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Regular Articles

Proposal and simulation investigation of optical format conversion between quaternary amplitude-shift keying signals based on cascaded modulators

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ABSTRACT

We propose a simple and novel format conversion scheme based on a polarization modulator (PolM) and a zero-chirp intensity modulator (IM) to perform NRZ to RZ conversion for quaternary amplitude-shift keying (4-ASK) signals. Simulation shows that the scheme is capable of realizing format conversion from 20-Gbit/s NRZ-4-ASK signal to RZ-4-ASK signal with tunable pulse-width for 4-level intensity modulation format. The converted signals can transmit over a dispersion-managed fiber link from 200 km to 300 km confirming the high quality conversion.

1. Introduction

The rapid growth of the information exchanges over the world demands for ultrahigh speed connectivity, which is provided mainly by the optical fiber communications. But the bandwidth of the optical fiber is not unlimited, which would impose a restriction on the further increase of the communication capacity of the optical fiber communication system. A variety of technologies, such as advanced modulation formats, wavelength division multiplexing (WDM), optical time division multiplexing (OTDM), polarization division multiplexing (PDM) [1], have been proposed to solve the problem. Multilevel modulation format, as a way to increase the communication capacity, becomes an attractive topic due to their higher spectral efficiency and tolerance to the impairment caused by dispersion and nonlinearity [2–4]. Although the M-ASK modulation formats, especially when $M > 4$, has a low BER at the cost of nonlinearity tolerance, in order to upgrade the current optical transmission network, the use of multilevel modulation formats in combination with optical multiplexing-based networks will still be highly desirable; meanwhile, NRZ-to-RZ conversion plays an important role in those network since it is a key optical signal processing technology to link the WDM and OTDM-based networks. Besides, NRZ and RZ signal should be selectively used to increase the flexibility of networks according to the different size and data-rates requirement [5,6]. NRZ-to-RZ conversion of ON–OFF keying (OOK) has been investigated for many years, yet NRZ-to-RZ conversion for advanced modulation formats has rarely been reported to the best of our knowledge [7–9]. In Ref. [9], we have demonstrated a novel NRZ-to-RZ format converter for 4-ASK signal based on cascaded lithium niobate-based phase and intensity modulator and a dispersion compensation fiber (DCF) module. However, the DCF is incapable of compensating for the whole chirp induced by the phase modulator (PM). The resulting residual chirps locating at the pedestals may lead to extinction ratio (ER) degradation and poor transmission performance after conversion in real optical communication system. In addition, the length of the DCF should be flexibly varied according to the pulse-width requirement of the converted RZ signal, which is neither cost-efficient nor commercial unavailable.

In this paper, we propose a simple and novel NRZ-to-RZ format converter for 4-ASK signal based on a commercial GaAs-based polarization modulator (PolM) and a $LiNbO_3$-based intensity modulator (IM). A simulation is carried out for 20-Gb/s NRZ-4-ASK to RZ-4-ASK conversion with tunable pulse-width. Simulation shows that the conversion can be easily realized by only adjusting the phase modulation index of the PolM without inducing residual chirp and obvious pedestal, and the converted signal can be transmitted up to 300 km over the dispersion-managed fiber link. Moreover, this scheme can be suitable for NRZ-to-RZ conversion of phase modulation formats and multichannel operation.

2. Setup and operation principle

The schematic diagram of the proposed format converter is shown in Fig. 1. The input NRZ-4-ASK signal is first launched into

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a PolM with a polarization angle of 45° with respect to the principal axis of the PolM. The PolM and the IM are driven by a microwave signal with frequency equals to the symbol rate of the input NRZ-4-ASK signal. After the PolM, a pair of complementary phase-modulated signals with the identical amplitude envelops at both x and y axis are obtained. If the optical field of the input signal can be expressed as:

$$E_i(t) = E(t)\exp(-i\omega t) \tag{1}$$

where $E(t)$ is the amplitude of the input NRZ-4-ASK signal, and ω is the angular frequency of the carrier. The electric fields along the x and y directions are:

$$E_x(t) = \frac{\sqrt{2}}{2}E(t)\exp\left(-i\frac{\alpha}{2}\sin(2\pi f_m t) - i\omega t\right) \tag{2}$$

$$E_y(t) = \frac{\sqrt{2}}{2}E(t)\exp\left(i\frac{\alpha}{2}\sin(2\pi f_m t) - i\omega t\right) \tag{3}$$

where α represents the phase-modulation index of the PolM, and f_m corresponds to the symbol rate of the input signal. The complementary signals are then combined at a polarizer with its transmission direction also oriented at 45° to one principal axis of the PolM and the output thus can be expressed as:

$$E_{o1}(t) = E(t)\cos\left(\frac{\alpha}{2}\sin(2\pi f_m t)\right)\exp(-i\omega t) \tag{4}$$

It can be seen from Eqs. (3) and (4) that the phase-modulated information of the complementary signals is finally converted to intensity variation after the polarizer. The temporal waveforms of the signals are plotted in Fig. 2. Since the GaAs-based PolM does not introduce frequency chirp or time-related phase term during the conversion, the NRZ-4-ASK signal after the polarizer (solid curve) can be converted into a chirp-free RZ signal with some undesirable side-lobes. The more detailed feature and principle of a chirp-free GaAs-based modulator can be found in Refs. [11–14]. To suppress the side-lobes and select the original data information, a normal IM is introduced. By properly adjusting the time delay through a phase shifter between the PolM and the IM, the main lobe can undergoes the least loss while the undesired side-lobes can be greatly attenuated, as displayed in Fig. 2 (dashed line). Then, a chirp-free RZ signal with almost non-pedestal is obtained (solid line, bottom of Fig. 2). The optical field of the output signal is given by:

$$E_o(t) = E(t)\cos\left(\frac{\alpha}{2}\sin(2\pi f_m t)\right)\exp(-i\omega t) \cdot \cos\left(\beta\sin(2\pi f_m(t+\tau)) + \frac{\pi}{4}\right) \tag{5}$$

where β is the intensity modulation index and τ is the microwave time-delay between the two modulators. From Eq. (5), we find that the pulse-width of the converted RZ signal is determined by the phase-modulation index α. Thus, the RZ signals with tunable duty cycles can be achieved by only varying the drive voltage of the PolM, which will be of benefit for further transmission management with the easy realization of tunable pulse-width [15]. Moreover, it is worth to note from Eqs. (4) and (5) that the format converter is promising to support arbitrary-level intensity or phase modulation format conversion since no additional intensity or phase information is introduced during the conversion process. The proposed scheme also shows feasibility in multichannel operation owing to the low wavelength dependency of the modulators used [10].

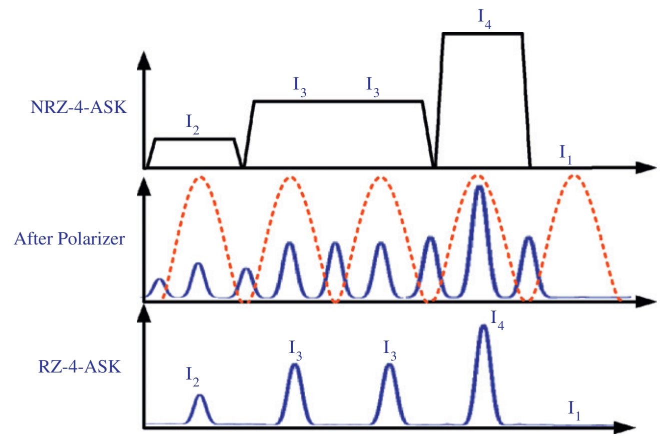

Fig. 2. Operation principle illustration of NRZ 4-ASK to RZ 4-ASK conversion.

3. Results

In this part, we first numerically investigate the dependence of the pulse-width of the converted signal on the phase-modulation index of the PolM. As shown in Fig. 3, the input NRZ-4-ASK signal is a 20-Gb/s sequence generated by delayed-multiplexing two pseudo-random binary sequences (PRBS) with word length of 2^7-1, respectively. The time-delay between the IM and PolM is optimized to suppress the side-lobes. The four levels of the NRZ-4-ASK signal correspond to 2-bits digital signal of '00', '01', '10', '11' and the optimal level spacing is optimized around 0:1:4:9 [16]. The intensity modulation index is fixed at $\pi/4$. It can be seen from Fig. 3 that the pulse-width of the converted RZ signal decreases as the phase modulation index increases. The pulse-width can reach to 13 ps when the phase modulation index is only 1.2π. Fig. 4 shows the simulated temporal waveforms of the original NRZ-4-ASK signal and the converted RZ-4-ASK signal with pulse-width of 15 ps. We believe that the high quality of the converted RZ signal in terms of narrow pulse-width and small timing jitter and negligible pedestal enables it to be multiplexed to 40 Gb/s by time division multiplexing technology.

Furthermore, the conversion performance of the proposed scheme is further evaluated by demonstrating transmission perfor-

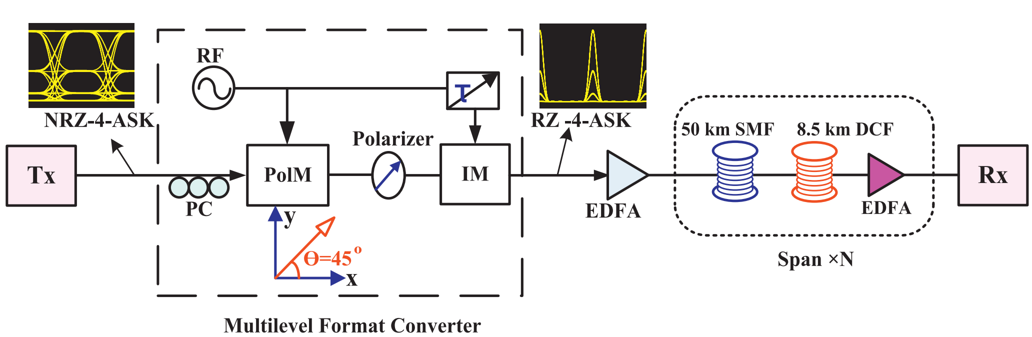

Fig. 1. Set up of the format converter.

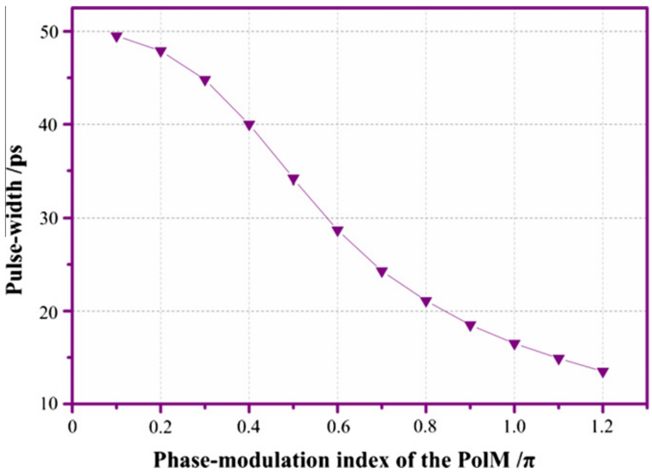

Fig. 3. The influence of the phase-modulation index of PolM on the pulse-width of the converted RZ signal.

mance of the original NRZ-4-ASK signal and the converted RZ-4-ASK signals with pulse-width at 15 ps, 28 ps and 40 ps respectively, over dispersion-managed fiber link. The simulated experimental setup is shown in Fig. 1. In the fiber link, the group-velocity dispersion β_2 is completely compensated after each SMF span of 50 km and the attenuation is compensated by EDFAs with noise figure of 5 dB. Parameters of the SMF and DCF are listed in Table 1. Here, polarization mode dispersion (PMD) and high-order nonlinear effects are ignored in the following transmission simulation.

At the receiver, the optical signal is detected by an APD and then electrically filtered by a fifth Bessel–Thomason low-pass filter with 3-dB bandwidth of 8.5 GHz. To estimating the signal quality and system performance, the signal is measured by using average BER calculation method which is given by Ref. [17]

$$\mathrm{BER} = \frac{1}{L}\sum_{i=1}^{L-1}\left[Q\left(\frac{I_{i+1} - Thr_i}{\sigma_{i+1}}\right) + Q\left(\frac{Thr_i - I_i}{\sigma_i}\right)\right]$$

Table 1
Fiber parameters in simulation.

Parameters	SMF	DCF
Attenuation (dB/km)	0.2	0.5
Dispersion (ps/nm km)	17	−100
Slope (ps/nm^2 km)	0.056	−0.22
Nonlinear index (W^{-1} km^{-1})	1.3	5.2

where L, I_i, Thr_i and σ_i correspond to number of levels, average power of the ith symbol, optimal decision level and standard variance of the power level. The $Q(x)$ is defined as

$$Q(x) = \frac{1}{2}erfc\left(\frac{x}{\sqrt{2}}\right)$$

In Fig. 5, we plot the BER curves for the original back-to-back (BTB) NRZ formats, the converted RZ formats and the RZ signals after transmission over 200 km and 300 km. It can be clearly seen from Fig. 5a that the RZ-4-ASK signals show better receiver sensitivity performance compared to NRZ-4-ASK signals. Negative power penalty at a BER of 10^{-9} are obtained for different RZ-4-ASK signals and RZ-4-ASK with pulse-width of 15 ps shows the best BER performance (power penalty of about −5.5 dBm compared to NRZ signal). The BER performance for NRZ and RZ signals after transmission over 200 km and 300 km dispersion-managed fiber link is shown in Fig. 5b and c respectively. The lower receiver sensitivity maintained for the converted RZ signals verify that the RZ signal has a better quality. It should also be noted that as the distance of the transmission link increases to 300 km, the NRZ-4-ASK will have a BER floor near 10^{-6}. However, the BER for RZ-4-ASK signals can be lower than 10^{-8}, where RZ-4-ASK with duty cycle of 15% and 28% can be error-free (lower than 10^{-9}). This result could be attributed to the higher nonlinear tolerance of RZ signal when it is being transmitted over long distance with complete dispersion compensation, which can be referred to the case of OOK [18]. The results shown above do not only verify the excellent conversion performance of the proposed scheme but also show its potential application in future optical nodes between metro or access

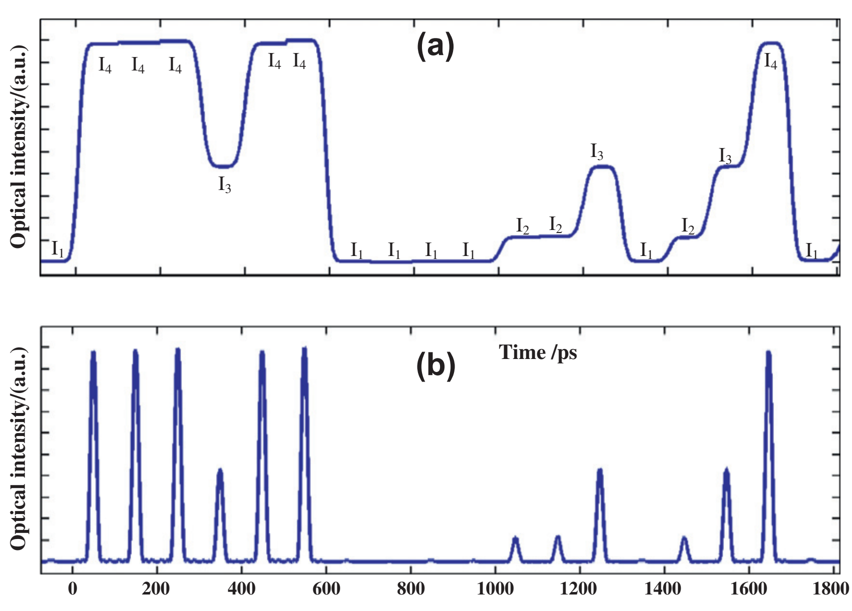

Fig. 4. Temporal waveforms before (a) and after (b) conversion.

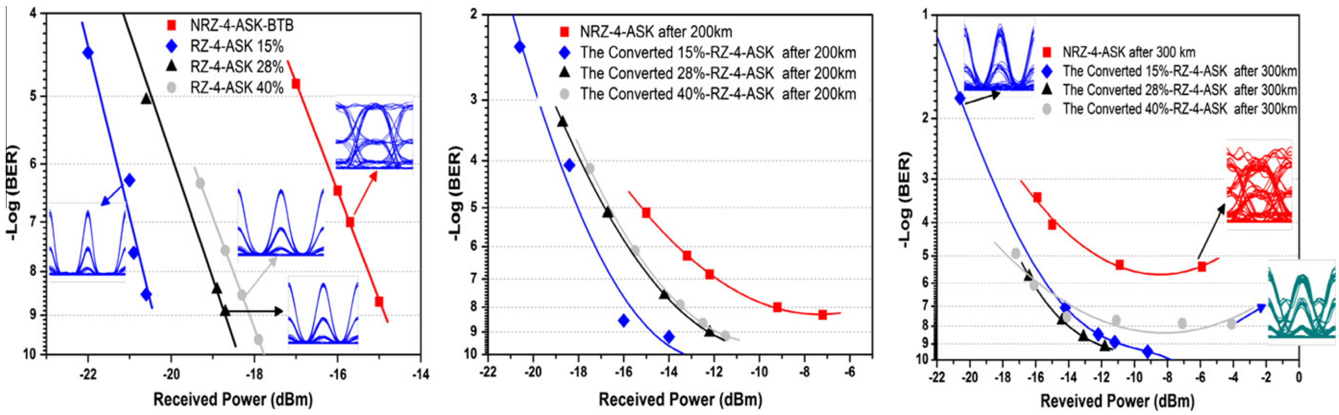

Fig. 5. Measured BER curves (a) BTB NRZ-4-ASK signal and the converted RZ-4-ASK signals, (b) NRZ and the converted RZ signals after 200 km transmission, (c) NRZ and the converted RZ signals after 300 km transmission.

network linked with high speed backbone network since NRZ and RZ formats are considered to be the promising candidate in those networks.

4. Conclusions

A simple and novel scheme for NRZ-4-ASK to RZ-4-ASK format conversion has been proposed and investigated based on a polarization modulator and an intensity modulator. Numerical simulations of NRZ-4-ASK signal to RZ-4-ASK signal conversion and transmission over dispersion-managed fiber link at different distance are carried out. It shows that 20-Gb/s NRZ-4-ASK to RZ-4-ASK conversion can be successfully achieved with chirp-free, small pedestal, and tunable pulse-width. The pulse-width tunability can be easily realized by only adjusting the drive voltage to the PolM, which will be beneficial for further time-division multiplexing and transmission management. Research results also show that the converted RZ-4-ASK signals outperform NRZ-4-ASK in terms of transmission performance especially when the transmission distance increases. The proposed scheme features a simple structure, potential for multi-formats and multichannel operation, and being insensitive to input power, which can find many applications in future large scale optical networks.

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