All-optical NRZ-to-PRZ format transformer with an injection-locked Fabry-Perot laser diode at unlasing condition

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Abstract: By using an optical nonreturn-to-zero (NRZ) format data-stream to injection-lock an synchronously modulated Fabry-Perot laser diode at below threshold condition (without DC driving current), an output data-stream with pseudo-return-to-zero (PRZ) format can be generated at bit rate of up to 2.488 Gbit/s. Such an NRZ-to-PRZ format transformation is due to the injection-locking induced gain-switching of the FPLD with the incoming NRZ data. The PRZ data-stream with a maximum on/off extinction ratio of 12.2 dB is obtained under the optical injecting power of -2 dBm and the RF driving power of 24.4 dBm. The best side-mode suppression ratio of 40 dB and the lowest timing jitter of 0.4 ps for the PRZ data-stream are observed. A power penalty of 1.2 dB is measured at a bit-error rate of 10^{-9} after NRZ-to-PRZ transformation. In application, the demonstration of an all-optical OR logic gate using the FPLD-based NRZ-to-PRZ transformer is also reported.

OCIS codes: (060.2330) Fiber optics communications; (140.2020) Diode lasers; (200.3760) logic-based optical processing; (200.4560) Optical data processing.

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#4908 - $15.00 US
Received 30 July 2004; revised 6 September 2004; accepted 9 September 2004

1. Introduction

The Fabry-Perot laser diode (FPLD) based ultrafast all-optical signal processing techniques are expected to play important roles in future all-optical networks [1-5]. Versatile techniques such as the clock frequency division [2,3], the wavelength conversion [4], and a nonreturn-to-zero (NRZ) to pseudo-return-to-zero (PRZ) format transformation [5], have been demonstrated. Recently, Jeong *et al.* [5] used transverse-magnetic mode absorption of an FPLD and the self-phase modulation technique to achieve NRZ-to-PRZ data format conversion. In this Letter, we demonstrate a new scheme to translate an optical NRZ-format data into an optical PRZ-format data by biasing an FPLD synchronously modulated at unlasing condition. In contrast to the previous approach, the FPLD in our scheme is operated just below the threshold condition by minimizing the DC driving current and appropriately setting the RF driving power. The FPLD becomes gain-switching when its threshold current is reduced by an external injection. That is, the FPLD receives the incoming NRZ data with high level (“1” bit) and results in the generation of a PRZ data, whereas the low-level (“0” bit) data ceases the lasing of the FPLD. Such an external injection-locking not only achieves the NRZ-to-PRZ transformation, but also helps to suppress the gain of side modes and spontaneous emission, providing the FPLD output data-stream a higher side mode suppression ratio (SMSR) and lower noise level. In application, an all-optical logical OR gate operation is also demonstrated.

2. Experimental setup and principle of operation

The FPLD-based NRZ-to-PRZ transformer is shown in Fig. 1. The FPLD with a threshold current of 13 mA and a longitudinal mode spacing of 1.2 nm is modulated at a RF driving power just below the threshold condition (24.4 dBm). In particular, the FPLD is only driven by the amplified RF sinusoidal wave via a Bias Tee circuit without any DC driving current. The temperature of the FPLD is controlled at 27.5^{o}C with fluctuation of <0.1 ^{o}C to prevent the drift of the wavelength of the FPLD’s longitudinal modes. One branch of a 3-dB optical coupler (OC) is used to connect the FPLD with the external injection source, and the other branch outputs the gain-switched pulse into an erbium-doped fiber amplifier (EDFA) for amplification. First, the optical path ‘A’ (see Fig. 1) is used to investigate the gain-switching phenomenon induced by an externally optical injection of a tunable laser (TL). Second, by using a Mach-Zehnder intensity modulator (MZM) in connection with the TL and a pattern generator (PG) to simulate an NRZ data stream, the characteristics of the NRZ-to-PRZ transformer such as eye diagrams, a bit-error rate (BER), and a power penalty are measured (see the optical path ‘B’). The detailed experimental parameters are listed in Sections 2.1 and 2.2, respectively. Finally, the operating principle is shown in Fig. 2 and explained in Section 2.3.

2.1. CW external injection

To investigate the gain-switching of the FPLD via external optical injection, the FPLD is modulated only by an amplified RF signal of 24.4 dBm below the lasing threshold. The RF operating frequency ranges from 1 GHz to 2.5 GHz in the experiments of continuous-wave (CW) and NRZ-encoded external injection. In the experiment of NRZ-to-PRZ transformation, the RF operating frequency of the synchronously modulated laser diode is completely the same as the clock signal required for the pattern generator which generates the electrical NRZ data-stream. With an injection power of -2 dBm and a wavelength coincident with that of the FPLD’s longitudinal mode, the effective threshold current of the FPLD will be reduced by the external TL injection. The injection of TL (through optical path (A) in Fig. 1) thus results in the gain-switching of the FPLD. The pulsewidth and peak power of the FPLD’s output are 44 ps and up to 135 mW (corresponding to average power of 5.94 mW).

#4908 - $15.00 US Received 30 July 2004; revised 6 September 2004; accepted 9 September 2004

2.2. NRZ-format data external injection

To simulate an incoming data stream with NRZ modulation format, the PG is used to drive a MZM to encode the external injection light, as depicted by optical path (B) in Fig. 1. The MZM (JDS Uniphase; OC-192 Modulator with $V_\pi = 5V$) is biased at linear operating region. The external-injection-induced gain-switching is initiated when the FPLD receives the incoming NRZ data stream, providing a transformed PRZ data stream output from the FPLD. Note that a polarization controller (PC) before the injection branch is used to adjust the polarization of the injection light to match that of the FPLD.

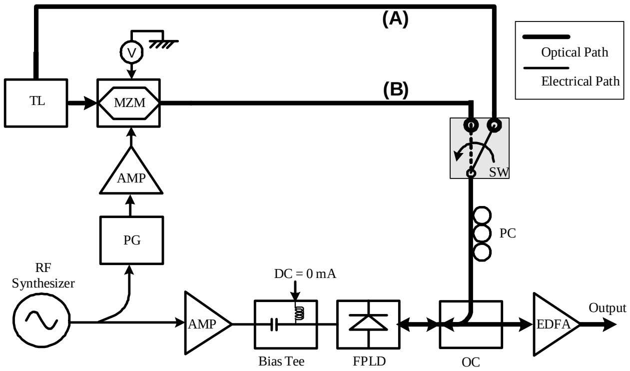


Fig. 1. Experimental setup for the NRZ-to-PRZ format transformer: AMP: power amplifier; EDFA: Erbium-doped fiber amplifier; FPLD: Fabry-Perot laser diode; MZM: Mach-Zehnder modulator; OC: optical coupler; PC: polarization controller; PG: pattern generator; SW: optical switch; TL: tunable laser.

2.3. Principle of operation

Figure 2 illustrates the operating principles of the typical gain-switching and the external-injection-induced gain-switching methods. In a typical gain-switching operation shown in Fig. 2(a), the DC driving current is set near the threshold current and then a large sinusoidal wave is applied to gain-switch the FPLD. In contrast, the external-injection-induced gain-switching requires that the DC driving current is set at 0 mA and a larger sinusoidal wave is applied to bias the FPLD at just below threshold condition, as shown in Fig. 2(b). In this case, the FPLD originally is un-lasing.

The principle of the FPLD based NRZ-to-PRZ transformation is described below. The derived threshold current of a FPLD at free running condition can be expressed as

$$I_{th} = \frac{eN_{th}V}{\tau_s} = \frac{eV\left[\dfrac{G(N_{th})}{G_N} + N_0\right]}{\tau_s} \qquad (1)$$

$$G_N = \frac{\partial g}{\partial N} \upsilon_g \tau_{ph}$$

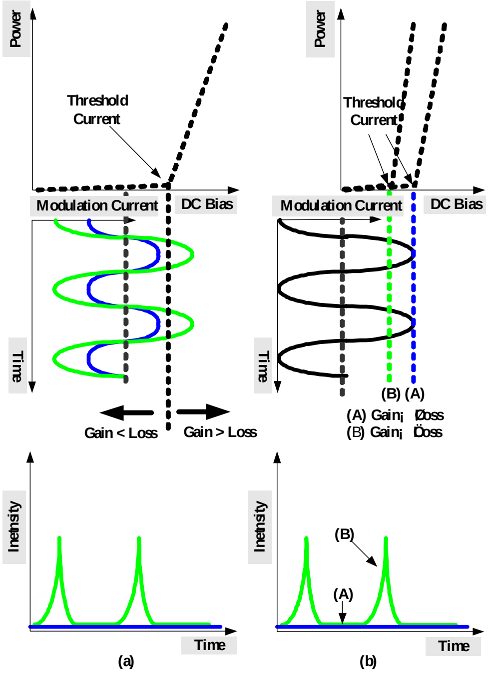
where e is the electronic charge, V is the volume of the active region, τ_s is carrier lifetime in active region of the laser diode, $G(N_{th})$ is the normalized gain of the laser diode at threshold condition, $\partial g/\partial N$ is the differential gain coefficient, v_g is the group velocity of light, τ_{ph} is the photon lifetime, and N_0 is the carrier number in active region of the laser diode at transparent condition. In particular, the threshold current is a nonlinear function of external injection power or photon density, as described by [6,7]

$$I_{th}' = I_{th} - \frac{eV\tau_{ph}}{G_N \tau_s}\left[\frac{R_{sp}}{S_{Lm}} + \sqrt{4\alpha^2 k_c^2 S_i \big/ (1+\alpha^2) S_{Lm}}\right] \qquad (2)$$

Received 30 July 2004; revised 6 September 2004; accepted 9 September 2004

where R_{sp} is spontaneous emission rate, S_{Lm} is maximum photon number in the locked mode, α is linewidth broadening factor, k_c is coupling coefficient, and S_i is photon number injected into the laser cavity.

Therefore, as the FPLD is externally injection-locked by a single-mode CW light, the effective threshold current of the FPLD is decreased (see the line (B) in Fig. 2(b)). Such a phenomenon is also observed by S. Sivaprakasam *et al.* [8] Under the external injection, the FPLD will be translated from unlasing to gain-switching operation. By applying such an anomalous operation of an FPLD, the all-optical signal processing can be realized. As a result, an incoming NRZ data whose high-level ("1") bit will cause the FPLD gain-switching, whereas the low-level ("0") bit will not. Consequently, the NRZ-to-PRZ data format transformation is achieved.



(a) (b)

Fig. 2. (a) The 'general' gain-switching method; (b) The 'anomalous' gain-switching method: (A) without external injection; (B) with external injection.

3. Results and discussion

3.1. CW external injection

The gain-switched pulses exhibit largest peak power and shortest pulsewidth as the wavelength of the TL exactly matches that of a longitudinal mode in FPLD. As the wavelength of the TL is detuned away from the longitudinal mode of the FPLD, the gain-switched FPLD pulses degrade significantly and eventually diminish after detuning for 0.4 nm, as shown in Fig. 3. The maximum SMSR of the TL injected FPLD is up to 34 dB when the wavelengths of TL and FPLD mode are coincident each other.

The on/off extinction ratios (ERs) of the FPLD pulse under the switching of injecting power and wavelength are also characterized. As the injection wavelength was switched away from the FPLD's longitudinal mode by 0.6 nm (exactly half of the mode spacing of the FPLD), the on/off ER is 10.5 dB. By switching the external intensity, the gain-switched FPLD pulse exhibits an on/off ER of up to 12.2 dB under injecting power of -2 dBm (see Fig. 3). Note

#4908 - $15.00 US Received 30 July 2004; revised 6 September 2004; accepted 9 September 2004

that a higher amplified spontaneous emission (ASE) of the FPLD under switching off condition is observed. The external injection causes the suppression of the ASE and side modes and the reduction of threshold current of one specified FPLD longitudinal mode during gain-competition process.

Moreover, the variation of the RF driving power and the external injection power can strongly affect the on/off ER of the gain-switched FPLD, as shown in Fig. 4. When the RF driving power is increased by 2% of its threshold value (24.4 dBm), the on/off switching phenomenon of the FPLD pulses no longer exists since the FPLD is self gain-switched by the RF signal (see trace (a) in Fig. 4). The tolerance on the RF driving power for optimized on/off ER performance is severe, and only 1 dB increase of the RF driving power will cause a serious degradation on the on/off ER of the FPLD. The optimized RF driving power is ranged from 24.4 to 24.7 dBm, which are within 1.5% beyond the threshold condition.

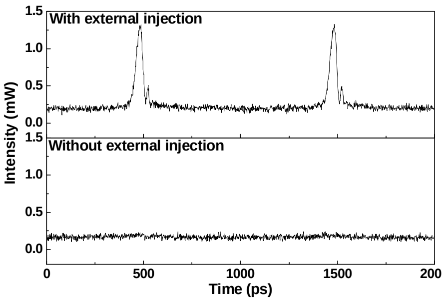


Fig. 3. The pulse intensity with and without light injection.

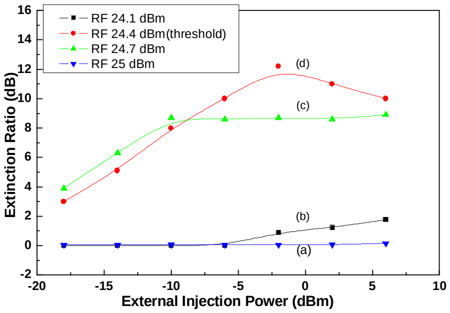


Fig. 4. ER versus external injection power under different RF driving power of the NRZ-to-PRZ transformer.

Suitable injection power is needed to obtain the maximum on/off ER. The decrease in on/off ER under excess external injection power can be attributed to the contribution of the external injection to CW component of the output. Moreover, the variations of the peak intensity and the SMSR of such an externally injected FPLD gain-switched at different injection power are also measured (see Fig. 5). A best SMSR of 40 dB under injection power of 6 dBm is obtained at a cost of slightly decreasing peak power (~140 mW) of the FPLD.

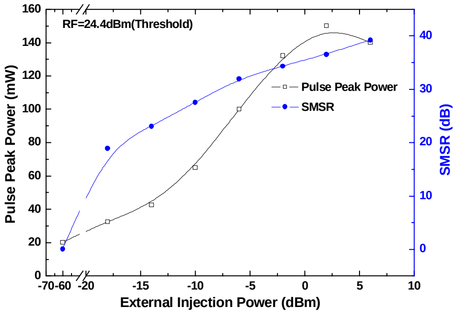


Fig. 5. The peak power and the SMSR at different injecting powers.

The single-sided-band (SSB) phase noise and the associated timing jitter of the gain-switched FPLD pulses externally injected at wavelength matching condition are also evaluated. With an external injection power of 6 dBm, the gain-switching pulses generated from the externally injected FPLD exhibit relatively low phase noise of -100 dBc/Hz at >1 kHz offset from carrier frequency (see Fig. 6). The corresponding rms timing jitter of 0.4 ps (integrating over a frequency band of 10 Hz-5 kHz) is also shown in Fig. 6. The rms timing

Received 30 July 2004; revised 6 September 2004; accepted 9 September 2004

jitter decreases from 0.7 ps to 0.4 ps as the external injection power increases from -14 dBm to 6 dBm (see Fig. 7). When the injection power is smaller, the rms timing jitter is dominated by spontaneous emission. As the injection power is increased, the externally injected light provides an initial excitation well above the level of spontaneous emission in a desired cavity mode. This excitation will reduce the fluctuations in the photon density around t_o, resulting in a corresponding reduction in rms timing jitter [9]. The pulsewidth of the gain-switched FPLD also shortens from 47 ps to 44 ps with the increase of the external injection power.

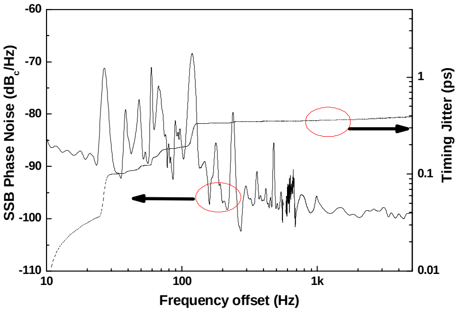


Fig. 6. The SSB phase noise and the associated rms timing jitter. The integral range is 10 Hz-5 kHz.

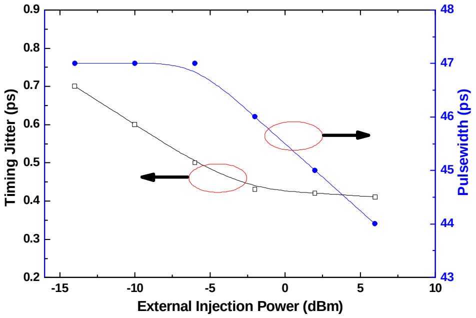


Fig. 7. RMS timing jitter and pulsewidth versus external injection power.

3.2. Optical NRZ-format data external injection

In the second experiment, the transformation of an optical NRZ-format data-stream to an optical PRZ-format is demonstrated using the synchronously modulated FPLD at below threshold condition. Figure 8 shows the electrical NRZ data before the MZM, the optical NRZ data after the MZM, and the FPLD-transformed PRZ data at 2.488Gbit/s data rate, respectively. An 8-bit edited optical NRZ pattern is then transformed into a PRZ pattern, as shown in Figs. 8(b) and 8(c). The duty cycle of such a PRZ-format data has the potential for the time-division multiplexing (TDM) with a passive TDM technique to enhance the bit rate and increase the network throughput. Figure 9 shows the corresponding eye diagrams of the electrical NRZ, the optical NRZ, and the transformed PRZ data, respectively. Note that the transformed PRZ-format data has a larger amplitude noise than the optical NRZ data due to a considerable spontaneous noise of the FPLD at the non-injected condition (i.e., “0” state). This drawback can be improved further by using two-mode injection locking (TMIL) technique [10], which transfers the unwanted spontaneous noise to another wavelength.

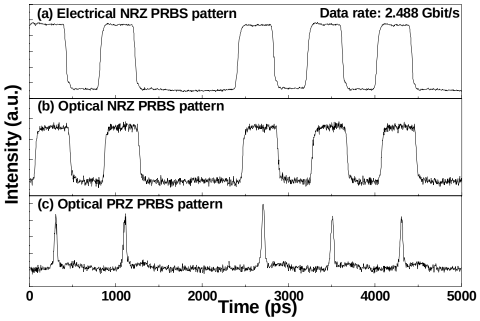


Fig. 8. The patterns: (a) the electrical NRZ data before the MZM; (b) the PG-encoded optical NRZ data; (c) the transformed PRZ signal generated from the single-mode FPLD. The data rate is 2.488 Gbit/s.

Received 30 July 2004; revised 6 September 2004; accepted 9 September 2004

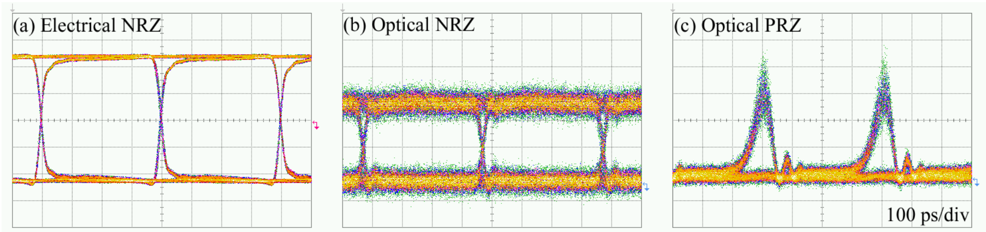


Fig. 9. The corresponding eye diagrams: (a) the electrical NRZ data before the MZM; (b) the PG-encoded optical NRZ data; (c) the transformed PRZ data. The data rate is 2.488 Gbit/s.

Moreover, the BER measurements of the PRZ data are shown in Fig. 10. The PRZ data is detected by a lightwave clock/data receiver (Agilent, 83446A), incorporating a high-gain avalanche photodiode (APD), a gain-controlled amplifier, and a clock/data recovery circuit. The received power is measured in the back-to-back (BtB) NRZ data and the BtB transformed into PRZ data at 2.488 Gbit/s. By using a 2^{23}-1 bit pseudorandom NRZ data, power penalty of 1.2 dB is measured at a BER of 10^{-9} in the NRZ-to-PRZ data transformer. The power penalty may be attributed to the considerable spontaneous noise at bit 0 and the amplitude fluctuation at bit 1 in an NRZ-to-PRZ data transformer. And error-free (BER $< 10^{-12}$) of PRZ-format output signal can be achieved when the received optical power is larger than -22 dBm. Similarly, the BER of PRZ-format signal is also affected by the intensity of the external injection power. Figure 11 shows that the BER increases with reduction of the injection power. When the external injection power is larger than 3 dBm, the BER of the PRZ-format output data can be as small as 10^{-9}. The BER of 10^{-12} can be observed with external injection power of 6 dBm.

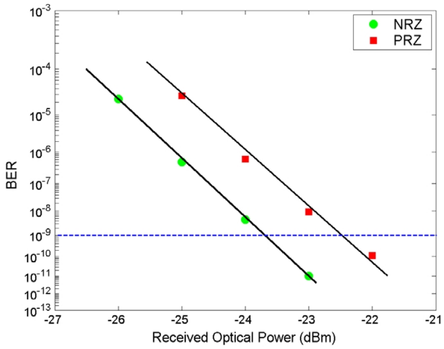


Fig. 10. The BER performance at 2.488 Gbit/s.

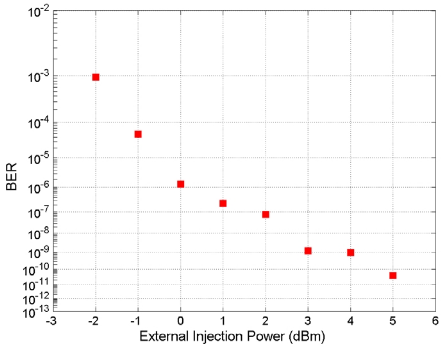


Fig. 11. The BER versus the external injection power.

3.3. All-optical OR gating and NRZ-to-PRZ conversion

In application, the optical OR gate function of the FPLD based NRZ-to-PRZ format transformer is demonstrated. This is implemented by seeding the FPLD with two different NRZ data-streams, as depicted in Fig. 12. As a result, the incoming data patterns in Ch1 10001010 and Ch2 10100010 are shown in Figs. 13(a) and 13(b), and the output PRZ data-stream with pattern of 10101010 is shown in Fig. 13(c). The optimized RF driving power of the FPLD for achieving this function is 24.7 dBm due to its larger tolerance in the external injection power (see trace (c) in Fig. 4) at such condition. Although the on/off ER (> 8.6 dB) of the FPLD based NRZ-to-PRZ is slightly sacrificed at a larger RF modulating power, it has already met the requirement for SONET/SDH OC-48/STM-16 standards of the Telecommunication Standardization Sector of International Telecommunication Union (ITU-T) [11].

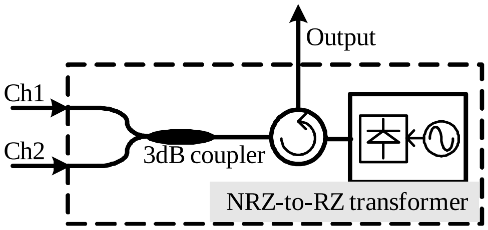


Fig. 12. An all-optical logical OR gate by using the NRZ-to-PRZ format transformer.

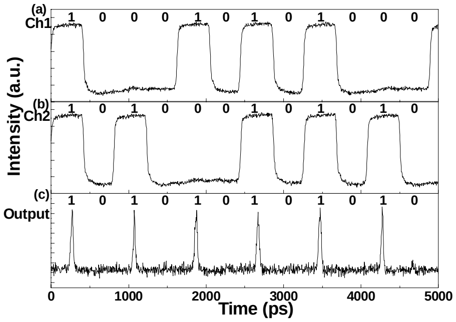


Fig. 13. Illustration of the test data (Ch1 and Ch2) and the data (Output) after OR operation.

5. Conclusions

An NRZ-to-PRZ format transformer based on an anomalous operation of an FPLD at 2.488 Gbit/s was demonstrated by biasing the FPLD under un-lasing condition. In contrast to previous demonstrations, the external injection-induced NRZ-to-PRZ transformation is realized by carefully setting the RF driving power of the FPLD to just below threshold condition. The FPLD translates from non-lasing to gain-switching under the external light injection. Such an operation can be applied to transform an optical NRZ data stream into optical PRZ data one. The maximum on/off extinction ratios are 10.5 dB and 12.2 dB under wavelength and amplitude switching operations, respectively. In addition, the extinction ratio of the FPLD based NRZ-to-PRZ transformer is found to strongly correlate with the external injection power and the RF driving power of the FPLD. The optimized RF driving power of 24.4 dBm and the external injection power of -2 dBm are determined. Moreover, the rms timing jitter decreases from 0.7 ps to 0.4 ps and the pulsewidth decreases from 47 ps to 44 ps as the external injection power increases from -6 dBm to 6 dBm. With external injection power of 6 dBm, the gain-switching pulses exhibit relatively low phase noise of -100 dBc/Hz at 5 kHz offset from carrier frequency. A 1.2-dB power penalty at a BER of 10^{-9} is obtained by using the NRZ-to-PRZ data transformer. The BER as low as 10^{-12} is obtained with external injection power of 6 dBm. In application, an optical OR gate is realized by using the FPLD based NRZ-to-PRZ format transformer at an appropriate RF driving power.

Acknowledgments

The authors thank the National Science Council of the Republic of China, Taiwan, for financially supporting this research under grants NSC92-2215-E-009-028 and NSC 93-2215-E-009-007.

Received 30 July 2004; revised 6 September 2004; accepted 9 September 2004