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A New All-optical Flip-flop Based on Absorption Nulls of an Injection-locked FP-LD

Hyuek Jae Lee*

Department of Information & Communication Engineering, Kyungnam University, Changwon 51767, Korea

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A new all-optical flip-flop (AOFF) method based on the absorption nulls of an injection-locked Fabry-Perot laser diode (FP-LD) in transverse magnetic (TM) mode is proposed and experimentally demonstrated. For the set and reset operations of the AOFF, injection locking and the destructive minus of beating in transverse electric (TE) mode are used. The absorption nulls on the TM mode are modulated according to the operations, and then non-inverted (Q) and inverted ($\overline{Q}$) outputs can be obtained simultaneously. Thanks to the use of several absorption nulls, the proposed AOFF can achieve multiple outputs with extinction ratios of more than 15 dB. Even though the experiment is demonstrated at 100 Mbit/s, the results of previous experiments using the injection of a CW holding beam imply that the operation speed can increase to 10 Gbit/s.

Keywords : All-optical flip-flop (AOFF), Injection locking, Optical bi-stability, Optical beating, Absorption nulls

OCIS codes : (060.1155) All-optical networks; (060.2330) Fiber-optic communications; (230.1150) All-optical devices

I. INTRODUCTION

All-optical flip-flop (AOFF) devices have recently generated a great deal of research interest because an AOFF is a key element for buffer memories and self-routing devices in optical packet switching systems [1, 2]. Several AOFFs have been demonstrated [3-9], most of which are based on the bi-stable operation of various laser diodes and semiconductor optical amplifiers. Of these methods, the AOFF using injection-locked FP-LDs [7-9] has recently attracted the most attention. The basic structure of an AOFF is a master-slave configuration of two coupled single-mode Fabry-Perot laser diodes (FP-LDs), in which one laser is used to suppress the activity of the other laser and unlock injection locking. AOFFs have successfully been demonstrated at a high speed of 8.5 Gbit/s with a high extinction ratio (ER) of more than 20 dB in an optical SR latch with simultaneous inverted and non-inverted outputs [9]. Nevertheless, this method is too complicated to make large-sized optical buffer memories. Recently, using a very simple structure composed of only one FP-LD, a new AOFF based on optical beating and bi-stability in an injection-locked FP-LD was proposed [10]. Despite its advantages, it has only a non-inverted output with a rather low extinction ratio.

In this paper, to overcome the limited number of outputs with low extinction ratio, an AOFF based on absorption nulls in an injection-locked FP-LD is proposed. The set and reset operations of the AOFF are the same as those of Ref. [10]. To get several inverted and non-inverted outputs, modulation of the absorption nulls, which operate as a result of the set/reset, is used. The primary advantage of this method is that it is possible to obtain multiple outputs with high extinction ratio simultaneously, despite the simple structure of one FP-LD.

II. OPERATIONAL PRINCIPLES

An AOFF based on an injection-locked FP-LD with bi-stability generally shows a low extinction ratio (ER) because the power of the injected external beam must

*Corresponding author: hyuek@kyungnam.ac.kr, ORCID 0000-0002-8697-6914
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increase beyond a certain amount to obtain clear bi-stability. Figure 1 illustrates the general characteristics of the bi-stable behavior of an injection-locked FP-LD. To turn the FP-LD on, the set pulse, I_{set}, is added to the external continuous wave (CW) pump beam, I_{CW}, which exceeds the locking threshold. This makes the state of the FP-LD move from point *a* to point *b*, and it stays at point *c* after I_{set} disappears. Conversely, to turn the FP-LD off, the optical beating technique in Ref. [10] using a reset pulse, I_{reset}, is applied, so the system falls below the unlocking threshold. The system moves from point *c* to point *d* and then returns to point *a*. Here, the ER is I_{ON}/I_{OFF}. I_{OFF} is proportional to the input power (*i.e.* the external CW pump beam, I_{CW}), while I_{ON} is independent, as seen in Fig. 1. Thus, it is difficult to obtain more than 10 dB of ER because of the relatively high intensity of I_{CW} (7.0 dB in Ref. [7] and 6.5 dB in Ref. [10]). This problem can be solved dramatically by using two single-mode FP-LDs [8]

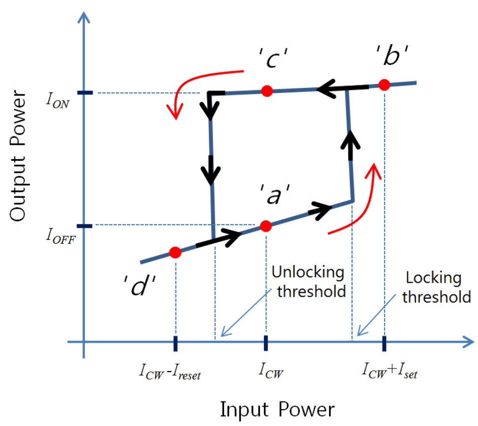

FIG. 1. General characteristics of the bi-stable behavior of an injection-locked FP-LD.

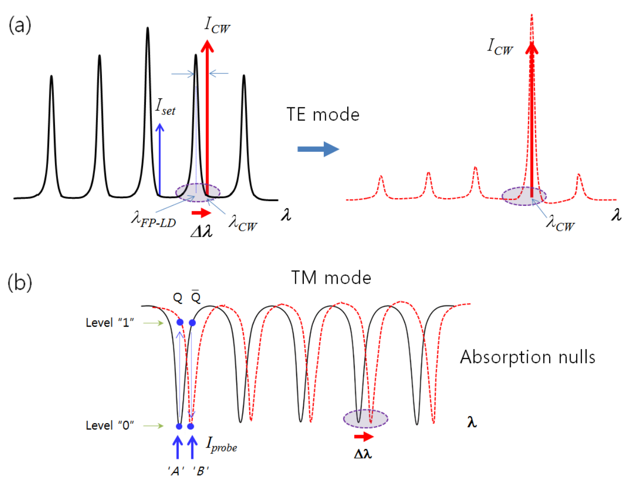

FIG. 2. Operating principle of the proposed method based on the absorption nulls of an injection-locked FP-LD: (a) injection locking in TE mode and (b) modulation of absorption nulls in TM mode.

that are based on self-locking without an external beam. The method is further improved upon to create an optical SR latch with a high ER of 20 dB at 8.5 Gbit/s [9]. However, it requires two coupled single-mode FP-LDs, and, furthermore, a sophisticated fabrication is needed to allow for single-mode operation of the FP-LD. Thus, it is too complicated to make large-sized optical buffer memories.

To construct a simple AOFF, a method in Ref. [10] that can be configured with the only commercially available FP-LD was recently proposed. However, it has a disadvantage in that it cannot obtain a high ER and an inverted output. To solve this problem, the absorption nulls [11-16] in the transverse magnetic (TM) mode of a multiple-quantum well (MQW) FP-LD, which favors the transverse electric (TE) mode, are used. When a MQW-type FP-LD is applied over a threshold current, it creates laser light on the TE mode. On the other hand, the TM mode shows only absorption nulls owing to the very small TM gain inside the Fabry-Perot resonator, instead of lasing. Absorption nulls have already been put to use in various ways, such as for an NRZ-to-PRZ converter [15], an FP-LD modulator [16], a wavelength converter [11-13], and an optical logic gate [14].

Figure 2 illustrates the operating principle of the proposed method. The TE mode side of the FP-LD engages the external CW pump beam, I_{CW}, and the set pulse, I_{set}, to induce injection locking, as shown in Fig. 2(a). Here, I_{set} disappears after the injection is locked. Due to the strong coupling between the semiconductor gain and refractive index, injection locking causes a change in carrier density that results in a red shift ($\Delta\lambda = \lambda_{CW} - \lambda_{FP\text{-}LD}$) of the absorption nulls in the TM mode, as shown in Fig. 2(b). When the TM-polarized probe beam, I_{probe}, initially located at one of the absorption nulls, *i.e.* point *A* in Fig. 2(b), is coupled into the FP-LD, the resulting red shift ($\Delta\lambda$) increases the reflection and changes the non-inverted output (Q) from 0 to 1. On the other hand, the probe beam, I_{probe}, can be located at a little longer wavelength relative to the absorption null, *i.e.* point *B* in Fig. 2(b). In this case, the red shift ($\Delta\lambda$) causes reflection of I_{probe} to decrease, thus changing the inverted output ($\bar{Q}$) from level 1 to 0.

III. EXPERIMENTS AND RESULTS

Figure 3 illustrates an experimental setup for measuring the general characteristics of the bi-stable behavior and the absorption null modulation in an injection-locked FP-LD. To investigate the bi-stable characteristics, the optical circuit in the dotted box of Fig. 3 was first used. Here, the FP-LD has a nominal lasing wavelength of 1554.35 nm and longitudinal mode spacing of 1.16 nm, which was biased at 17.5 mA (threshold current I_{th} = 10 mA). The PC1, PBS and PC2 make the polarization of the I_{CW} into TE polarization and pass it to be incident on the FP-LD favoring TE mode.

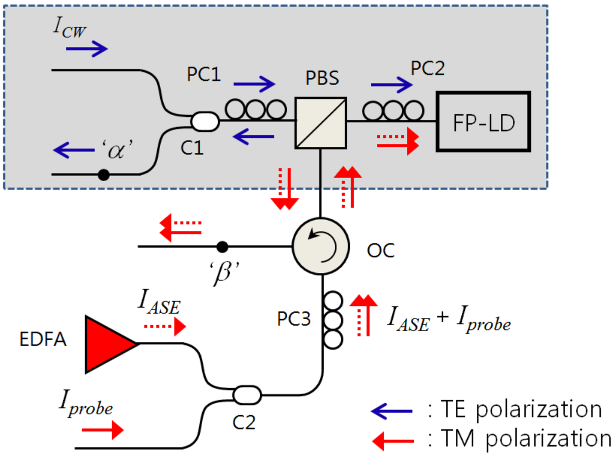

FIG. 3. Experimental setup for measuring the general characteristics of the bi-stable behavior and the absorption null modulation in an injection-locked FP-LD (PC: Polarization Controller; EDFA: Er-doped Fiber Amplifier; C: 3-dB Coupler; PBS: Polarization Beam Splitter; FP-LD: Fabry-Perot Laser Diode; OC: Optical Circulator).

Figure 4 depicts the output measured at the point α in Fig. 3 according to the optical power (*i.e.* the external CW pump beam, I_{CW}) injected into the FP-LD, which shows the bi-stability of an injection-locked FP-LD. Here, $\Delta\lambda$ is the wavelength detuning (it represents the amount of the red shift in Fig. 2) between the I_{CW} and one of longitudinal modes of the FP-LD, which was set to 0.16 nm by λ_{CW} = 1557.99 nm and $\lambda_{FP\text{-}LD}$ = 1557.83 nm. For injection locking, the power of I_{CW} must be greater than the locking threshold power of -3.05 dBm in Fig. 4. At this power, the FP-LD was locked and showed an ER of 5.1 dB (ER at locking). Once the locking threshold is exceeded, the FP-LD is locked to the external CW pump beam, I_{CW}, and the locking state persists even if the power of I_{CW} is reduced below the locking threshold power (*i.e.* -3.05 dBm), as shown in Fig. 4. When the power of I_{CW} dropped below the unlocking threshold power of -4.85 dBm, the FP-LD was unlocked with an ER of 7.1 dB (ER at unlocking). Generally, as the $\Delta\lambda$ becomes wider, the necessary I_{CW} power injected into the FP-LD increases, for stronger bi-stability. To investigate this relationship in more detail, we measured locking/unlocking threshold powers of the external injected I_{CW} and ERs versus $\Delta\lambda$; the results are shown in Fig. 5. As $\Delta\lambda$ increases beyond 0.08 nm, the bi-stable states grow further apart. Note that a large $\Delta\lambda$ requires more injected power of I_{CW} but shows a smaller ER. Eventually, if $\Delta\lambda$ is greater than 0.2 nm, injection locking does not occur properly. For the experimental demonstration of the proposed AOFF, $\Delta\lambda$ was chosen as 0.16 nm. Of course, for high-speed operation, a smaller $\Delta\lambda$ should be selected [9]. However, in this experiment, we focused on verifying the function of the proposed AOFF rather than on the speed issue.

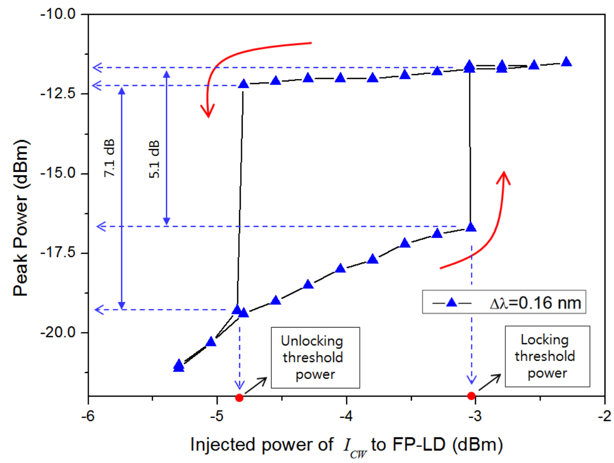

FIG. 4. Measured bi-stable characteristic of an injection-locked FP-LD when $\Delta\lambda$ = 0.16 nm.

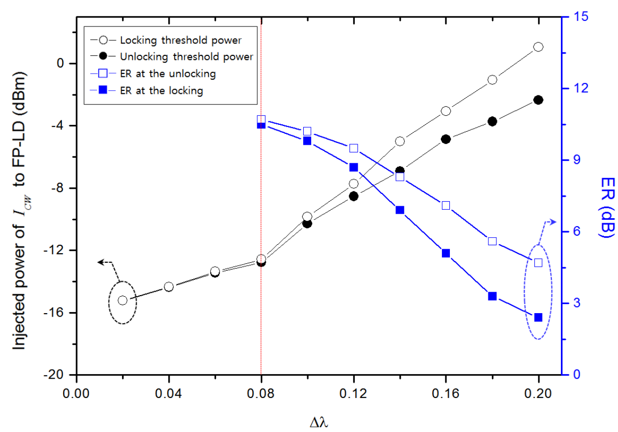

FIG. 5. Measured locking/unlocking threshold powers and ERs versus $\Delta\lambda$.

For the spectra measurement of Fig. 6, the entire optical circuit in Fig. 3 was used. Figure 6(a) shows the TE mode spectra of a free-running (dotted line) and injection-locked (solid line) FP-LD measured at point α of Fig. 3, when λ_{CW} = 1557.99 nm. The measured side mode suppression ratio (SMSR) was about 36 dB, but the measured ER was 5.6 dB. The reason for the low ER was explained earlier (Section II). Figure 6(b) shows the TM mode spectra of the absorption nulls and CW probe beam (I_{probe}) measured at point β of Fig. 3 when the FP-LD is injection-locked (solid line) and when it is not (dotted line). This clearly shows the red shift of the absorption nulls, and is based on the proposed AOFF mechanism. The TM mode spectra were measured by feeding an amplified spontaneous emission (ASE) source (I_{ASE}) of the EDFA together with the CW probe beam (I_{probe}), which was aligned with the TM axis of the FP-LD by using the C2, PC3, OC, PBS and PC2 as shown in Fig. 3. The I_{probe} at λ_{probe} = 1554.93 nm, which was located at a slightly longer wavelength next to one of the absorption nulls ($\lambda_{abs\text{-}null}$ = 1554.77 nm),

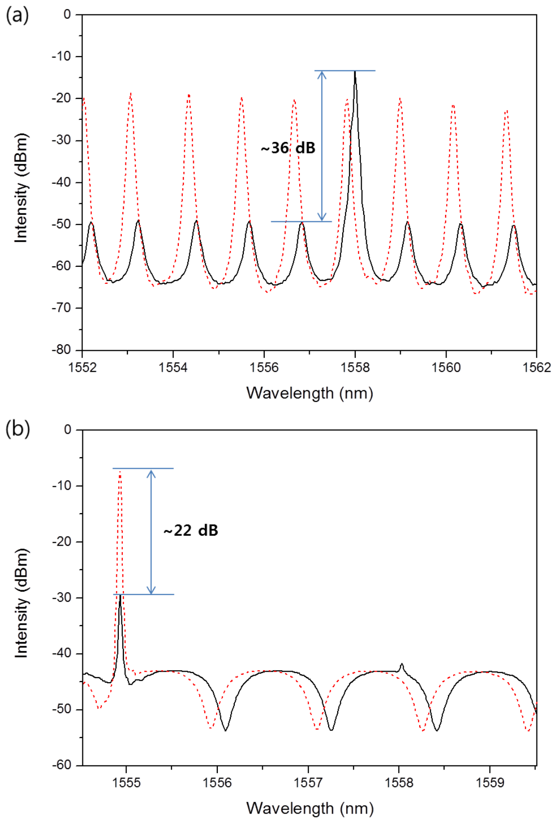

FIG. 6. Optical spectra of the TE and TM modes for explaining the operation principle of the proposed AOFF. (a) TE mode spectra of a free-running (dotted line) and injection-locked (solid line) FP-LD. (b) TM mode spectra of the absorption nulls and CW probe beam (Iprobe) when the FP-LD is injection-locked (solid line) and when it is not (dotted line).

was coupled into the FP-LD. As injection locking occurs, the absorption nulls simultaneously undergo red shifting. The red shift ($\Delta\lambda = 0.16$ nm) causes the TM-polarized I_{probe} to be located at the center wavelength of the absorption null, and a high ER of ~22 dB was achieved, as shown in Fig. 6(b).

The experimental setup used to demonstrate the AOFF operation is shown in Fig. 7. Two tunable lasers (T-LD1 and T-LD2) were used for the set and reset pulses, I_{set} and I_{reset}. Both pulses were optically modulated at a bit rate of 100 Mbit/s in non-return-to-zero (NRZ) format with LiNbO3 Mach-Zehnder modulators (Mod1 and Mod2). The optical powers of I_{set} and I_{reset} for AOFF operation were -10.5 dBm and -7.2 dBm, respectively, at 1556.97 nm (λ_{set}) and 1558.01 nm (λ_{reset}). The optical power of I_{CW} by the tunable laser (T-LD3) was set to -4.5 dBm; we judged it best to set it slightly larger than the unlocking threshold of -4.85 dBm, at 1557.99 nm (λ_{CW}) as shown in Fig. 4. Here, λ_{reset} must be set within a certain range (~0.03 nm) around the λ_{CW} in order to achieve optical beating [10]. However, it should not exactly equal to the λ_{CW}, because that would introduce the possibility of not meeting the reset condition.

The pulse, I_{set} or I_{reset}, and the I_{CW} were combined by the 3-dB coupler (C2) and then injected into the FP-LD through the polarization controllers (PC3-PC7) and the polarization beam splitter (PBS), by which it was aligned with TE polarization. Here, the I_{set} and I_{reset} are not incident at the same time in the SR latch condition. The FP-LD has a nominal lasing wavelength of 1554.35 nm and longitudinal mode spacing of 1.16 nm, which was biased at 17.5 mA (threshold current $I_{th} = 10$ mA). The I_{probe} from the T-LD4 was coupled into the FP-LD through the optical circulator

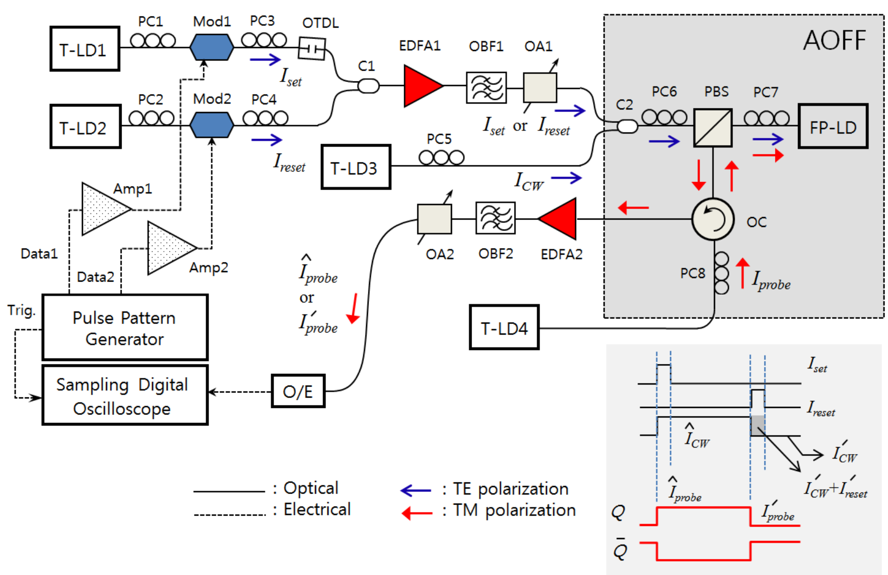

FIG. 7. Experimental setup used to demonstrate the proposed AOFF operation (T-LD: Tunable Laser Diode; Mod: Optical Modulator; PC: Polarization Controller; EDFA: Er-doped Fiber Amplifier; C: 3-dB Coupler; PBS: Polarization Beam Splitter; OC: Optical Circulator; OBF: Optical Bandpass Filter; OA: Optical Attenuator; OTDL: Optical Tunable Delay Line; FP-LD: Fabry-Perot Laser Diode; Amp: Electrical Amplifier).

(OC) and the PBS after being aligned with the TM polarization. Here, the expensive PBS and OC were only used for reasons of convenience and can be replaced with an inexpensive optical coupler. In this case, PC3, PC4, and PC5 create TE polarization and PC8 creates TM polarization of the incident lights entering the FP-LD.

To obtain inverted (Q) or non-inverted ($\overline{Q}$) output, the probe beam is positioned at the center of the absorption null or at a slightly deviated wavelength, as described earlier. Figure 8(a) shows the oscilloscope traces of the set and reset pulse with a time delay of 20 ns, and Fig. 8(b) shows the oscilloscope traces of the outputs in inverted and non-inverted format with ERs of 18.1 ($\overline{Q}$) and 16.8 (Q). Here, $\hat{I}_{probe}$ and I'_{probe} denote the level 1 output and level 0 output, respectively, created by the I_{probe} by injection locking and unlocking. It is worth noting that crosstalk does not appear anywhere in the level 0 output, because the red shift occurs immediately upon unlocking and the wavelength of I_{probe} is far enough from the wavelength of the other inputs (I_{set}, I_{reset}, and I_{CW}) to filter out. In an earlier study [10], the reflected reset pulse, I'_{reset} in Fig. 7, was not completely filtered out while resetting due to the similarity of the wavelengths of λ_{CW} and λ_{reset} (~0.01 nm), and thus a crosstalk problem, $I'_{CW} + I'_{reset}$, occurred.

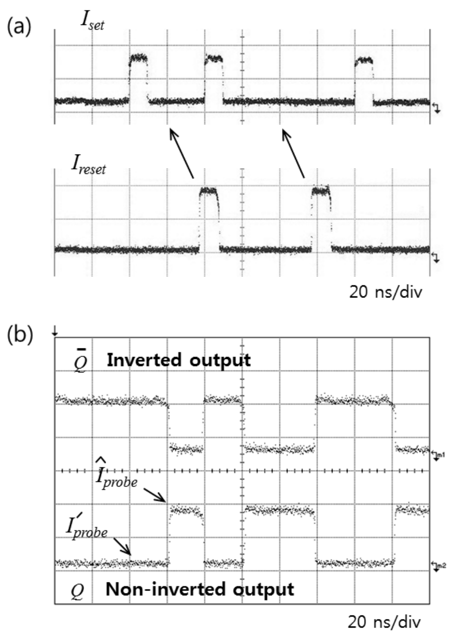

FIG. 8. Measured oscilloscope traces of (a) the set and reset pulses with a time delay of 20 ns, and (b) the outputs in inverted and non-inverted format.

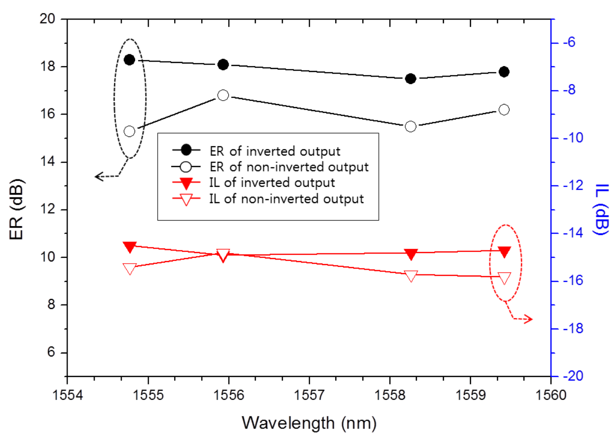

FIG. 9. Measured extinction ratios (ERs) and insertion losses (ILs) at four absorption null positions, 1554.77 nm, 1555.93 nm, 1558.26 nm, and 1559.42 nm.

Another advantage of the proposed AOFF is that it has multiple outputs as in Ref. [13]. To investigate the possibility of multiple outputs, the same experiments were conducted at four absorption null positions, 1554.77 nm, 1555.93 nm, 1558.26 nm, and 1559.42 nm by adjusting the wavelength (λ_{probe}) of I_{probe}. In order to experiment more accurately, they had to be carried out at the same time, but in the limited equipment, they were tested each. Figure 9 shows the measured ERs and insertion losses (ILs) at the four positions. The inverted output ($\overline{Q}$) has a slightly higher ER, in the range of 17.5 to 18.3 dB, than does the non-inverted output (Q), with an ER range of 15.3 to 16.8 dB. In contrast, the ILs had similar measured values (within 1.3 dB), with an average IL of -15.1 dB.

IV. CONCLUSION

A new AOFF based on absorption nulls in an injection-locked FP-LD with optical bi-stability has been proposed and experimentally demonstrated. While injection locking and beating on TE mode are used for the set and reset operations, the absorption nulls on TM mode are modulated to obtain non-inverted (Q) and inverted ($\overline{Q}$) outputs. In addition, the system might achieve multiple outputs by using several nulls in the FP-LD. The AOFF can be constructed using only a commercially available FP-LD, which indicates that the method would be quite advantageous for the implementation of large-sized optical memory. Even though the experiment was carried out at 100 Mbit/s, the operation speed may be increased to a few or even 10 Gbit/s, as is experimentally demonstrated by other studies [12, 15]. The operation speed can be enhanced by using a CW holding beam, i.e. the carrier lifetime reduction technique [17]. Thus, the rising and fall time of the AOFF might be no longer dominated by the slow carrier lifetime.

With still maintaining a simple structure, the low ER, the crosstalk and limited number of outputs problem present in a previous paper [10] were solved. However, high insertion loss newly becomes a problem. One solution is to replace the FP-LD with a single-mode FP-LD, as in [9, 12]. An AOFF using a single-mode FP-LD will be reported in a future paper.

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