Multi-state Optical Flip-flop Memory Based on Cascaded Lasers

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A multi-state optical flip-flop memory based on cascaded lasers is presented. We show that only one of the lasers can lase at a time, thus the state of the optical memory is determined by the wavelength of the dominant laser. The light from the dominant laser suppresses its neighboring lasers through gain saturation, but still receives amplification by the active element of the suppressed lasers, compensating for coupling losses. This light passes through each of the successive lasers, simultaneously suppressing and being amplified, thus all other lasers are suppressed. A five-state optical memory based on this concept is experimentally demonstrated.

Introduction

Optical memories have received considerable attention since they act as a fundamental building block for sophisticated digital optical signal processing [1-2]. Many types of optical memories have been explored, which all have in common that optical storage elements with two states can be realized [3-6]. Few memory concepts however allow extension into multi-state optical memory, which is interesting for applications in telecommunication systems, since they have potential to switch multiple packets.
A three-state optical memory based on coupled lasers is presented in [7]. This concept requires that each laser is connected with all the other lasers, making the number of inter-connections large and the operating power high. The optical memory based on coupled ring lasers [8] allows extension into more states, but its output is oscillating, which makes that the concept is hard to apply in communication systems.
In this paper, we present a multi-state optical memory based on serially interconnected lasers, whose wavelengths are different. The lasers are connected in such a way that each of the lasers can be set to suppress its consecutive lasers through gain quenching [6]. The active elements in the suppressed lasers can still be used to amplify the injected light to compensate losses, so that the dominant laser suppresses all the other lasers as a chain reaction. We demonstrate this concept by realizing an optical memory based on five serially interconnected lasers.

Operation principle

The schematic of the multi-state optical memory based on serially interconnected lasers is shown in Fig. 1. Five identical lasers are interconnected. Each laser has a Fabry-Perot cavity; a semiconductor optical amplifier (SOA) acts as the active element. Two couplers are placed in the cavity to output light and to receive external injection. The wavelength dependent mirrors determine the lasing wavelength. Laser 1 and laser 2 are coupled by connecting port B of laser 1 and port C of laser 2. If laser 1 is set to be lasing first, the output light of laser 1 injects into laser 2 and saturates SOA2. Lasing in laser 2 is suppressed if the injected power P0 is sufficiently large. It is the same for laser 2 to suppress laser 1 if laser 2 is set lasing first. This is bi-stability [6] based on gain quenching.
Note that in the case that laser 1 suppresses laser 2, the injected light from laser 1 still receives amplification from the saturated SOA2. The amount of amplification can compensate the loss for the injected light passing from port C to port E through SOA2. Therefore the injected light

from laser 1 gets its power recovered to be P_0 at port E of laser 2, and continues to quench laser 3. After receiving amplification from SOA 3, the injected light from laser 1 quenches the rest of the lasers in the same way. Eventually, laser 1 dominates all the other lasers.

If laser 2 is set lasing first, the output light of laser 2 quenches laser 1 and laser 3 through gain quenching. After receiving amplification from SOA3, the injected light from laser 2 at port H keeps on quenching the rest of the lasers. Eventually, laser 2 suppresses all the other lasers in a chain reaction. Therefore, any of the five lasers can dominate all the others in a similar way. Since each laser has a different wavelength, fivefold-stability is thus realized.

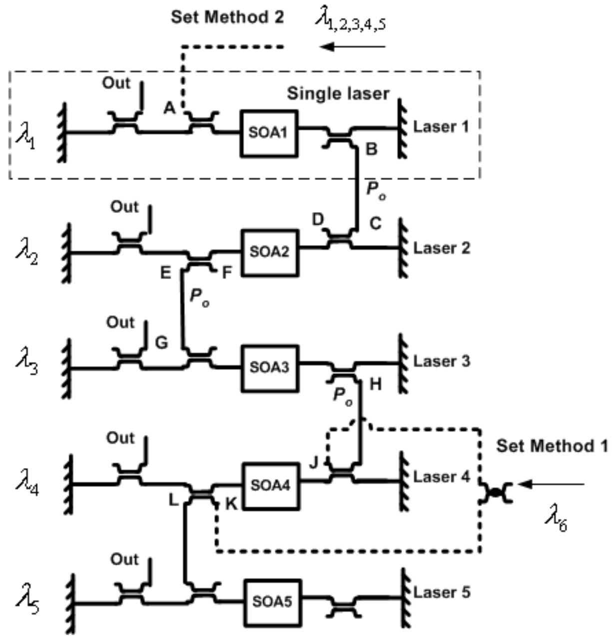

Fig. 1. Configuration of multi-state optical memory based on serially interconnected lasers.

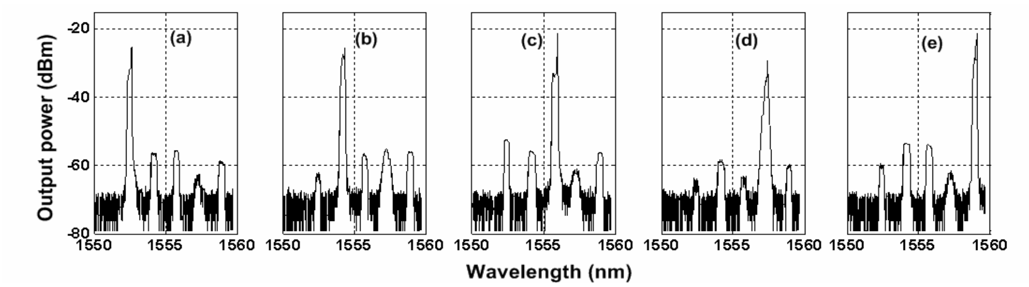

Fig. 2. Spectrum showing fivefold–stability

Experiment

The schematic of Fig. 1 was implemented by fiber pig-tailed components. The wavelength dependent mirrors of laser 1, 2, 3 and 5 were Fiber Bragg Gratings (0.60 nm FWHM) with center wavelengths of 1552.52 nm, 1554.20 nm, 1555.75 nm and 1558.90 nm, respectively. Due to the lack of components, we combined an arrayed waveguide grating (AWG) and one loop mirror to act as a wavelength dependent mirror to form the cavity of laser 4. The AWG served as a filter (3-dB bandwidth 0.80 nm) with center wavelength of 1557.40 nm. All the couplers connected with the lasers had a ratio of 40/60. The port with 60% ratio was used to couple with other lasers. All the couplers used to output light had a ratio of 80/20. 20% of the light was coupled out. The injection currents for SOA 1-5 were 189.4 mA, 177.9 mA, 198.4 mA, 210.7 mA and 192.5 mA, respectively. The power (P0) of the lasing light coupled to the neighbouring lasers was about 0.0 dBm. The system turned out to be fivefold stable, the corresponding spectrums are shown in Fig. 2. Any of the five lasers dominated the rest of the lasers with a contrast ratio over 30 dB.

There are two methods to all-optically select the desired state. One is to externally inject light, at a different wavelength as the lasers, into all the lasers except the desired laser [6-7]. For example, when laser 2 was lasing, we injected the external light at the wavelength of 1550.00 nm through ports J and K to make laser 4 become lasing. The external light was divided into two parts: one part was injected into port K of laser 4 to quench laser 5; the other part was injected into port J of laser 4 to firstly quench laser 3 and then laser 2 and 1 through gain saturation. Note that the injected light could not saturate SOA 4 inside laser 4. Thus laser 4 became lasing automatically since all the other lasers were quenched. Fig. 3a shows the output power of laser 2 (indicated by solid line) and the output power of laser 4 (indicated by dashed line) versus the power of the externally injected light through port J. Laser 4 became lasing and laser 2 was suppressed when the power of the external light exceeded the threshold value of -3.5 dBm. When the external light was removed, the system still kept the new state.

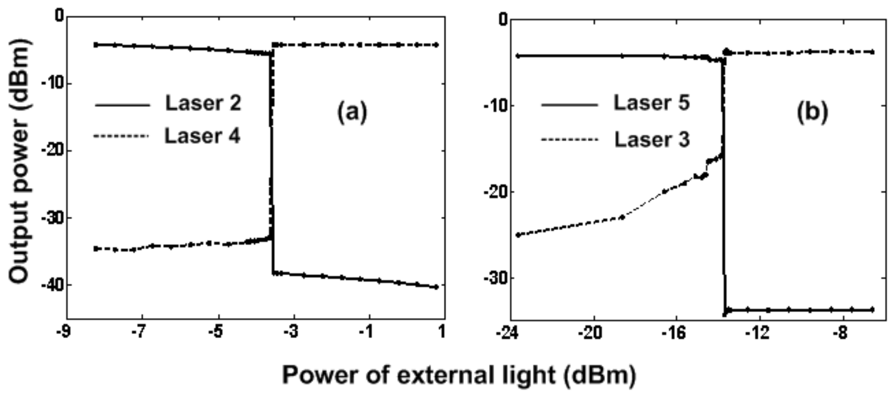

Fig.3. Switching by external light injection. a: Switching between from laser 2 lasing to laser 4 lasing by injecting external light through ports J and K; b: Switching between from laser 5 lasing to laser 3 lasing by injecting external light at λ_3 through port A.

The other switching method is to inject external light, at the wavelength of the desired laser, always through port A. For example, when laser 5 was lasing, we injected the external light at 1555.75 nm, which was the same as the center wavelength of laser 3, through port A of laser 1 to make laser 3 become lasing. The external light first passed through lasers 1-5, saturating the corresponding SOAs. Note that the injected light only resonated in the laser cavity of laser 3 because it had the same wavelength. The resonant injected light in the cavity of laser 3 returned to inject into all the other lasers to saturate the corresponding SOAs further, which leaded to a weaker power of switching threshold value. It is clearly visible in Fig. 3b that laser 5 was suppressed when the power of external light exceeded -13.75 dBm, which is about 10 dB smaller than that of the previous method. Laser 3 simultaneously became dominant when laser 5 was suppressed because the resonant injected light out of laser 3 still kept the other lasers suppressed. When the external light was removed, the system still kept the new state.

The dynamic operation was demonstrated as shown in Fig. 4. Two beams of external light were modulated by external optical modulators into two regular sequences of optical pulses, which had a period of 25.00 μs with duty cycle of 10%. The sequence of optical pulses setting laser 3 lasing, was at wavelength 1555.75 nm, as shown in Fig. 4a. The other sequences of optical pulses setting laser 5 lasing, was at wavelength 1558.90 nm and had a delay of half period compared with the first sequence of optical pulses, as shown in Fig. 4b. The toggling between the states of laser 3 lasing and laser 5 lasing as response of the setting pulses is shown in Fig. 4c and 4d.

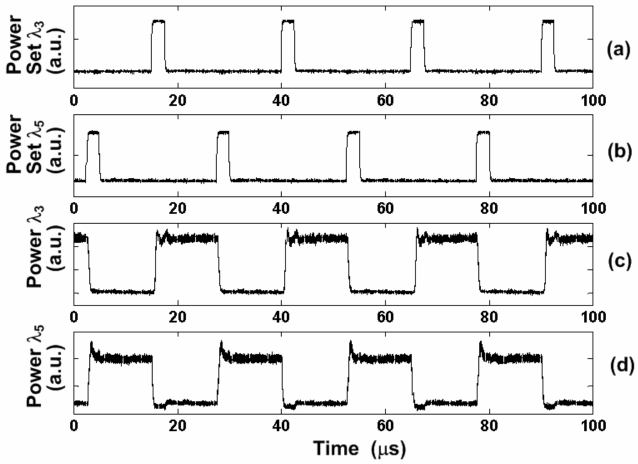

Fig. 4. Dynamic operation by injecting external light at different wavelengths through port A. Panel (a) and (b): The sequences of optical pulses at wavelength 1555.75 nm and 1558.90 nm, to set laser 3 lasing or laser 5 lasing, respectively; Panel (c) and (d): Dynamic operation of laser 3 or laser 5 lasing.

Conclusions

A five-state optical memory based on serially interconnected lasers through gain quenching was experimentally demonstrated. The switching speed is determined by the size of each laser and the distance between the lasers. Operation speed can be improved by integration, since no isolators are used. An advantage of the concept is the linear scalability that more states operation can be realized by connecting more lasers.

References

[1] H.J.S. Dorren, et al., "Optical packet switching and buffering by using all-optical signal processing methods," IEEE/OSA J. Lightwave Technology., Vol. 21, pp. 2-12, 2003.

[2] H.M. Gibbs, Optical bistability: controlling light with light, Academic Press, London, 1985.

[3] H. Kawaguchi, Bistabilities and Nonlinearities in Laser Diodes, Artech House, Boston, London, 1994.

[4] L. Xu, et al, "Optical spectrum bistability in a semiconductor fiber ring laser through gain saturation in a SOA", IEEE Photonics Technol. Lett., Vol. 14, pp. 149-151, 2002.

[5] M. Takenaka and Y. Nakano, Realization of all-optical flip-flop using directionally coupled bistable laser diode, IEEE Photonics Technol. Lett., Vol. 16, pp. 45-47, 2004.

[6] M.T. Hill, et al, "All-optical flip-flop based on coupled laser diodes," J. Quant. Electron., Vol. 37, 405-413, 2001.

[7] Y. Liu, et al., "Three-state all-optical memory based on coupled ring lasers," IEEE Photonics Technol. Lett., Vol.15, pp. 1461-1463, 2003.

[8] S. Zhang, et al., "Ring-laser optical flip-flop memory with single active element," IEEE J. Select. Top. Quant. Electron., Vol. 10, pp.1093-1100, 2004.