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Characterization of an optical frequency-shift-keying transmitter based on carrier-suppressed phase modulation

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ABSTRACT

We experimentally characterize an optical frequency-shift-keying transmitter based on optical carrier-suppressed phase modulation. Only one laser source is needed to generate an optical FSK signal. The demonstration of 10-Gb/s FSK signal generation and 50-km transmission verified the improved performance of the proposed transmitter, compared with the previous two-laser schemes. To further reduce the complexity of the transmitter, the phase modulator is omitted and a single MZM modulator is used for both optical carrier-suppression (OCS) and phase modulation. This simplified structure is verified by simulation, implying the feasibility that a FSK transmitter can be constructed with only one laser source and one modulator.

1. Introduction

Optical frequency-shift keying (FSK) has attracted increasing research attention in recent years, due to its constant intensity envelope which can support many networking applications [1–5]. An early scheme of the optical FSK transmitter was based on direct modulation of a distributed feedback (DFB) or a tunable laser [1], where the performance was limited by the response of the laser. In [2], a novel optical FSK transmitter was proposed based on an optical phase modulator (PM). By feeding two phase-modulated optical carriers into an optical delay interferometer (DI), they were converted into two complementarily intensity-modulated signals and thus an optical FSK signal was generated. This scheme was able to operate at high speed with good performance. However, it comprised two laser sources and had limitation on frequency spacing. In [3], another FSK transmitter based on the polarization modulation in the PM was proposed. The structure can continuously tune the wavelength spacing but the polarizations of the two lasers required careful adjustment in order to meet their orthogonal relations. Recently, an optical FSK transmitter was proposed by using a single laser source [4]. It utilized a specialized integrated optical modulator consisting of four parallel phase modulators, which made its structure complicated and expensive. In [5], a FSK transmitter was proposed with OCS, but an unconventional and special-designed asymmetric modulator was used, which limited its operation speed and cost.

In this paper, we experimentally demonstrate a novel optical FSK transmitter using a single laser source and commercial electro-optical modulators. A continuous-wave (CW) optical carrier is employed to generate two coherent sub-carriers via OCS modulation [6,7]. The two generated sub-carriers are then fed into a PM, followed by a DI to form the optical FSK signal. Compared with previous schemes, our proposed transmitter has simpler structure and improved performance. The proposed transmitter has been experimentally demonstrated and the performance of the generated optical FSK signal has been characterized. We further simplify the structure by using one MZM modulator for both OCS and phase modulation, whose feasibility was verified by simulation.

2. Transmitter structure and operation principle

Fig. 1a illustrates the structure and the operation principle of the proposed optical FSK transmitter. A single CW light beam, f, is first fed into a Mach–Zehnder modulator (MZM) biased at its null point and driven by an electrical clock. The optical carrier, f, is suppressed and two coherent sub-carriers, f_{sub1} and f_{sub2} are generated by the MZM through OCS. We assume the driving sinusoidal clock has a frequency of f_c (Hz) and thus the frequency spacing between the newly generated sub-carriers is $2f_c$ after OCS. Then the two sub-carriers are modulated by the differentially pre-coded data at B bits/s via a $LiNbO_3$ optical phase modulator (PM) to generate two differential phase-shift-keying (DPSK) signals before fed into a DI, whose relative arm delay is about $1/B$ s. The DI demodulates the two DPSK signals and converts the phase-modulated signals into intensity-modulated ones. Given the frequency-dependent characteristics of DI, whose typical frequency response is shown

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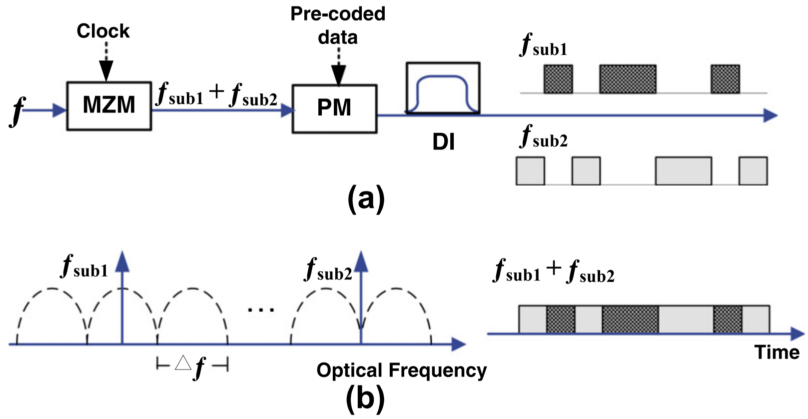

Fig. 1. FSK transmitter and operation principle. (a) Proposed FSK transmitter consisting of a Mach–Zehnder intensity modulator (MZM) and a phase modulator (PM) and (b) frequency response of DI and the generated FSK signal. MZM: Mach–Zehnder modulator. PM: phase modulator, OCS: optical carrier suppression, DI: delay interferometer, f: optical CW carrier, f_{sub1} and f_{sub2}: the two generated sub-carriers. Δf: the period of DI's frequency response.

in Fig. 1b, the two demodulated signals have complementary intensity characteristics only if one signal has its carrier frequency set at the maximum transmission point of the DI and the other has its carrier frequency set at the minimum transmission point of the DI. Therefore, the generated two sub-carriers should be aligned with the DI response curve as shown in Fig. 1b. One of the sub-carriers is located at the maximum transmission point and the other one is at the minimum transmission point of the DI response curve to guarantee the demodulated DPSK signals have complementary intensity as in Fig. 1a. Thus, the combined signal as shown in Fig. 1b, has an constant intensity and forms an FSK signal. For analysis convenience, the relations among clock, MZM, DI are illustrated as following equations:

$$V_p = V_\pi \tag{1}$$

$$f_{sub2} - f_{sub1} = 2f_c \tag{2}$$

$$f_{sub2} - f_{sub1} = \Delta f \cdot (m + 1/2) \tag{3}$$

where V_p is the amplitude of the clock, V_π is the half-wave voltage of the MZM, m is a positive integer, Δf is the period of the frequency response of the DI. Eq. (1) shows the constraint for the amplitude of the clock to enable OCS. Eq. (2) shows the relation between the two generated sub-carriers through OCS. Eq. (3) guarantees that one of the sub-carriers is set at the maximum transmission point and the other one is at the minimum transmission point of the DI response curve. From (1)–(3), the frequency of clock signal should satisfy the following condition: $2f_c = (m + 1/2)\Delta f$ in order to generate an FSK signal employing the proposed scheme.

3. Experiment and results

Fig. 2a illustrates the experimental setup of the proposed scheme. A CW light at 1550.19 nm was first fed into a 40-Gb/s optical intensity modulator, driven by an 18.61-GHz clock to perform OCS and create two sub-carriers. The frequency f_c = 18.61 GHz was chosen to match the DI's relative delay 94.3 ps. That is, Δf = 10.64 GHz, so the relation $2f_c = (m + 1/2)\Delta f$ was satisfied

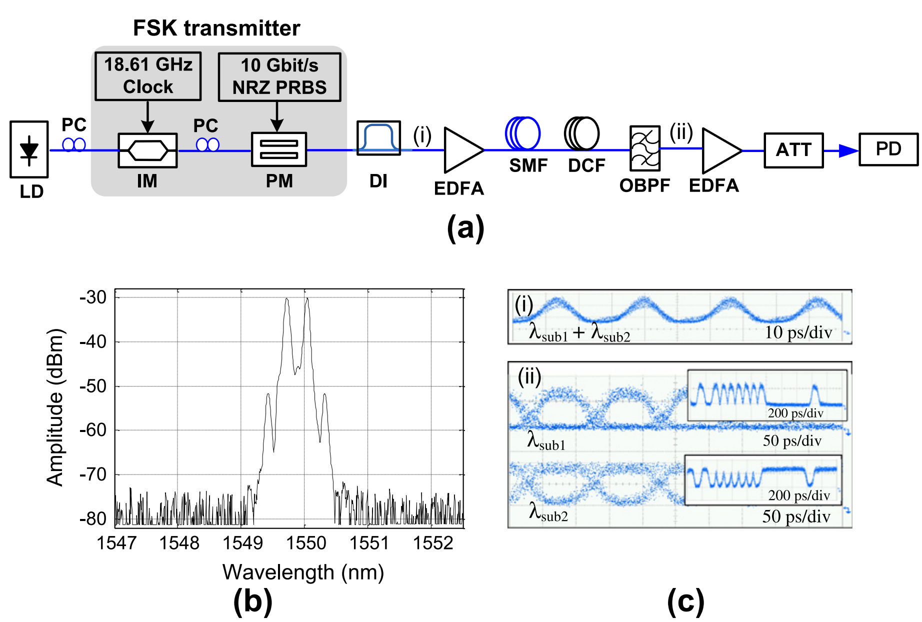

Fig. 2. (a) Experimental setup. (b) The optical spectrum after intensity modulator (IM) for optical carrier suppression with resolution bandwidth of 0.08 nm. (c) Measured waveform of ($\lambda_{sub1} + \lambda_{sub2}$) after DI and their respective signal after OBPF. LD: laser diode, IM: intensity modulator, PC: polarization controller, PG: pattern generator, PM: phase modulator, EDFA: erbium-doped fiber amplifier, ED: error detector, OBPF: optical tunable band-pass filter, SMF: single mode fiber, DCF: dispersion compensation fiber.

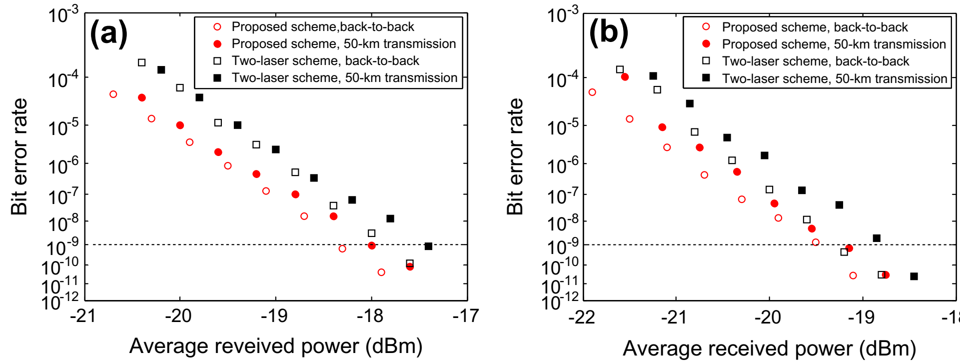

Fig. 3. BER of the 10-Gb/s optical FSK signals using the proposed OCS scheme and the two-laser scheme [2], respectively, when the frequency spacing of the two FSK sub-carriers is (a) 26.6 GHz and (b) 37.22 GHz.

where $m = 3$. Therefore, one of the sub-carriers was located at the maximum transmission point of the DI's response curve while the other was at the minimum point. The carrier suppression ratio was about 16 dB and the spacing between the sub-carriers was 0.3 nm (or 37.22 GHz), as shown in Fig. 2b. The OCS signal was then modulated by a 10-Gb/s non-return-to-zero (NRZ) $2^{31} - 1$ pseudorandom binary sequence via a $LiNbO_3$ PM. The output of the PM was then fed into the DI with a relative delay of 94.3 ps to demodulate the phase modulated signals into two complementarily intensity modulated signals. After that, the two demodulated signals with complementary intensity forms an optical FSK signal and then amplified by an erbium-doped fiber amplifier (EDFA) to about 5 dB m before being coupled into 50-km single mode fiber (SMF), followed by a piece of 8-km dispersion compensating fiber (DCF). At the receiver side, an optical band-pass filter (OBPF) with a 3-dB bandwidth of 0.2 nm was used to demodulate the FSK signal.

Fig. 2c first shows the waveform of the generated FSK signal captured after DI. This combined signal shows a sinusoidal waveform, which may be mainly attributed to the sinusoidal clock used to modulate the optical CW. Besides, phase modulation may also induce some intensity fluctuations of the FSK envelope. Fig. 2c also shows eye diagrams of the demodulated FSK signals after the OBPF, as well as their waveforms in the insets. Widely-open eyes can be observed implying a good performance. And the waveforms of the demodulated FSK signals shown in the insets are complementary to each other.

Fig. 3 shows the measured bit error ratio (BER) of the optical FSK signals based on the proposed scheme in the back-to-back case and after 50-km-SMF transmission at FSK carrier frequency spacing of (a) 26.6 GHz (where $m = 2$) and (b) 37.22 GHz (where $m = 3$). In Fig. 3a, in which the sub-carrier frequency spacing is 26.6 GHz, the receiver sensitivity at BER = 10^{-9} was -18.4 dB m for the back-to-back case and around 0.4-dB power penalty was observed after 50-km transmission with partial dispersion compensation by the DCF. For comparison, we have also measured the BER of the optical FSK signals generated by the previous two-laser scheme [2]. It shows the proposed scheme had around 0.6-dB better sensitivity than the two-laser scheme when the frequency spacing was 26.6 GHz. Similarly, as shown in Fig. 3b, in which the sub-carrier frequency spacing is 37.22 GHz, the proposed scheme showed a receiver sensitivity of about -19.5 dB m at BER = 10^{-9} for back-to-back case and was around 0.2-dB better than the two-laser scheme. This is attributed to the fact that the beating of the two individual lasers would induce intensity fluctuation [2], while the proposed scheme produced two coherent sub-carriers which avoided such beating, thus the beating-induced intensity fluctuation could be alleviated.

The receiver sensitivity of the optical FSK signal at BER = 10^{-9} was further characterized at different frequency spacing, as shown in Fig. 4. It is shown that the optical FSK signal achieved the best performance at the frequency spacing of 58.5 GHz after 50-km transmission. When the sub-carrier frequency spacing was further increased, the signal suffered from more degradation due to higher accumulated dispersion and poorer extinction ratio of OCS at higher driving frequency. On the other hand, too narrow frequency spacing limited the FSK demodulation performance using the 0.2-nm OBPF, or a narrower OBPF should be used.

In our proposed FSK transmitter, a MZM biased at the null point is employed to generate two sub-carriers through OCS and a PM to realize phase modulation. However, phase modulation can not only realized by a PM, but also by a MZM when the MZM is biased at the null point and the peak-to-peak amplitude of data signal is set $2V_\pi$. Since OCS and phase modulation can potentially be implemented in a single MZM simultaneously, the proposed FSK transmitter can be further simplified by omitting a PM, as shown in Fig. 5. The mechanisms to generate FSK signals in both proposed FSK transmitter and the simplified one are exactly the same. Therefore, the frequency and amplitude of the clock signal satisfy the same condition, except for the amplitude of the data signal, whose peak-to-peak value should be $2V_\pi$ in order to realize phase modulation in a MZM.

We have setup up simulations to investigate the performance for the transmitters both in Figs. 1 and 5. Simulation results of BER performances after 50-km transmission employing both transmitters are shown in Fig. 6, when the FSK frequency spacing

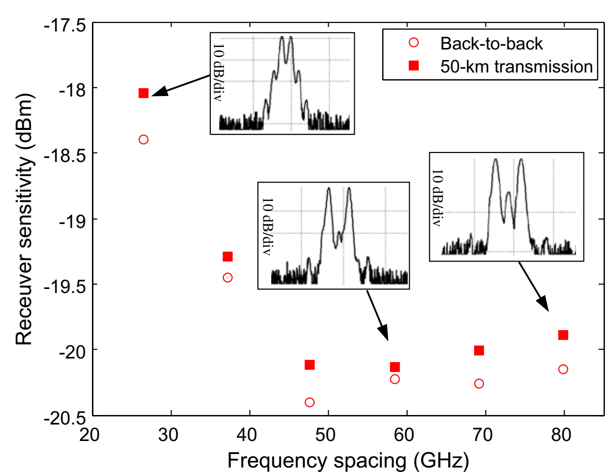

Fig. 4. Receiver sensitivity at 10-Gb/s at different frequency spacing of the two sub-carriers. Insets show the respective optical spectra at the selected frequency spacing values.

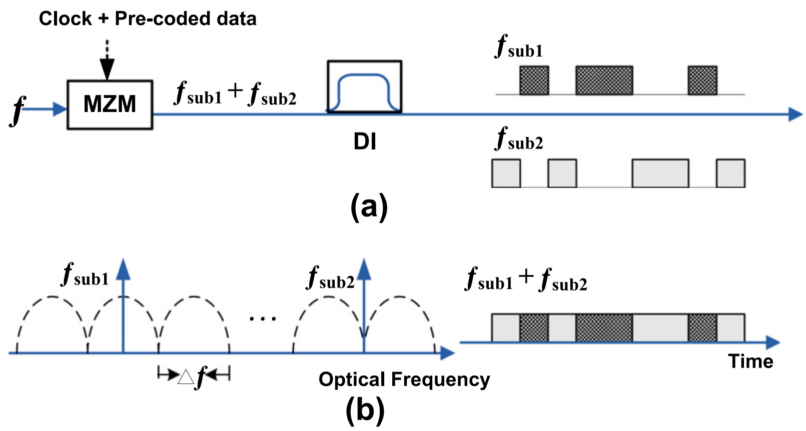

Fig. 5. Simplified FSK transmitter. (a) Simplified FSK transmitter consisting of one MZM and (b) frequency response of DI and the generated FSK signal.

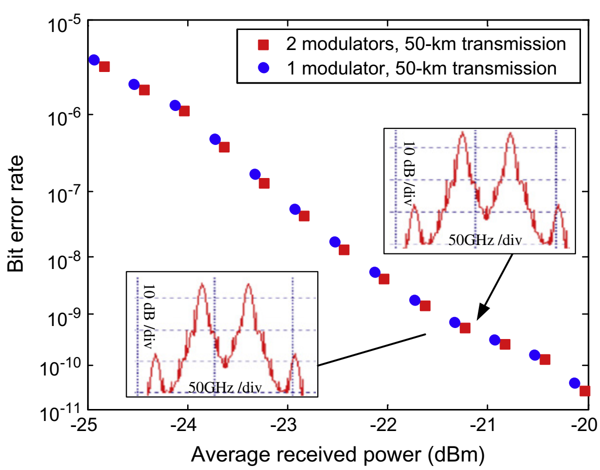

Fig. 6. Simulation results of BER performance after 50-km transmission employing two modulator scheme (■) and one modulator scheme (●) with a clock signal of 18.61-GHz when the FSK frequency spacing is 37.22 GHz.

is 37.22 GHz. The simplified structure with single MZM modulator performed similarly with the structure using two modulators. The optical spectra at the output ports of the transmitters, shown in the insets of Fig. 6, had similar properties. The receiver sensitivities for both schemes at BER = 10^{-9} were around −21.5 dB m. Note that the simplified structure employing one MZM requires an extra electrical high-frequency combiner.

4. Summary

We have experimentally demonstrated a high-speed optical FSK transmitter based on optical carrier suppressed phase modulation. The transmitter utilizes only one laser source and avoids using any complicated modulators. Experimental demonstration proved the good signal performance generated by the proposed transmitter. Compared with the previous scheme using two lasers, this transmitter allows narrower channel spacing which can potentially improve the spectral efficiency and transmission performance.

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