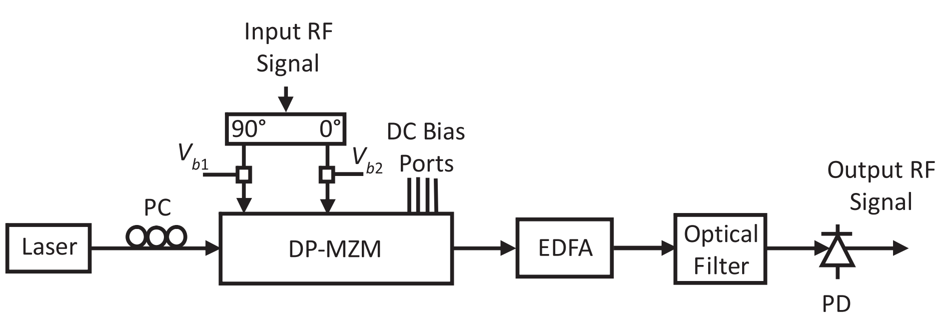
IEEE Photonics Journal
An IEEE Photonics Society Publication

Photonics-Based Wideband Microwave Phase Shifter

Volume 9, Number 3, June 2017

Xudong Wang
Tong Niu
Erwin Hoi Wing Chan
Xinhuan Feng
Bai-ou Guan
Jianping Yao



DOI: 10.1109/JPHOT.2017.2697207

Photonics-Based Wideband Microwave Phase Shifter

Xudong Wang,[1] Tong Niu,[1] Erwin Hoi Wing Chan,[2] Xinhuan Feng,[1] Bai-ou Guan,[1] and Jianping Yao[3]

[1]Guangdong Provincial Key Laboratory of Optical Fiber Sensing and Communications, Institute of Photonics Technology, Jinan University, Guangzhou 510632, China
[2]School of Engineering and Information Technology, Charles Darwin University, Casuarina, NT 0810, Australia
[3]School of Electrical Engineering and Computer Science, University of Ottawa, Ottawa, ON K1N 6N5, Canada

DOI:10.1109/JPHOT.2017.2697207

Manuscript received January 16, 2017; revised April 14, 2017; accepted April 18, 2017. Date of publication April 25, 2017; date of current version May 10, 2017. This work was supported in part by the National Natural Science Foundation of China under Grant 61501205 and Grant 61475065; in part by the Guangdong Natural Science Foundation under Grant 2014 A030310419, Grant 2015 A030313322, and Grant S2013030013302; and in part by the Fundamental Research Funds for the Central Universities under Grant 21615325. Corresponding author: Xinhuan Feng (e-mail: tfengxh@jnu.edu.cn).

Abstract: A wideband microwave photonic phase shifter implemented based on a special dual-parallel Mach–Zehnder modulator (DP-MZM) consisting of two sub-MZMs and a polarization rotator is proposed and demonstrated. A microwave signal to be phase shifted is applied to the two sub-MZMs, via a 90° hybrid coupler, to generate two orthogonally polarized intensity-modulated optical signals, which are combined at a polarization beam combiner. A phase-shifted microwave signal is obtained by detecting the combined signal at a photodetector. The tuning of the phase shift is realized by tuning the DC bias voltages applied to the sub-MZMs. Since the phase shift tuning has been done electrically, high speed phase tuning can be implemented. The proposed phase shifter is experimentally demonstrated. A continuous phase tuning from 0° to 360° with small magnitude variations of less than ±1 dB and phase ripple standard deviation of less than 2.7° in a decade bandwidth from 2.5 to 25 GHz is realized. The system insertion loss is measured to be 10.8 dB. Investigation on the cause of magnitude and phase deviations is also performed by simulations, which are confirmed by experimental measurements.

Index Terms: Radio frequency photonics, fiber optic links and subsystems, analog optical signal processing, wideband phase shifters.

1. Introduction

Processing microwave signals in the optical domain has been a subject of interest over the past 30 years as it has numerous advantages such as wide bandwidth, large tunability, and low loss when distributing microwave signals over an optical fiber [1]. The immunity to electromagnetic interferences (EMIs) is another important feature which makes the processing and transmission of microwave signals in the optical domain extremely attractive, especially in an electromagnetic complex environment [1], [2]. For wireless communications and radar systems, the transmission performance can be improved using a phased array antenna by which the direction of a microwave beam can be steered electrically at a fast speed without mechanical movement. The key devices in a phased array antenna are the phase shifters which should have a large phase tunable range over a wide bandwidth with a low loss [3], [4].

Numerous photonics-based microwave phase shifters have been proposed in the last few years [5]–[15]. The phase tuning can be realized by optical means, through either tuning the optical wavelength [5]–[7] or the optical power [8], [9]. The major limitation associated with optical tuning is the slow tuning speed and poor tuning resolution. For example, in [5], an optically-controlled microwave phase shifter implemented based on stimulated Brillouin scattering (SBS) was reported, in which the tuning of the phase shift was realized by controlling the optical pumping wavelength. The tuning of the pumping wavelength was realized by modulating a light wave having a fixed wavelength with a microwave signal to produce a double sideband without an optical carrier. Thus, by tuning the microwave frequency, the pumping wavelength could be tuned. The phase shift tuning speed is determined by the frequency tuning speed of a microwave signal generator, which is in the range of hundreds of microsecond for a commercial microwave signal generator. In addition, the phase shifter in [5] has a complicated structure and is expensive since two modulators, a microwave signal generator and a long fiber as an SBS medium are needed which would also increase the loss and deteriorate the noise figure due to the strong SBS noise. In [10], a photonics-based microwave phase shifter was reported in which the tunable phase shift was realized based on controlling the phase of the two sidebands of a double-sideband modulated optical signal using a Fourier-domain optical processor. The settling time of a commercial Fourier-domain optical processor is 500 ms [16], which is too slow for most beamforming applications. In [11], a microwave phase shifter with a tunable phase shift realized by tuning the light polarization state was reported, in which an electrically-controlled polarization controller was used to tune the light polarization state. The use of an electrically-controlled polarization controller can ensure a high-speed phase tuning, but the device is bulky and expensive. A microwave phase shifter can also be implemented using a dual-parallel Mach-Zehnder modulator (DP-MZM), in which two sub-MZMs and a phase modulator are integrated. The phase tuning is realized by tuning the bias voltages applied to the two sub-MZMs and the phase modulator [12]. However, three DC bias voltages are needed.

In this paper, we propose and experimentally demonstrate a fully electrically tunable photonics-based wideband microwave phase shifter with a simple structure and a low loss. The microwave modulation and phase shifting are simultaneously achieved at a special DP-MZM consisting of two sub-MZMs and a polarization rotator where two orthogonally polarized intensity-modulated optical signals are generated. A phase-shifted microwave signal is obtained by combining the two orthogonally polarized optical signals at a polarization beam combiner (PBC) and detected at a photodetector (PD). The tunable phase shift is realized by tuning the DC bias voltages applied to the upper and lower sub-MZMs in the DP-MZM. Since the tuning is done electrically, the tuning speed is ultrafast and the resolution is high. The proposed phase shifter is experimentally demonstrated. A continuous phase tuning from 0° to 360° with small magnitude variations of less than ±1 dB and phase ripple standard deviation of less than 2.7° in a decade bandwidth from 2.5 to 25 GHz is realized.

2. Topology and Operation Principle

In a microwave receiver where a photonics-assisted phased array antenna is employed, the microwave signal received by the antenna needs to be converted to an optical signal, which is usually done using an optical modulator. In addition, the phase of the received microwave signal needs to be controlled for beamforming. It has been demonstrated that controlling the DC voltages into two or more modulators connected in parallel can shift the phase of an RF modulated optical signal [12]–[14]. Therefore, a modulator with two parallel MZMs has two functions; one is RF signal modulation and the other is RF signal phase shift. This reduces the phase array receive antenna system complexity and weight. However, in the past, the modulators that have the ability to control the RF signal phase are not commercially available [13], the phase shifters have a limited lower operating frequency and high loss due to the use of an optical filter to remove one RF signal modulation sideband [14], and/or require at least three modulator DC bias voltages [12], [14].

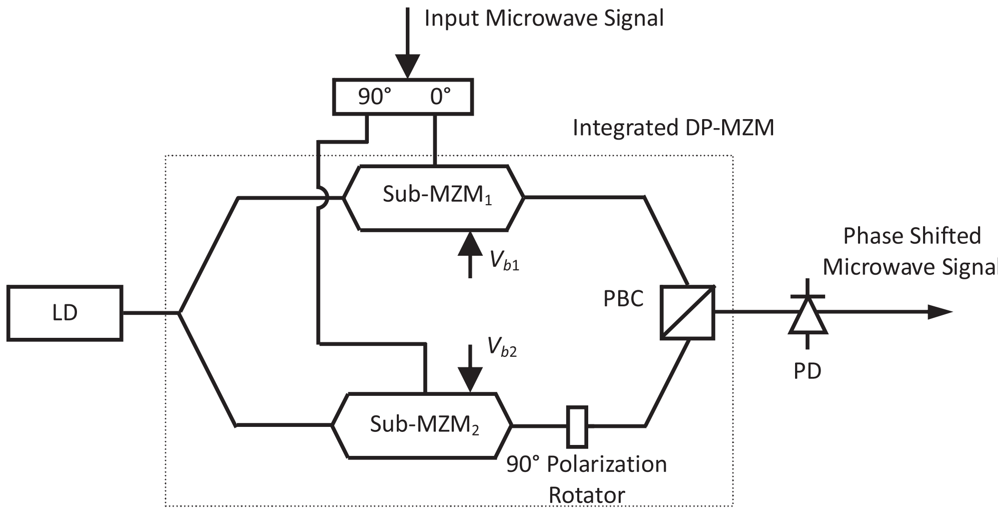


Fig. 1. Proposed photonics-based microwave phase shifter. LD: laser diode, MZM: Mach-Zehnder modulator, PBC: polarization beam combiner, PD: photodetector.

In this paper, we propose to implement a microwave photonic phase shifter using only a single DP-MZM to perform both electrical-to-optical conversion and microwave phase shifting. Fig. 1 shows the structure of the proposed photonics-based microwave phase shifter that can be used in a microwave receiver for phased array beamforming. A continuous-wave light from a laser diode (LD) is sent to a DP-MZM. The DP-MZM is a special modulator that consists of two sub-MZMs (sub-MZM$_1$ and sub-MZM$_2$) and a 90° polarization rotator connected after sub-MZM$_2$ to make the two light waves from the sub-MZMs orthogonally polarized. A 90° polarization rotation can be realized by using a TE-TM mode converter [17] or a half wave plate. The sub-MZMs are driven by a pair of 90° phase difference microwave signals. The two orthogonally polarized RF modulated optical signals at the output of the special DP-MZM are combined at a PBC and then applied to a PD. Thanks to the polarization orthogonality between the two RF modulated optical signals, the detection of the two signals at a PD would enable a phase shift by controlling the two DC bias voltages to the two sub-MZMs. Since only a single DP-MZM with only two DC bias voltages is employed, the system is greatly simplified.

A microwave signal with an angular frequency ω_{RF} to be phase shifted is applied to the two sub-MZMs in the integrated DP-MZM via a 90° hybrid coupler. The electric fields at the outputs of the two sub-MZMs are given by

$$E_{out,top} = \frac{\sqrt{2}}{4} E_{in} e^{j\omega_c t} \sqrt{t_{ff}} \left[1 + e^{j(\beta_{RF} \sin \omega_{RF} t + \beta_{b1})}\right] \tag{1}$$

$$E_{out,bottom} = \frac{\sqrt{2}}{4} E_{in} e^{j\omega_c t} \sqrt{t_{ff}} \left[1 + e^{j(\beta_{RF} \cos \omega_{RF} t + \beta_{b2})}\right] \tag{2}$$

where E_{in} is the amplitude of the electric field into the DP-MZM, ω_c is the optical carrier angular frequency, t_{ff} is the MZM insertion loss, $\beta_{RF} = \pi V_{RF}/V_\pi$ is the modulation index, V_{RF} is the RF signal voltage into the modulator, V_π is the modulator switching voltage, $\beta_{b1} = \pi V_{b1}/V_\pi$, $\beta_{b2} = \pi V_{b2}/V_\pi$, and V_{b1} and V_{b2} are the bias voltages applied to sub-MZM$_1$ and sub-MZM$_2$, respectively. Since the optical signals from sub-MZM$_1$ and sub-MZM$_2$ are orthogonally polarized, the combined optical power into the PD is given by

$$P_{out} = \left|E_{out,top}\right|^2 + \left|E_{out,bottom}\right|^2 \tag{3}$$

with

$$\left|E_{out,top}\right|^2 = \frac{1}{4}P_{in}t_{ff}[1 + \cos(\beta_{RF}\sin\omega_{RF}t + \beta_{b1})] \tag{4}$$

$$\left|E_{out,bottom}\right|^2 = \frac{1}{4}P_{in}t_{ff}[1 + \cos(\beta_{RF}\cos\omega_{RF}t + \beta_{b2})] \tag{5}$$

where P_{in} is the optical power into the DP-MZM. Since the photocurrent is the product of the optical power into the PD with its responsivity $\Re$, the output photocurrent at the RF signal frequency can be obtained from (3) and is given by

$$I_{RF,out} = -\frac{1}{4}\Re P_{in}t_{ff}\beta_{RF}\sqrt{\sin^2\beta_{b1} + \sin^2\beta_{b2}} \times \sin\left(\omega_{RF}t + \tan^{-1}\left(\frac{\sin\beta_{b2}}{\sin\beta_{b1}}\right)\right). \tag{6}$$

It can be seen from (6) that both the amplitude and phase of the output RF photocurrent are dependent on β_{b1} and β_{b2}, which in turn are dependent on the two bias voltages to the sub-MZMs. By designing β_{b1} and β_{b2} to have the relationship

$$\beta_{b1} = \frac{\pi}{2} - \beta_{b2} \tag{7}$$

the output RF photocurrent becomes

$$I_{RF,out} = \frac{1}{4}\Re P_{in}t_{ff}\beta_{RF}\sin(\omega_{RF}t + \beta_{b2} + \pi). \tag{8}$$

This shows the output RF signal phase shift can be tuned by controlling the bias voltages to the sub-MZMs while the output RF signal amplitude remains unchanged. Equation (8) also shows the phase shift produced by the proposed phase shifter has a linear relationship with the modulator bias voltage V_{b2}.

By connecting a phase shifter having a structure shown in Fig. 1 to each antenna element in a phased array antenna system and using wavelength division multiplexing (WDM), the beam direction can be steered via controlling the bias voltages. The advantage of using the proposed technique is that the phase shifting and RF modulation can be achieved using a single DP-MZM, which simplifies greatly the receiver system and reduces the cost compared to the previously reported DP-MZM based microwave photonic phase shifters, which either rely on an additional optical filter to remove one RF signal modulation sideband [14], or require two laser sources or two PDs to avoid the coherent interference problem [15]. In addition, the number of DC bias voltages used in the proposed phase shifter is less than that used in a conventional DP-MZM which requires three DC bias voltages [18]. Since the phase shift tuning speed is dependent on the speed of the DC bias tuning, which can be ultra-fast, the phase shifter can thus provide high speed phase shift tuning. For example, a DC power supply from Keysight Technologies [19] has a fast transient time of $<50\ \mu$s. This DC power supply also has a high voltage resolution of 1 mV, which enables the realization of a high phase shift resolution of $<1°$.

Note that a 90° hybrid coupler is required in the proposed phase shifter to produce two 90° phase difference RF signals into the DP-MZM. The bandwidth of the 90° hybrid will limit the bandwidth of the entire phase shifter. Currently, 90° hybrid couplers with a bandwidth of tens of GHz are available [20]. However, the frequency-dependent magnitude and phase imbalance in the coupler outputs would cause ripples in the magnitude and phase responses. In our analysis, by including the non-ideal magnitude and phase characteristic of a 90° hybrid coupler, the output RF photocurrent is given by

$$I_{RF,out} = -\frac{1}{4}\Re P_{in}t_{ff}\beta_{RF} \times \sqrt{\begin{array}{l}[\sin\beta_{b1} + k(\omega_{RF})\cos(\theta(\omega_{RF}))\sin\beta_{b2}]^2\\ +[\sin(\theta(\omega_{RF}))\sin\beta_{b2}]^2\end{array}} \times \sin(\omega_{RF}t + \varphi) \tag{9}$$

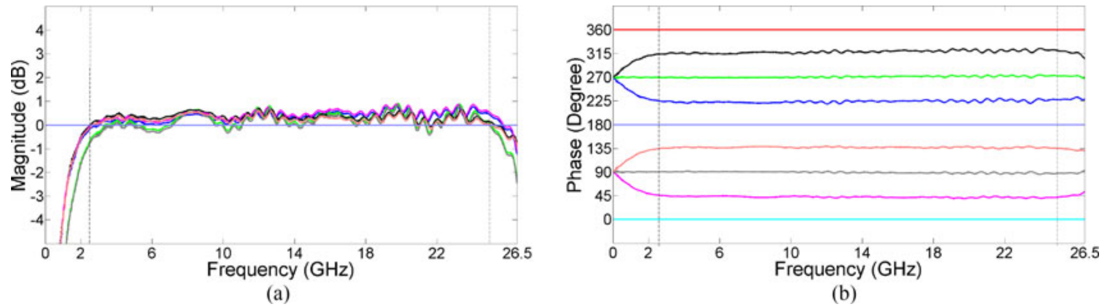


Fig. 2. Simulated (a) magnitude and (b) phase responses of the proposed microwave photonic phase shifter with the inclusion of the frequency response of a commercial 2-26.5 GHz bandwidth 90° hybrid coupler.

where

$$\varphi = \tan^{-1}\left(\frac{k(\omega_{RF})\sin(\theta(\omega_{RF}))\sin\beta_{b2}}{\sin\beta_{b1} + k(\omega_{RF})\cos(\theta(\omega_{RF}))\sin\beta_{b2}}\right) \tag{10}$$

and $k(\omega_{RF})$ and $\theta(\omega_{RF})$ are the ratio between the two RF signal voltages and the phase difference between two RF signals at the 90° hybrid coupler outputs, respectively. They are dependent on the RF signal frequency. Note that when $k(\omega_{RF}) = 1$ and $\theta(\omega_{RF}) = 90^\circ$, (9) can be simplified to (6). The magnitude and phase responses of a commercial 2–26.5 GHz bandwidth 90° hybrid coupler are measured to obtain the value of $k(\omega_{RF})$ and $\theta(\omega_{RF})$, which are used together with (9) and (10) to simulate the magnitude and phase responses of the proposed photonic phase shifter for different phase shifts as shown in Fig. 2. The variations in magnitude for 0°–360° phase shifting operation within the 90° hybrid coupler bandwidth are within 3 dB. For a slight smaller frequency range of 2.5–25 GHz, the magnitude variations and phase deviations are $<\pm 1$ dB and $<\pm 2^\circ$, respectively. Phase shifter output amplitude reduction and phase deviation from the desired value in the 0–2 GHz frequency range can be seen in Fig. 2. This is due to the insertion loss of the 2–26.5 GHz bandwidth 90° hybrid coupler used in the simulation increases as the frequency reduces to below 2 GHz. Using a coupler that has a lower operating frequency of <1 GHz in the phase shifter structure enables the phase shifter to operate at lower frequencies. Such 90° hybrid couplers are commercially available from manufacturers such as Marki Microwave. Nevertheless, the simulation results in Fig. 2 reveal the proposed phase shifter has a flat magnitude and phase responses over 2.5–25 GHz frequency range, which cannot be achieved using a phase shifter that relies on an optical filter to remove one RF signal modulation sideband.

3. Experimental Results

An experiment was conducted based on the setup shown in Fig. 3. A 1550-nm continuous-wave light from a laser source with an optical power of 14 dBm and a linewidth of 100 kHz was launched into the DP-MZM (Fujitsu FTM7980). An RF signal from a microwave generator was sent to a 2-26.5 GHz bandwidth 90° hybrid coupler (Marki Microwave QH0226). A bias tee with a bandwidth of 40 GHz was connected between the output of the 90° hybrid coupler and the RF port of the DP-MZM. The reason to not use the DC bias ports of the DP-MZM is to increase the tuning speed since the DC bias ports have a low response speed. Note that the phase shift tuning speed is determined by the system response time, and the response time is inversely proportional to the bandwidth. The bandwidth of the DP-MZM RF port and DC port were measured to be >25 GHz and <10 MHz, respectively. Therefore the phase shifter can have a much faster response speed only limited by the DC power supplies when applying the DC bias voltages into the modulator RF ports to control the RF signal phase, compared to that when applying the DC bias voltages into the modulator DC ports. This leads to high phase shift tuning speed. Note that the two RF ports

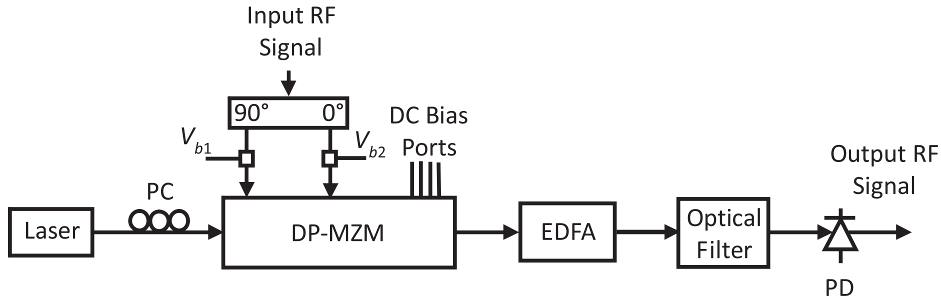


Fig. 3. Experimental setup of the proposed photonics-based microwave phase shifter.

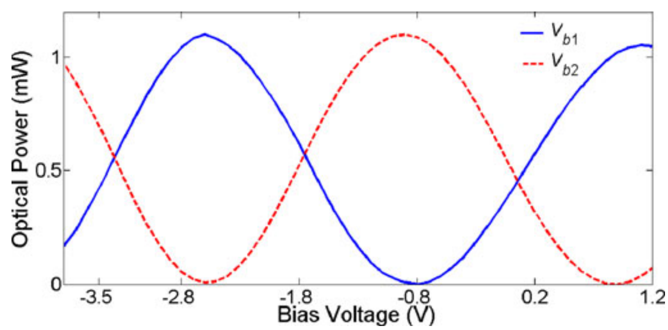


Fig. 4. Measured transfer functions of the upper (blue line) and lower (red line) sub-MZMs inside the DP-MZM.

also have smaller switching voltages of 1.8 V and 1.7 V compared to those of 8.2 V and 8.75 V for the DC bias ports in the upper and lower sub-MZMs, respectively. This enables DC power supplies with small output voltages to be used in the proposed microwave photonic phase shifter to realize the full 0°–360° phase shift. Since all the components in the DP-MZM were integrated on a Lithium Niobate substrate, there are no length matching and polarization control problems inside the DP-MZM. A polarization controller (PC) was placed before the DP-MZM to align the polarization state of the incident light to minimize the polarization-dependent loss. An erbium-doped fiber amplifier (EDFA) was connected to the output of the DP-MZM to compensate for the system loss, and a 1 nm bandwidth optical filter was connected after the EDFA to reduce the amplified spontaneous emission (ASE) noise. Note that the EDFA and the optical filter can be eliminated if a high-power laser source was used. The optical signal at the output of the optical filter was detected by a 33-GHz PD (Discovery Semiconductors DSC20H). The magnitude and phase responses of the phase shifter were measured by a 26.5-GHz bandwidth vector network analyzer (VNA, Agilent N5222A).

The transfer functions of the upper and lower sub-MZMs inside the DP-MZM were measured with the modulator RF port as an input port in order to determine the bias voltages V_{b1} and V_{b2} required to obtain a given phase shift. This was done by connecting a PC and a polarization beam splitter (PBS) after the DP-MZM to select one polarization state. The optical power at the output of the PBS was measured while sweeping the bias voltage V_{b1} or V_{b2}, and the measurements are shown in Fig. 4. It can be seen that the upper sub-MZM has a switching voltage of 1.8 V and the lower sub-MZM has a switching voltage of 1.7 V. The figure also shows the upper and lower sub-MZM transfer functions were shifted by 1.1 V and −0.9 V respectively. According to (8) and the transfer functions, when $\beta_{b2} = -\pi$, the output RF signal phase is 0°, which requires the bias voltage V_{b2} to be −2.6 V. Meanwhile, V_{b1} needs to be 0.06 V to satisfy the condition $\beta_{b1} + \beta_{b2} = \pi/2$. The frequency-dependent characteristic of the RF cables, the DP-MZM and the PD were calibrated out when the modulator bias voltages of $V_{b1} = 0.06$ V and $V_{b2} = -2.6$ V were chosen for 0° phase shift.

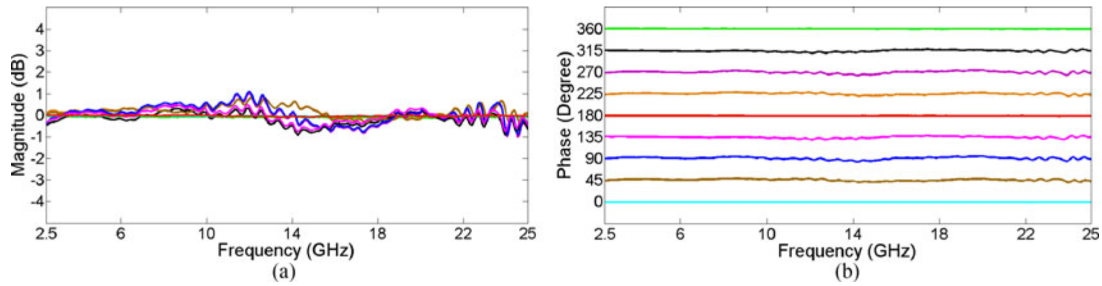


Fig. 5. Measured (a) magnitude and (b) phase response of the new DP-MZM based microwave photonic phase shifter.

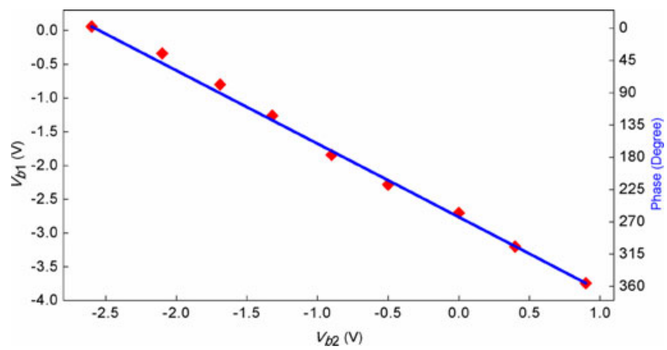


Fig. 6. Measured (dotted) and simulated (solid) phase shifts for different DC bias voltages (V_{b1} and V_{b2}).

By continuously increasing the bias voltage V_{b2} while adjusting the bias voltage V_{b1} to satisfy the condition given in (7), the phase shifter magnitude and phase responses were measured, as shown in Fig. 5. The experimental results reveal that, in a 2.5–25 GHz frequency range, the phase shifter has magnitude variations of $<\pm 1$ dB and phase deviation standard deviation of $<2.7^\circ$, which agree well with the simulated results given in Fig. 2. The magnitude variations and phase deviations are mainly resulted from the magnitude and phase imbalance of the 90° hybrid coupler, as discussed in the previous section. It can be seen from Fig. 5 that the frequency ranges where the phase has relatively large deviation are 10–14 GHz and 22–25 GHz. The reason why these frequency ranges have a larger phase deviation than other frequency ranges is the 90° hybrid coupler used in the experiment has large phase ripples in these frequency ranges. Using a 90° hybrid coupler with a flatter phase response than the coupler used in the experiment can improve the phase shifter phase deviation performance. The phase shift for different bias voltages was measured and is shown in Fig. 6. The simulated phase shift is also shown. Again, the experimentally achieved phase shift agrees well with the simulated phase shift. Note that the simulation result shown in Fig. 6 was obtained using (7) together with the upper and lower sub-MZM switching voltages and transfer function shifts found from the measured sub-MZM transfer functions. A look up table for the modulator bias voltages (V_{b1} and V_{b2}) required to obtain a given phase shift can be created from Fig. 6, which can be used to program the DC power supplies connected to the DP-MZM input. Programmable DC power supplies with a fast transient time and a high voltage resolution are commercially available [19].

The impact of the wavelength variations on the accuracy of the generated phase shift was investigated. To do so, we tuned the laser wavelength by 1 nm. The results show a phase change of less than 1° was observed, which demonstrates that the phase shift is not sensitive to the laser wavelength change and a critical control in the laser wavelength is not required. The carrier to noise ratio (CNR) of a phase shifted signal at the output of the phase shifter was also measured at a

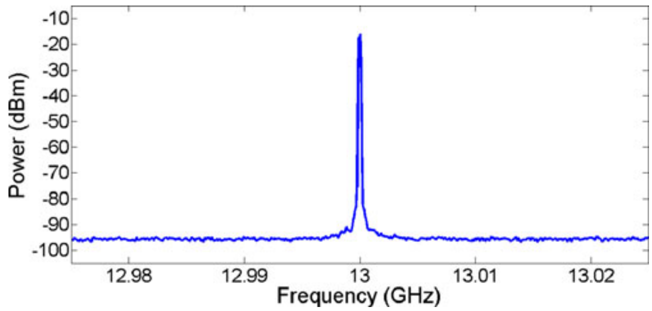
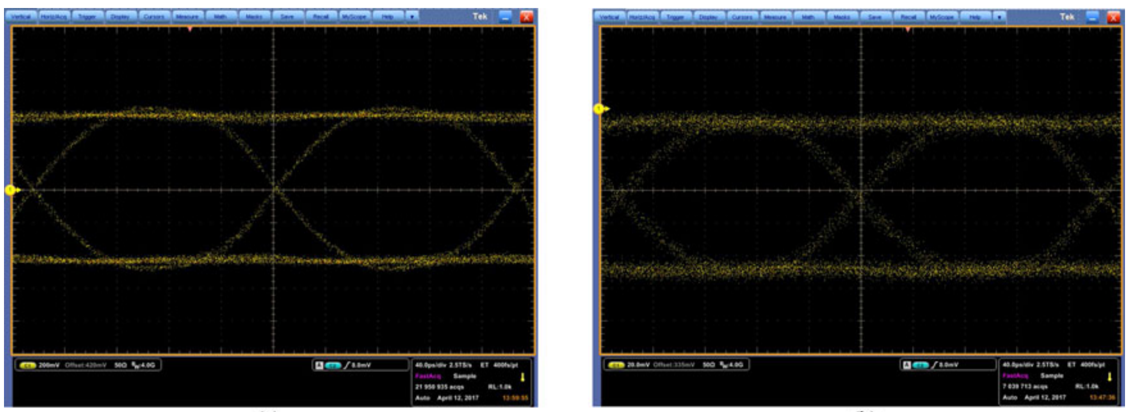


Fig. 7. Measured spectrum of the phase shifted RF signal for a 13 GHz RF signal into the DP-MZM.



(a) (b)

Fig. 8. Eye diagram of a 2.7 Gbit/s PRBS at the (a) input and (b) output of the microwave photonic phase shifter.

phase shift of 90° ($V_{b1} = -0.8$ V and $V_{b2} = -1.69$ V) for an RF signal at 13 GHz with a power of −3.7 dBm into the 90° hybrid coupler. A CNR of 130.2 dB·Hz, was measured by an electrical spectrum analyser with a 100 kHz resolution bandwidth, as shown in Fig. 7. In the measurement, the optical power into the PD was controlled to be 15 dBm. Note that this PD is a high optical power handling PD. It was found from experiment that the photocurrent at the PD output has a linear relationship with the input optical power between 0 mW to 35 mW. Therefore the second order harmonic component generated by the PD is small compared to those generated by the special DP-MZM, which is biased in the way to shift the RF signal phase. It should be pointed out that previously reported microwave photonic phase shifters implemented using two MZMs connected in parallel [12], [15] also generate second order harmonic components. The insertion loss of the phase shifter was 10.8 dB. To compare its insertion loss with a simple fiber optic link, we constructed a fiber optic link using the same laser source, the same EDFA and the same PD, while the DP-MZM was replaced by a 40-GHz bandwidth MZM (Photline MX-LN-40). The insertion loss of the fiber optic link was found to be 5.3 dB when operating under the same conditions, i.e., the same modulation index and the same optical power into the PD, as the phase shifter. This shows the proposed phase shifter only introduces an additional 5.5 dB loss compared to a fiber optic link. This additional 5.5 dB loss is due to the combination of various factors. These include the special DP-MZM splits the input light into two and combines them in an orthogonal polarization state, which introduces an additional loss compared to a quadrature-biased MZM in a fiber optic link, the insertion loss of the 90° hybrid coupler at the DP-MZM input, and the DP-MZM and the MZM used in the experiment have different switching voltages. A pattern generator generating a 2.7 Gbit/s pseudorandom binary sequence (PRBS) was connected to the phase shifter input port. An eye diagram at the input and output of the phase shifter were measured on a 4 Gbit/s oscilloscope and are shown in Fig. 8. It can be seen that the phase shifter output has an open eye and is slightly noisier than the eye at the phase shifter input.

4. Discussion and Conclusion

The proposed microwave photonic phase shifter has a simple structure as it only involves a laser source, a DP-MZM and a PD. It utilizes both the upper and lower RF modulation sidebands for the phase shifting operation. As a result, its insertion loss performance is 3 dB better than a phase shifter using single-sideband modulation. The proposed phase shifter is not sensitive to wavelength change while phase shifters that rely on the use of an optical filter to remove one sideband require a critical control of the laser wavelength. The proposed phase shifter has a high CNR performance since it has low insertion loss and does not introduce additional noise components other than the laser intensity noise, the shot noise and the thermal noise, which are the fundamental noise components in a fiber optic link.

In conclusion, a wideband microwave photonic phase shifter implemented based on a special DP-MZM consisting of two sub-MZMs was proposed and experimentally demonstrated. The phase shifting operation was realized by adjusting the bias voltages to the two sub-MZMs in the DP-MZM. Unlike the phase shifters using a conventional DP-MZM, here a special DP-MZM with a 90° polarization rotator in one branch was used, thus the RF modulated optical signals at the output of the DP-MZM were orthogonally polarized. The detection of the two orthogonally polarized optical signals at a PD would generate a phase shifted microwave signal with its phase shift determined by the bias voltages applied to the two sub-MZMs. The key advantages of the proposed phase shifter include: simple structure, high tuning speed, low insertion loss, high CNR, and insensitive to optical wavelength change. An experiment was conducted to evaluate the operation of the proposed phase shifter. The generation of a tunable phase shift from 0° to 360° over a bandwidth of 2.5–25 GHz was demonstrated.

References

[1] R. A. Minasian, E. H. W. Chan, and X. Yi, “Microwave photonic signal processing,” *Opt. Exp.*, vol. 21, no. 19, pp. 22918–22936, Sep. 2013.
[2] J. Capmany and D. Novak, “Microwave photonics combines two worlds,” *Nature Photon.*, vol. 1, no. 6, pp. 319–330, Sep. 2007.
[3] M. Y. Frankel, P. J. Matthews, R. D. Esman, and L. Goldberg, “Practical optical beamforming networks,” *Opt. Quantum Electron.*, vol. 30, no. 11, pp. 1033–1050, Dec. 1998.
[4] N. A. Riza, S. A. Khan, and M. A. Arain, “Flexible beamforming for optically controlled phased array antenna,” *Opt. Commun.*, vol. 227, pp. 301–310, Nov. 2003.
[5] A. Loayssa and F. J. Lahoz, “Broad-band RF photonic phase shifter based on stimulated brillouin scattering and single-sideband modulation,” *IEEE Photon. Technol. Lett.*, vol. 18, no. 1, pp. 208–210, Jan. 2006.
[6] X. Wang, E. H. W. Chan, and R. A. Minasian, “All-optical photonic microwave phase shifter based on an optical filter with a nonlinear phase response,” *J. Lightw. Technol.*, vol. 31, no. 20, pp. 3323–3330, Sep. 2013.
[7] W. Li, N. H. Zhu, and L. X. Wang, “Photonic phase shifter based on wavelength dependence of brillouin frequency shift,” *IEEE Photon. Technol. Lett.*, vol. 23, no. 14, pp. 1013–1015, May 2011.
[8] H. Shahoei and J. Yao, “Tunable microwave photonic phase shifter based on slow and fast light effects in a tilted fiber bragg grating,” *Opt. Exp.*, vol. 20, no. 13, pp. 14009–14014, Jun. 2012.
[9] W. Li, W. H. Sun, W. T. Wang, and N. H. Zhu, “Optically controlled microwave phase shifter based on nonlinear polarization rotation in a highly nonlinear fiber,” *Opt. Lett.*, vol. 39, no. 11, pp. 3290–3293, Jun. 2014.
[10] X. Wang, J. Yang, E. H. W. Chan, X. Feng, and B. Guan, “Photonic microwave phase shifter based on dual sideband phase control technique,” *Opt. Lett.*, vol. 40, no. 15, pp. 3508–3511, Aug. 2015.
[11] S. Pan and Y. Zhang, “Tunable and wideband microwave photonic phase shifter based on a signal-sideband polarization modulator and a polarizer,” *Opt. Lett.*, vol. 37, no. 21, pp. 4483–4485, Nov. 2012.
[12] E. H. W. Chan, W. Zhang, and R. A. Minasian, “Photonic RF phase shifter based on optical carrier and RF modulation sidebands amplitude and phase control,” *J. Lightw. Technol.*, vol. 30, no. 23, pp. 3672–3678, Dec. 2012.
[13] J. Han, B. J. Seo, S. K. Kim, H. Zhang, and H. R. Fetterman, “Single-chip integrated electro-optic polymer photonic RF phase shifter array,” *J. Lightw. Technol.*, vol. 21, no. 12, pp. 3257–3261, Dec. 2003.
[14] J. Shen, G. Wu, W. Zou, and J. Chen, “A photonic RF phase shifter based on a dual-parallel Mach-Zehnder modulator and an optical filter,” *Appl. Phys. Exp.*, vol. 5, no. 7, Jul. 2012, Art. no. 072502.
[15] J. F. Coward, T. K. Yee, C. H. Chalfant, and P. H. Chang, “A photonic integrated-optic RF phase shifter for phased array antenna beam-forming applications,” *J. Lightw. Technol.*, vol. 11, no. 12, pp. 2201–2205, Dec. 1993.

[16] WaveShaper, "4000S multiport optical processor data sheet," 2014. [Online]. Available: http://www.finisar.com
[17] H. Porte, J. P. Goedgebuer, R. Ferriere, and N. Fort, "Integrated TE-TM mode converter on Y-cut Z-propagating LiNb03 with an electrooptic phase matching for coherence multiplexing," *IEEE J. Quantum Electron.*, vol. 25, no. 8, pp. 1760–1762, Aug. 1989.
[18] S. Shimotsu *et al.*, "Single side-band modulation performance of a LiNbO3 integrated modulator consisting of four-phase modulator waveguides," *IEEE Photon. Technol. Lett.*, vol. 13, no. 4, pp. 364–366, Apr. 2001.
[19] Keysight Technologies, "E36100 series programmable DC power supplies data sheet," 2016. [Online]. Available: http://www.keysight.com
[20] ET Industries, "Stripline 90 degree hybrid Q2 coupler Q-467-90 datasheet," 2015. [Online]. Available: http://www.etiworld.com