A wideband tunable phase shifter based on orthogonal optical single-sideband

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We present a novel technique to generate an orthogonally polarized optical single sideband (OSSB) generated by a tunable bandpass filter (TBF). When the OSSB passes through the other polarization modulation (PolM) which is polarization dependent, the phase shift of the optical carrier and first-order sideband is different under different bias. As a result, a wideband tunable phase shifter is realized by adjusting the bias applied to the polarization modulator.

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Microwave signals processing in optical domain has been a topic of interest thanks to the advantageous features such as broad bandwidth, low loss, light weight, tunability, reconfigurability, and immunity to electromagnetic interference offered by photonics. And it does not need electrical to optical or optical to electrical conversion. Recently, the use of orthogonally polarized single sideband modulated signals (OSSB) for microwave processing schemes has been focused, as the OSSB can find applications in antenna beamforming[1,2] and implementing complex coefficients[3]. Many methods have been proposed to realized the OSSB in the past few years, such as stimulated Brillouin scattering (SBS) signal processing[4], spatial light modulation technologies[5] and using a differential group delay (DGD) module[6], but these methods are too bulk and complicated to be integrated.

In this letter, a novel and simple method to achieving OSSB and a tunable wideband phase shifter based on polarization modulators and tunable bandpass filter (TBF) is firstly proposed and demonstrated. Compared with the methods in the past few years, it is simple and wideband tunable.

The schematic of the proposed OSSB and phase shifter is shown in Fig. 1. A linearly polarized lightwave

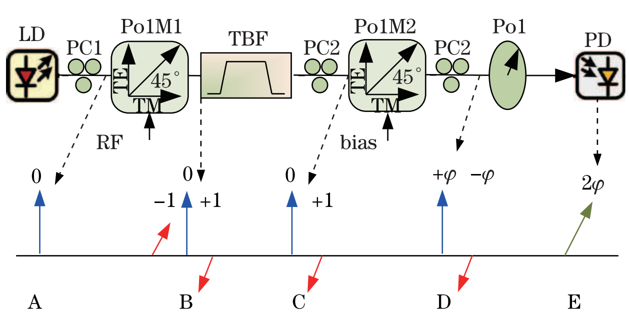

Fig. 1. The experimental schematic of the proposed phase shifter. LD: laser diode; PC: polarization controller; PolM: polarization modulation; TBF: tunable bandpass filter; PD: photonic detector; Pol: polarizer; RF: radio frequency.

generated by a LD is phase modulated in the PolM1 (Versawave Technology, half wave voltage 5.0 V) along the x and y directions by a radio frequency (RF) signal. The polarization controller (PC1) is used to adjust its polarization state with an angle of 45° to the principal axis of the PolM. When a microwave signal $2m\sin(\omega_e t)$ is applied to the PolM1, where $2m$ is the RF modulation depth and ω_e is the angular modulation frequency, the Jones vector at the output of the PolM1 of point B along the x and y-directions can be written as the time-dependent polarization vector[7,8]:

$$E_{\mathrm{PolM1}} = \begin{bmatrix} E_x(t) \\ E_y(t) \end{bmatrix} = \sqrt{P_0}\begin{bmatrix} \cos[\omega_0 t - m\sin(\omega_e t)] \\ \cos[\omega_0 t + m\sin(\omega_e t)] \end{bmatrix}$$

$$= \frac{\sqrt{P_0}}{2}\begin{bmatrix} \exp[-im\sin(\omega_e t)] \\ \exp[im\sin(\omega_e t)] \end{bmatrix}\exp(i\omega_0 t) + \frac{\sqrt{P_0}}{2}$$

$$\begin{bmatrix} \exp[im\sin(\omega_e t)] \\ \exp[-im\sin(\omega_e t)] \end{bmatrix}\exp(-i\omega_0 t), \quad (1)$$

where $\sqrt{P_0}/2$ is the amplitude of the incident light waves along the two orthogonal polarization directions E_x and E_y.

The field in Eq. (1) can be Fourier expanded and expressed as a carrier with sidebands in Eq. (2).

$$E_{\mathrm{PolM1}} = \begin{bmatrix} E_x(t) \\ E_y(t) \end{bmatrix} = \sqrt{P_0}\{J_0(m)\cos(\omega_0 t)\begin{bmatrix} 1 \\ 1 \end{bmatrix}$$

$$- J_1(m)\cos((\omega_0+\omega_e)t)\begin{bmatrix} 1 \\ -1 \end{bmatrix}$$

$$+ J_1(m)\cos((\omega_0-\omega_e)t)\begin{bmatrix} 1 \\ -1 \end{bmatrix}$$

$$+ J_2(m)\cos((\omega_0+2\omega_e)t)\begin{bmatrix} 1 \\ 1 \end{bmatrix}$$

$$+ J_2(m)\cos((\omega_0 - 2\omega_e)t)\begin{bmatrix}1\\1\end{bmatrix} + \cdots + \}. \quad (2)$$

From this equation, we can see that the polarization of optical carrier is orthogonal to the first-order sidebands. Under small signal condition, the high order sidebands are much smaller compared to the first-order sidebands, so they can be neglected. When a tunable optical filter is applied to the PolM, filtering the lower sideband, an orthogonal single sideband is generated at point C, that means

$$E_{\mathrm{TBF}} = \sqrt{P_0}\Big\{J_0(m)\cos(\omega_0 t)\begin{bmatrix}1\\1\end{bmatrix} - J_1(m)\cos((\omega_0 + \omega_e)t)\begin{bmatrix}1\\-1\end{bmatrix}\Big\}. \quad (3)$$

The OSSB is sent to the PolM2 through a second PC (PC2), with the polarization directions of optical carrier and first-order sideband aligned with the two principal axes of the PolM. The PolM is a special phase modulator that has opposite modulation indices along the two principal axes[9,10]. The two optical sidebands are complementarily phase modulated at the PolM by the bias voltage. Mathematically, the optical signal at the output of PolM2 of point D can be expressed as[9,10]

$$E_{\mathrm{PolM2}} = \alpha\sqrt{P_0}\Big\{J_0(m)\cos(\omega_0 t - \varphi)\begin{bmatrix}1\\1\end{bmatrix} - J_1(m)\cos((\omega_0 + \omega_e)t + \varphi)\begin{bmatrix}1\\-1\end{bmatrix}\Big\}, \quad (4)$$

where α is the attention introduced by the TBF, PC2 and PolM2, $\varphi = \pi\frac{V_{\mathrm{bias}}}{V_\pi}$ is the phase shift introduced by the bias voltage V_{bias}, and V_π is the half wave voltage of PolM2.

After that, When the transmission axis of the polarizer is aligned with an angle of 0° or 90° to the polarization direction of the carrier or sideband, only the carrier or sideband is generated at the output of polarizer, the polarization is shown in Figs. 2(a) and (b). From this figure, we can see they are orthogonal.

When the transmission axis of the polarizer is aligned with an angle of 45° to the polarization direction of the carrier or sideband, the signal at the output of the polarizer is given by

$$E_{\mathrm{Pol}} = \frac{\sqrt{2}}{2}\alpha\sqrt{P_0}\Big\{J_0(m)\cos(\omega_0 t - \varphi) - J_1(m)\cos\Big((\omega_0 + \omega_e)t + \varphi\Big)\Big\}. \quad (5)$$

By beating the carrier and sideband at PD, the output signal at point E can be expressed as

$$P = \frac{P_0}{2}\alpha^2 J_0(m)J_1(m)\cos(\omega_e t + 2\varphi). \quad (6)$$

From this equation, we can see that the phase of the generated microwave signal can be tuned by adjusting the bias voltage to the PolM2, and the power will keep unaltered over a wideband. The advantage of this method is that the bias introduced by the tunable voltage source will not drift as the mach-zehnder modulator (MZM). In the stimulation, we assume that the half wave voltage of the modulator V_π is 5 V, the microwave frequency is 10 GHz, and the waveform and phase shift of received electrical under different bias is shown in Figs. 3 and 4. We can see that the phase changes with the bias voltage and the power keeps constant.

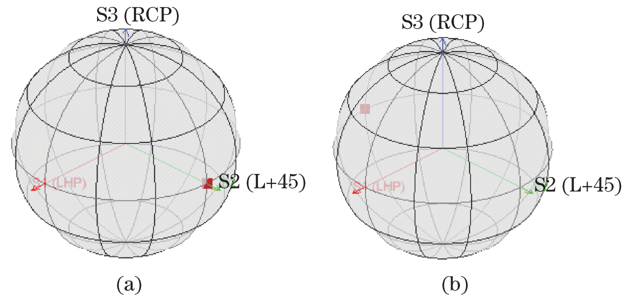

Fig. 2. (Color online) (a) The polarization of optical carrier; (b) the polarization of first order sideband.

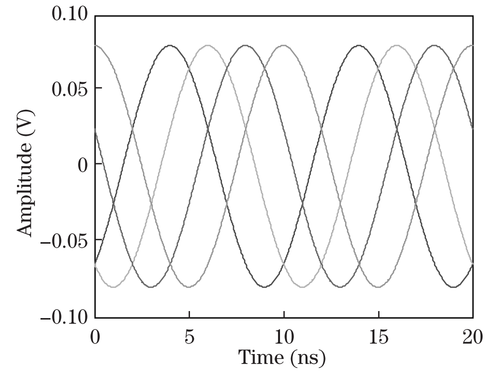

Fig. 3. (Color online) The electrical signal under different bias.

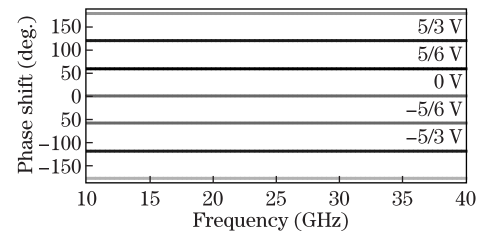

Fig. 4. (Color online) 360° phase shifter under different bias.

In conclusion, A novel method to generate the orthogonally polarized optical single sideband and realize a wideband tunable filter is proposed in this letter. The carrier and first-order sideband output of PolM is orthogonally, so that if a tunable filter is adopted to the lower sideband, an OSSB is generated. When the OSSB passes through the other PolM which is polarization dependent, the phase shift of the orthogonal signal is different under different bias. Then by simply controlling the bias voltage of the PolM, the phase shifter can be continuously tuned over 360° while the output microwave power maintains unchanged.

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References

1. J. F. Coward, C. H. Chalfant, and P. H. Chang, J. Lightwave Technol. **11,** 2201 (1993).
2. S. T. Winnall, A. C. Lindsay, and G. A. Knight, IEEE Trans. Microw. Theory Tech. **45,** 1003 (1997).
3. Y. Yan and J. Yao, IEEE Photon. Technol. Lett. **19,** 1472 (2007).
4. A. Loayssa and F. J. Lahoz, Photon. Technol. Lett. **18,** 208 (2006).
5. T. Mengual, B. Vidal, and J. Martí, Opt. Commun. **281,** 2746 (2008).
6. Z. Li, C. Yu, Y. Dong, L. Cheng, L. F. K. Lui, C. Lu, A. P. Lau, H. Y. Tam, and P. K. Wai, Opt. Lett. **35,** 1881 (2010).
7. A. L. Campillo and F. Bucholtz, Appl. Opt. **45,** 2742 (2006).
8. A. L. Campillo, Opt. Lett. **32,** 3152 (2007).
9. Q. Wang and J. Yao, J. Lightwave Technol. **25,** 3626 (2007).
10. W. Zhang and J. Yao, IEEE Photon. J. **4,** 889 (2012).