RZ-to-NRZ and NRZ-to-PRZ Format Conversions using a Photonic Crystal Fiber Based Mach-Zehnder Interferometer

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We have fabricated a photonic crystal fiber based Mach-Zehnder interferometer and demonstrated its use in both RZ-to-NRZ and NRZ-to-PRZ pulse format conversions for 10-Gb/s OOK signals. The PCF length is only ~165 cm.

OCIS codes: (060.2400) Fiber properties; (060.4510) Optical communications

1. Introduction

All-optical pulse format conversion is an important technique in advanced optical communications. With the conversion capability, signals can be switched between different formats to adapt to different system requirements and applications. As an example, none return-to-zero on-off keying (NRZ-OOK) is more frequently used in wavelength domain multiplexing (WDM) networks due to its higher spectral efficiency over return-to-zero on-off keying (RZ-OOK). However, RZ-OOK will be necessary for optical time domain multiplexing (OTDM) systems in order to improve the time domain usage efficiency for high speed communications. With the conversion between RZ and NRZ formats, the system will be more robust and more tolerable for use in different networks like WDM or OTDM [1]. Also, with NRZ to pseudo-RZ (PRZ) format conversion, clock recovery becomes readily available for NRZ-OOK signal since a clock tone will be generated [2].

Photonic crystal fiber based Mach-Zehnder interferometer (PCF-MZI) is a novel all-fiber in-line device which, as a delay interferometer (DI), has a relative delay introduced by the index difference between the core mode and the cladding mode of the PCF [3]. Due to the unique air-hole structure of PCFs, the index difference between the core mode and the cladding mode can be quite large (usually larger than 0.01), which implies that a short PCF can be used to introduce a large delay while keeping optical attenuation of the cladding mode at a low level. Multimode fiber and polarization-maintaining loop mirror can also achieve similar delay interference but a much longer fiber will be required. For a 100-ps relative delay, about 25-m multimode fiber or 110-m birefringent fiber will be needed [4, 5]. However, the in-fiber PCF-MZI only requires about 3 m to introduce 91 ps delay (~ 3.25 m for 100 ps delay), which has been demonstrated for DPSK demodulation in our previous work [3]. In this work, we achieve both RZ-to-NRZ and NRZ-to-PRZ pulse format conversions for 10-Gb/s OOK signals using an in-fiber PCF-MZI with only ~165 cm PCF.

2. Experiment results

Fig. 2 shows the experiment setup. A 10-Gb/s RZ-OOK signal (PRBS, 2^{31}-1) is generated at 1549.8 nm using two electro-optic modulators (EOMs), one for intensity modulation and the other for pulse carving. The duty cycle is 50%. The signal undergoes RZ-to-NRZ format conversion after its transmission in the in-fiber PCF-MZI, which is built with only ~165 cm PCF to introduce 50-ps relative delay for the interference. The delay results in a transmission spectrum with ~10 dB interference extinction ratio as shown in Fig. 2(a) (the red curve). The PCF in this work has a 2.9-µm hole-to-hole spacing, a 1.69-µm hole diameter in the cladding, and a ~3.9-µm core diameter, and is of the same kind of structure used in Ref. 3.

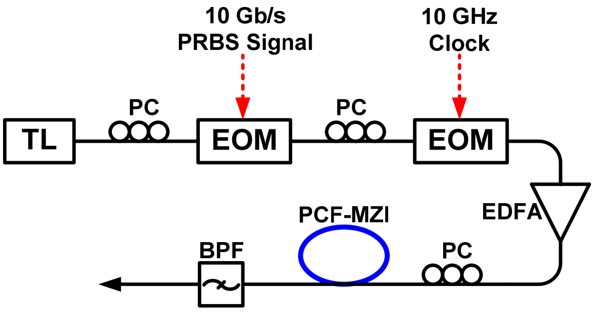

Fig. 1 Experimental setup for in-fiber PCF-MZI based pulse format conversion. TL: tunable laser; PC: polarization controller; BPF: band pass filter.

The DI transmission spectrum shows a destructive interference at the sidebands and a constructive interference at the center carrier frequency of the input 10-Gb/s RZ-OOK signal. With the two sideband tones suppressed by destructive interference of the in-fiber PCF-MZI, the output signal has been converted to an NRZ-OOK signal. The output spectrum obtained after 0.3-nm Gaussian filtering (3-dB bandwidth) is shown at the bottom of Fig. 2(a) (the blue curve). The input and output waveforms for a fixed pattern of "1100101" are depicted in Fig. 2(b), clearly showing the pulse format conversion. Next, with the PRBS data, we perform bit error rate (BER) measurement. The result is shown in Fig. 2(c). A power penalty of ~1dB is observed at the error free detection level (BER=10^{-9}).

We also study the effectiveness of our scheme for pulse format conversion of RZ input signals with different duty cycles. The input and output eye diagrams are shown Fig. 3. It is observed that the output extinction ratios for input duty cycles of 36%, 50%, and 63% are 14 dB, 11 dB, and 9 dB, respectively. The result indicates a more effective suppression of the side tones for input data pulses with a lower duty cycle within the range.

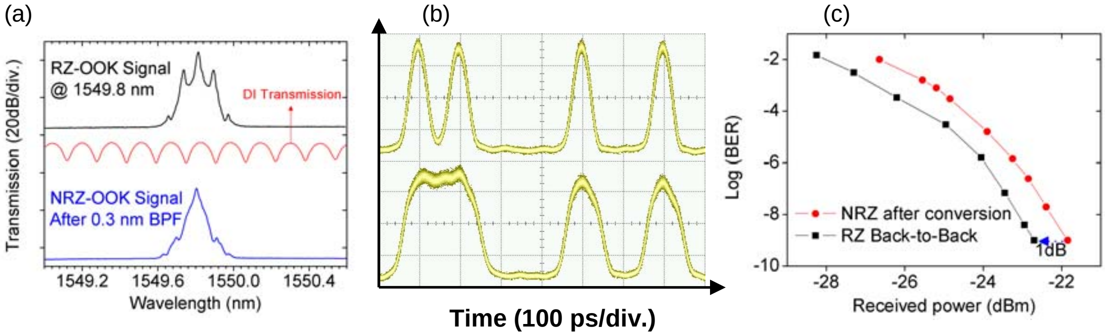

Fig. 2 RZ-to-NRZ format conversion for 10-Gb/s OOK signals with a duty cycle of ~50%. (a): Spectra of the input signals (upper), DI transmission (middle) and output signals (bottom); (b): Input RZ (upper) and output NRZ (bottom) waveforms for a data sequence of 1100101; (c): BER measurement result showing a 1 dB power penalty after the conversion.

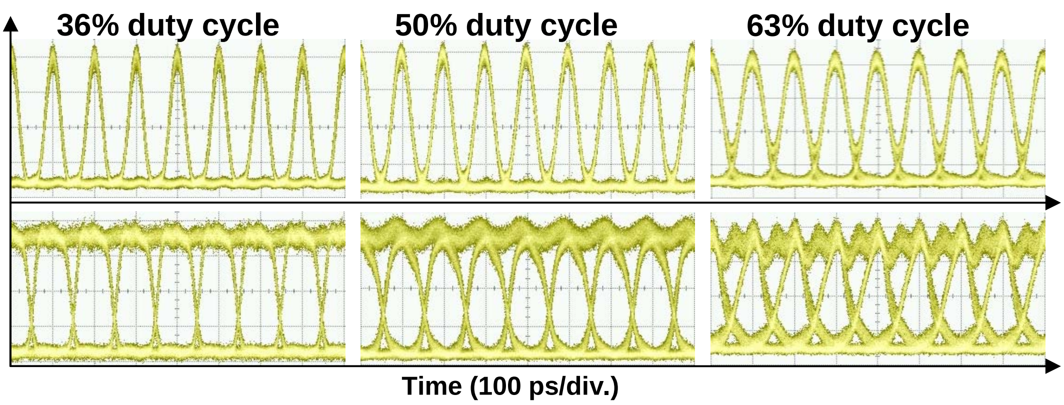

Fig. 3 Eye diagrams for RZ-to-NRZ format conversions for 10-Gb/s OOK signals with duty cycles of 36%, 50% and 63%. Upper: input RZ-OOK signals; Lower: output NRZ-OOK signals.

For NRZ-to-PRZ format conversion, we adopt nearly the same setup to generate 10-Gb/s NRZ-OOK signals, except that the second EOM for pulse curving has been removed. The pulse format conversion is achieved by destructive interference of the DI using the same in-fiber PCF-MZI with ~165 cm PCF. The input NRZ and the output PRZ spectra are shown in Fig. 4(a). The ~50 ps delay results in a destructive interference at the carrier frequency and changes the shape of the spectrum. In the time domain, the output signals show an RZ waveform for a fixed input pattern, and an RZ eye diagram for PRBS input. It should be noted that the outputs do not carry the exact original data and are in fact PRZ signals. The results are shown in Fig. 4(b) and Fig. 4(c).

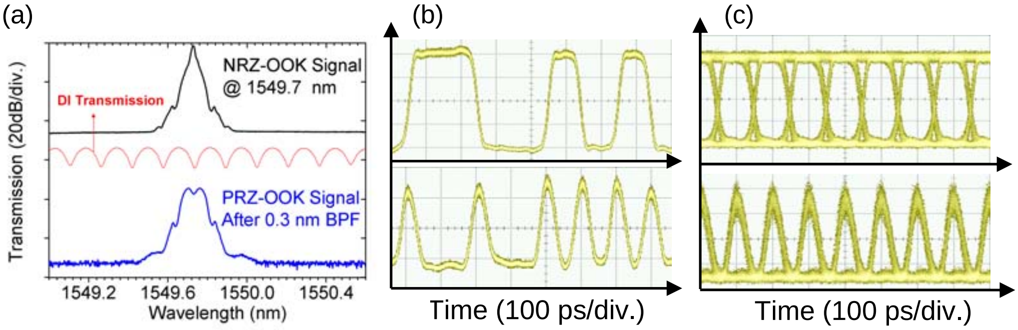

Fig. 4 NRZ-to-PRZ format conversion for 10-Gb/s OOK signals. (a): Spectra of the input signals (upper), DI transmission (middle) and output signals (lower); (b): Input NRZ- and output PRZ-waveforms for an input sequence of 1100101; (c): Input NRZ- and output PRZ-OOK eye diagrams.

With a shorter length of PCF to introduce a smaller delay (such as ~10.4 cm PCF for 3.2 ps delay), the in-fiber PCF-MZI can be further developed for higher speed RZ-to-NRZ and NRZ-to-PRZ format conversions. The investigation of such high-speed operations is under progress. Improvements can also be made by using PCFs with various kinds of specially designed structures, such as a hollow core PCF that can further shortens the required fiber length to a few centimeters for 10-Gb/s signals. Compared with other techniques of pulse format conversion, our in-fiber PCF-MZI offers advantages in its simplicity, coupler-free operation, in-line structure, ease of fabrication, and potential low cost.

3. Conclusion

Both RZ-to-NRZ and NRZ-to-PRZ pulse format conversions have been demonstrated for 10-Gb/s OOK signals based on an in-fiber PCF-MZI containing only ~165 cm PCF. For the RZ-to-NRZ conversion, the output extinction ratio has been investigated for RZ input signals of different duty cycles. Widely opened eye diagrams have been obtained. The power penalty for the conversion of RZ signal at ~50% duty cycle is about 1 dB.

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