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A novel wavelength shift keying transmitter using a pair of Mach–Zehnder modulators

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Abstract

A novel and simple method to achieve wavelength shift keying (WSK) modulation is proposed and experimentally demonstrated. The proposed WSK transmitter consists of a pair of Mach–Zehnder modulators (MZMs) that are biased appropriately to achieve complementary operation. When a non-return-to-zero data stream is applied to the two MZMs, thanks to the complementary operation of the MZMs, the WSK-modulated signal can be obtained by combining the two intensity-modulated optical signals. A tunable optical delay line (ODL) is applied to achieve synchronization between the two optical signals. The ODL can also be used to compensate for the dispersion-induced walk-off effect between the two optical carriers. The application of the proposed WSK transmitter in a passive optical network is demonstrated, in which the downstream WSK signal is reused as optical carrier for upstream intensity-modulated data transmission. The proposed approach is experimentally realized; experimental results verify the feasibility of the approach.

Keywords: Optical communications; Modulation formats; Wavelength shift keying; Optical frequency shift keying; Mach–Zehnder Modulator; Passive optical network

1. Introduction

Wavelength shift keying (WSK) or optical frequency shift keying (OFSK) has been a topic of research interest recently. Due to the feature of constant light intensity, the WSK modulation can be used to reduce the unwanted cross gain modulation in a semiconductor optical amplifier and the four-wave mixing in a WDM system [1]. It is demonstrated that the WSK modulation can be applied in a passive optical network (PON), where the upstream data is intensity-modulated upon the downstream WSK signal [2,3]. In addition, we may also use the WSK modulation in an optical packet or burst switching network to implement optical labeling of the payload data [4]. Among the various WSK formats, binary WSK is the most widely used modulation formats, which can be implemented utilizing two optical wavelengths, with one carrying non-return-to-zero (NRZ) data stream and the other synchronously carrying the complementary data stream. At the receiver end, the binary WSK signal can be easily converted to intensity-modulated data by using an optical bandpass filter (OBPF) to remove one of the two wavelengths.

Several approaches to implementing the WSK modulation have been recently proposed. One approach is based on the conversion from optical phase modulation to intensity modulation by using a delay line interferometer [2]. This approach can operate at a high-speed. However, a differentially pre-coded data stream should be applied to the phase modulator in this approach, which increases the complexity of the system. The WSK modulation has also been demonstrated based on polarization modulation [5,6], in which a high cost polarization modulator is required to achieve complementary modulation of the

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two wavelength channels. Recently, an integrated $LiNbO_3$ high-speed OFSK modulator based on a specially designed Mach–Zehnder structure was demonstrated [7]. In their approach, the OFSK carrier spacing relies on the input RF signal, which is limited to the tens of GHz due to the inherent constraint of $LiNbO_3$. Note that, due to the narrow wavelength spacing between the two wavelength channels, a stable optical filter with narrow passband has to be used to achieve the conversion from WSK modulation to intensity modulation at the receiver side. The OFSK modulation can also be realized based on direct current modulation in a tunable laser; however, the achievable bit rate is limited to several hundreds Mb/s [8].

In this paper, we present a novel and simple approach to implementing high-speed WSK modulation. The proposed WSK transmitter consists of a pair of conventional Mach–Zehnder modulators (MZMs), which are biased at different transmission points to achieve complementary operation. Thanks to the complementary operation of the MZMs, a pair of complementary intensity-modulated optical signal can be generated. By combing the two complementary signals, the WSK-modulated signal is achieved. In our system the WSK carrier spacing can be continuously tunable and the data rate can be as high as that can be accommodated by the MZMs. To achieve synchronization between the two optical signals, a tunable optical delay line (ODL) is applied in one arm. The ODL can also be used to compensate for the dispersion-induced walk-off effect between the two optical carriers. A proof-of-concept experiment is performed to demonstrate the application of the proposed WSK transmitter in PON systems, in which the downstream WSK signal is reused as the optical carrier for upstream data transmission. The presented experimental results verify the feasibility and potentials of the proposed approach.

2. Operation principle

The schematic diagram of the proposed WSK transmitter is illustrated in Fig. 1. The light beams from two continuous-wave laser diodes (LDs) with small wavelength

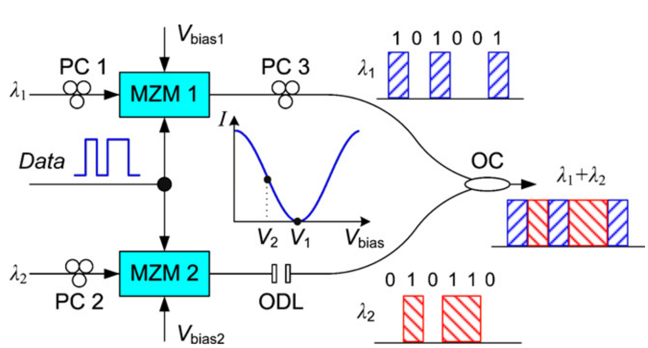

Fig. 1. The configuration of the proposed WSK transmitter (PC: polarization controller; MZM: Mach–Zehnder modulator; ODL: optical delay line; OC: optical combiner).

spacing are fed into two MZMs (MZM1 and MZM2). Two polarization controllers (PC1 and PC2) are employed at the inputs of the MZMs to align the polarization states of the input lightwaves with the polarization axis of the MZMs, to minimize the polarization-dependent loss. At the output of MZM1, the PC3 is used to ensure the polarization state of the output lightwave from MZM1 is well aligned with that from MZM2 before combining at the optical combiner. A tunable ODL is incorporated in the lower arm to ensure synchronization between the two data streams. The NRZ data steam is fed to the two MZMs via a power divider.

The key to achieve a WSK modulation in the proposed scheme is to bias the two MZMs at different transmission points, to ensure a complementary operation of the two MZMs, as shown in the inset of Fig. 1. Assume that the signal voltage of the input data stream at bit 1 is V_1, the bias voltages applied to the two MZMs should be controlled to be V_π and $V_\pi - V_1$, where V_π is the half-wave voltage of the MZM (corresponding to the minimum transmission point). As we know, the normalized transfer function of a single-drive MZM is given as

$$I_{out} = I_{in}\left[\frac{1}{2} + \frac{1}{2}\cos\left(\frac{V_s + V_{bias}}{V_\pi}\pi\right)\right], \quad (1)$$

where I_{in} and I_{out} are respectively, the input and output optical powers, V_{bias} is the bias voltage applied to the MZM, and V_s is the voltage of the data stream applied to the MZM,

$$V_s = \begin{cases} V_1, & \text{bit 1} \\ 0, & \text{bit 0} \end{cases}. \quad (2)$$

Therefore, the output signal from the MZM1 (with bias voltage $V_{bias1} = V_\pi$) is

$$\begin{aligned} I_{\lambda_1}^{out} &= I_{\lambda_1}^{in} \cdot \left[\tfrac{1}{2} + \tfrac{1}{2}\cos\left(\tfrac{V_s+V_\pi}{V_\pi}\pi\right)\right] \\ &= \begin{cases} \tfrac{1}{2} I_{\lambda_1}^{in}\left[1 - \cos\left(\tfrac{V_1}{V_\pi}\pi\right)\right], & \text{bit 1} \\ 0, & \text{bit 0} \end{cases}, \end{aligned} \quad (3)$$

and the output signal at MZM2 (with bias voltage $V_{bias2} = V_\pi - V_1$) is

$$\begin{aligned} I_{\lambda_2}^{out} &= I_{\lambda_2}^{in} \cdot \left[\tfrac{1}{2} + \tfrac{1}{2}\cos\left(\tfrac{V_s+V_\pi-V_1}{V_\pi}\pi\right)\right] \\ &= \begin{cases} 0, & \text{bit 1} \\ \tfrac{1}{2} I_{\lambda_2}^{in}\left[1 - \cos\left(\tfrac{V_1}{V_\pi}\pi\right)\right], & \text{bit 0} \end{cases}. \end{aligned} \quad (4)$$

From (3) and (4), we can see that if the optical powers from the two LDs are equal, the output data streams from two the MZMs are complementary. The combination of the two complementary data streams at the output of the optical combiner would generate a WSK-modulated signal, given that the optical path lengths of the two arms are equal (which is ensured by tuning the optical delay line). It is worth noting that the approach using a pair of MZMs that are respectively biased at positive and negative slopes of the MZM′s modulation curve to achieve complementary modulation has found applications in microwave photonic filters with negative coefficient(s) [9,10].

3. Experiment results and discussion

The proposed WSK transmitter as shown in Fig. 1 is experimentally evaluated. In the experiment, the wavelengths λ_1 and λ_2 are set at 1550.00 nm and 1550.80 nm, respectively. The polarization states of the input lightwaves from the two LDs are adjusted by the two PCs to maximize the output powers. A 2.5 Gb/s NRZ data stream from a bit error rate tester (BERT) is fed to the two MZMs via a power divider. The two MZMs are biased at $V_\pi - V_1$ and V_π, where the half-wave voltage V_π is around 7.9 V and the input data stream voltage V_1 is around 2.3 V. The ODL in the lower arm is carefully tuned to compensate for the optical path length difference of the two arms in order to achieve synchronization between the two data streams. PC3 at the output of MZM1 is used to ensure the output lightwave from MZM1 is well aligned with that from MZM2 before combining at the OC. In addition, the powers of the two LDs are also adjusted to compensate for the loss difference between the two arms in order to ensure the same optical power levels at the OC. Fig. 2 shows the measured intensity-modulated waveforms at the outputs of MZM1 and MZM2. The WSK waveform at the output of the OC is also shown. It is clearly seen that the data streams at the outputs of the two MZMs are complementary, and the intensity of the combined signal is nearly constant.

One of the important applications of the proposed WSK modulation technique is in a PON system where the downstream WSK signal can be reused as the optical carrier for upstream data transmission using intensity modulation thanks to the constant envelop of the WSK-modulated signals [2,3]. To demonstrate this application, a proof-of-concept experiment with the setup as shown in Fig. 3 is

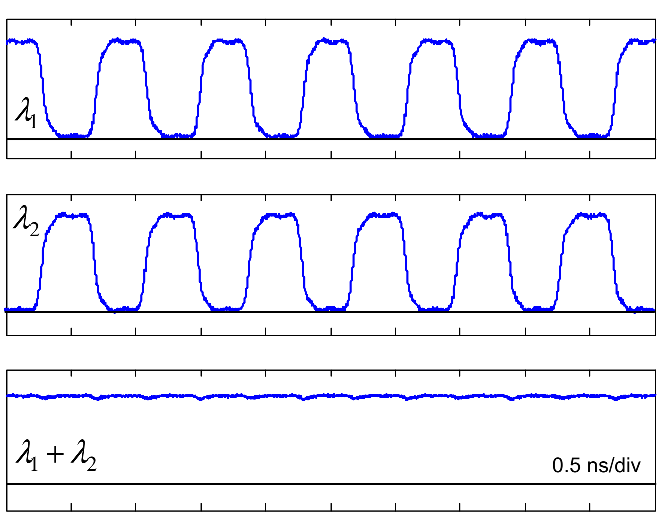

Fig. 2. The measured intensity-modulated waveforms at the outputs of the two MZMs, and the waveform after combination at the output of the OC.

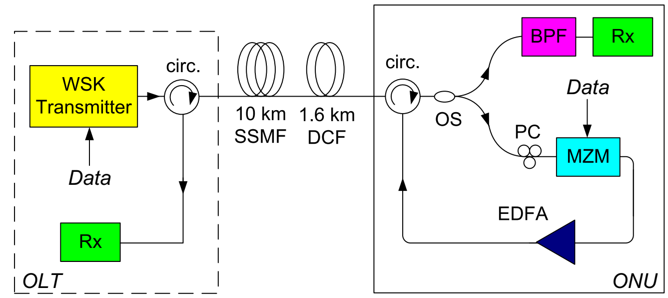

Fig. 3. Experimental setup for demonstrating the reuse of WSK signal as optical carrier for data re-modulation (circ: optical circulator; SSMF: standard single mode fiber; DCF: dispersion compensation fiber; OS: optical splitter).

implemented. A pair of optical circulators is used to multiplex the upstream and downstream signals onto a single optical fiber link. The WSK transmitter is placed at the optical line terminal (OLT) side. The downstream signal from the WSK transmitter, after propagation through 10 km standard single mode fiber (SSMF) and 1.6 km dispersion compensation fiber (DCF), is split into two beams via a 50:50 optical coupler at the optical network unit (ONU) side. One is fed to an optical bandpass filter (OBPF) with 0.2 nm bandwidth to select one of the two wavelengths to perform WSK to IM conversion. The converted IM signal is detected by a PIN photo-receiver. The other beam is reused as the optical carrier which is fed to an MZM to intensity-modulate the upstream data. The upstream data is then transmitted to the OLT through a 10 km SSMF and 1.6 km DCF.

We first investigate the dispersion effect on the performance of the system. To do so, we measure the WSK envelope after transmission through a length of SSMF. As can be seen in Fig. 4a, the envelope of the WSK signal is not constant after transmission in a 10 km SSMF due to the dispersion-induced walk off between the two wavelength channels. To reduce the walk-off effect, we may choose two wavelengths with smaller wavelength spacing. Fig. 4b and c show the cases where the wavelength spacing are 0.1 and 0.02 nm, respectively. It is shown that the variations in the envelope intensity almost disappear in the case when the wavelength spacing is 0.02 nm. However, the use of such small wavelength spacing would necessitate the use of an athermal OBPF with ultra-narrow bandwidth at the receiver end to perform the WSK to IM conversion [3]. An alternative solution is to use dispersion compensation fiber (DCF) to eliminate the dispersion-induced walk-off while keeping larger wavelength spacing. Fig. 4d shows the WSK envelope after transmission through 10 km SSMF with dispersion compensation using 1.6 km DCF. A constant intensity envelope is observed.

The bit error rate (BER) performance of the WSK transmitter is then investigated. In this case, the wavelength spacing is kept as 0.8 nm. We measure the BER vs. the received optical power for two cases: back-to-back and 10 km SSMF + 1.6 km DCF transmission. The results are

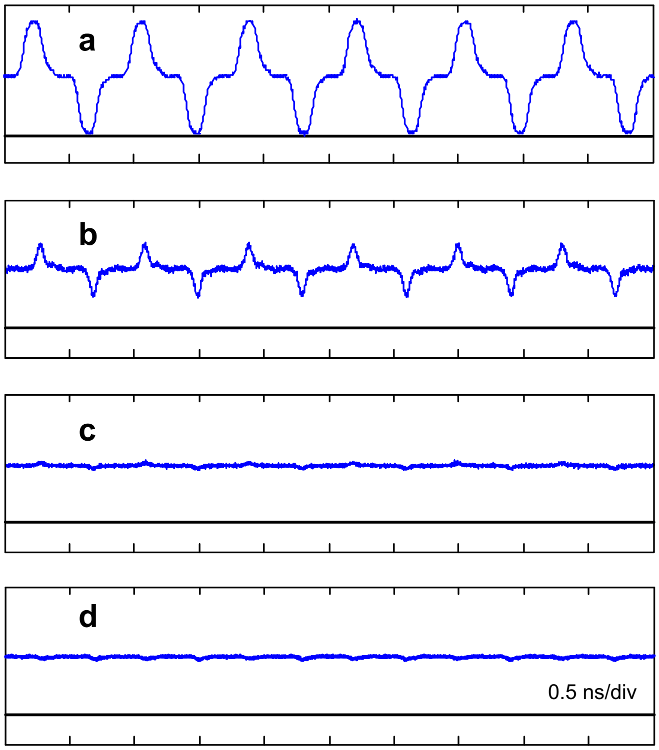

Fig. 4. The measured WSK envelope. (a) Wavelength spacing of 0.8 nm, 10 km SSMF without DCF; (b) wavelength spacing of 0.1 nm; 10 km SSMF without DCF; (c) wavelength spacing of 0.02 nm, 10 km SSMF without DCF; (d) wavelength spacing of 0.8 nm; 10 km SSMF with 1.6 km DCF.

shown in Fig. 5. A 0.4 dB power penalty is observed at a BER level of 10^{-9}. The spectra of the WSK signal before and after the OBPF are shown in the inset of Fig. 5. Finally, we reuse the received WSK signal to intensity-modulate a 2.5 Gb/s data stream for upstream data transmission. The experimental setup is also show in Fig. 3. Again two cases are evaluated: back-to-back and 10 km SSMF + 1.6 km DCF transmission. The BER test results are shown in Fig. 6. A 0.7 dB power penalty is observed at a BER level of 10^{-9}. Although some residual intensity modulation from the downstream WSK channel still remains, considerable performance of the upstream intensity modulation signal is observed. An eye diagram showing the re-modulated signal for back-to-back transmission when the received power is −9 dBm, which is given in the inset of Fig. 6. The eye diagram is widely open which shows a good performance when reusing the WSK signal for upstream transmission.

As mentioned above, the smaller wavelength spacing between the two wavelength channels requires an optical filter with narrower passband; on the other hand, larger wavelength spacing would alleviate this requirement while magnifying the dispersion-induced walk-off effect. A dispersion compensation scheme is employed to suppress the dispersion-induced walk-off effect in the above experimental demonstration. Note that a tunable ODL is applied in the proposed WSK transmitter to ensure synchronization of the two complementary data streams at the output of the optical combiner. In fact, this ODL can be further employed to compensate for the inter-band dispersion in the optical link. Therefore, the DCF module is unnecessary if the ODL in the WSK transmitter is finely re-tuned for a given optical link. The BER performance of the system without DCF module is re-measured in the case the ODL is re-tuned to cancel the inter-band dispersion; the results are shown as the triangles in Figs. 5 and 6. Around 0.1 dB power penalty of the downstream WSK-modulated signal is observed at a BER level of 10^{-9} compared to the

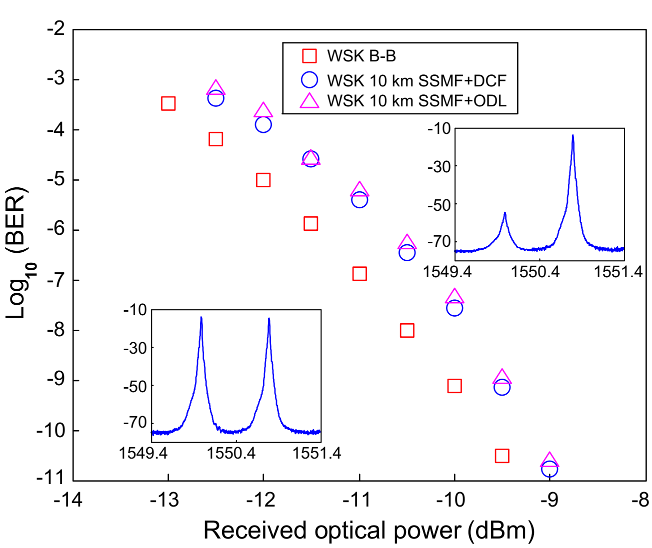

Fig. 5. Performance of WSK signal transmission. Square: back-to-back; circle: 10 km SSMF with DCF module; triangle: 10 km SSMF with the ODL-based walk-off cancellation (inset: the spectra before and after filtering).

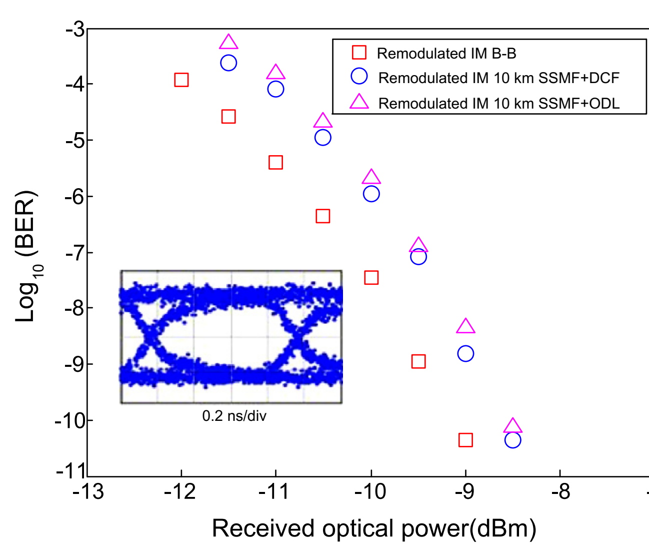

Fig. 6. Performance of re-modulated IM signal transmission: Square: back-to-back; circle: 10 km SSMF with DCF module; triangle: 10 km SSMF with the ODL-based walk-off cancellation (inset: the eye diagram of the back-to-back transmission at a received optical power of −9 dBm).

case with DCF module; and around 0.3 dB power penalty of the upstream intensity-modulated signal is observed. These small power penalties are mainly attributed to the intra-band dispersion. Note that, in a system with higher bit rate or longer optical fiber link, the dispersion compensation scheme has to be applied to compensate for the intra-band dispersion, since the ODL is only effective for the inter-band dispersion. It is worth noting that the basic idea of the dispersion canceling based on ODL in our approach is similar to the approach proposed in [11], in which the ODL is placed at the receiver side to compensate for the group delay mismatch between the two wavelength channels.

The major advantage of the proposed scheme is that a pair of MZMs is employed to realize WSK modulation without the requirement of special modulator or data pre-coding as compared with the approaches in [2,5,6]. As compared with the approach based on direct current modulation in a tunable laser [8], our approach can support bit rate as high as tens of Gb/s due to the high bandwidth capacity of MZMs. The $LiNbO_3$ OFSK modulator proposed in [7] provided a feasible way to realize high-speed OFSK modulation in spite of the limitation on the channel spacing. In our experiment, we have demonstrated that the wavelength spacing in our approach can be arbitrarily set with the help of a dispersion canceling scheme based on ODL. Larger wavelength spacing would reduce the requirement on the filter in the WSK receiver. Note that in the application of metropolitan network or access network (which is one of the major applications of the WSK technique), the bandwidth resource in optical fibers is usually not a major limitation.

4. Conclusions

We have demonstrated a novel and simple method to achieve WSK modulation. The key in the proposed approach is the use of two MZMs that are biased at different transmission points to operate in a complementary manner. The WSK signal is obtained by combining the two complementary data streams. The wavelength spacing between the two carriers of the WSK signal is tunable. In addition, the tunable ODL within the WSK transmitter can be used to compensate for the dispersion-induced walk-off effect between the two optical carriers. The WSK transmitter and the reuse of the WSK signal for data re-modulation have been experimentally demonstrated, which verifies the feasibility of the proposed scheme.

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