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Multistate Optical Memory Based on Serially Interconnected Lasers

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Abstract—A multistate optical memory based on serially interconnected 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. By this mechanism, all other lasers are suppressed. A five-state optical memory based on this concept is experimentally demonstrated. The contrast ratio between different states is over 30 dB. Dynamic flip-flop operation based on two different all-optical switching methods is also demonstrated.

Index Terms—Multivalued optical logic, optical bistability, optical memories, semiconductor optical amplifiers (SOAs).

I. 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]–[7]. The existence of multistable optical logic building blocks is interesting for applications in telecommunication systems, since they have potential to switch multiple packets.

Very few of the existing optical memory concepts can be extended into multistate operation. In [8], a three-state optical memory based on coupled lasers is presented. This concept requires that each laser is connected with all the other lasers in the memory, making the number of interconnections large and the operating power high. The optical memory concept, based on coupled ring lasers presented in [7] allows extension into more

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Fig. 1. Configuration of multistate optical memory based on serially interconnected lasers.

states, but its output is oscillating, making the concept hard to apply in more sophisticated systems.

Here we present a multistate optical memory that consists of a large number of serially interconnected lasers. In [6], it is shown that two serially interconnected lasers form a bistable configuration. Multistate optical memories based on a large number of serially connected lasers have the advantage that the active elements in the suppressed lasers can still be used to amplify the injected light to compensate losses, so that the dominant laser quenches all the other lasers as a chain reaction. This reduces the number of connections between the lasers as well as the operating power. We demonstrate this concept by realizing an optical memory based on five serially interconnected lasers.

II. OPERATION PRINCIPLE

The schematic of the multistate optical memory based on serially interconnected lasers is shown in Fig. 1. Five identical lasers are interconnected. Each laser has a Fabry-Pérot cavity, a semiconductor optical amplifier (SOA) that acts as the active element. Two couplers are placed in the cavity to output light and to receive external injection. The lasing wavelength is determined by the wavelength-dependent mirrors. Suppose one laser

is lasing, and external light is injected into the laser cavity. The external light can quench the lasing by saturating the SOA if the injected power is sufficiently large.

Suppose that Lasers 1 and 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 P_0 is sufficiently large. It is the same for Laser 2 to suppress Laser 1 if Laser 2 is set lasing first. This is the bistability [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 Ports C to E through SOA2. Therefore, the injected power from Laser 1 is recovered at Port E of Laser 2, and continues to quench Laser 3. After receiving amplification from SOA3, 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 Lasers 1 and 3 through gain saturation. 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. Therefore, any of the five lasers can dominate all the others in a similar way. Since each laser has a different wavelength, five-fold stability is, thus, realized.

III. EXPERIMENT

The schematic of Fig. 1 was implemented by fiber pigtailed components. The wavelength-dependent mirrors of Lasers 1, 2, 3, and 5 were fiber Bragg gratings [0.60-nm full-width at half-maximum (FWHM)] with center wavelengths of 1552.52, 1554.20, 1555.75, 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 (0.80-nm FWHM) with a center wavelength of 1557.40 nm. All the couplers that interconnected 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. Twenty percent of the light was coupled out. The employed SOAs were commercially available strained bulk SOAs that have a typical small gain of 20 dB at 200 mA and a 3-dB saturation power of -5 dBm. Different currents were injected into the SOAs to make the system symmetrical in such a way that the output power of each laser was similar.

When the injection currents for SOA1–5 were 189.4, 177.9, 198.4, 210.7, and 192.5 mA, respectively, the power (P_0) of the lasing light coupled to the neighboring lasers was about 0 dBm and was recovered by receiving amplification from the saturated SOAs. Since 0-dBm power was sufficiently large to quench the neighboring lasers (the threshold injection power was about -3.5 dBm for any single laser), the system turned out to be five-fold stable. The corresponding spectrums are shown in Fig. 2. Any of the five lasers dominated all the other lasers with a contrast ratio over 30 dB. Note that the spectrum of Laser 4 shown in Fig. 2(d) had broader bandwidth because the AWG used as a wavelength-dependent element had a wider

Fig. 2. Spectrum showing five-fold stability.

bandwidth. If we modify the injection current of any of the five SOAs within a range of about 10 mA, while keeping the injection currents of the other four SOAs unchanged, the five-fold stability still exists. However, the contrast ratio between the states changes, due to the changed amplification by one of the SOAs.

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], [8]. 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 first quench Laser 3 and then Lasers 2 and 1 through gain saturation. Note that the injected light could not saturate SOA4 inside Laser 4. Thus, Laser 4 began lasing automatically since all the other lasers were quenched. Fig. 3(a) 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. (a) Switching from Laser 2 lasing to Laser 4 lasing by injecting external light at 1550.00 nm through Ports J and K. (b) Switching from Laser 5 lasing to Laser 3 lasing by injecting external light at 1555.75 nm through Port A.

Fig. 4. Dynamic operation by injecting external light through Port A with different wavelength. (a) Oscilloscope traces of the externally injected optical pulses at wavelength 1555.75 nm, to set Laser 3 lasing. (b) Oscilloscope traces of the external injected optical pulses at wavelength 1558.90 nm, to set Laser 5 lasing. (c) and (d) The dynamic operation of Lasers 3 or 5 lasing.

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 led to a weaker power of switching threshold value. It is clearly visible in Fig. 3(b) 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 based on the latter method 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 have a period of $25.00 \mu\text{s}$ with the duty cycle of 10%. The sequence of optical pulses setting Laser 3 lasing, was at a wavelength of 1555.75 nm, as shown in Fig. 4(a). The other sequences of optical pulses setting Laser 5 lasing, was at a wavelength of 1558.90 nm and had a delay of half period compared to the first sequence of optical pulses, as shown in Fig. 4(b). The toggling between the states of Laser 3 lasing and Laser 5 lasing as response of the corresponding setting pulses is shown in Fig. 4(c) and (d).

IV. CONCLUSION

A five-state optical memory based on serially interconnected lasers through gain quenching was experimentally demonstrated. The contrast ratio is over 30 dB, which can be further improved by using wavelength-dependent components with narrower bandwidth. Two different switching methods with low power operation were demonstrated.

The switching speed is determined by the size of each laser and the distance between the lasers. Consider, for example, a flip-flop with N stable states. The worst case occurs when the Laser N is active and the device is switched to Laser 1, at the opposite end. The injected pulse must first travel the length of the device to suppress the active laser. The effects will not be felt at Laser 1 until the last light from Laser N has time to travel the length of the device. Then Laser 1 begins lasing. The time for lasing building up is determined by the size of each laser since a certain number of round trips are required. Operation speed can be improved by integration, which is applicable for the configuration shown in Fig. 1 since no isolators are used.

The advantage of the concept presented here is the linear scalability that in principle enables realization of optical memories with large number of states. It should be said, however, that several aspects associated with increasing the number of interconnected lasers need to be investigated further. These are the possibly detrimental effects from SOA-facets and coupler reflections, the possible dynamical instabilities induced by the large number of coupled lasers, and the influence of the various propagation times between the lasers.

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