A Polarization-Insensitive Optical Heterodyne Downconverter

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Abstract—A polarization-insensitive optical heterodyne downconverter is proposed and demonstrated, which comprises of a polarization beam splitter (PBS), two Mach-Zehnder modulators (MZMs) and a balanced photodetector (BPD). By biasing the MZMs at the opposite linear transmission points and the balanced detection, the performance of the proposed optical heterodyne downconverter is almost independent of the polarization state of the input optical microwave signal. An experiment is carried out. The polarization dependent loss (PDL) of the proposed downconverter is less than 0.5 dB. A 20-GHz RF signal with 50-MBaud 16 quadrature amplitude modulation (QAM) baseband data is successfully downconverted to a 2.4-GHz IF signal. The variation of the error vector magnitude (EVM) of the downconverted signal is less than 1% when the optical microwave signal for down-conversion has different polarization states.

Keywords—Heterodyne downconverter, polarization, microwave photonics.

I. Introduction

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 over a certain distance. In the RoF systems, frequency down-conversion is an important part to convert the information from high-frequency band to low intermediate frequency (IF) band for further processing. Conventionally, the down-conversion is implemented by an electrical mixer, which always has a small operation bandwidth and introduces large conversion loss and signal distortion. To overcome the problem, various photonic frequency downconverter to perform the down-conversion directly in the optical domain have been proposed, such as the schemes based on cascaded Mach-Zehnder modulators (MZMs) [2], an injection-locked distribute feedback laser [3], a semiconductor optical amplifier (SOA) [4]-[9], and a parametric optical loop mirror [10]. However, most of these schemes are highly polarization dependent, so adaptive polarization controlling is required to achieve the highest conversion efficiency, which is complex, costly and bulky. Although optical downconverter based on the polarization-insensitive SOA [7,8] can achieve polarization-insensitive down-conversion, the signal after down-conversion is severely distorted due to the complex nonlinear effects (such as cross-gain modulation, cross-phase modulation, and four-wave mixing) and the relatively slow gain recovery in the SOA. In addition, the conversion efficiency of the scheme is low since the signal mixing in the SOA is usually weak.

In this paper, we propose a novel polarization-insensitive optical heterodyne downconverter comprising of a polarization beam splitter (PBS), two MZMs biased at the opposite linear transmission points and a balanced photodetector (BPD). Experiment result shows that the polarization dependent loss (PDL) of the proposed downconverter is less than 0.5 dB.

II. Principle

Fig. 1(a) shows the schematic diagram of the proposed polarization-insensitive optical heterodyne downconverter. An optical microwave signal for down-conversion is split by a PBS into two branches. In each branch, a MZM is inserted to perform the downconversion directly in the optical domain. By biasing the MZMs at the opposite linear transmission points and the balanced detection, the performance of the proposed optical heterodyne downconverter is almost independent of the polarization state of the input optical microwave signal. An experiment is carried out. The polarization dependent loss (PDL) of the proposed downconverter is less than 0.5 dB. The polarization dependent loss (PDL) of the proposed downconverter is less than 0.5 dB. A 20-GHz RF signal with 50-MBaud 16 quadrature amplitude modulation (QAM) baseband data is successfully downconverted to a 2.4-GHz IF signal. The variation of the error vector magnitude (EVM) of the downconverted signal is less than 1% when the optical microwave signal for down-conversion has different polarization states.
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 lengths 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.

To simplify the analysis, we assume that the optical microwave signal for down-conversion is a single-sideband modulated signal with 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

\[
E_x = \begin{bmatrix} A_e e^{j\alpha t} + A_o e^{j(\omega_{RF} + \omega_{LO})t + \phi(t))} \end{bmatrix} \begin{bmatrix} \cos \alpha e^{j\beta t} \\ \sin \alpha \end{bmatrix}
\]

where \(\omega_{LO}\) is the angular frequency of the optical carrier, \(\omega_{RF}\) is the angular frequency of the RF signal, \(A_e\) and \(A_o\) are the amplitudes of the optical carrier and the sideband, \(\phi(t)\) denotes the information in the optical microwave signal, \(\alpha\) is the angle between one principal axis of the PBS and the polarization direction of the injection signal, and \(\beta\) is a phase difference. After split by the PBS and modulated by the MZMs, the optical signals in the two branches are then written as

\[
\begin{align*}
E_1 &= P_1 \cos \alpha e^{j\beta_1} E(t) [e^{j(\beta_{RF} + \omega_{RF})t + \phi(t)] + 1] \\
E_2 &= P_2 \sin \alpha E(t) [e^{j(\beta_{RF} + \omega_{RF})t + \phi(t)] + 1]
\end{align*}
\]

where \(P_n (n=1, 2)\) denotes the loss of optical power in each branch, \(\omega_{RF}\) is the angular frequency of the LO signal, \(\beta_n (n=1, 2)\) are 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

\[
I_w = I_1 - I_2 = 9\Re\left(E_1^* - E_2^*\right)
= 4\Re A_e A_o \cos[(\omega_{RF} - \omega_{LO})t + \phi(t)]
\times [P_1 \cos^2 \alpha J_1(\beta_1) + P_2 \sin^2 \alpha J_1(\beta_2)]
\]

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

\[
P_1 J_1(\beta_1) = P_2 J_1(\beta_2) = C
\]

where \(C\) is a constant, we have

\[
I_w = 4\Re A_e A_o \cos[(\omega_{RF} - \omega_{LO})t + \phi(t)]
\]

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

### III. Experimental Demonstration

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 sent to an intensity modulator implemented by a polarization modulator (PolM) (Versa wave Inc.) followed by a PBS [11]. 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). A tunable OBPF (Yenista XTM-50) with an edge slope of more than 500 dB/nm and a top flatness of 0.2 dB is incorporated to remove one sideband of the signal. Then, the OSSB modulated signal is transmitted over a 4.4-km SMF, and introduced to the proposed downconverter. In the downconverter, a LO signal with a frequency of 17.6 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) via their RF ports. MZM1 (FTM7938EZ) and MZM2 (FTM7939EZ) 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 (FTM7939EZ) 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 band-pass filter with a bandwidth of 200 MHz and a center frequency of 2.4 GHz. The electrical spectrum is measured by an electrical signal analyzer (Agilent N9030A).

![Figure 2. Electrical spectrum of the IF signal obtained at output of the proposed downconverter (RBW=300 kHz).](image)
A novel polarization-insensitive heterodyne downconverter comprising of a PBS, two MZMs and a BPD was proposed and demonstrated. The PDL is less than 0.5 dB, and the variation of the EVM of the downconverted signal with 50-MBaud 16-QAM baseband data is less than 1% when the optical microwave signal for down-conversion 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.

IV. Conclusion

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References


Figure 3. (a) Electrical spectrum (RBW=300 kHz) and (b) constellation diagram of the 20-GHz RF signal with 50-MBaud 16-QAM baseband data, and (c) electrical spectrum and (d) constellation diagram of the 2.4-GHz downconverted IF signal.