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Chirp-adjustable optical intensity modulator with tunable OCSR based on Sagnac interferometer

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ABSTRACT

In this paper a novel optical intensity modulator with tunable optical carrier-to-sideband ratio (OCSR) and adjustable chirp parameter is proposed and theoretically investigated. It is based on a bidirectional phase modulator (PM) and a tunable nonreciprocal optical phase shifter in a Sagnac interferometer (SI). Because no bias is necessary for a PM, the bias-drift problems are automatically removed. Besides, clockwise (CW) and counter clockwise (CCW) propagating lights travel in the same path so enhances robustness against environmental perturbations. In this modulator two radio frequency (RF) signals with opposite phases and tunable power ratio are applied to the bidirectional PM. Chirp parameter and OCSR of the modulator can be tuned by tuning the phase shift of the optical phase shifter and RF power ratio. Besides, this modulator can have two complementary balanced outputs. So common-mode noises such as relative intensity noise (RIN) of the laser can be suppressed in a microwave photonic link (MWPL) based on this modulator and using a balanced receiver. This novel modulator can also operate bidirectionally. An intensity modulated optical signal with tunable OCSR and chirp parameter is achieved by adjusting the optical phase shifter and the RF power ratio. The effect of the lossy SI and finite optical extinction ratio on the performance of the proposed modulator is theoretically investigated. In addition applications of the proposed chirp-adjustable modulator to overcome fiber dispersion-induced power penalty in a MWPL is investigated It is shown that by adjusting the chirp parameter, link distance for a given frequency (or bandwidth for a given link distance) doubles.

1. Introduction

Microwave photonics (MWP) is a multidisciplinary field that uses the advantages of photonic technology for generation, transmission, distribution, control, detection, processing and measurement of RF, microwave, mm-wave and THz signals. MWPL is one of the main blocks in most of the MWP applications, including radio over fiber (RoF) [1], satellite communications [2], optically controlled phased array antennas [3], optoelectronic oscillators (OEO) [4–7], photonic signal processing of microwave signals [8], MWP mixers [9], phase shifters [10], frequency transposers [11] and delay lines [12–14]. The most commonly used MWPLs are based on intensity modulation with direct detection links due to the receiver simplicity.

One of the main limiting factors for improving the performance of a MWPL is dispersion of the link (such as chromatic dispersion of the optical fiber) which results in frequency-dependent power fading [15–18] that reduces the transmission distance or signal bandwidth. Many different approaches have already been proposed to decrease the effect of fiber dispersion-induced power penalty, such as using dispersion shifted fiber [19], optical single-sideband modulation [19], dispersion compensation in optical regenerators [20] and low-chirp transmitters [19]. It was shown that modulators with adjustable chirp can reduce fiber dispersion-induced power penalties [19]. Therefore, external modulator which can provide a low or adjustable chirp parameter, is a key component of high performance MWP systems.

External Mach-Zehnder modulator (MZM) produces chirp in modulated signal [21–25]. Chirp-free MZM can also be obtained by driving a dual-drive MZM (DDMZM), which has two arms with equal power losses, in push-pull mode [21–23]. Even though the input/output Y-coupler of the DDMZM are 50:50, since its two arms are not exactly the same, so the power losses and phase changes of the two arms are not essentially equal and change with environmental perturbations. Besides, MZM needs dc bias voltage which drifts during operation. Therefore, performance of a Mach-Zehnder interferometer (MZI)-based MWP system degrades with environmental perturbations and bias drift. Hence, a bias stabilization and tracking is necessary to suppress bias-

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drift problems while increases the size, weight and power consumption of the system [26,27].

It has already been shown that an optimum OCSR can improve performance of a MWP system [28,29]. Novel approaches to realize optical modulation with tunable OCSR have been proposed based on a polarization-maintaining fiber Bragg grating [29], DPMZM [30], cascaded polarization modulators (PolMs) [31], DPMZM in a SI [32] and dual-polarization MZM [33].

In this paper a novel chirp-adjustable optical intensity modulator with tunable OCSR based on a bidirectional PM in a SI is proposed and theoretically investigated. It is shown that the proposed modulator is low drift and bias free and can operate bidirectionaly with balanced dual outputs.

SI has already been used in fiber gyroscopes [34], MWP filters [35], downconvertors [36], balanced optical–microwave phase detectors [37–38], optical regenerators [39], modulators [40–42], sensors [43–47], and OEOs [5–7]. Here, we apply it to perform a low-drift bias-free optical intensity modulator with tunable OCSR and adjustable chirp parameter. The novel structure is introduced and investigated in Section 2. Effect of the lossy SI and finite optical extinction ratio on the chirp parameter and OCSR is investigated in Section 3. One of the applications of the proposed chirp-adjustable modulator to overcome fiber dispersion penalty in a MWPL is theoretically investigated in Section 4.

2. Chirp-adjustable optical intensity modulator with tunable OCSR: a novel structure

The proposed optical intensity modulator is shown in Fig. 1. It is based on a SI which is composed of a bidirectional PM, a tunable nonreciprocal optical phase shifter, an optical isolator, a 180° RF hybrid coupler and two RF power attenuators. A continuous wave light is fed into a polarization-maintaining 2×2 optical coupler which forms a SI. The power is divided by the 2×2 coupler so that first half propagates in CW and the second half propagates in the CCW.

It is worth mentioning here that the bidirectional PM is a commercial traveling-wave phase modulator, but electrical termination ($\sim 50\,\Omega$) of the electrode is removed, so that access is given to both input and output ports (such as those used in [48–50] from EOspace with a bandwidth of 20 GHz). Bidirectional PM has already been used, ex. to realize MWP mixers [48–49], and high-linearity MWP links [50], etc. Besides, nonreciprocal optical phase shifter can be realized by employing a quarter-wave plate placed between two oppositely placed $\pi/4$ Faraday rotators, which has already been used to realize optical modulators [40], MWP phase shifters [51], OEOs [6–7], etc. So, we can use a bidirectional PM such as those used in [48–50] and a

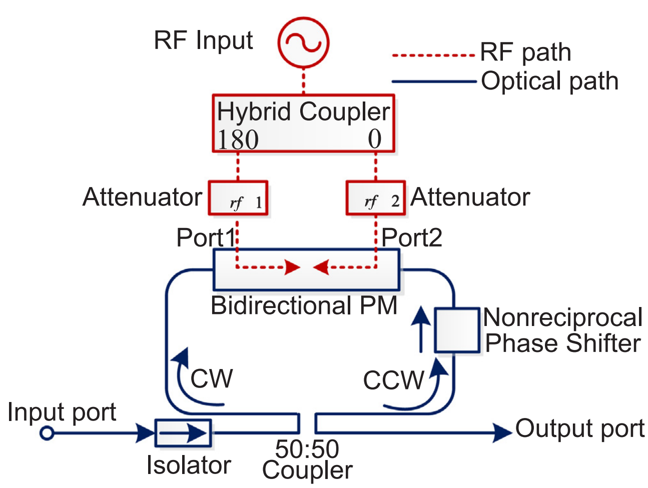

Fig. 1. Structure of the proposed chirp-adjustable optical intensity-modulator with tunable OCSR based on a bidirectional phase modulator.

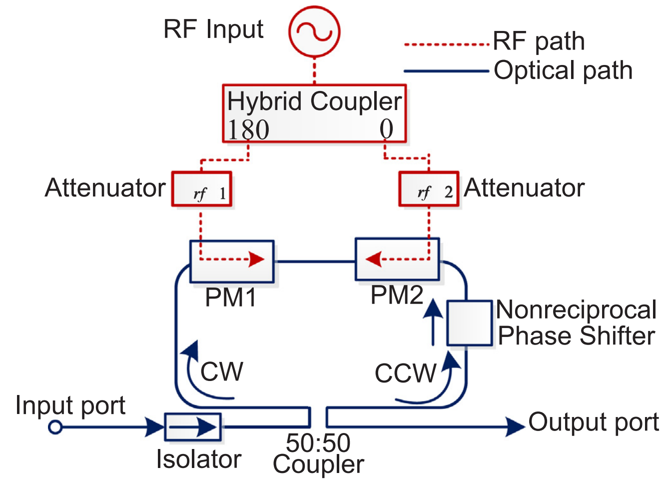

Fig. 2. Structure of the proposed chirp-adjustable optical intensity-modulator with tunable OCSR based on two unidirectional phase modulators.

nonreciprocal optical phase shifter such as those used in [6–7,40,51] in the proposed intensity modulator.

It is also worth mentioning here that the bidirectional PM in Fig. 1 can be replaced by two commercial traveling-wave unidirectional phase modulators which are connected in opposite directions that is shown in Fig. 2, such as one has already been used in a MWP mixer [36].

In the proposed modulator (Fig. 1 or Fig. 2), the reverse modulations are ignored because of the high velocity mismatch of the PMs at high frequencies [7,49,50,57,58]. So, when optical waves are bidirectionally traveling through the PMs, each wave is only modulated by the electrical wave launched in the same direction (copropagation) and it has very small modulation index for the electrical wave launched in the opposite direction (counterpropagation). So, it has effective modulation for CW light at the electric port 1 (in Fig. 1) or at PM1 (in Fig. 2) and for CCW light at the electric port 2 (in Fig. 1) or at PM2 (in Fig. 2) with almost the same modulation indices. But it has negligible modulation indices for the reverse modulation, i.e. for CW light at the electric port 2 (in Fig. 1) or at PM1 (in Fig. 2) and for CCW light at the electric port 1 (in Fig. 1) or at PM1 (in Fig. 2). Performance of the proposed modulator is investigated in the following subsections.

2.1. Optical field spectrum

According to Fig. 1, assume that signal of the RF source is $v_{RF}(t) = \sqrt{2}V_{rf}\cos(\omega_{rf}t)$ which is applied to a 180° RF hybrid coupler, so RF applied voltage to the two RF ports of the bidirectional PM can be expressed as

$$v_{RF-1}(t) = \gamma_{rf-1}V_{rf}\cos(\omega_{rf}t-\pi) \tag{1}$$

$$v_{RF-2}(t) = \gamma_{rf-2}V_{rf}\cos(\omega_{rf}t) \tag{2}$$

where, $0 \le \gamma_{rf-1}^2 \le 1$ and $0 \le \gamma_{rf-2}^2 \le 1$ are power attenuation factor of the two RF power attenuators. Here, assume that input optical signal to the coupler is $E_{in}\cos(\omega_0 t)$ and the optical coupler is lossy (with total power splitting/combining loss factor $0 \le t_c^2 \le 1$) and SI and PM is lossy too (with total power loss factor $0 \le t_{sm}^2 \le 1$) but assume that optical coupler splits/combines power equally (50:50), the case of unequal power splitting/combining (a: $1-a$) is considered in Section 3. Optical field spectrum can be found using the equations given in Appendix A. Optical field at the output port of Fig. 1 can be evaluated from (A.1) and (A.4) by substituting $a = 0.5$ for the 50:50 coupler as