Simultaneous All-Optical Waveform Reshaping of Two 10-Gb/s Signals Using a Single Injection-Locked Fabry–Pérot Laser Diode

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***Abstract*—All-optical waveform reshaping of a distorted 10-Gb/s nonreturn-to-zero (NRZ) pseudorandom bit sequence (PRBS) signal using two-mode injection locking in Fabry–Pérot laser diode (FP-LD) was demonstrated. Simultaneous waveform reshaping of two 10-Gb/s distorted NRZ PRBS signals using a single FP-LD was also demonstrated.**

***Index Terms*—Fabry–Pérot laser diode (FP-LD), multimode injection locking, waveform reshaping.**

I. INTRODUCTION

ALL-OPTICAL signal regeneration, 2R regeneration (reamplification and reshaping) and 3R regeneration (reamplification, reshaping, and retiming), are expected to play a major role in future all-optical networks to avoid accumulation of noise and waveform distortion during signal transmission [1]. Recently, all-optical waveform reshaping techniques based on injection locking in laser diodes have drawn attention [2], [3]. Weich *et al.* [2] demonstrated waveform reshaping of a 10-Gb/s return-to-zero (RZ) signal via wavelength conversion in a two-section Fabry–Pérot laser diode (FP-LD). Waveform reshaping was achieved by converting the pulse shape of the data signal to that of the undistorted clock signal. The technique is, however, not applicable to nonreturn-to-zero (NRZ) signal. Yamashita and Matsumoto [3] used the threshold property of injection locking in a distributed feedback laser diode (DFB-LD) to reshape a distorted 1.8-Gb/s pseudorandom bit sequence (PRBS) signal. The technique requires a narrow-band filter to remove the injected signal from the DFB-LD emission because of the narrow injection locking range of DFB-LD. Also, one DFB-LD is required to reshape the waveform of each wavelength channel.

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In this letter, we demonstrate waveform reshaping of distorted NRZ signals at 10 Gb/s using two-mode injection locking in an FP-LD. Similar work was carried out independently by Yamashita *et al.* [4]. Utilizing the intrinsic multimode nature of FP-LDs, we further show that a single FP-LD can be used to simultaneously reshape two distorted 10-Gb/s NRZ signals.

II. OPERATION PRINCIPLE

If an external optical signal is injected at a given detune from the closest free-running mode of an FP-LD, there exists a threshold of the injected signal power [3], [5] beyond which the external signal will injection-lock the FP-LD and force it to operate at the signal wavelength at a constant output power. If the power of external signal is below the injection-locking threshold, the injected signal will experience loss. The threshold power $P_{\rm th}$ is given by

$$P_{\rm th} = \frac{(2\pi\tau_d\Delta f)^2 P_i}{(1+\alpha^2)} \tag{1}$$

where Δf is the detune, τ_d is the photon lifetime, P_i is the output power of one of the longitudinal modes of the FP-LD at free running condition, and α is the linewidth enhancement factor [5]. The proposed all-optical waveform reshaping method is based on the threshold nature of injection locking. When a distorted pulse is injected to an FP-LD, only the part of the signal with power above the injection locking threshold will experience gain. The injection-locked output of the FP-LD from this part of the signal will be the same. Another part of the signal will experience loss. In order to improve the extinction ratio of the reshaped signal, we injected a continuous-wave (CW) light at another longitudinal mode of the FP-LD together with the data signal. The function of the CW light is to injection-lock the FP-LD when the input data signal is below the threshold level. Finally, since FP-LDs are multimode, an FP-LD can injection-lock several signals simultaneously, thus making it possible to use a single FP-LD to reshape multiple data signals [6]. Only one CW light is needed for waveform reshaping of multiple channels.

III. EXPERIMENTAL SETUPS AND RESULTS

A. Waveform Reshaping of a Single 10-Gb/s NRZ Signal

The experimental setup of all-optical waveform reshaping of both one 10-Gb/s NRZ signal and simultaneously two 10-Gb/s

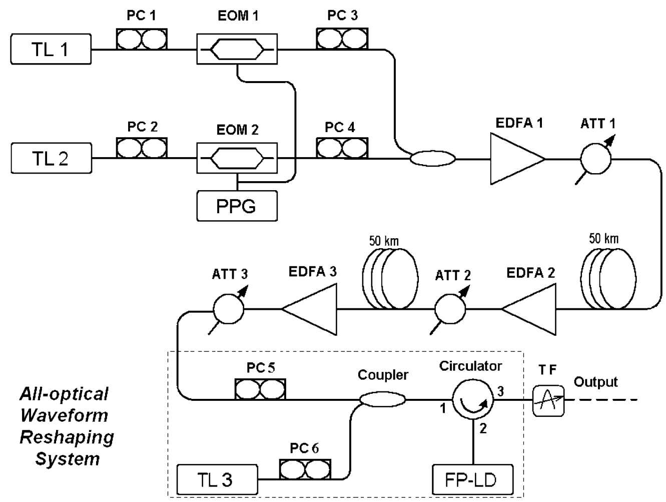

Fig. 1. Experimental setup for waveform reshaping of distorted 10-Gb/s NRZ signals.

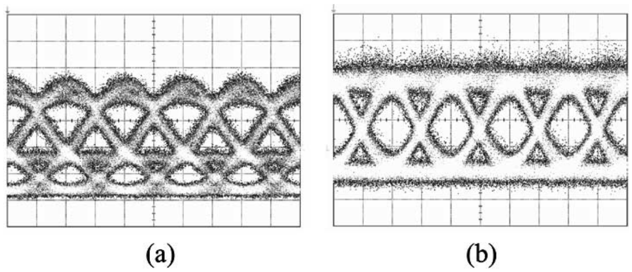

Fig. 2. Eye diagrams of a 10-Gb/s signal after propagation in 100-km SSMF (a) before waveform reshaping, and (b) after waveform reshaping. The time scale is 50 ps/div and the amplitude scale is 100 mv/div.

NRZ signals using a single FP-LD is shown in Fig. 1. For reshaping of one 10-Gb/s signal, the tunable laser TL2 was turned OFF. A pulse pattern generator generating a 10-Gb/s $2^{23}-1$ NRZ PRBS signal was used to modulate the tunable laser (TL1) via the $LiNbO_3$ modulator [electrooptic modulator (EOM)]. The modulated signal at a wavelength of 1550.325 nm was then propagated through two 50-km spans of standard single-mode fiber (Corning SMF-28). Three erbium-doped fiber amplifiers (EDFA1, EDFA2, and EDFA3) were used to compensate for the propagation loss and three tunable attenuators (ATT1, ATT2, and ATT3) were used to control the output power of each EDFA, respectively. The average power of the signal at the input ends of each fiber span were about -6 dBm. The total dispersion value of 100-km standard single-mode fiber (SSMF) is about 1700 ps/nm. The signal was severely distorted by dispersion after propagation for 100 km. Fig. 2(a) shows the eye diagram of the signal after propagation of 100 km.

We then injected the distorted signal at average power of -6 dBm into an FP-LD via a polarization controller (PC2), a 3-dB coupler, and an optical circulator. The FP-LD (model LDM5S813 of Wuhan Telecomm. Devices Co.) has a double-channel planar buried InGaAsP heterostructure. The mode spacing is about 1.1 nm. The bias current of the FP-LD is $1.27I_{\text{th}}$, where I_{th} is the threshold current. A CW signal (TL3) of power -4 dBm and wavelength 1544.775 nm was also injected into the FP-LD. The wavelengths of the data signal and the CW were chosen to be at the longer wavelength sides

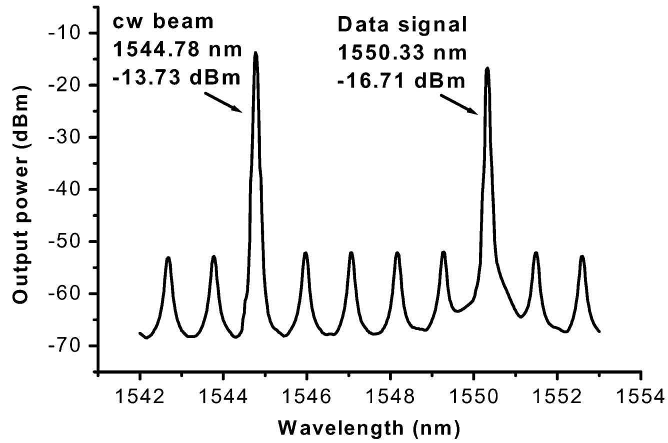

Fig. 3. Output spectrum of waveform reshaping of a single 10-Gb/s signal. The bias current is 1.27 times of the threshold current.

of different FP-LD longitudinal mode. The detune between the signal wavelength and the closest FP-LD longitudinal mode was 0.075 nm and that for the CW was 0.025 nm. Thus, the CW beam would be pulled out of the locking range whenever the data signal injected-locked the FP-LD. The powers and detunes of both the data signal and the CW were chosen such that 1) the power of the rising and falling edges of the data signal were not sufficient to initiate injection locking. The FP-LD was injection-locked by the CW light instead and the FP-LD emitted at the wavelength of the CW light. Consequently the rising and falling edges of the data signal experienced loss. 2) The power of the data signal around the peaks of the pulses was higher than the injection locking threshold of the FP-LD such that the FP-LD output at the data signal wavelength with a constant power. The function of the CW light used is to achieve faster response speed [7] as well as to improve the extinction ratio of the signal by removing the power of the FP-LD free running mode near the data signal when the power of the data signal is below the threshold level. Fig. 2(b) shows the eye diagram of the reshaped signal. From the open eye diagram, the distorted signal was successfully reshaped. Fig. 3 shows the corresponding output spectrum. The wavelength separation between the data signal and the CW signal is about 5.55 nm. Thus, CW beam was easily removed using a bandpass filter (TF) which has a 3-dB bandwidth of 0.8 nm at the data wavelength. The output powers of CW and data1 measured at Port 3 of the circulator are -13.73 and -16.71 dBm, respectively.

B. Simultaneous Waveform Reshaping of Two 10-Gb/s NRZ Signals

Tunable laser TL2 in Fig. 1 was now turned ON. The power and detune of the three signals from TL1 (data1), TL2, (data2), and TL3 (CW) were adjusted such that the CW light injection-locks the FP-LD only when both data1 and data2 do not injection-lock the FP-LD. The wavelengths and input powers of data1, data2, and CW were 1547.02, 1551.50, and 1543.70 nm and -6, -9, and 0 dBm, respectively. The corresponding detunes of data1, data2, and CW from their respective FP-LD free running modes were chosen as 0.07, 0.125, and 0.05 nm, respectively. The bias current of the FP-LD is $1.27I_{\text{th}}$. Fig. 4(a)

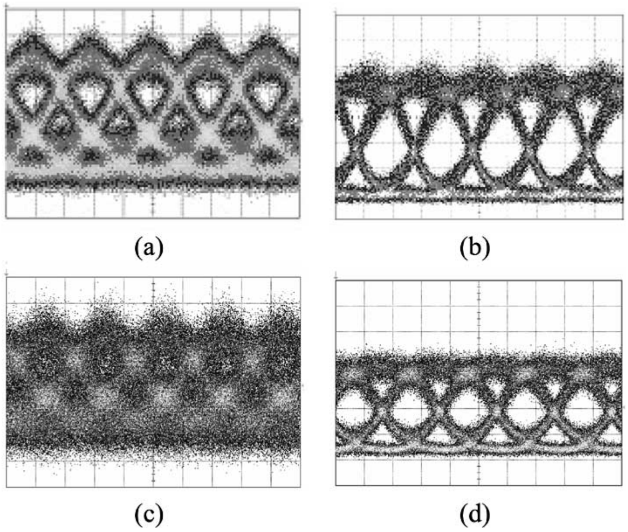

Fig. 4. Eye diagrams of (a) data1 and (c) data2 after propagation in 100 km of SSMF before waveform reshaping. Eye diagrams of (b) data1 and (d) data2 after simultaneously waveform reshaping using a single FP-LD. The time scale is 50 ps/div. The amplitude scales are (a) 71.6 mV/div, (c) 49.2 mV/div, and (b) and (d) 100 mV/div, respectively.

and (c) shows the eye diagrams of data1 and data2, respectively, before waveform reshaping, while Fig. 4(b) and (d) shows the eye diagrams of data1 and data2, respectively, after waveform reshaping. From Fig. 4(c), data2 was more distorted than data1 after propagation of 100 km because of the relatively low input power. The eye diagrams are clear and open after the waveform reshaping. We found that the crosstalk between data1 and data2 can be avoided using relative high power for the CW (0 dBm) compared to that of the data signals (-6 and -9 dBm). From the thickness of the "1" rails in Fig. 4(b) and (d), crosstalk between the two data signals induced by the waveform reshaping process is not significant. Fig. 5 shows the output spectrum of the three-wavelength injection-locked FP-LD. The output powers of CW, data1, and data2 measured at Port 3 of the circulator are -3.41, -5.39, and -7.98 dBm, respectively.

A single FP-LD has the potential to reshape multiple channels in a wavelength-division-multiplexed (WDM) communication system if the mode spacing of the FP-LD matches with the channel spacing of the WDM system. The detune between the wavelengths of the data channels and the FP-LD modes would be the same for all the channels because both the FP-LD mode comb and the channel spacing are fixed. It is not necessary to individually control the injected power into the FP-LD for each WDM channel because the output of an injection-locked FP-LD will be clamped at a fixed level. Thus, a single broad-band amplifier would be sufficient to control the input powers into the FP-LD as along as the wavelength channel with the lowest input power into the FP-LD can injection-lock the laser.

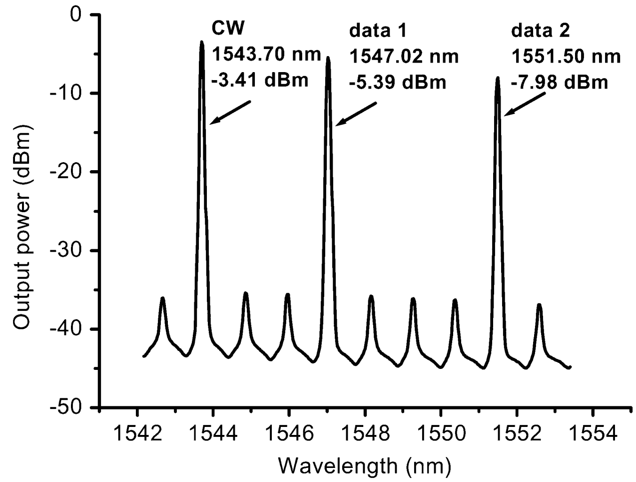

Fig. 5. Output spectrum of simultaneous waveform reshaping of two 10-Gb/s signals. The bias current is 1.27 times of the threshold current.

IV. Conclusion

We have presented an effective method to reshape the distorted signal in optical fiber communication systems. Using the injection-locking property of an FP-LD, we experimentally demonstrated waveform reshaping of one and simultaneously two 10-Gb/s NRZ signal with a single FP-LD. The proposed waveform reshaping technique is not data pattern dependent and can be applied to both NRZ and RZ formatted signals. Finally, a single FP-LD may be used to reshape multiple channels in a WDM optical fiber communication system.

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