All-optical modulation format conversion from NRZ-OOK to PSK-Manchester using SOA-MZI

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Proposed and demonstrated is an all-optical modulation format conversion from a non-return-to-zero on-off keying (NRZ-OOK) signal to a phase-shift keying (PSK)-Manchester format signal using a semiconductor optical amplifier based Mach-Zehnder interferometer (SOA-MZI). In the experiment, a 2.5 Gbit/s PSK-Manchester format signal was obtained from a NRZ-OOK signal and a 50 km error-free transmission of the converted PSK-Manchester format signal was achieved. In addition, the feasibility of the conversion at a higher data rate using SOAs with fast phase recovery was investigaged.

Introduction: Various and sundry optical networks have been proposed for different requirements of network scaling, transmission rate and capacity, power consumption and communication security. To satisfy the requirements of these optical networks, a variety of modulation formats have been proposed, which have their own unique benefits. Recently, many researches have investigated generations and applications of Manchester coding format, which has the advantages of simple timing extraction, self-clocking and simple error detection. In [1], the amplitude-shift keying (ASK)-Manchester coding format was used with a burst-mode optical packet receiver in a passive optical network (PON) system. However, the ASK-Manchester coding format is not robust to beat interference noise (BIN). Then, the phase-shift keying (PSK)-Manchester coding format was proposed for the stronger tolerance to BIN and was suggested to be used in a wavelength-division multiplexing (WDM) PON [2]. Besides, the Manchester coding format incorporating duobinary coding was evaluated and it presented an improved chromatic dispersion tolerance by nearly three times compared with the ASK-Manchester coding format [3]. The generation of a Manchester-duobinary format signal using a directly modulated chirp managed laser was experimentally demonstrated at 10 Gbit/s and enhanced chromatic dispersion tolerance was also achieved [4].

Besides generation of the Manchester coding format, it is necessary to realise modulation format conversions from/to Manchester coding format to suit the preferences of different networks. In [5], 10 Gbit/s NRZ-OOK to ASK-Manchester modulation format conversion was demonstrated employing nonlinear polarisation rotation in a highly nonlinear fibre (HNLF). In this Letter, we demonstrate NRZ-OOK to PSK-Manchester modulation format conversion using a semiconductor optical amplifier based Mach-Zehnder interferometer (SOA-MZI).

Operation principle: The proposed modulation format converter functions like an exclusive-OR (XOR) gate. A clock signal is '1' in the first half bit duration and '0' in the second half bit duration. The XOR logic gate operates at the double repetition rate of a NRZ-OOK signal. When the NRZ-OOK signal is bit '1', the output within this bit duration is '01', since in the first half bit duration, two inputs to the XOR gate are '1's, and in the second half bit duration, two inputs become '1' and '0'. When the NRZ-OOK signal is bit '0', the output is '10'.

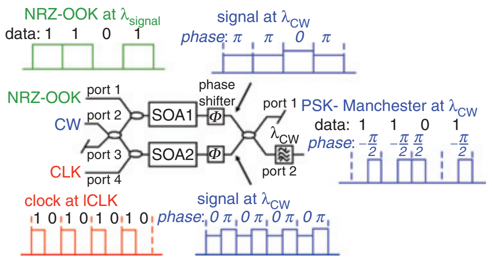

Fig. 1 *Operation principle of NRZ-OOK to PSK-Manchester modulation format conversion*

The function of the XOR gate is realised by an SOA-MZI, as illustrated in Fig. 1. A NRZ-OOK signal, a probe light and a clock signal are injected into input ports 1, 2 and 4, respectively. The NRZ-OOK signal and the probe light are coupled into the upper branch. When the NRZ-OOK signal is bit '1', the probe light experiences a phase shift and a gain modulation due to cross-phase modulation (XPM) and cross-gain modulation (XGM) in SOA 1. In SOA 2, the probe light is modulated with the clock signal every half bit. Two phase shifters are used for optimising the in-phase condition, under which the probe light has a constructive interference in output port 2. It is straightforward to show a mathematical expression of the output optical field as follows:

$$E_{out}(\theta) = \frac{A}{2} j[\exp(-\alpha_1 + j(\theta_1 + \varphi_1)) + \exp(-\alpha_2 + j(\theta_2 + \varphi_2))]\exp(j\omega_c t) \quad (1)$$

where A and ω_c are the amplitude and angular frequency of the probe light, α_1 and α_2 are the XGM coefficient, θ_1 and θ_2 are XPM phase shifts, and φ_1 and φ_2 are phase shifts introduced by the two phase shifters. When gain modulation depths are the same in the two SOAs, i.e. $\alpha_1 = \alpha_2$, intensities and phases of the output optical field are listed in Table 1. When the NRZ-OOK signal is bit '0', there is an output only in the first half bit duration and the phase of the output is $\pi/2$. If the NRZ-OOK signal is bit '1', the output is only in the second half bit duration and the phase is $-\pi/2$. The NRZ-OOK signal is converted into a format with binary phase shift and binary pulse position, i.e. PSK-Manchester format.

Table 1: Output of probe light with set of representative parameters

NRZ-OOK	Clock half bit	α_1	α_2	$\theta_1+\varphi_1$ (rad)	$\theta_2+\varphi_2$ (rad)	Output phase θ (rad)	Output Intensity $\lvert E\rvert^2$
0	0	0	0	0	π	0	0
0	1	0	α_1	0	0	$\pi/2$	$A^2(1+\exp(-\alpha_1))^2/4$
1	0	α_1	0	π	π	$-\pi/2$	$A^2(1+\exp(-\alpha_1))^2/4$
1	0	α_1	α_1	π	0	0	0

Experimental results and discussion: Fig. 2 shows the experimental setup. Three continuous-wave (CW) light sources at different wavelengths are used. The 1547 nm CW light is modulated with a 2.5 Gbit/s $2^{15}-1$ pseudorandom bit sequence data by an intensity modulator (IM). The 1553 nm CW light is modulated with a 2.5 GHz sinusoidal clock signal and controlled by a delay line for temporal alignment with the NRZ-OOK signal. The 1550 nm CW light is used as a probe light. The average powers of the probe light, NRZ-OOK and clock signals are 1.1, 0.18 and –0.32 dBm. An output is obtained from output port 2 and filtered out by a 2 nm BPF centred at 1550 nm. After that, the signal is transmitted to a photodiode for detection through 50 km transmission.

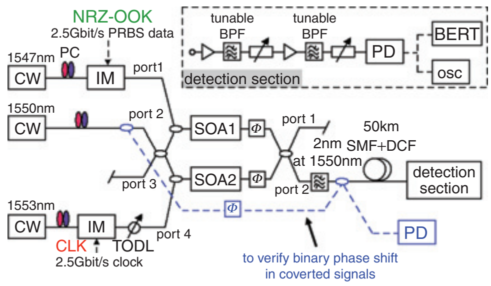

Fig. 2 *Experimental setup of proposed sheme*

The waveforms of the input and converted PSK-Manchester signals are illustrated in Figs. 3*a*–*c*. In the PSK-Manchester signal, pulses, representing bit '0', appear in the first half bit duration and pulses for bit '1' are in the second half bit duration, which confirms the theoretical analysis. Besides the characteristic of the binary pulse position, the binary phase shift of the converted signal is verified by an interference with the original CW light. A blue dashed line connected between input and output forms an interferometer as shown in Fig. 2. Figs. 3*d* and *e* show the outputs of the interference conditions. Under the constructive interference condition, pulses for bit '0' are obtained, while pulses for bit '1' appear only under the destructive interference condition. It indicates that there is a π-phase shift between bit '0' and '1', which is consistent with the theoretical analysis as well.

Bit error rate (BER) for both NRZ-OOK and converted PSK-Manchester signals are depicted in Fig. 4*a*. The converted PSK-Manchester signal has better performances and when BER $= 10^{-9}$

there is 0.3 and 0.6 dB improvement in the back-to-back situation and after 50 km transmission. The signal quality of the PSK-Manchester signal is degraded, which can be observed from eye diagrams as shown in Figs. 4*b* and *c*. Since the Manchester format consumes half the energy compared to NRZ-OOK, this enhanced energy efficiency makes up the degradation.

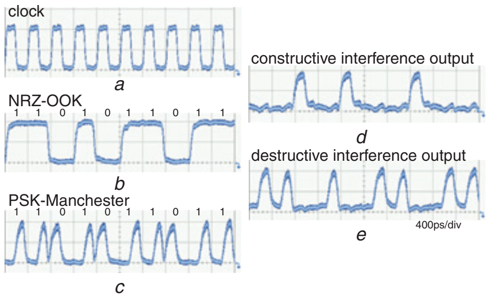

Fig. 3 *Experimental setup of proposed sheme*

a Input clock
b NRZ-OOK signals
c Converted PSK-Manchester signal
d and *e* Interference outputs

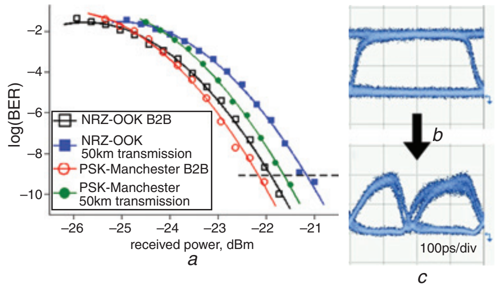

Fig. 4 *Measured BER performances, and eye diagrams*

a Measured BER performances
b and *c* Eye diagrams of NRZ-OOK and PSK-Manchester signals without transmission at BER = 10^{-9}

It is worth noting that the data rate is limited by the slow phase recovery of the SOAs (>120ps). In the calculation, we investigated the conversion at the data rate of 40 Gbit/s using two SOAs with 10–90% phase recovery of about 40 ps, as shown in Fig. 5*a*. Figs. 5*b* and *c* illustrate clear eye diagrams of the NRZ-OOK and converted PSK-Manchester signals. Error-free (BER < 10^{-9}) conversion in the calculation indicates the data rate of the proposed scheme has the potential to be improved if SOAs with fast phase recovery are employed.

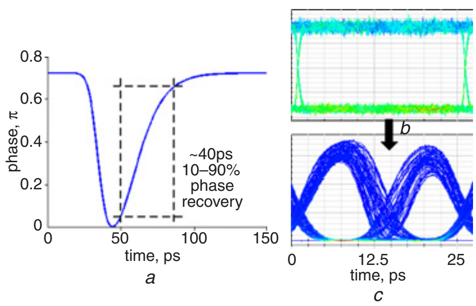

Fig. 5 *Calculated phase recovery of SOAs, and eye diagrams*

a Calculated phase recovery of SOAs
b and *c* Eye diagrams of calculated 40 Gbit/s NRZ-OOK and converted PSK-Manchester signals

Conclusion: We have theoretically analysed the operation principle of NRZ-OOK to PSK-Manchester modulation format conversion using an SOA-MZI based XOR gate. In the experiment, we achieved an error-free format conversion and investigated the characteristics of the binary pulse position and the binary phase shift of the converted PSK-Manchester signal. Based on the calculation results, we found the proposed scheme has the potential to operate at a high data rate. This SOA-MZI based modulation format conversion scheme allows photonic integration and is a promising technique for future diversified networks.

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One or more of the Figures in this Letter are available in colour online.

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