Analysis on the performance of RoF downlink with tunable optical millimeter-wave generation by employing triangular wave sweep

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Abstract: A tunable optical millimeter-wave generation scheme was proposed theoretically which was capable of obtaining high multiplication factor (MF), and the performance of Radio over Fiber (RoF) downlink was numerically analyzed. The scheme was based on a dual-driving Mach-Zehnder modulator (DD-MZM) which was driven by triangular wave instead of sine-wave. More harmonics can be generated by using triangular wave sweep. With the help of uniform fiber Bragg grating (UFBG), two of the harmonics can be selected to generate millimeter-wave signal of different MFs. The MF can be tunable by adjusting the Bragg wavelengths of two UFBGs respectively. Millimeter-wave signals with MFs of 4, 6, 8, 10 and 12 were achieved. The RoF downlink transmission performance of all these MFs was evaluated. The eye diagram after 10 km transmission is still wide open under the conditions of all the MFs. The results demonstrate that such a scheme can offer realistic solution to support future wireless systems.

Key words: radio-over-fiber; millimeter-wave; triangular-wave; fiber Bragg grating

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三角波扫频的可调谐毫米波 RoF 下行链路性能分析

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摘 要: 理论提出了一种获得高倍频因子的毫米波产生方案并对产生毫米波的 RoF 下行链路性能进行分析。方案中利用三角波替代正弦波来驱动双驱动马赫增德尔调制器。通过三角波扫频,可以产生更多的频率分量。均匀光纤布拉格光栅可以选择出所需的频率分量进行拍频产生毫米波信号。倍频因子的调谐可以通过调节两个均匀光纤布拉格光栅的中心波长来实现。方案可获得倍频因子分别为 4,6,8,10,12 mm 的波信号,并对各种倍频因子下的 RoF 下行链路性能进行了分析。结果表明,在各种倍频因子下,经过 10 km 光纤的传输,解调后眼图均能保持一定的张开度,满足通信需求。该方案为未来的无线电通信系统提供了一定的支持。

关键词: 光载无线电; 毫米波; 三角波; 光纤布拉格光栅

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0 Introduction

Next generation optical access networks are expected to carry multiple broadband services to customers which offer advantages including high data bandwidth, enhanced security and flexible scalability[1]. And in the future access services of wireless telecommunication, the millimeter wave radio over fiber (RoF) system is extremely attractive to meet the increasing demands of the wide-bandwidth, large capacity, low power consumption, as well as system cost-effective[2]. Consequently, RoF system is now considered as an efficient delivery method between multimedia services and wireless/mobile users [3]. The critical technique in RoF systems is the generation of a high-quality millimeter-wave (mm-wave) signal. Mm-wave carrier generation methods include: (1) intensity modulation direct detection (IMDD)[4-5]; (2) frequency up-conversion technique[6]; and (3) Optical self-heterodyne technique [7]. Considering the system complexity and cost, optical frequency multiplication (OFM) which can avoid the use of high frequency oscillators is a good candidate for mm-wave signal generation design. A dual-driving Mach-Zehnder modulator (DD-MZM) has been widely used in OFM due to its flexible modulation characteristic [8-10]. However, either the integrated nested MZM or the high voltage applied on MZM is hard to realize in practice.

To overcome these limitations, we proposed a one-modulator-based tunable mm-wave generation scheme. In the scheme, optical carrier generation and information modulation are separated. A DD-MZM is used as external modulator and driven by triangular wave to generate several optical harmonics. Triangular wave can be described as the sum of sine-waves, which means more harmonics can be generated. Besides, triangular waveform consists of only odd harmonics in spectrum, and higher harmonics roll off much faster than square wave do. Therefore, it is considered as a desirable waveform profile in signal processing, testing, and display in electrical and optical domain[11]. The triangular wave is also used as profile in the information modulation instead of square wave in the scheme. Following harmonics selection section uses two uniform Fiber Bragg Gratings (UFBGs), as a result, two optical harmonics are filtered out and combined to the intensity modulator. The frequency of mm-wave is decided by the frequency spacing between the selected harmonics. Tunable output is realized by adjusting the center wavelengths of the two UFBGs. As we know, when strain is applied on UFBG, the Bragg wavelength will shift[11]. Thus, by changing the applied strain, the wavelength spacing of the cascaded UFBGs can be controlled absolutely, which can realize the tunable mm-wave output.

1 Principles

The schematic model of the proposed ROF system is shown in Fig.1. The optical signal with the angular frequency of ω_c from the continuous wave (CW) laser is injected into a dual-driving $LiNbO_3$ Mach-zehnder modulator(DD-MZM). By choosing the appropriate direct current (DC) biases and making the phase difference of the two driving signals certain value, the even-order suppressed optical double-side (ODSB) modulation can be realized.

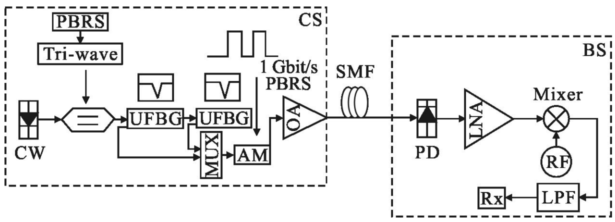

Fig.1 Schematic model of the proposed RoF system

The drive signal of DD-MZM is triangular wave. The Fourier expansion of a periodical triangular wave can be described as

$$f(t)=\frac{A}{2}+A\sum_{n=1}^{\infty}Sa^2\left(\frac{n\pi}{2}\right)\cos(n\omega_0 t)=\frac{A}{2}+A[\cos(\omega_0 t)+$$

$$\frac{1}{9}\cos(3\omega_0 t)+\frac{1}{25}\cos(5\omega_0 t)+\frac{1}{49}\cos(7\omega_0 t)\cdots] \quad (1)$$

where A and ω_0 represent the amplitude and angular frequency of the triangular wave respectively. Eq.(1) shows that the amplitudes of the harmonics with an order higher than fifth are very small and can be neglected without significant error[12]. The input optical field of the DD-MZM is generated by the CW laser with an angular frequency of ω_c and amplitude of A_c. With DD-MZM biased at its minimum transmission point, the output optical field of the DD-MZM can be expressed as:

$$E_{out}(t)=A_c\cos(\omega_c t)\begin{bmatrix}\exp(j\frac{\pi A}{2V_\pi}+j\sum_{n=1}^{7}\frac{\pi A}{V_\pi}Sa^2\left(\frac{n\pi}{2}\right)\cos(n\omega_0 t)) \\ -\exp(j\frac{\pi A}{2V_\pi}-j\sum_{n=1}^{7}\frac{\pi A}{V_\pi}Sa^2\left(\frac{n\pi}{2}\right)\cos(n\omega_0 t))\end{bmatrix}=$$
$$-j2A_c\cos(\omega_c t)\exp\left(j\frac{\pi A}{2V_\pi}\right)\times\{\sin[\frac{\pi A}{V_\pi}[\cos(\omega_0 t)+$$
$$\frac{1}{9}\cos(3\omega_0 t)+\frac{1}{25}\cos(5\omega_0 t)+\frac{1}{49}\cos(7\omega_0 t)]]\} \quad (2)$$

The same as above, high order harmonics with small amplitudes are neglected. Therefore, Eq.(2) can be simplified to:

$$E_{out}(t)\approx -j2A_c\exp\left(j\frac{\pi A}{2V_\pi}\right)\begin{Bmatrix}a\cos[(\omega_c\pm\omega_0)t] \\ +b\cos[(\omega_c\pm3\omega_0)t] \\ +c\cos[(\omega_c\pm5\omega_0)t] \\ +d\cos[(\omega_c\pm7\omega_0)t]\end{Bmatrix} \quad (3)$$

In Eq.(4), $\beta=\pi A/V_\pi$ represents the modulation index of the DD-MZM; a, b, c, and d are amplitudes of the corresponding harmonics, respectively; V_π denotes the switching voltage of DD-MZM. Then $E_{out}(t)$ is launched into a single-mode fiber (SMF) for transmission. Neglecting the attenuation, dispersion and nonlinearity of the SMF, the output optical field of the SMF can be expressed as:

$$E_{out}'(t)\approx -j2RA_c\exp\left(j\frac{\pi A}{2V_\pi}\right)\begin{Bmatrix}a\cos[(\omega_c\pm\omega_0)t] \\ +b\cos[(\omega_c\pm3\omega_0)t] \\ +c\cos[(\omega_c\pm5\omega_0)t] \\ +d\cos[(\omega_c\pm7\omega_0)t]\end{Bmatrix} \quad (4)$$

where R is the gain factor of the optical amplifier (OA). After optic-electric conversion, one can observe from Eq.(4) that the mm-wave with a MF of 2, 4, 6, 8, 10, 12, and 14 can be theoretically generated. However, the power of high order harmonics maybe ultra-small and the millimeter-wave of 12-fold or 14-fold maybe can't be obtained because of the relatively low modulation index of DD-MZM.

2 Simulations

To verify our scheme, simulations are implemented. Firstly, we compare the mm-wave the generation efficiency by using sine-wave with that by using triangular wave. In the simulation, the CW laser is operated at a wavelength of 193.01 THz with power A_c^2=30 mW. The DD-MZM is biased at quadrature transmission point with the switching voltage V_π=6 V and the modulation index setting to 1.5π. The frequencies of the triangular wave and sine-wave are both set to 10 GHz. The gain of OA is set to 10 dB. The SMF dispersive index is set as 17 ps·nm^{-1}·km^{-1}, the attenuation factor is 0.2 dB/km, and the fiber length is 10 km. After transmission, the frequency spectra in electric domain of the mm-wave are shown in Fig.2.

Figure 2 shows that more mm-waves with higher MF are generated by using triangular wave than that by using sine-wave signal. Although the 12-fold and 14-fold mm-wave can't be generated to match with the theoretical predictions given by Eq.(4). However, the situation can be improved by increasing the modulation index of DD-MZM.

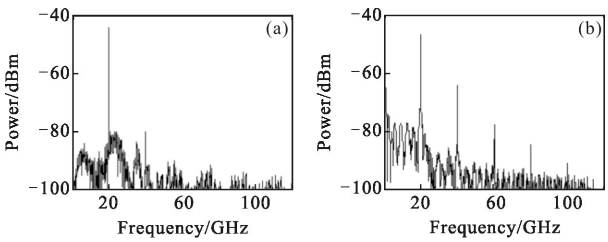

Fig.2 Spectra of output of PD with different modulation signal sine-wave signal (a) and triangular-wave signal (b)

It can be seen from Fig.1 that the output of the DD-MZM then passes through two UFBGs before it is injected into next modulator. It is noted that the output signal from the first UFBG becomes the input signal of the second UFBG. Both the reflective signals of the UFBGs are combined by a multiplexer(MUX), and then inject into the amplitude modulator (AM). The tunable output is realized by using UFBGs as tunable filters. The wavelength of UFBG can be adjusting by changing the applied strain on it. The corresponding frequency spacing between the UFBGs should be the same with the target frequency of the millimeter-wave. The 3 dB width are both 0.05 nm and reflection depth is more than 20 dB. By applying suitable axial strain on the two UFBGs, two proper harmonics can be reflected and combined to inject into the AM. After amplified and optic-electric conversion, the spectrum of generated mm-wave signal with MF of 4, 6, 8, 10, and 12 is shown in Fig.3. And under this situation, the modulation index of the DD-MZM is about 2π.

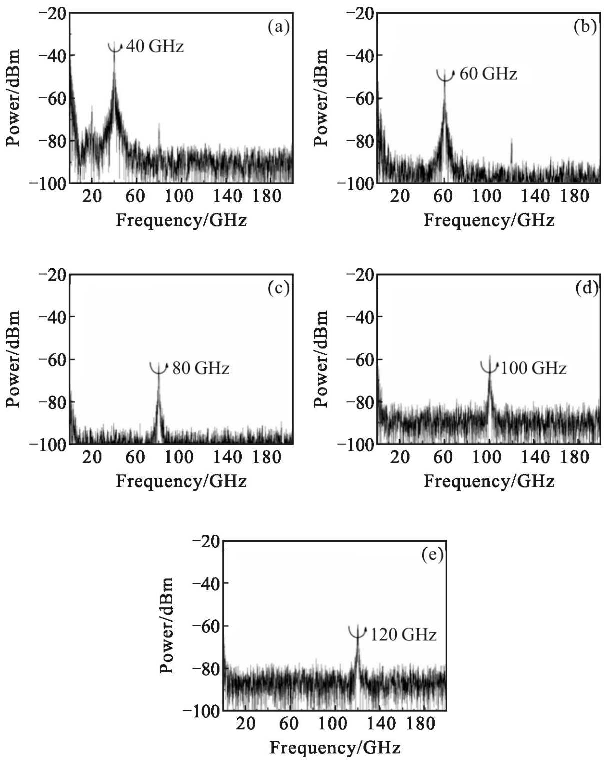

Fig.3 Spectra of generated mm-wave signals

It can be observed from Fig.3(e) and Fig.4 that the signal-to-noise (SNR) of the generated signal nearly reaches to 20 dB, which is almost high enough for normal communication. Millimeter-wave signal with different MFs can be obtained by adjusting the center frequency of two UFBGs. In theory, the signal with a MF of 14-fold can also be achieved, but the signal can't meet the demand of communication due to its low power.

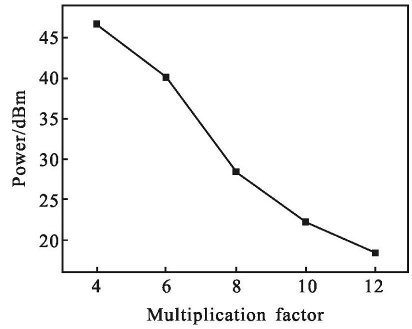

Fig.4 Power of the millimeter-wave signal at different multiplication factor

3 Analysis of the performance of RoF downlink

3.1 RoF link performance of different MF

By using the proposed scheme, mm-waves with different MFs are generated. However, its practicality in ROF system is dubious. Additional simulations based on mm-wave generation with different MFs are implemented to evaluate the transmission performance of the system. As is shown in Fig.1, the reflected harmonics from the UFBG are combined by a two-port multiplexer (MUX). The output of the MUX is injected into an AM. The 1 Gbps PRBS is modulated in amplitude to the selected harmonics via the AM. By controlling the center wavelength of the UFBG, different harmonics are chosen to be photo-detected by the PD, resulting in the generation of millimeter-wave with different MFs. Before photo-detection, the signals are always transmitted through a SMF of 10km. After demodulation, the PRBS data can be recovered and the eye diagrams are shown in Fig.5.

The simulation results clearly show that with the increasing of the MF, the eye diagrams gets worse, which indicates that the signal distortion is getting worse. However, the eye diagram is still wide open when the MF reaches to 12, which is enough for a typical RoF system.

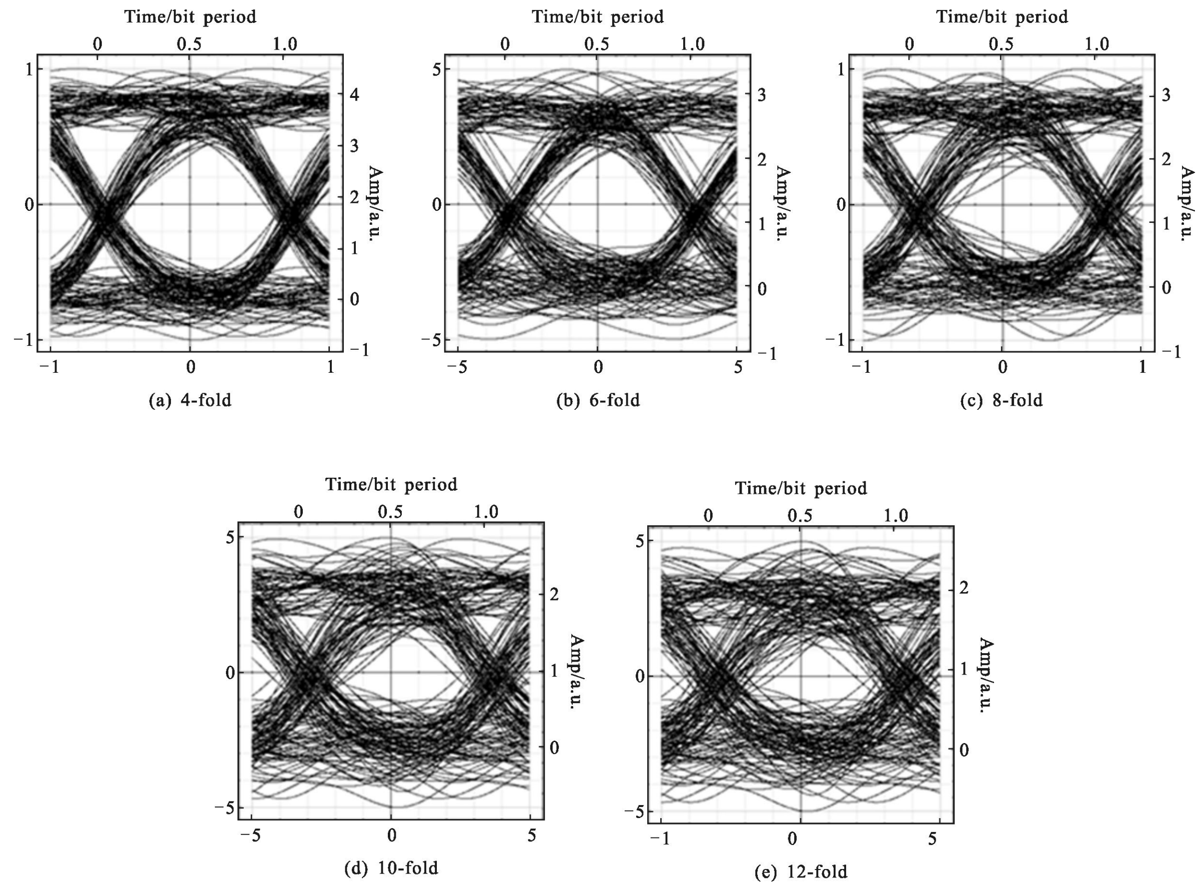

Fig.5 Eye diagrams with different MFs after 10 km SMF transmission

Figure 6 gives the performance comparison between the RoF downlinks with different MFs. It should be noted that it needs larger injected power for the PD to detect, when the MF becomes bigger. Under the condition of the 12-fold millimeter-wave generation, the receiving sensitivity is −20.3 dBm, while the 4-fold has the receiving sensitivity of −24.8 dBm. The simulation results are logical.

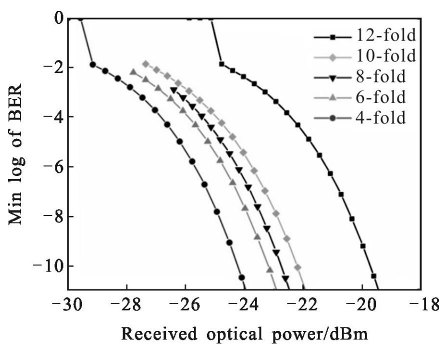

Fig.6 BER curve with 1Gbit/s data under different MFs after 10 km SMF transmission

3.2 Performance of the 12-fold signal after different lengths SMF transmission

Besides, we also evaluate the RoF downlink performance that the millimeter-wave signal with MF of 12 transmits through different lengths of SMFs. The BER patterns and BER curve are shown by Fig.7 and Fig.8 separately. The simulation results indicate that under the condition that the MF of the millimeter-wave signal is 12, it only can transmit within 10 km,

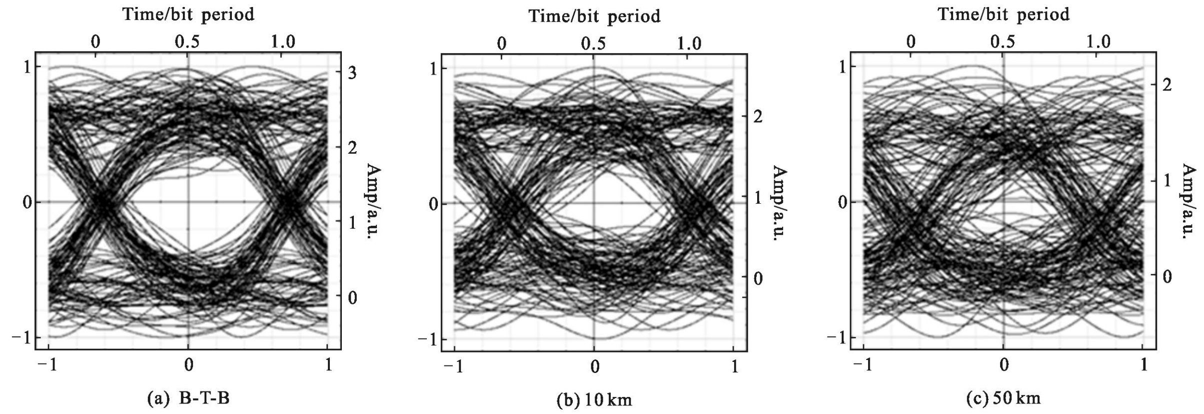

Fig.7 BER patterns of millimeter-wave signal with MF of 12 after transmitting the SMF length of 0 km, 10 km, and 50 km

which can hardly meet the demand of normal communication.

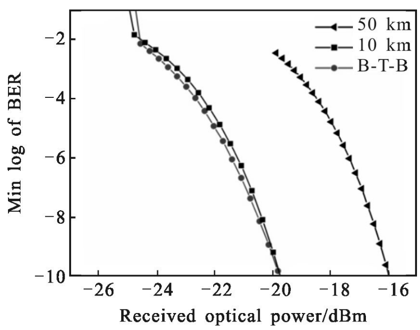

Fig.8 BER curve with 1 Gbit/s data under MF of 12 after different lengths of SMF transmission

4 Conclusion

In conclusion, we have proposed a RoF scheme which can realize mm-wave frequency multiplication by driving DD-MZM with triangular wave and evaluate its performance. This system can avoid the use of a high frequency oscillator. The tunable output is realized by changing the applied strain on UFBGs. The MF can reach to 12 and the generated mm-wave signals can have a SNR nearly reach to 20 dB. Also, the system transmission performance is good. The eye diagram is still wide open after 10 km transmission, which indicates that this system is capable of long-haul transmission. We believe that it can provide a good solution to high frequency mm-wave generation without using complex optical components in ROF systems.

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