Linear photonic radio frequency phase shifter using a differential-group-delay element and an optical phase modulator

Zhaohui Li,[1] Changyuan Yu,[2,3,]* Yi Dong,[4] Linghao Cheng,[1] L. F. K. Lui,[1] Chao Lu,[5] Alan Pak Tao Lau,[5] Hwa-Yaw Tam,[5] and P. K. A. Wai[5]

[1]*Institute of Photonics Technology, Jinan University, Guangzhou, China*

[2]*Department of Electrical and Computer Engineering, National University of Singapore, 117576, Singapore*

[3]*A*STAR Institute for Infocomm Research (IIR), 138632, Singapore*

[4]*State Key Laboratory of Advanced Optical Communication Systems and Networks,*
Shanghai Jiao Tong University, Shanghai 200240, China

[5]*Photonics Research Centre, The Hong Kong Polytechnic University, Hung Hom, Hong Kong, China*
**Corresponding author: eleyc@nus.edu.sg*

Received January 12, 2010; revised March 18, 2010; accepted April 19, 2010;
posted May 12, 2010 (Doc. ID 122657); published May 27, 2010

We demonstrate a stable and linear photonic radio frequency (RF) phase shifter based on a differential-group-delay element and the polarization sensitive effect of an optical phase modulator. The phase shift can be tuned continuously over 360° for RF signals over 40 GHz with an electrical control voltage from –7.5 to +7.5 V. © 2010 Optical Society of America

OCIS codes: 280.5110, 060.5060.

Radio frequency (RF) phase shifters play key roles in phased-array beam-forming systems and smart antenna applications. The photonic RF phase shifter has raised attention owing to its potential on the broadband and large phase tuning range compared with the conventional electrical RF phase shifter [1]. Various schemes of photonic RF phase shifters have been demonstrated, based on homodyne mixing, vector sum, and nonlinear effects [2–10]. However, each of these techniques suffers from one or more of the following disadvantages: (i) limited bandwidth, (ii) limited phase shift range, (iii) variation of RF power as phase shifting, (iv) slow response speed, and (v) high system complexity and power consumption. Recently, a compact and linear photonic RF phase shifter with a single control voltage based on the polarization sensitive effect of an optical phase modulator with a delay interferometer was demonstrated. However, the performance of this scheme may not be stable enough for practical applications, since the two required optical subcarriers in the setup are not phase locked [11].

In this Letter, we utilize a tunable differential-group-delay (DGD) element to generate two phase-locked orthogonal-polarization optical subcarriers and, thus, a stable and linear photonic RF phase shifter is realized based on the polarization-sensitive effect of an optical phase modulator [12]. The RF phase shift can be stably tuned, resulting in a linear and continuous tuning range from –180° to +180° with an electrical control voltage from –7.5 to +7.5 V.

Figure 1 shows the concept of our technique and the experimental setup. To control the phase of an RF signal with a desired frequency f, we modulate an RF tone with half of the desired frequency ($f/2$, realized by a frequency divider) to a cw optical light through a Mach–Zehnder modulator (MZM) biased at the transmission null point, which suppresses the optical carrier and generates two optical subcarriers with a frequency difference f. These two optical subcarrier are called the lower subcarrier (LSC) at frequency f_l (smaller than the optical carrier frequency) and the upper subcarrier (USC) at frequency f_u (larger than the optical carrier frequency), respectively, and both of them have the same state of polarization (SOP) right after the MZM, which can be described by Eq. (1):

$$\vec{E}_{\mathrm{MZM}}(t) = \hat{x} \cdot (A_1 e^{j2\pi f_l t} + A_2 e^{j2\pi f_u t}). \tag{1}$$

Then the modulated optical signal is aligned 45° with respect to the principal states of polarization (PSPs) of a tunable DGD element. The DGD value is tuned by the internal free-space scheme of the DGD element, which is quite stable even when the environment, such as temperature, changes. After propagating through the DGD element, the DGD causes the SOPs of the LSC and the USC to vary by different amounts. It can be shown that, when $\mathrm{DGD} = 1/(2f)$, the SOP of the LSC will be orthogonal to the USC [13–15]. Therefore, we get the optical signal with two phase-locked and orthogonally polarized subcarriers through a tunable DGD element, as shown in Eq. (2):

$$\vec{E}_{\mathrm{DGD}} = (\hat{x} \cdot A_1 e^{j2\pi f_l t}) + (\hat{y} \cdot A_2 e^{j2\pi f_u t}). \tag{2}$$

This modulated optical signal is then coupled into a phase modulator by a polarization controller (PC), which

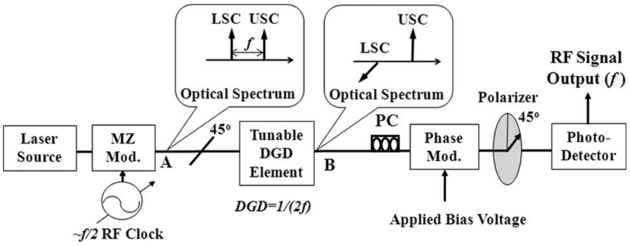

Fig. 1. Experimental setup of the proposed linear photonic RF phase shifter.

aligns the LSC and the USC to the TE and TM modes of the optical phase modulator, respectively. Both the TE and TM modes can pass through the optical phase modulator with different phase-shifting efficiency. Because of the different phase-shifting efficiencies for the TE and TM modes, the two subcarriers of the optical signal with orthogonal polarization obtain a relative phase difference when a bias voltage is applied to the optical phase modulator, as shown in Eq. (3):

$$\vec{E}_{\mathrm{PM}}(t) = (\hat{x}\cdot A_1 e^{j2\pi f_l t+(V/V_\pi)\pi}) + (\hat{y}\cdot A_2 e^{j2\pi f_u t+\eta(V/V_\pi)\pi}). \tag{3}$$

After the optical phase modulator, the phase-shifted optical signal with two orthogonally polarized subcarriers is sent to a polarizer aligned at 45° relative to the TE mode and the TM mode, and the optical signal at the output of the polarizer can be expressed by $E_{\mathrm{pol}}(t)$:

$$\vec{E}_{\mathrm{pol}}(t) = \frac{\sqrt{2}}{2}\cdot\hat{x}(A_1 e^{j2\pi f_l t+(V/V_\pi)\pi} + A_2 e^{j2\pi f_u t+\eta(V/V_\pi)\pi}). \tag{4}$$

The relative phase difference between the two subcarriers of the optical signal can be expressed by Eq. (5) [11]:

$$\phi = (\eta - 1)\pi V/V_\pi, \tag{5}$$

where ϕ is the phase difference, V is the bias voltage, $V\pi$ is the half-wave voltage of the phase modulator, and η is the ratio of phase-shifting efficiency for the TE mode to the TM mode. After the polarizer, the two subcarriers of the optical signal beat with each other, producing an RF signal after optical-to-electrical conversion by a photodetector (with 40 GHz bandwidth in our setup), which can be expressed by Eq. (6):

$$\begin{aligned} i(t) &\propto A_1A_2\cos[j2\pi(f_u - f_l)t + (\eta - 1)\pi V/V_\pi] \\ &= A_1A_2\cos(j2\pi f t + \phi). \end{aligned} \tag{6}$$

The phase of the resulting RF signal is equal to the phase difference ϕ derived in Eq. (5). Therefore, we can control the phase of the RF signal linearly and continuously by varying the bias voltage applied to the phase modulator.

To demonstrate the proposed design, we first demonstrate phase shifting for the 19.906 GHz RF signal ($f = 19.906$ GHz). We modulate the 9.953 GHz ($f/2$) RF signal obtained from a frequency divider to the MZM biased at the transmission null point to generate two optical subcarriers with a frequency difference of 19.906 GHz. Figure 2 shows the optical spectrum of this modulated optical signal. The optical carrier is suppressed by more than 20 dB when compared to the two subcarriers. At point A, we measure the beating RF power of two optical subcarriers by coupling the optical signal directly to a photodetector with a RF spectrum analyzer. The measured power of the generated 19.906 GHz RF signal is –19.83 dBm. We set the DGD value of the tunable DGD element to be 25.118 ps, which is equal to $1/(2f)$. After the DGD element, the SOPs of the two subcarriers become orthogonal to each other. Therefore, there should be no beating between them. At point B, we measure the beating RF power of two orthogonally polarized optical subcarriers by coupling the optical signal directly from point B to the photodetector with the RF spectrum analyzer. The measured power of the 19.906 GHz RF signal becomes –54.33 dBm. Compared to the RF power at point A, the power of the 19.906 GHz RF signal is suppressed by more than 30 dB, which means the two subcarriers in the optical signal now become orthogonal.

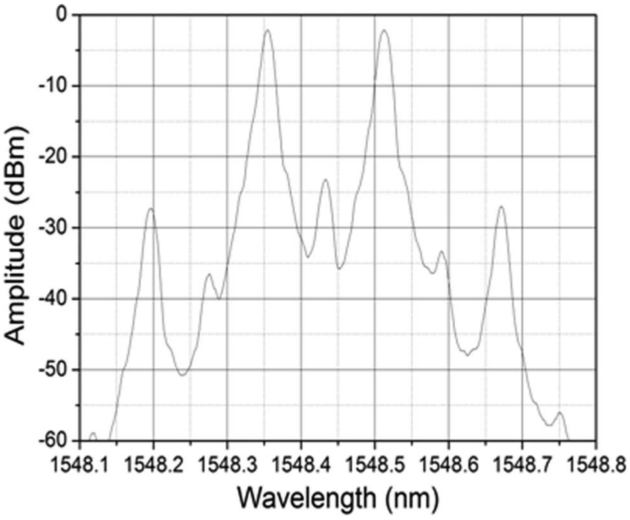

Fig. 2. Optical spectrum of modulated optical signal.

Two phase-locked orthogonally polarized optical subcarriers are then coupled into the phase modulator by the PC and we apply different bias voltage to the optical phase modulator. After the photodetector, an RF signal with a different phase shift is generated. Figure 3 shows the waveforms of the obtained 19.906 GHz RF signal

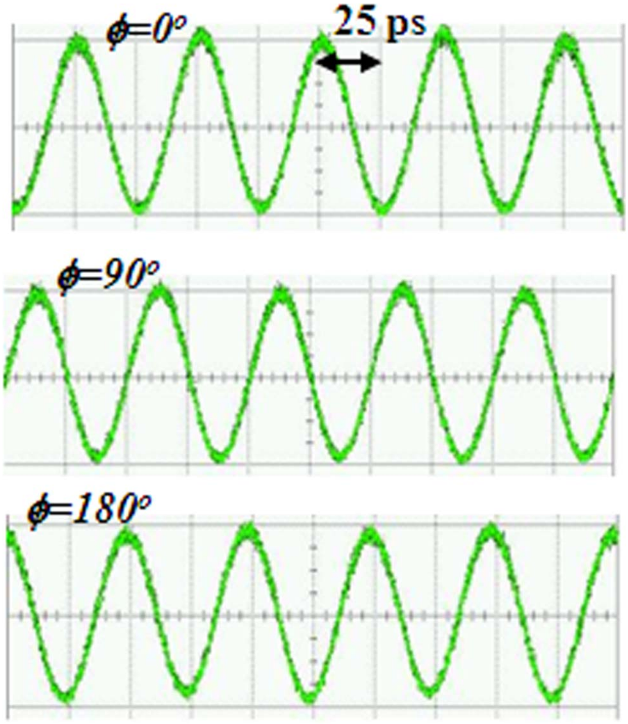

Fig. 3. (Color online) Waveforms of the obtained 19.906 GHz RF signal with phase shifts of 0°, 90°, and 180°.

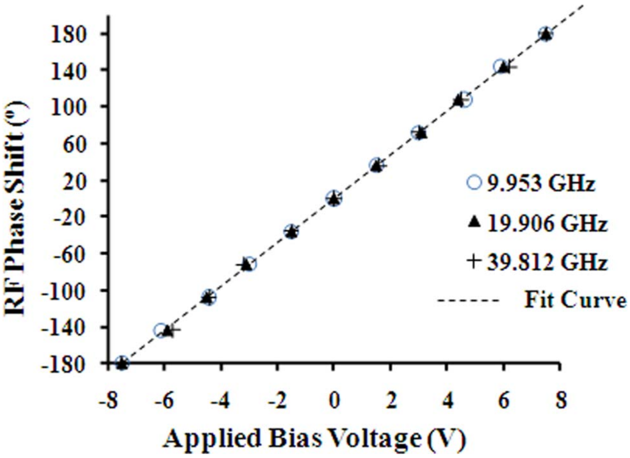

Fig. 4. (Color online) Measured phase shift versus applied bias voltage to the phase modulator.

captured by an oscilloscope with phase shifts of 0°, 90°, and 180°, which correspond to applied bias voltage of the phase modulator at 0, 3.75, and 7.5 V, respectively. The waveforms are the same for different phase shifts. We also examine the variation of the RF power while tuning the phase shift. The measured powers of the 19.906 GHz RF signal in the cases of 0°, 90°, and 180° phase shifts are −26, −26.17, and −26.33 dBm, respectively, showing an RF power fluctuation within ±0.2 dBm.

Figure 4 plots the measured phase shift versus applied bias voltage to the phase modulator. For comparison, we also demonstrate the phase shifting for 9.953 and 39.812 GHz RF signals ($f = 9.953$ and 39.812 GHz) by modulating the $f/2$ RF signal to the MZM and setting the DGD value of the DGD element as $1/(2f)$. From Fig. 4, we find that the RF phase shift can be tuned linearly and continuously in a range from −180° to +180° with a low electrical control voltage from −7.5 to +7.5 V. We also observed that the results do not depend on the RF frequency, because the 9.953 and 39.812 GHz RF signals have almost the same phase shift as the 19.906 GHz RF signal when the same bias voltage is applied.

In conclusion, we demonstrate a stable and linear photonic RF phase shifter based on a DGD element and the polarization-sensitive phase-shifting efficiency of an optical phase modulator. The RF phase shift can be tuned linearly and continuously from −180° to +180° with an electrical control voltage from −7.5 to +7.5 V. The linear tuning range of the phase shift can be beyond 360° if higher control voltage is applied. For the same control voltage, RF signals at different frequencies obtain the same phase shift.

The authors acknowledge the support of grants G-YF65 and G-YF50 from The Hong Kong Polytechnic University.

References

1. W. S. Birkmayer and M. J. Wale, Proc. Inst. Electr. Eng. J Optoelectron. **139**, 301 (1992).
2. J. Han, H. Erlig, D. Chang, M. C. Oh, H. Zhang, C. Zhang, W. Steier, and H. Fetterman, IEEE Photonics Technol. Lett. **14**, 531 (2002).
3. S. S. Lee, A. H. Udupa, H. Erlig, H. Zhang, Y. Chang, C. Zhang, D. H. Chang, D. Bhattacharya, B. Tsap, W. H. Steier, L. R. Dalton, and H. R. Fetterman, IEEE Microwave Guided Wave Lett. **9**, 357 (1999).
4. S. T. Winnall, A. C. Lindsay, and G. A. Knight, IEEE Trans. Microwave Theory Tech. **45**, 1003 (1997).
5. K. Ghorbani, A. Mitchell, R. B. Waterhouse, and M. W. Austin, IEEE Trans. Microwave Theory Tech. **47**, 645 (1999).
6. J. F. Coward, T. K. Yee, C. H. Chalfant, and P. H. Chang, J. Lightwave Technol. **11**, 2201 (1993).
7. A. Loayssa and F. J. Lahoz, IEEE Photonics Technol. Lett. **18**, 208 (2006).
8. W. Xue, S. Sales, J. Capmany, and J. Mork, Opt. Lett. **34**, 929 (2009).
9. Y. Dong, H. He, W. Hu, Z. Li, Q. Wang, W. Kuang, T. H. Cheng, Y. J. Wen, Y. Wang, and C. Lu, Opt. Lett. **32**, 745 (2007).
10. Q. Chang, Q. Li, Z. Zhang, M. Qiu, T. Ye, and Y. Su, IEEE Photonics Technol. Lett. **21**, 60 (2009).
11. H. Chen, Y. Dong, H. He, W. Hu, and L. Li, Opt. Lett. **34**, 2375 (2009).
12. H. Park, J. Yi, Y. Byun, S. Lee, S. Kim, M. Takenaka, and Y. Nakano, J. Appl. Phys. **42**, 4378 (2003).
13. C. Yu, Q. Yu, Z. Pan, A. B. Sahin, and A. E. Willner, IEEE Photonics Technol. Lett. **16**, 341 (2004).
14. C. D. Poole, N. S. Bergano, R. E. Wagner, and H. J. Schulte, J. Lightwave Technol. **6**, 1185 (1988).
15. D. Derickson, *Fiber Optic Test and Measurement* (Prentice-Hall, 1997).