



# A wideband photonic microwave phase shifter with 360-degree phase tunable range based on a DP-QPSK modulator

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## ABSTRACT

A novel wideband photonic microwave phase shifter with 360-degree phase tunable range is proposed based on a single dual-polarization quadrature phase shift-keying (DP-QPSK) modulator. The two dual-parallel Mach-Zehnder modulators (DP-MZMs) in the DP-QPSK modulator are properly biased to serve as a carrier-suppressed single-sideband (CS-SSB) modulator and an optical phase shifter (OPS), respectively. The microwave signal is applied to the CS-SSB modulator, while a control direct-current (DC) voltage is applied to the OPS. The first-order optical sideband generated from the CS-SSB modulator and the phase tunable optical carrier from the OPS are combined and then detected in a photodetector, where a microwave signal is generated with its phase controlled by the DC voltage applied to the OPS. The proposed technique is theoretically analyzed and experimentally demonstrated. Microwave signals with a carrier frequency from 10 to 23 GHz are continuously phase shifted over 360-degree phase range. The proposed technique features very compact configuration, easy phase tuning and wide operation bandwidth.

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## 1. Introduction

Microwave phase shifter is an important electrical device, which is used to shift the input microwave signal with arbitrary phase. In many applications, such as the phased array radar, satellite communication and mobile communication, phase shifters are the core components [1–4]. With the rapid development of the radar and the communication systems, the carrier frequency of the wireless signal is increasing towards much higher frequency band, and the bandwidth of the signal also becomes larger and larger, which means the phase shifters in these systems should have the ability to work in such high frequency and large bandwidth. Conventionally, microwave phase shifters are implemented in the electrical domain [5]. However, the operation bandwidth, the operation frequency and the tuning speed of the phase shifters are always limited by the well-known electronic bottleneck. As a result, traditional electrical phase shifters cannot fulfill the new requirements of the latest applications. Microwave photonics [1,6] is the promising technique to solve the problems encountered in traditional electronic technique, which is an interdisciplinary area that connect the microwave technology and the optical technology. Thanks to the large bandwidth, high operation frequency, good tunability, and immunity to electromagnetic interference offered by modern photonics, the unavailable or extremely expensive electrical functions in the electrical domain can be realized efficiently and inexpensively in the optical domain.

Photonic microwave phase shifters have attracted great attentions and been extensively studied during the past few years to overcome the disadvantages of traditional electrical phase shifters. Many different photonic approaches to implement microwave phase shifters have been reported. One method is based on the vector-sum principle [7,8], where the phase of the microwave signal can be tuned by properly controlling the amplitudes of two microwave signals with 90-degree phase difference. In [7], a photonic microwave phase shifter with 360-degree phase tunable range is proposed based on the joint use of a DP-MZM, a phase modulator (PM) and a balanced detector. The phase of the microwave signal is controlled by tuning the control voltage applied to the PM. The major disadvantage of the technique in [7] is that the configuration of the phase shifter is too complicated. The method in [8] has a very compact structure, but the phase tuning is realized by simultaneously controlling two bias voltages of a dual-parallel Mach-Zehnder modulator (DP-MZM), which makes the phase shifter complex to be tuned, and influences the stability of the phase shifter. In [9,10], photonic microwave phase shifters are proposed based on a polarization modulator (PolM) and an optical band-pass filter (OBPF). However, the employment of an OBPF limits the frequency-tunable range and influences the stability of the phase shifter.

Another method to implement a photonic microwave phase shifter is realized by beating two optical wavelengths with locked phases at

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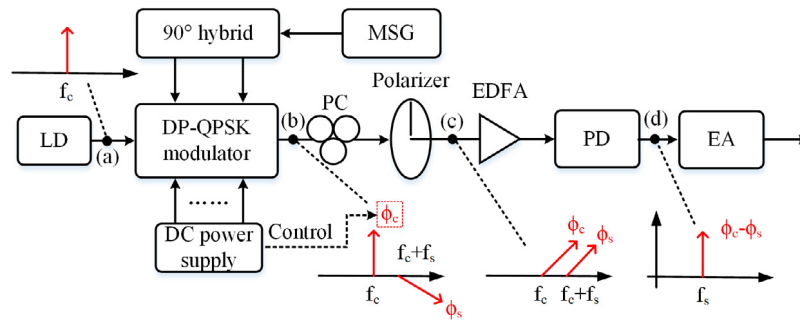


Fig. 1. Schematic diagram of the proposed 360-degree microwave phase shifter. LD, laser diode; DP-QPSK modulator, dual-polarization quadrature phase shift-keying (DP-QPSK) modulator; MSG, microwave signal generator; PC, polarization controller; EDFA, erbium-doped fiber amplifier; PD, photodetector; EA, electrical amplifier.

a photodetector (PD). The generated microwave signal has a phase identical to the phase difference between the two optical wavelengths. In [11–13], photonic microwave phase shifters based on optical single-sideband (OSSB) modulation and stimulated Brillouin scattering (SBS) effect are proposed. The optical carrier of an OSSB modulated optical signal is pumped by a carrier-suppressed double-sideband (CS-DSB) modulated optical signal. As a result, the amplitude of the optical carrier remains unchanged, but the optical phase shift on the optical carrier is doubled. The phase-shifted optical carrier and the original optical sideband from the OSSB modulated optical signal are beaten at a PD to generate a phase tunable microwave signal. The major limitation of the approaches in [11–13] is that the use of the SBS effect makes the phase shifter too complicated, where another optical modulator and microwave source are required for the generation of the CS-DSB pump signal. Another way to realize the phase control of two phase-correlated optical wavelengths is based on an OSSB modulator and a fiber Bragg grating (FBG) [14]. However, the operation bandwidth of this approach is limited by the frequency response of the FBG, which limits its application. Phase modulation is another way to introduce a phase difference between two phase-correlated optical wavelengths [15–17]. In [15], a photonic phase shifter is demonstrated using a DP-MZM followed by an OBPF, a CS-DSB optical signal generated from one Mach-Zehnder modulator (MZM) in the DP-MZM is combined with a phase tunable optical carrier from another MZM in the DP-MZM, which is then filtered by an OBPF to remove one of the two first-order optical sidebands. The optical carrier and the other first-order optical sideband are beaten at the PD to generate a microwave signal, whose phase is controlled by adjusting the phase of the optical carrier. Another wideband tunable phase shifter is proposed in [16] based on a PolM and a polarization-maintaining fiber Bragg grating (PM-FBG). An optical carrier and a first-order optical sideband with opposite phase values are selected from the polarization modulated optical signal from the PolM using the PM-FBG, which can be used for the generation of a microwave signal with its phase being controlled by the bias voltage of the PolM. The major limitation of the technique in [15,16] is that a frequency-dependent OBPF or PM-FBG is used, which limits the bandwidth and stability of the phase shifters. In [17], a dual-polarization quadrature phase shift-keying (DP-QPSK) modulator is used to generate two orthogonally polarized optical signal consisting of one optical carrier and a first-order optical sideband, which is then modulated by another polarization-dependent optical phase shifter (OPS) to introduce complementary optical phases to the optical sideband and the optical carrier. Then the optical signal from the OPS is applied to a polarizer to combine the optical carrier and the optical sideband before being detected at a PD to generate a microwave signal with the phase controlled by the optical phase introduced by the OPS. The major disadvantage of the technique in [17] is that an extra OPS is employed to introduce the phase difference, which makes the system complicated and expensive.

In this paper, we propose a novel wideband photonic microwave phase shifter with 360-degree phase tunable range based on a DP-QPSK modulator. The two DP-MZMs in the DP-QPSK modulator are

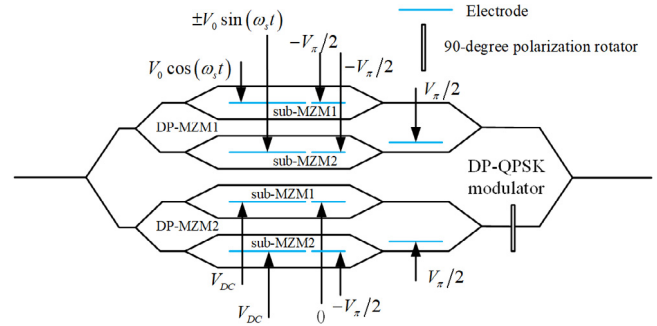


Fig. 2. A diagram of the detail structure of the DP-QPSK modulator and how the electrical signals are applied to the DP-QPSK modulator.

properly biased to serve as a carrier-suppressed single-sideband (CS-SSB) modulator and an OPS, respectively. The microwave signal is applied to the CS-SSB modulator, while a control direct-current (DC) voltage is applied to the OPS. The first-order optical sideband generated from the CS-SSB modulator and the optical carrier from the OPS are combined and then detected in a PD, where a microwave signal is generated with its phase controlled by the DC voltage applied to the OPS. The phase shifter has a very compact structure mainly consisting of a DP-QPSK modulator, and no optical filter or extra modulator is employed. The proposed technique is theoretically analyzed and verified by a proof-of-concept experiment. Microwave signals with a carrier frequency from 10 to 23 GHz are continuously phase shifted over 360-degree phase range.

## 2. Principle of operation

The schematic diagram of the proposed photonic microwave phase shifter is shown in Fig. 1. A linearly polarized CW light wave generated from a laser diode (LD) is injected into a DP-QPSK modulator. A DP-QPSK modulator mainly consists of two DP-MZMs and a 90-degree polarization rotator. A microwave signal generated from a microwave signal source (MSG) is applied to the DP-MZM1 in the DP-QPSK modulator via an electrical 90-degree hybrid, so the two microwave signals applied to the RF ports of the DP-MZM1 have a 90-degree phase difference. The RF ports of the DP-MZM2 in the DP-QPSK modulator is driven by DC voltages from DC power supplies. At the output of the DP-QPSK modulator, the two outputs from the two DP-MZMs are on the two orthogonal polarization states, respectively. The optical signal at the output of the DP-QPSK modulator is sent to a polarizer through a polarization controller (PC), and then amplified by an erbium-doped fiber amplifier (EDFA) before being detected in a PD. The photocurrent from the PD is the generated phase-shifted microwave signal, which is amplified by an electrical amplifier (EA).

Fig. 2 gives a detail structure of the DP-QPSK modulator and shows how the electrical signals are applied to the DP-QPSK modulator. In the

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