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The transmission performance degradation of the optical millimeter-wave signals by fiber chromatic dispersion

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ABSTRACT

The influence of the fiber chromatic dispersion on double sideband (DSB), optical carrier suppression (OCS), and single sideband (SSB) optical mm-wave signals is investigated based on the Taylor expansion of the propagation constant and is verified by simulation. According to our theoretical results, the fading effect suppresses the signal power of the DSB optical mm-wave periodically in a cosine-like pattern, and it can be described by the zero-order Taylor expansion of the propagation constant. For the optical mm-wave with the signal modulated on two or more tones, the bit pulses of the mm-wave signal are distorted by the dispersion-inducing bit walk-off effect between tones, which is expressed by the first-order Taylor expansion of the propagation constant. Moreover, as the signal rate and the transmission distance are increased further, higher-order Taylor expansion of the propagation constant still degrades the optical mm-wave signal even if both the fading effect and the bit walk-off effect are eliminated completely. The distortion of the signal pulses of SSB optical mm-wave is derived based on the second-order Taylor expansion of the propagation constant. This degradation is verified by the simulation with the eye diagram evolution of the SSB optical mm-wave signal.

1. Introduction

The explosive growth of global wireless access services recently places a heavy burden on the already congested wireless spectrum of the microwave region. It forces us to exploit the large unused bandwidths of sub-millimeter (mm) or mm-wave frequency regions for the future super broadband wireless services [1]. The mm-wave at 40–60 GHz band is becoming the effective radio carrier for multi-gigabit/s wireless communications. However, due to the limited frequency response of electronic components and the large transmission loss in the air, cost-effective generation and long-haul transmission of the mm-wave signal are of utmost importance in the high speed wireless communication system.

Radio over fiber (RoF) technology with the microwave signal generation by photonics technique and transmission over fiber has been extensively investigated [2–4]. Many methods to generate the optical mm-wave signal have been reported, such as direct intensity modulation, external modulation, and remote optical heterodyning [5–9]. Among them, the external modulation with $LiNbO_3$ Mach–Zehnder modulator (LN-MZM) is regarded as an optimal option because of its large bandwidth, small power consumption, and high saturation optical power [4]. In addition, the bandwidth requirement of the external modulator and electrical amplifier in RoF link can be reduced largely if some enabling techniques are employed [7,8]. When the electrical mm-wave signal is modulated on the lightwave, two or more optical tones with the frequency spacing equal to or multiple of the electrical mm-wave frequency are generated [6–8], which is called optical mm-wave signals. After transmission in optical domain, the electrical mm-wave signal is recovered by beating these tones of the optical mm-wave via a square-law photodiode (PD). Optical fiber is a good medium for long haul transmission of the optical mm-wave signal because of its very low propagation loss, almost unlimited bandwidth and the light weight as well as its immunity to electromagnetic interference. However, the fiber chromatic dispersion degrades the optical mm-wave signal greatly in such manners as fading effect, and/or bit walk-off effect because it naturally consists of more than one tone. In [10], fading effect and bit walk-off effect of the optical mm-wave signal are analyzed according to an empirical format, but only the first-order dispersion is considered, so the conclusion is not very accurate.

In this work, the degradation of the optical mm-wave signal by the fiber chromatic dispersion is systemically analyzed as it is transmitted along the dispersive fiber based on the general fiber transmission model. According to the Taylor expansion of the lightwave propagation constant, the fading effect and the bit walk-off effect as well as the further performance degradation of the optical mm-wave signal are originated. The fading effect, suffered from the optical mm-wave signal with three or more tones, can be described with the zero-order Taylor expansion of the propagation constant. It is the main disadvantage of the typical double sideband (DSB) optical mm-wave signal, and can be eliminated by filtering the excess tones and reserving only two, such as single sideband (SSB) and optical carrier suppression (OCS) optical mm-wave signals. However, as the signal is modulated on two or more tones of the optical mm-wave, the signal pulses carried by different tones go forward at different velocities, as is called the bit walk-off effect. The transmission

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distance of the dual-tone optical mm-wave signal is limited by the bit walk-off effect, and this maximum transmission distance is formulized with the first-order Taylor expansion of the propagation constant. The bit walk-off effect can be overcome as the signal is modulated on one tone of the optical mm-wave. In fact, the dual-tone optical mm-wave with the signal modulated only on one tone can eliminate both fading effect and bit walk-off effect. However, when the transmission distance is beyond 100 km and the baud rate are increased to multi-gigabyte/s, this SSB optical mm-wave signal is also worsened by the second-order Taylor expansion of the propagation constant. In our research, the pulse outline distort of the SSB optical mm-wave signal is analyzed based on the second-order Taylor expansion of the propagation constant.

In this paper, the optical mm-wave signal generation via LN-MZM is theoretically analyzed in a general form in Section 2. In Section 3, the RoF link with the optical mm-wave signal transmission along the dispersive fiber is modeled analytically, and the influence of the fiber dispersion on the optical mm-wave signal is systemically analyzed based on the zero-, first-, and second-order Taylor expansion of the propagation constant. The theoretical results are verified by simulation. In Section 4, the influences of the fiber dispersion between the two tones and within one tone are discussed. At last, a conclusion is drawn in Section 5.

2. Generation of the optical mm-wave signal via a $LiNbO_3$ external modulator

Fig. 1 shows the principle scheme of the RoF link. The optical mm-wave signal generated by the transmitter is distributed over the optical fiber to the receiver far away, and then is down converted to the electrical mm-wave signal by a PD for being radiated to the terminals wirelessly. At the transmitter, the lightwave emitted from the laser diode (LD) can be expressed as $E(t)=E_0e^{j\omega_c t}$, and is injected into LN-MZM. The electrical mm-wave signal, $V(t)=\mathrm{Re}\{A(t)e^{j[\omega_m t+\theta(t)]}\}=A(t)[\cos\theta(t)\cos\omega_m t-\sin\theta(t)\sin\omega_m t]=I(t)\cos\omega_m t+Q(t)\sin\omega_m t$ carrying the vector signal of $S(t)=A(t)e^{j\theta(t)}$ with electrical carrier frequency at $f_m=\omega_m/2\pi$, drives the dual-electrode MZM with a phase shift of φ. After optical modulation, the output optical mm-wave signal becomes

$$E(t)=\frac{1}{2}\alpha E_0 e^{j\omega_c t}\left\{e^{j\frac{\pi}{V_\pi}[V_{DC1}+A(t)\cos(\omega_m t+\theta(t))]}+e^{j\frac{\pi}{V_\pi}[V_{DC2}+A(t)\cos(\omega_m t+\theta(t)+\varphi)]}\right\} \quad (1)$$

Here, assume that $\pi A(t)/V_\pi=m(t)$ and the direct current bias voltage $V_{DC1}-V_{DC2}=V_b$ for simplification and consider Bessel expansion of the complex exponent function, there is

$$\begin{aligned} E(t) &= \frac{1}{2}\alpha E_0 e^{j\pi\frac{V_{DC2}}{V_\pi}}e^{j\omega_c t}\left[e^{j\pi\frac{V_b}{V_\pi}}e^{jm(t)\cos(\omega_m t+\theta(t))}+e^{jm(t)\cos(\omega_m t+\theta(t)+\varphi)}\right] \\ &= \frac{1}{2}\alpha E_0 e^{j\pi\frac{V_{DC2}}{V_\pi}}\sum_{n=-\infty}^{\infty}j^n\left[\gamma e^{j\pi\frac{V_b}{V_\pi}}+(1-\gamma)e^{jn\varphi}\right]\cdot\left[J_n(m(t))e^{jn\theta(t)}\right]e^{j(\omega_c+n\omega_m)t} \\ &= \sum_{n=-\infty}^{\infty}A_n(t)e^{j(\omega_c+n\omega_m)t} \end{aligned} \quad (2)$$

where

$$A_n(t)=\frac{1}{2}\alpha E_0 e^{j\pi\frac{V_{DC2}}{V_\pi}}j^n\left(e^{j\pi V_b/V_\pi}+e^{jn\varphi}\right)\cdot\left[J_n(m(t))e^{jn\theta(t)}\right] \quad (3)$$

From Eqs. (2) and (3), we can see that the RF modulation produces many sidebands aside the optical carrier at ω_c with the frequency spacing of ω_m because of the nonlinearity of MZM, as shown by the simulated spectrum in Fig. 2(i). The amplitudes of the sidebands depend on the dc bias voltage V_b of MZM, RF voltage and the phase shift φ between the two arms as well as the Bessel function according to Eq. (3). On the basis of the characteristic of Bessel function, the sideband amplitudes decrease with the increase of their orders, and it is reasonable to consider optical carrier and some lower sidebands if the modulation depth is small enough. Eq. (3) shows that the amplitude and phase of the vector signal are modulated on each sideband. Although the amplitude of the signal varies because of the nonlinearity of MZM, and the phase signal is multiplexed for the nth-order sidebands, it can be demodulated with a proper design.

According to the factor $(e^{j\pi V_b/V_\pi}+e^{jn\varphi})$ in Eq. (3), we can suppress some sidebands and enhance the others by properly adjusting the MZM's parameters V_b, φ. When $\varphi=\pi/2$ and $V_b=V_\pi/2$, there is $A_n(t)=\frac{\alpha}{2}E_0e^{j\pi V_{DC2}/V_\pi}\left[j^{n+1}+(-1)^n\right]\cdot\left[J_n(m(t))e^{jn\theta(t)}\right]$, and the $(4n-1)th$-order sidebands are suppressed, as shown in Fig. 2(ii), which corresponds to the single sideband (SSB) modulation as the second and other higher-order sidebands are small enough to be neglected. When $\varphi=\pi$ and $V_b=V_\pi$, there is $A_n(t)=-\frac{\alpha}{2}E_0e^{j\pi V_{DC2}/V_\pi}j^n\left[1-(-1)^n\right]\cdot\left[J_n(m(t))e^{jn\theta(t)}\right]$, and the optical carrier and even-order sidebands are suppressed, as shown in Fig. 2(iii), which corresponds to the OCS modulation. When $\varphi=\pi$ and $V_b=0$, there is $A_n(t)=\frac{\alpha}{2}E_0e^{j\pi V_{DC2}/V_\pi}j^n\left[1+(-1)^n\right]\cdot\left[J_n(m(t))e^{jn\theta(t)}\right]$, the odd-order sidebands are suppressed, as shown in Fig. 2(iv). Based on the above, Eq. (2) can stand for different forms of the optical mm-wave signal generated by a single MZM. If the two or more MZMs are integrated together with parallel or serial configuration by proper design, the optical mm-wave signal with various spectra can be realized. Here some sidebands of the optical mm-wave signal have zero or constant amplitude and phase, but at least, one of them is required to carry the required signal $A_n(t)$ with IM, ASK, PSK or QAM modulation.

Fig. 2 The optical spectra of the generated optical mm-wave with different conditions: (1) $V_b=2$ V, $V_{RF}=2$ V, $\varphi=0°$; (2) $V_b=2$ V, $V_{RF}=2$ V, $\varphi=90°$; (3) $V_b=4$ V, $V_{RF}=2$ V, $\varphi=180°$; and (4) $V_b=0$, $V_{RF}=2$ V, $\varphi=180°$.

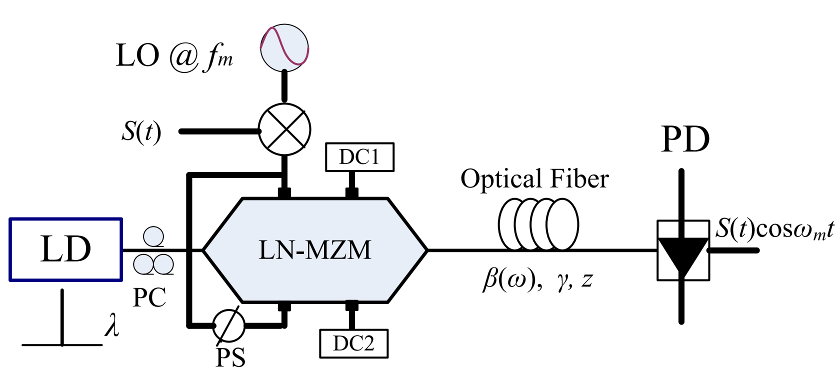

Fig. 1. The principle scheme of the RoF link.