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A novel optical millimeter-wave signal generation approach to overcome chromatic dispersion

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ABSTRACT

In this paper, a novel frequency octupling approach for optical millimeter-wave signal generation to overcome chromatic dispersion is proposed and demonstrated. The frequency octupling mm-wave with the baseband signal carried only by -4th order sideband is generated by properly adjusting a series of parameters, which are the modulation constant, the gain of baseband signal, the direct current bias and the different phase of the modulation arms. As the optical millimeter-wave signal is transmitted along the fiber, there is no time shift caused by chromatic dispersion. Theoretical analyses and simulated results show that when the optical mm-wave carrying 2.5 Gbps baseband signal transmits a distance of over 110 km, the eye diagram still keeps open and clear. The power penalty is about 0.4 dB after the optical signal transmits over 40 km. In additions, given the $+4$th order sideband carries no data, a full-duplex RoF link based on wavelength reuse is built for the uplink. The bidirectional 2.5 Gbps baseband signal could successfully transmit over 40 km with about 0.8 dB power penalty in the simulation. Both theoretical analyses and simulation results show that the full-duplex RoF link has good performance.

1. Introduction

Radio-over-fiber (RoF) has been considered a promising technique to wireless access networks for it could increase the capacity, mobility and bandwidth of the network [1]. In a RoF link, a high frequency 40–60 GHz millimeter-wave (mm-wave) can be generated directly in the optical domain. However, due to the limitation of the frequency response of optical modulator, the generation of high frequency mm-wave remains a huge challenge in various optical fiber-supported systems, and the transmission distance and capacity are severely limited by chromatic dispersion in fiber.

Recently, some technologies for optical mm-wave generation which could overcome the problem of chromatic dispersion have been reported [1–9]. In Ref. [1], a new approach to generate optical carrier suppression mm-wave signal is proposed. However, the frequency of the optical mm-wave is only two times faster than that of the local oscillator (LO) signal. In order to generate high frequency mm-wave signal, expensive electrical equipment which could increase the cost of the RoF link is still needed. In Ref. [2], a new approach to generate quadrupling-frequency optical mm-wave is proposed. However, in order to suppress the optical carrier, the microwave signal power has to be selected carefully. This approach will complicate the frequency tuning of the approach for the half-wave voltage of Mach–Zehnder modulator is frequency dependent. When the microwave frequency changes, it must be calculated carefully to obtain the accurate value.

In this paper, a novel frequency octupling approach for optical millimeter-wave signal generation to overcome chromatic dispersion is proposed. The novel approach is based on a Dual-Parallel Mach–Zehnder modulator (DPMZM) and a wavelength-fixed optical notch filter. The DPMZM contains two major inter-modulators, namely MZM_a and MZM_b which are used to modulate the LO signal. And a wavelength-fixed optical notch filter is followed to remove the optical carrier. The frequency octupling mm-wave with the baseband signal carried only by -4th order sideband is generated by properly adjusting a series of parameters which are the modulation constant, the gain of baseband signal, the direct current bias and the phase difference of the modulation arms. By beating the two 4th order sidebands at the photodetector (PD), the electrical mm-wave signal at eight times of the frequency of the electrical LO signal is generated. As the optical mm-wave signal is transmitted along the fiber, there is no time shift of the codes caused by chromatic dispersion. In addition, because the $+4$th order sideband is not modulated by the baseband signal, it can be reused to carry upstream data for the full-duplex RoF link. In this way, it can utilize optical power more effectively and reduce the operation cost of the system.

2. Theoretical analysis

The block diagram of the novel RoF link is shown in Fig. 1. A light wave emitted from a tunable laser diode (LD) source can be

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expressed as $E_c(t)=E_c(j\omega_c t)$, where E_c is the light wave amplitude, and ω_c is the angular frequency. The baseband signal $s(t)$ is modulated onto LO signal of $V_{\mathrm{LO}}\cos(\omega_{\mathrm{LO}}t)$ by a phase modulator. V_{LO} and ω_{LO} are the amplitude voltage and the angular frequency of LO, and the modulation constant is $\pi/8$. Then the baseband signal $s(t)$ is boosted by an electrical amplifier (EA), and the exported signal can be expressed as $6s(t)$, which is summed with the modulated LO signal to drive the DPMZM. In DPMZM, MZM_a and MZM_b with a $\pi/2$ phase difference. In both of MZM_a and MZM_b, the phase difference of LO signals introduced in two modulation arms is π, and the bias voltages of the two arms are adjusted at the maximum transmission point. The MZM_c bias voltage is set to let the signals transmit from the two modulators in phase. A wavelength-fixed optical notch filter is incorporated to remove the optical carrier, and a wideband PD is followed to perform the optical-to-electrical conversion.

The baseband signal carried by LO signal can be expressed as

$$V_{\mathrm{LO}}(t)=V_{\mathrm{LO}}\cos\left[\omega_{\mathrm{LO}}t+\frac{\pi}{8}s(t)\right] \tag{1}$$

The signals that drive both two arms in MZM_a and MZM_b can be expressed as

$$\begin{aligned}
V_a(t)&=V_{\mathrm{LO}}\cos\left[\omega_{\mathrm{LO}}t+\frac{\pi}{8}s(t)\right]+6s(t)\\
V_b(t)&=V_{\mathrm{LO}}\cos\left[\omega_{\mathrm{LO}}t+\frac{\pi}{8}s(t)-\pi\right]+6s(t)\\
V_c(t)&=V_{\mathrm{LO}}\cos\left[\omega_{\mathrm{LO}}t+\frac{\pi}{8}s(t)-\frac{\pi}{2}\right]+6s(t)\\
V_d(t)&=V_{\mathrm{LO}}\cos\left[\omega_{\mathrm{LO}}t+\frac{\pi}{8}s(t)-\frac{\pi}{2}-\pi\right]+6s(t)
\end{aligned} \tag{2}$$

The optical mm-wave exported from DPMZM can be expressed as

$$\begin{aligned}
E_{out}(0,t)=&\frac{\partial}{2}E_c\exp(j\omega_c t)\left\{\exp\left[jm\cos\left[\omega_{\mathrm{LO}}t+\frac{\pi}{8}s(t)\right]+j\frac{6\pi s(t)}{V_\pi}\right]\right.\\
&+\exp\left[-jm\cos\left[\omega_{\mathrm{LO}}t+\frac{\pi}{8}s(t)\right]+j\frac{6\pi s(t)}{V_\pi}\right]\\
&+\exp\left[jm\sin\left[\omega_{\mathrm{LO}}t+\frac{\pi}{8}s(t)\right]+j\frac{6\pi s(t)}{V_\pi}\right]\\
&\left.+\exp\left[-jm\sin\left[\omega_{\mathrm{LO}}t+\frac{\pi}{8}s(t)\right]+j\frac{6\pi s(t)}{V_\pi}\right]\right\}\\
=&\partial E_c\exp(j\omega_c t)\exp\left(j\frac{6\pi s(t)}{V_\pi}\right)\left\{\cos\left\{m\cos\left[\omega_{\mathrm{LO}}t+\frac{\pi}{8}s(t)\right]\right\}\right.\\
&\left.+\cos\left\{m\sin\left[\omega_{\mathrm{LO}}t+\frac{\pi}{8}s(t)\right]\right\}\right\}
\end{aligned} \tag{3}$$

where ∂ is the insertion attenuation. $V_\pi=4$ V is the half-wave voltage of DPMZM (@10 GHz). m is the modulation index defined as $m=\pi V_{\mathrm{LO}}/V_\pi$. Eq. (3) can be saved as the formula of Bessel function. It can be expressed as

$$\begin{aligned}
E_{out}(0,t)=&\partial E_c\exp(j\omega_c t)\exp\left(j\frac{3\pi}{2}s(t)\right)\\
&\left\{\sum_{n=-\infty}^{+\infty}(-1)^n J_{2n}(m)\exp\left[j2n\left(\omega_{\mathrm{LO}}t+\frac{\pi}{8}s(t)\right)\right]\right.\\
&\left.+\sum_{n=-\infty}^{+\infty}J_{2n}(m)\exp\left[j2n\left(\omega_{\mathrm{LO}}t+\frac{\pi}{8}s(t)\right)\right]\right\}\\
=&\partial E_c\exp(j\omega_c t)\exp\left(j\frac{3\pi}{2}s(t)\right)\\
&\left.\sum_{n=-\infty}^{+\infty}J_{4n}(m)\exp\left[j4n\left(\omega_{\mathrm{LO}}t+\frac{\pi}{8}s(t)\right)\right]\right\}
\end{aligned} \tag{4}$$

where $J_{4n}\ (m)$ is the $4n$th order Bessel function of the first kind. From Eq. (4) it can be seen that there are only optical carrier and $4n$th order sidebands left. The Bessel function $J_{4n}\ (m)$ for $n\geq 2$ is much smaller than that of $n=1$. Therefore, the higher order sidebands are neglected. Moreover, after the output signal is directed into optical notch filter, the optical carrier is suppressed. Eq. (4) can be simplified as

$$\begin{aligned}
E_{out}(0,t)\approx&\partial E_c\exp(j\omega_c t)\exp\left(j\frac{3\pi}{2}s(t)\right)\left\{J_4(m)\exp\left[j4\left(\omega_{\mathrm{LO}}t+\frac{\pi}{8}s(t)\right)\right]\right.\\
&\left.+J_{-4}(m)\exp\left[-j4\left(\omega_{\mathrm{LO}}t+\frac{\pi}{8}s(t)\right)\right]\right\}\\
=&\partial E_c\exp(j\omega_c t)\{J_4(m)\exp(j4\omega_{\mathrm{LO}}t+2\pi s(t))\\
&+J_{-4}(m)\exp[-j(4\omega_{\mathrm{LO}}t-\pi s(t)]\}\\
=&\partial E_c\exp(j\omega_c t)\{J_4(m)\exp(j4\omega_{\mathrm{LO}}t)+J_{-4}(m)\exp[-j(4\omega_{\mathrm{LO}}t-\pi s(t)]\}
\end{aligned} \tag{5}$$

From Eq. (5) it can be seen that the baseband signal is modulated on the −4th order sideband, while the +4th order sideband does not carry the baseband signal, as a result, two optical 4th order sidebands separated by eight times the frequency of LO signal are generated.

In back-to-back (BTB) case, two sidebands are beat in PD, and then a frequency octupling mm-wave signal is generated. The photocurrent can be expressed as

$$\begin{aligned}
I(0,t)&=R|E_{out}(0,t)|^2\\
&=2R\partial^2E_c^2J_4^2(m)[1+\cos(8\omega_{\mathrm{LO}}t-\pi s(t))]
\end{aligned} \tag{6}$$

where R is the responsivity of PD. The photocurrent includes direct current and radio frequency octupling mm-wave signal which we

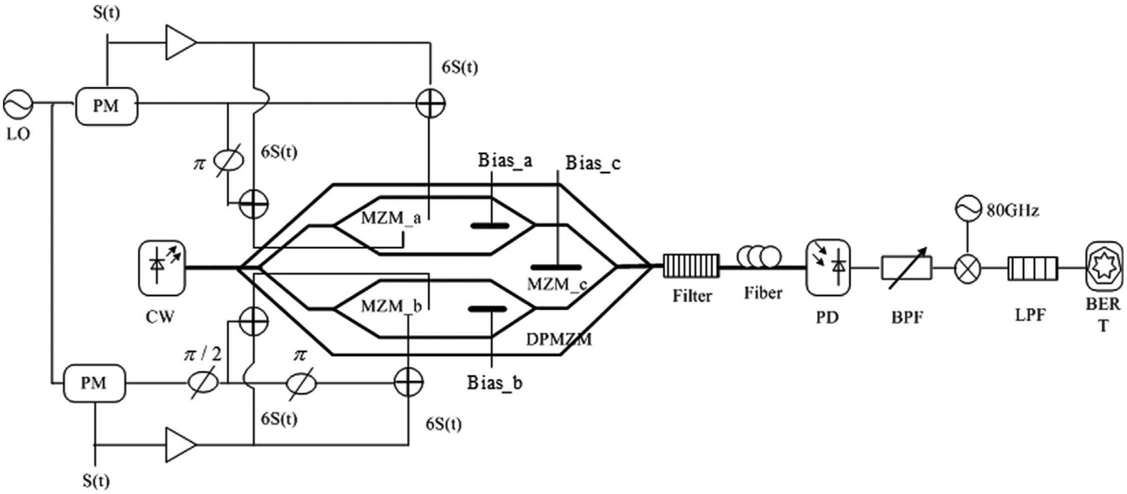

Fig. 1. The block diagram of the RoF link on the proposed frequency octupling optical mm-wave generation approach. LD: laser diode; PM: phase modulator; PD: photodetector; EA: electrical amplifier; BPF: band pass filter; LPF: lower pass filter; BERT: bit error tester.