

# All-optical flip-flop based on the bistability of injection locked Fabry-Perot laser diode

Yong Deok Jeong, Jeong Sik Cho and Yong Hyub Won

*School of Engineering, Information and Communications University  
119 Munjiro, Yuseong-Gu, Daejeon, 305-714, Korea  
[kumdong@icu.ac.kr](mailto:kumdong@icu.ac.kr)*

Hyuek Jae Lee

*Division of Information & Communication Engineering, Kyungnam University  
449 Wolyong-Dong, Masan, Kyungnam, 631-701, Korea*

Hark Yoo

*Optical Communication Research Center, Electronics and Telecommunications Research Institute  
1110-6 Oryong-Dong, Buk-Gu, Gwangju, 500-480, Korea*

**Abstract:** We demonstrate the operation of a novel all-optical flip-flop. The flip-flop consists of a slave Fabry-Perot laser diode (FP-LD) and a specially designed master FP-LD which has a built-in external cavity and operates in single longitudinal mode oscillation. The set and reset pulses were generated by external modulators at 1 Gbit/s. The rising and falling times of the output signal in on-off operation of the flip-flop were about 50 ps. The required powers of both set and reset pulses were less than -9 dBm.

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**OCIS codes:** (210.4680) Optical memories; (200.4560) Optical data processing; (190.1450) Bistability

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## 1. Introduction

All-optical flip-flop devices can provide a latching function which is utilized for self-routing or buffering in optical packet switching networks [1, 2]. A flip-flop operation can be realized using bistable devices that have S-shaped hysteretic characteristics. However, since there is no "negative" optical pulse, an optical bistable device can not perform flip-flop operation on an all-optical basis by itself. To solve this problem, Otsuka and Ikeda proposed a coupled-element bistable system, in which each element has nonlinear susceptibility and operates in the bifurcation regime with alternative optical trigger pulses [3, 4]. On the other hand, recently, all-optical gain control of semiconductor lasers or semiconductor optical amplifiers have been studied for implementing all-optical flip-flop, such as methods based on the architectures of coupled ring laser, coupled Mach-Zehnder interferometers or coupled nonlinear polarization switches [5-8]. However, these schemes are too complicated and bulky to realize optical memories with multi-state all-optical flip-flop.

In this paper, a novel scheme for all-optical flip-flop based on the bistability of an injection locked Fabry-Perot laser diode (FP-LD) is proposed and experimentally demonstrated. The injection locking property and/or filter-like usage of a FP-LD offers various opportunities for all-optical signal processing, like, for example, wavelength conversion [9], clock recovery [10], logic gate [11], and so on. Moreover, an injection locked FP-LD has the bistability of the S-shaped hysteretic curve, which was first predicted by Otsuka, *et al.* [12] and experimentally demonstrated using a resonant-type semiconductor laser amplifier [13] and a distributed feedback laser [14]. In particular, a multi-wavelength injection locked FP-LD was used for optical header processing and packet switching [15]. To our knowledge, it is the first time to achieve all-optical flip-flop operation experimentally using its bistability.

The main advantage of the proposed all-optical flip-flop is its simple and cost effective structure since only two coupled FP-LDs are used. One of the two FP-LDs is an ordinary commercial FP-LD and the other is specially designed with a built-in external cavity and operates in single longitudinal mode with high side mode suppression ratio (SMSR) [16]. The on-off state of the proposed optical flip-flop is determined by whether the former FP-LD (called slave FP-LD) is injection locked or not in accordance with separate set and reset pulses.

## 2. Operation principle

To set up an injection locking operation, the power of an injected beam should be greater than the locking threshold which is related to the wavelength difference between the injection beam and the selected mode in the slave FP-LD. Bistability concerns to the locking threshold and its nature is shown in Fig. 1, which is a typical hysteresis curve. Once the input power of the injection beam exceeds the locking threshold, the slave FP-LD is injection locked to the injection beam and the locking state is maintained even if the input power is lowered than the initial threshold.

In the schematic structure of the proposed all-optical flip-flop as shown in Fig. 2(a), three beams are used to form latching output. Separate set and reset pulses are external control

signals and the sustaining beam from the master FP-LD is always injected into the slave FP-LD. Figure 2(b) illustrates the power levels of each beam on the timeline. A dual mode injection locking method is used to reduce the locking threshold for making the “on” state using the external “set” pulse. The dashed line in Fig. 2(c) shows the reduced locking threshold at dual mode injection locking ( $P_{th2}$ ) compared with that at one mode injection locking ( $P_{th1}$ ) on the solid line. It can be achieved in step 2 in Fig. 2(b) by concurrent injection of sustaining beam and set pulse.

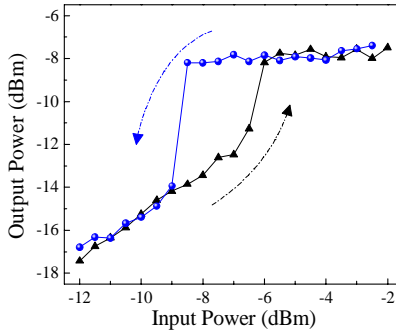


Fig. 1. The bistable characteristics of the injection locked FP-LD. The FP-LD is fully injection locked when the injection power is -6 dBm, and the locking state is released when the injection power decreases to -9 dBm.

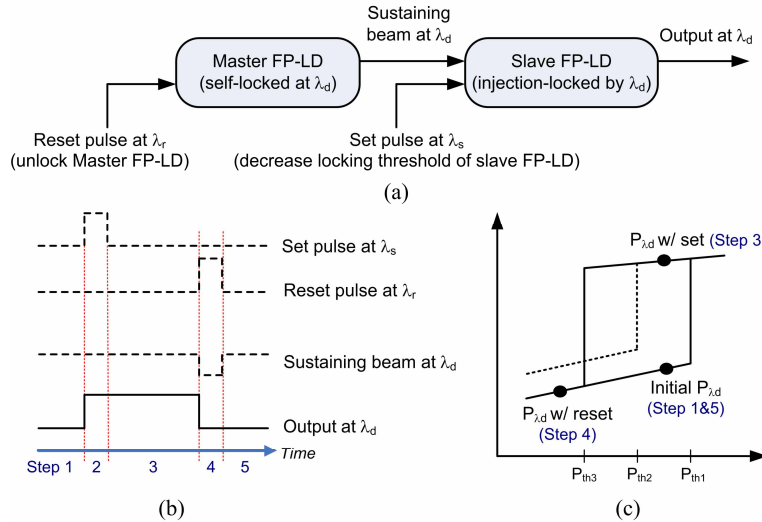


Fig. 2. (a) Schematic structure of the proposed all-optical flip-flop, (b) operation of the all-optical flip-flop, and (c) description of each step on the hysteresis curve.

The optical spectrum of the slave FP-LD with an injection beam at a wavelength of  $\lambda_d=1539.16$  nm is shown in Fig. 3(a).  $\lambda_d$  is detuned by an amount of 0.12 nm from a selected mode of the slave FP-LD and its power,  $P_{\lambda_d}$ , is chosen to be  $P_{th2} < P_{\lambda_d} < P_{th1}$  (as depicted in Fig. 2(c)). When another control signal at  $\lambda_s$  is injected, the slave FP-LD is injection locked to  $\lambda_s$  and the mode near to  $\lambda_d$  is also injection locked as shown in Fig. 3(b). This is because the locking threshold at  $\lambda_d$  is reduced due to the red shift of the modes in the presence of injection locking at  $\lambda_s$ . After the control signal is removed, the FP-LD maintains its injection locking

state at  $\lambda_d$  by virtue of the bistable characteristics as shown in Fig. 3(c). When we use the control signal at  $\lambda_s$  as an optical “set” pulse, the injection locking state at  $\lambda_d$  will depict the ‘on’ state of the optical flip-flop.

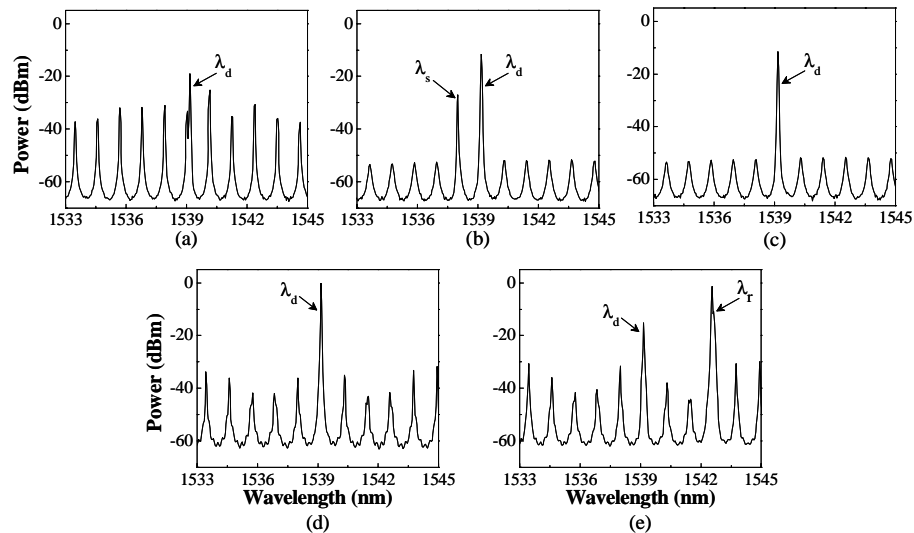


Fig. 3. Output optical spectra of sequential states in the slave FP-LD (a) with the sustaining beam only at  $\lambda_d$ , which is always injected into the slave FP-LD (step 1 and 5), (b) with set signal at  $\lambda_s$  (step 2), (c) after removal of set signal (step 3). (d) and (e) are spectra of the master FP-LD without and with reset signal at  $\lambda_r$ , and (e) represents step 4.

To reset the optical flip-flop (step 4 in Fig. 2(b)), the power of the sustaining beam should be reduced by another control signal, the so-called “reset” pulse. For this purpose, we use a specially designed FP-LD as a master LD from which the beam would be injected into the slave FP-LD. Generally, a FP-LD itself or a filtered FP-LD is not adequate for the master LD in injection locking operation since it inherently has multi longitudinal modes and mode hopping noise. However, the FP-LD used in our experiment operates in single longitudinal mode with SMSR of more than 30 dB as shown in Fig. 3(d). The overall structure of the commercial coaxial packaging of the FP-LD is not changed; however, the facet of the coupling fiber, which usually has an inclination of 6~8 degrees in order to prevent optical feedback from the fiber, has no inclination. We utilize the fiber facet as a feedback source to form a built-in external cavity. The phase matching condition is dominated by the relationship between an external cavity length and a laser cavity length, and the amount of optical feedback. Strong side mode suppression for the multimode laser is achieved with proper phase matching. The phase matching condition can be adjusted by operating temperature with a thermo-electric cooler, which is externally attached to the packaged FP-LD. By varying the temperature, any mode inside the gain bandwidth of the FP-LD can be selected for single mode operation. The tuning range is almost 10 nm as the temperature changes about 15 °C [16].

When another strong beam is injected into this self-locked FP-LD, the single mode operation collapses as shown in Fig. 3(e). Due to the disturbance of the injection beam at  $\lambda_r$  near to one of the modes in the FP-LD, the power of the self-locked peak at  $\lambda_d$  decreases below the power,  $P_{th3}$  in Fig. 2(c). Since the peak power at  $\lambda_d$  is used to sustain the injection locking state in the slave FP-LD, its power reduction causes it to break the locking state. Therefore, the pulse injection at  $\lambda_r$  into the master FP-LD can complete the reset process in the flip-flop operation. Consequently, Fig. 3(a) and Fig. 3(c) depict the “off” state and “on” state of the optical flip-flop, respectively.

### 3. Experiment and results

Figure 4 shows the experimental setup for demonstration of an all-optical flip-flop operation. The flip-flop consists of a slave FP-LD, a master FP-LD and a few passive components such as optical circulators, coupler, band-pass filters and polarization controllers. Both FP-LDs have InGaAsP multiple quantum well structures and favor transverse electric (TE) polarization mode. Hence, the injection beam should also be aligned with the TE polarization mode by the polarization controller in order to make the injection locking operation effectively. The slave FP-LD with a longitudinal mode spacing of about 1.16 nm was biased at 13 mA above the threshold current ( $I_{th}=11$  mA). One mode to be injection locked was selected at a wavelength of 1539.04 nm. The master FP-LD has the same threshold current as the slave FP-LD and was biased at 21 mA. The lasing wavelength,  $\lambda_d$ , was 1539.16nm with 31dB SMSR. This beam was injected into the slave FP-LD passing through the optical band-pass filter, two circulators and 3 dB coupler. The power was adjusted by filter detuning and its amount was a little less than the injection locking threshold of the slave FP-LD.

Two tunable lasers were used for set and reset pulses. Both pulse signals were generated by 1 Gbit/s non-return-to-zero (NRZ) pattern modulation using LiNbO<sub>3</sub> Mach-Zehnder modulators. Both pattern lengths were 16 bits composed of one “1” level and fifteen “0” levels. This means that the pulse duration is 1 ns and the pulse repeats every 16 ns. The optical powers of the set and reset pulses were -11.08 dBm and -9.23 dBm, respectively. The set pulse was injected into the slave FP-LD through a 3 dB coupler and had a wavelength of 1537.96 nm, which was carefully tuned to be well matched with one longitudinal mode of the slave FP-LD. On the other side, the reset pulse was injected into the master FP-LD through the optical circulator. As well, the wavelength of the reset pulse was matched with a mode of the master LD and the value was 1542.56 nm. Since the flip-flop output state is determined by whether the slave FP-LD is injection locked or not at wavelength  $\lambda_d$ , the output from the slave FP-LD was observed via the optical circulator and optical band-pass filter. The on-off contrast of the flip-flop can be estimated by investigating the spectrum data shown in Fig. 3(a) and 3(c), and its ratio turned out to be about 7dB.

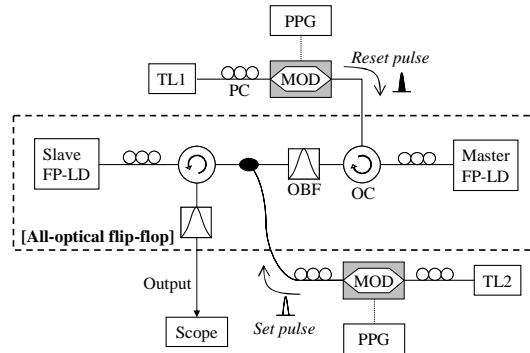


Fig. 4. Experimental Setup. TL: tunable laser, PC: polarization controller, MOD: Mach-Zehnder modulator, OBF: optical band-pass filter, OC: optical circulator, PPG: pulse pattern generator, Scope: sampling oscilloscope

Figure 5 shows the corresponding oscilloscope traces of the output from the optical flip-flop. In Fig. 5(a) and 5(a'), we did not control the timing of set pulse and reset pulse, which would be determined by fiber delay length in the experiment setup. To identify that the set and reset operations worked properly, reset pulse was delayed or set pulse advanced by using a pulse pattern generator that was applied for pulse generation. The set pulse was advanced by 2 bit (2 ns) sequentially, and Fig. 5(b), 5(c), 5(d), 5(e) and 5(f) show the corresponding output traces for each experiment. It can be found that the “on” state of the output rises as early as the same amount of advance in the set pulse for each case. Similarly, Fig. 5(b'), 5(c'), 5(d'),

5(e') and 5(f') show the output traces when the reset pulse was delayed by 2 bit sequentially. In addition, the rising and falling times of the toggling output were measured and both values were about 50 ps as shown in Fig. 6.

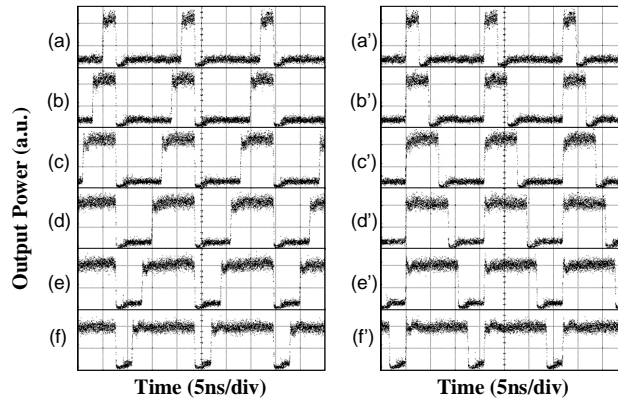


Fig. 5. Oscilloscope traces of the flip-flop output. (a) and (a') are the initial trace. (b), (c), (d), (e) and (f) are traces when the set signal is advanced sequentially from (a) by an amount of 2 ns, respectively. (b'), (c'), (d'), (e') and (f') are traces when the reset signal is delayed sequentially from (a') by an amount of 2 ns, respectively.

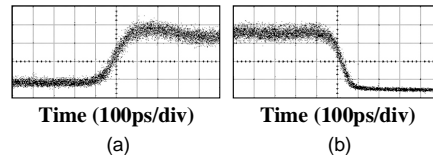


Fig. 6. (a) Rising edge and (b) falling edge of the flip-flop output.

#### 4. Conclusion

A novel all-optical flip-flop is proposed and experimentally demonstrated. The control signals (set and reset pulses) are generated by 1 Gbit/s NRZ pattern modulation and have a period of 1 ns. The operation speed is limited by the response time of an injection locked FP-LD and the fiber delay length of the control signal. If the entire components are integrated and the control signal path length is minimized, the operation speed can be extended to a few Gbit/s since the rising time and falling time of the output signal are only 50 ps, and a 10 Gbit/s injection locking operation has already been proven in other applications [9]. For practical use, the power levels of the set and reset pulses are also important and the minimum required power for each set or reset pulse in our proposed scheme is less than -9 dBm. This simple and cost-effective architecture of an all-optical flip-flop will be useful for future all-optical signal processing systems such as optical buffering, optical memory and the self-routing network.

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