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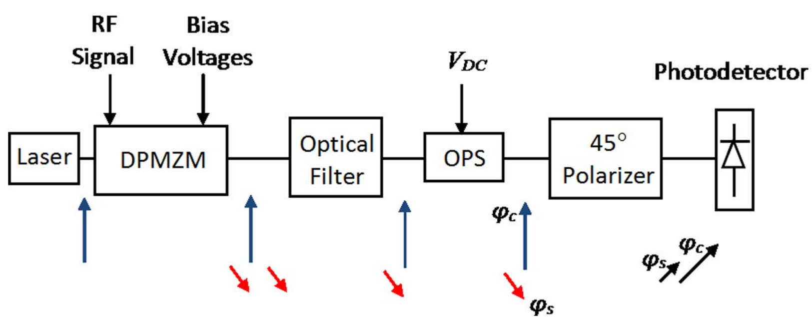

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All-Optical Photonic Microwave Phase Shifter Requiring Only a Single DC Voltage Control

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Abstract: An all-optical photonic microwave phase shifter that requires only a single dc voltage control to realize continuous 0° to 360° radio-frequency (RF) signal phase shift over a wide frequency range is presented. It is based on using an integrated dual-parallel Mach Zehnder modulator (DPMZM) with a 90° polarization rotator in one arm to generate an orthogonally polarized optical carrier and RF modulation sidebands and using a polarization-dependent optical phase shifter to introduce different optical phase shifts to these orthogonal polarization components. The phase shifter has a fast response time, a high resolution, and a compact structure. Experimental results are presented, which demonstrate a continuous 360° phase shift with a flat phase and amplitude response performance over a microwave frequency range of 6.5–26.5 GHz.

Index Terms: Radio-frequency (RF) photonics, fiber optics links and subsystems, analog optical signal processing, wideband phase shifters.

1. Introduction

Microwave phase shifting is an important signal conditioning function that is required in phased-array beamforming networks for radar and satellite communication systems [1]. Applying photonics technology to microwave phase shifting has the advantages of wide bandwidth, immunity to electromagnetic interference, excellent isolation, and the ability to provide antenna remoting [2], [3]. Photonic microwave phase shifters are also inherently compatible with fiber optic microwave systems. They can be implemented by controlling the optical phase difference between an optical carrier and RF modulation sidebands, and converting this optical phase difference into an RF phase shift at the photodetector. Various techniques to control the phase of an optical carrier and RF modulation sidebands have been reported [4]–[13]. These include adjusting the DC bias voltages of a dual-parallel Mach Zehnder modulator (DPMZM) [4], tuning the wavelengths of two phase modulated optical signals into an optical filter with a nonlinear phase response [5], and adjusting the power of the pump and probe light into a highly nonlinear fiber [6]. While these techniques can realize broadband 360° RF phase shift, they require simultaneously

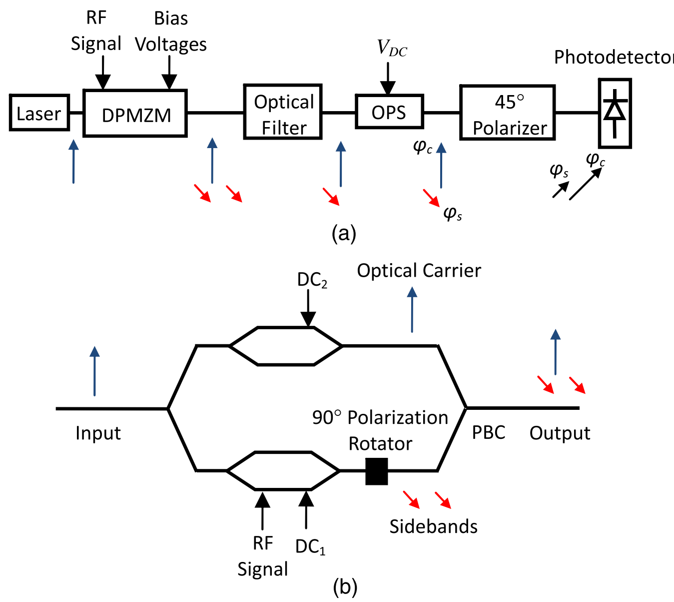

Fig. 1. (a) Topology of the new photonic microwave phase shifter and (b) structure of the dual-parallel Mach Zehnder modulator used in the new photonic microwave phase shifter.

controlling two components to avoid having large changes in the output RF signal amplitude. Phase shifters with a single control are preferred in practice. This can be achieved by using a computer to program a Fourier-domain optical processor (FD-OP) [7]; using a microwave signal generator to tune the pump frequency into a Brillouin medium [8], [9]; adjusting the polarization state of a polarization modulated optical signal into a polarizer [10]; and controlling the laser wavelength into a fiber Bragg grating with a nonlinear phase response [11]. Although a continuous 0° to 360° phase shift have been demonstrated using these techniques, they cannot simultaneously satisfy other requirements such as fast response time, low cost, simple structure, wide bandwidth, and low amplitude variation while shifting the RF signal phase.

In this paper, we present a photonic microwave phase shifter based on an integrated DPMZM with a 90° polarization rotator in one arm and a polarization dependent optical phase shifter (OPS). It only involves optical components and has the novelty of only requiring a single linear DC voltage control to realize 0° to 360° phase shift over a wide frequency range. Experimental results are presented that demonstrate the realization of a continuous 0° to 360° phase shift, with small amplitude variation of < 1.7 dB and phase deviation of < 4.5°, over a microwave frequency range of 6.5–26.5 GHz.

2. Topology and Operation Principle

The structure of the new photonic microwave phase shifter is shown in Fig. 1(a). The continuous wave light from a laser source is launched into an integrated DPMZM, which consists of two Mach Zehnder modulators (MZMs) connected in parallel and a 90° polarization rotator as shown in Fig. 1(b). The light is split equally into the two MZMs. The optical carrier in the top path passes through the upper MZM biased at the maximum transmission point. The lower MZM is driven by an RF signal and is biased at the minimum transmission point. Thus, the optical carrier at the output of the lower MZM is suppressed leaving two RF modulation sidebands. The polarization state of these two RF modulation sidebands is rotated by 90° before combining with the optical carrier from the top path in a polarization beam combiner (PBC). Hence, the output of the DPMZM consists of an optical carrier and two RF modulation sidebands in an orthogonal polarization state. The right sideband is filtered out by an optical filter as shown in Fig. 1(a). The orthogonally polarized optical carrier and RF modulation sideband pass through a polarization dependent OPS, which introduces different amount of optical phase shift to the carrier and the sideband dependent on their polarization states via a control voltage. A linear polarizer with a transmission axis at a 45° angle with the *x*-axis converts the polarization states of the orthogonally polarized optical carrier and RF modulation sideband to have an angle of 45° with respect to the *x*-axis. This also causes a 3 dB power loss in both the carrier and sideband. The carrier and RF modulation sideband, which have the same polarization state, beat at the photodetector generating an output RF signal. The phase of the output RF signal is dependent on the phase difference between the optical carrier and the RF modulation sideband, which in turn depends on the DC voltage applied to the polarization dependent OPS. Hence, an RF phase shifting operation can be realized by controlling the voltage into the polarization dependent OPS.

Note from Fig. 1(a) that the polarization dependent OPS, which is used to control the RF signal phase shift, is separated from the DPMZM that is used for RF signal modulation. This enables the RF phase shifting operation to be performed not only at the transmitter but anywhere in a fiber optic link, and to be controlled in a remote location. This solves the problem presented in previously reported phase shifters, e.g., [12], in which the RF signal modulation and the RF phase shifting operation are performed on the same device. Having an RF phase shifting operation separates with RF signal modulation makes the new photonic microwave phase shifter attractive to remote beamforming applications.

3. Analysis

With reference to the photonic microwave phase shifter structure shown in Fig. 1(a), the electric field of a linearly polarized light with a polarization in $\hat{y}$ direction into the DPMZM is given by

$$E_{\text{in}} = \hat{y} E e^{j\omega_c t} \quad (1)$$

where E is the amplitude of the input electric field, and ω_c is the optical carrier angular frequency. When the upper MZM is biased at the maximum transmission point and the lower MZM is biased at the minimum transmission point and is driven by an RF signal with an angular frequency ω_{RF}, the DPMZM output electric field can be written as

$$E_{\text{out,DPMZM}} = \hat{y} E_c e^{j\omega_c t} + \hat{x} E_s e^{j(\omega_c + \omega_{\text{RF}})t} + \hat{x} E_s e^{j(\omega_c - \omega_{\text{RF}})t} \quad (2)$$

where $\hat{x}$ and $\hat{y}$ are the orthogonal polarization directions, and E_c and E_s are the electric field amplitude of the optical carrier and RF modulation sideband, respectively. Both E_c and E_s are dependent on the modulator input electric field amplitude and the modulator insertion loss. E_s is also dependent on the modulator input RF signal amplitude. The electric field after the optical filter, the polarization dependent OPS and the 45° angle linear polarizer becomes

$$E_{\text{out}} = \sqrt{\frac{L}{2}} \left[E_c e^{j(\omega_c t + \varphi_c)} + E_s e^{j((\omega_c - \omega_{\text{RF}})t + \varphi_s)} \right] \quad (3)$$

where L is the product of the optical filter, OPS, and polarizer insertion loss, and φ_c and φ_s are the optical phase introduced by the polarization dependent OPS to the optical carrier and RF modulation sideband respectively. The optical power is the output electric field square, and the photocurrent is the product of the optical power and the photodiode responsivity. Thus the phase shifter output photocurrent at the RF signal frequency can be obtained from (3) and is written as

$$I_{\text{RF}} = \Re L E_c E_s \cos[\omega_{\text{RF}} t + (\varphi_c - \varphi_s)] \quad (4)$$

where $\Re$ is the photodiode responsivity.

Equation (4) shows that the phase of the output RF signal can be tuned by changing the phase difference between the optical carrier and the RF modulation sideband, which can be done by using a polarization dependent OPS. A $LiNbO_3$ electro-optic phase modulator can be used to realize a polarization dependent optical phase shifting operation. It operates based on the Pockels effect, in which the phase of the input light is shifted by changing a DC voltage into the modulator. $LiNbO_3$ electro-optic phase modulators can support light travelling in both TE and TM polarization states with different modulation efficiencies [14]. The relationship between the carrier and sideband phase difference and the DC voltage V_{DC} into the phase modulator used as a polarization dependent OPS in Fig. 1(a) can be written as

$$\varphi_c - \varphi_s = \frac{\pi V_{DC}}{V_{\pi,PM}}(1-\alpha) \tag{5}$$

where $V_{\pi,PM}$ is the switching voltage of the phase modulator for light travelling in the TM polarization state, and α is the ratio of the TE polarized light to TM polarized light phase modulation efficiency. Equations (4) and (5) show a linear relationship between the control voltage and the RF phase shift, which is preferred in practice. On the other hand, phase shifters such as those presented in [7] and [10] do not have a simple relationship between the control input and the RF phase shift. Note that the phase shifter presented in [10] uses a tunable polarizer to shift an RF signal phase. This is a mechanical tuning technique and hence it has a limited phase shift tuning speed. Alternatively a polarization controller and a fixed polarizer can be used. However, a programmable polarization controller is required for the phase shifter to be used in practice, which is bulky and costly.

Note that the voltage into the phase modulator only introduces different optical phases to the optical carrier and RF modulation sideband without affecting their amplitudes. Hence the photonic microwave phase shifter output RF signal amplitude remains unchanged during the RF phase shifting operation. It should be pointed out that a photonic microwave phase shifter using an optical phase modulator to introduce a polarization dependent optical phase shift has been reported [13]. However, this phase shifter can only work at a certain RF signal frequency depending on the free spectral range of the delay interferometer used in the phase shifter structure, and has almost 10 dB changes in RF signal amplitude during the RF phase shifting operation.

4. Discussion

The novel photonic microwave phase shifter has a simple structure. It only involves a single laser source and a single photodetector. The key component is the integrated DPMZM with a 90° polarization rotator in one arm which is biased in the way so that the output optical carrier and RF modulation sidebands have an orthogonal polarization state. This DPMZM is commercially available from manufacturers such as Fujitsu and was initially developed for dual-polarization binary phase shift keying (DP-BPSK) optical transmission systems. Note that the phase modulator used to realize a polarization dependent optical phase shifting operation does not need to have a wide bandwidth. Hence the cost of implementing this photonic microwave phase shifter is low compared to those using an FD-OP [7] or stimulated Brillouin scattering (SBS) [8]. The DPMZM and polarization dependent OPS based photonic microwave phase shifter has a single linear control property in which only around 10 V changes in DC voltage is required to realize the full 360° RF signal phase shift. The phase shifter tuning time is set by the response time of the $LiNbO_3$ electro-optic phase modulator, which is in the nanosecond range. The phase shifter resolution is dependent on the resolution of the DC power supply that is used to control the RF signal phase shift. DC power supplies with a high resolution of 1 mV are commercially available. Therefore, an agile and high-resolution RF phase shifting operation can be obtained. The lower operating frequency of the phase shifter is limited by the residual right RF modulation sideband that cannot be fully removed by the optical filter. Simulation results show the phase shifter can be operated from 2 GHz by using a commercial optical filter with an ultra-sharp edge roll-off of 1500 dB/nm (12 dB/GHz) [15] to largely suppress the right RF modulation sideband. The separation between the laser and optical filter center frequency needs to be maintained to avoid changes in the phase shifter lower operating frequency. In other words, both the laser frequency and the optical filter center frequency need to be stable. Simulation results show a 4 pm change

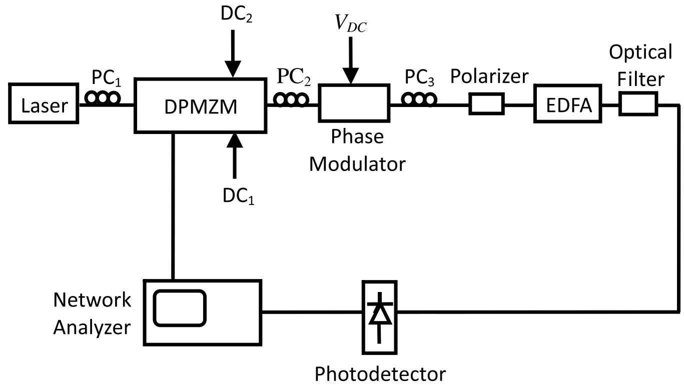

Fig. 2. Experimental setup of the DPMZM and polarization-dependent OPS-based photonic microwave phase shifter.

in the separation between the laser and optical filter center wavelength results in 0.5 GHz changes in the phase shifter lower operating frequency. A DFB laser with high wavelength stability of better than 3 pm over 2000 hours [16] and an optical filter with < 1 pm/°C thermal wavelength drift [17] can be used to minimize changes in the phase shifter lower operating frequency. Since no electrical components are involved in the structure, the phase shifter maximum operating frequency is only limited by the DPMZM bandwidth, which can be extremely wide as electro-optical modulators with 100 GHz bandwidth have been demonstrated [18]. The DPMZM and polarization dependent OPS based photonic microwave phase shifter can be operated over a wide input RF power range. The minimum and maximum input RF power is limited by the system noise floor and the nonlinear components generated by the modulator respectively. Since the lower MZM is biased at the minimum transmission point, no even order modulation sidebands are generated at the output. Therefore the phase shifter has the advantage of no second order harmonic distortion. The third order nonlinear term generated by the modulator is the dominant nonlinear component in the system.

5. Experimental Results

An experiment was set up as shown in Fig. 2 to verify the concept of the DPMZM and polarization dependent OPS based photonic microwave phase shifter. A tunable laser with a linewidth of less than 100 kHz was used as an optical source. The continuous wave light from the laser source, after passing through a polarization controller (PC_1), was launched into a DPMZM (Fujitsu FTM7980). The PC was used to align the light polarization state to maximize the DPMZM modulation efficiency. The upper MZM was biased at the maximum transmission point to minimize the loss of the optical carrier travelling in the top path of the DPMZM. The lower MZM was driven by an RF signal with 0 dBm power and was biased at the minimum transmission point. Over 40 dB carrier suppression was measured at the DPMZM output. A Z-cut $LiNbO_3$ phase modulator (Covega Mach-10 053-10-S-A-A) with a switching voltage of 3.5 V was used as a polarization dependent OPS. Since the phase modulator had a normal single mode fiber at the input and output port, a PC was placed before and after the phase modulator. PC_2 was used to align the polarization state of the carrier and sidebands at the DPMZM output to the TM axis and TE axis of the phase modulator respectively. PC_3 was used to rotate the polarization state of the carrier and RF modulation sidebands to have a 45° angle before launching into a linear polarizer with a transmission axis pointing in the $\hat{y}$ direction. It should be noted that the three PCs (PC_1, PC_2, and PC_3) can be avoided by using polarization-maintaining fibers between the laser, DPMZM, phase modulator and a 45° angle linear polarizer. An erbium-doped fiber amplifier was connected to the polarizer output to compensate for the system loss. A 1 nm bandwidth optical filter was used to filter out the right sideband and to reduce the amplified spontaneous emission noise. The optical signal was

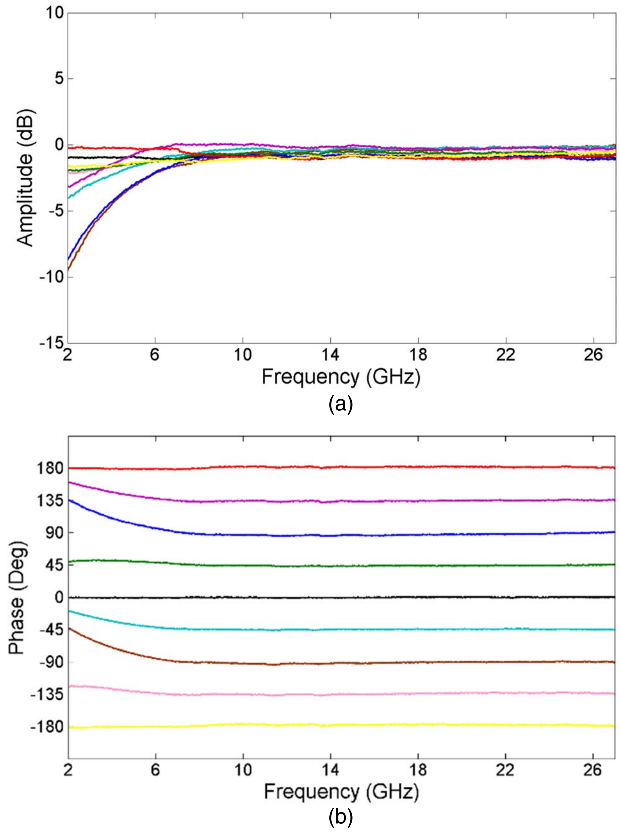

Fig. 3. Measured (a) amplitude and (b) phase response of the DPMZM and polarization-dependent OPS-based photonic microwave phase shifter for different dc voltages into the phase modulator.

detected by a 50 GHz bandwidth photodetector, which was connected to a 26.5 GHz bandwidth vector network analyzer to display the output RF signal amplitude and phase response.

The frequency-dependent characteristic of the DPMZM, the photodetector and the electrical cables used in the experiment were calibrated out before performing the phase shifter amplitude and phase response measurement. A continuous −180° to 180° phase shift, having the measured amplitude and phase response as shown in Fig. 3, was obtained by adjusting the DC voltage V_{DC} into the phase modulator. The measurements show < 1.7 dB amplitude variation and < 4.5° phase deviation over the 6.5–26.5 GHz microwave frequency range for full 360° phase shift. The small amplitude variation was mainly due to the residual optical carrier at the output of the lower MZM that was not fully suppressed. It can be seen from the figure that at low frequencies, the phase shifter output amplitude reduces and the phase shift deviates from the design value. The phase shifter lower operating frequency was limited by the sharpness of the optical filter edge roll-off as was discussed in Section 4. Using single sideband suppressed carrier modulation instead of an optical filter to filter out one sideband enables the phase shifter to operate at low frequencies. This requires the lower MZM inside the integrated DPMZM to be replaced by two MZMs connected in parallel and are driven by a 90° phase difference RF signal from an electrical 90° hybrid coupler [19]. However, incorporating electrical components in the system limits the phase shifter upper operating frequency and causes ripples in the phase shifter amplitude and phase response due to the 90° hybrid coupler amplitude and phase imbalance. Due to the lack of a wide bandwidth network analyzer, the phase shifter was only demonstrated up to 26.5 GHz. Fig. 4 shows a total of 9.2 V DC voltage is required to obtain −180° to 180° RF signal phase shift. The measurement verifies a linear relationship between the RF signal phase shift and the control voltage. The slight deviation from the linear phase shift to voltage relationship

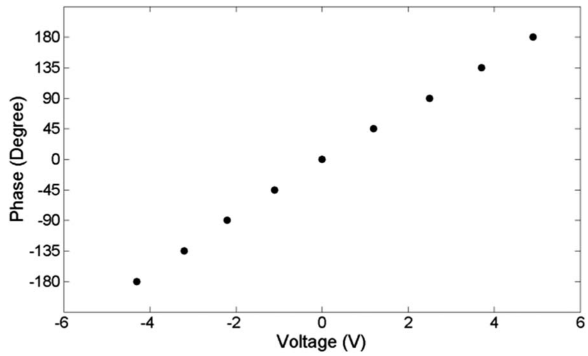

Fig. 4. Measured output RF signal phase shift versus dc voltage into the phase modulator.

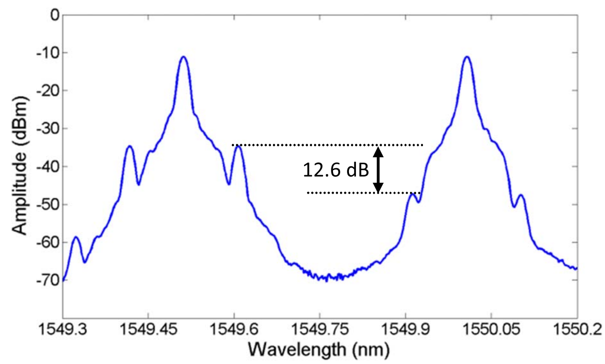

Fig. 5. Measured phase modulator output optical spectrum for two different wavelengths of light having TE and TM polarization states into the phase modulator driven by a 10-GHz RF signal.

shown in Fig. 4 is due to the fact that polarization controller in front of the phase modulator was not properly adjusted or that the light polarization state drifted during the measurement. This can be avoided by using a polarization maintaining fiber to connect between the DPMZM and the phase modulator.

The TE to TM polarized light modulation efficiency ratio α of the phase modulator used in the experiment was measured. This was done by using a PBC to combine the output of two different wavelength (1549.5 nm and 1550 nm) laser sources having the same optical power but an orthogonal polarization state. The output of the PBC was connected to a PC followed by the phase modulator driven by a 10 GHz RF signal. The PC between the PBC and the phase modulator was adjusted to maximize and minimize the sideband amplitudes of the 1549.5 nm and 1550 nm optical carrier, respectively, as shown in Fig. 5. It can be seen from the figure that the sidebands have 12.6 dB difference in amplitude. This corresponds to 0.23 phase modulator TE to TM polarized light modulation efficiency ratio. Using this modulation efficiency ratio and (5), a total of 9.14 V changes in DC voltage into the phase modulator is required to achieve full 360° RF phase shift, which agrees with the measurement shown in Fig. 4.

6. Conclusion

In conclusion, a photonic microwave phase shifter based on an integrated DPMZM consists of two MZMs and a 90° polarization rotator and a polarization dependent OPS has been presented. An RF phase shifting operation is realized by simply adjusting the DC voltage into the polarization dependent OPS to introduce different amount of optical phase shift to the orthogonally polarized optical carrier and RF modulation sidebands. The phase shifter has the advantages of wide bandwidth, simple structure, and fast response time. It also allows the phase shifting operation to be controlled in a remote location and requires only a single linear DC voltage control to achieve full 360° RF signal phase shift. Experimental results demonstrate that the novel photonic microwave phase shifter has very small amplitude variation of < 1.7 dB and low phase deviation of < 4.5° over 20 GHz operating range from 6.5–26.5 GHz for −180° to 180° RF signal phase shift, as well as a linear control voltage to RF phase shift relationship.

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