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Influence of the modulation index of Mach–Zehnder modulator on RoF link with ASK millimeter-wave signal

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ABSTRACT

In this paper, the influence of the modulation index of $LiNbO_3$ Mach–Zehnder modulator on the radio over fiber (RoF) link based on single sideband (SSB) optical millimeter (mm)-wave with ASK signal is theoretically and numerically investigated. Our investigation shows that there exists an optimal modulation index to generate the SSB optical mm-wave with a maximal RF photocurrent. Although the fiber dispersion distorts the code form and degrades the performance of the RF signal demodulated from the SSB optical mm-wave after fiber transmission, it does not cause the closure of the eye diagram. However, the influence of the fiber dispersion becomes more obvious as the modulation index increases. For the duplex RoF link with the optical carrier of the uplink recovered from the downlink, a larger modulation index of the downlink causes a worse crosstalk from the downlink to the uplink.

1. Introduction

The demand of the wideband radio access services makes the use of the millimeter band radio necessary for the future wireless telecommunication [1,2]. The 40–70 GHz millimeter (mm)-wave becomes the first choice and is preferred to be transmitted by the optical fiber than by air or metal wave guides because of the high loss in air and the expensive value of the metal guide before it is distributed to the user by the antenna via the air. To transmit the mm-wave signal in the fiber, it must be modulated onto the lightwave first, which is called the optical mm-wave signal. So, the optical modulation of the mm-wave signal onto lightwave is an essential technique in the radio-over-fiber (RoF) system. Usually, the Mach–Zehnder modulator (MZM) and electro-absorption modulator (EAM) are used to implement this. However, different prototypes of MZM can generate the optical mm-wave with different spectra, such as double sideband (DSB), optical carrier suppression (OCS), and single sideband (SSB), while each of them has different immunity capacity for the fiber dispersion [3–6]. The DSB optical mm-wave suffers not only from the fading effect but also from the time shift of the code caused by the sidebands' walk-off [3]. Although the OCS optical mm-wave and the SSB optical mm-wave with the signal carried by both the optical carrier and its sideband is immune to fading, time shift of the code limits its transmission [4–6]. The SSB optical mm-wave with the signals carried only by optical sideband can overcome both the fading effect and the time shift of the code [7]. This kind of SSB optical mm-wave can be generated by $LiNbO_3$ MZM with the dc bias at its half-wave voltage and driven by two mm-waves with a $\pi/2$ phase shift at a small RF modulation voltage. But the amplitudes of the optical carrier and its sideband have great difference, which requires a large input optical power to generate the mm-wave with a given power. Although the increase of the RF modulation index can reduce the difference of the optical carrier and its sideband, the increase of modulation index leads to the optical carrier being modulated by the signal and causes the dips on optical carrier to become deep. This degrades the transmission performance of the SSB optical mm-wave notably. In addition, for the duplex link with the uplink optical carrier recovered from the downlink [8,9], the deep modulation of MZM can increase the amplitude of the sideband which improves the downlink performance of the optical mm-wave [7], but the deep modulation also print the signals onto the optical carrier, which not only influences the downlink performance but also causes the crosstalk from the downlink to the uplink. Moreover, the unwanted higher-order sidebands are also amplified although it can be suppressed by filtering. Since the amplitude shift keying (ASK) is the fundamental signal modulation format and is the simplest one, our work on the optical mm-wave with ASK signal gains some insight into the optical mm-wave with other signal modulation formats.

In this paper, we have investigated the influence of the modulation index of MZM on the downlink and the uplink.

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Firstly, using the mathematical model of MZM with SSB-modulation scheme, we find that a deeper modulation of MZM will print the signal onto the optical carrier, and that there exists an optimal modulation index to generate the optical mm-wave with the maximal amplitude in Section 2. Then, we disclose the influence of the modulation index of the downlink on the mm-wave down-converted by the photo-detector from the optical mm-wave after transmission along the fiber in Section 3, which is verified by our simulation. Based on this, a duplex RoF link with the uplink optical carrier recovered from the downlink is setup to check the influence of the RF modulation index of the downlink on the uplink performance in Section 4 with the aid of the numerical simulation. Finally, a conclusion is given in Section 5.

2. Generation of the optical mm-wave

The diagram showing the principle of the SSB optical mm-wave link is given in Fig. 1. The laser diode (LD) is the narrow bandwidth lightwave source with the angular frequency at ω_c. The data signal $I(t)=\Sigma_n I_n g(t-nT)$ is first modulated onto the mm-wave local oscillator (LO) $V_{LO}(t)=V_m \cos\omega_m t$ with the angular frequency of ω_m, where I_n is the digital signal sequence and $I_n \in \{0,1\}$ in this paper; $g(t)$ is the code form function, and T is the code duration. The signal carried by the mm-wave can be expressed as

$$\begin{aligned} V(t) &= V_m \sum_n I_n g(t-nT)\cos\omega_m t \\ &= V_D(t)\cos\omega_m t \end{aligned} \quad (1)$$

Then the mm-wave signal is split into two equal parts with the phase shift of 90°, and drives the dual-electrode MZM (DE-MZM). The MZM has the half-wave voltage of V_π and is biased at quadrature to obtain the single sideband modulation.

If the modulation index of MZM is defined as $m_h=\pi V_m/V_\pi$, and the attenuation of MZM is α, the optical mm-wave output from the DE-MZM with the optical split ratio of 1/2 can be expressed as

$$\begin{aligned} E(0,t) &= \frac{\alpha}{2}A_0\,e^{j\omega_c t}[\exp j(m_h(t)\cos\omega_m t)+j\exp j(m_h(t)\sin\omega_m t)] \\ &= \frac{\alpha}{2}A_0 \sum_{k=-\infty}^{\infty} J_k(m_h(t))[j^k+j]\,e^{j(\omega_c+k\omega_m)t} \end{aligned} \quad (2)$$

Here $m_h(t)=\pi V_D(t)/V_\pi$, $a_k=\alpha|J_k(m_h(t))(j^k+j)|/2$, $\varphi_k=\arg[J_k(m_h(t))(j^k+j)]$. $J_k(\cdot)$ is the kth-order Bessel function of the first kind. It can be seen that the $(4k-1)$th-order sidebands are suppressed, while the $(4k+1)$th- sidebands are doubled in amplitude. The signal is carried by the optical carrier and all of its sidebands via the modulation index $m_h(t)$. The lightwave field amplitudes of the kth-order sidebands are proportional to the kth Bessel function. Usually, the radio voltage V_m is smaller than V_π, so the sidebands' amplitude increases while the optical carrier decreases with the increase of the modulation index m_h, as shown in Fig. 2. At a given

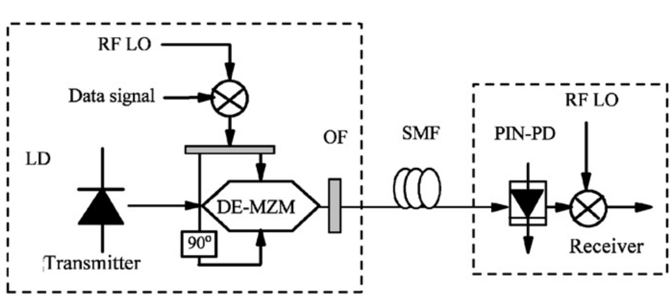

Fig. 1. The principle diagram of the SSB optical mm-wave links. LO: local oscillator; LD: laser diode; DE-MZM: dual-electrode MZM; 90°: a phase shifter with 90°; OF: optical filter; SMF: single-mode fiber; PIN-PD: p-i-n photo-detector.

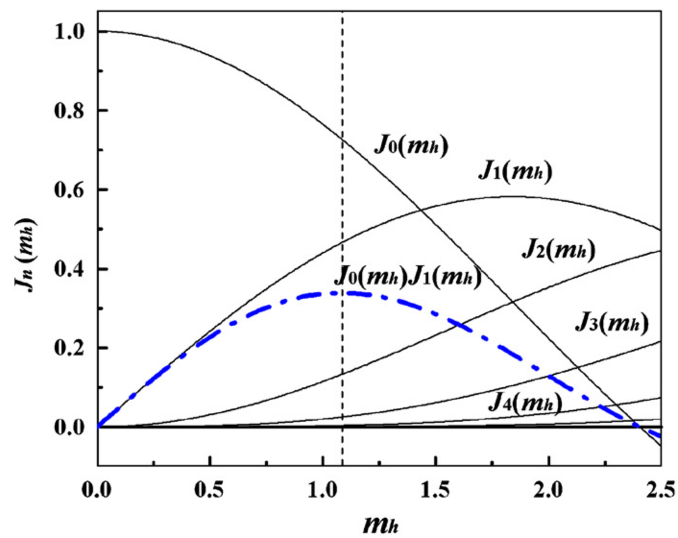

Fig. 2. The 0–5th order Bessel functions of the first kind, which determine the amplitudes of the optical carrier and its sidebands. Here horizontal axis denotes the modulation index m_h. The second- and higher-order Bessel functions are smaller than the first-order one as $m_h<2$. $J_0(m_h)$ decreases and $J_1(m_h)$–$J_5(m_h)$ increase with the increase of the modulation index m_h.

m_h, the amplitude of the sidebands decreases with the increase of its orders. Because the higher-order sidebands not only make the spectrum complicated, but also influence the transmission of the optical mm-wave, an optical filter is used to suppress the second and higher sidebands. Thus, the SSB optical mm-wave can be expressed approximately as

$$E(0,t)\approx \alpha A_0\left\{\frac{\sqrt{2}}{2}J_0(m_h(t))\,e^{j(\omega_c t+\pi/4)}+J_1(m_h(t))\,e^{j[(\omega_c+\omega_m)t+\pi/2]}\right\} \quad (3)$$

Eq. (3) shows that both the optical carrier and its first-order sidebands carry the signals, but they have different relationships. The first sideband represents the code "0" and "1" by the amplitude 0 and $J_1(m_h)\approx m_h$, respectively. With the increase of the modulation index, the amplitude of the pulse representing code "1" increases, as seen from simulation results by the time serials in left column of Fig. 3. For the optical carrier, the code "0" and "1" are represented by the amplitude 1 and $J_0(m_h)$, respectively, namely, the code "1" is denoted by the dip on the high level, which is greatly different from the SSB optical mm-wave signal that we have reported in [4]. If the modulation index is low, $J_0(m_h)\approx 1$, the dip is much low, namely, the amplitudes of the pulse representing the code "0" and "1" have little difference, as shown in Fig. 3(I), where we can assume that the optical carrier does not carry the signal. However, $J_0(m_h)$ decreases as the modulation index m_h increases, which induces a deeper dip for each code "1", as can be seen from the time serials in the right column of Fig. 3. This dip degrades the signal performance of the RoF link.

To validate our analysis, a RoF link is setup by the simulation software OptiSystem. In the simulation link, a narrow bandwidth continuous wave (CW) from LD with the wavelength of 1552.524 nm is modulated via a dual-electrode $LiNbO_3$ MZM (DE-LN-MZM) with a dc bias voltage of $0.5V_\pi$ and driven by two RF sinusoidal waves with a $\pi/2$ phase shift, here $V_\pi=4$ V. The 40-GHz RF sinusoidal wave is first amplitude-modulated by 2-Gbit/s pseudo-random bit serial (PRBS) NRZ signal with a word length of 2^7-1 before it drives MZM. An optical filter with the center frequency at 1552.364 nm and a 3-dB bandwidth of 50 GHz follows to suppress the higher-order sidebands. The optical carrier