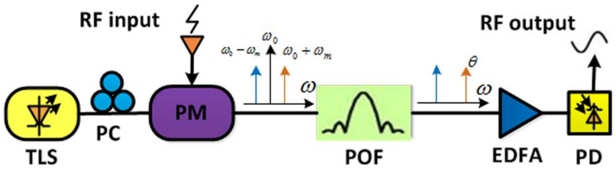
IEEE Photonics Journal
An IEEE Photonics Society Publication

Open Access

Multichannel Continuously Tunable Microwave Phase Shifter With Capability of Frequency Doubling

Volume 6, Number 1, February 2014

Zhenhua Feng
Songnian Fu
Tang Ming, Senior Member, IEEE
Deming Liu



DOI: 10.1109/JPHOT.2013.2295457
1943-0655 © 2013 IEEE

Multichannel Continuously Tunable Microwave Phase Shifter With Capability of Frequency Doubling

Zhenhua Feng, Songnian Fu, Tang Ming, *Senior Member, IEEE*, and Deming Liu

National Engineering Laboratory for Next Generation Internet Access System, School of Optics and Electronic Information, Huazhong University of Science and Technology, Wuhan 430074, China

DOI: 10.1109/JPHOT.2013.2295457

1943-0655 © 2013 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission.
See http://www.ieee.org/publications_standards/publications/rights/index.html for more information.

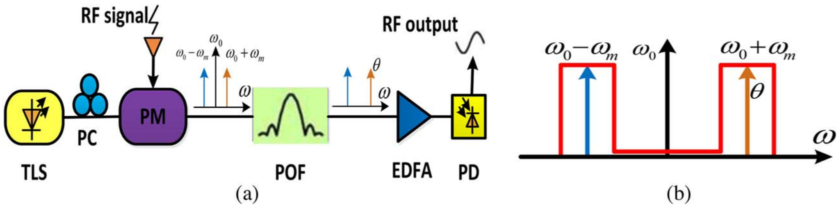
Manuscript received December 4, 2013; accepted December 10, 2013. Date of publication December 20, 2013; date of current version January 3, 2014. This work was supported in part by the National Basic Research Program of China (973 Program) under Grant 2010CB328302, by the 863 High Technology Plan under Grants 2012AA011301 and 2013AA013402, and by the National Natural Science Foundation of China under Grants 61275069 and 61331010. Corresponding author: S. Fu (e-mail: songnian@mail.hust.edu.cn).

Abstract: A photonic generation of tunable microwave phase shifter with capability of frequency doubling is proposed and experimentally demonstrated using optical spectral shaping technique. Our proposed configuration only consists of a phase modulator (PM), a programmable optical filter, and one photodetector (PD). The phase modulated optical signal is fed into the programmable optical filter, where two specific harmonic sidebands of the modulated signal are chosen in order to apply a tunable phase shift to one of the selected sidebands. After optical amplification and beating at the PD, a frequency doubling microwave signal with continuously tunable phase shifter from 0° to 360° is obtained with less than 2.5 dB power fluctuation over a frequency range from 20 GHz to 33 GHz. Moreover, simultaneous four-channel microwave signals with independent phase shift setting are achieved, due to that the proposed configuration is compatible with wavelength division multiplexing (WDM) operation.

Index Terms: Microwave photonics, microwave signal generation, microwave phase shifter, spectral shaping.

1. Introduction

Microwave phase shifters are key components for many microwave applications, such as phase-array antennas [1] and microwave filters [2]. Until now, several photonic approaches have been reported to realize microwave phase shifters [3]–[11]. A fixed phase shift of 180° has been achieved based on cross-phase modulation (XPM) in a nonlinear loop mirror, where the beating of the optical carrier and the sideband modulated via XPM can generate a microwave signal with fixed phase shift [3]. Using a distributed feedback (DFB) laser together with wavelength conversion technique [4], a phase shift of 110° with around 6 dB power fluctuation has been obtained. A phase shift can be introduced to a new wavelength after wavelength conversion, while the value of phase shift can be tuned by controlling the injection current. Microwave phase shifters can also be implemented utilizing slow-light effects in a tilted fiber Bragg grating [5], or semiconductor optical amplifiers (SOAs) [6]. However, these methods failed to provide a full 360° range of phase shift within a compact setup. Stimulated Brillouin scattering (SBS) in optical fiber has been put forward to achieve



(a) (b)

Fig. 1. Schematic configuration of the proposed system and the insets illustrate the optical spectrum before and after optical spectral shaping (a) architecture of microwave phase shifter; (b) amplitude and phase response profile of the programmable optical filter. TLS: tunable laser source, PM: phase modulator, POF: programmable optical filter, PD: photodector.

a phase shift of 360° with less than 3 dB microwave power fluctuation [7]. However, in order to trigger the SBS, high-power optical pump source is required and the optical fiber is usually long. In addition, the SBS effect is so sensitive to environmental perturbation that the generated phase shift is unstable. A tunable and wideband phase shifter with full 360° range using a polarization modulator (PolM), an optical band-pass filter and a polarizer has been experimentally verified [8], where the phase shift is introduced by tuning the polarization direction of the polarizer. Therefore, generation of two orthogonally polarized phase-modulated signals with complementary phase modulation is indispensable to their approach. Furthermore, silicon-on insulator (SOI) micro-ring resonators (MRRs) have been used as phase shifters [9], [10]. However, it is difficult to realize a full 360° phase shift by using a single MRR, which limits its practical applications in microwave systems. In particular, the RF power varies dramatically during the phase shifter tuning operation. Recently, a photonic approach to implementing a microwave photonic phase shifter for a linear polarization single sideband (SSB) modulated signal with a large bandwidth and a full 360° phase shift has been proposed and demonstrated [11], based on a polarization maintaining fiber Bragg grating (PM-FBG). However, this system is complicated and unstable because the polarization state is not easy to manage. Especially, the tunable microwave phase shifters mentioned above lack the capability to realize frequency multiplication and support multi-wavelength operation simultaneously.

In this paper, we experimentally demonstrate simultaneous achievements of tunable microwave phase shifter and microwave frequency doubling within a simple configuration, where only commercial devices are used. Thus the stability can be greatly enhanced. By selecting two specific harmonic sidebands of the phase modulated optical signal with the help of a programmable filter, continuously tunable phase shift from 0 to 360° is experimentally verified and demonstrated with less than 2.5 dB power fluctuation over frequency range from 20 GHz to 33 GHz. Furthermore, four-channel microwave signals with independent phase shift setting are achieved using the same setup, in order to support wavelength division multiplexing (WDM) ROF application.

2. Operation Principle

The schematic setup of our proposed microwave phase shifter is illustrated in Fig. 1(a). The phase modulator is used to generate phase modulated signal with harmonic components generation of the input optical carrier, and the programmable optical filter is used to realize spectral shaping for the phase modulated optical wave. The optical signal after spectral shaping is then launched into an Erbium doped fiber amplifier (EDFA) before detection. Theoretically, the optical field at the output of the PM can be described as:

$$E(t)=\sqrt{P_0}\sum_{n=-\infty}^{\infty} i^n J_n(m)e^{j(\omega_0+n\omega_m)t}. \tag{1}$$

Under the approximation of small RF signal modulation, higher than 1st order sidebands can be neglected so that the output of the PM can be expressed as:

$$E(t)=\sqrt{P_0}\left\{J_0(m)e^{j(\omega_0 t)}+J_1(m)\left[e^{j\left[(\omega_0+\omega_m)t+\frac{\pi}{2}\right]}-e^{j\left[(\omega_0-\omega_m)t-\frac{\pi}{2}\right]}\right]\right\} \tag{2}$$

where P_0 is the input optical power, ω_0 and ω_m are the angular frequency of the optical carrier and the RF signal, respectively. $J_n(\cdot)$ is the nth order Bessel function of the first kind, and $m = \pi V/V_\pi$ is phase modulation index, V is the RF signal amplitude while V_π represents the half-wave voltage of the PM. Then the signal is sent to an optical filter with programmable amplitude and phase response. In our experimental setup, the programmable optical filter is realized by Waveshaper (Finisar 4000S), which can achieve four-channel narrowband optical filters with arbitrary center wavelength and channel bandwidth setting, together with manipulation of the amplitude and phase response. The programmable optical filter is set to be a symmetrical dual pass bands filter, whose central wavelength has 20 GHz frequency spacing, while the two pass bands have the same bandwidth of 10 GHz. Since the filter is programmed to be a symmetrical response in our configuration, the center of the stop band matches the carrier wavelength and the two pass-bands exactly cover the two ±1 order sidebands, while a phase shift is introduced to the +1st order sideband independent of microwave frequency, as shown in Fig. 1(b).

Therefore, considering the carrier suppression ratio of the filter, the optical field after optical filtering is given by:

$$E(t) = \sqrt{P_0}\left\{J_1(m)\left[e^{j\left[(\omega_0+\omega_m)t+\frac{\pi}{2}+\theta\right]} - e^{j\left[(\omega_0-\omega_m)t-\frac{\pi}{2}\right]}\right] + \beta J_0(m)e^{j\omega_0 t}\right\}. \tag{3}$$

Where θ is the phase shift of the +1st order sideband induced by optical spectral shaping, and β represents the carrier suppression ratio of the filter. Beating at the PD, the photocurrent can be described as:

$$i(t) = 2RP_0J_1^2(m)[1+\cos(2\omega_m t+\theta)] + \beta^2RP_0J_0^2(m) + 2RP_0\beta J_0(m)J_1(m)[\sin(\omega_m t) - \sin(\omega_m t+\theta)] \tag{4}$$

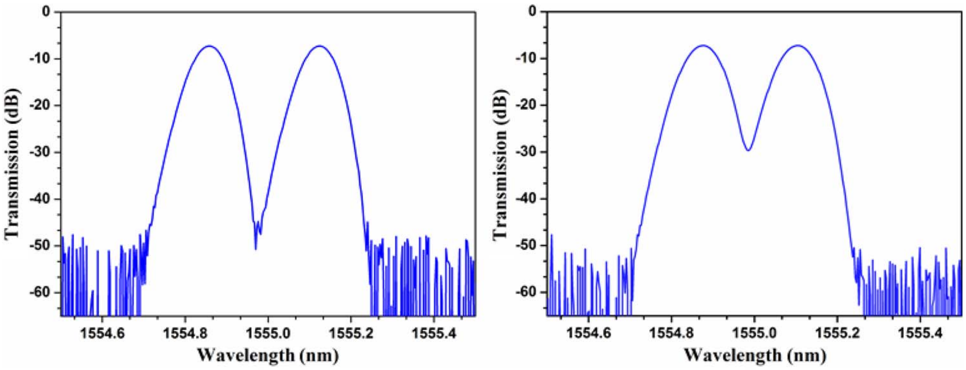
where R is the responsivity of the PD. Note that under the condition of carrier suppression *ratio* greater than 20 dB (i.e. corresponding $\beta < 0.01$), these items containing β is small enough to be neglected. This case can be well satisfied for commercially available optical filters. Therefore Eq. (4) can be simplified into:

$$i(t) = 2RP_0J_1^2(m)[1+\cos(2\omega_m t+\theta)]. \tag{5}$$

According to Eq. (5), a frequency doulbing microwave signal is generated and the phase shift introduced in optical domain can be directly mapped into electric domain. Subsequently, the phase of the output microwave signal can be tuned from 0 to 360° by setting different phase values to one pass band of the programmable filter. Moreover, by designing a proper filter response profile, we can even realize arbitrary frequency doubling within a wide frequency range. For example, if the optical filter is programmed with its notch filter centered at the carrier frequency while its two passbands centered at the $\pm 2^{\text{rd}}$ order sidebands, respectively, then a phase shifted microwave signal together with frequency quadrupling can be accomplished. In particular, taking advantage of the four-channel outputs of WaveShaper, we can realize a WDM compatible microwave phase shifter with a capability of frequency doubling.

3. Experimental Results and Discussion

The proposed phase shifted microwave signal generation system is experimentally verified using the setup, as shown in Fig. 1. A continuous wave from a tunable laser source (TLS) is launched to a PM driven by a microwave signal with frequency of 12.5 GHz and a fixed power of 10 dBm. In order to achieve the optical carrier suppression, the programmable optical filter is set properly, so that the optical carrier is set at the center of the stop band, while two 1st order sidebands are located within the two pass band, respectively. In our experiment, the programmable optical filter is set to be a symmetrical dual passbands filter, whose notch bandwidth is 20 GHz while the two passbands have the same bandwidth of 10 GHz. Firstly, we investigate the influence of programmable optical filter response on the system performance. When we change the passband bandwidth from 10 GHz to 20 GHz, other frequency components are found in the electrical spectrum due to the beating



(a) (b)

Fig. 2. Response characterization of the programmable filter (a) with 20 GHz notch band; (b) with 10 GHz notch band.

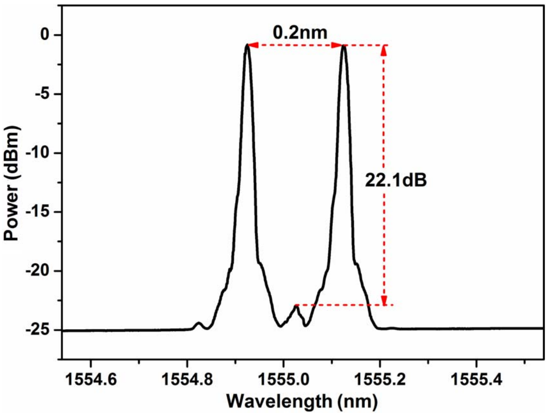


Fig. 3. The filtered optical spectrum after amplification.

between residual harmonic sidebands. Next, we change the bandwidth of the notch band from 20 GHz to 10 GHz (minimum filter bandwidth of Waveshaper). However, as shown in Fig. 2, the optical carrier suppression ratio becomes poor, when the notch band gets narrower. Therefore, the optimized parameters for the programmable optical filter can be obtained. In particular, when the passband of the programmable filter is set to 10 GHz, the 3 dB bandwidth is measured to be 10.3 GHz while the 30 dB bandwidth is found to be 28.5 GHz. Meanwhile, the insertion loss of passband is characterized around 7 dB. If the transition response can be even shaper, for example with a rectangle or high-order supper-Gaussian shape, the performance of our proposed scheme can be significantly improved by higher carrier and sideband suppression.

After spectral shaping, we select the two 1st order sidebands, one of which is phase shifted by the programmable optical filter with full range from 0° to 360°. Fig. 3 shows the filtered optical spectrum after amplification by an erbium doped fiber amplifier (EDFA). As can be seen, the suppression ratio between carrier and the 1st order sideband is about 22.1 dB. Beating at a 40 GHz PD, a 25 GHz phase shifted microwave signal is observed in a 70 GHz sampling oscilloscope, when the PM is driven by a 12.5 GHz RF signal. Fig. 4 shows the temporal waveforms of the generated 25 GHz microwave signal with full range of tunable phase shift, and the input driving RF signal with a frequency of 12.5 GHz is provided as a reference at the bottom, indicating that the capabilities of both frequency doubling and tunable phase shift are realized simultaneously.

We also investigate the power variation of the proposed microwave phase shifter. First, we measure the peak-to-peak amplitude of generated phase shifted microwave signal at fixed

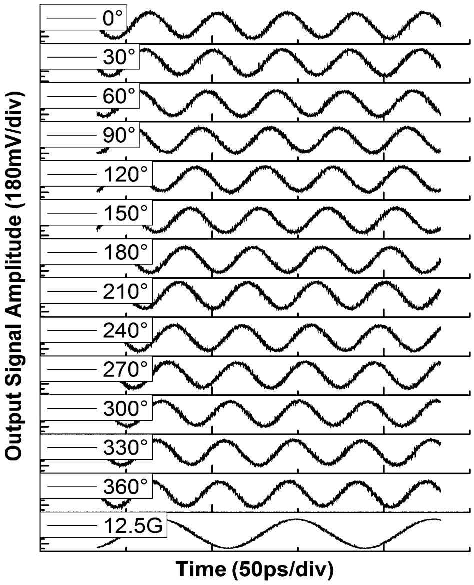


Fig. 4. Temporal waveforms of the generated 25 GHz microwave signal with phase shift from 0° to 360°.

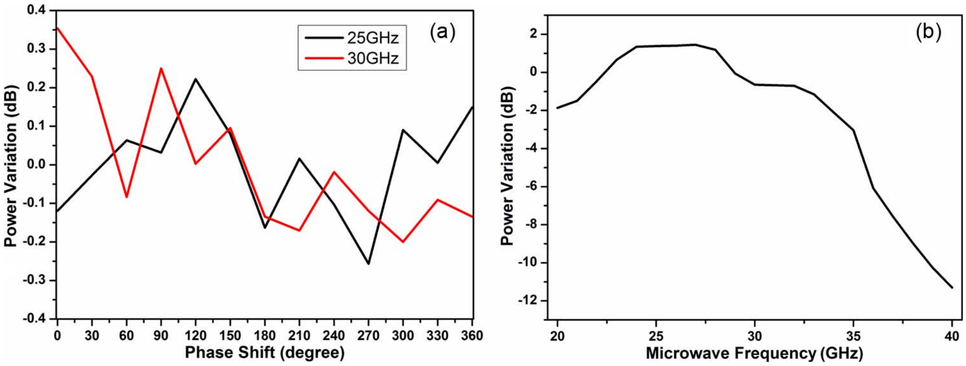


Fig. 5. Power variation of the proposed microwave phase shifter (a) with respect to different phase shifts; (b) with respect to different microwave frequencies.

frequencies. The results are summarized in Fig. 5(a), indicating that less than 0.35 dB power variation is secured when the phase shift is tuned from 0 to 360°. Additionally, we measure the peak-to-peak amplitude of the output microwave signal at different frequencies. It can be seen from Fig. 5(b) that, without any modification to the optical filter parameters described above, our proposed system can generate phase shifted microwave signals with less than 2.5 dB power variation within a frequency scale from 20 GHz to 33 GHz, when the phase shift is fixed at 360°. With the limited Q available offered by the WaveShaper, both the power and operation bandwidth of our proposed system are observed with some fluctuation, as shown in Fig. 5. During the experiments, we observe that bandwidth of both the notch filter and passbands have close relationship to the carrier suppression ratio and the frequency response of the microwave phase shifter. In principle, the maximum frequency of the generated microwave signal is only limited by the bandwidth of the phase modulator and photodetector, while the minimum frequency is limited by the minimum filter bandwidth of the programmable optical filter (Waveshaper4000S: 10 GHz), namely the minimum spacing between the two passbands. Next, in order to further evaluate the performance of generated phase-shifted microwave signal, an electrical spectrum analyzer (ESA, Agilent E4447A) is used to perform the electrical spectrum and phase noise measurement, as shown in Fig. 6. The

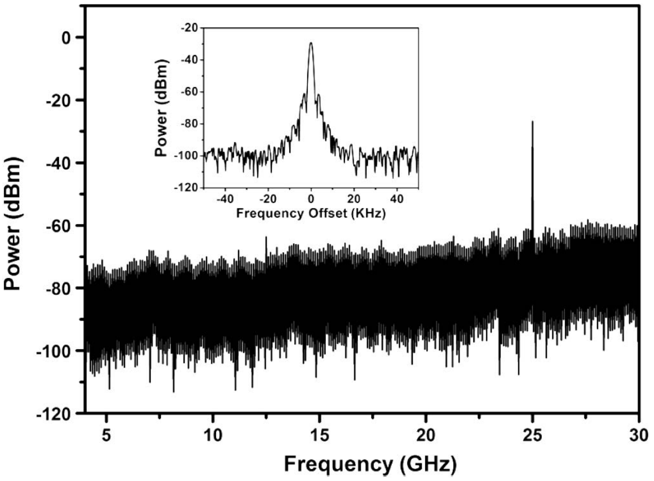


Fig. 6. Electrical spectrum of the generated 25 GHz phase-shifted microwave signal, the inset is a zoom in view of the 25 GHz signal with a frequency span of 100 KHz.

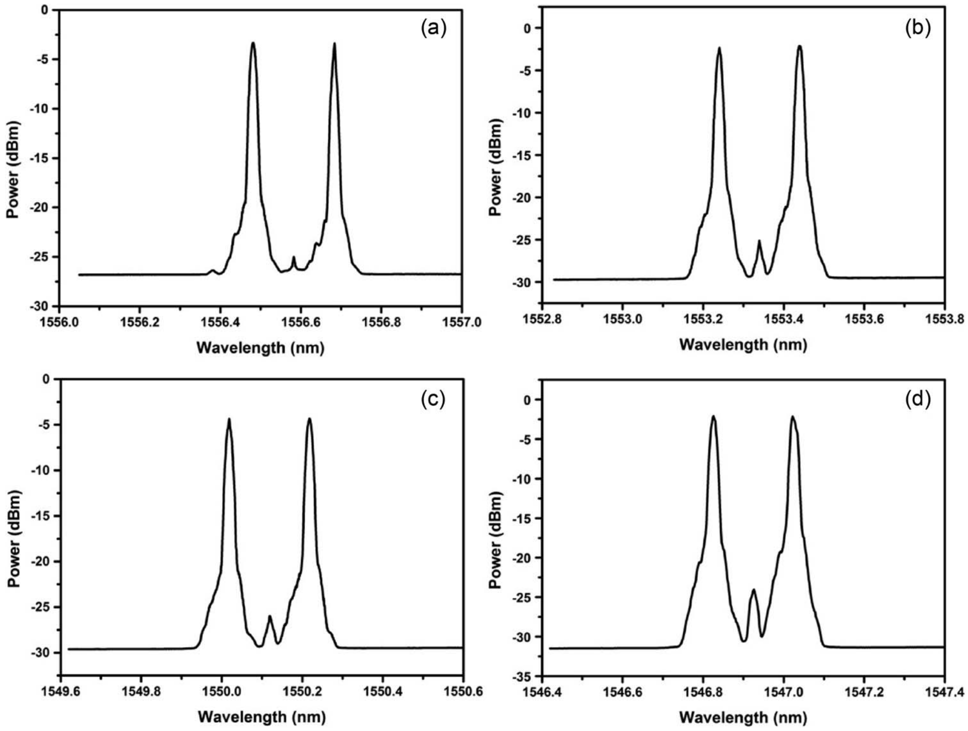


Fig. 7. Filtered optical spectra after amplification for four channels with center wavelengths at: (a) 1556.5 nm, (b) 1553.3 nm, (c) 1550.1 nm, (d) 1546.9 nm.

measured carrier-to-noise ratio (CNR) of the generated microwave signal is around 45 dB. Meanwhile, the SSB phase noise is -109.57 dBc/Hz at a frequency offset of 10 KHz.

In order to demonstrate the capability of WDM compatible operation, four laser sources with wavelength spacing of 3.2 nm are combined by a wavelength division multiplexer, and launched into the PM driven by a microwave signal with frequency of 12.5 GHz. Next, the four-channel phase modulated signal are spectral shaped by the WaveShaper 4000S with four channels whose the frequency and phase response can be programmed individually. The filtered optical spectra are

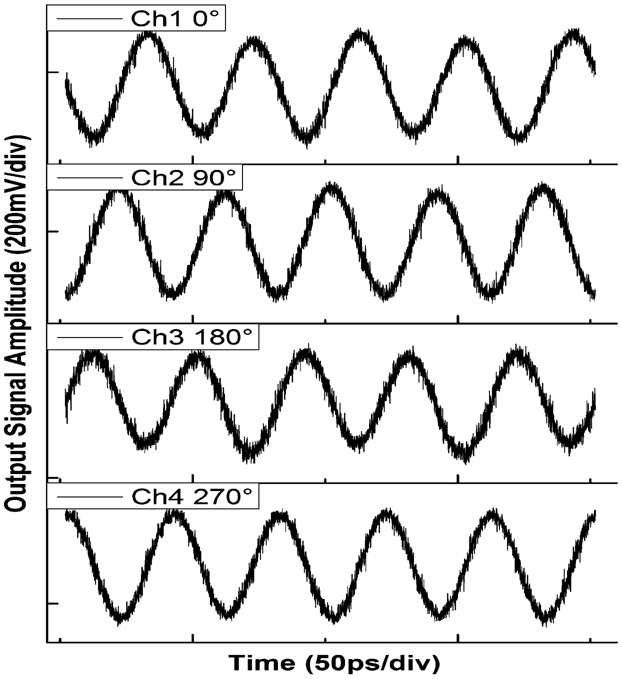


Fig. 8. Output microwave signals with different phase shifts at different center wavelengths of 1556.5 nm, 1553.3 nm, 1550.1 nm, 1546.9 nm.

shown in Fig. 7. It is clearly observed that four-channel phase-shifted microwave signals with individual tunable phase shift can be obtained simultaneously, in spite of some tiny differences appear in their spectra due to slightly different filter responses. After optical-to-electronic conversion, four-channel frequency doubling microwave signals can be observed simultaneously with different phase shift settings, as shown in Fig. 8. Therefore, capability of WDM operation is experimentally verified in our proposed system.

4. Conclusion

We have proposed and demonstrated a photonic approach to achieving microwave frequency doubling and a full 360° tunable phase shifter simultaneously. Phase shifted microwave signals with frequency doubling are obtained with a flat amplitude and phase response over a frequency range from 20 GHz to 33 GHz. Furthermore, four-channel microwave signals with independent phase shift setting has also been experimentally validated in order to satisfy WDM operation. The proposed method has potential applications in WDM radio-over-fiber system, broadband and high frequency beam-forming system, and array signal processing systems. On the other hand, in order to reduce the cost, we can use the liquid crystal on silicon based array to act as programmable optical filter [12]. Meanwhile, the TLS (tunable laser source) can be replaced by a laser source with fixed wavelength. In particular, as we can generate four channels of phase shifted microwave signals simultaneously, the average cost can be further reduced.

References

[1] S. Tonda-Goldstein, D. Dolfi, A. Monsterleet, S. Formont, J. Chazelas, and J.-P. Huignard, “Optical signal processing in radar systems,” *IEEE Trans. Microw. Theory Tech.*, vol. 54, no. 2, pp. 847–853, Feb. 2006.

[2] J. Capmany, B. Ortega, D. Pastor, and S. Sales, “Discrete-time optical processing of microwave signals,” *J. Lightw. Technol.*, vol. 23, no. 2, pp. 702–723, Feb. 2005.

[3] Y. Dong, H. He, W. Hu, Z. Li, Q. Wang, W. Kuang, T. H. Cheng, Y. J. Wen, Y. Wang, and C. Lu, “Photonic microwave phase shifter/modulator based on a nonlinear optical loop mirror incorporating a Mach-Zehnder interferometer,” *Opt. Lett.*, vol. 32, no. 7, pp. 745–747, Mar. 5, 2007.

[4] M. R. Fisher and S. L. Chuang, "A microwave photonic phase-shifter based on wavelength conversion in a DFB laser," *IEEE Photon. Technol. Lett.*, vol. 18, no. 16, pp. 1714–1716, Aug. 15, 2006.

[5] H. Shahoei and J. P. 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. 14 009–14 014, Jun. 8, 2012.

[6] W. Xue, S. Sales, J. Capmany, and J. Mørk, "Microwave phase shifter with controllable power response based on slow- and fast-light effects in semiconductor optical amplifiers," *Opt. Lett.*, vol. 34, no. 7, pp. 929–931, Mar. 18, 2009.

[7] 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. 1, 2006.

[8] S. Pan and Y. Zhang, "Tunable and wideband microwave photonic phase shifter based on a single-sideband polarization modulator and a polarizer," *Opt. Lett.*, vol. 37, no. 21, pp. 4483–4485, Oct. 25, 2012.

[9] Q. Chang, Q. Li, Z. Zhang, M. Qiu, T. Ye, and Y. Su, "A tunable broadband photonic RF phase shifter based on a silicon microring resonator," *IEEE Photon. Technol. Lett.*, vol. 21, no. 1, pp. 60–62, Jan. 1, 2009.

[10] M. Pu, L. Liu, W. Xue, Y. Ding, H. Ou, K. Yvind, and J. M. Hvam, "Widely tunable microwave phase shifter based on silicon-on-insulator dual-microring resonator," *Opt. Exp.*, vol. 18, no. 6, pp. 6172–6182, Mar. 11, 2010.

[11] W. Liu, W. Li, and J. P. Yao, "An ultra-wideband microwave photonic phase shifter with a full 360 phase tunable range," *IEEE Photon. Technol. Lett.*, vol. 25, no. 12, pp. 1107–1110, Jun. 15, 2013.

[12] G. Baxter, S. Frisken, D. Abakoumov, H. Zhou, I. Clarke, A. Bartos, and S. Poole, "Highly programmable wavelength selective switch based on liquid crystal on silicon switching elements," presented at the Optical Fiber Communication Conf. Exposition National Fiber Optic Engineers Conf., Technical Digest (CD) Optical Society of America, Anaheim, CA, USA, Mar. 2006, Paper OTuF2.