Polarization-insensitive photonic microwave downconversion

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A polarization-insensitive photonic microwave downconverter is proposed and demonstrated, which is comprised of a polarization beam splitter, two Mach–Zehnder modulators (MZMs), and a balanced photodetector. By biasing the MZMs at the quadrature bias points with opposing modulation slopes, the performance of the proposed photonic microwave downconverter is almost independent of the polarization state of the optical microwave signal for down conversion. An experiment is performed, which shows that the polarization dependent loss of the proposed downconverter is less than 0.06 dB. The downconverter is also evaluated in a radio-over-fiber link. A 20 GHz RF signal with 20 MBaud 16 quadrature amplitude modulation baseband data is successfully downconverted to a 1 GHz IF signal. When the polarization state of the input optical microwave signal is adjusted, the variation of the error vector magnitude of the downconverted signal is less than 0.4%.

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The advantages of low loss, high bandwidth, and immunity to electromagnetic interference (EMI) offered by radio-over-fiber (RoF) system [1] make it an ideal candidate for applications where microwave signals must be transmitted to a center office for processing or the antenna units must be as simple as possible. In RoF systems, it is of great interest that the information can be downconverted directly in the optical domain from a high-frequency band to a low intermediate frequency (IF) band. Previously, various photonic frequency downconverters were proposed, including the schemes based on cascaded Mach–Zehnder modulators (MZMs) [2], parallel electro-optic modulators (EOMs), and a balanced photodetector (BPD) [3], an injection-locked distributed feedback laser [4,5], a semiconductor optical amplifier (SOA) [6–12], and a parametric optical loop mirror [13]. However, most of these schemes are highly polarization dependent, so adaptive polarization control is required at the center office to achieve the highest conversion efficiency, which is complex, costly, and bulky. Although optical downconverters based on the polarization-insensitive SOA [10,11] can achieve photonic microwave downconversion with a very small polarization sensitivity, the signal after downconversion is severely distorted due to the complex nonlinear effects and the relatively slow gain recovery in the SOA, especially when the downconverted signal occupies a wide bandwidth.

In this Letter, we propose a novel polarization-insensitive photonic microwave downconverter comprised of a polarization beam splitter (PBS), two MZMs biased at the opposite linear transmission points and a BPD. Experimental results show that the polarization dependent loss (PDL) of the proposed downconverter can be as low as 0.06 dB. In addition, the quality of the downconverted signal is almost unaffected by the polarization state of the incident signal.

Figure 1(a) shows the schematic diagram of the proposed polarization-insensitive photonic microwave downconverter. An optical microwave signal for downconversion is split by a PBS into two branches. In each branch, an MZM is inserted to perform electro-optical mixing [2]. The two MZMs are biased at the quadrature bias points with opposing modulation slopes. An electrical LO signal is divided into two paths by an electrical power divider and sent to the two MZMs via their RF ports. To ensure that the length of the two signal paths are identical, an optical tunable delay line (OTDL) is inserted. Besides, a variable optical attenuator (VOA) is incorporated to eliminate the differences of the insertion losses of the two branches and the half-wave voltages of the two MZMs. The downconverted optical signals from the two branches are then detected by a BPD. An IF filter and an amplifier are followed to select and amplify the IF electrical signal.

Assume that the optical microwave signal for downconversion is a double-sideband modulated signal with

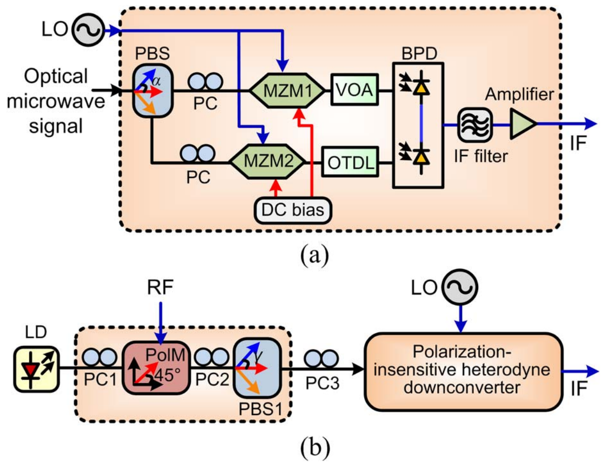

Fig. 1. (a) Schematic diagram of the proposed polarization-insensitive photonic microwave downconverter and (b) experimental setup for evaluating the performance of the proposed downconverter. PBS, polarization beam splitter; VOA, variable optical attenuator; OTDL, optical tunable delay line; BPD, balanced photodetector; LD, laser diode; PC, polarization controller; PolM, polarization modulator.

an arbitrary polarization state. Mathematically, the optical field of the optical microwave signal along the two principal axes of the PBS can be expressed as

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = (A_1 e^{j[(\omega_c-\omega_{RF})t-\phi(t)]} + A_0 e^{j\omega_c t} + A_1 e^{j[(\omega_c+\omega_{RF})t+\phi(t)]}) \begin{bmatrix} \cos\alpha e^{j\varphi} \\ \sin\alpha \end{bmatrix}, \quad (1)$$

where ω_c is the angular frequency of the optical carrier, ω_{RF} is the angular frequency of the RF signal, A_0 and A_1 are the amplitudes of the optical carrier and the sidebands, $\phi(t)$ denotes the information in the optical microwave signal, α is the angle between one principal axis of the PBS and the polarization direction of the injection signal, and ϕ is a phase difference. After the optical signals in the two branches are split by the PBS and modulated by the MZMs, they are then written as

$$\begin{cases} E_1 = \sqrt{P_1/2} E_x [e^{j(\beta_1 \cos\omega_{LO} t + 3\pi/2)} + 1] \\ E_2 = \sqrt{P_2/2} E_y [e^{j(\beta_2 \cos\omega_{LO} t + \pi/2)} + 1] \end{cases}, \quad (2)$$

where $P_n (n = 1, 2)$ denotes the loss of optical power in each branch, ω_{LO} is the angular frequency of the LO signal, and $\beta_n (n = 1, 2)$ is the modulation indices of the MZMs.

Applying the optical signals to the BPD for square law detection and ignoring the DC and higher frequency components, we obtain

$$\begin{aligned} I_{IF} &= I_1 - I_2 = \Re(|E_1|^2 - |E_2|^2) \\ &= 4\Re A_0 A_1 \cos[(\omega_{RF} - \omega_{LO})t + \phi(t)] \\ &\quad \times [P_1 \cos^2\alpha J_1(\beta_1) + P_2 \sin^2\alpha J_1(\beta_2)], \end{aligned} \quad (3)$$

where $\Re$ is the responsivity of the BPD and J_1 denotes the first-order Bessel function of the first kind. If the VOA is adjusted to let

$$P_1 J_1(\beta_1) = P_2 J_1(\beta_2) = C, \quad (4)$$

where C is a constant, we have

$$I_{IF} = 4C\Re A_0 A_1 \cos[(\omega_{RF} - \omega_{LO})t + \phi(t)]. \quad (5)$$

As can be seen from Eq. (5), the information $\phi(t)$ is downconverted from a high frequency of ω_{RF} to a low IF of $\omega_{RF} - \omega_{LO}$, and the power of the IF signal is independent of α and ϕ, i.e., the polarization state of the incoming optical signal. As a result, the proposed downconverter is polarization insensitive.

When the optical microwave signal for downconversion is a single-sideband modulated signal,

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = (A_0 e^{j\omega_c t} + A_1 e^{j[(\omega_c+\omega_{RF})t+\phi(t)]}) \begin{bmatrix} \cos\alpha e^{j\varphi} \\ \sin\alpha \end{bmatrix}. \quad (6)$$

With the same mathematical manipulation, a similar result can be obtained,

$$I_{IF} = 2C\Re A_0 A_1 \cos[(\omega_{RF} - \omega_{LO})t + \phi(t)]. \quad (7)$$

As a result, the polarization-insensitive photonic microwave downconversion is effective for all intensity-modulated optical microwave signals. Due to the possibly imperfect power allocation in the two branches, the condition in Eq. (4) may not be satisfied. In that case, the PDL would be

$$\mathrm{PDL} = 10\log_{10} \max\left\{\frac{P_2 J_1(\beta_2)}{P_1 J_1(\beta_1)}, \frac{P_1 J_1(\beta_1)}{P_2 J_1(\beta_2)}\right\}. \quad (8)$$

Because all the PBS, MZMs, and BPD can be fabricated on GaAs substrates [14], and the PCs, VOAs, and OTDL can be removed if the photonic integrated circuit is carefully designed, the proposed scheme is monolithically integratable. It should be noted that the proposed scheme is different from that in [3] because the parallel MZMs and the BPD in this work is not used for improving the linearity of the photonic microwave mixer.

An experiment is performed based on the setup shown in Fig. 1(b) to evaluate the performance of the proposed downconverter. A lightwave from a tunable laser source (Agilent N7714A) is intensity modulated by a polarization modulator (PolM, Versawave Inc.) followed by a PBS [15]. The PolM has a bandwidth of 40 GHz and a half-wave voltage of about 3.5 V, which is driven by a 20 GHz RF signal generated by a vector signal generator (Agilent E8267D). The generated optical microwave signal is then introduced to the proposed downconverter. In the downconverter, an LO signal with a frequency of 19 GHz generated by an analog signal generator (Agilent E8257D) is split by a power divider into two paths and led to two MZMs (MZM1 and MZM2). Mach–Zehnder modulator 1 (MZM1, FTM7938EZ) has a bandwidth of 40 GHz, a half-wave voltage of 2.1 V and an insertion loss of 3.9 dB, while the bandwidth, half-wave voltage, and insertion loss of MZM2 (FTM7937EZ) are 40 GHz, 1.8 V, and 6.3 dB, respectively. A BPD (BPDV2150R) with a responsivity of 0.6 A/W and a bandwidth of 41 GHz is used to perform the optical-to-electrical conversion. The generated electrical IF signal is selected by a low-pass filter (LPF) with a cut-off frequency of 1.2 GHz. The electrical spectrum is measured by an electrical spectrum analyzer (Agilent E4447A).

Figure 2(a) shows the electrical spectrum of the downconverted signal observed after the BPD. A 1 GHz IF signal is achieved when an optical microwave signal with a 20 GHz sinusoidal signal is input into the downconverter. The power of the 20 GHz RF, 19 GHz LO, and input optical microwave signals are 10, 17, and 12 dBm, respectively. After being selected by the LPF, all the higher frequency components are eliminated. The power of the generated 1 GHz IF signal is −6.16 dBm, and the power variation is about 0.1 dB when the polarization state of the input signal is fixed. This power variation should originate mainly from the power variation of the RF source and the measurement error of the electrical spectrum analyzer. To measure the polarization dependence of the downconverter, we adjust PC3, which varies the polarization state of the input optical signal. The power variation of the 1 GHz IF signal is increased

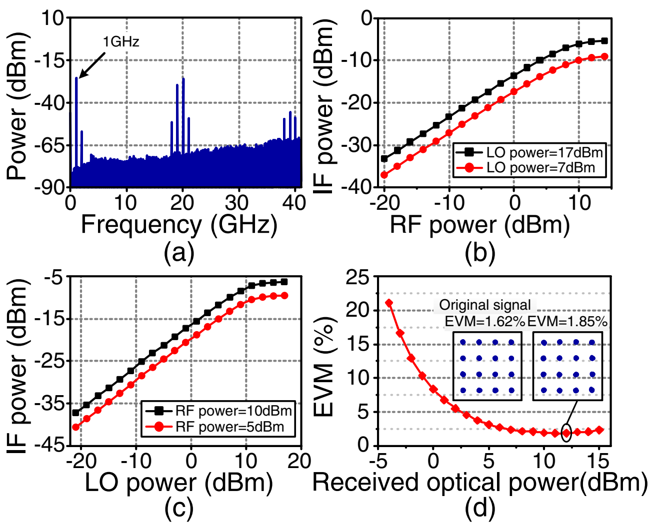

Fig. 2. (a) Electrical spectrum of the IF signal at the output of the BPD (RBW = 300 kHz); the measured IF power of the signal as a function of (b) RF power; (c) LO power; and (d) the measured EVM of the IF signal versus the received optical power, insets: constellation diagrams.

to about 0.3 dB. Considering that the variation of insertion loss of PC3 is 0.07 dB for different settings and the optical-to-electrical conversion is square law, the PC itself introduces a 0.14 dB power variation. As a result, the PDL of the proposed downconverter is less than 0.06 dB. In addition, the conversion efficiency [2] of the downconverter, defined as the power ratio of the output IF signal to the input RF signal, is −16.16 dB after a 19.44 dB electrical amplification, which is better than that based on the cascaded MZMs [2] but worse than those reported in [8–12] because no optical amplifier is applied in the proposed downconverter.

Figure 2(b) shows the IF power as a function of the power of the input RF signal when the LO power is 17 or 7 dBm. When the input RF power is smaller than 9 dBm, a good linear relationship between input RF power and the output IF power is achieved, indicating that the conversion efficiency is almost the same for a given LO power. Figure 2(c) shows the IF power as a function of the input power of the LO signal when the RF power is 10 or 5 dBm. Again, a good linear relationship is achieved when the input LO power is less than 10 dBm, so the conversion efficiency is almost proportional to the LO power.

To further evaluate the performance of the proposed downconverter, a 20 GHz RF signal with a 20 MBaud 16 quadrature amplitude modulation (QAM) baseband data, is introduced to the PolM in Fig. 1(b). Figure 2(d) shows the measured error vector magnitude (EVM) of the 1 GHz downconverted IF signal as a function of the received optical signal power. The constellation diagrams of the input RF signal and the output IF signal are also measured by an electrical signal analyzer (Agilent N9030A), which is shown in the insets of Fig. 2(d). The power of the RF signal and the IF signal are 10 and 17 dBm, respectively. The EVM of the RF signal evaluated by 1000 symbols is 1.62%. After frequency downconversion by the proposed downconverter, the signal is downconverted to the 1 GHz band. The EVM is degraded to 1.85%. The deterioration of the EVM is 0.23%, which is preferable as compared with the previously reported approach [8]. When PC3 is fixed, due to the variations of other parts in the system and the measurement error of the signal analyzer, the variation of the EVM is about 0.2%. By adjusting PC3, the variation of the EVM is increased by 0.4%, showing again that the proposed downconverter is polarization-insensitive.

In conclusion, a novel polarization-insensitive photonic microwave downconverter comprised of a PBS, two MZMs, and a BPD was proposed and demonstrated. The PDL is less than 0.06 dB, and EVM variation of the downconverted signal with a 20 MBaud 16 QAM baseband data is within 0.4% when the optical microwave signal for downconversion has different polarization states. Since the bandwidth of the devices used in the downconverter is greater than 40 GHz, the scheme is possibly operated at the 40 GHz band, which can find applications in antenna remoting, RoF communications, and other microwave photonic systems.

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