High-speed operation of optical exclusive OR circuit based on balanced detection and intensity modulation

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Abstract: We report the evaluated results of an optical exclusive OR (XOR) circuit for high-speed binary signals, which operates based on balanced detection and intensity modulation. This circuit partly adopts simple electronics in order to achieve simple configuration and operation. Two input optical binary signals into a balanced photo detector produce an electrical signal for directly driving a modulator. The modulator modulates the lightwave from a laser diode and generates optical XOR output of the two input optical signals. After briefly explaining its configuration and operating principle, We demonstrate some experimental results to show its potential. We show its successful operation at 40 Gbit/s binary signals including bit error rate measurement.

1 Introduction

It is important to develop logical optical signal processing technology with a view to realising various functions which analogue technology to process signals does not attain. An optical exclusive OR circuit (XOR circuit) is particularly significant for realising high-speed and secure optical networks. This is because that the optical XOR circuit can be applied to various sorts of functions

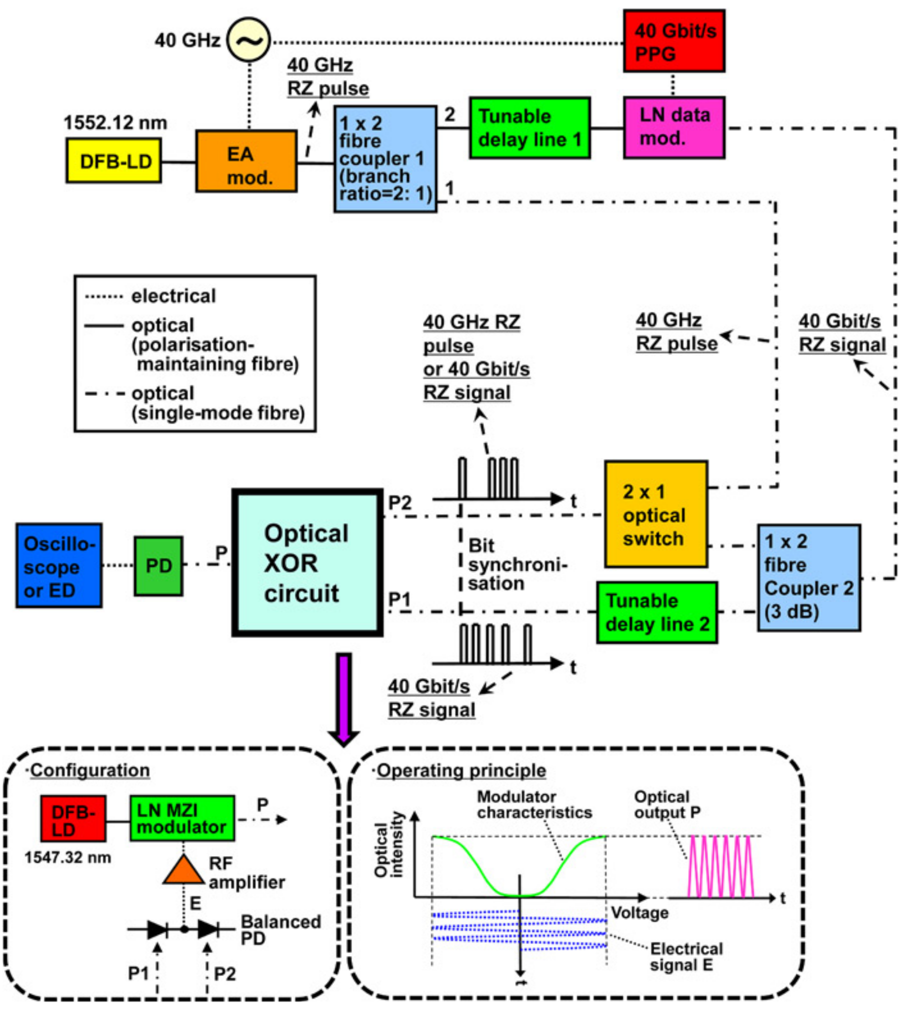

Fig. 1 *Configuration and operating principle of XOR circuit and experimental setup for evaluating XOR circuit*

and highly functional optical devices such as modulators and demodulators, encoders and decoders, error detectors (EDs) and correctors, and processors for linear-feedback shift registering. Some XOR circuits were proposed with a view to realising ultra-high-speed logical operation all-optically [1–4]. These circuits utilised optical non-linearity in optical waveguides, semiconductor optical amplifiers, or optical fibres. In addition, to realise an optical XOR circuit with moderate-speed (several tens of Gbit/s), simple configuration and operation is also important. The combination of optical and electronic technology can potentially achieve this kind of XOR circuit [5, 6]. We previously put forward and reported an optical XOR circuit with simple configuration and operation, which consists of a balanced photo detector (PD) and a Mach–Zehnder interferometer-based intensity modulator (MZI-modulator) [7]. Two optical signals, which are input into the balanced PD, generate an electrical signal for activating the intensity modulator. The intensity modulator eventually produces an optical XOR signal corresponding to the two input optical signals. We previously reported some preliminary experimental results to show the circuit operation at 10 Gbit/s non-return-to-zero (NRZ) and on–off keying (OOK) signals. In addition to these experiments, it is also important to indicate that the circuit operates at higher-speed optical signals around several tens of Gbit/s in order to clarify its potential and effectiveness in this bit rate range.

In this paper, We demonstrate the operation of the XOR circuit when 40 Gbit/s optical return-to-zero (RZ) and OOK data are used as input signals. We report the characteristics including bit error rate (BER) measurement. These results indicate that the XOR circuit is adequately operable at several tens of Gbit/s.

2 Configuration and experimental setup

Fig. 1 shows the optical XOR circuit configuration for OOK signals (a dashed square at the bottom left of the figure) and the experimental setup for evaluating the XOR circuit. The operating principle of the XOR circuit is also shown at a dashed square at the bottom right of Fig. 1.

Main components of the XOR circuit are a balanced-type PD and an $LiNbO_3$ (LN) MZI-based modulator. The 3 dB down balanced PD bandwidth was 21.4 GHz, and the half-wave voltage $V\pi$ and bandwidth of the intensity modulator were 2.1 V and 36.9 GHz, respectively. We connected the intensity modulator to a distributed feedback laser diode (DFB-LD) whose operation mode was continuous. The DFB-LD wavelength was 1547.32 nm. The balanced PD produces an electrical signal E whose amplitude changes based on the combination of two input optical signal intensities $P1$ and $P2$ input into the two PDs. E becomes 0 when $P1$ coincides with $P2$, and E is −1 or 1 when ($P1$, $P2$) is (0, 1) or (1, 0), respectively. To obtain the optical XOR output, We drove the modulator with the biased electrical signal E after a radio frequency (RF) amplifier in order to make the modulator output intensity P maximum and minimum when E becomes ±1 and 0, respectively. The 3 dB down bandwidth of the RF amplifier was 40.3 GHz. This means that the bias and peak-to-peak driving voltage of the modulator is set at a null point and $2\,V\pi$, respectively. Thus, P outputs an XOR signal of $P1$ and $P2$ [7]. In Fig. 1, the lightwave at a wavelength of 1552.12 nm from another DFB-LD was modulated with an electro-absorption modulator to produce optical RZ pulses whose repetition rate was 40 GHz. One of the divided pulses at a fibre coupler 1 was modulated with another LN intensity modulator to produce optical 40 Gbit/s RZ and OOK signals. The branch ratio of the coupler 1 was around 2:1, and pulses with higher intensity were introduced into the modulator. We drove the modulator with a sequence of 40 Gbit/s NRZ data generated with a pulse pattern generator (PPG). The pseudo random bit sequence of the data was 2^7-1. A bulk-optic-based tunable delay line 1 was used to adjust the timing between the RZ pulse generation and data modulation. The generated 40 Gbit/s RZ signals were divided into two

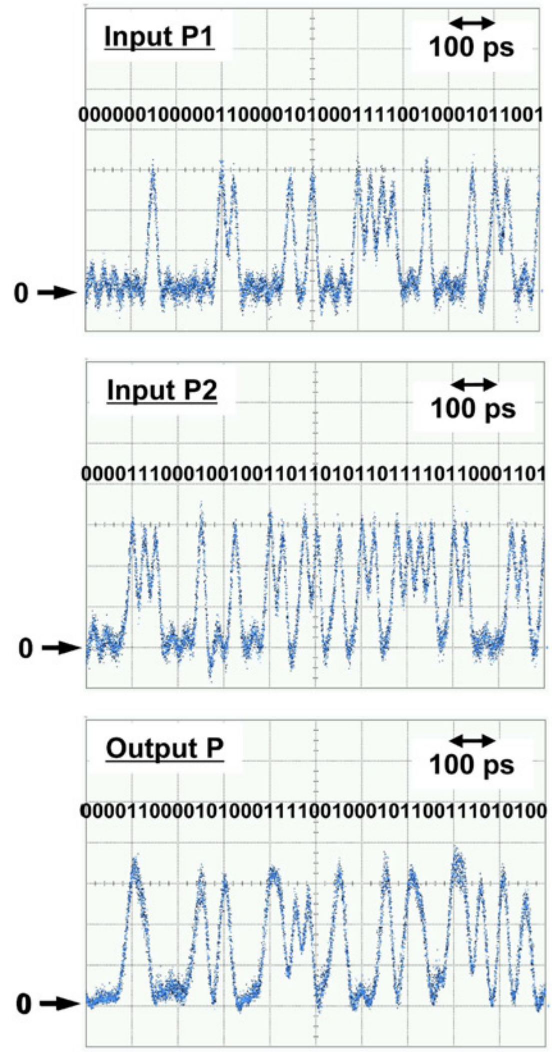

Fig. 2 *Measured temporal waveform of XOR circuit*

signals with a 3 dB fibre coupler 2. Other RZ pulses after the coupler 1 were utilised for BER measurement of the XOR circuit output P as we describe later. A 2×1 switch was used to select the signal into the XOR circuit input $P2$ depending on the measurement mode. A tunable delay line 2 was set so that the two input signals into the XOR circuit were decorrelated and the bit synchronisation between them was precisely adjusted. The output optical signals of XOR circuit were converted into electrical signals through a PD with a transimpedance amplifier and the 3 dB down bandwidth of 37.0 GHz, and their temporal waveforms and BERs were evaluated with a sampling oscilloscope and an ED, respectively.

3 Experimental results

Fig. 2 shows measured temporal waveform of the XOR circuit output P when we inserted the two 40 Gbit/s optical pulse patterns into the two inputs $P1$ and $P2$ of the XOR circuit at the different timing. These figures indicate some parts of the whole patterns. The obtained results in Fig. 2 indicate that we successfully realised the operation of the optical XOR circuit for 40 Gbit/s RZ and OOK signals by utilising the configuration shown in Fig. 1. In Fig. 2, the output temporal waveforms look like NRZ signals at some parts. This is because the limited bandwidth of balanced PD (21.4 GHz) caused the broadening of output temporal pulse width. The reason why the signals were not converted into complete NRZ signals is that dips in the signals took place when the intensity combination of the two input signals, which made an output level 1,

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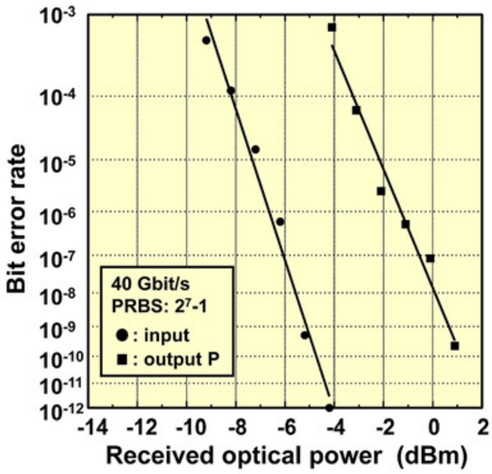
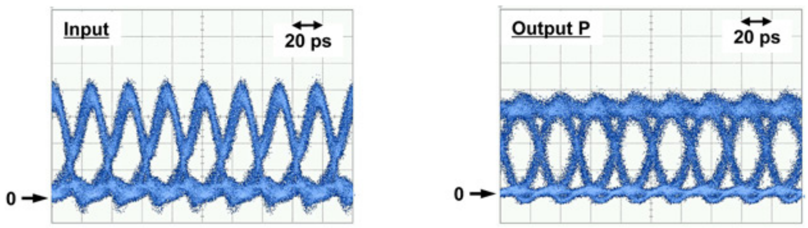


a



b

Fig. 3 *Measured BERs and eye diagrams of input and output signals of XOR circuit*
a BERs
b Eye diagrams

turned. In this instance, there was a cross-over point at which the intensity of the two input signals equalled each other [7].

Figs. 3*a* and *b* show measured BERs and correspondent eye diagrams (at BERs of 10^{-9}) of input and output signals, respectively, of the XOR circuit. The 40 Gbit/s input signals into P2 were substituted with 40 GHz RZ pulses to carry out the simple BER measurement of the output signals. In this case, the output signals corresponded to logical inversion of the 40 Gbit/s input signals *P*1 [2]. The eye diagram of output signals was clearly open and similar to that of NRZ signals as was expected from the results in Fig. 2. The BER below 2.3×10^{-10} was attained for the output signals, and the power penalty compared with the input signals was 5.7 dB at BER of 10^{-9}. These results confirm that the proposed XOR circuit also operates properly at 40 Gbit/s. The power penalty was mainly caused by the limited bandwidth of the balanced PD (21.4 GHz), which induced the pulse broadening and the degradation of the pulse extinction ratio as shown in Fig. 3*b*. In addition, the responsivity difference between the two PDs comprising the balanced PD (responsivity: 0.58 and 0.62 A/W) is also a factor to degrade the pulse extinction ratio.

4 Conclusion

We reported the configuration, operating principle, and characteristics of an optical XOR circuit, which comprises a balanced-type PD and an MZI-based modulator. This optical XOR circuit has simple operating principle and configuration without using complicated non-linear optical effect or electronic processing. The electrical output of the balanced PD produced by the two input optical signals directly drives the modulator for generating the optical XOR output. We demonstrated its successful operation at 40 Gbit/s RZ and OOK signals including eye diagram and BER measurement, and could show its feasibility for several tens of Gbit/s signals.

To apply this circuit to highly functional optical devices and to integrate all the components into one chip are next key issues. It is also important to decrease the power consumption of the XOR circuit, e.g. by utilising a low driving voltage semiconductor modulator and/or removing the RF amplifier through the use of a high-output balanced PD.

5 Acknowledgments

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6 References

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