a) shows the phase stability when the frequency is 30 GHz. As can be seen, no evident phase variation is observed for different phase shifts, indicating that the short-term stability of the proposed phase shifter is very good.

Although Eq. (6) is obtained based on small signal analysis, the phase shifter is also effective when the modulation index is large. Figure 4(b) shows the phase shift when the power of the input electrical signal is swept from −10 to 25 dBm. No observable phase variation is found, showing the phase shifter is insensitive to the power level of the input signal. The large noise in the low-power regime is due to the insufficient signal-to-noise ratio of the signal, which creates difficulty for the phase estimation of the VNA.

In conclusion, a novel microwave photonic phase shifter featuring wideband operation, continuous phase tuning ranging from −180 to 180 deg, flat power response, power independent operation, large tuning speed, and compact configuration was proposed and demonstrated. The approach was based on a single-sideband PolM and a polarizer, and the phase shift was tuned by simply adjusting the angle between the polarization direction of the polarizer and the principal axis of the PolM. The proposed photonic phase shifter can find applications in photonic microwave signal processing and photonic microwave beamforming networks.

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