All-optical flip-flop with high on-off contrast ratio using two injection-locked single-mode Fabry-Perot laser diodes

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Abstract: An all-optical flip-flop with inverted output is presented. The flip-flop is realized based on the optical bistability of an injection-locked single-mode Fabry-Perot laser diode (FP-LD). The operation principle is explained and experimental results are presented in this paper. The flip-flop with separate optical set and reset inputs had an on-off contrast ratio of over 35 dB.

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

References and links

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1. Introduction

All-optical flip-flops are anticipated playing an important role in future photonic networks such as optical burst switching and packet switching networks. They provide latching functions that can be applied for bit-length conversion, time-division multiplexing/demultiplexing, packet buffering, reshaping, and retiming. The current research on all-optical flip-flops is still in an early stage. Recently, many different technologies have been considered to store light [1-3].

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In our previous work, we achieved an all-optical flip-flop using two coupled Fabry-Perot laser diodes (FP-LDs) [4]; one of the two FP-LDs is an ordinary commercial FP-LD, and the other is an FP-LD specially designed with a built-in external cavity, operating in single longitudinal mode with the high side mode suppression ratio (SMSR) of over 27 dB, this special FP-LD is called tunable single-mode FP-LD [5]. However, the flip-flop had a low on-off contrast ratio of about 7 dB. The cause of this problem is because, in a commercial FP-LD, the difference between the peak powers of a mode in original state and in fully injection-locked state is small. In this paper, an all-optical flip-flop with high on-off contrast ratio is proposed. The flip-flop is realized using two tunable single-mode FP-LDs. When fully injection locking occurs in the single-mode FP-LD by the injection of external light, the dominant longitudinal mode of the single-mode FP-LD is fully suppressed; therefore, a high on-off ratio of the dominant longitudinal mode is obtained. Taking advantage of this characteristic, the problem of the low on-off contrast ratio in the previous work is resolved.

2. Optical principle

The key principle of the flip-flop is based on the optical bistability of the injection-locked single-mode FP-LD. The optical bistability was experimentally observed in the power of the dominant longitudinal mode λ_o (self-locked mode) of the single-mode FP-LD versus the power of the injection beam λ_{ext} which was injected into a selected side mode of the single-mode FP-LD as shown in Fig. 1(a). The wavelength difference between the injection beam and the selected mode (defined as wavelength detuning) is adjusted in the injection-locking range where injection locking occurs [6]. Figure 1(b) shows the optical bistability of inverted S-shaped hysteretic curve observed in the dominant longitudinal mode λ_o with wavelength detuning d = 0.04 nm. Once optical injection power exceeds -6.5 dBm (unlocking threshold), the single-mode FP-LD is locked to new dominant longitudinal mode at λ_{ext}, resulting in the drastic power reduction of the self-locked mode λ_o. By the bistable characteristic as shown in Fig. 1(b), this unlocked state of the mode λ_o is maintained even if the injection power is lowered than the unlocking threshold.

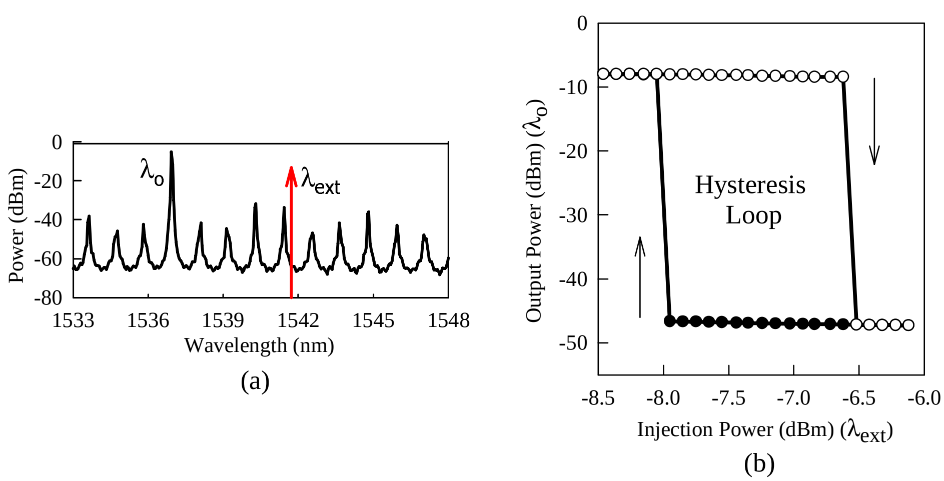

Fig. 1. (a) Description of the observed dominant longitudinal mode λ_o with the injection beam λ_{ext}; (b) Optical bistability observed in the dominant longitudinal mode λ_o of the injection-locked single mode FP-LD

The schematic diagram of the flip-flop is shown in Fig. 2(a), in which one single mode FP-LD is used as a master LD, and the other is used as a slave LD. Separate set and reset pulses are external control signals and the sustaining beam at λ_d from the master LD is always injected into the slave LD. The power of the sustaining beam, $P_{\lambda d}$, is chosen to be $P_{th2} < P_{\lambda d} <$

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P_{th1} as depicted in Fig. 2(b). The latchable flip-flop output is observed in the self-locked mode at λ_o of the slave LD. The set and reset operations of the flip-flop are shown in Fig. 2(c).

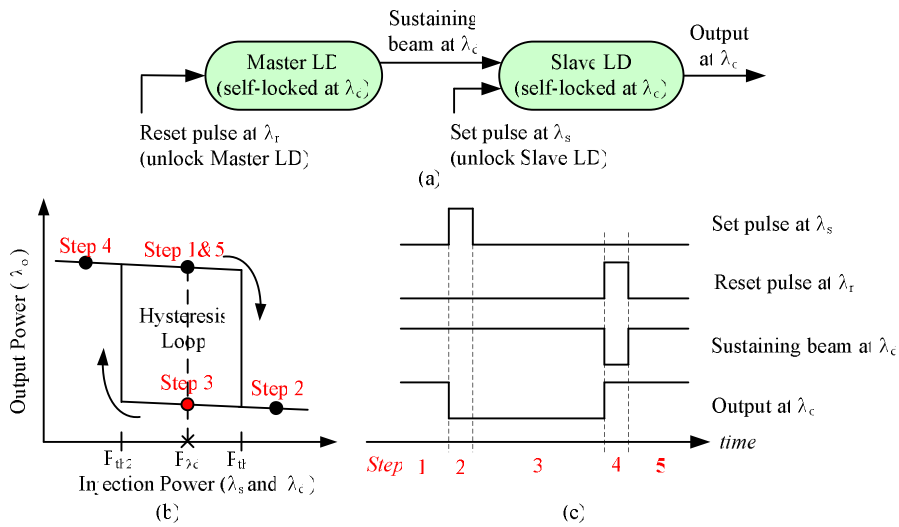

Fig. 2. (a) Schematic diagram of the proposed flip-flop, (b) optical bistability of the slave LD observed in the self-locked mode at λ_o, and (c) set and reset operations of the flip-flop

Initially, the flip-flop output is in high power state ("on" state) (step 1). When a set signal at λ_s is injected into the slave LD, the slave LD is injection-locked to λ_s. Therefore, its self-locked mode at λ_o is suppressed, leading to the flip-flop output in low power state ("off" state) (step 2). After the set signal is removed, the "off" state of the the flip-flop output is still maintained because the slave FP-LD is injection-locked by the sustaining beam at λ_d (step 3). To reset the flip-flop, the power of the sustaining beam should be reduced less than P_{th2} (re-locking threshold). For this purpose, a reset signal at λ_r is injected into the master LD. Due to the disturbance of this reset signal, the self-locked mode at λ_d of the master LD is suppressed; thus the peak power at λ_d is lowered than the re-locking threshold. Then the slave LD returns to its self-locked state (step 4). After the reset signal is removed, the self-locked state is still sustained since the sustaining beam cannot cause the unlocking of the slave LD by itself (step 5). With the above set and reset operations, the all-optical flip-flop has an inverted latchable output. And as presented in Fig. 1(b), the on-off contrast ratio of the slave LD is over 35 dB, so a high on-off contrast ratio of the flip-flop can be achieved.

3. Experiment and discussion

The experimental diagram of the proposed flip-flop is shown in Fig. 3. Figure 4 shows the output optical spectrum of the master and slave LDs operating in the condition of single mode oscillation. The wavelength at single mode oscillation of the master LD was 1541.46 nm (λ_d) with a SMSR of 29 dB when operating temperature was 24.8^{o}C with a bias current of 21 mA. The wavelength at single mode oscillation of the slave LD was 1536.94 nm (λ_o) with a SMSR of 27 dB when operating temperature was 23.3^{o}C with a bias current of 20 mA. The side-mode wavelength of the slave LD chosen for the injection of the sustaining beam and set signal was 1541.42 nm.

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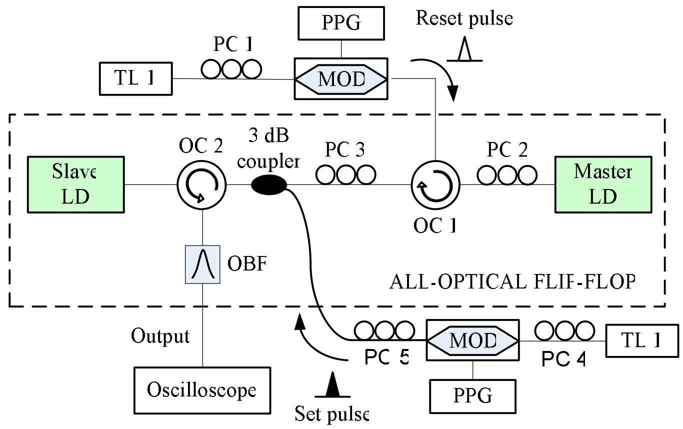

Fig. 3. Experimental diagram: TL - Tunable laser; PC - Polarization controller; PPG - Pulse pattern generator; MOD - Mach-Zehnder modulator; OC - Optical circulator; OBF - Optical band-pass filter

Two tunable lasers were used for set and reset signals. The both signals were optically modulated at a bit rate of 1 Gbit/s in non-return-to-zero (NRZ) pattern format using Mach-Zehnder modulators to make a optical pulse duration of 1 ns. The optical power levels of the set and reset pulses to perform the transitions between the flip-flop states were -13.1 dBm and -12.2 dBm, respectively. The set pulse was injected into the slave LD through the 3dB coupler and OC 2 at wavelength λ_s = 1541.46 nm; and the reset pulse was injected into the master LD through the OC 1 and PC 2 at wavelength λ_r = 1544.86 nm. The sustaining beam at λ_d was injected into the slave LD through the PC 2, OC 1, PC 3, 3dB coupler, and OC 2. The power of this beam on the slave LD was adjusted by the PC 3. Since FP-LDs favor TE-polarized light for injection locking [7, 8], the polarization change of the sustaining beam using the PC 3 results in its power change on the slave LD. The flip-flop output at λ_o was filtered out by the OBF and the output waveforms of the flip-flop were observed by an oscilloscope. Figure 5 represents output optical spectra of sequential states in the slave LD. An OBF right after the OC 1 to filter out only wavelength λ_d from the master LD was not necessary; since the master LD has a high SMSR, the side modes of the master LD do not affect the spectrum of the slave LD in general as shown in Fig. 4(b), 5(a). Without the optical band-pass filter, the wavelength λ_r of the reset pulse, which is injected into the master LD, was chosen so that it only unlocks the master LD but does not unlock the slave LD as shown in Fig. 5(d).

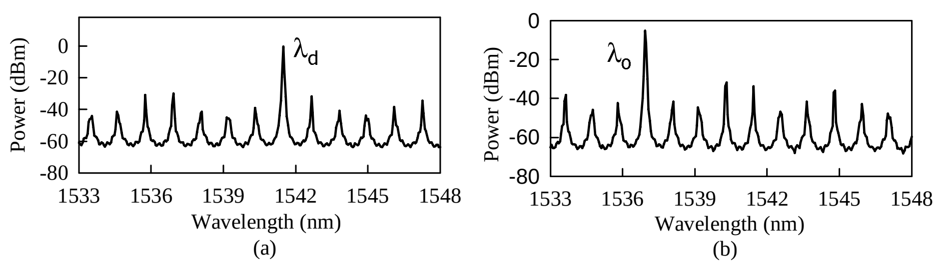

Fig. 4. Optical spectra of (a) the master LD and (b) slave LD

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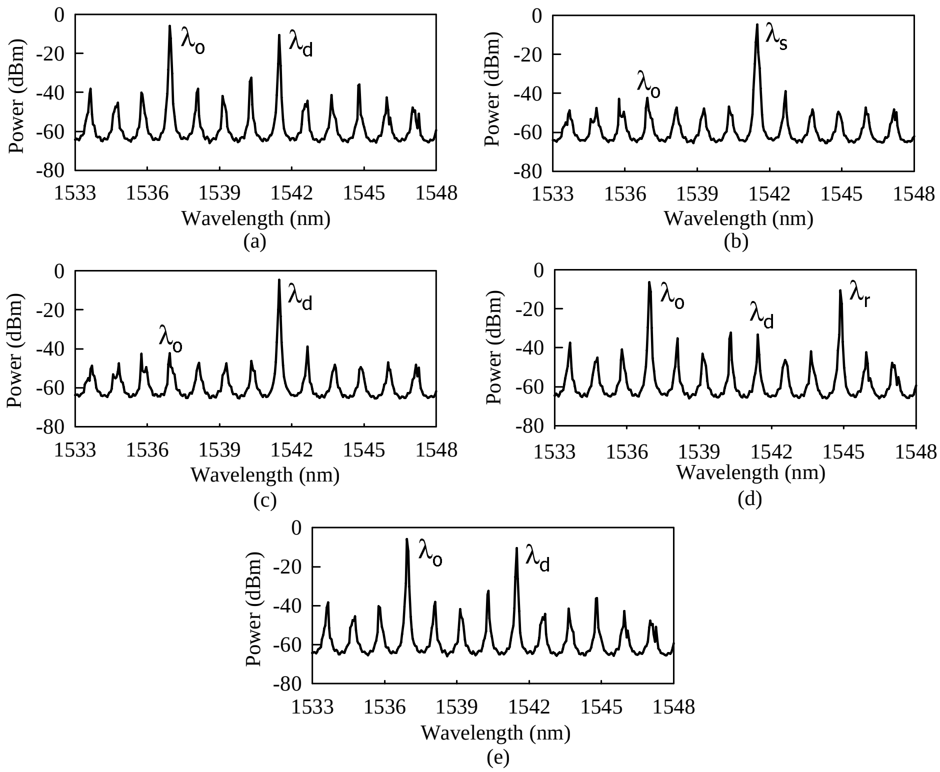

Fig. 5. Output optical spectra of sequential states in the slave LD (a) with the sustaining beam at λ_d, which is always injected into the slave LD (step 1), (b) with set signal at λ_s (step 2), (c) after removal of set signal (step 3), (d) with reset signal at λ_r (step 4), (e) after removal of reset signal (step 5)

Figure 6 shows oscilloscope traces from the flip-flop output. To identify that the set and reset operations of the flip-flop work properly, the set signal was advanced sequentially by 2 bits (2 ns) (Fig. 6(b), 6(c), and 6(d)). The rising and falling times of the toggling output were 0.9 ns and 0.1 ns, respectively.

The on-off contrast ratio of the flip-flop was estimated based on the spectrum data shown in Fig. 5 and it was over 35 dB.

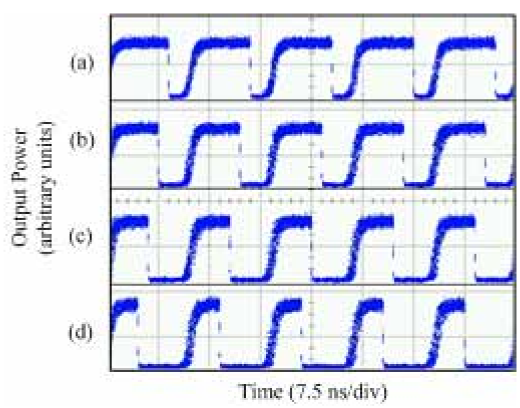

Fig. 6. Oscilloscope traces of the flip-flop output: (a) are the initial traces; (b), (c), and (d) are traces when set signal is advanced sequentially by 2 bits

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Indeed, due to the large difference between the peak powers of the self-locked mode λ_o of the slave LD in the original state and in the unlocked state, such a high on-off contrast ratio was easily achieved. In addition, the flip-flop obtained a fast switching time since the rising and falling times were just 0.9 ns and 0.1 ns, respectively. The operation speed of the flip-flop investigated in the experiment was 1 GHz. The limitation on the operation speed is owing to the response time of injection-locked single mode FP-LD and the fiber delay length of the control signal. An integrated version of the flip-flop would help minimize the control signal path length. With this minimization, the switching time is even increased faster and the operation speed can be extended more. Besides, the power levels of the set and reset pulses were very low, only -13.1 dBm and -12.2 dBm, respectively; these are very important for practical use.

4. Conclusion

In this paper, an all-optical flip-flop was proposed and experimentally demonstrated. The flip-flop achieved the high performance as the high on-off contrast ratio of over 35 dB, the fast switching time, and the low power levels of the set and reset pulses. With a simple and cost-effective architecture plus the good results, the all-optical flip-flop will be useful for future photonic networks such as optical burst switching and packet switching networks.

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