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# Photonic Generation of Millimeter-wave Signals with Arbitrary and Tunable Frequency Multiplication Factors

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Abstract. To generate millimeter-wave (mm-wave) signals with arbitrary and tunable frequency multiplication factors (FMFs), a photonic approach is proposed. Firstly, a Dual-driving Mach-Zehnder modulator (DD-MZM) and a phase modulator (PM) are used to produce an optical frequency comb (OFC). Then an acousto-optic tunable filter based on the uniform fiber Bragg grating (UFBG-AOTF) chooses the optical carrier and two symmetric harmonics from the OFC. Finally, the characteristic of an optical band-stop filter (OBSF) followed the UFBG-AOTF determines whether the mm-wave is arbitrary times or even times of the local frequency. For even-times FMF, mm-wave with a frequency up to 28 times of the LO frequency can be generated. Also, for the arbitrary-times FMF, mm-wave up to 11 times of the LO frequency can be obtained in principle. The flexible tunability of FMF can be achieved by controlling the frequency of the signal applied on the UFBG-AOTF. Mm-waves with FMF of 11 and 22 are both generated by simulation. Results of the research show that the 2-Gbit/s data can be successfully transmitted over 50km single mode fiber with power penalties of only about 1.72dB and 0.81dB, separately. Moreover, the generated mm-wave with the FMF of 28 has a sideband-suppressed ratio (SSR) higher than 20dB, which is enough for a normal communication.

Keywords: arbitrary-times, even-times, frequency multiplication factor, millimeter-wave, UFBG-AOTF

## 1 Introduction

Millimeter wave (mm-wave), large-scale antenna and ultra-dense network are considered to be the three most important technologies of the fifth-generation (5G) communication [1-2]. Among these key technologies, mm-wave is extremely important, which can further improve the wireless communication capacity and solve the problem of spectrum congestion in the low-frequency microwave band. Thus, it is a direct means to make the most of spectrum resources. Therefore, generating mm-wave signals of high quality, high purity and high frequency is of great significance to improve the capacity and transmission rate of 5G communication system.

Optical mm-wave signal generation is a key technology to realize low cost and excellent transmission performance for the 5G access network. In recent years, a lot of optical generation methods have been reported [3-9]. Among all the approaches, the ones based on the external modulator are relatively mature and low-cost techniques. External modulators shown high reliability and have been widely employed in the practical optical transmission systems for high-speed signal modulation. In order to realize the generation of mm-wave signals with high frequency multiplication factor, external modulation techniques employing cascaded or structurized Mach-Zehnder Modulators (MZMs) have been employed

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in optical mm-wave generation. In Ref. [10], two cascading polarization modulators (PolM) are used to generate millimeter-wave signals with frequency multiplification factors (FMF) of 4, 6, 8 by changing the modulation index of two PolMs and the polarization state of the output light and other conditions. In Ref. [11], an integrated polarization multiplexing dual-parallel Mach-Zehnder Modulator (PDM-DPMZM) is used to generate millimeter wave signals with a FMF of 8 by adjusting the angle of the polarizer, and related parameters of the modulator, but the rotation angle of the polarization controller needs to be accurately controlled. In Ref. [12], multi-frequency phase-coded microwave signal based on a dual-output Mach-Zehnder modulator (DOMZM) can be generated based on a dual-output MZM and balanced detection. Similarly, Ref. [13] proposed a photonic generation of frequency quadrupling linearly chirped waveform with large tunable range employing a dual-output dual-parallel Mach-Zehnder modulator (DPMZM). Also, two methods were reported using three parallel MZMs [14] and two parallel dual-parallel MZMs [15], which can achieve 18-tupling and 12-tupling mm-wave signal generation, respectively. Approaches employing structurized MZMs have a good performance of the optical sideband suppression ratio and a high spectral purity of the generated mm-wave signals, but suffer from high complexity. What's more, the FMFs can't be tuned flexibly in the schemes referred above.

To realize the flexible tunability of the generated mm-wave's FMF. We have proposed a mm-wave signal generation with tunable FMF by employing UFBG-based acousto-optic tunable filter (UFBG-AOTF) in Ref. [16]. However, the scheme can only generate the mm-waves with a FMF up to 10. In order to improve the mm-wave's FMF, the cascade of a Dual-driving MZM and a phase modulator (PM) is designed to generate mm-wave with a FMF of 16 in Ref. [17]. Since the data in the above two schemes are modulated firstly on the output frequency comb, it may lead to some losses when they are processed by the UFBG-AOTF. The losses will directly damage the performance of the communication system. What's more, only mm-waves with even-times FMFs can be generated in them, while for the mm-waves with odd-times FMFs (such as 1, 3, 5, 7, 9…) can't be generated. This can't meet the versatile requirements of communication.

In this paper, an optical mm-wave signals generator with tunable and arbitrary FMF is proposed. The cascading of a Dual-driving Mach-Zehnder Modulator (DD-MZM) and a phase modulator (PM) is aimed to producing an optical frequency comb. Two harmonics in the optical frequency comb are chosen by the combination of UFBG-AOTF and an optical band-stop filter (OBSF) to generate mm-waves with tunable and arbitrary FMFs up to 28. The FMF can be tuned by adjusting the frequency of the applied acoustic wave on the FBG-AOTF. The characteristic of the OBSF determines whether the FMF is an arbitrary-times or an even-times. When the central wavelength of the OSBF is identical with that of the optical carrier, this scheme can generate mm-wave signals with FMFs of even-times, which can be up to 28 or even more. When the central wavelength of the OSBF is identical with that of a sideband, this scheme can generate mm-wave signals with FMFs of arbitrary-times, which can be up to 11 or even more. Mm-waves with FMF of 11 and 22 are both generated by simulation. Results of the research show that the 2-Gbit/s data can be successfully transmitted over 50km single mode fiber with relatively small power penalties.

## 2 Principle Analysis on the Scheme

### 2.1 Operation Principle

The conceptual diagram of the proposed scheme is shown by Fig. 1. The optical signal from the continuous wave (CW) laser is firstly modulated by a local oscillation (LO) signal through a DD-MZM. The output of the DD-MZM is composed of the optical carrier and symmetric sidebands of each-order. The output signal is then injected into a PM. After the cascade, not only the original frequency harmonics of the signal output from DD-MZM are reserved, but also most of their corresponding amplitudes are increased [18-19]. In addition, some harmonics that amplitudes are rather small can also be strengthened. As a result, an OFC is generated. Both the modulation index of the DD-MZM and PM determine the amount of harmonics in the optical frequency comb. The output OFC from the PM is injected into port 1 of the optical circulator. Port2 of the circulator is connected with a UFBG-AOTF. The UFBG-AOTF is aimed at choosing three target sidebands including the optical carrier and two sidebands. Three harmonics are output from the port 3 of the circulator to inject into the OBSF. The characteristic of the OBSF determines whether the combination of two symmetric sidebands (① in Fig. 1) is left or the combination of optical carrier and one sideband (② in Fig. 1) is left. If the central wavelength of the OBSF is identical with the optical carrier, mm-waves with FMFs of even-times (such as 2, 4, 6, 8, 10, …) can be generated. If the central wavelength of the OBSF is the same with one sideband, mm-waves with FMFs of arbitrary-times (such as 1, 2, 3, 4, 5, 6, …) can be generated. An amplitude modulator (AM) adds the baseband data on the generated optical mm-wave signal. After amplification of the Erbium Doped Fiber Amplifier (EDFA), the signal is transmitted through certain lengths of single mode fiber (SMF) before optical-to-electrical conversion via a PIN photodiode (PD). The bit-error-rate (BER) performance is evaluated by a BER tester after the module of demodulation.

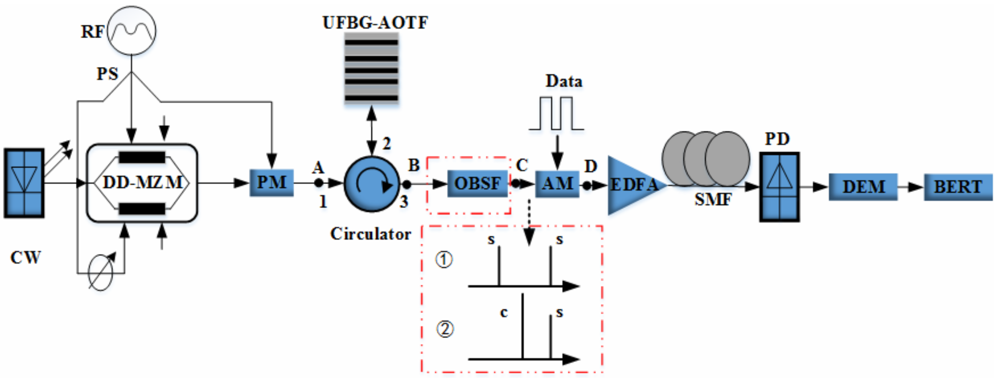



**Fig. 1.** Conceptual and simulation diagram of the proposed mm-wave signal generation scheme (c: carrier; s: sideband; Dem: demodulate.)

### 2.2 Principles of the UFBG-AOTF

A UFBG-based AOTF [20-21] shown in Fig. 2 is composed of a UFBG inscribed on an SMF, a acoustic silica horn and a shear-mode piezoelectric ceramic transducer (PZT). To actuate piezoelectric material in shear mode, an electric signal is applied perpendicular to the direction of polarization. This introduces a strain or displacement in the direction of polarization, and creates a longitudinal vibration along the fiber axis. As a periodic modulating result, expansion and compression on the UFBG periodically are caused finally, to ensure the UFBG-AOTF has an appreciable filtering characteristic.

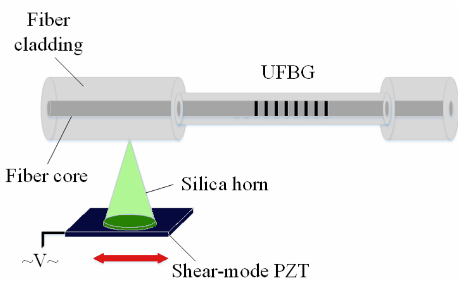



**Fig. 2.** Prototype of the UFBG-AOTF

Researches on the UFBG-AOTF indicate that [22-23], except the parameters of the UFBG and PZT, the applied electric signal mainly determines the filtering characteristic. Specifically, the frequency of electric signal decides the amount and location of the reflections. The primary reflective peak is surrounded by the two inspired symmetric first-order reflections. The frequency distance $\Delta f$ between the primary reflection and the first-order reflection can be calculated by the following expression:

$$\Delta f = 17.47 f_E \quad \textbf{(1)}$$

Where $f_E$ denotes the frequency of the applied electric signal.

The output OFC from the PM is substantially an optical double-sideband (ODSB) signal. Frequency distance between each sideband is the same as the LO frequency. In the process of generating mm-waves, if the $n$th-order ($n$=1, 2, 3, 4 …) sideband should be selected, then the central frequency of the first-order reflection in the UFBG-AOTF should be in accordance with the *n*th-order sideband. After calculation combined with Eq.(1), the relationship between the frequency distance among the optical carrier and the *n*th-order sideband (denoted as $\Delta f_C$ ) and $f_E$ can be described by Fig. 3. This relationship can help choosing applied electric signals in the premise that desired mm-wave's FMF is given.

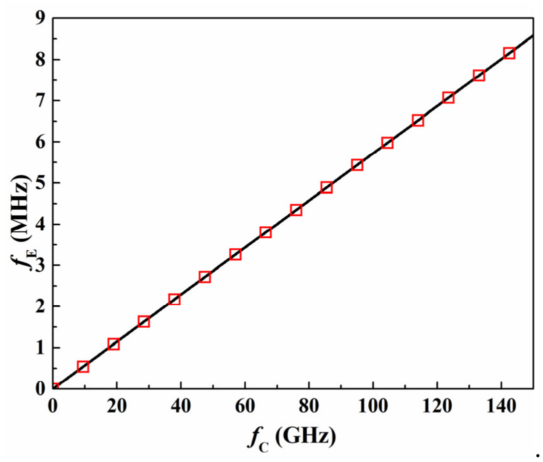



**Fig. 3.** Relationship between $f_E$ and $f_C$

## 3 Simulation Analysis on the Proposed Scheme

For testing the feasibility and performance of proposed scheme, a complete simulation system is built up based on a commercial simulation platform [24] as shown in Fig. 1. The output of the CW has a central frequency of 1544.4nm. At the same time, the UFBG-AOTF also has a central wavelength of 1544.4nm. The DD-MZM works under the quadrature bias point and a modulation index of $m$=2.5π to realize ODSB modulation. Modulation index of the PM is set as 5. Frequency of the LO signal and the data signal are 10GHz and 2-Gbit/s, respectively. The optical spectrum of the output OFC from the PM is shown by Fig. 4. It can be seen that, harmonics up to ±15th-order in the OFC have rather considerable amplitudes.

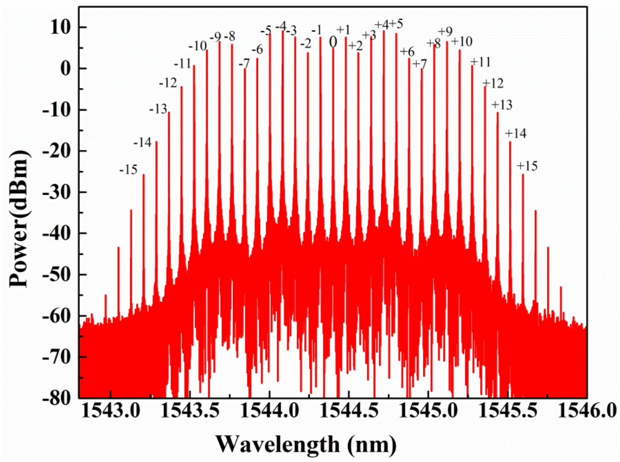
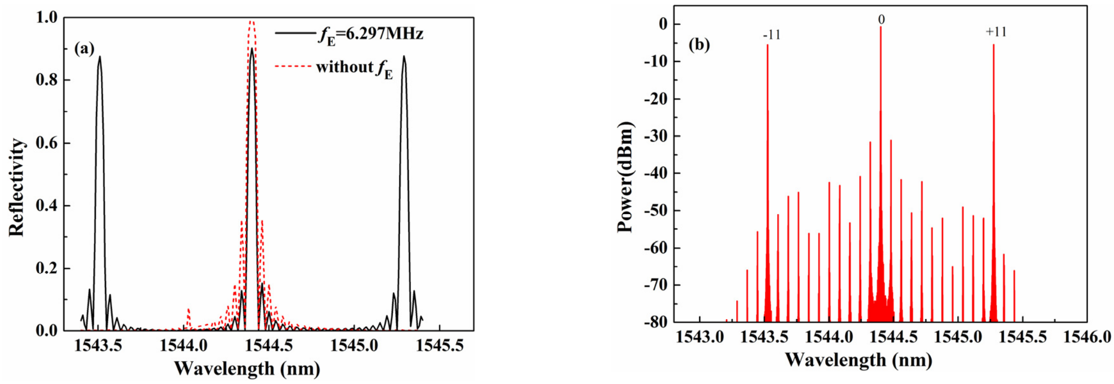



**Fig. 4.** Optical spectrum of the OFC generated from the DD-MZM and PM

Supposing that, the optical carrier and ±11th-order sidebands are reflected from the FBG-AOTF and output from port 3 of the circulator. According to Fig. 3, $f_E$ applied on the FBG-AOTF should be 6.297MHz. Then the reflective characteristic of the UFBG-AOTF is depicted by Fig. 5(a). After transmission through the AOTF, both optical carrier and the ±11$^{th}$-order sidebands are reflected, shown by Fig. 5(b). The central frequencies of the -11$^{th}$-ordder and +11$^{th}$-order sideband are 1543.53nm and 1545.28nm, separately.



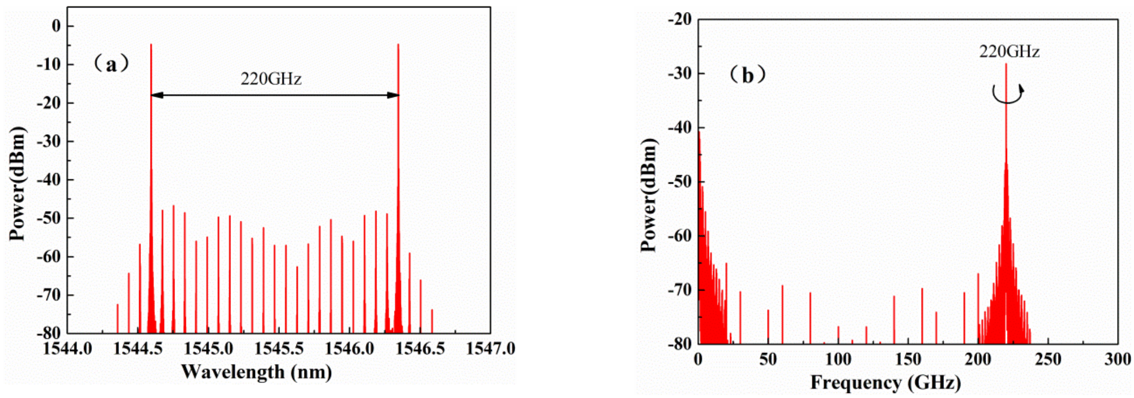

(a) Reflective characteristic of the FBG-AOTF under 6.297MHz

(b) Optical spectrum of the signal reflected from the FBG-AOTF

**Fig. 5.**

### 3.1 Generation of Mm-waves with FMFs of Even-times

An inverted Gaussian OBSF follows the circulator to filter out the optical carrier of the signal at point B, thus its central wavelength should be also set as 1544.40nm, the same as that of the optical carrier. As a result, both the -11$^{th}$-order and +11$^{th}$-order sidebands are left in Fig. 5(b), and the output signal from the OBSF (point C) is given by Fig. 6(a). Amplify the signal in an EDFA with a gain of 3dB. Ultimately, after frequency beaten in PD, the mm-wave with a FMF of 22 is generated, shown by Fig. 6(b).




(a) Optical spectrum at point C

(b) electrical spectrum of the generated mm-wave signal with FMF of 22

**Fig. 6.**

For observing the performance of the communication link, data of 2-Gbit/s is transmitted through SMFs of 0km (B-T-B) and 50km, separately. The BER performance after different fiber distances are shown in Fig. 7, in case of the FMF is 22. It should be mentioned that, after transmitting through SMF of 50km, the power penalty of the system is only about 0.81 dB, which is rather small.

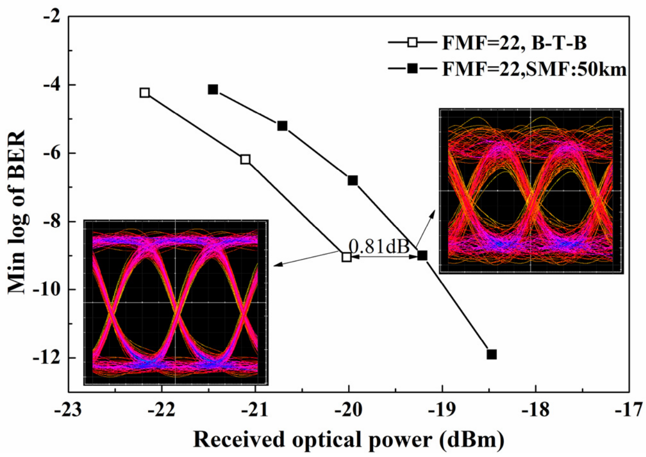



**Fig. 7.** BER curves and the eye diagrams of the signal after transmitting through 0km and 50km, when the FMF is 22

By tuning the applied electric signal's frequency according to Fig. 3, different reflective characteristic of the UFBG-AOTF can be obtained to select certain harmonics. Thus, the mm-waves with FMFs of even-times (such as 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28) can be generated at the output of PD. Both the power and the sideband-suppression ratio (SSR) of generated mm-waves at different FMFs are shown in Fig. 8. It should be mentioned that when the FMF is smaller than 22, both the power and SSR of the mm-wave are rather high, which are higher than -28dBm and 28.5dB, separately. These mm-waves can meet the requirement of high-quality communication.

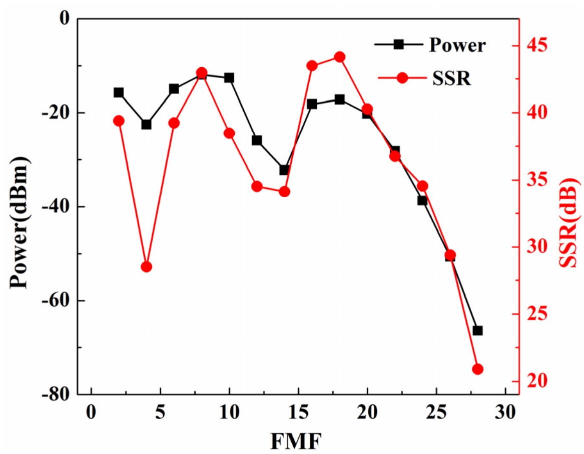



**Fig. 8.** Power of the mm-waves versus FMF (black rectangles ), and SSR of the mm-waves versus FMF (red circles)

The generated mm-wave with FMF of 28 is shown by Fig. 8. The SSR is still higher than 20dB, which can meet basic communication requirement. The power can be strengthened by introducing amplifier. In fact, FMF higher than 28 can also be generated since the harmonics higher than 14$^{th}$-order still have appreciable power. The obtaining of higher FMF can be achieved by improving the modulation index of the MZM and PM, or adding some amplifiers.

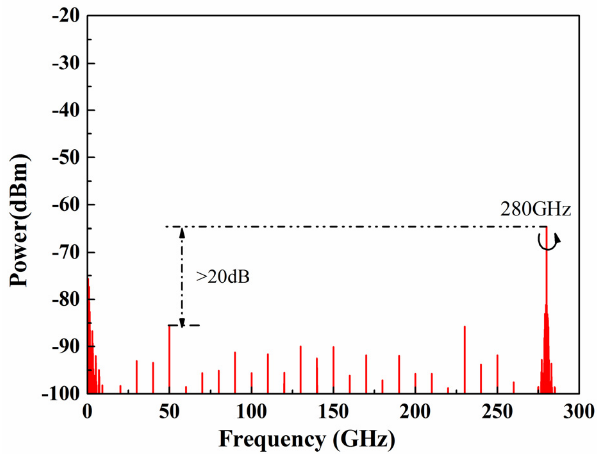
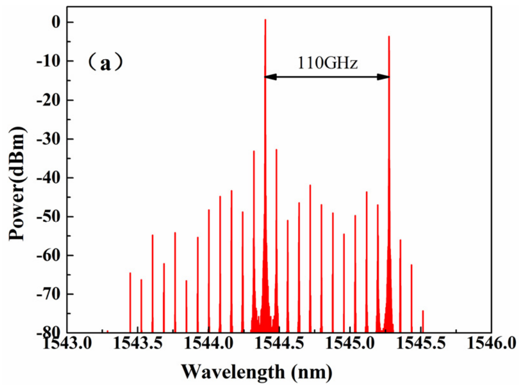


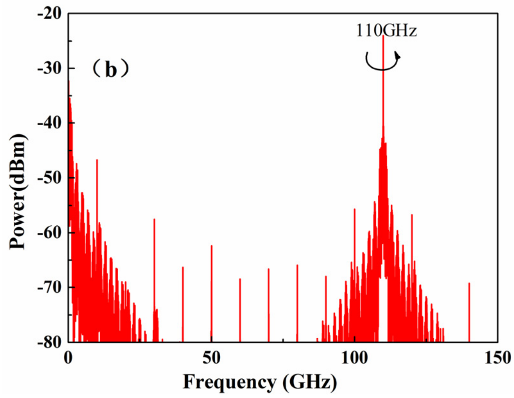

**Fig. 9.** Electrical spectrum of the generated mm-wave signal with FMF of 28

## 3.2 Generation of Mm-waves with FMFs of Arbitrary-times

The inverted Gaussian OBSF connected behind the circulator should have a central of 1543.53nm, the same with the lower -11$^{th}$-order sideband in Fig. 5(b), to filter out the lower sideband signal at point B. After the process of OBSF with above characteristic, only the optical carrier and +11$^{th}$-order sideband are left. Thus, the output signal from the OBSF (point C) can be given by Fig. 10 (a). Then the signal is amplified in an EDFA with a gain of 3dB. Finally, after the process of PD, the mm-wave with a FMF of 11 is generated, shown by Fig. 10(b).




(a) Optical spectrum at point C




(b) Electrical spectrum of the generated mm-wave signal with FMF of 11

**Fig. 10.**

The BER performance for the data of 2-Gbit/s after transmitting through SMFs of 0km (B-T-B) and 50km are shown in Fig. 11, when the FMF is 11. By calculation, after transmission over SMF of 50km, the power penalty of the link is about 1.72dB.

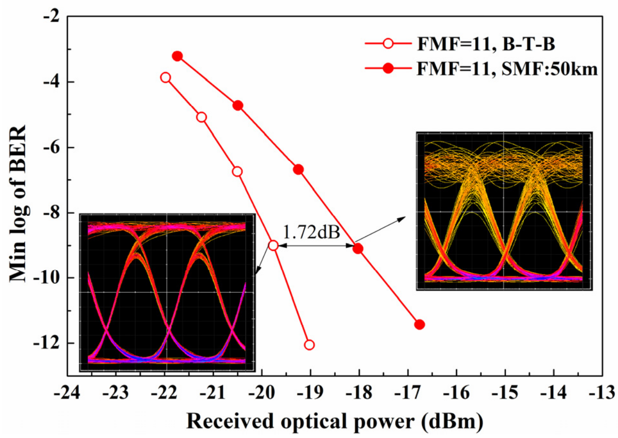



**Fig. 11.** BER curves and the eye diagrams corresponding to the signal transmitting different fiber distances, when the FMF is 11

By tuning the applied electric signal according to Fig. 3, and changing the OBSF's central wavelength, the mm-wave with FMFs of arbitrary-times (such as 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11) can be generated at the output of PD. Both the power and the SSR of mm-waves at different FMFs are shown in Fig. 12. It should be mentioned that when the FMF is smaller than 11, both the power and SSR of the mm-wave are rather high, which are higher than -17dBm and 21.9dB, separately. These mm-waves can meet the requirement of high-quality communication.

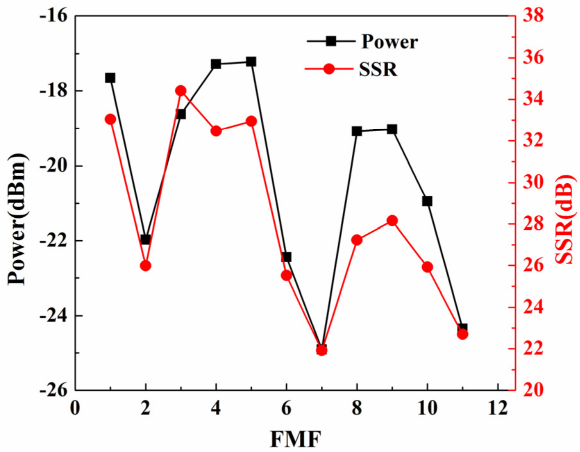



**Fig. 12.** Power of the mm-waves versus FMF (black rectangles), and SSR of the mm-waves versus FMF (red circles)

## 4 Conclusion

Summarily, we have proposed a photonic generation scheme for millimeter-wave signal with arbitrary and tunable FMF. The DD-MZM and PM are cascaded to generate an OFC which contains the optical carrier and symmetric sidebands. The FBG-AOTF and OBSF are used to choose the two harmonics which are used to beaten to generate mm-waves with FMFs of even-times or arbitrary-times. The tunability of FMFs can be realized by choosing the appropriate electric signal. By applying UFBG-AOTF the electric signal of 6.297MHz, the mm-wave with FMF of 22 and 11 can be achieved by simulation. After transmission over SMF of 50km, the power penalties of the links are only about 0.81dB and 1.72dB, separately. Moreover, this method can generate the mm-waves with FMF up to 28 or even more. The proposed scheme offers an easy and convenient way for generating mm-wave with high and arbitrary FMFs. What's more, mm-waves with higher FMF can be obtained by improving the modulation index of the DD-MZM and PM or introducing appropriate amplification.

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