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RESEARCH ARTICLE

Novel frequency shift keying modulation based on fiber Bragg gratings and intensity modulators

Liu YANG, Fengguang LUO (✉)

National Engineering Laboratory for Next Generation Internet Access System, School of Optical and Electronic Information,
Huazhong University of Science and Technology, Wuhan 430074, China

Abstract This paper proposed and investigated a novel frequency shift keying (FSK) modulation based on two fiber Bragg gratings (FBGs) and two intensity modulators. Then the transmission of 10 Gbit/s FSK signal after a 50 km single mode fiber (SMF) was studied in this paper. The power penalty at the bit error rate (BER) of 10^{-9} was below 0.1 dB. The FSK modulation system can be applied to optical transmission system

Keywords fiber Bragg grating (FBG), frequency shift keying (FSK), modulation mode, intensity modulator

1 Introduction

Optical label switching (OLS) is a promising approach in the future high-speed optical packet switching. One of the key techniques of the OLS is the modulation mode of the payload and label. Currently, there are some modulation modes, such as amplitude shift keying (ASK) based on the amplitude modulation, phase shift keying (PSK) based on the phase modulation and frequency shift keying (FSK) based on the frequency modulation [1–5], which have been applied to modulate the payload and label. FSK is a valuable modulation method in optical data modulation, as it not only improves the performance of the transmission of the payload and label, but also can be demodulated just with an optical filter.

FSK orthogonal modulation, combining the FSK and other modulation method (like the intensity modulation (IM) or the phase modulation (PM)), is a promising technology in the optical label switching [6,7]. In this technology, the label and the payload are modulated by IM (or PM) and FSK, respectively. The merit of this orthogonal modulation is that the demodulation process of the IM (or PM) label is independent from that of the FSK payload, that is, the label and the payload are processed without affecting each other. Right now, some results about FSK modulation have been reported [8–12], such as FSK transmitter based on an external FSK modulator consisting of six phase modulators [7–9] and FSK transmitter based on an integrated distributed feedback (DFB) laser-electro absorption (EA) modulator [10]. However, these approaches previous proposed are either lower in its transmission performance with speed below 10 Gbit/s, or difficult to realize with some immature devices. For example, the devices in Ref. [5] were hard to be produced, so it cannot be used in a wide range. In addition, the frequency response of the FSK modulator in Ref. [5]. was demonstrated that the 6 dB bandwidth was 17 GHz, where the FSK response over 10 GHz was diminished. The frequency of the sinusoidal signals should not be too high (12.5 GHz). Thus, the small frequency difference of the subcarriers can limit the FSK transmission. In the paper, we reported a FSK transmitter based on intensity modulators and FBGs, which can be widely applicable for civil use and has the larger frequency difference of the subcarriers.

2 FSK modulation system

Figure 1 shows the architecture of the FSK modulation. The $LiNiO_3$ Mach-Zehnder modulator (MZM) is biased at the null of the transmission curve and driven by the switching voltage with a sine wave. The amplitude of direct current (DC) voltage is equal to half-wave-voltage (V_π), and the amplitude of the sine wave is equal to twice the half-wave-voltage ($2V_\pi$). The phase difference between the sine wave signals at the two sides of the MZM reaches 180°. In this method, subcarriers were generated with the suppressing of optical carrier. Then two fiber Bragg

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E-mail: fgluo@hust.edu.cn

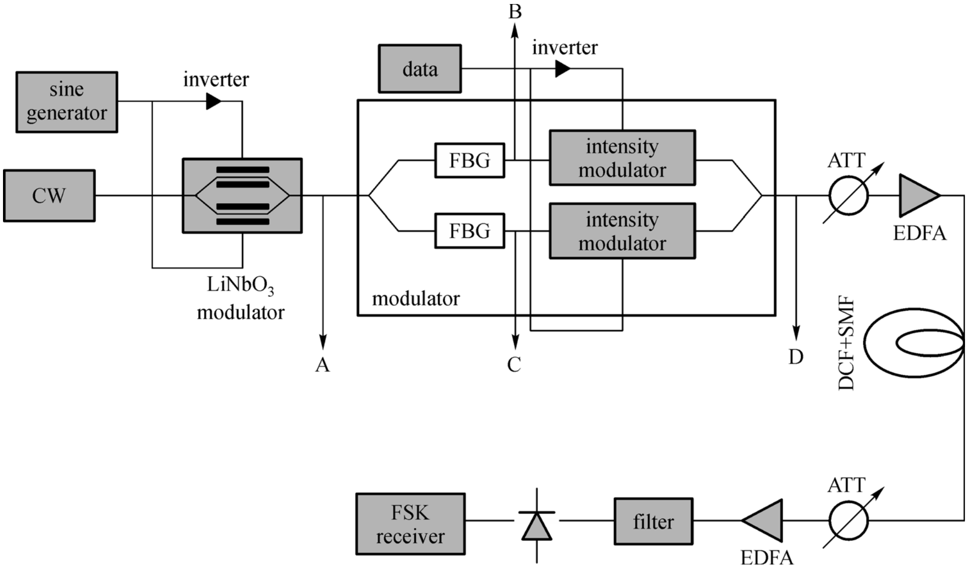


Fig. 1 Architecture of FSK modulation system. CW: continuous wave, FBG: fiber Bragg grating, ATT: attenuator, EDFA: erbium doped fiber amplifier, DCF: dispersion compensation fiber. SMF: single mode fiber, FSK: frequency shift keying

gratings (FBGs) whose center frequencies are correspond to the center frequencies of the subcarrier, respectively, were applied to filter the two subcarriers in this system. Therefore, through the FBGs, the subcarriers were separated into two optical beams with different frequencies. To realize symmetric optical spectrum, a reflective optical wave was used. As shown in Fig. 1, intensity modulators, connected after the two FBGs, respectively, modulate the input subcarriers from the two FBGs with the divided data signals from the pseudo random binary sequence (PBRS) generator. The signal in the upper modulator was reversed with that of the lower modulator, that is, the upper signal is 1 while the lower signal is 0 or the upper signal is 0 while the lower is 1. Thus, the optical beam was modulated by the data signal, and then the subcarriers carried different signals. The intensities of the two subcarriers were complementary and the amplitudes of the two subcarriers were equal. In this way, the FSK signal was generated with constant optical power.

The two FBGs and the two intensity modulators can be integrated on one silicon chip. The architecture of the integrated modulator is shown in Fig. 2. The FBGs are the transmission path, where the optical wave travels into the intensity modulator.

3 Simulation results and discussion

To investigate the performance of the FSK modulation in optical communication system, a 10 km dispersion compensation fiber (DCF) and a 50 km single mode fiber (SMF) transmission was set up, as shown in Fig. 1. The generated FSK signal was amplified and then sent to the 10 km DCF and 50 km SMF. At the receiver, an optical receiver unit consisting of a rectangle optical filter and a photodiode was employed.

Ten Gbit/s FSK signal and 50 GHz sine wave were used in the simulation. The parameters of two FBGs are 193.15, 193.05 THz (frequency), 1.45 (effective index), and 2 mm (length), respectively. The parameters of the rectangle optical filter are 193.15 THz (center frequency), and 30 GHz (bandwidth). The parameters of the photodiode are 1 A/W (responsivity), 10 nA (dark current), 1×10^{-22} W/Hz (thermal noise). The spectrum charts of the points (A, B, C, D) in Fig. 1 are shown in Figs. 3(a)–3(d), respectively. The eye diagram in Fig. 3(e), which is at the bit error rate (BER) of 10^{-15}, shows the demodulation of the FSK signal at the receiver unit. And Fig. 3(f) indicates the eye diagram, which is at the BER of 10^{-5}, without the 10 km DCF.

The BER performance versus the frequency of the sine wave is shown in Fig. 4. The simulation result shows that the BER was gradually reduced when the frequency of the sine wave was increased. Uniquely, the odd frequency of

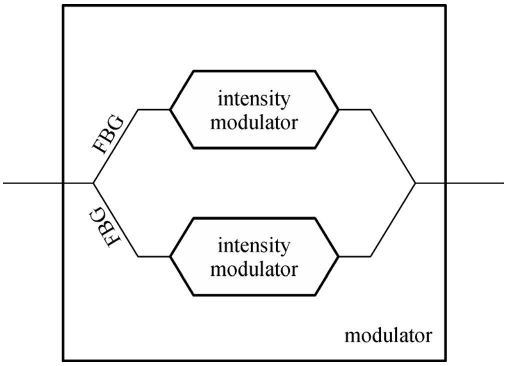
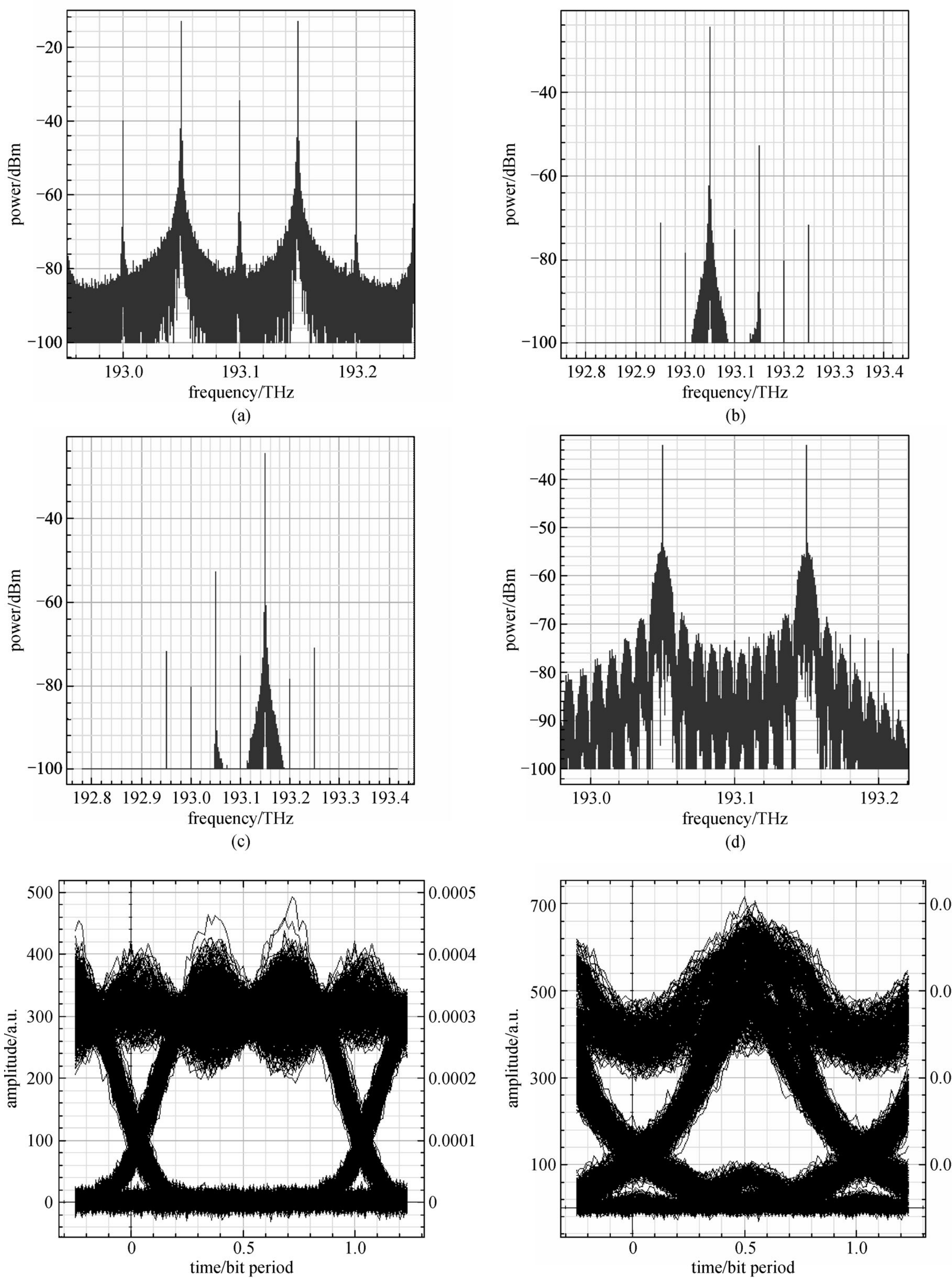


Fig. 2 Architecture of integrated modulator



(a) (b) (c) (d) (e) (f)

Fig. 3 (a)–(d) show the optical spectrum of the point A, B, C, D, respectively; (e) shows the eye-diagram of 10 Gb/s FSK signal at received unit; (f) shows the eye diagram of FSK signal without 10 km DCF

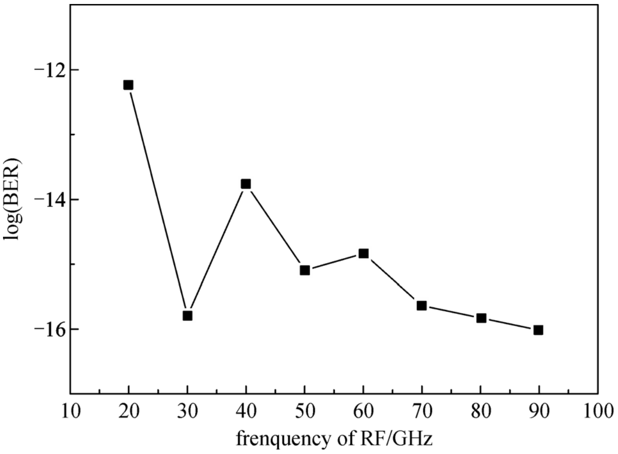


Fig. 4 Frequency of sine wave versus the BER of FSK signal

the sine wave is superior to the even frequency. The large difference between the frequencies can decrease the symbol interference which was induced when the two frequencies were coupled at the second 3 dB coupler.

Because the FSK signal was generated by the symmetric FBGs and the intensity modulators, the influences of the asymmetry between the upper and lower path on the FSK transmission performance need to be considered. Figures 5 and 6 show the time delay and the power difference in the two optical paths.

The BER of the FSK signal versus the time delay of the two optical waves is shown in Fig. 5. The time delay induced by the asymmetry of the FBGs and the intensity modulators was simulated. It was found that when the time delay was 0.5 bit, the BER of the FSK signal had a minimal value: the max *D*-value of the log(BER) < 1. Besides this point, the difference of the BER induced by the time delay can be neglected.

The BER versus the different amplitude between the upper and lower paths is shown in Fig. 6. As we can see from Fig. 6, the larger the difference between the amplitudes was, the better the BER was achieved. This is because the large amplitude difference can decrease the influence of two optical frequencies. Figure 6 also shows that when the amplitude difference was 3 dB, the log (BER) between 3 dB and 0 dB was less than 1. It suggests that the influence of the amplitude difference on BER performance is small.

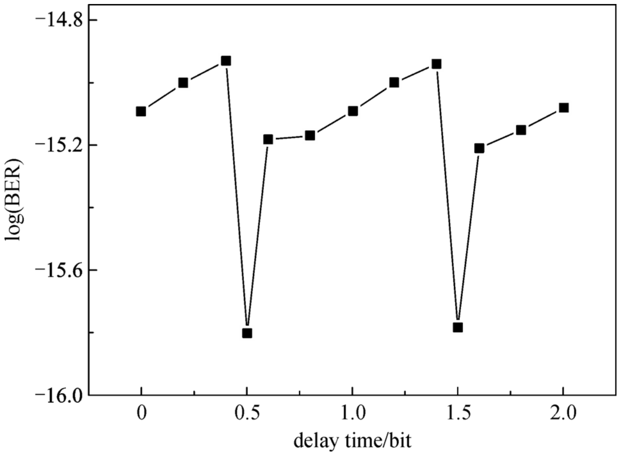


Fig. 5 BER of FSK signal versus the time delay of two optical waves

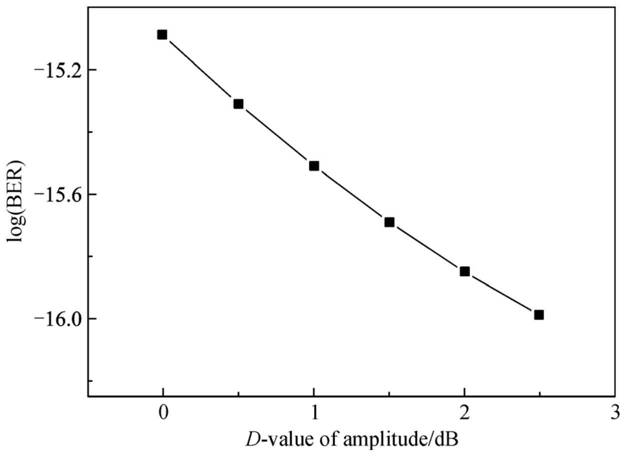


Fig. 6 BER of FSK signal versus the different amplitude between the upper and lower paths

The BER performance of the FSK signal versus the received power is shown in Fig. 7. Transmission span consisted of a 10 km DCF and 50 km SMF. The simulation result showed a < 0.1 dB power penalty at the BER of 10^{-9} for the FSK signal after 10 km DCF and 50 km SMF transmission. The power penalty had a significant improvement compared with 0.8 dB reported in Ref. [5].

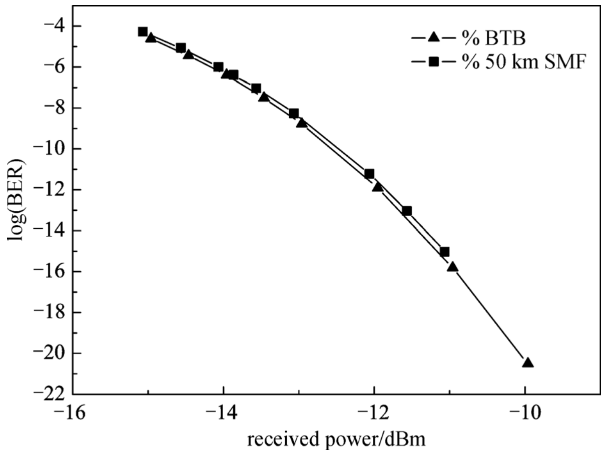


Fig. 7 Received power versus the BER of FSK signal. BTB: back to back

4 Conclusions

A novel FSK modulation architecture based on two FBGs and two parallel intensity modulators was proposed in this paper. Then we studied the transmission performance of the 10 Gbit/s FSK signal through the proposed FSK modulation system. Simulation result in this paper showed that < 0.1dB power penalty at the BER of 10^{-9} for the FSK signal was observed after 60 km transmission. In addition, we studied the influence of the frequency of the sine wave on the BER performance in this system. The asymmetry of the upper and lower path also studied in this paper. In conclusion, the FSK modulation system achieves the expected performance and can be applied to the optical transmission system.

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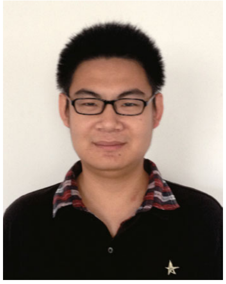

Liu Yang received his B.S. degree from Shandong University, Shandong, China, in 2012. Now, he is pursuing the Ph.D. degree in School of Optical and Electronic Information, Huazhong University of Science and Technology, Hubei, China. Now, his research interest is in the high-speed optical transmission system, especially in the advanced modulation formats.

Fengguang Luo received his B.S., M.S. and Ph.D. degrees from Huazhong University of Science and Technology, China, in 1984, 1989 and 1999, respectively. From 1984 to 1986, he spent two years at Wuhan Research Institute of Posts & Telecommunications in China. Since 1989, he has been working at School of Optical and Electronic Information, Huazhong University of Science and Technology. His research interests are optical communication and optical switch.