Simultaneous multichannel NRZ-to-RZ format conversion of 4-ASK signal based on phase-intensity hybrid modulation and dispersion compensation fiber

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We propose and investigate a novel technique to realize non-return-to-zero (NRZ) to return-to-zero (RZ) format conversion of a multichannel 4-ary amplitude shift keying (4-ASK) signal. The proposed format converter composed of two modulators and a dispersion compensating fiber (DCF) is theoretically investigated using numerical simulation as basis. Research shows that a 4-channel 20-Gb/s NRZ-4-ASK signal can be converted to a RZ-4-ASK signal simultaneously without wavelength shifting and signal quality degradation, with the converted signal multiplexed to 40 Gb/s.

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Recent unprecedented development of dense wavelength division multiplexing (DWDM) optical networks has stimulated the necessity for researching advanced modulation formats with high spectral efficiency; this necessity stems from the limitations imposed by the gain bandwidth of amplifiers and low-loss window of the optical fiber on the available optical bandwidth of DWDM[1−3]. A higher spectral efficiency modulation format can be achieved through amplitude multiplexing, such as multilevel amplitude shift keying (M-ASK). The bandwidth occupancy of a M-ASK signal is $1/\log_2 M$ of the conventional 2-ASK signal for a specific bit rate, where M is the number of the intensity levels. 4-ASK has attracted considerable interest because this type of signal enables doubling the bit rate and exhibits higher tolerance to chromatic dispersion and polarization mode dispersion[4−11]. To the best of our knowledge, however, few studies on signal processing of 4-ASK or multichannel 4-ASK have been reported. The return-to-zero (RZ) 4-ASK signal has been demonstrated to have better dispersion robustness than the non-return-to-zero (NRZ) 4-ASK signal[9]. NRZ-to-RZ format conversion also has potential applications in optical nodes between DWDM and optical time division multiplexing (OTDM) optical networks[12]. In this letter, a NRZ-4-ASK to RZ-4-ASK format converter is proposed and investigated using numerical simulation as basis. The converter can be used in multichannel conversions in a broad bandwidth. Research shows that a 4-channel 20-Gb/s NRZ-4-ASK signal can be successfully converted to a RZ-4-ASK signal simultaneously without signal quality degradation in the numerical simulation.

The proposed converter (Fig. 1) is composed of two components. The first is a $LiNbO_3$ phase-intensity hybrid modulator used to generate a flattened optical multicarrier and short pulse source[13,14]; the second is a dispersion compensating fiber (DCF). The operation schematic of the converter is shown in Fig. 2. The NRZ-4-ASK signal is first launched into a phase modulator (PM) to acquire chirps (dashed lines) without changing signal intensity. Here, the clock frequency is equal to the input signal and must be adjusted to ensure that the central part of every period of the input signal corresponds to the down-chirp generated by the PM. Then, it passes through an intensity modulator (IM), in which the timing between PM and IM is controlled by an adjustable microwave phase-shifter. This approach enables the down-chirp to be gated in the IM and the up-chirp to correspond to the lower transmission area of intensity modulation (shaded areas). Subsequently, the signal passes through a section of the DCF for down-chirp compensation to realize RZ conversion (solid lines, bottom of Fig. 2). The converter is applicable to multi-wavelength

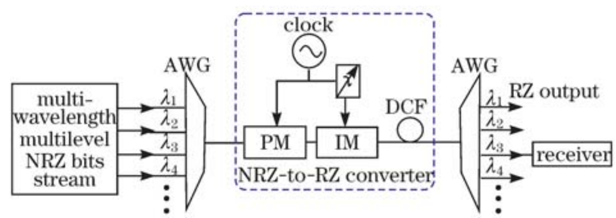

Fig. 1. Setup of format converter. AWG: arrayed waveguide grating.

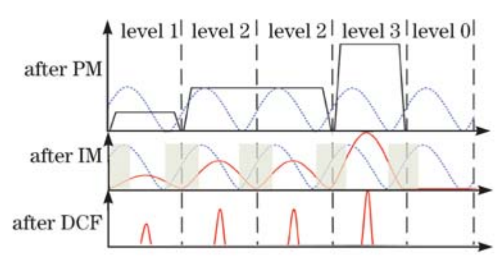

Fig. 2. Operation principle illustration of NRZ-4-ASK to RZ-4-ASK format conversion.

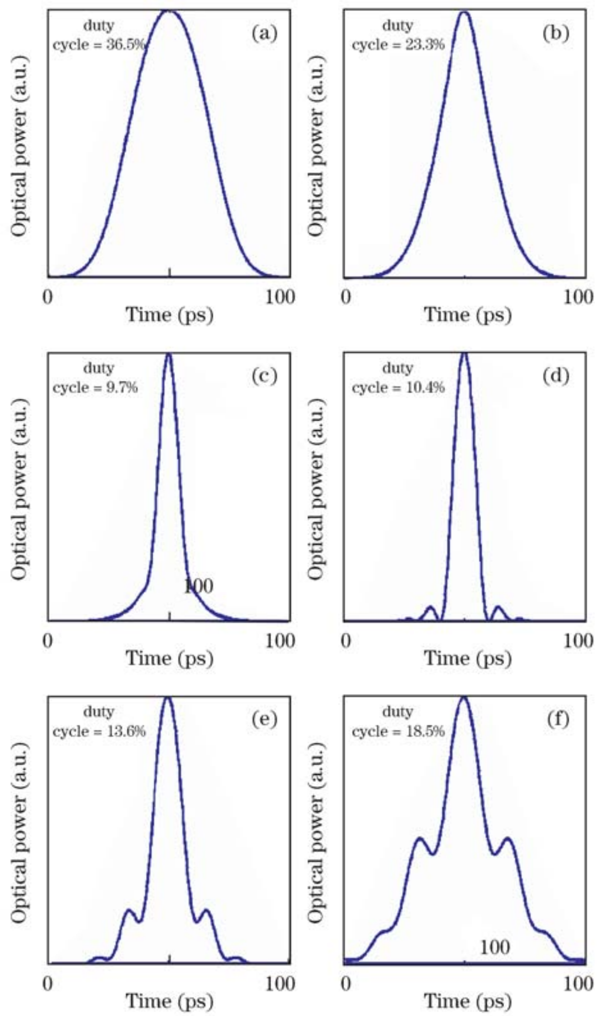

Fig. 3. Eye diagrams of converted signal with different DCF lengths in the converter. (a) 0.1 km; (b) 0.2 km; (c) 0.4 km; (d) 0.6 km; (e) 0.9 km; (f) 1.2 km.

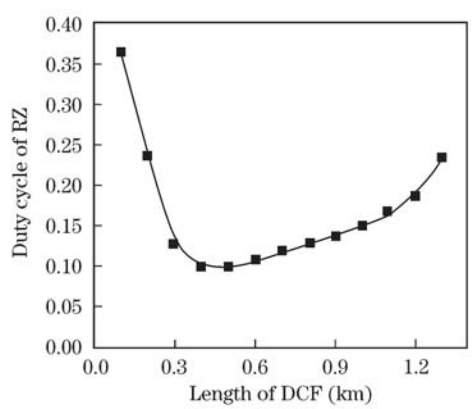

Fig. 4. Duty cycle of the converted RZ as a function of DCF length.

operation because of the low wavelength dependency of $LiNbO_3$ and the small change in the dispersion parameter of the DCF in a broad bandwidth near 1550 nm.

To meet the requirement of chirp compensation in our NRZ-to-RZ converter, the length and dispersion parameter of the DCF were optimized according to the different

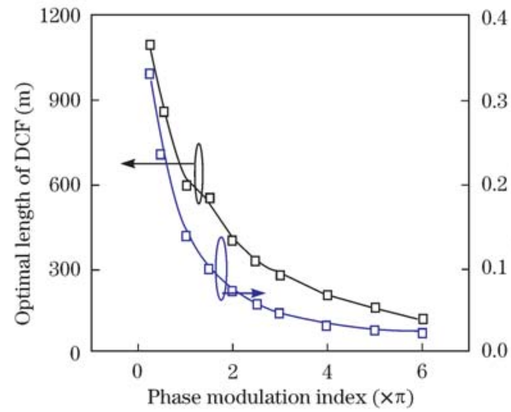

Fig. 5. Dependence of the optimal DCF length on the phase-modulation index and the corresponding duty cycle of the RZ signal.

phase modulation indices of the PM. As discussed above, the chirp is independent of the optical power of the input signal; hence, the proposed converter can also be used for other intensity modulation formats, such as on-off keying (OOK). To analyze the converter, one only needs to investigate the conversion of NRZ-OOK to RZ-OOK. First, the influence of the length of the DCF on the converter was investigated. The input NRZ signal was centered at 1545 nm, and then a pseudo-random binary sequence (PRBS) with a bit length of 2^7-1 at a bit rate of 10 Gb/s was taken into account. The phase modulation index was 1.5π and the dispersion parameter of the DCF was -100 ps/(nm·km) at 1545 nm. The IM operated in the linear regime with an intensity modulation index of 0.22π. The attenuation induced by the DCF was disregarded in all the calculations. Figure 3 shows the eye diagrams of the converted RZ-OOK signal with the DCF lengths at 0.1, 0.2, 0.4, 0.6, 0.9, and 1.2 km. Figure 4 displays the relationship between the length of the DCF and the duty cycle of the converted RZ signal. Clearly, the low duty cycle (duty cycle is defined as FWHM/T, where FWHM is the full-width at half-maximum of bit "1" and T is the bit period) RZ signal with a small pedestal can be obtained when the DCF length is around 0.5 km. However, the duty cycle and the pedestal increase, and optical wave breaking occurs with the increase of DCF length. This reaction originates from the over-compensation and linear chirp compensation of the DCF because the nearly-linear down-chirp is generated only in the central part of the NRZ signal. The calculation results in Figs. 3 and 4 indicate that the length of the DCF should be optimized to obtain a RZ signal with a low duty cycle and small pedestal; a RZ signal with different duty cycles can be obtained by changing the DCF length. The optimal length of the DCF versus different phase modulation indices and the corresponding duty cycle of the converted RZ signal were calculated (Fig. 5). The optimal length of the DCF and the duty cycle of the converted signal decrease as the phase-modulation index increases.

A numerical simulation of the 4-channel 20-Gb/s PRBS NRZ-4-ASK to RZ-4-ASK signal with bit length of 2^7-1 was conducted, with the simulation setup shown in Fig. 1. The four levels of the NRZ-4-ASK signal correspond

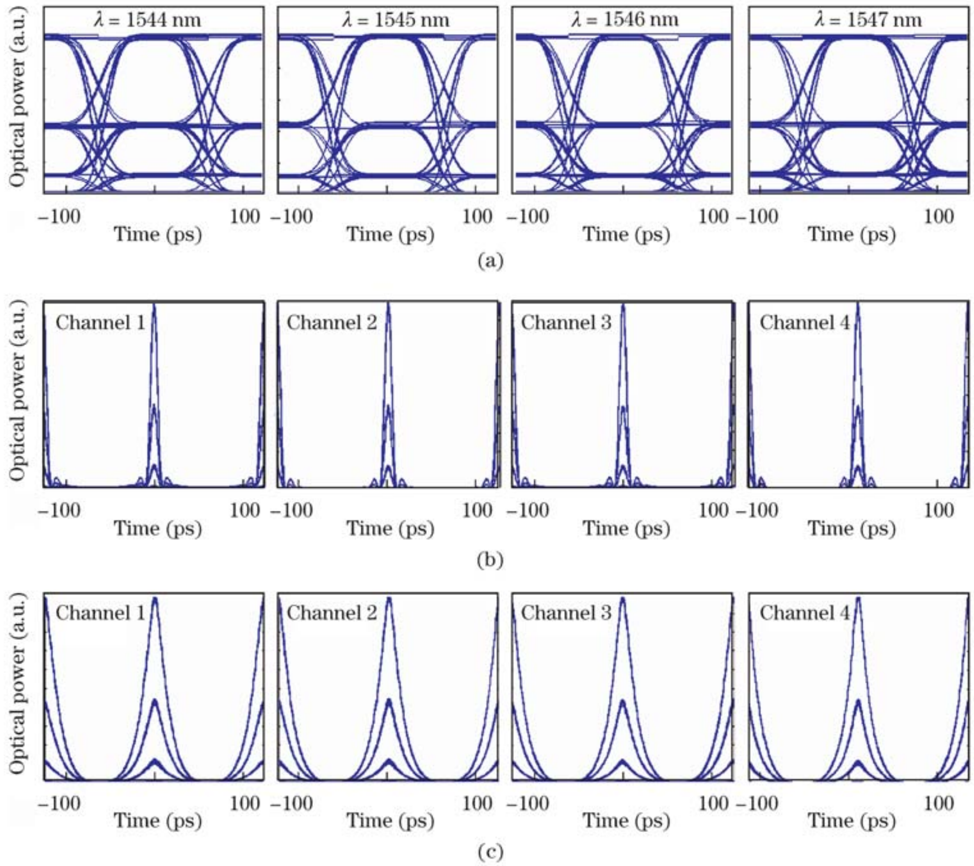

Fig. 6. Eye diagrams of four channels. (a) Input NRZ-4-ASK signal; (b) converted RZ-4-ASK signal with the DCF of 0.55 km; (c) converted RZ signal with the DCF of 0.2 km.

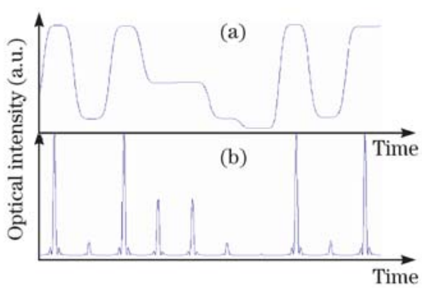

Fig. 7. Waveforms (a) before and (b) after conversion of Channel "1".

to 2-bit digital signals of "00", "01", "10", and "11", with the optimal level spacing set around 0:1:4:9[4]. The wavelength interval of the input signals was assumed to be 1.0 nm (λ_1=1544 nm, λ_2=1545 nm, λ_3=1546 nm, and λ_4=1547 nm), and the corresponding dispersion parameters of the DCF were −95, −100, −104, and −108 ps/(nm·km). Phase modulation index was assumed to be 1.5π. Two arrayed waveguide gratings (AWGs) were used as the WDM multiplexer and demultiplexer. The baud period of all channels was synchronized at the input of the AWG multiplexer. The simulation results are shown in Fig. 6. Figure 6(a) shows the eye diagrams of the original 4-channel NRZ-4-ASK signal with random noise. Figure 6(b) shows the corresponding converted RZ-4-ASK signal with a DCF of 550 m, equal to the optimal length as calculated in Fig. 3. Figure 6(c) displays the converted signal with a higher duty cycle with the length of the DCF reduced to 200 m. The level spacing of the converted RZ-4-ASK signal does not degrade, which means that the signal-to-noise ratio (SNR) does not degrade either, and the eye-opening penalty is low by this scheme. The converted RZ-4-ASK signal at different wavelengths has almost the same signal quality, and the wavelength of every channel is unchanged. By comparing Fig. 6(b) with Fig. 6(c), we can see that the length of the DCF determines the duty cycle and the waveform of the converted signal. Figure 6 shows that the amplitude noise and timing jitter of the converted signals do not increase. There are some small pedestals in the converted signal; the pedestals can be seen in the eye diagrams and mitigated by increasing the phase-modulation index and adopting an optical band pass filter with an appropriate bandwidth[14]. The format conversion waveforms of Channel "1" with a DCF of 550 m are clearly displayed in Fig. 7. The converted result indicates that the converted signal can be multiplexed to 40 Gb/s because of the low duty cycle, high extinction ratio, and small jitter. The converted RZ-4-ASK signal can be narrow enough to be multiplexed to a higher bit rate by designing the converter because the duty cycle can be very low as calculated in Fig. 5. However, if the four 4-ASK signals at the input of the AWG multiplexer are not synchronized, extinction ratio degradation and pedestal increase occur because the up-chirp of the unsynchronized channels is enhanced.

In conclusion, a novel technique of multichannel NRZ-4-ASK to RZ-4-ASK format conversion has been proposed and investigated based on phase-intensity hybrid modulation and a short DCF. Numerical simulation results show that simultaneous 4-channel 20-Gb/s NRZ-4-ASK to RZ-4-ASK conversion can be achieved with low eye-opening penalty and without the increase of amplitude noise and timing jitter; the converted signal can be multiplexed to 40 Gb/s. The converter can accommodate multichannel intensity modulation formats in a broad bandwidth; the duty cycle of the converted signal can be controlled by designing the phase-modulation index and the length of the DCF. The working rate of the proposed scheme is limited only by the bandwidth of the modulators; however, we believe that the scheme can currently work at 80 Gb/s for a 4-ASK signal.

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