Optics Communications 356 (2015) 522–525

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

A wideband photonic microwave phase shifter using polarization-dependent intensity modulation

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ARTICLE INFO

Article history:
Received 29 June 2015
Received in revised form
14 August 2015
Accepted 17 August 2015

Keywords:
Microwave photonic phase shifter
MZM
Single-sideband modulation

ABSTRACT

We present a tunable and wideband microwave photonic phase shifter based on polarization-dependence of the $LiNbO_3$ Mach–Zehender modulator (MZM). In the proposed device, an orthogonal single sideband modulation is implemented by using a MZM and an optical band-pass filter. With the polarizer to synthesize the polarization orthogonal optical carrier and sideband, the phase of the optical microwave signal output from the polarizer can be tuned from 0 to 360° by simply adjusting the polarization direction of the lights whereas the amplitude keeps constant. A full range tunable phase shifting in the frequency range of 10–35 GHz is achieved.

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1. Introduction

Microwave phase shifter (MPS) is an indispensable component in the fields of phased-array antennas [1] and broadband wireless communications [2]. However, the phase shift realized in electrical domain totally suffers from a series of problems in respect of tunability and anti-electromagnetic interference. By means of the distinct advantages of photonic technology, the full-range tunable and ultra-wideband photonic MPS that is immune to electromagnetic interference has been proposed and demonstrated [3–5]. In 1993, the photonic MPS based on optical vector synthesis technique was firstly proposed [6]. In [7–8], a tunable optical phase shift can be converted to an RF phase shift by heterodyning two optical wavelengths at a photo-detector (PD). Tunable RF phase shift can also be generated based on two-dimensional array of liquid crystal on silicon pixels [9], or based on the nonlinear effects in an optical element such as stimulated Brillouin scattering in optical fiber [10], thermal nonlinear effect in a silicon microring [11], cross-phase modulation and cross-gain modulation effects in a semiconductor optical amplifier [12]. Unfortunately, these methods mentioned above always suffer from the limited bandwidth, slow response speed, large power variation with phase shifting and limited phase tuning range. A simplified approach has been proposed to get the same phase shifting function using a polarization modulator (PolM) and an optical frequency discriminator [13]. In this device, two optical signals with different wavelengths and orthogonal polarization states were sent to a PolM which was driven by the RF signal to be phase shifted. The power of the phase-shifted RF signal was maintained constant over the full tunable range of 360°. An improved polarization-based phase shifter was proposed and demonstrated [14], where two single-sideband (SSB) intensity-modulated optical signals with orthogonal polarization states are generated by using PolM and optical band pass filter (OBPF). The phase shift of the optical microwave signal was tuned by simply adjusting the angle of the optical axis of the polarizer and the polarization direction of optical signal. Nevertheless, as an unconventional component, the PolM is bound to increase the device's cost, while, it is not suitable to be adopted widely in practice.

In this paper, we propose a novel photonic MPS based on the polarization-dependence of the commercial $LiNbO_3$ MZM. In the proposed scheme, the special double sidebands (DSB) modulation is implemented in which the polarization direction of the optical carrier (OC) is orthogonal with that of the $\pm$1st order sidebands [15]. An OBPF is used to obtain the +1st order sideband and the OC. With the polarizer to synthesize the sideband and OC, the optical microwave signal with phase shifting of 360° can be achieved by adjusting the polarization controller (PC) before the polarizer. Such simple method is of great potential for applications in the future due to its cost advantage.

2. Principle

The schematic illustration of the proposed MPS is shown in Fig. 1, which consists of a laser diode (LD), a commercial $LiNbO_3$

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http://dx.doi.org/10.1016/j.optcom.2015.08.045
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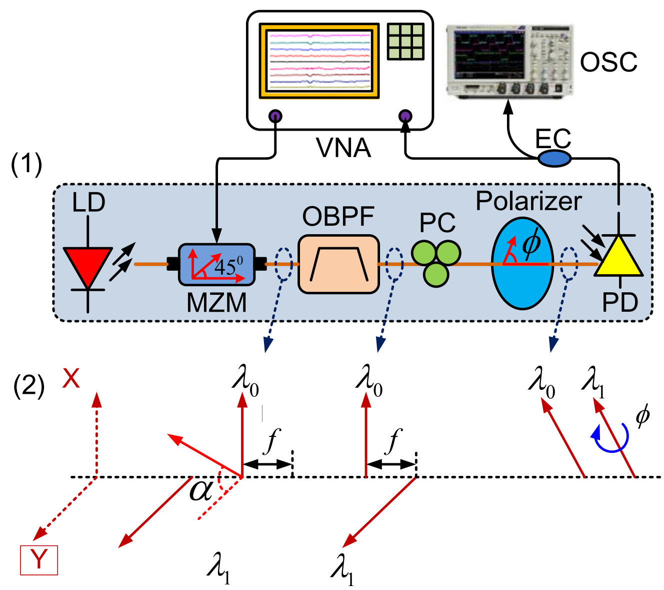

Fig. 1. Schematic illustration of the proposed Schematic diagram of the proposed microwave photonic phase shifter. (LD: semiconductor laser diode; MZM: Mach–Zehender modulator; OBPF: optical band-pass filter; PC: polarization controller; PD: photo-detector; VNA: vector network analyzer. OSC: optical sampling oscilloscope; EC: electrical coupler).

MZM, an OBPF, a PC, a polarizer, and a PD. The original RF signal is applied on the MZM to modulate the light output from the LD. In general, the modulation efficiency of the $LiNbO_3$ in the direction of the externally applied electric field, namely the principal axis of the crystal (Y-axis), is around 3.58 times that in the orthogonal direction (X-axis) due to the electro-optical properties of the $LiNbO_3$ crystal [16]. Therefore, when the linearly polarized incident light is oriented at an angle of α with the principal axis of the MZM, the projected optical component parallel to the Y-axis will be effectively modulated by microwave signal but the modulation for the X-axis component of the light is insignificant. In this case, the modulated light output from the MZM could be expressed as:

$$\begin{bmatrix} E_x(t) \\ E_y(t) \end{bmatrix} \propto \begin{bmatrix} \cos\alpha \exp(j\omega_c t) \\ \sin\alpha \exp(j\omega_c t)\sin[\beta\cos(\omega_m t)] \end{bmatrix} \tag{1}$$

where ω_c is the angular frequency of the optical carrier, β is the phase modulation index expressed as $\beta=\pi V_m/V$, where V_π is the half-wave voltage, ω_m and V_m is the angular frequency and amplitude of the original RF signal, respectively. As the MZM is biased at the transmission null point, the modulated light at the Y-axis will be only keeping the $\pm$1st order sidebands due to that the fact that the modulator works in the form of carrier suppression modulation. The electrical filed of the modulated light could be further expressed as:

$$\begin{bmatrix} E_X(t) \\ E_Y(t) \end{bmatrix} \propto \begin{bmatrix} \cos\alpha \exp(j\omega_c t) \\ \sin\alpha \exp(j\omega_c t)[J_1 \exp(j\omega_m t) + J_1 \exp(-j\omega_m t)] \end{bmatrix} \tag{2}$$

where $J_n(\cdot)$ is the Bessel function of the first kind of order n. α is the polarization angle between the OC and the principal axis of the MZM. It can be seen that a special DSB modulation is implemented where the polarization direction of the OC is orthogonal with that of the $\pm$1st order sidebands. Using an OBPF to select out the OC and the +1st order sideband, the electrical filed is given by:

$$\begin{bmatrix} E_X(t) \\ E_Y(t) \end{bmatrix} \propto \begin{bmatrix} \cos\alpha \exp(j\omega_c t) \\ \sin\alpha J_1 \exp j(\omega_c - \omega_m)t \end{bmatrix} \tag{3}$$

In order to facilitate analysis of the effect of PC, we define two orthogonal axes, X_0 and Y_0, which have an angle of 45° with the original X and Y axes. When $\alpha=45°$ (in our system, we get a MZM who integrated a polarizer at the input port,and granted that the direction of the polarizer is aligned 45° to the principle of the MZM), the optical fields decomposed along the X_0 and Y_0 axes can be expressed as:

$$\begin{bmatrix} E_{X_0}(t) \\ E_{Y_0}(t) \end{bmatrix} \propto \begin{bmatrix} \exp(j\theta)[\exp(j\omega_c t) - J_1 \exp j(\omega_c - \omega_m)t] \\ \exp(j\omega_c t) + J_1 \exp j(\omega_c - \omega_m)t \end{bmatrix} \tag{4}$$

where θ is the phase difference between E_{X0} and E_{Y0}, which is introduced by the PC. Then, the polarizer with its polarization direction aligned by the PC to have an angle of ϕ to the X_0 axis is incorporated to combine the OC and sideband with orthogonal polarization state, The optical signal output from the polarizer presents as

$$E_{out}(t) = E_{X_0}\cdot\cos\phi + E_{Y_0}\cdot\sin\phi \tag{5}$$

when the signal in Eq. (5) is sent to the PD for square-law detection, the output current can be written as:

$$\begin{aligned} I(t) &\propto E_{out}(t)E_{out}^*(t) \\ &\propto 1 + J_1^2 - J_1^2\cos 2\phi\cos\theta + 2J_1\cos(\omega_m t)\cos(2\phi) + \\ &J_1[\cos(\omega_m t + \theta) - \cos(\omega_m t - \theta)]\sin(2\phi) \end{aligned} \tag{6}$$

When we set $\theta=\pi/2$, Eq. (6) can be simplified as following

$$I_{out} \propto A\cos(\omega_m t - 2\phi) \tag{7}$$

where $A=2J_1$. As can be seen from Eq. (7), when ϕ changes in the range of [0, π], just by tuning the PC, the phase of the signal would be varied in [0, 2π] and the amplitude remains unchanged. Thus, a tunable phase shift with a full 360° phase tunable range is achieved.

3. Experiment and results

The parameters of the key devices used in the experiment are summarized as follows. The wavelength and the power of the LD are 1550 nm and 28 mW, respectively. The polarization dependence MZM has a 3 dB bandwidth of 30 GHz. The electrically driven signal to the MZM is an RF signal generated by a 40 GHz vector network analyzer. The power of the RF signal is 0 dBm to ensure small signal modulation. A tunable OBPF with an edge slope of more than 800 dB/nm and 3-dB bandwidth of 650 nm is applied to filter out the generated −1st order optical sideband. After the filter, a PC is placed before the polarizer to adjust the angle between the polarization direction of the modulated light and the optical axis of the polarizer. A PD with a bandwidth of 40 GHz was used to perform optical-to-electrical conversion.

In order to verify the polarization property of the modulated light, we set the angle between the polarization direction of the optical carrier and the optical axis of the polarizer at 0° or 90°. Fig. 2(a) shows the optical spectrum before polarizer and the optical spectra after polarizer in these two cases. It is clearly indicated that only the optical carrier or sidebands appeared after the polarizer when the angle equals 0° or 90°, which means that the polarization state of the generated optical carrier and sideband output from the MZM are orthogonal. These experimental results confirm that the special DSB modulation is implemented as expected. The dashed line in Fig. 2(b) illustrates the optical spectrum when the OBPF was replaced. Comparing with the original

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