

# Photonic microwave phase shifter/modulator based on a nonlinear optical loop mirror incorporating a Mach-Zehnder interferometer

Yi Dong, Hao He, and Weisheng Hu

State Key Lab of Advanced Optical Communication Systems and Networks, Shanghai Jiao Tong University, Shanghai 200240, China

Zhaohui Li, Qijie Wang, Wu Kuang, and Tee Hiang Cheng

Nanyang Technological University, 639798, Singapore

Yang Jing Wen and Yixin Wang

Institute for Infocomm Research, 21 Heng Mui Keng Terrace, 119613, Singapore

Chao Lu

Hong Kong Polytechnic University, Hong Kong

Received November 7, 2006; revised January 18, 2007; accepted January 18, 2007;  
posted January 22, 2007 (Doc. ID 76812); published March 5, 2007

We realize a novel photonic microwave phase shifter/modulator based on a nonlinear optical loop mirror incorporating a Mach-Zehnder interferometer. A near-linear phase shifter exceeding  $180^\circ$  and a phase modulation with 2.5 Gbit/s baseband signal are obtained for a 10 GHz microwave signal by this proposed device. © 2007 Optical Society of America

OCIS codes: 280.5110, 190.4370.

Recently, phased-array beam-forming and smart antennas have been playing an increasingly important role in electronic warfare systems and broadband wireless access networks. However, practical implementation of phased-array beam-forming systems or smart antennas is limited by complex feed structures and active phase-shifting elements. This problem can be solved through the use of a photonic phased-array beam-forming technique that offers the advantages of low cost, light weight, and low power consumption.<sup>1</sup> The photonic microwave phase shifter and phase modulator are two key components of such an approach, which can provide a controllable phase shift to the microwave signal for antenna beam forming and modulate the baseband data onto the phase of microwave signal for downlink transmission.

Various techniques for realizing photonic microwave phase shifters have been proposed.<sup>2–5</sup> However, in these schemes, the amplitude of the microwave signal was also modified by associated amplitude modulation in addition to the phase change, which is not desired in practical phased-array antenna systems. To overcome this drawback, a scheme was introduced using a stimulated Brillouin scattering-based signal processing technique to introduce a phase shift to the microwave signal without affecting its amplitude.<sup>5</sup> However, such a stimulated Brillouin scattering-based signal-processing scheme requires a stable pump source, which is complex and costly for practical implementation. In addition, the phase-shift speed of these reported photonic microwave phase shifters is too slow for them to be used as microwave phase modulators.

In this Letter, we report a novel photonic microwave phase shifter/modulator based on a nonlinear optical loop mirror (NOLM) incorporating a Mach-Zehnder interferometer (MZI). Since this proposed photonic microwave phase shifter is based on cross-phase modulation (XPM) in optical fiber, it has the intrinsic capability for a fast phase shift. In addition, it can also be used as a microwave phase modulator. A near-linear phase shift exceeding  $180^\circ$  and a phase modulation with a 2.5 Gbit/s pseudorandom bit se-

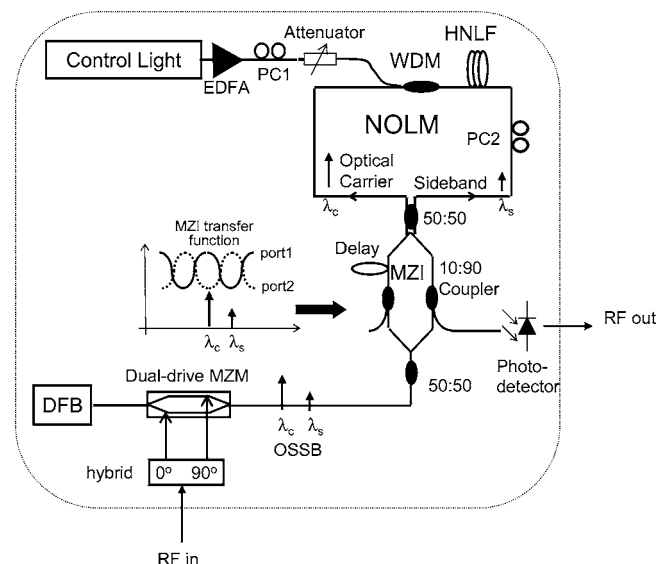


Fig. 1. Experimental setup for the photonic microwave phase shifter. WDM, wavelength division multiplexer. Other abbreviations defined in text.

quence (PRBS) signal are achieved for a 10 GHz microwave signal by this device.

The basic configuration of the proposed photonic microwave phase shifter/modulator is shown in Fig. 1. First, the 10 GHz input microwave signal (RF in) is split by a 90° 3 dB coupler into in-phase (I) and quadrature (Q) components, which are used to drive the dual-drive Mach–Zehnder modulator (MZM). The optical source for the modulator is a 1558.97 nm continuous-wave DFB laser. An optical single-sideband (OSSB) signal output is obtained by biasing the modulator at the transmission quadrature point. The OSSB provides direct mapping between the optical and electrical domains, i.e., with OSSB modulation, a change of the optical signal is directly translated to the electrical domain.<sup>5</sup> The optical field of OSSB is given by

$$E_{\text{OSSB}} = A_c \exp j(\omega_c t) + A_s \exp j(\omega_c - \omega_{\text{RF}})t, \quad (1)$$

where  $A_c$  and  $A_s$  are the amplitudes of the optical carrier and sideband, respectively;  $\omega_c$  and  $\omega_{\text{RF}}$  are the frequencies of the optical carrier and the microwave signal, respectively; and  $t$  is the time.

The OSSB signal was processed using a NOLM after passing the signal through a MZI. The two output ports of the NOLM are connected with those of the MZI. As the free spectral range of the MZI is two times the frequency of the microwave signal, the optical carrier and sideband of the OSSB will be separated by the MZI filter and then launched into the NOLM in copropagating and counterpropagating directions, respectively. The NOLM includes a high-nonlinearity optical fiber (HNLF), which serves as the nonlinear medium for XPM. A polarization controller is inserted in the NOLM to adjust the polarization state of the propagating lights. A 10:90 coupler is embedded in each arm of the MZI to tap out the phase-shifted microwave signal. In this experiment, the nonlinear coefficient, attenuation coefficient, and length of the HNLF were  $15 \text{ W}^{-1} \text{ km}^{-1}$ ,  $0.4 \text{ dB/km}$ , and  $1 \text{ km}$ , respectively. The free spectral range of the MZI was 20 GHz for a matching 10 GHz microwave signal.

The nonlinear phase shift induced by XPM in optical fiber is dependent on the relative propagating direction and the relative state of polarization between the pump (i.e., the control light) and signal waves.<sup>6</sup> This means different nonlinear phase shifts will be introduced into the optical carrier and sideband in the NOLM, due to the difference in the relative propagation direction and the states of polarization relative to the control light. In this experiment, the control light was copropagating with the optical carrier and counterpropagating with the sideband and had parallel polarization with the optical carrier and orthogonal polarization with the sideband by adjusting polarization controllers PC1 and PC2. The wavelength of the control light is 1551.72 nm. The nonlinear phase shift induced in the optical carrier and the sideband by the controlling light is shown in Eqs. (2):

$$\varphi_c = 2\gamma L P_{\text{control}}(t), \quad (2a)$$

$$\varphi_s = -\frac{2}{3}\gamma L \overline{P_{\text{control}}(t)}, \quad (2b)$$

where  $\varphi_c$  and  $\varphi_s$  are the nonlinear phase shifts of the optical carrier and sideband, respectively;  $\gamma$  is the nonlinear coefficient of the HNLF;  $L$  is the HNLF length;  $P_{\text{control}}(t)$  is the optical signal of the control light; and  $\overline{P_{\text{control}}(t)}$  is the average optical power of the control light.

Due to the counterpropagation of the sideband and the control light in the HNLF, the sideband can experience only the average optical power of the controlling light, while the optical carrier will experience the detailed power  $P_{\text{control}}(t)$  due to copropagating with the control light. The optical field at the output of the 10:90 tap coupler is given by

$$E_{\text{out}} = A_c \exp j(\omega_c t + \varphi_c) + A_s \exp j[(\omega_c - \omega_{\text{RF}})t + \varphi_s]. \quad (3)$$

Then, the output signal from NOLM was detected using a 20 GHz photodetector (PD), and the AC part of the output current from the PD is

$$i_{\text{AC}}(t) = 2RA_c A_s \cos(\omega_{\text{RF}}t + \Delta\varphi),$$

$$\Delta\varphi = \varphi_c - \varphi_s = 2\gamma L \left( P_{\text{control}}(t) - \frac{1}{3}\overline{P_{\text{control}}(t)} \right), \quad (4)$$

where  $R$  is the responsivity of the PD and  $\Delta\varphi$  is the phase difference between the optical carrier and the sideband, which is induced by the XPM effect of HNLF in the NOLM.

Therefore, the relative phase-shift modification of the two optical waves is directly translated to the phase of the microwave signal. Since  $\Delta\varphi$  is influenced by the control light, the phase of the output microwave signal can be changed by tuning the power of the control light.

The static phase shift of this photonic microwave phase shifter versus the power of the control light was first studied. Under the static condition, a continuous wave was used as the control light, so  $P_{\text{control}}(t) = \overline{P_{\text{control}}(t)} = P_{\text{control}}$ . As a result, the phase different  $\Delta\varphi$  induced in NOLM is

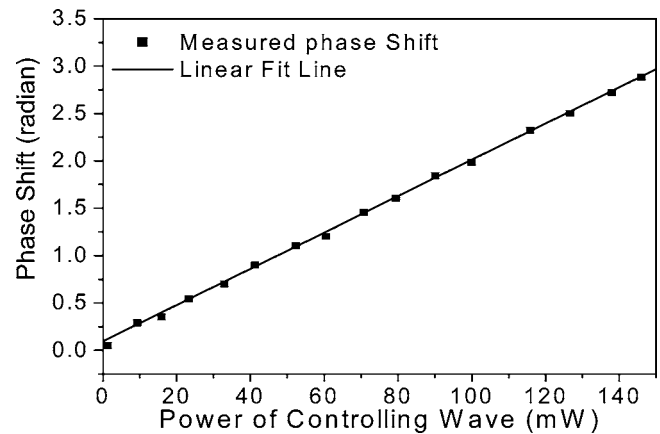


Fig. 2. Measured RF phase shift versus the optical power of the control light.

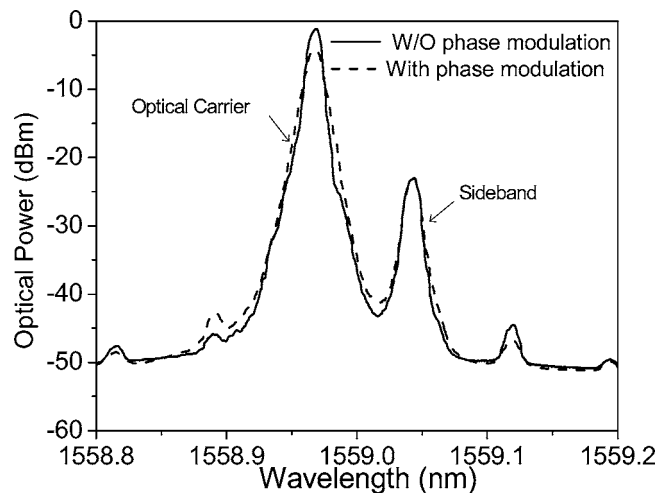


Fig. 3. Optical spectra of the optical single sideband signal.

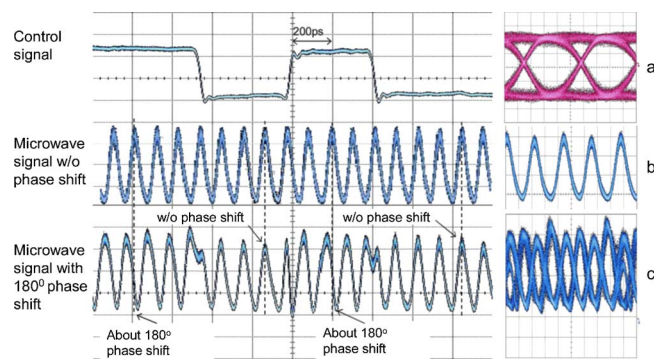


Fig. 4. (Color online) Waveforms and eye diagrams of a, control signal; b, original microwave signal; c, microwave signal with a 180° phase shift.

$$\Delta\varphi = \varphi_c - \varphi_s = \frac{4}{3}\gamma LP_{\text{control}}. \quad (5)$$

Figure 2 shows the measured microwave phase shift versus the optical power of control light. The near-linear 0 to  $\pi$  phase shift was realized by tuning the power of the control light from 0 to 140 mW. A phase shift higher than  $\pi$  is expected if the power of the control light is increased further.

As described earlier, this proposed photonic microwave phase shifter can also be used as a high-speed microwave phase modulator. A microwave phase modulator based on this scheme was also studied in

this experiment. The control light was modulated by a 2.5 Gbit/s PRBS with a length of  $2^{23}-1$  by use of MZM and amplified by an erbium-doped fiber amplifier (EDFA); then the 2.5 Gbit/s PRBS was phase modulated onto the optical carrier through the NOLM.

Figure 3 shows the optical spectra of OSSB optical signals. The solid curve in Fig. 3 shows the optical spectrum without phase modulation, while the dotted curve shows the spectrum after phase modulation. Here the resolution was 0.01 nm. It can be found that the optical carrier after phase modulation is broadened, while the sideband does not change.

Figure 4a shows the waveform and eye diagram of the control light. The rise time of the control light is less than 100 ps. Figure 4b show the waveform and eye diagram of the microwave signals without control light. Figure 4c shows the waveform and eye diagram of the microwave signal with a phase shift. About 180° phase shift is achieved at a high level of the control signal, and the phase-shift time is less than 100 ps, which is limited only by the rise time of the control signal.

In conclusion, a photonic microwave phase shifter/modulator based on a nonlinear optical loop mirror incorporating a Mach-Zehnder interferometer was realized. Both the static phase shift and the phase modulation of this device were studied. A near-linear 0- $\pi$  phase shift and a phase modulator with a 2.5 Gbit/s PRBS baseband signal were achieved for a 10 GHz microwave signal with this device.

This work is supported by the National Natural Science Foundation of China (No. 60472001). Y. Dong's e-mail address is yidong@sjtu.edu.cn.

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