Generation of optical carrier suppressed-differential phase shift keying (OCS-DPSK) format using one dual-parallel Mach-Zehnder modulator in radio over fiber systems

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Abstract: We present and experimentally demonstrate a new method to generate optical carrier suppressed-differential phase-shift keying (OCS-DPSK) modulation format in radio over fiber (RoF) systems. In our scheme, a single dual-parallel Mach-Zehnder modulator (DPMZM) is used to produce OCS-DPSK signal based on amplitude shift keying (ASK) to DPSK format conversion by suppressing the spectral tones of an OCS-ASK signal.

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1. Introduction

Radio over fiber (RoF) has become a promising method in providing broadband wireless access with increased mobility and reduced cost [1]. In RoF systems, the generation of millimeter-wave (MMW) and all-optical up-conversion of baseband data are key techniques to realize high transmission performance. Optical carrier suppression (OCS) technique with intensity modulation, i.e., optical carrier suppressed–amplitude shift keying (OCS-ASK) format, was demonstrated to show the simplicity in system configuration and good performance in long distance transmission [2-5].On the other hand, differential phase-shift keying (DPSK) format has attracted significant interest as it can enhance the signal's robustness to chromatic dispersion and cross-phase modulation impairment [6]. Moreover, since the DPSK signal is a constant-intensity phase-modulated format, the ASK signal can be superimposed onto the DPSK signal to form hybrid ASK/DPSK format for spectral-efficiency improvement [7-11], and the downlink DPSK signal can be used as the optical carrier for uplink re-modulation to reduce the system cost [12-14]. Therefore, it is desirable to transmit OCS-DPSK format in RoF systems for more flexible applications in future broadband access networks. Recently, several experimental demonstrations based on OCS-DPSK modulation have been performed. Ref. [15] has shown a bi-directional RoF system with OCS-DPSK format for downlink signal delivery, and the uplink data transmission was realized by re-modulating the downlink OCS-DPSK data. A full-duplex multi-band RoF system [16] based on OCS-DPSK modulation format exhibited good feasibility to provide multi-services. In these OCS-DPSK modulation schemes [15, 16], two cascaded optical modulators are required, where one phase modulator or Mach-Zehnder modulator (MZM) is employed to produce a DPSK data and a following MZM biased at the transmission null for up-converting the DPSK data to MMW to produce an OCS-DPSK format.

In this paper, we propose a simple method to generate OCS-DPSK signal using a single dual-parallel Mach-Zehnder modulator (DPMZM) [17]. Based on non-return-to-zero (NRZ)-ASK to NRZ-DPSK format conversion, the OCS-DPSK format is generated by suppressing the spectral tones of the OCS-ASK signal. Since the DPMZM is a commercial off-the-shelf device fabricated on a single chip, our scheme enables the transmitter to possess a compact structure, convenient alignment, and small insertion loss compared with conventional OCS-DPSK transmitters.

2. Theory and operation principle

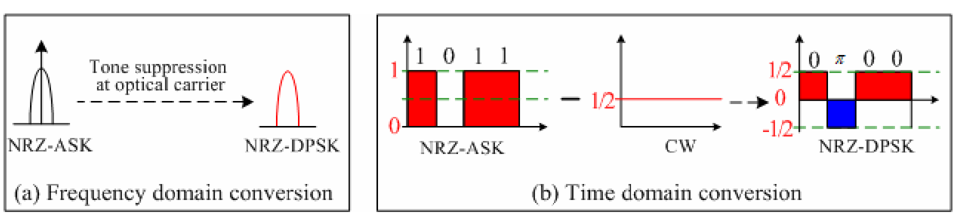

Fig. 1. Schematic diagram of ASK to DPSK conversion.

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The optical spectrum of the NRZ-ASK signal consists of continuous spectral components corresponding to the data pulse, and a discrete tone at the carrier wavelength. The spectral density $P_{NRZ-ASK}(f)$ can be described as [18]:

$$P_{NRZ-ASK}(f)=\frac{T_s}{16}\left[\left|\frac{\sin\pi(f+f_c)T_s}{\pi(f+f_c)T_s}\right|^2+\left|\frac{\sin\pi(f-f_c)T_s}{\pi(f-f_c)T_s}\right|^2\right]+\frac{1}{16}[\delta(f+f_c)+\delta(f-f_c)] \quad (1)$$

where f_c is the optical carrier and T_s is the bit period. While for the DPSK signal, the optical power is constant and the optical field shifts between"1" and "-1", thus the average optical field is zero and there is no carrier component in the optical spectrum of the DPSK signal [19]. The spectral density $P_{NRZ-DPSK}(f)$ is given by [18]:

$$P_{NRZ-DPSK}(f)=\frac{T_s}{4}\left[\left|\frac{\sin\pi(f+f_c)T_s}{\pi(f+f_c)T_s}\right|^2+\left|\frac{\sin\pi(f-f_c)T_s}{\pi(f-f_c)T_s}\right|^2\right] \quad (2)$$

Equation (1) and (2) show that the spectra of the two formats are identical except the discrete carrier tone $1/16[\delta(f+f_c)+\delta(f-f_c)]$. Figure 1(a) illustrates such relation between the NRZ-ASK and the NRZ-DPSK formats in frequency domain, where the NRZ-DPSK is generated by suppressing the carrier tone of the NRZ-ASK. On the other hand, in time domain, if the optical NRZ-ASK signal subtracts a CW light with a half amplitude but the same frequency and phase, the "0" bit of the NRZ-ASK becomes "-1/2", and the subtraction of the CW from the "1" bit results in "1/2". Consequently, the amplitude of the resulting signal keeps identical and the phase alternates between 0 and π, as shown in Fig. 1(b). Thus, an NRZ-ASK signal is converted into an NRZ-DPSK format by eliminating the tone at the carrier of the NRZ-ASK signal [20].

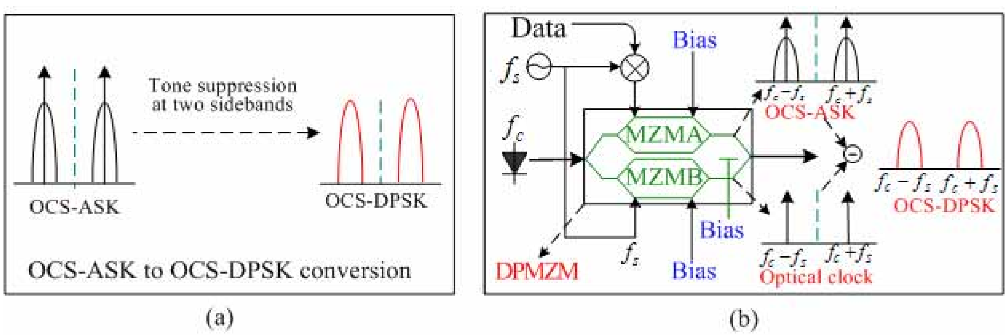

Fig. 2. Schematic diagram of the OCS-ASK to OCS-DPSK conversion (a) and the architecture of the OCS-DPSK signal generation based on a single DPMZM (b).

This can be applied to achieve the conversion from OCS-ASK to OCS-DPSK format, as illustrated in Fig. 2(a), where the OCS-DPSK signal is generated by suppressing the two tones of the OCS-ASK signal, which can be implemented using one DPMZM. The DPMZM [17] consists of a pair of x-cut LiNbO3 MZMs (MZMA, MZMB) embedded in the two arms of a main MZM structure. The two sub-MZMs have the same architecture and performance, and the main MZM combines the outputs of the two sub-MZMs. The DPMZM have three bias ports, which belong to the two sub-MZMs and the main modulator, respectively. Fig. 2(b) plots the architecture of the OCS-DPSK signal generation based on the DPMZM. An

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electrical sub-carrier multiplexed (SCM) signal is obtained by mixing a baseband data with a local oscillator (LO) signal. The sub-MZMA is biased at its transmission null and driven by the SCM signal to generate an OCS-ASK format [5], which equals to two NRZ-ASK components with a spacing of twice the LO frequency. The sub-MZMB is also biased at the null and driven by a same LO signal to generate an optical clock signal, which compromises two CW lights with the same frequency spacing as the OCS-ASK signal. The two optical signals from the two sub-MZMs are destructively combined by adjusting the bias of the main MZM. It should be noted that the two optical signals need to have a proper intensity ratio and phase matching, which can be adjusted by changing the amplitudes of the two electrical driving signals and controlling an electrical phase shifter, respectively. Then, the two tones of the optical OCS-ASK signal are completely counteracted by the optical clock and thus result in an OCS-DPSK signal. Therefore, the generation of the OCS-DPSK format is dependent on the intensity ratio and the phase matching of the two modulating signals. The mismatch of these parameters results in residual tones in the generated OCS-DPSK, causing certain power fluctuations and thus degrading the signal performance. However, once the optimized parameters are set, they do not drift much and can maintain good stability in operation.

3. Experimental results

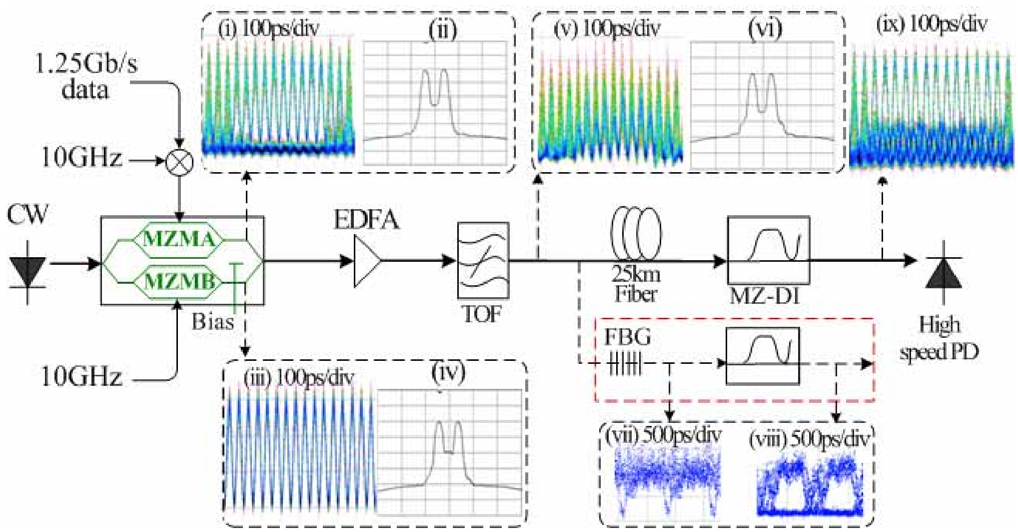

Fig. 3. Experimental setup for the generation of OCS-DPSK based on the DPMZM. Spectrum resolution: 0.07 nm; Start wavelength: 1548.86nm; Stop wavelength: 1550.86nm; The X axis scale is 0.2 nm/div, the Y axis scale is 5 dB/div. (i) The optical eye diagram of the OCS-ASK signal, (ii) The optical spectrum of the OCS-ASK signal, (iii) The optical eye diagram of the optical clock signal, (iv) The optical spectrum of the optical clock signal, (v) The optical eye diagram of the OCS-DPSK signal, (vi) The optical spectrum of the OCS-DPSK signal, (vii) The optical eye diagram of the filtered sideband, (viii) The optical eye diagram of the filtered sideband after MZDI demodulation, (ix) The optical eye diagram of the OCS-DPSK signal after MZDI demodulation.

Figure 3 shows the experimental setup for the generation and transmission of the OCS-DPSK signal. At the central station (CS), a 10-GHz DPMZM (COVEGA Mach-10^{TM}060, 5.8-dB insertion loss) is used to modulate a CW light. The V_π of the two sub-MZMs is 5.6 V at direct current (DC) frequency and that of the main MZM is 5.2 V. An electrical SCM signal is obtained by mixing a 1.25-Gbps pseudo-random bit sequence (PRBS) baseband data of a 2^7-1 word length with a 10-GHz LO signal. Then the electrical SCM signal is amplified (~6.8-V peak-to-peak voltage) to drive the sub-MZMA, which is biased at the transmission null to obtain an OCS-ASK signal with a 20-GHz frequency spacing, the optical eye diagram and the optical spectrum of the OCS-ASK signal are provided in Fig. 3(i) and Fig. 3(ii), respectively.

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The sub-MZMB is also biased at the null and driven by an amplified 10-GHz LO signal (~5.5-V peak-to-peak voltage) to generate an optical clock with the same frequency spacing, the optical eye diagram and the optical spectrum are shown in Fig. 3(iii) and Fig. 3(iv), respectively. There is no obvious difference between the optical spectra of Fig. 3(ii) and (iv) due to the limited resolution of the optical spectrum analyzer (OSA) of 0.07 nm. The two optical signals from the two sub-MZMs are destructively added to produce OCS-DPSK format, which is then amplified by an erbium-doped fiber amplifier (EDFA). The amplified spontaneous emission (ASE) noise is suppressed by a tunable optical filter (TOF) with 3-dB bandwidth of 0.4 nm. The optical eye diagram and the optical spectrum are shown in insets (v) and (vi) of Fig. 3, respectively. For the particular device we used, the tones of the OCS-ASK signal are not completely suppressed and the generated OCS-DPSK contains residual tones, which show small intensity modulation and cause certain power fluctuation in the optical eye diagram (v). This issue can be resolved if a DPMZM with better performance is used. Currently, there are such commercially available modulators of choices with the advance in device technology. We use a fiber Bragg grating (FBG) to filter one sideband of the OCS-DPSK signal for detection, the eye diagrams of the filtered tone (in Fig. 3(vii)) and after the Mach-Zehnder delay interferometer (MZDI) demodulation (in Fig. 3(viii)) further verify that the generated signal is an OCS-DPSK format. After transmission over a 25-km standard single-mode fiber (SMF), the 1-bit MZDI is used to convert the OCS-DPSK signal into an intensity signal with the optical eye diagram after MZDI demodulation shown in Fig. 3(vii). The MZDI is made from two couplers, where the length difference between the two arms to realize 1-bit delay is ~15.96 cm for the 1.25-Gb/s DPSK signal. There are some ripples in the eye diagram due to the imperfect OCS-DPSK signal. In practice, a high-speed receiver is needed to convert the demodulated optical signal to a 20-GHz electrical wireless signal for broadcasting through an antenna. At the receiver, the 20-GHz wireless signal is down-converted to baseband by mixing with a 20-GHz LO signal [4] for BER detection. In this particular experiment, we focus on the OCS-DPSK signal generation and transmission, and the signal is detected using a method similar to that in [16], where the bit-error-ratio (BER) measurements is performed by detecting the upper-sideband component employing a 2.5-GHz low-speed photo-detector (PD) due to the lack of high-speed electronics. The detected electrical eye diagram is provided in Fig. 4(a). The measured BER performance after transmission of the 25-km SMF is indicated in Fig. 4(b), where the receiver sensitivity is ~ -11.5 dB. Compared with the back-to-back case, the power penalty is less than 1.2 dB, which can be attributed to the chromatic dispersion of the SMF in RF frequency band, and the residual components during the generation process of the OCS-DPSK signal. We compare the difference of the BER performances in the receivers between filtering one side-band and using a mixer for the down-conversion [4] by VPI simulation software. The recovered signals based on the two detection methods show similar quality, and the penalties for the signal through 25-km transmission with the two detection schemes are almost the same.

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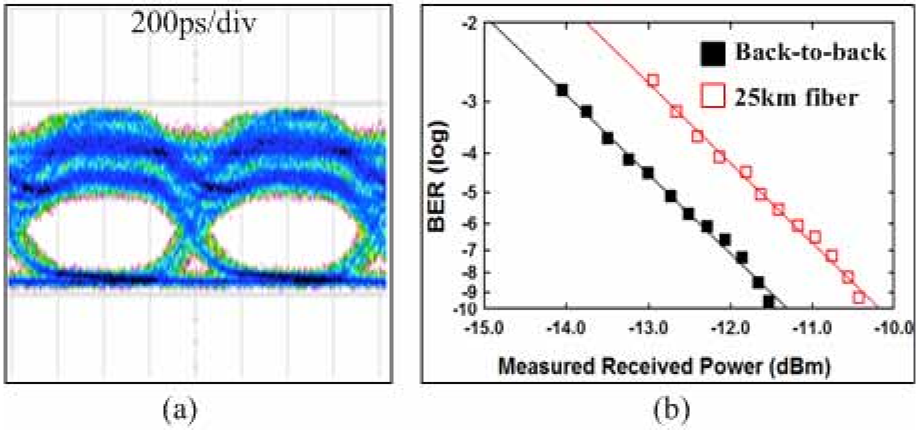

Fig. 4. Electrical eye diagram (a) and BER curves (b).

4. Conclusion

We have proposed a simple scheme to obtain the OCS-DPSK format using only one integrated DPMZM based on ASK to DPSK conversion technique with a linear processing. We experimentally demonstrated the generation and transmission of 1.25-Gb/s DPSK data at 20-GHz microwave frequency, the power penalty after the 25-km fiber transmission is less than 1.2 dB. The use of the single DPMZM enables the transmitter to possess a compact structure.

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