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All-optical image-reject frequency down-conversion based on cascaded electro-optical modulators

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ABSTRACT

An all-optical image-reject frequency down-converter based on cascaded modulators and a wavelength demultiplexer is presented. The radio-frequency (RF) and the local-oscillator (LO) signal are fed to a phase modulator and a dual-parallel Mach–Zehnder modulator, respectively. Using a wavelength demultiplexer, two down-conversion channels can be obtained. Quadrature phase difference between the two down-converted signals is achieved by properly setting the modulator bias. Image rejection can thus be realized based on Hartley architecture. Experimental results show that image rejection ratios of 32.5 dB in a 10-MHz instantaneous bandwidth and over 50 dB for a single frequency can be obtained. The scheme can be applied to antenna remoting applications, and a 25-km fiber transmission is demonstrated.

1. Introduction

The microwave frequency down-converter, which mixes the radio-frequency (RF) signal with a local oscillator (LO) to produce an intermediate-frequency (IF) signal, is a critical component for various RF applications. Featuring large bandwidth, low transmission loss, and anti-electromagnetic interference over the conventional electrical solution [1], photonics-based microwave frequency down-conversion has gained great attention [2–5].

For an RF heterodyne receiver, due to the presence of image signal, the down-converted IF signals might contain both the desired signal and the unwanted image interference, which might lead to ambiguity in frequency discrimination or even distort the desired IF signal. To mitigate the image interference, a straightforward approach is to filter out the image signal in advance [6,7]. However, an RF filter with wideband operation ability and adequate selectivity is not easy to implement. Another possible way is to cancel the image interference using Hartley architecture, where RF signal is down-converted by quadrature LO signals, and the resulting IF signals, after one of them is phase shifted by 90°, are combined [8]. Based on this architecture, several photonic frequency down-converters with image-rejection function have been reported in recent years [9].

Photonic image-reject down-conversion can be realized using multiple Mach–Zehnder modulators (MZMs) [10] or a polarization-division multiplexing MZM [11], and a 90-degree RF hybrid is required to generate quadrature LO signals. However, it is not easy for an RF hybrid coupler to produce a wideband 90-degree phase shift, which might limit system operational bandwidth. To solve this problem, photonic phase shifting methods [12,13] can be adopted to provide wideband phase tuning. Image-reject down-conversion using two photonic phase-tunable mixers are reported in [14], where quadrature phase difference is introduced by properly setting the modulator bias voltage. However, the RF/LO signals are needed to feed the two mixers through wideband RF couplers, resulting in a complex system configuration. The quadrature phase difference can also be introduced by an optical hybrid coupler [15–17]. Due to the environmental disturbance, undesired phase fluctuations might be introduced between the separated links, which might challenge the system stability. Polarization division multiplexing technique is used in [18,19], where quadrature phase difference is obtained by properly changing the polarizations via a polarization controller (PC). The demerit for these schemes is that the tuning ability of PC is restricted in terms of accuracy and stability. In [20], wavelength division multiplexing technique is used to solve this problem. However, schemes based on parallel modulation [15,17–20] are not suitable for scenarios where the antenna sites are remotely located from the central office. Image-reject frequency down-conversion for antenna remoting applications can be performed using a phase modulator (PM) and a polarization modulator put in tandem [21], while the quadrature phase difference is also introduced by changing polarization.

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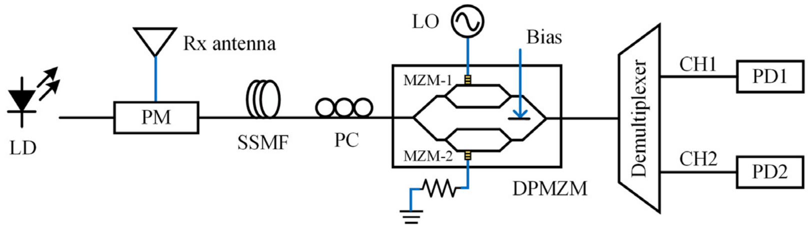

Fig. 1. Schematic of the proposed system. LD: laser diode; PM: phase modulator; SSMF: standard single mode fiber; PC: polarization controller; DPMZM: dual-parallel Mach–Zehnder modulator; PD: photodiode.

In this work, we propose and experimentally demonstrate an all-optical microwave frequency down-converter with image rejection ability based on cascaded electro-optical modulators and wavelength division multiplexer. A PM and a dual-parallel Mach–Zehnder modulator (DPMZM) put in tandem are driven by the RF and the LO signals, respectively. After an optical wavelength de-multiplexer, two down-conversion channels are obtained. When the DP-MZM is properly biased, the quadrature phase difference can be achieved. Finally, image-reject frequency down-conversion is realized by combining the outputs from the two channels via an electrical IF 90-degree hybrid coupler. Thanks to the tandem structure, the proposed down-converter has an infinite isolation between RF/LO ports. When a length of fiber is inserted between the two modulators, the system can be applied to antenna remoting applications. Compared with previous down-converters using cascaded modulators, the proposed scheme supports frequency down-conversion with phase shifting ability, which enables an all-optical image-reject down-converter to be achieved. In another all-optical approach [21], two polarization controllers have to be carefully adjusted, which would challenge the system stability as the polarization states is very sensitive to environmental vibrations. Furthermore, different from [21] in which single-sideband modulation is adopted, both signal sidebands are more efficiently utilized in the proposed system, as two channels are employed instead of a single one.

2. Operation principle

Fig. 1 illustrates the schematic of our proposed photonic down-converter. A laser source provides a continuous-wave light into a PM. When the modulator is driven by an RF signal with an angular frequency of ω_r, the output optical signal can be expressed as

$$E_{PM}(t) = \sqrt{P_{in}} \exp\left[j\omega_c t + j m_r \sin(\omega_r t)\right] \tag{1}$$

where P_{in} and ω_c are the power and angular frequency of the laser source, respectively. $m_r = \pi V_{RF}/V_{\pi 1}$ is the modulation index produced by the RF signal, V_{RF} is the amplitude of the driving signal and $V_{\pi 1}$ is the half-wave voltage of the PM. It should be noted that, for the sake of simplicity, the insertion loss of the optical components is ignored in theoretical analysis. Under the condition of small RF signal modulation, Eq. (1) can be approximately rewritten as

$$E_{PM}(t) \approx \sqrt{P_{in}} e^{j\omega_c t} \begin{bmatrix} J_0(m_r) + J_1(m_r)\exp(j\omega_r t) \\ -J_1(m_r)\exp(-j\omega_r t) \end{bmatrix} \tag{2}$$

The phase-modulated optical signal is sent to a DPMZM through a PC. In the DPMZM, MZM-1 is driven by an LO signal with an angular frequency of ω_l and operates at null point, while MZM-2 is unloaded and biased at maximum point. The twice-modulated optical signal is then given by

$$E_{DPMZM}(t) \approx \frac{E_{PM}(t)}{2} \begin{bmatrix} J_1(m_l)\exp(j\omega_l t + j\varphi_{DC}/2) \\ -J_1(m_l)\exp(-j\omega_l t + j\varphi_{DC}/2) \\ +\exp(-j\varphi_{DC}/2) \end{bmatrix} \tag{3}$$

where $m_l = \pi V_{LO}/2V_{\pi 2}$ is the modulation index related to the LO signal, $V_{\pi 2}$ is the modulator half-wave voltage, and V_{LO} is the amplitude of the LO signal. φ_{DC} is the optical phase shift induced by the main bias. By substituting (2) into (3), we have

$$E_{DPMZM}(t) \approx \frac{\sqrt{P_{in}}}{2} e^{j\omega_c t} \times \begin{cases} J_0(m_r)\exp(-j\varphi_{DC}/2) \\ -J_1(m_r)J_1(m_l)\exp\left[\pm j(\omega_r - \omega_l)t + j\varphi_{DC}/2\right] \\ J_1(m_r)J_1(m_l)\exp\left[\pm j(\omega_r + \omega_l)t + j\varphi_{DC}/2\right] \\ \pm J_0(m_r)J_1(m_l)\exp(\pm j\omega_l t + j\varphi_{DC}/2) \\ \pm J_1(m_r)\exp(\pm j\omega_r t - j\varphi_{DC}/2) \end{cases} \tag{4}$$

An optical wavelength demultiplexer is then utilized to suppress the optical carrier and separate the upper and lower sidebands. By neglecting the higher-order terms, the resulting optical signal at the outputs of the two channels can be expressed by

$$E_{CH1,2}(t) = \pm \frac{\sqrt{P_{in}}}{4} e^{j\omega_c t} \begin{bmatrix} J_0(m_r)J_1(m_l)\exp(\pm j\omega_l t + j\varphi_{DC}/2) \\ +J_1(m_r)\exp(\pm j\omega_r t - j\varphi_{DC}/2) \end{bmatrix} \tag{5}$$

The two optical signals are then sent to two PDs for photodetection, producing

$$I_{1,2}(t) \propto \Re P_{in} m_l m_r \cos\left[(\omega_l - \omega_r)t \pm \varphi_{DC}\right] \tag{6}$$

where $\Re$ is the responsivity of the PD. As can be seen from (5), the phase difference between the two IF signals (i.e. $2\varphi_{DC}$) can be tuned by simply adjusting the main bias of the DPMZM.

When the quadrature phase difference is realized by setting the φ_{DC} to $\pi/4$, this two-channel mixer becomes an IQ microwave down-converter [20]. According to Hartley architecture, image rejection can be realized by introducing a 90-degree phase shift for the quadrature IF signals and adding them together. This operation can be performed using an electrical 90-degree hybrid coupler or an ADC followed by a digital signal processing (DSP) module [21].

For antenna remoting application, a length of standard single-mode fiber (SSMF) can be adopted between the two modulators. When a phase-modulated optical signal is sent to the SSMF, fiber chromatic dispersion should also be considered. Eq. (2) can thus be modified as

$$E_{PM}(t) \approx \sqrt{P_{in}} e^{j\omega_c t} \begin{bmatrix} J_0(m_r) + J_1(m_r)\exp(j\omega_r t + j\theta_{+1}) \\ -J_1(m_r)\exp(-j\omega_r t + j\theta_{-1}) \end{bmatrix} \tag{7}$$

where $\theta_{\pm 1} = \pm z\beta_1\omega_r + z\beta_2\omega_r^2/2$ is the fiber-induced phase shift relative to the optical carrier [22]. β_1 denotes the first-order derivative of the propagation constant. β_2 and z are the dispersion coefficient and the length of the fiber, respectively. We can then derive the corresponding photocurrent of fiber transmission

$$I_{1,2}(t) \propto m_l m_r \cos\left[(\omega_l - \omega_r)t - z\beta\omega_r \pm (\varphi_{DC} - z\beta_2\omega_r^2/2)\right] \tag{8}$$

According to (7), φ_{DC} should be modified to maintain the quadrature phase difference and we have

$$\varphi_{DC} = \pi/4 + z\beta_2\omega_r^2/2 \tag{9}$$

Obviously, by properly setting the main bias of the DPMZM, the proposed image-rejection down-converter can be applied to antenna remoting applications.