A Photonic Frequency Downconverter based on a Single Dual-drive Mach-Zehnder Modulator

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Abstract—A novel photonic frequency downconverter is proposed and demonstrated using a single dual-drive Mach-Zehnder modulator (DMZM). In the proposed scheme, the local oscillator (LO) and radio frequency (RF) signals are sent to the two RF ports of the DMZM, respectively. By biasing the modulator at the minimum transmission point, a downconverted intermediate frequency (IF) signal with the RF and LO components suppressed is obtained. An experiment is carried out to demonstrate the feasibility of the downconverter. Results show that a 30-GHz RF signal with 50-Mbaud 16 quadrature amplitude modulation (QAM) is successfully downconverted to the 2.4-GHz IF band. The error vector magnitude (EVM) of the downconverted signal is less than 2.0%.

Keywords—dual-drive Mach-Zehnder modulator, frequency downconversion, radio over fiber, microwave photonics

I. INTRODUCTION

Radio over fiber (RoF) system attracts significant interests because of the large bandwidth, high data rate and low transmission loss provided by the photonic technologies. In the RoF system, the frequency downconversion is one of the essential parts to shift a high-frequency RF signal to the baseband or intermediate frequency (IF) band, which is conventionally realized by an electrical mixer. Because the electrical mixer usually has narrow operational bandwidth, high conversion loss and high distortion, photonic frequency downconverters become attractive. Several schemes have been proposed, which are generally implemented based on cascaded electro-optical modulations, such as a direct-modulated laser diode (LD) followed by a Mach-Zehnder modulator (MZM) [1], a polarization modulator (PolM) followed by a MZM [2], cascaded MZMs [3], and cascaded phase modulators (PMs) with optical filtering [4]. However, due to the limited modulation bandwidth of the LD, the photonic microwave downconverter in [1] can only be effective when the frequency of the RF signal is less than 10 GHz. The cascaded external modulation [2-4] can provide large bandwidth, but two external modulators are needed, which leads to low conversion efficiency, large insertion loss and high cost. To solve the above problems, approaches based on a single modulator have been proposed [5-7]. In [5], [6], the local oscillator (LO) and RF signals are combined by a microwave combiner and then applied to a direct-modulated LD or an external modulator. Frequency downconversion is achieved due to the nonlinear effects in the LD or external modulator. The key limitation associated with this approach is that the improvement of the conversion efficiency is always accompanied with the increase of the nonlinear distortion. Taking advantages of the highly integrated dual-parallel MZM (DPMZM), wideband downconversion [7] can be achieved using a single device. But three bias voltages have to be carefully controlled to obtain high conversion efficiency, which may degrade the stability of the system. Besides, a significant cost reduction of the DPMZM is required to make the scheme affordable to the RoF applications. A semiconductor optical amplifier (SOA) can also be used for frequency downconversion [8]-[11], but an optical LO should be generated first which requires one more electro-optical modulation. The quality of the converted signal is also poor because of the complex nonlinear effects and the relatively slow gain recovery in the SOA. In addition, the previously reported photonic downconverter always outputs a IF signal together with strong LO and RF components. These components are usually eliminated by connecting a microwave filter to the PD, or by inserting a microwave photonic filter based on a multi-wavelength source [12], which places a restriction to the frequency of the IF signal.

In this paper, we propose to implement the photonic frequency downconversion by introducing the LO and RF signals to the two RF ports of a single dual-drive MZM (DMZM). By properly setting the bias voltage of the DMZM, the IF signal is generated by a LD and sent to a DMZM via a polarization controller (PC). The RF and LO signals are sent to the two RF ports of the DMZM, respectively. Mathematically, the normalized optical field at the output of the DMZM is written as
where $\omega_{RF}$ and $\omega_{LO}$ are the frequencies of the RF and LO signals, $\beta_{RF} = \pi V_{RF}/V_z$ and $\beta_{LO} = \pi V_{LO}/V_z$ are the modulation indices in the two arms of the DMZM, $V_{RF}$ and $V_{LO}$ are the amplitudes of the RF and LO signals, $V_z$ is the half-wave voltage of the DMZM, and $\phi_0$ is the phase difference, which is introduced by the bias voltage applied to the DMZM.

![Fig. 1. Schematic diagram of the proposed photonic frequency downconverter. LD: laser diode; PC: polarization controller; DMZM: dual drive Mach-Zehnder modulator; PD: photodetector.](image)

Under small-signal modulation, (1) can be expanded as
\[
E_i = e^{i\omega_{RF}t} \cdot e^{i\phi_0} \left[ J_1(\beta_{RF}) e^{-j\omega_{RF}t} + J_0(\beta_{RF}) + j J_1(\beta_{RF}) e^{j\omega_{RF}t} \right] + e^{i\omega_{LO}t} \left[ J_1(\beta_{LO}) e^{-j\omega_{LO}t} + J_0(\beta_{LO}) + j J_1(\beta_{LO}) e^{j\omega_{LO}t} \right]
\]
where $J_n$ are the $n$th-order Bessel function of the first kind. The AC term of the detected signal is given by
\[
i_{AC} = -J_1(\beta_{RF}) J_0(\beta_{LO}) \sin \phi_0 \cos \omega_{RF} t + J_1^2(\beta_{RF}) \cos(2\omega_{RF} t) + J_0(\beta_{RF}) J_1(\beta_{LO}) \sin \phi_0 \cos \omega_{LO} t + J_1(\beta_{RF}) J_1(\beta_{LO}) \cos \phi_0 \cos(\omega_{RF} - \omega_{LO}) t + \ldots
\]

As can be seen from (3), the downconverted IF component at $\omega_{IF} = \omega_{RF} - \omega_{LO}$ is obtained and its power is dependent on $\phi_0$. Obviously, when $\phi_0 = \pi/2$, the amplitude of the IF signal is zero, which means the downconversion is not realized. On the other hand, when $\phi_0 = 0$ or $\pi$, the IF signal is of the largest amplitude. Meanwhile, the unwanted frequency components at $\omega_{RF}$ and $\omega_{LO}$ are fully eliminated.

### III. EXPERIMENT AND RESULTS

An experiment based on the configuration shown in Fig. 1 is carried out. A lightwave at 1552.5 nm from a LD (Agilent N7714A) is sent to a 40-GHz DMZM (Fujitsu FTM7937EZ) via a PC. The half-wave voltage of the DMZM is 1.8 V. The output signal is then sent to a PD with a bandwidth of 40 GHz and a responsivity of 0.65 A/W. The RF and the LO signals are generated by a vector signal generator (Agilent E8267D) and an analog signal generator (Agilent E8257D), respectively. The optical and electrical spectra are measured by an optical spectrum analyzer (YOKOGAWA AQ6370C) and an electrical signal analyzer (Agilent N9030A).

![Fig. 2. Optical spectra and electrical spectra of the signals at the output of the DMZM when (a), (b) $\phi_0=\pi/2$ and (c), (d) $\phi_0=\pi$.](image)

Fig. 2 shows the typical optical and electrical spectra of the signals at the output of the DMZM with different $\phi_0$. The RF signal is set to be 30 GHz and the LO is 25 GHz. The powers of the RF and LO signals are 0 dBm. When $\phi_0 = \pi/2$, as can be seen, several optical sidebands at $\omega_{RF} + n\omega_{LO}$ and $\omega_{RF} + n\omega_{LO}$ (n=0,±1,...) are observed. However, according to the analysis in (3), the RF signal cannot be shifted to the IF band, so no IF signal is presented in Fig. 2(b). By setting the bias voltage to let $\phi_0=\pi$, the frequency downconversion is realized. As can be seen in Fig. 2(c), the optical carrier is suppressed by more than 20 dB. Correspondingly, a strong IF signal is generated with the unwanted RF and LO signals suppressed, as shown in Fig. 2(d). The zoom-in view of the IF signal at a span of 10 kHz is also shown as an inset in Fig. 2(d), showing the high-quality of the downconverted signal.

![Fig. 3. Electrical power of the IF signal as a function of (a) the RF power, (b) the LO power.](image)

In order to investigate the conversion efficiency of the proposed frequency downconverter, we have measured the power of the obtained IF signal as a function of the power of the LO and RF signals. The measured results are shown in Fig. 3. As can be seen in Fig. 3(a), at a given LO power, the power of the IF signal is linearly proportional to the power of the RF signal when the RF power is less than -6 dBm. The slope (which can be defined as the conversion efficiency) is about -10 dB at a LO power of 10 dBm. For the RF power greater than 0 dBm, significant saturation phenomenon is presented, which is due to the cosine transmission response of the DMZM. Similar curves are observed in Fig. 3(b), which shows a linear
relationship between the powers of the IF and LO signals when the LO power is below -6 dBm. When the LO power is greater than 0 dBm, again, significant saturation effect presented. It should be noted that since the optical carrier, which is usually the dominated optical component in a double sideband signal, is suppressed in the proposed downconverter, the power handling capability of the PD is significantly increased, which can be used to improve the conversion efficiency.\cite{4, 8}.

Fig. 4. (a) Electrical spectrum and (b) constellation diagram of the 2.4-GHz downconverted IF signal.

\[ 	ext{Power (dBm)} \]
\[ \begin{array}{cccc}
2.30 & 2.35 & 2.40 & 2.45 \\
-30 & -20 & -10 & 0 \\
\end{array} \]

\[ \begin{array}{cccc}
0.5 & 1.0 & 1.5 & 2.0 \\
0 & 0.5 & 1.0 & 1.5 \\
\end{array} \]

\[ \begin{array}{cccc}
\text{In phase} & \text{Quadrature} \\
1.0 & 0.5 & 0.0 & -0.5 \\
1.0 & 0.5 & 0.0 & -0.5 \\
\end{array} \]

\[ \begin{array}{cccc}
50 \text{Mbaud} & 20 \text{Mbaud} & 10 \text{Mbaud} \\
8.29\% & 7.08\% & 1.03\% \\
\end{array} \]

\[ \begin{array}{cccc}
0 & 4 & 8 & 12 \\
0 & 4 & 8 & 12 \\
\end{array} \]

\[ \begin{array}{cccc}
0 & 8 & 16 & 24 \\
0 & 8 & 16 & 24 \\
\end{array} \]

\[ \begin{array}{cccc}
\text{EVM\%} \\
8.29\% & 7.08\% & 1.03\% \\
\end{array} \]

\[ \begin{array}{cccc}
\text{RF power} \\
1.0 \text{Mbaud} & 2.0 \text{Mbaud} & 3.0 \text{Mbaud} \\
1.0 & 2.0 & 3.0 \\
\end{array} \]

\[ \begin{array}{cccc}
\text{LO Power (dBm)} \\
-1.0 & -0.5 & 0.0 & 0.5 \\
-1.0 & -0.5 & 0.0 & 0.5 \\
\end{array} \]

Fig. 5. Error vector magnitude of the downconverted IF signal as a function of (a) the RF power and (b) the LO power at the symbol rates of 10 Mbaud, 20 Mbaud and 50 Mbaud.

To further study the performance of the proposed frequency downconverter, a 30-GHz signal modulated by a 50-Mbaud 16 QAM baseband data with a power of 0 dBm is used as the RF input. The frequency and power of the LO signal is 27.6 GHz and 10 dBm, respectively. Fig. 4 shows the electrical spectrum and constellation diagram of the 2.4 GHz downconverted IF signal. The EVM of the IF signal evaluated by 1000 symbols is 1.06 % and the signal to noise ratio (SNR) is 36.95 dB, indicating a high conversion performance. Fig. 5 shows the EVM of the downconverted IF signal as a function of the LO power and the RF power. As can be seen in Fig 5 (a), the EVM decreases as the RF power increases when the RF power is below 0 dBm. When the RF power continues to grow, the EVM performance become worse because of the cosine transmission response of the DMZM. The best EVM is achieved when the RF power is 0 dBm, which are smaller than at all symbol rates. Fig. 5 (b) shows the EVM curves when the RF power is fixed at 0 dBm and the LO power varies from -25 to 10 dBm. The EVM decreases as the LO power increases. When the LO power is larger than 0 dBm, the EVM is smaller than 2.0 %.

IV. CONCLUSION

We have proposed and demonstrated a simple photonic frequency downconverter based on a single DMZM. The LO and the RF signals are sent to the two RF ports of the DMZM. By properly setting the bias voltage applied to the DMZM, the frequency downconversion is realized, which features high conversion performance, simple configuration and robust operation. The proposed downconverter was experimentally demonstrated. A 30-GHz RF signal with 50-Mbaud 16 QAM was successfully downconverted to a 2.4-GHz IF signal with an EVM of less than 2.0 %.

REFERENCES


