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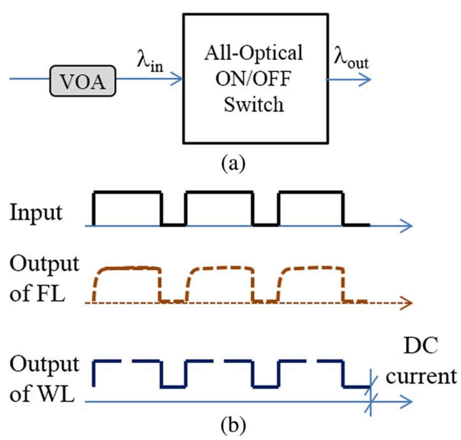

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Speed Enhancement of a Single-Mode FP-LD-Based Switch Using the Weak-Lock Technique

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Abstract: A technique called weak-lock (WL) has been proposed and applied to a simple optical on/off switch to increase its working speed from 1 to 12 Gb/s with clear output waveforms, whereas the required injection power is decreased. The switch is based on the injection-locking property of a single-mode Fabry–Pérot laser diode (SMFP-LD). Unlike the case of full-lock (FL) in which self-locked mode and all side modes of the SMFP-LD are fully suppressed due to high injected input power, in the WL case, the injection power is gradually decreased as if the SMFP-LD's self-locked mode is still maintained. It was observed that the output waveform's rising edge, taken at the self-locked mode's wavelength after the filter, in the WL case is clean at speed of 12 Gb/s compared to the blur and noisy rising edge in the FL case even at much lower speed (1 Gb/s). In summary, the WL technique shows advantages compared to the conventional FL technique in terms of lower injection power and higher on/off switching speed.

Index Terms: Weak-lock, full-lock, single-mode FP-LD, optical on/off switch.

1. Introduction

Several applications of various purposes have been realized basing on injection-locking properties of Fabry–Pérot laser diode (FP-LD), single mode FP-LD (SMFP-LD) [1], and semiconductor optical amplifier (SOA). For examples, all-optical wavelength conversion [2], [3], all-optical logic gates [4]–[6], all-optical flip-flop [7], data format conversion [8], [9], channelized transmission [10], [11], address decoder [12], [13], and all-optical switch [14]–[18]. For switching application, the SOA based switch has advantages in high speed and easy integration; however, it requires much more power ($>$ 250 mA) [14], [15] and is a much more expensive component ($>$ \$1500) [19] compared to those using SMFP-LD ($<$ 20 mA and $<$ \$80) [18]. SMFP-LD based all-optical switch shows even more advantages compared to those of FP-LD based in terms of simpler configuration and cost efficiency because SMFP-LD has self-locked mode and does not require additional injection beam to get locked like commercially available FP-LD. For SMFP-LD based switch, the recovery time, after the locking state of an SMFP-LD is released, is a critical issue which affects its overall on/off switching speed.

In this paper, we experimentally verified the working speed of an all-optical on/off switch based on injection-locking property of SMFP-LD in two cases, WL and FL. The terminology "on/off switch", which is used throughout the manuscript, means a switch which has only two states, ON and OFF, at the output port. In our experiment, the on/off switch is actually a *NOT* gate which inverts the high (ON) and low (OFF) states, at the input port, into OFF and ON states, at the output port, respectively. It was observed that the rising edge of SMFP-LDs self-locked mode at the output port was blur and noisy when input power is high (full-lock) even when the working speed is low (about 1 Gb/s); however, it was much improved (clearer) even when the working speed is high (about 12 Gb/s) if input power is low enough to have weak-lock. In other words, the overall on/off switching speed of the all-optical *NOT* gate is much increased in the WL case compared to that in the FL case. Moreover, the injection power in WL case is lower than that in the FL case.

2. Operation Principles

For switching applications using injection-locking properties of FP-LD, the on/off switching speed is mainly dependent on recovery time (rising edge). After being fully locked by external injection beam, the FP-LD starts to recover its original state while the injection beam is OFF. This recovery time is normally slow and can be improved by using additional beam as reported in this paper [16]. The contribution of output waveforms falling time can be negligible compared to that of rising time due to fast on/off state from modulator (< 30 ps) and high power gain from external source that causes the FP-LD to be locked quickly. Typically, in the case of FL, injection (input) power is adjusted so that input beam can fully lock the SMFP-LD in which the self-locked mode and other side modes of the SMFP-LD are fully suppressed. However, in the case of WL, the power of an injection beam is adjusted so that it can just reduce the power of the self-locked mode as much as possible but not destroy the locking state of the self-locked mode. The recovery time (rising time) of a SMFP-LD in WL case is the duration from its lowest to highest self-locking power sates; whereas the recovery time in FL case is summation of two durations. The first duration is from almost zero power level (the self-locking mode is fully suppressed in FL state) to lowest locking power (at WL state) plus recovery time in the WL case. Because the duration in which self-locked mode power is recovered from zero to lowest self-locking power levels is much longer compared to the duration in which self-locked mode power is recovered from lowest locking power to highest locking power, the overall recovery time of WL case is much shorter than that of the FL case.

Fig. 1(a) shows the block diagram of the on/off switch. The variable optical attenuator (VOA) is used to get the desired injection power. Fig. 1(b) presents the input/output waveforms relationship of the FL and WL cases. The output waveforms rising edge is distorted in the FL case; however, it is not distorted in the WL case. Though DC current is observed in WL case, it can be removed in electrical field, after the receiver. Fig. 2 shows power management procedures to get WL, where λ_{in} is input wavelength; λ_{out} is output wavelength taken at the SMFP-LD's self-locked mode; $\Delta P_{\lambda_{out}FL}$ and $\Delta P_{\lambda_{out}WL}$ are output power differences in cases FL and WL, respectively; and $\Delta P_{\lambda_{out}FL}$ is the difference of required input powers between the cases FL and WL. At the beginning, the SMFP-LD is unlocked because there is no input power; hence, the output spectrum of SMFP-LD is shown in Fig. 2(a). Then, Input power is adjusted as follows; it is gradually increased till all the SMFP-LDs side modes are fully suppressed as presented in Fig. 2(b); next, the injection power is gradually decreased till self-locked mode appears as shown in Fig. 2(c). We can find the proper power level at which WL happens after several times adjusting the input power.

3. Experimental Setup and Results

Fig. 3 shows the experimental setup of a simple all-optical on/off switch basing on the WL phenomenon of a SMFP-LD. In this figure, the SMFP-LD's threshold current, working current, and working temperature are 11 mA, 19 mA, and 25.4 °C, respectively. Under those working

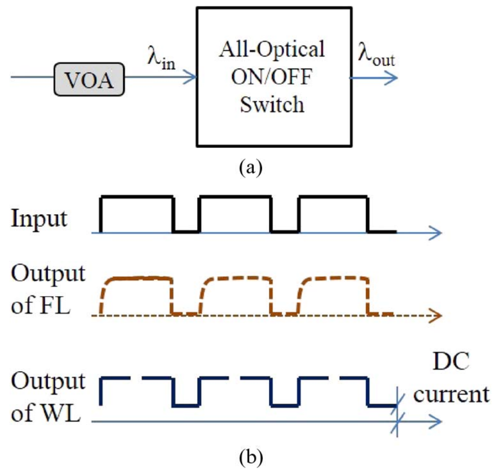

Fig. 1. (a) Block diagram of an all-optical on/off switch (*NOT* gate), where λ_{in} = input wavelength, and λ_o = output wavelength taken at the self-locked mode of the SMFP-LD. VOA: variable optical attenuator. (b) Input and output waveforms of the on/off switch in the case FL and WL, respectively.

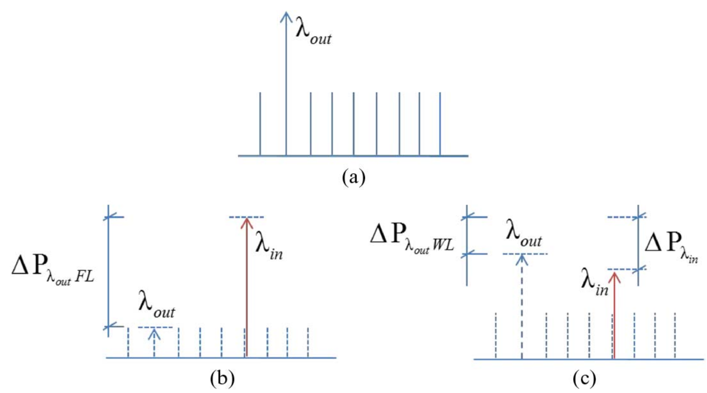

Fig. 2. Power management procedures. (a) Unlocked. (b) Fully locked. (c) Weakly locked.

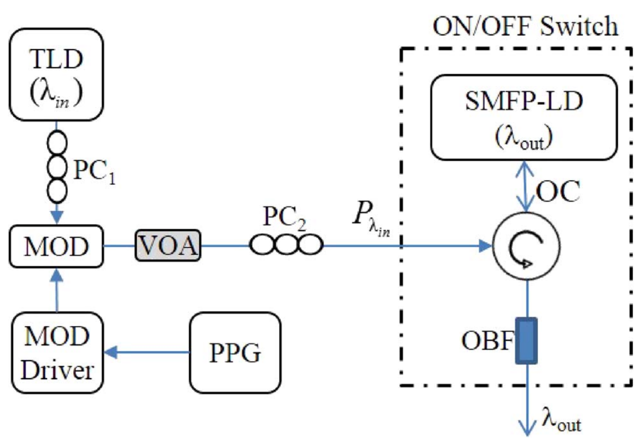

Fig. 3. Experimental setup of a simple all-optical on/off switch basing on WL of a SMFP-LD.

conditions, the SMFP-LD has the dominant (self-locked) modes at λ_{out} (1547.60 nm) and is fully injection-locked at input power of about −8.2 dBm given that wavelength detuning is 0.04 nm. Input beam λ_{in} is set at 1552.12 nm which is corresponding to the side modes wavelength of

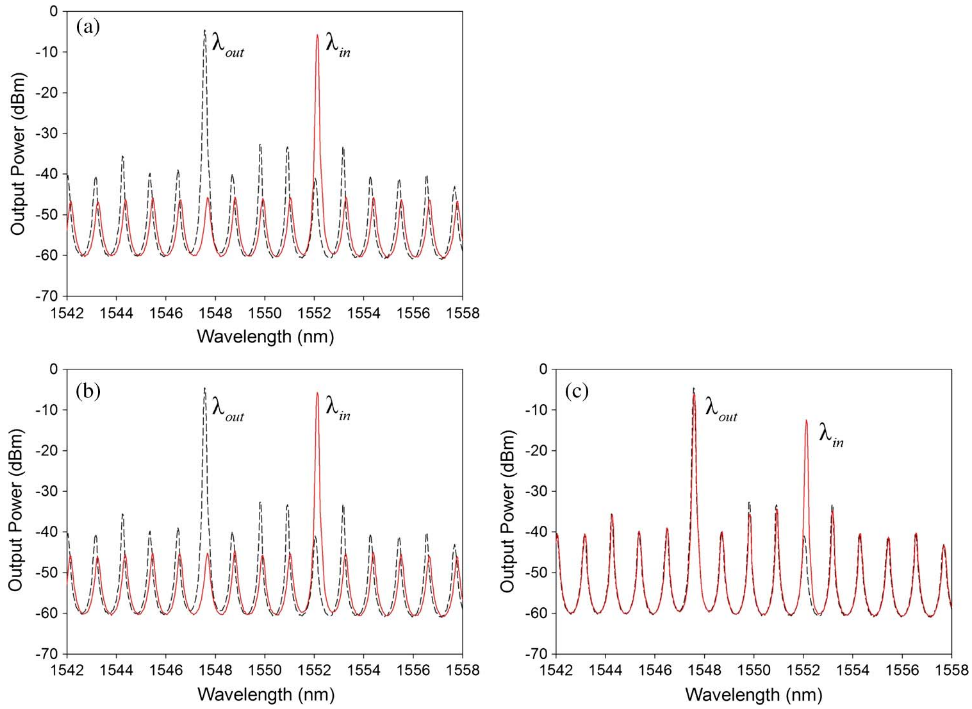

Fig. 4. Output spectra of the SMFP-LD in cases without input (black dash line) and with inputs (a) at −5.5 dBm (full-lock), (b) at −8 dBm (full-lock), and (c) at −11.8 dBm (weak-lock) (solid red line).

1552.04 nm (wavelength detuning: $\Delta\lambda = 0.08$ nm). The polarization controllers PC_1 and PC_2 were used to minimize the polarization dependent loss in the Mach–Zehnder modulator (MOD) and maximize TE optical power, from MOD, injected into SMFP-LD. Due to injection-locking property of FP-LD, the more TE power is injected into the SMFP-LD, the more suppression of its side modes and the higher power at the injected mode. We have conducted an experiment with several input power levels from −11.8 dBm to −5.5 dBm; however, only spectra of two cases are shown in this paper due to space limitation.

Fig. 4 presents output spectra of SMFP-LD before OBF in cases of without input (black dash line) and with input power (red solid line) in three cases of input powers: (a) −5.5 dBm, (b) −8.0 dBm, and (c) −11.8 dBm. In Fig. 4(a) and (b), the SMFP-LD's self-locked mode (at λ_{out}) is fully collapsed due to input power is greater than the full-lock power level; however, in Fig. 4(c), the self-locked mode is not destroyed because input power is smaller than the full-lock power level. Hence, both self-locked mode and injected mode are intentionally kept. The power of the self-locked mode is reduced when input power is applied. When input power is at OFF state, output spectrum is the same as that of the SMFP-LD. Fig. 5 shows output waveforms of the all-optical on/off switch which is measured at the self-locked modes wavelength (λ_{out}), after the OBF, and when input power and working speed are (−5.5 dBm, 1.0 Gb/s) (a), (−5.5 dBm, 2.5 Gb/s) (b), (−8.0 dBm, 1.0 Gb/s) (c), (−8.0 dBm, 2.5 Gb/s) (d), (−8.0 dBm, 12.0 Gb/s) (e), (−11.8 dBm, 1.0 Gb/s) (f), (−11.8 dBm, 2.5 Gb/s) (g), and (−11.8 dBm, 12.0 Gb/s) (h), respectively. The continuous light beam from the tunable laser was modulated by NRZ data whose bit pattern was set as 1111111100000000. From Fig. 5, we can recognize that the all-optical switch shows bad waveform even at low speed (1 Gb/s) when input power is −5.5 dBm which is higher than the fully locked power level (−8.2 dBm). The switch has better output waveforms when input power is −8.0 which is near the full-lock power level of the SMFP-LD; and it has best output waveforms when input power is −11.8 dBm which is the smallest input power of given above three cases.

To measure rising and falling times of output signal, the continuous light beam from the tunable laser was modulated by 10 Gb/s NRZ data whose bit pattern was set as

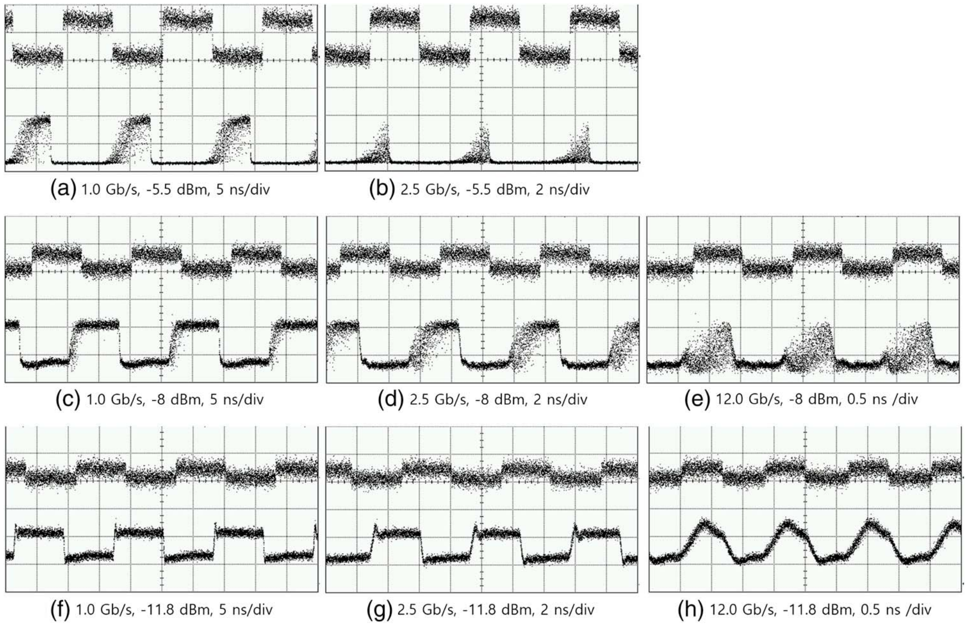

Fig. 5. Output waveforms measured after the OBF at the self-locked modes wavelength (λ_{out}) when input power and working speed are (−5.5 dBm, 1.0 Gb/s) (a), (−5.5 dBm, 2.5 Gb/s) (b), (−8.0 dBm, 1.0 Gb/s) (c), (−8.0 dBm, 2.5 Gb/s) (d), (−8.0 dBm, 12.0 Gb/s) (e), (−11.8 dBm, 1.0 Gb/s) (f), (−11.8 dBm, 2.5 Gb/s) (g), and (−11.8 dBm, 12.0 Gb/s) (h), respectively. (a) 1.0 Gb/s, −5.5 dBm, 5 ns/div. (b) 2.5 Gb/s, −5.5 dBm, 2 ns/div. (c) 1.0 Gb/s, −8 dBm, 5 ns/div. (d) 2.5 Gb/s, −8 dBm, 2 ns/div. (e) 12.0 Gb/s, −8 dBm, 0.5 ns/div. (f) 1.0 Gb/s, −11.8 dBm, 5 ns/div. (g) 2.5 Gb/s, −11.8 dBm, 2 ns/div. (h) 12.0 Gb/s, −11.8 dBm, 0.5 ns/div.

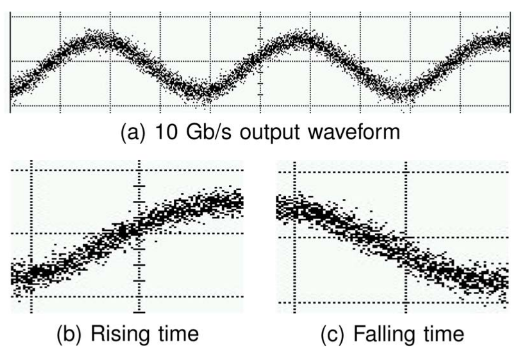

Fig. 6. Output waveform, rising, and falling time of the output signal measured at 10 Gb/s, where the oscilloscope has time resolution of 50 ps/div. (a) 10 Gb/s output waveform. (b) Rising time. (c) Falling time.

1010101010101010. Output waveforms with rising and falling times were captured as shown in Fig. 6 where the oscilloscope has time resolution of 50 ps/div. The measured rising time and falling time are about 48.12 and 40.44, respectively. With such rising/falling time, the maximum working speed of the on/off switch might be over 15.9 Gb/s $((10^{12}/\sqrt{48.12^2 + 40.44^2})$ b/s$)$. Generally, the proposed technique has been verified experimentally.

4. Conclusion

A technique called weak-lock has been proposed and experimentally verified with an optical on/off switch; and the switch is based on injection-locking property of an SMFP-LD. The weak-lock technique shows advantages that it can increase the working speed of the switch (from 1 Gb/s to 12 Gb/s), while it requires less injection power compared to that in the case of using full-lock. Basing on measured rising and falling times of output waveform at 10 Gb/s; about 48.12 and 40.44, respectively; the maximum working speed of the optical on/off switch might be over 15.9 Gb/s. Since the weak-lock technique does not require any additional components and is easy to implement, it would be promising technique to improve the working speed of SMFP-LD based applications. To some extent, the operation mechanism of the on/off switch, in this paper, is basically a cross-gain-depletion based wavelength conversion of which the theoretical model can be referred from [20].

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