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A tunable and wideband microwave photonic phase shifter based on dual-polarization modulator

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ABSTRACT

A microwave photonic phase shifter based on dual-polarization Mach-Zehnder modulator (DPol-MZM) is proposed and experimentally demonstrated in this paper. A polarization multiplexed double sideband (DSB) signal is produced by a DPol-MZM. An optical bandpass filter (OBPF) follows after the DPol-MZM to filter out the optical carrier and one sideband. The polarization multiplexed signal is converted into a linear polarization light by a polarizer (Pol), and then beat at a photodiode (PD) to obtain the phase shifted signal. Experiments are carried out, and a continuous phase shift from −180° to 180° over a wide microwave frequency range of 10–33 GHz can be achieved by changing the polarization state using a polarization controller (PC). We also studied the spurious free dynamic range (SFDR) in the experiments. The features of this proposed phase shifter are large operation bandwidth, full-range 360° phase shift, and simple structure.

1. Introduction

Microwave phase shifter is of great importance to microwave signal processing systems, such as photonic microwave beam forming network [1] and microwave filters [2]. Conventional electronic phase shifters based on magneto dielectric disturber [3], PIN diodes [4], and monolithic microwave integrated circuits [5], suffer from serious electronic bottleneck when operating at high frequency. To overcome the limitation, microwave photonic phase shifter is adopted due to its advantages of immunity to electromagnetic interference, light weight, and large operation bandwidth [6,7].

In the last few years, several schemes of microwave photonic phase shifter have been reported based on transversal filters and Hilbert transform [8], vector-sum technique [9], stimulated Brillouin scattering (SBS) effect [10,11], or fast and slow light effect [12,13]. However, in [8], the implementation of the phase shifter is complicated due to the requirement of negative taps. The scheme using the SBS effect requires long optical fiber. As for the method based on fast and slow light effect, several semiconductor optical amplifiers (SOA) are usually jointly needed, which make the phase shifter bulky, expensive, and complicated. Besides, the microwave photonic phase shifter utilizing a polarization modulator (PolM) and a polarizer has been reported in [14]. In the scheme, a continuous 360° phase shift is achieved over the frequency range from 11 to 43 GHz. In [15], a wideband 360° tunable phase shifter is implemented based on a dual-drive Mach-Zehnder modulator (DDMZM) and an optical bandpass filter (OBPF). In addition, a phase shifter based on a polarization modulator (PolM) and a polarization-maintaining fiber Bragg grating (PM-FBG) is capable of realizing a 360° phase shift over the frequency range from 30 to 40 GHz [16]. In [16], the spurious free dynamic range (SFDR) is also studied and is about 88 dB $Hz^{2/3}$.

In this paper, a new microwave photonic phase shifter utilizing dual-polarization Mach-Zehnder modulator (DPol-MZM) is proposed and experimentally demonstrated. The phase shifter consists of a DPol-MZM, an OBPF, a polarizer (Pol) and a polarization controller (PC). The DPol-MZM produces an optical carrier and a carrier-suppressed double sideband (CS-DSB) signal along two orthogonal directions, respectively. The optical carrier and one sideband of the polarization multiplexed DSB signal are filtered out by an OBPF so as to produce a polarization multiplexed single sideband (SSB) signal. The two signals are combined in the following polarizer (Pol). By changing the polarization direction of the Pol using a polarization controller (PC), the proposed phase shifter is capable of realizing a continuous −180–180° phase shift with little power variation over a wide frequency bandwidth. Demonstration experiments are conducted and a continuous full-range 360° phase shift is easily achieved over a wide microwave frequency range of 10–33 GHz. The measured SFDR of this proposed microwave photonic phase shifter is 93 dB $Hz^{2/3}$.

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2. Principle

Fig. 1 illustrates the schematic diagram of the microwave phase shifter based on DPol-MZM. An optical signal from the tunable laser source (TLS) is injected into the DPol-MZM. The DPol-MZM is comprised of a Y splitter, two parallel MZMs (X-MZM and Y-MZM), and a polarization beam combiner (PBC). The optical carrier is split into two identical parts inside the modulator. One is injected into X-MZM on the upper arm of the DPol-MZM while the other one is sent to the Y-MZM on the lower arm of the DPol-MZM. X-MZM and Y-MZM both have two RF input ports. For easy implementation, the RF signal is only introduced to one RF port of the X-MZM. The bias voltage of X-MZM is based at the minimum transmission point and a CS-DSB signal can be obtained after X-MZM. The Y-MZM is biased at the maximum transmission point and the RF ports are unloaded. Then the CS-DSB signal and the optical carrier arrive at the PBC which can orthogonalize their polarization directions. At the output of the DPol-MZM, a polarization multiplexed DSB signal is produced. An OBPF filters out the optical carrier and the higher sideband of the polarization multiplexed signal in order to generate a polarization multiplexed SSB signal. Then the polarization multiplexed signal is applied to a polarizer to produce a linear polarization signal and is then detected by a PD to obtain the phase shifted RF signal.

Assuming the optical carrier output from the TLS is expressed as $\exp(j\omega_c t)$, where ω_c denotes its angular frequency. The RF signal is written as $V_R \sin(\omega_R t)$, where ω_R and V_R are the angular frequency and the magnitude respectively. The CS-DSB signal $E_X(t)$ output from X-MZM, as shown in Fig. 1(a), can be expressed as

$$\begin{aligned} E_X(t) &= \frac{\exp(j\omega_c t)}{2\sqrt{2}}\left[\exp(jm_R\sin(\omega_R t)) - 1\right] = \frac{\exp(j\omega_c t)}{2\sqrt{2}}\left[\sum_n J_n(m_R)\exp(jn\omega_R t) - 1\right] \\ &\approx \frac{\exp(j\omega_c t)}{2\sqrt{2}}\left[J_0(m_R) + J_1(m_R)\exp(j\omega_R t) - J_1(m_R)\exp(-j\omega_R t) - 1\right] \\ &\approx \frac{\exp(j\omega_c t)}{2\sqrt{2}}\left[J_1(m_R)\left[\exp(j\omega_R t) - \exp(-j\omega_R t)\right]\right] \end{aligned}$$

where $m_R = \pi V_R / V_\pi$ is the modulation index of the X-MZM, and V_π denotes its half-wave voltage. $J_n(m_R)$ is the Bessel function of the first kind of order n at m_R. Assuming small-signal modulation condition, the second order and the higher order sidebands can be ignored. An optical carrier $E_Y(t)$ output from Y-MZM, as shown in Fig. 1(b), can be expressed as

$$E_Y(t) = \frac{\exp(j\omega_c t)}{\sqrt{2}}$$

Then the two signals arrive at the PBC and are combined as a polarization multiplexed signal. The output signal from the DPol-MZM can be expressed as

$$\begin{bmatrix} E_X(t) \\ E_Y(t) \end{bmatrix} \approx \frac{\exp(j\omega_c t)}{2\sqrt{2}} \begin{bmatrix} J_1(m_R)\left[\exp(j\omega_R t) - \exp(-j\omega_R t)\right] \\ 2 \end{bmatrix} \tag{1}$$

The OBPF filters out the upper sideband and the carrier, and the polarization multiplexed SSB signal can be expressed as follow

$$E_{OBPF}(t) = \begin{bmatrix} E'_X(t) \\ E'_Y(t) \end{bmatrix} = \frac{\exp(j\omega_c t)}{2\sqrt{2}} \cdot \begin{bmatrix} J_1(m_R)\exp(j\Omega_R t) \\ 2 \end{bmatrix} \tag{2}$$

After the OBPF, the polarization multiplexed SSB signal is obtained, as can be seen in Fig. 1(c). The angle between the polarizer and one principal axis of the PBC is set at 45°, by adjusting PC. The combined optical signal can be represented as follow

$$\begin{aligned} E_{pol}(t) &= \frac{1}{\sqrt{2}} E'_X(t) + \frac{1}{\sqrt{2}} E'_Y(t)\exp(j\theta) \\ &= \frac{\exp(j\omega_c t)}{4}\left\{J_1(m_R)\exp(j\Omega_R t) + 2\exp(j\theta)\right\} \end{aligned} \tag{3}$$

where θ is the difference in phase between the optical carrier and the higher sideband, which can be arbitrarily adjusted by PC [17], as illustrated in Fig. 1(d). Then signal in (3) beat at a PD and the output current is given by

$$i(t) = \eta E_{pol}(t) \cdot E^*_{pol}(t) \propto \frac{\eta}{4} J_1(m_R)\cos(\omega_R t - \theta) \tag{4}$$

After detected by the PD, the phase of microwave signal is shifted, as can be seen in Fig. 1(e). By controlling the polarization direction through PC, the phase shift θ is adjusted from 0° to 360° and the magnitude remains unchanged.

3. Experiment results and discussion

A proof-of-concept experiment based on the setup shown in Fig. 1 is carried out. An optical signal from a TLS (Yokogawa AQ2200) with a power of about 10 dBm and a wavelength of 1549.845 nm is injected into a DPol-MZM (Fujitsu, FTM7980EDA). The DPol-MZM has a half-wave voltage of about 3.5 V and a 3 dB bandwidth of above 30 GHz. The RF signal generated from a 40-GHz vector network analyzer (VNA; Anritsu, MS46122A) is injected into one RF input port of X-MZM on the upper arm of the DPol-MZM. An FBG with a 3 dB bandwidth of 23 GHz and a suppression ratio of above 20 dB is used as an OBPF to filter out the optical carrier and one sideband of the polarization multiplexed DSB signal. A Pol cascaded with a PC converts the polarization multiplexed signal into a linear polarization light, and a PD (U2T,

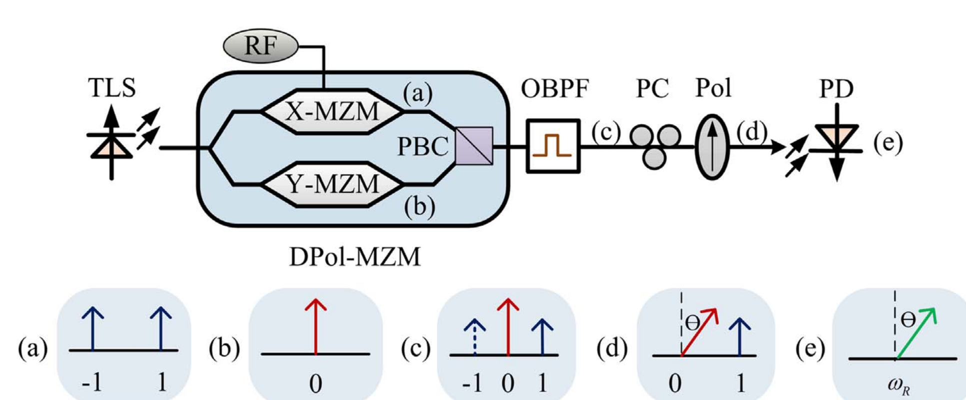

Fig. 1. Schematic diagram of the microwave photonic phase shifter. TLS, tunable laser source; DPol-MZM, Dual-Polarization modulator; OBPF, optical bandpass filter; PC, polarization controller; Pol, polarizer; PD, photodiode; RF, radio frequency. (*a*-e): Schematics of the optical spectra at different locations in the proposed phase shifter.