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Abstract. We propose and experimentally demonstrate all-optical return-to-zero (RZ) to nonreturn-to-zero (NRZ) format conversion by using multiple cross-phase modulation (MXPM) in a highly nonlinear fiber. The proposed all-optical format converter can perform simultaneously wavelength conversion and dual-channel signal multicasting. This is achieved by properly filtering two broadened probe spectra induced by MXPM between the RZ signal and continuous-wave double probe lights. We also study experimentally wavelength tunability for the proposed format converter at 40 Gbit/s, which is feasibly achieved by varying the central wavelengths of the double probe lights. Our results show that a wide operation wavelength range of 24 nm is obtained. By monitoring eye diagrams, the converted 40 Gbit/s NRZ signals can have an extinction ratio of 10.9 dB and the *Q*-factor of 6.1, respectively. Moreover, the proposed scheme is simple and robust, which is promising for high-speed optical fiber communication applications. [DOI: 10.1117/1.OE.52.5.055002]

Subject terms: nonlinear optics; all-optical format conversion; return-to-zero; nonreturn-to-zero; multiple cross phase modulation; highly nonlinear fiber.

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1 Introduction

With a wide range of applications of video distributions, teleconferencing and other new bandwidth-intensive services, future transparent photonic networks are likely to employ a hybrid of wavelength division multiplexing (WDM) and optical time division multiplexing (OTDM) by combining the advantages of both multiplexing schemes to efficiently support high-speed data communications.[1,2] In OTDM networks, the return-to-zero (RZ) data format is widely used due to its large tolerance to polarization mode dispersion, inter-symbol interference, and other fiber transmission impairments, whereas the nonreturn-to-zero (NRZ) format is more suitable for WDM metro and access networks. This is because the NRZ data signal has a narrower spectral width and a higher timing-jitter tolerance than the RZ signal.[3] As a result, all-optical format conversion between RZ and NRZ can be an important interface for connecting ultra-fast OTDM networks with WDM metro or access networks.[4] So far, various methods have been proposed to achieve all-optical RZ-to-NRZ format conversion. These can be based on, for example, polarization bistable vertical-cavity surface-emitting laser,[5] injection locked laser diode,[6] nonlinear optical loop mirror,[7–9] semiconductor optical amplifiers (SOAs),[10–13] interferometer devices,[14–18] micro-fiber or silicon microring resonator,[19,20] and spectral line-by-line pulse shaping,[21] respectively. However, the relatively long gain recovery time in SOAs ultimately limits their operation performance, while interferometer-based devices usually have a complicated structure and can even need temperature control. Currently, the high manufacturing cost for microring resonators may prevent them from practical applications, and micro-fiber knot resonators are also very sensitive to the surrounding environment. On the other hand, optical fibers are commercially available with high product reliability and have been widely used in high-speed communication systems/networks. Recently, dispersion-shifted fibers (DSF) have been employed for all-optical RZ-to-NRZ data format conversion.[8,22,23] A small nonlinear coefficient of DSFs, however, requires a long interaction fiber length in order to obtain sufficient nonlinear effects in DSFs for the given powers of signal and control lights. To solve this problem, we can consider the use of a highly nonlinear fiber (HNLF) to implement an all-optical data format converter that should be more compact than those employing a conventional DSF, because of the shortened fiber length. Nevertheless, it is noticed that most of previous researches on all-optical RZ-to-NRZ format converters are based on fixed wavelength operation and focus on single-to-single channel format conversion. All-optical RZ-to-NRZ format conversion with tunable wavelength conversion and single-to-dual channel signal multicasting has not been reported until now. However, increasing demand for video distributions and teleconferencing requires optical fiber communication networks to

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possess a function of wavelength multicasting.[24] From the viewpoint of practical applications, it is thus very desirable that a single-channel RZ signal from a backbone network can be converted to multi-channel NRZ signals which can be further multicast at different wavelengths to multiple target nodes simultaneously in a metro or access network. This can reduce the complexity, power consumption and cost of the photonic networks, respectively. Moreover, it can provide a high flexibility for the network interface and can also enable optical parallel processing.

In this paper, we propose and demonstrate a novel single-to-dual channel RZ-to-NRZ format converter with a function of wavelength conversion and multicasting by using multiple cross-phase modulation (MXPM) in a HNLF. In this case, the HNLF acts as a nonlinear element to broaden the spectrum of input continuous-wave (CW) double probe lights due to MXPM effect. Then two optical bandpass filters (OBPF) with appropriate bandwidths are used to extract two central spectral components from the broadened spectra of both probe lights in order to achieve single-to-dual channel RZ-to-NRZ format conversion. Moreover, we carry out the experimental study of wavelength tunability for our designed format converter at 40 Gbit/s by using two wavelength-tunable CW lasers and tunable OBPFs, respectively. The influence of an input signal power on the eye diagram of the converted NRZ signal is also considered in the experiment. The proposed RZ-to-NRZ format converter has the advantages of simple structure, low cost, efficient operation with wide wavelength range, and a transparency to data bit rates.

2 Operating Principle and Experimental Setup

The schematic diagram of a single-to-dual RZ-to-NRZ format converter is shown in Fig. 1. An RZ optical data signal of wavelength $\lambda_{\mathrm{signal}}$ is combined with double CW probe lights of wavelength λ_{cw1} and λ_{cw2} by an optical 2×1 optical coupler (OC) before passing through an erbium-doped fiber amplifier (EDFA). Then they are launched into a HNLF. Here the EDFA is used to ensure that the powers of RZ data signal and CW probe lights are sufficiently high to create enough MXPM effect in a HNLF. In general, the injected optical RZ data pulses with sufficiently high peak power propagating in a nonlinear medium (i.e., HNLF) and leads to a refractive-index change of the HNLF via the optical Kerr effect. This causes a nonlinear phase shift of two co-propagating CW probe lights via MXPM, and therefore, generates both red and blue chirps on two sides of individual probe lights, respectively. The magnitude of the chirp is governed by the rate of change of the input RZ signal power level.[22] The instantaneous wavelength remains unchanged only when the rate of change of the RZ signal power is zero.[22,25,26] If the central wavelength of an OBPF at the designed format converter is tuned to the central wavelength of each of CW probe lights so as to filter out the un-chirped spectral component, an inverted rectangle-like pulse waveform is obtained, as illustrated in Fig. 1. In this way, the outputs (from two OBPFs) of the format converter are the dual-channel NRZ optical data signals at the wavelengths of λ_{cw1} and λ_{cw2}, respectively.

Figure 2 illustrates the experimental setup for the all-optical RZ-to-NRZ format conversion with wavelength conversion and dual-channel signal multicasting. An actively mode-locked semiconductor laser emits a 10 GHz optical short pulse train at the wavelength $\lambda_{\mathrm{signal}} = 1550.5$ nm. The generated pulses are modulated by a $\mathrm{LiNbO_3}$ modulator that is driven by a 10 Gbit/s pseudorandom binary sequence from a pattern generator with a bit length of $2^7 - 1$. After power amplification and noise filtering, the 10 Gbit/s optical pulse signal is fed into a fiber-based interleaver that performs optical time division multiplexing to produce a 40 Gbit/s RZ

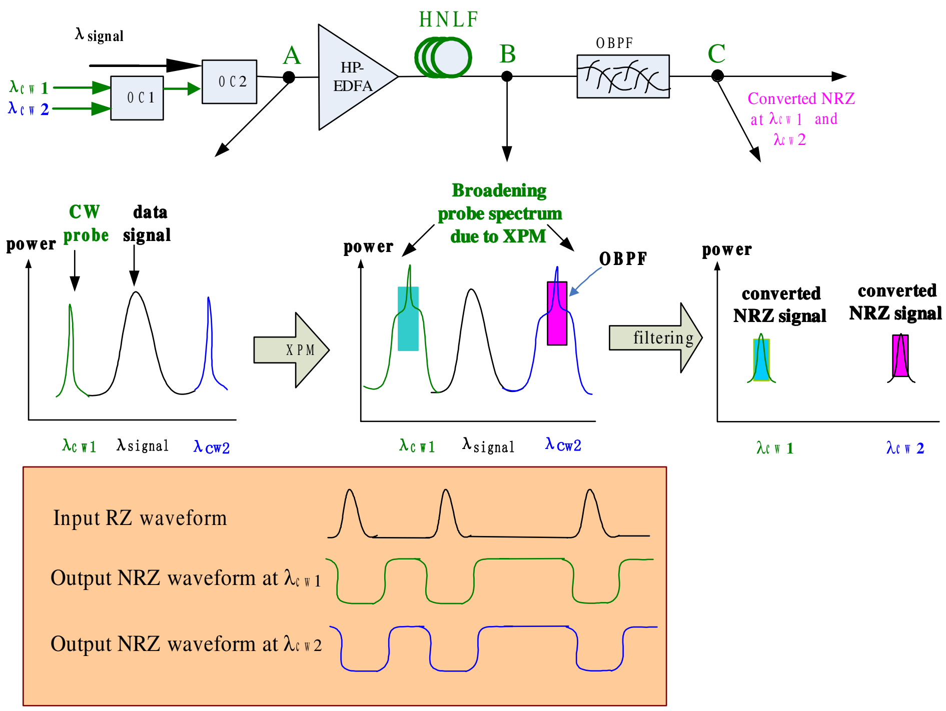

Fig. 1 Operating principle of the proposed single-to-dual channel RZ-to-NRZ format conversion.

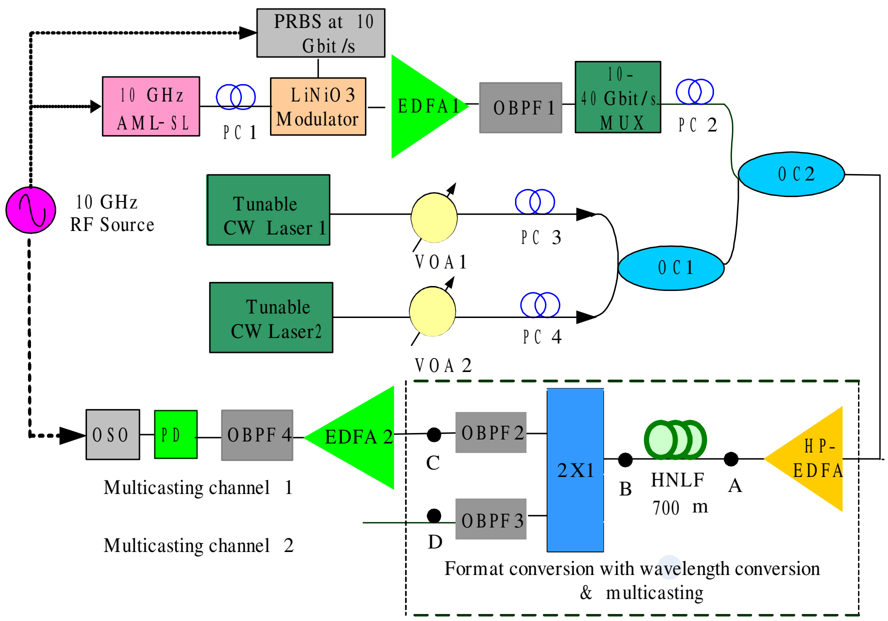

Fig. 2 Experimental setup for an all-optical single-to-dual channel RZ-to-NRZ format converter using a HNLF.

signal for use in the experiments of format conversion. The probe lights are generated by two tunable CW lasers (CW1: Santec, MLS-2100; CW2: Amonics, ATL-C-12-B-FA) with capability of continuously tuning their central wavelengths in the full C-band. A 3 dB OC is used to combine the 40 Gbit/s RZ data signal with the double CW probe lights. They are then amplified by a high power erbium-doped fiber amplifier (HP-EDFA, model KPS-CUS-BT-C-35-PB-111-FA-FA) before entering a 700-m-long HNLF. The HP-EDFA can provide a high saturation output power of 34 dBm with an operating wavelength range from 1535 to 1565 nm and a noise figure of less than 6 dB. Due to the good separation in wavelengths of those lights and the low nonlinearity of the erbium-doped fiber, very little interaction of the RZ data pulse and CW probe lights is expected in the HP-EDFA. The HNLF acts as a nonlinear medium to modify the phase of the input probe lights by MXPM, resulting in the spectral broadening of two CW probe lights. The nonlinear coefficient of the HNLF is $9\ \mathrm{W}^{-1}\,\mathrm{km}^{-1}$ and its dispersion is $-2.42\ \mathrm{ps}/(\mathrm{nm\,km})$ at 1550 nm. The dispersion slope and attenuation coefficient of this HNLF is less than 0.02 ps/nm km and 0.43 dB/km over 1500 to 1600 nm, respectively. In the experiment, the central wavelengths of two wavelength-tunable OBPFs (i.e., OBPF2 and OBPF3) with a 3 dB bandwidth of 0.38 nm are adjusted to λ_{cw1} and λ_{cw2}, respectively, in order to select the corresponding central components of two broadened probe spectra at the HNLF output. In this way, two filtered output signals are the dual-channel 40 Gbit/s optical data signals with NRZ format at two different wavelengths, respectively. Therefore, the proposed RZ-to-NRZ format converter with wavelength conversion and multicasting functionality is feasibly demonstrated. Then the converted NRZ signals are input to a 70 GHz photodetector (U^2t model number XPDV 3120R) for the optical-to-electrical conversion of which the output 40 Gbit/s electronic signal is fed into a wide-bandwidth electrical digital sampling oscilloscope (Tektronix model number 80E06) to monitor the waveform or eye diagram of the format-converted data signal. An EDFA after OBPF2 or OBPF3 is used to ensure that the sufficient photocurrent is fed into the digital sampling oscilloscope, if the format-converted data signal is relatively weak at the HNLF output. The OBPF4 with tunable bandwidth is used to suppress the amplified spontaneous noise and to further optimize the converted NRZ signal by optical spectral tailoring. To monitor the optical spectra of CW probe lights and the converted data signal lights on different multicast channels, we also connect an optical spectrum analyzer (OSA, Yokogawa-AQ6370, Mitaka) of resolution 0.02 nm with the input and output ports of a HNLF as well as the output ports of the OBPFs, corresponding to points A, B, C, and D indicated in Fig. 2.

3 Results and Discussion

In the experiments, an input 40 Gbit/s optical RZ signal is combined with CW double probe lights, and they are injected into the RZ-to-NRZ format converter. These hybrid lights with power of -2.3 dBm are then amplified by a

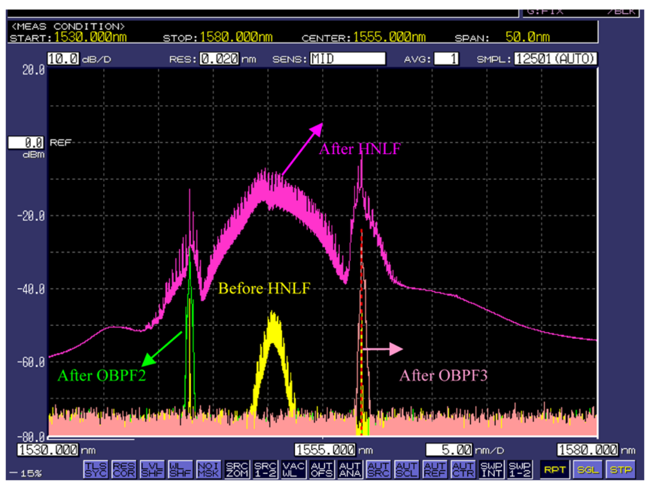

Fig. 3 Optical spectra of input signal (1550.5 nm) and two CW probe lights (1542 and 1558 nm) before & after the HNLF, and after the OBPF, respectively.

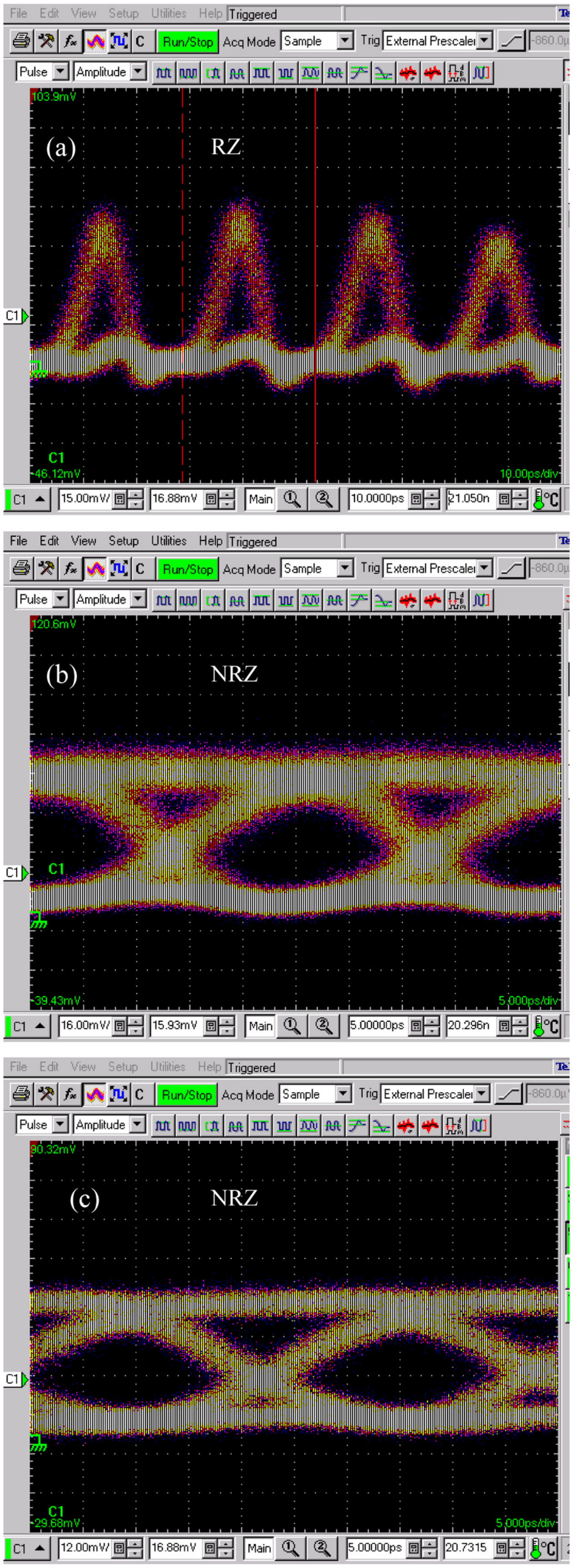

Fig. 4 The measured 40 Gbit/s eye diagrams of (a) input RZ signal at 1555.0 nm, (b) converted NRZ signal on multicasting channel 1 of 1542 nm, and (c) converted NRZ signal on multicasting channel 2 of 1558 nm.

HP-EDFA to 23.5 dBm before they are launched into the HNLF. Significant MXPM effect appears due to high peak power of the RZ signal light. Because MXPM is polarization dependent, we can practically use three polarization controllers to align the polarization states of 40 Gbit/s RZ data signal and CW double probe lights in order to optimize the format conversion process. Figure 3 shows the optical spectra of input data signal and CW double probe lights before entering the HNLF, after passing through the HNLF (undergoing spectrum broadening by MXPM in the HNLF), and after the OBPF, respectively, which are measured by placing an optical spectrum analyzer at points A, B, C, and D in Fig. 2. We can easily see that the 20 dB spectrum width of two CW probe lights is broadened obviously at the HNLF output. This is caused by MXPM between the RZ data signal with high peak power and two CW probe lights. The data signal itself also shows a significant amount of spectral broadening caused by self-phase modulation. We

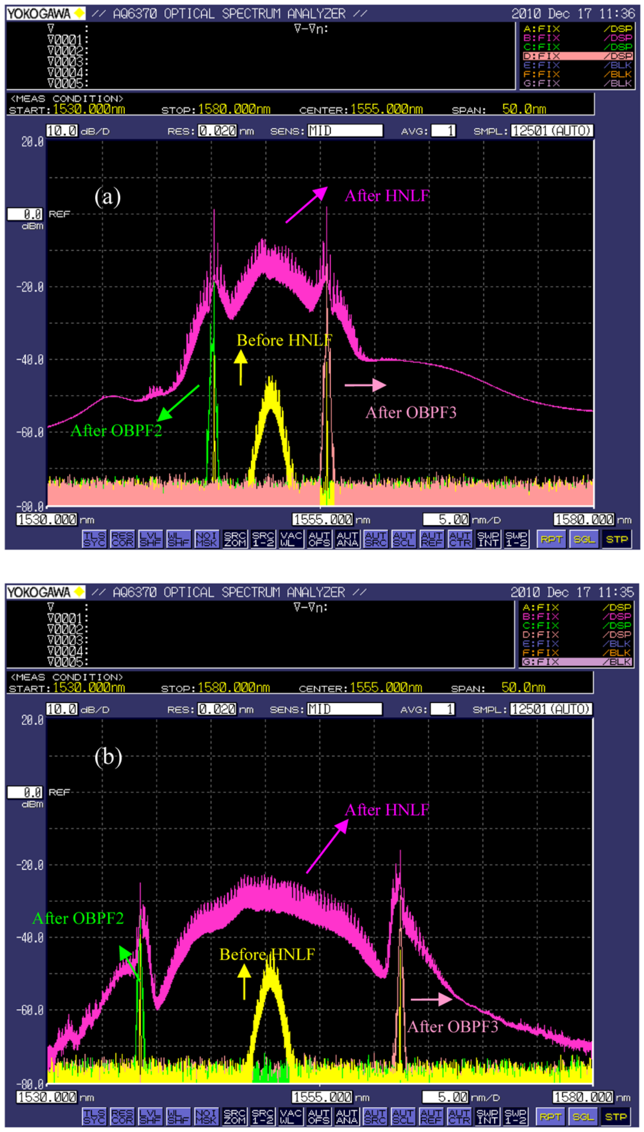

Fig. 5 Optical spectra at the input and output of the HNLF, and the output of OBPF for different central wavelengths of probe lights: (a) $\Delta\lambda_1 = -5.5$ nm, $\Delta\lambda_2 = 4.5$ nm, and (b) $\Delta\lambda_1 = -12.5$ nm, $\Delta\lambda_2 = 11.5$ nm.

obtain two output NRZ signals by using two wavelength-tunable OBPFs to filter out the un-chirped central spectral components at λ_{cw1} and λ_{cw2} from two broadened probe spectra, respectively. After optical amplification and noise filtering, each converted 40 Gbit/s NRZ signal is input to a 70 GHz photodiode. Then the signal eye diagram is measured by connecting the photodiode with a 70 GHz digital sampling oscilloscope. Figure 4 shows the eye diagrams of the input RZ and output NRZ signals at 40 Gbit/s. Clear and open eyes of the converted NRZ signals are obtained with little ripple on the top. No additional noise and pattern effect can be found. After carefully adjusting the power of an input optical RZ signal and monitoring the corresponding eye diagrams of output NRZ signals at a 700-m-long HNLF, we find out in the experiment that the optimal Q factor and extinction ratio (ER) of the two converted NRZ signals are 6.1 and 10.9 dB (directly read out from a 70 GHz digital sampling oscilloscope), respectively.

As far as all-optical RZ-to-NRZ format conversion with wavelength multicasting is concerned, a wide operating wavelength range is highly desirable for practical applications. Hence, we carry out an experimental investigation into the wavelength tunability of the resulting single-to-dual channel RZ-to-NRZ format converter. In this experiment, the 40 Gbit/s RZ data pulse signal has a central wavelength $\lambda_{signal} = 1550.5$ nm, whereas the central wavelengths λ_{cw1} and λ_{cw2} of two CW probe lights are all tunable. The tuning characteristic of the format converter is measured by varying the detuning values $\Delta\lambda_1 = \lambda_{cw1} - \lambda_{signal}$ and $\Delta\lambda_2 = \lambda_{cw1} - \lambda_{signal}$, where "+" and "−" signs indicate the wavelength "up-conversion" and "down-conversion", respectively. Some typical optical spectra of the RZ-to-NRZ format conversion results are shown in Fig. 5. The corresponding eye diagrams are measured and shown in Fig. 6. It is clear that open eye diagrams are obtained. The results indicate that our proposed all-optical format converter can achieve a wide operating wavelength range of nearly 24 nm. This is substantially limited by operation bandwidth of the tunable OBPF, dispersion characteristic of the HNLF and gain bandwidth of the HP-EDFA in our experiments.

The power variation of input signal light cannot be avoided completely in practical networks owing to the

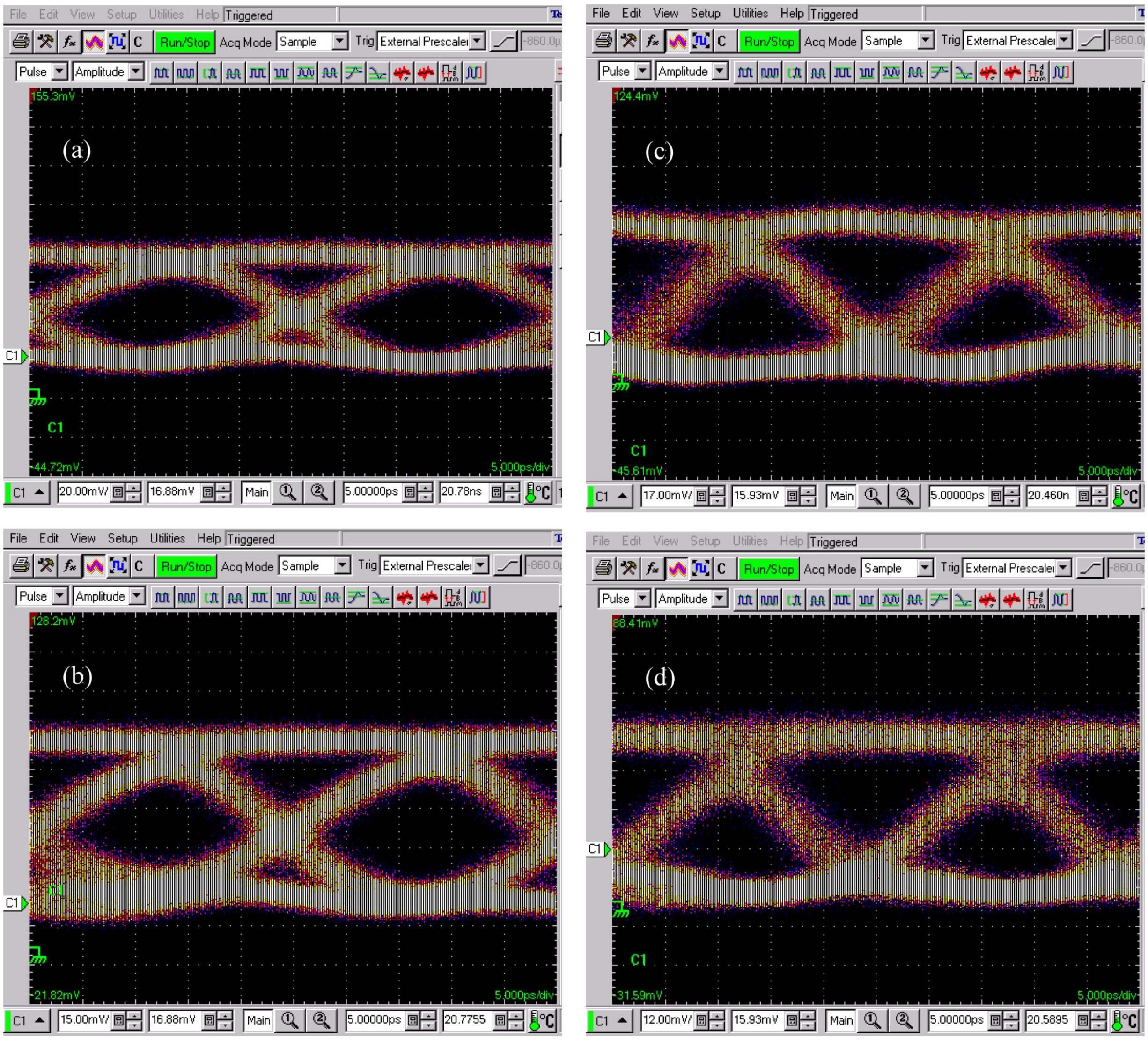

Fig. 6 Eye diagrams of output 40 Gb/s NRZ signals on multicasting channels 1 and 2 for (a) $\lambda_{cw1} = 1545$ nm, (b) $\lambda_{cw2} = 1555$ nm, (c) $\lambda_{cw1} = 1538$ nm, and (d) $\lambda_{cw2} = 1562$ nm, respectively.

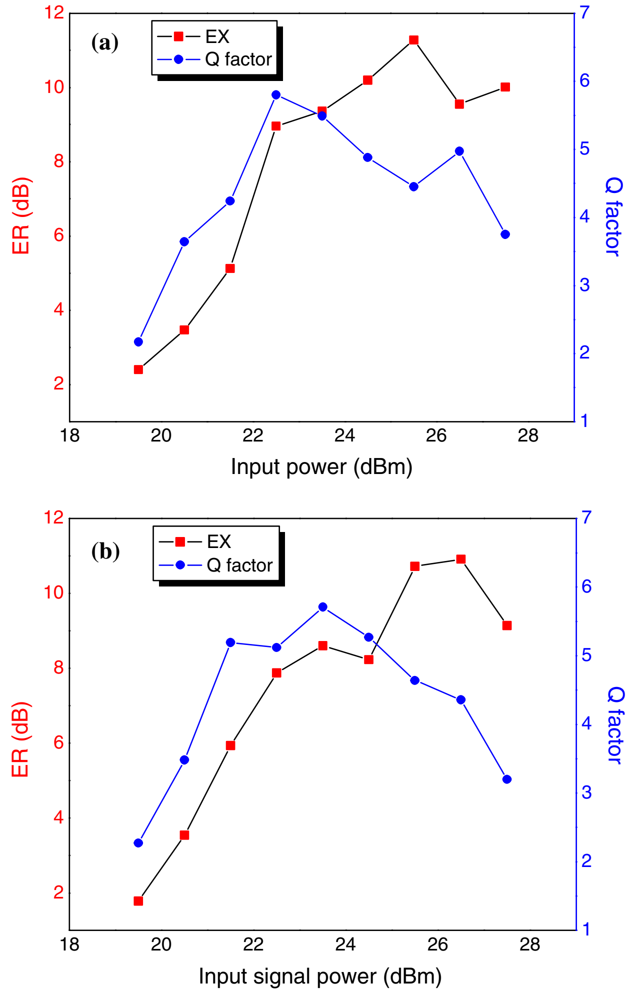

Fig. 7 The measured ER and Q factor versus the input signal power for (a) multicasting channel 1 at 1542 nm and (b) multicasting channel 2 at 1558 nm, respectively.

change of system operation conditions and environments. This requires the all-optical RZ-to-NRZ format converters to have some tolerance to the input optical power fluctuation. In the experiment, we test the designed format converter by varying the optical RZ signal power from 19.5 to 27.5 dBm at the input of a 700-m-long HNLF, while maintaining other parameters constant to make the results comparable. In this case, the central wavelengths of two CW probe lights are set to 1542 nm and 1558 nm, while the signal wavelength is 1550.5 nm. When an input RZ signal light has sufficiently high power, the MXPM induces the spectral broadening for CW double probe lights, and the degree of phase modulation increases with increased input signal power. However, further increase of input signal power leads to stronger self-phase modulation of the optical RZ signal. In the experiment, the effect of changing the input RZ signal power on the eye diagrams of output NRZ signals is feasibly studied by using a wideband electrical sampling oscilloscope after an ultrafast photodiode to measure the ER and Q factor at the output of our designed RZ-to-NRZ format converter. Figure 7 shows the measured ER and Q factor (plotted as a function of the input RZ signal power) for two multicasting channels with NRZ data format. Generally speaking, we can see that ER and Q factor are first increased with the increase of input signal power up to ∼23 dBm. Then the Q factor is decreased, while the ER is increased gradually, for the input signal power in a range of about 23 to 26 dBm. With a further increase of input signal power beyond ∼26 dBm, the ER is also decreased. In the case of low input signal power, the ER and Q factor of the converted NRZ signal are small and are limited by the insufficient MXPM-induced spectral broadening between the input RZ signal and double probe lights. However, for high input signal power, the reduction of ER and Q factor is caused by the strong optical nonlinear effect in a HNLF. Moreover, one can see that the best ER and Q factors are not present at the same level of the input RZ signal power. Hence, there is a trade-off between ER and Q factor for our proposed RZ-to-NRZ format converter with wavelength conversion and multicasting capabilities.

4 Conclusions

We have proposed and experimentally demonstrated a novel all-optical single-to-dual channel RZ-to-NRZ format conversion based on MXPM in a highly nonlinear fiber. The proposed format converter also has a function of wavelength conversion and dual-channel signal multicasting. This is achieved by optically filtering out the un-chirped central spectral components of two broadened probe spectra that are caused by MXPM. The converted 40 Gbit/s NRZ signal can have the ER and Q factor of 10.9 dB and 6.1, respectively. Moreover, we have experimentally studied the wavelength tunability of the proposed format converter at 40 Gbit/s by varying the central wavelengths of two CW probe lights individually. It has been shown that the operating wavelength range of 24 nm is achieved. The effect of the input RZ signal power on ER and Q factor of output NRZ signals has been also studied experimentally by measuring the corresponding eye diagram of the obtained NRZ signal, and the proposed format converter has shown a reasonably good tolerance to the input signal power fluctuation. Our proposed scheme has an advantage of simple and robust structure compared with the interferometer-based format conversion or the scheme based on a nonlinear optical loop mirror.

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Biographies and photographs of the other authors not available.