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RESEARCH ARTICLE

Generation and transmission analysis of 4-ary frequency shift keying based on dual-parallel Mach-Zehnder modulator

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Abstract We proposed an optical 4-ary frequency shift keying (FSK) modulation scheme applying dual-parallel Mach-Zehnder (MZ) modulator. The 4-ary FSK based on the single-side-band modulation scheme can greatly lower the transmission speed in each sub-carriers and increase the transmission performance, comparing with the 2-FSK signal. The transmission performance of the 4-ary FSK was demonstrated after a 50 km single mode fiber. The results showed that the 4-ary FSK can realize error-free transmission. Moreover, we analyzed the influence of factors (such as disperse compensation and demodulation bandwidth) on the transmission performance in this paper. The analysis of the influenced factors can provide a theoretical basic for experiment.

Keywords 4-ary frequency shift keying (FSK), modulation scheme, disperse compensation

1 Introduction

With the increasing demand for high-speed communication, frequency shift keying (FSK), as an advanced modulation scheme, has attracted a lot of attention for its advantages of high nonlinear tolerance and 3 dB sensitivity improvement with balanced detectors, which make it attractive in future optical access network [1,2]. In previous work, FSK signal can be generated by direct modulation of the current in the laser [3]. Furthermore, it was reported that FSK signal can be also generated by single high-speed external FSK modulator, such as dual-parallel Mach-Zehnder (MZ) FSK modulator with one laser and a high-speed FSK modulator with two lasers [4,5]. Reference [4] based on dual-parallel MZ modulator can generate the FSK signal with the least optical devices (only one modulator and one laser). Therefore, 4-ary FSK signal based on this modulation scheme can be generated with simple structure (two dual-parallel MZ modulators). In addition, the two modulators can be integrated as one modulator easily.

Multi-level optical modulation formats, such as M-ary phase shift keying (PSK), quadrature amplitude modulation (QAM), M-ary FSK, and M-ary pulse position modulation (PPM), enable high spectral efficiency and increase the transmission performance in the high-speed optical system [6–11]. In these multi-level optical modulation formats, QAM and PPM modulation schemes have been widely investigated [6 – 9]. On the other hand, M-ary FSK modulation scheme has scarcely been studied, although it has good performance. This is because the FSK transmitter and receiver are complicated in these schemes [10,11]. The M-ary FSK signal in previous work was generated by orthogonal frequency-division multiplexing (OFDM) modulation scheme applying electrical methods [11].

In this paper, we applied dual-parallel MZ FSK modulator to realize 4-ary FSK signal and analyzed the transmission performance and influencing factors. The merits of M-ary FSK signal can decrease the modulation speed of each FSK sub-carriers and then decrease the influence factors (such as dispersion, non-linear) on the transmission performance.

2 Principle of 4-ary FSK signal

Figure 1 shows the structure of the dual-parallel MZ modulator and the scheme of 4-ary FSK modulation. When we applied a pair of radio frequency (RF) signals, which were of the same frequency and had a 90 phase difference, to the electrodes RF_A and RF_B, frequency shifted lightwave can be generated at the output port of modulator. The RF_A and RF_B electrodes were biased at null-bias point

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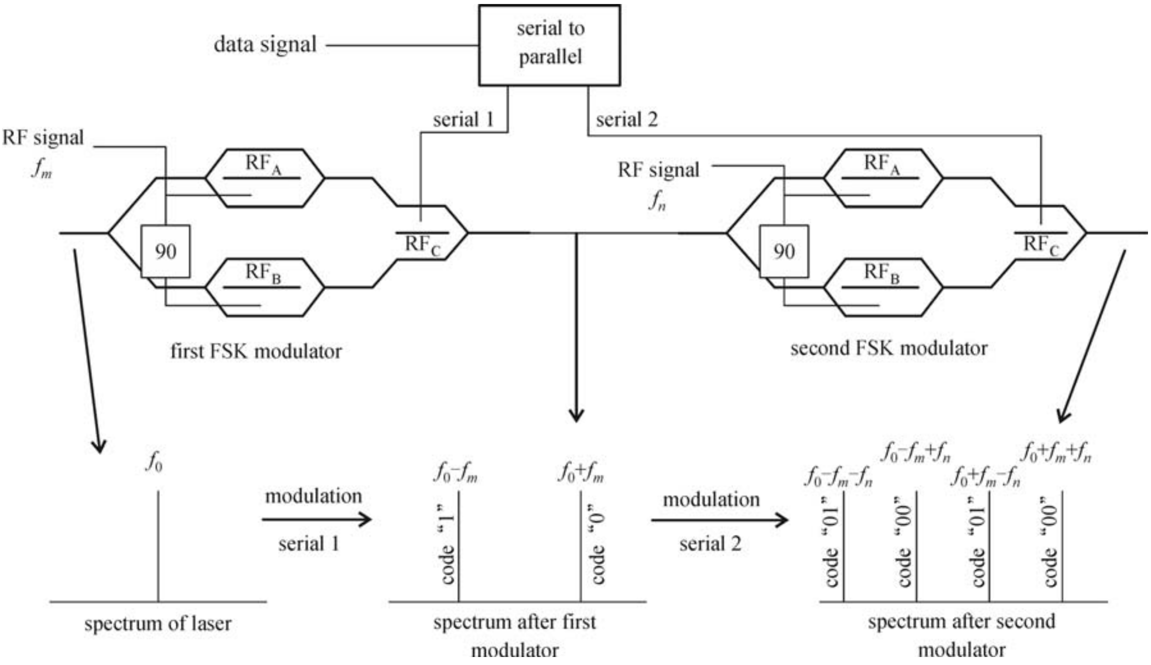


Fig. 1 Structure of dual-parallel FSK modulation and the scheme of 4-ary FSK modulation

of the MZ modulator. When data signal was added to the electrode RF$_C$, FSK signal was generated [4]. The output signal from the output of the first modulator can be expressed by

$$\begin{aligned} E_1 &= E(t)\cos(w_m t)\exp(\mathrm{i}s_1) + E_1\cos(w_m t + \frac{\pi}{2}) \\ &= E(t)J_1(A_1) \times \{[1+\sin(s_1)]\exp(\mathrm{i}w_m t) \\ &\quad +[1-\sin(s_1)]\exp(-\mathrm{i}w_m t)\}, \end{aligned} \tag{1}$$

where $E(t)$ is the optical signal from the laser, w_m is the frequency of the RF applied to the first modulator, $J_1(A_1)$ is the first order of first Bessel function, and s_1=± 90° is the induced phase modulated by serial 1.

When the FSK signal is modulated by the same modulation scheme in subsequent dual-parallel MZ modulator, each sub-carrier of the FSK signal can generate a new FSK signal, therefore, four frequencies of 4-ary FSK signal can be generated after two times of FSK modulation. The output signal can be expressed by

$$\begin{aligned} E &= E_1\cos(w_n t)\exp(\mathrm{i}s_2) + E_1\cos(w_n t + \frac{\pi}{2}) \\ &= E_1 J_1(A_2) \times \{[1+\sin(s_2)]\exp(\mathrm{i}w_n t) \\ &\quad +[1-\sin(s_2)]\exp(-\mathrm{i}w_n t)\}, \end{aligned} \tag{2}$$

where w_n is the frequency of the RF applied to the second modulator, $J_1(A_2)$ is the first order of first Bessel function, and s_2=± 90° is the induced phase modulated by serial 2.

Then we neglect the constant, and the equation is

$$\begin{aligned} E &\cong \{[1+\sin(s_1)]\exp(\mathrm{i}w_m t) + [1-\sin(s_1)]\exp(-\mathrm{i}w_m t)\} \\ &\quad \times\{[1+\sin(s_2)]\exp(\mathrm{i}w_n t) + [1-\sin(s_2)]\exp(-\mathrm{i}w_n t)\}. \end{aligned} \tag{3}$$

According to the different s_1 and s_2, we can get four sub-carriers: $\pm w_m \pm w_n$.

The spectrum in Fig. 1 shows the principle of 4-ary FSK modulation. Data signal was divided into two serial data flows after serial to parallel conversion. The lightwave was modulated by serial 1 data flow to realize FSK modulation after the first FSK modulator. Two sub-carriers of FSK signal, which carry code "1" or "0" of the serial 1, were then modulated by serial 2 and generated two sub-carriers, respectively. The four sub-carriers after twice modulations can carry the codes of both serials 1 and 2, and each sub-carrier represents only one of the four codes, which means 4-ary FSK signal was generated.

The demodulation of 4-ary FSK signal can be realized just by three sub-carriers. The spectrum after the second modulation in Fig. 1 shows that the frequencies $f_0-f_m-f_n$ and $f_0-f_m+f_n$ contain all the information of serial 1, it means that adding these two frequencies can obtain the correct information of serial 1. Similarly, adding frequencies $f_0-f_m-f_n$ and $f_0+f_m-f_n$ can obtain the information of serial 2. Through serial to parallel conversion, we can recover the data signal from serial 1 and serial 2.

3 Simulation results and discussion

Figure 2 shows the structure of 4-ary FSK modulation scheme. In the transmission system, the frequency of laser was 193.1 THz, and the frequencies of RF signals 1 and 2 were 40 and 20 GHz, respectively. Data signal from 40 Gb/s pseudo random binary sequence (PRBS) generator was divided into two serials by serial to parallel conversion. These two serials directly driven two dual-parallel FSK modulators, and therefore, 4-ary FSK signal was generated. The transmission link contained a 50 km standard single mode fiber (SSMF) and a 10 km dispersion compensation fiber (DCF). The dispersion and dispersion slop of SSMF were 16.75 ps/nm/km and 0.075 ps/nm^2/km, and those of DCF were -83.75 ps/nm/km and -0.375 ps/nm^2/km, respectively. In the receiver, the central frequencies of three optical filters with the same bandwidth of 30 GHz were 193.04, 193.08, and 193.12 THz, respectively. Because both serials 1 and 2 needed to use the signal with the frequency of 193.04 THz, this signal was divided into two parts to add the other two frequencies. At the end, a bit error rate tester (BERT) was used to test the transmission performance of 4-ary FSK signal. The data signal was recovered from serials 1 and 2 by serial to parallel conversion, therefore, the transmission performance was determined by these two data flows. However, some factors had different effects on the data flows. Therefore, in order to analyze these influences, we used the two data flows to analyze the transmission performance of 4-ary FSK signal. In this paper, the frequency difference of each carriers were described as below: the frequency difference of serial 1 (40 GHz), which was equal to that of 4-ary FSK signal (40 GHz), was half of that of serial 2 (80 GHz).

Figure 3 shows the spectrums of the points in Fig. 2. The spectrums were the same to the theoretical analysis shown in Fig. 1, which means that 4-ary FSK modulation scheme is feasible.

Figure 4 shows the transmission performance of 4-ary FSK signal after 50 km SSMF and 10 km DCF with complete dispersion compensation under different dispersion slop compensations, (a) -0.375 ps/nm^2/km and (b) 0.26 ps/nm^2/km. The inserts are the eye-diagrams of serial 1 and 2 after 50 km SSMF transmission and back-to-back (BTB) transmission at the BER of 10^{-9}. The eye-diagrams, which open clearly, mean that the 4-ary FSK signal can realize error-free transmission after SSMF. From Fig. 4(a), the power penalty of 50 km transmission compared with that of BTB transmission was so small that it can be neglected. The power penalty of serial 1 in comparison with serial 2 was 0.4 dBm, which means the frequency of sub-carriers can have positive influence on transmission performance. When common dispersion compensation fiber with the dispersion slop of 0.26 ps/nm^2/km was used in the transmission link, it can only compensate the dispersion without dispersion slop (see Fig. 4(b)). The power penalties of serial 1 and 2 after 50 km transmission comparing with BTB were 0.3 and 1 dBm, respectively. In addition, the eye-diagram of serial 2 after 50 km SSMF transmission was bad comparing with other eye-diagrams. The results indicated that dispersion slop had passive influence on the transmission performance of the 4-ary FSK signal: the lager the frequency difference of sub-carriers was, the worse the transmission performance was. Therefore, the frequency difference should be considered under incomplete dispersion slop compensation.

To analyze the influences of dispersion and dispersion slop on the transmission performance of 4-ary FSK signal, the received powers of serials 1 and 2 at the BER of 10^{-9} under different dispersions and dispersion slops are shown in Fig. 5. From Fig. 5(a), it can be seen that dispersion slop has influence on the transmission performances of serials 1 and 2, and the performance of serial 2 was worse than that of serial 1 with the deviation of completed dispersion slop compensation. The power penalties of serials 1 and 2 are small, about 0.5 and 0.7 dBm (± 6 ps/nm^2 with reference to 0) respectively. Figure 5(b) shows that dispersion had great influence on the performance of serial 2 (power penalty was 3.7 dBm), but it had little influence on that of serial 1 (power penalty was 0.2 dBm). The reason is that the dispersion and dispersion slop have greater influence on the transmission performance with larger frequency differences. The frequency difference of serial 2 was larger than that of serial 1, therefore, the performance of serial 2 was worse than that of serial 1 with the deviations of completed dispersion and dispersion slop. However, the performance of serial 2 was better than that of serial 1 with complete compensation. In addition, when the frequency difference was large (like serial 2), dispersion (3.7 dBm) had greater influence on the transmission performance than dispersion slop (0.7 dBm). In contrast, when the frequency difference was small (like serial 1), dispersion slop (0.5 dBm) had greater influence on transmission performance than dispersion (0.2 dBm).

The difference of transmission performance between serials 1 and 2 was derived from the frequency difference of their sub-carriers between serials 1 and 2. To analyze the influence of the frequency difference on the transmission performance, the modulation and demodulation bandwidth were demonstrated in this paper. Figure 6 shows the received power versus demodulation bandwidth under the modulation bandwidths of 30, 40 and 50 GHz. The modulation bandwidth was the frequency difference of 4-ary FSK signal, and the demodulation bandwidth was the bandwidth of optical filter. As shown in Fig. 6, both the serials 1 and 2 with the same modulation bandwidths of 30, 40, 50 GHz, reached the best transmission performance at the same demodulation bandwidths of 25, 30, 30 GHz, respectively. Comparing to 30 GHz modulation bandwidth, the transmission performances of serials 1 and 2 with the modulation bandwidths of 40 and 50 GHz were improved greatly (about 1.6 dB). The power penalties of serial 1 with reference to serial 2 decreased from 0.6, 0.4 to 0.05 dBm at the best demodulation bandwidth with the modulation bandwidths of 30, 40, and 50 GHz. It indicates that larger frequency difference of sub-carriers can improve the transmission performance of 4-ary FSK signal.

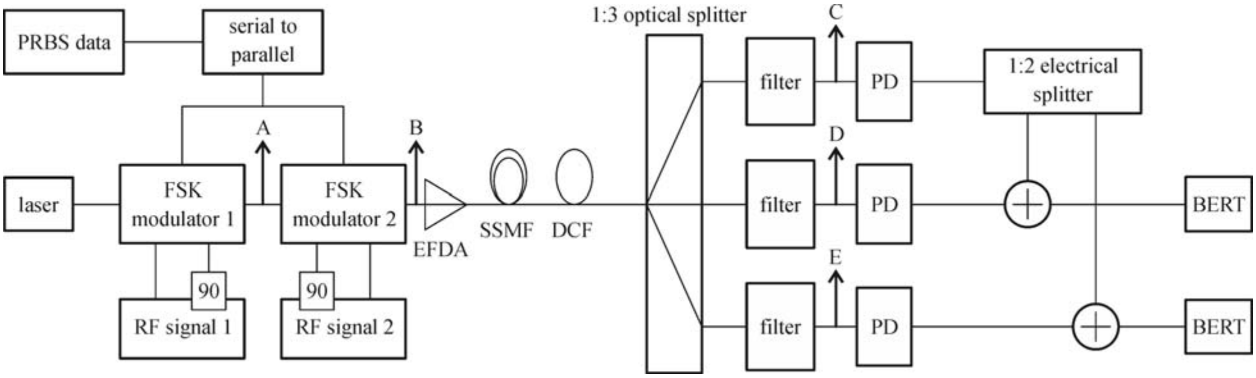


Fig. 2 Structure of 4-ary FSK transmission. PRBS: pseudo random binary sequence, RF: radio frequency, EDFA: Erbium doped fiber amplifier, SSMF: standard single mode fiber, DCF: dispersion compensation fiber, PD: photodiode, BERT: bit error rate tester

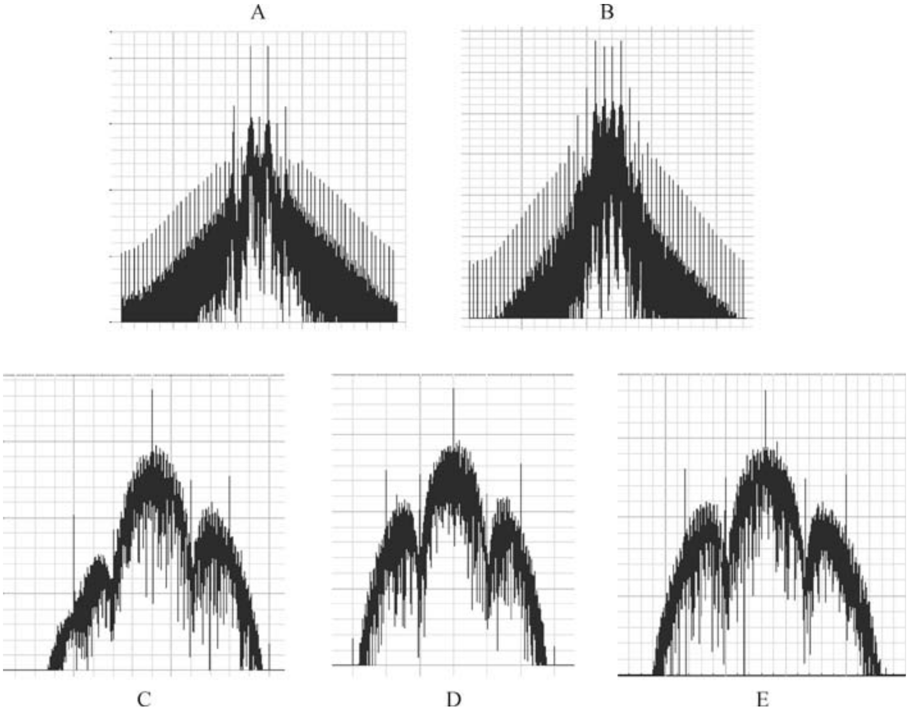


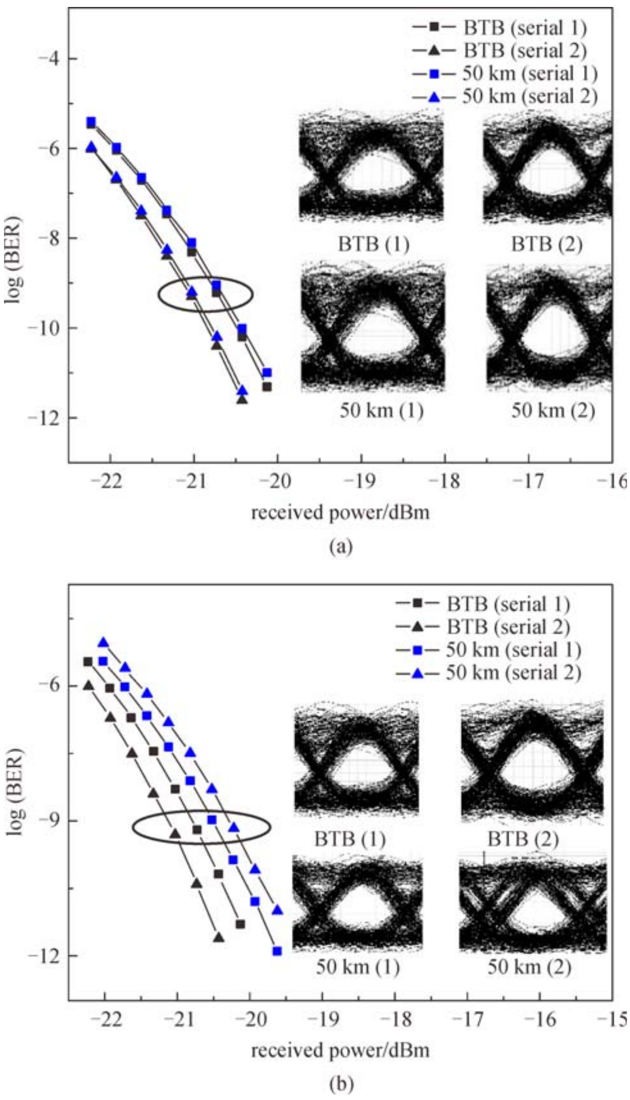
Fig. 3 Spectrums of A–E points in Fig. 2

We simulated the transmission performance of the 80 km SSMF. Figure 7 shows the BER performance versus the received power after 80 km SSMF. It can be seen that the power penalties after 80 km SSMF transmission comparing with 50 km SSMF at the BER of 10^{-9} were less than 0.1 dB. It suggested that the transmission performances were similar between 50 km SSMF and 80 km SSMF.

The central bandwidth of optical filters should be located at the frequencies of the 4-FSK sub-carriers. However, a certain error may be occurred. We analyzed the influence of the deviation of the central bandwidth on the transmission performance. Figure 8 shows the received power versus the deviation of the central frequency (193.04 THz) at the BER of 10^{-9}. It showed that the largest power penalty under different deviation was 0.4 dB compared with the deviation of 0.

4 Conclusion

We proposed a 4-ary FSK modulation scheme applying dual-parallel MZ modulator. The transmission performances of 4-ary FSK signal were carefully investigated. It indicated that the free error transmission can be realized after 50 km SSMF and 10 DCF transmission. The dispersion and dispersion slop were analyzed in this paper. The results showed that when the frequency



(a)

(b)

Fig. 4 Transmission performance of 4-ary FSK signal after 50 km SSMF and 10 km DCF. The dispersion slop of DCF is (a) -0.375 ps/nm^2/km and (b) 0.26 ps/nm^2/km

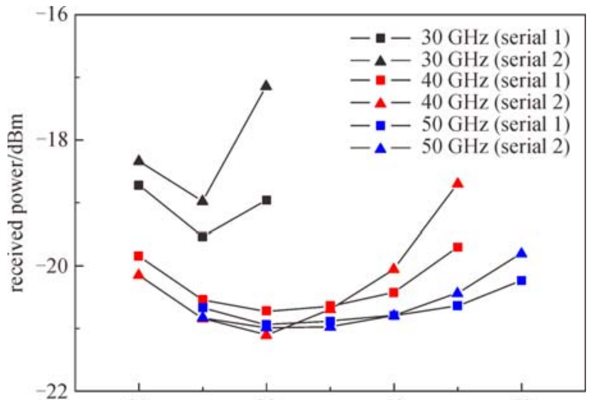
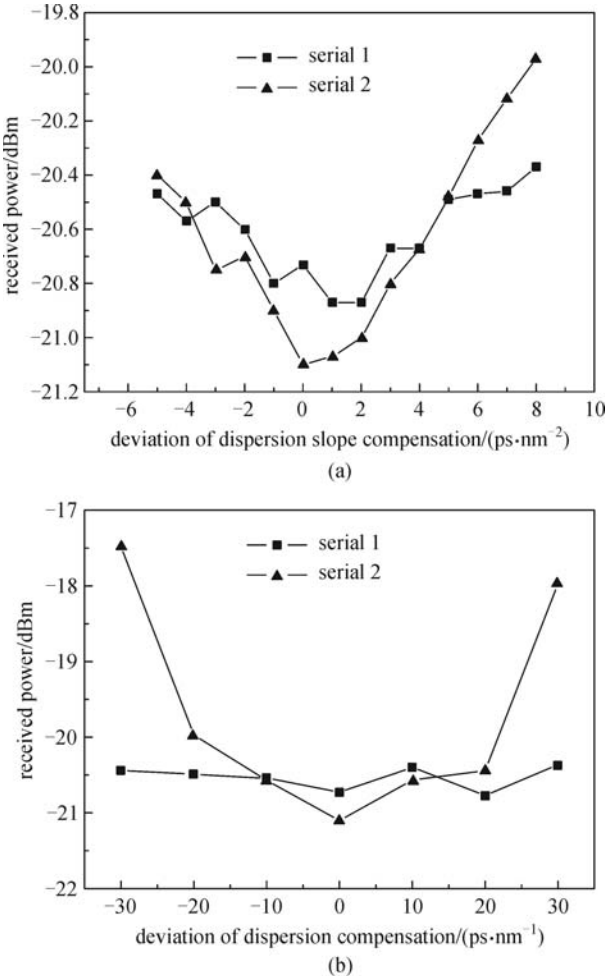


Fig. 6 Transmission performance of 4-ary FSK signal under different modulation and demodulation bandwidths



(a)

(b)

Fig. 5 Transmission performances of 4-ary FSK signal under different (a) dispersion slop compensations and (b) different dispersion compensations

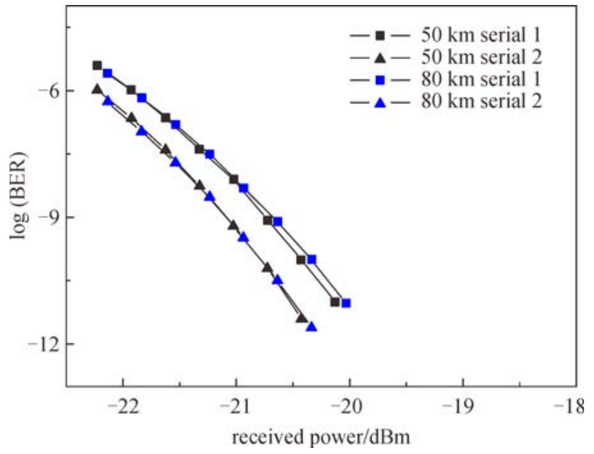


Fig. 7 BER performance versus received power

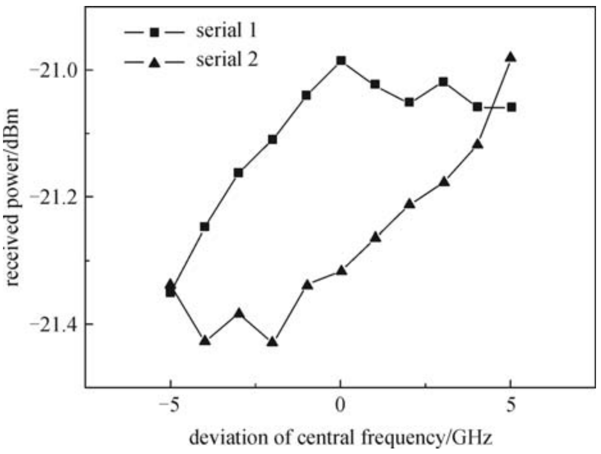


Fig. 8 Received power versus the deviation of central frequency

difference was large (like serial 2), dispersion (3.7 dBm) had greater influence on transmission performance than dispersion slop (0.7 dBm); however, when the frequency difference was small (like serial 1), dispersion slop (0.5 dBm) had greater influence on transmission performance than dispersion (0.2 dBm). In addition, the demodulation bandwidth and modulation bandwidth were demonstrated. The bandwidth analysis can provide the basic for selecting the frequency difference of sub-carriers.

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