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Microwave photonic phase shifter based on a nonreciprocal optical phase shifter inside a Sagnac interferometer

E.H.W. Chan *

School of Electrical and Information Engineering and Institute of Photonics and Optical Science, University of Sydney, NSW 2006, Australia

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ABSTRACT

A new microwave photonic phase shifter is presented. It is based on an optical single-sideband modulator and an optical phase shifter inside a Sagnac interferometer. It relies on the use of the novel nonreciprocal optical phase shifter to obtain an optical phase shift, which converts into an RF phase shift. The microwave photonic phase shifter has the advantages of realising a continuous 0–360° phase shift on microwave signals using off-the-shelf components and only requiring a single control. It also has a compact structure and robust performance. Experimental results are presented, which demonstrate 0–360° phase shift of microwave signals over a sub-octave frequency band.

1. Introduction

Photonic signal processing offers a new and powerful paradigm for processing high bandwidth signal. It eliminates the electromagnetic interference and overcomes the bottlenecks caused by limited sampling speeds in conventional electrical signal processors [1]. Many applications such as radars and phased array antennas require controlling the phase of a microwave signal. The current electrical phase shifters either have limited bandwidth, have limited phase shift range, or can only realise discrete phase shift. As such, research on microwave photonic phase shifters has been conducted over the past 30 years. Various architectures with different performances have been reported [2–17]. The technique [4–7] that relies on converting an optical phase shift into an RF phase shift is of interest because of its simplicity as only one control is needed. However, it requires coherent detection of two optical signals in a Mach Zehnder interferometer. Hence, the phase shifter needs to be implemented on an integrated optical structure in order to obtain a stable performance. Stimulated Brillouin scattering can be used to implement a microwave photonic phase shifter via the conversion of an optical phase shift into an RF phase shift without the need of using an integrated optical structure [13]. However, it requires a long length of fibre, which needs to be temperature controlled in order to obtain a stable performance, and requires two optical modulators, which increases the cost and the system complexity.

In this paper, we present for the first time that a microwave photonic phase shifter based on the optical-to-RF phase shift conversion technique implemented using a Sagnac interferometer. The new microwave photonic phase shifter has a compact structure and can be constructed using commercially available optical components while having a robust performance. The Sagnac interferometer based microwave photonic phase shifter is verified using VPItransmissionMaker photonic simulation software [18] and is demonstrated experimentally. Both the simulation and experimental results confirm continuous 0–360° RF phase shift that can be obtained by controlling the nonreciprocal optical phase shift inside a Sagnac interferometer.

This paper is organised as follows. The operation principle of the Sagnac interferometer based microwave photonic phase shifter is described in Section 2. The analysis and the simulation results of the phase shifter are presented in Section 3. This section also presents the Jones matrix analysis of the novel nonreciprocal optical phase shifter (NOPS) to realise the nonreciprocal optical phase shift for the light travelled in opposite direction inside the Sagnac interferometer. Experimental results for the microwave photonic phase shifter, which demonstrate a continuous 0–360° phase shift on an RF signal over a sub-octave frequency band, are described in Section 4. Finally, conclusions are given in Section 5

2. Phase shifter topology and operation principle

A microwave photonic phase shifter can be implemented by integrating an optical frequency shifter in parallel with an optical

* Tel.: +61 2 9351 4866; fax: +61 2 9351 3847.
E-mail address: erwin.chan@sydney.edu.au

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phase shifter as shown in Fig. 1 [5]. An RF phase shift can be obtained by controlling the phase of the optical carrier through the optical phase shifter. The same principle is used to realise an RF phase shift in the Sagnac interferometer based microwave photonic phase shifter.

Fig. 2(a) shows the topology of the Sagnac interferometer based microwave photonic phase shifter. Continuous wave light from a laser source is fed into a polarisation maintaining optical coupler connected in a way to form a polarisation maintaining Sagnac interferometer. The light is split equally, so that half travels in the clockwise (CW) direction and the other half travels in the counter clockwise (CCW) direction. Inside the interferometer, there is a single-sideband (SSB) modulator, which is formed by a dual-drive Mach Zehnder modulator and a 90° hybrid coupler [19]. The SSB modulator is driven by an input RF signal and is biased at the quadrature point. Note that, due to the velocity mismatch effect in the $LiNbO_3$ travelling wave electro-optic modulator, the modulation efficiency is low at high frequencies when the modulator operates in the reverse direction [20]. Hence, the CCW light passed

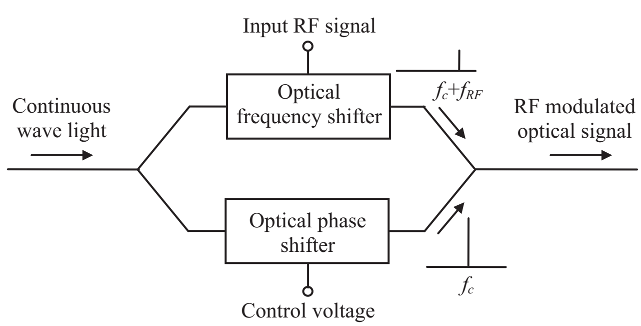

Fig. 1. A conventional microwave photonic phase shifter structure. f_c and f_{RF} are the continuous wave light carrier frequency and the input RF signal frequency respectively.

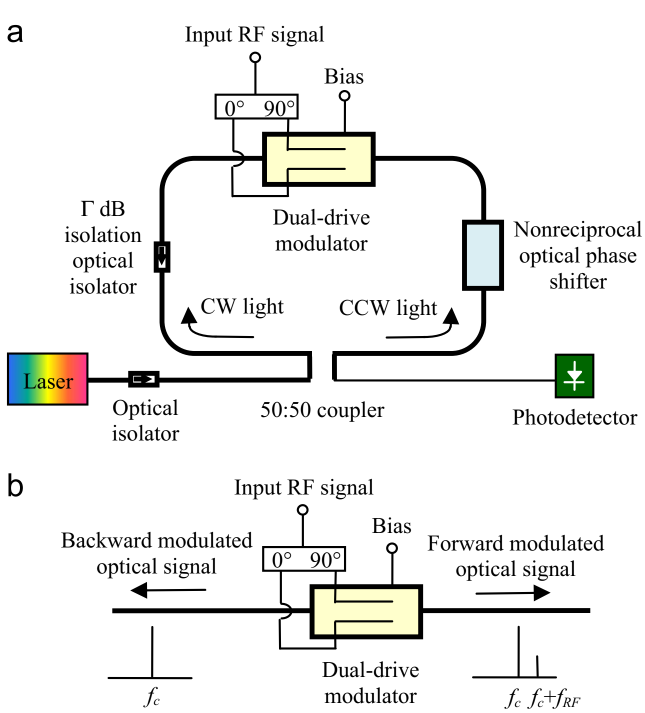

Fig. 2. (a) Structure of the Sagnac interferometer based microwave photonic phase shifter. (b) Optical spectrum of the light passed through the single-sideband modulator in opposite direction. The bold line represents polarisation maintaining components.

through the SSB modulator in opposite direction to the RF signal propagating inside the modulator consists of an optical carrier and a small-amplitude RF modulation sideband. The amplitude of this RF modulation sideband reduces as the frequency increases. At high frequencies (> 10 GHz), this sideband is negligible compared to the sideband carried by the light travelled in the CW direction inside the Sagnac interferometer. Hence one can think of the light passed through the SSB modulator in backward direction consists of an optical carrier only. On the other hand, the light passed through the SSB modulator in the forward direction consists of an optical carrier and an RF modulation sideband as shown in Fig. 2(b). It can be seen from Fig. 2 that if an optical filter is used after the modulator to filter out the optical carrier carried by the CW light then the optical components of the two counterpropagating light after travelling through the Sagnac interferometer are the same as that of the conventional microwave photonic phase shifter shown in Fig. 1. Hence an RF phase shift can be obtained by using a NOPS to control the phase of the optical carrier travelled in the CCW direction inside the Sagnac interferometer.

An optical isolator with Γ dB isolation can be used as a unidirectional attenuator inside the Sagnac interferometer as shown in Fig. 2 (a) to suppress the unwanted optical carrier travelled in the CW direction. This makes the CW light carrier to be much smaller than the CCW light carrier. Therefore, after photodetection, the wanted output RF signal generated by the CCW light carrier beats with the CW light RF modulation sideband dominates the unwanted output RF signal generated by the beating between the carrier and the RF modulation sideband carried by the CW light. Note that the use of a Γ dB isolation optical isolator inside the Sagnac interferometer also reduces the amplitude of the RF modulation sideband carried by the CW light, which causes output RF signal power reduction. However, this problem can be overcome by using a high power laser source or using an erbium-doped fibre amplifier (EDFA) to increase the optical power into the photodetector. The CW and CCW light after travelling through the Sagnac interferometer recombine at the coupler and are then detected by the photodetector.

Fig. 3 shows the topology of the novel NOPS used in the Sagnac interferometer to obtain the nonreciprocal optical phase shift. It consists of a variable waveplate in between two oppositely oriented 45° Faraday rotators connected in free space. The variable waveplate, which is normally referred to as a Babinet compensator, is adjusted to have a 45° device angle and its phase angle can be set between 0° and 360°. The NOPS does not change the light polarisation state but introduces different amounts of optical phase shift to the light passed through the NOPS in opposite direction. A nonreciprocal optical phase shift is obtained by controlling the phase angle of the variable waveplate.

Due to the presence of the NOPS inside the Sagnac interferometer, the two counterpropagating light components have different optical phases. This optical phase difference is converted to an RF phase shift when the CCW light optical carrier beats with the RF modulation sideband carried by the CW light at the photodetector. Since the two counterpropagating lights travel in exactly the same path, there is no coherent interference problem. Hence the output of the Sagnac interferometer based microwave photonic phase shifter is stable and insensitive to environmental perturbations. An optical modulator inside a Sagnac interferometer has been used

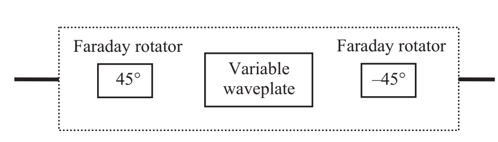

Fig. 3. Structure of the nonreciprocal optical phase shifter. The Faraday rotators and the variable waveplate are connected in free space.