All-Optical Data Format Conversion in Synchronously Modulated Single-Mode Fabry–Pérot Laser Diode Using External Injection-Locking-Induced Nonlinear Threshold Reduction Effect

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***Abstract*—High-speed all-optical data-format conversion and logic gate from a synchronously modulated Fabry–Pérot laser diode (FPLD) below threshold condition is demonstrated by using external injection-induced nonlinear threshold reduction effect of the FPLD. A pulsed pseudoreturn-to-zero (PRZ) data with maximum extinction ratio of 14.5 dB is obtained by externally seeding the 9.953-Gb/s (OC-192) nonreturn-to-zero (NRZ) data stream to optically gain-switch the FPLD. At optimized radio frequency and optical injecting powers of 24 and 4 dBm, the root mean square timing jitter and the duty-cycle (pulsewidth) of the PRZ eye pattern are determined as 0.4 ps and 45% (44 ps), respectively. The bit-error rate (BER) can be as low as 10^{-13} under the 4-dBm external injecting power. A 1.5-dB power penalty with the BER of $<10^{-9}$ is measured at a bit rate of 9.953 Gb/s. Highest NRZ-to-PRZ conversion rate of 12.5 Gb/s is achieved by increasing biasing current of the FPLD.**

***Index Terms*—Data format conversion, injection locking, laser diode, optical communication.**

I. Introduction

FABRY-PÉROT laser diode (FPLD)-based ultrafast all-optical signal processors have recently emerged for all-optical networks, which include functions such as clock recovery [1], wavelength conversion [2], [3], upstream traffic transmission [4], and particularly, the nonreturn-to-zero to pseudoreturn-to-zero (NRZ-to-PRZ) data-format conversion [5], [6], etc. However, the FPLDs have drawbacks such as multimode lasing spectrum, low sidemode suppression ratio (SMSR), and a bad extinction ratio (ER), that degrade the data transmission and decoding. To overcome these drawbacks, various approaches enabling single-mode and wavelength-tunable operations of FPLDs via self-seeding and external injection schemes have emerged [7], [8]. Chow *et al.* [5] demonstrated the wavelength-converted single-mode NRZ-to-PRZ conversion by injection-locking a continuous-wave lasing FPLD with an optical pulse-train at the wavelength of one longitudinal mode of the FPLD, and concurrently seeding the FPLD with an optical NRZ data stream at the wavelength of another longitudinal mode. This scheme provides a −9.5-dB negative power penalty at a bit-error rate (BER) of 10^{-9}, a maximum wavelength tuning range over 45 nm, and an ER exceeding 10 dB. Later on, a mutual injection-locking technique successfully transfers the gain-switched FPLD from multimode to single-mode lasing [9]. The NRZ-to-PRZ conversion was also implemented using the feature of the transverse-magnetic (TM) mode absorption of an FPLD with the self-phase modulation (SPM) of the NRZ data. In this letter, we propose an NRZ-to-PRZ data-format converter by simply injecting optical NRZ data into an unlasing FPLD, which can provide all-optical converted PRZ data at the highest data rate of 12.5 Gb/s can be achieved. The FPLD is neither lasing nor gain-switching without external injection. No additional distributed-feedback laser diodes are required in contrast to the previous approach [5].

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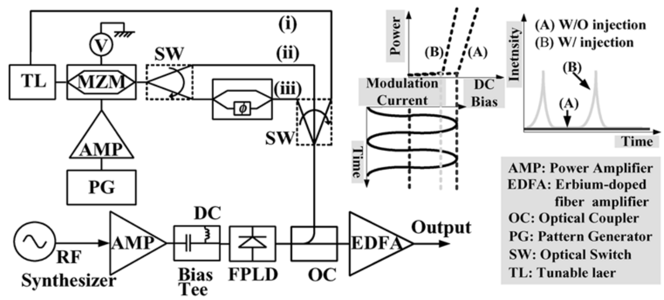

Fig. 1. Experimental setup and operating principle for the FPLD-based NRZ-to-PRZ format converter. The right illustrates the FPLD (A) without external injection and (B) under an optical injection-locking-induced gain-switching condition.

II. Experimental and Principle

The schematic diagram of the proposed NRZ-to-PRZ converter is shown in Fig. 1. The FPLD exhibits a 10-mA threshold current and a 1.2-nm longitudinal mode spacing, and is *synchronously* modulated by an amplified radio frequency (RF) clock. The RF power is adjusted just below the threshold condition of the FPLD. The optimized condition for the external-injection-induced gain-switching of the FPLD is first investigated (see path (i) in Fig. 1) using a tunable laser (TL). Subsequently, the FPLD is externally injected by an optical NRZ data stream,

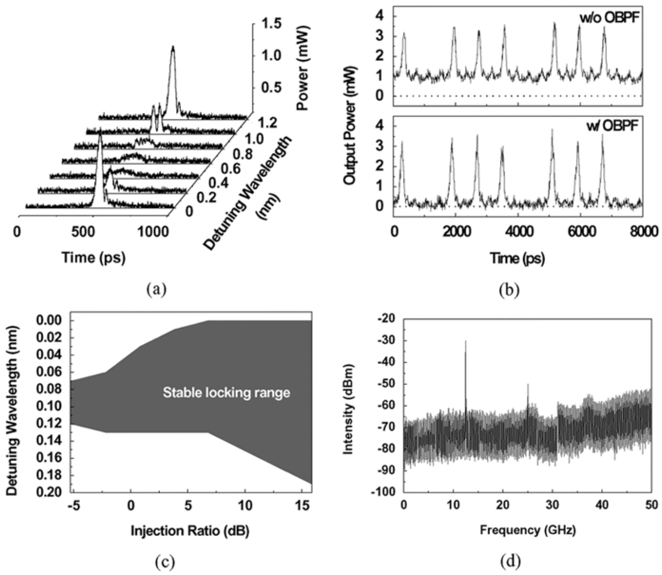

Fig. 2. (a) Evolution of FPLD pulse shapes under the external injection at different wavelengths. (b) The FPLD converted PRZ data stream with and without OBPF. (c) The detuning wavelength and stable locking range as a function of injection ratio. (d) The RF spectrum of the FPLD-based PRZ data-stream converter operated at 12.5 GHz.

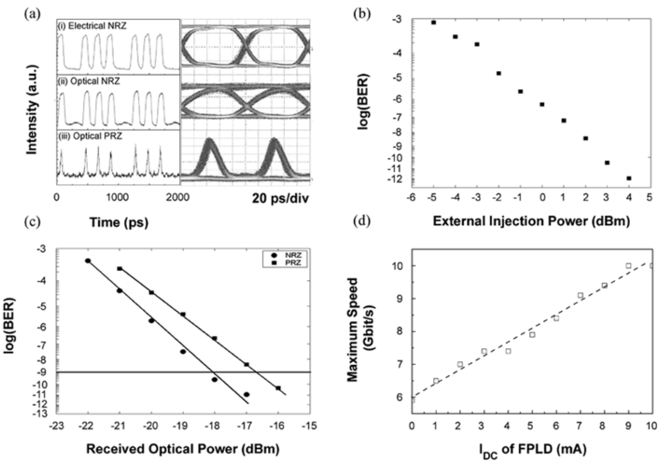

Fig. 3. (a) Pattern and eye diagrams of electrical NRZ (upper), optical NRZ (middle), and PRZ data streams (lower) at 9.953 Gb/s. (b) BER of PRZ data as a function of injecting power. (c) BERs of optical NRZ and PRZ data streams at different receiving powers. (d) Maximum data rate achieved at different biases of FPLD.

as shown in the path (ii) of Fig. 1. The threshold current of the FPLD is reduced by *logic 1* of the NRZ data stream, resulting in the gain-switching of the FPLD and the generation of the corresponding PRZ data. In our experiment, a critical requirement when using this NRZ-to-PRZ conversion scheme is that the system clock must be recovered. One approach to deriving the required clock is to optically tap part of the input NRZ data, and then recover the clock with an electrical clock recovery circuit.

The conceptual diagram of the threshold reduction induced by external injection-locking is shown in the right side of Fig. 1.

When the FPLD is injection-locked by the external light, the threshold current will be decreased. Such a phenomenon was also experimentally observed and theoretically interpreted by Sivaprakasam *et al.* [10]. With external injection-locking, the FPLD operated at below threshold can be single-mode gain-switching, which can subsequently be applied to implement the NRZ-to-PRZ conversion by *synchronously* modulating the unlasing FPLD.

III. Results and Discussion

The best SMSR of 40 dB is obtained under 6-dBm continuous wave (CW) injecting power, while the ER linearly increases with the increase of the optical CW injecting power and saturates at 14.5 dB. The pulsewidth of the converted PRZ data shown in Fig. 2(a) is 44 ps. As the CW injecting wavelength is detuned away from the wavelength of the FPLD mode by half of the mode spacing, the gain-switching effect diminishes, eventually degrading the pulse amplitude and width, SMSR, and signal-to-noise ratio (SNR). The original converted PRZ data stream carries a large amount of the amplified spontaneous emission (ASE) noise from the erbium-doped fiber amplifier, providing the data with a large dc offset level and a bad SNR. Such a drawback can be overcome by using an optical bandpass filter (OBPF) to suppress the ASE outside the transmitted wavelength, and a cleaner PRZ data stream (i.e., with a smaller dc offset level and a better SNR) can be obtained, as shown in Fig. 2(b). The variations in the RF driving power and the external injecting power strongly affect the ER of the converted PRZ data. The detuning tolerance on the RF driving power is small (for example, 24.4–24.7 dBm under the injecting power of -2 dBm). Increasing the RF power by only 0.5 dBm caused a serious degradation on the ER of the PRZ data because of the self-gain-switching of the FPLD. There is a tradeoff between the ER and the external injecting power since the larger external injecting power contributes an additional CW component to the PRZ data. In addition, the single-sideband phase noise of the PRZ data is as low as -100 dBc/Hz at 5-kHz offset from the carrier frequency, corresponding to the root mean square (rms) timing jitter of 0.4 ps (integral range from 10 Hz to 5 kHz). It is observed that the timing jitter linearly decreases with the increase of injecting power; the minimum jitter can be obtained at the injecting power of >-4 dBm. When the injecting power is small, the timing jitter is dominated by spontaneous emission in FPLD. The increase of the injecting power provides a larger stimulated emission, which leads to a significant reduction in timing jitter and shorting in pulsewidth.

Subsequently, a single-mode optical NRZ pattern converted from an 8-bit edited electrical NRZ pattern is employed to externally injection-lock the FPLD. In the experiment, all-optical transformed PRZ-format data stream with bit rates larger than 12.5 Gb/s can be obtained by optimizing the RF synchronous modulation power and the dc current of the FPLD, as shown in Fig. 2(d). For example, the eye diagrams of electrical and the optical NRZ, and the converted PRZ data stream at a SONET/synchronous digital heirarchy (SDH) data rate of 9.953 Gb/s (SONET OC-192 or SDH SD-64) are analyzed in Fig. 3(a). The amplitude fluctuation of the FPLD converted PRZ data stream due to the reflection of the light at the interface between fiber connectors can be up to $\Delta V/V = 16\%$, which can be 3 dB suppressed (with a $\Delta V/V$ of 8.2%) by fusing the

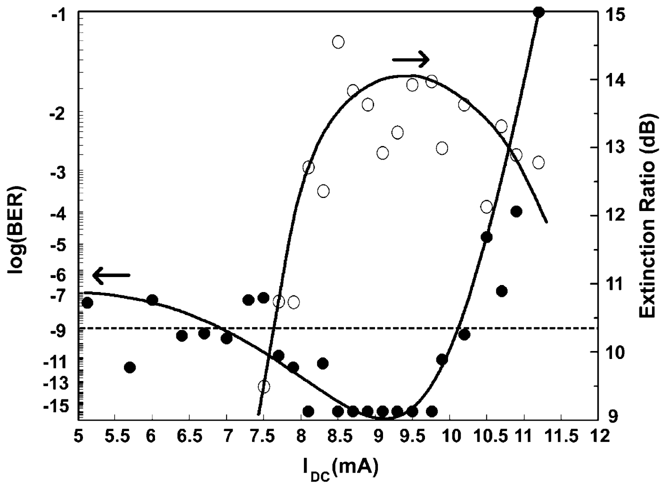

Fig. 4. BER and ER of PRZ data at different dc driving currents of FPLD with optimized RF driving power.

connective nodes between FPLD and the injecting coupler. Only a limited jitter of <0.4 ps is applied to the corresponding eye diagram of the converted PRZ data stream. The BER of the received PRZ data stream decreases from 10^{-9} to 10^{-12} as the injecting power increases from 0 to 4 dBm, as shown in Fig. 3(b). Note that the FPLD is operated in the stable injection-locking range, which is sensitive to both the wavelength detuning and the power of the injected beam, as shown in Fig. 2(c). In Fig. 3(c), the BER is plotted as a function of the receiving optical power for the NRZ-format optical data and the converted PRZ-format data, which reveals that the FPLD-based NRZ-to-PRZ data format converter has a power penalty of only 1.5 dB at 10^{-9} BER level. A nearly error-free (the BER 10^{-12}) PRZ data can still be analyzed at receiving optical power of -16 dBm.

To operate at a higher data rate, the increase in the dc biasing current (for enhancement of the analog modulating bandwidth of the FPLD) and the reduction in the RF modulating power required for keeping the FPLD unlasing are necessary. The highest data rate with BER of $< 10^{-9}$ achieved at different dc biasing currents of FPLD is shown in Fig. 3(d). Note that the dc biasing current is not necessary for a data rate of <6 Gb/s. By increasing the dc biasing current of the FPLD to 9 mA, the NRZ-to-PRZ conversion at the data rate of >10 Gb/s can be achieved, which is eventually limited by the carrier lifetime and the maximum biasing level of the FPLD. Such an RF/dc biasing configuration is more cost-effective than that using a high-power RF amplifier at low dc current condition. In addition, Chang *et al.* suggested that the modulation bandwidth of laser diode could be improved by several times under external-injection-locking condition [11]. With the same technique, Huang *et al.* have also shown the enhancement on the modulation bandwidth of a distributed feedback laser diode from ~10 to 35 GHz [12]. Finally, the BER and the ER of the converted PRZ data at different dc currents with the optimized RF driving power are also measured (see Fig. 4). To obtain a BER of $<10^{-9}$ at 9.953 Gb/s, the dc current added to the FPLD has to be >7 mA at least. The best ER (>14 dB) and the error-free operation are observed when the deviation between dc biasing and FPLD threshold current is within 10%. In comparison, a larger dc current enhances more the modulation bandwidth (increase the data-converting rate), but fails to remain the quality of the converted PRZ data because of the significant degradation of its BER and ER, caused by the lasing of the FPLD even without external injection.

IV. Conclusion

We have demonstrated an optical NRZ-to-PRZ data format converter, whose data rate is up to 12.5 Gb/s, in a *synchronously* modulated unlasing FPLD through the external-injection-locking-induced nonlinear threshold reduction effect. The proposed scheme excludes the requirement of optical pumping and cross-gain modulation techniques, and only one *synchronously* modulated FPLD is required to buildup the whole NRZ-to-PRZ data-format converter, which is different from the newly proposed scheme using transverse-mode absorption and SPM technique in a FPLD. At the data rate of 9.953 GHz (OC-192/SD-64), the maximum ER of 14.5 dB is observed at the optimized RF driving power of 24 dBm and the external injecting power of 4 dBm. The rms timing jitter and the duty cycle (pulsewidth) of the PRZ eye pattern are 0.4 ps and 45% (44 ps), respectively. With the external injecting power of 4 dBm, the BER can be as low as 10^{-13}. The power penalty at a BER of 10^{-9} is as small as 1.5 dB.

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