Mode-locked ring lasers and their application in a coupled all-optical flip-flop

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We demonstrate the generation of picosecond optical pulses source by using semiconductor optical amplifier (SOA) in a ring cavity. An all-optical flip-flop is realized based on two coupled identical actively mode-locked lasers. Each ring-laser outputs optical pulses with duration of 3 ps (FWHM) at a repetition rate of 10 GHz. We characterize the static and dynamic and of the flip-flop memory.

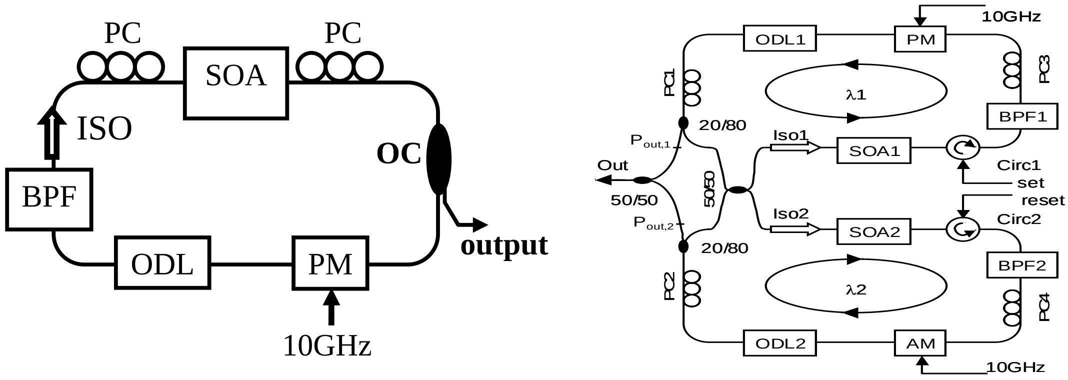
1. Introduction

Light sources capable of producing ultra-short optical pulses play a key role in optical communication systems [1,2]. Fiber ring lasers have been shown to be useful in producing continuous wave (CW) light as well as ultrashort pulses [3-5]. Higher repetition rates in fiber ring-lasers can be realized by employing active mode locking [6].

All-optical flip-flops (AOFFs) have many applications in optical telecommunications, such as threshold functions, 3R regeneration, demultiplexing, rate conversion and temporary storage of data packets [7]. AOFFs can be realized out of two coupled identical non-linear optical elements, such as laser diodes, Mach-Zehnder interferometers and non-linear polarization switches [8-10]. These AOFFs exhibit continuous wave (CW) operation and their output states can be set or reset by using amplitude-modulated signals. In this paper, we describe an AOFF realized with two coupled active mode-locked ring lasers (MLRLs) that each generates a train of pulses with duration of 3 ps at a repetition rate of 10 GHz. This AOFF has a large operational wavelength range and can be realized using commercially available standard fiber pigtailed components. Our flip-flop has a contrast ratio of 30 dB and an optical switching power of 1 mW.

2. Mode-locked ring lasers

A mode-locked ring laser can act as a building block for an optical flip-flop memory. Fig. 1(a) shows the schematic of an actively mode-locked ring laser. Each ring laser generates a train of pulses with duration of 3 ps at a repetition rate of 10 GHz. The cavity contains a phase- or amplitude modulator (AM/PM), an optical delay line (ODL), an isolator (ISO), a band-pass filter (BPF), an SOA, a circulator (CIRC), and polarization controllers (PCs). A bulk InGaAsP-InP ridge waveguide SOA acts as a gain medium, as shown in Fig. 1(a). The SOA can provide 23 dB small-signal gain at a bias current of 300 mA. In the ring cavity, the SOA exhibits a polarization sensitivity of 2 dB, and the AM and PM modules 3~4 dB. These sensitivities were minimized by using PCs. The ISO's were used to ensure unidirectional lasing. The BPF (5 nm, FWHM) defined the central wavelength of each cavity and the ODL was used to precisely match multiples of the cavity resonance frequency to the repetition rate. The total cavity loss was 10-13dB and the cavity fundamental frequency was 6.698MHz. To operate the ring laser in the mode locking condition, the external modulation frequency should be exactly equal to an integer multiple of the cavity fundamental frequency. This was achieved by fine-tuning the cavity length with the ODL. The ring then generates pulses with duration of 3-4 ps and a spectrum bandwidth of 2-3 nm.



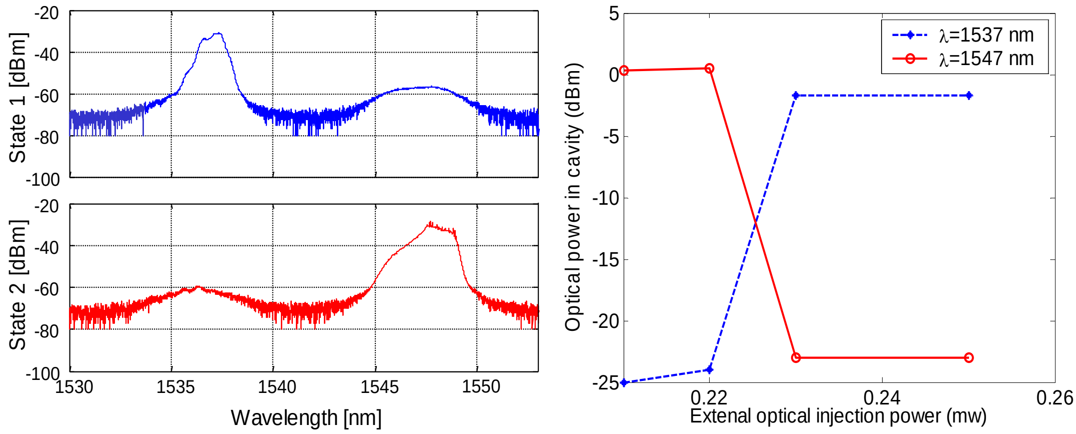
(a) (b)

Figure 1: (a). Setup of actively mode-locked ring laser. (b). Flip-flop based on two coupled actively mode-locked ring lasers with set and reset functions. SOA stands for the semiconductor optical amplifier, and ODL: optical delay line, BPF: band-pass filter, ISO: isolator, CIRC: circulator, PC: polarization controller, PM/AM: phase/ amplitude) modulator, OC: optical coupler.

3. All-optical flip-flop

A schematic of the all-optical flip-flop is shown in Fig. 1(b), where SOA1 was pumped with 170 mA of current and the injection current for SOA2 was 300 mA. The asymmetry in the injection currents is caused by the difference in the laser cavity losses. We measured the average power inside the master cavity is about 1 mW when I=170 mA. Flip-flop operation is realized by symmetrically connecting the two cavities such that one laser acts as a master suppressing lasing action in the other laser, which consequently acts as a slave. The role of master and slave can be interchanged due to system symmetry. Thus the system has two states. Each state is determined by the wavelength of the laser that is dominant. Thus the states of the flip-flop are determined by the central wavelengths λ1=1537 nm and λ2=1547 nm respectively. To switch between the states, external light has to be injected into the master. The external light quenches the gain of the master so that lasing is stopped. The absence of light from the master laser allows the slave laser to start lasing and become the master. The flip-flop remains in the new state after the external light is removed.

The contrast between each state of the flip-flop was investigated by using an optical spectrum analyzer. Fig. 2(a) shows that static contrast ratio between states of the flip-flop is greater than 30 dB. In order to change between the states, an external CW beam with a central wavelength of 1550 nm was injected into the master laser. The switching power is investigated by injecting external light in the dominant laser. The result is shown in Fig 2(b). It follows that if the externally injected power is 0.22 mW, the power in the dominant cavity drops and the power in the suppressed cavity increases. If the injected power is larger than 0.23 mW the dominant laser has switched off (the power has decreased with 20 dB) and the suppressed laser has switched on. After switching, the system remains stable, also if injection of external light has terminated.



(a) (b)

Figure 2: (a). Spectra of the two-state operation are shown for the two-coupled ring laser system. (b). The optical power in cavities versus the external switching optical average power around the transition states. The contrast ratio between the signal-noise levels is about 30 dB.

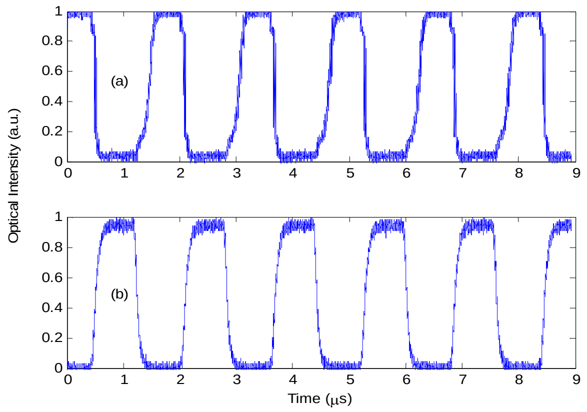


Figure 3: Regular toggling between two flip-flop states, (a). 1537 nm; (b). 1547 nm.

The flip-flop switching speed is determined by the length of the cavities and the distance between the lasers. Since our experiments were performed on a proof of concept basis by using standard commercial pigtailed components, the lasers had a cavity length of about 20 meters and the distance between the lasers was 3 meters. This implies that the switching speed is in the order of μs. An integrated flip-flop will shorten the lasing build-up time considerably to a (sub) nanosecond range because the physical lengths are reduced to millimetres.

The dynamic operation of the flip-flop is demonstrated by toggling its state by injecting a regular sequence of optical pulses into the laser that was currently the master. The injected pulses had a central wavelength of 1551 nm, duration of a few nanoseconds, and the average power of the injected light was 1 mW. The pulses were injected into the flip-flop once every 0.96 μs through the set (or reset) port. The flip-flop output was detected by a slow photodetector and displayed on an oscilloscope. Due to the limitation of the detector response time, Fig. 3 shows only the envelope of the picosecond pulse train, however the regular toggling between the states is clearly visible. The flip-flop was operated at 521.3 KHz, which indicates about 2 μs of recovery time. This implies that the pulses can buildup after about 40 round-trips assuming the cavity length is 20 meters.

4. Conclusions

An all-optical flip-flop memory based on two coupled actively mode-locked ring lasers was realized. Each ring laser generates a train of pulses with duration of 3 ps (FWHM) at a repetition rate of 10 GHz. The contrast ratio between the flip-flop output states was over 30 dB, the nominal wavelength spacing was 10 nm, the optical switching power was 1 mW and the switching speed was about 1 μs. The switching speed can be reduced to (sub) nanoseconds by shortening the dimension of the flip-flop through optical integration.

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