

Three-State All-Optical Memory Based on Coupled Ring Lasers

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Abstract—An all-optical memory with three states is presented. The memory is realized from three coupled ring lasers. The state of the optical memory is determined by the wavelength of the memory's output light. In each state, only one wavelength is dominant. The three-state all-optical memory can be utilized in all-optical packet switches. The concept of the memory is explained and experimental results are presented that demonstrate that a contrast ratio larger than 40 dB between output states of the memory can be obtained.

Index Terms—All-optical memories, multiple state, packet switching, semiconductor optical amplifier.

I. INTRODUCTION

ALL-OPTICAL packet switches are considered as important building blocks for future all-optical telecommunication nodes [1]. In [2], a 1×2 all-optical packet switch has been presented. A key component of this packet switch is a two-state all-optical memory. In principle, the number of states of the memory determines the number of output states of the packet switch. Therefore, all-optical memories with more states are crucial for extending the 1×2 all-optical packet switch of [2] to a larger dimension ($1 \times N$). In this letter, we describe an all-optical memory that has three states. This three-state memory concept can be extended to create an all-optical memory with an arbitrary number of states. A two-state all-optical memory can be realized from two-coupled nonlinear optical elements. Examples are an all-optical memory that is made from two-coupled lasers [3], an all-optical memory that is made from two-coupled nonlinear polarization switches [4], [5], and an all-optical memory that is realized out of two-coupled Mach-Zehnder interferometers [6]. In this letter, we demonstrate that it is possible to construct a three-state optical memory based on three coupled identical ring lasers. The state of the optical memory is determined by the wavelength of the memory's light output. In each state, only one laser lases and the other lasers are suppressed, thus only one wavelength is dominant. This all-optical memory implementation has separate inputs to set the memory in a particular state. We demonstrate the feasibility of the concept and we show that the contrast ratio between output states of the memory is over 40 dB.

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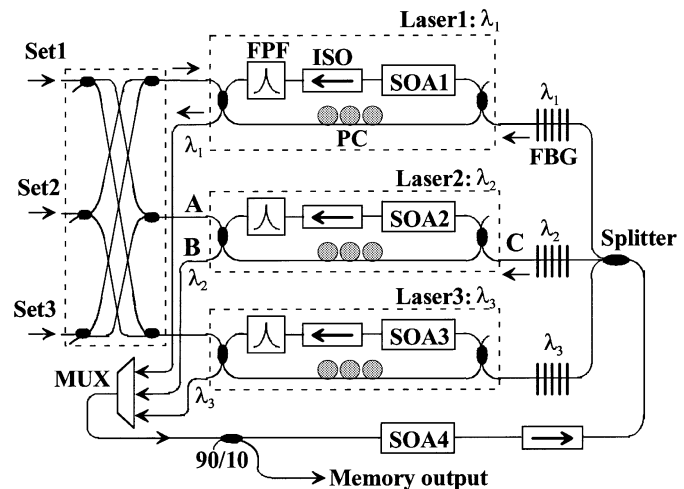


Fig. 1. Configuration of the three-state all-optical memory based on coupled ring lasers. SOA: Semiconductor optical amplifier; ISO: Isolator; FPF: Fabry-Perot filter; PC: Polarization controller; MUX: Optical multiplexer; and FBG: Fiber Bragg grating.

This letter is organized as follows. In Section II, the system concept is explained. Experimental results are presented in Section III. Finally conclusions are given.

II. SYSTEM CONCEPT

The three-state all-optical memory concept is depicted in Fig. 1. It consists of three coupled identical ring lasers. As shown in the Fig. 1, in each single ring laser a semiconductor optical amplifier (SOA) acts as the laser gain medium. The wavelengths are selected by Fabry-Perot filters (FPFs). Optical isolators (ISOs) are used to allow the light to travel in only one direction, thus ensuring lasing in one direction. The operation principle of a single ring laser is described in [7]. If the gain of the SOA is higher than the threshold of the ring laser, lasing starts. However, the SOA can be saturated by injection of high intensity external light, which causes the gain at the lasing wavelength to be reduced. If the reduced gain at the lasing wavelength is below the threshold value, lasing stops. Fig. 2 shows the typical (experimental) ring laser output as a function of the intensity of the saturating external light. It is clearly visible that external light with sufficient intensity can suppress lasing.

Two identical lasers can be coupled to make a two-state all-optical memory [3]. The output of the first laser (Laser 1) is coupled in a second identical laser (Laser 2), and the output of

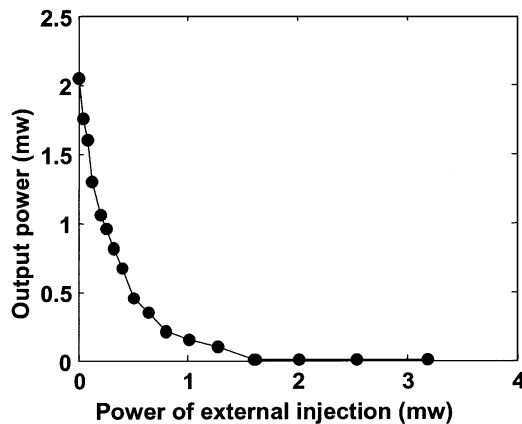


Fig. 2. Output power of Laser 2 at Port B versus the input power via Port C.

Laser 2 is coupled into Laser 1. In such a configuration, one laser can act as the master laser, which suppresses lasing in the other laser (the slave). Due to the symmetry of this master-slave configuration, the role of master and slave can be interchanged. Thus, two states are possible. In state 1, Laser 1 is lasing and Laser 2 is suppressed and in state 2, Laser 2 is lasing and Laser 1 is suppressed. To change the states, lasing of the dominant laser can be stopped by injecting external light, which has different wavelength from the dominant laser, into the dominant laser cavity [3].

The concept in [3] can be extended to a three-state optical memory. In Fig. 1, three identical ring lasers are coupled to each other to construct a three-state optical memory. The output of each ring laser has to be coupled into the other two lasers, but not into its own cavity. To realize this, the outputs of each ring laser are first combined by using a multiplexer. Ten percent of the combined light is coupled out of the system by using a 90/10 coupler. This is the memory output. The other 90% of the combined light is first fed into SOA 4 to be amplified and then fed back into each ring laser through a system of fiber Bragg gratings (FBGs). FBGs are used to prevent light at the lasing wavelength reentering the ring laser cavity. Thus, the output of each laser is coupled into the other lasers, but not into its own cavity due to the FBGs. The amplification by SOA 4 ensures that the light injected in each laser is sufficient to suppress the lasing mode. Since the system is symmetric, all the lasers can suppress lasing in the other lasers and, thus, each laser can become dominant. Therefore, the memory has three possible states, depending on which laser is lasing. The state of the memory is determined by the wavelength of the memory's output light. In each state, only one laser lases and the other lasers are suppressed, thus only one wavelength is dominant. In state 1, Laser 1 dominates and suppresses the lasing in the other lasers, thus λ_1 is dominant. In state 2, Laser 2 is dominant and suppresses lasing in the other two lasers, therefore, λ_2 is dominant. In state 3, only Laser 3 is lasing and suppresses Laser 1 and Laser 2, thus, λ_3 is dominant.

To select the state of the memory, external light is injected via one of set ports, as shown in the Fig. 1. The external light, which is used to change the state of the memory, is firstly sent through a small network that is made from 3-dB couplers. (See the dashed-box on the left-hand side in Fig. 1). The function

of this network is to dispense the external light into some specific lasers, depending which input port is used. External light injected in one set port can set the memory in a particular state. For instance, external light injected in Set 1 Port can set the memory in state 1 (Laser 1 dominates). In this case, the external light suppresses Laser 2 and Laser 3. Thus, the external light is distributed over the all the lasers except Laser 1. The saturating external light stops or reduces the light exiting from the lasers in which the external light is injected, no matter if these lasers are dominant or suppressed. As a consequence, Laser 1, in which no external light is injected, can increase its output light and thus become the dominant laser (suppress the other lasers). This state remains after the external light is removed.

The state of the memory can be changed by injection of external light with arbitrary polarization that has sufficient power, since the switching principle is based on SOA gain saturation [3].

III. EXPERIMENT AND RESULTS

The three-state all-optical memory is implemented as in Fig. 1. All the couplers in the experiment are 50/50 couplers except one 90/10 coupler that is indicated in the Fig. 1. The wavelength of the lasers is $\lambda_1 = 1552.18$ nm, $\lambda_2 = 1554.17$ nm, and $\lambda_3 = 1555.78$ nm, respectively. The SOAs were manufactured by JDS Uniphase and employ a strained bulk active region. The SOA injection currents are set in such a way that the system is symmetric. The SOA injection currents were 200 mA for Laser 1 (the threshold current is 152 mA), 151 mA for Laser 2 (the threshold current is 87 mA) and 186 mA for Laser 3 (the threshold current is 96 mA), respectively. SOA 4 is biased with 300 mA of current, providing an optical power of 13 dBm at the output of SOA 4.

The output power of Laser 2 at Port B is plotted versus the input power via Port C (see Fig. 1) in Fig. 2. Fig. 2 shows that for such a ring laser, it is sufficient to inject 3.98 dBm (2.5 mW) of light to suppress lasing in the ring laser.

The dynamic operation of the memory is demonstrated by toggling the state of the memory by injecting a regular sequence of optical pulses into each of the set ports (see Fig. 1). The injected pulses had a wavelength of 1550.92 nm and a duration of 2.5 μ s. The pulses to change the state of the memory were injected once every 12.7 μ s, as shown in the upper panels of Fig. 3(a)–(c). The optical peak power of pulses was 15 dBm at each input port of the memory. These optical pulses only have around 6 dBm peak power left when they are injected into the ring lasers due to 9 dB of coupling loss in the input network. Fig. 3(d)–(f) shows the oscilloscope traces of the optical output power of the memory for each state. In Fig. 3, regular toggling between memory output states every 12.7 μ s is visible. Furthermore, it can be observed that the memory's state is stable in the time between changing states. Also, the contrast between each state of the memory was investigated by using an optical spectrum analyzer. It is shown in Fig. 4 that contrast ratio between the each state of the memory is over 40 dB. In Fig. 4, the linewidth of Laser 1 is larger than the other two lasers due to the bandwidth of Fabry–Perot filter (0.5 nm) in Laser 1, which is wider than the bandwidth of Fabry–Perot filters in the other

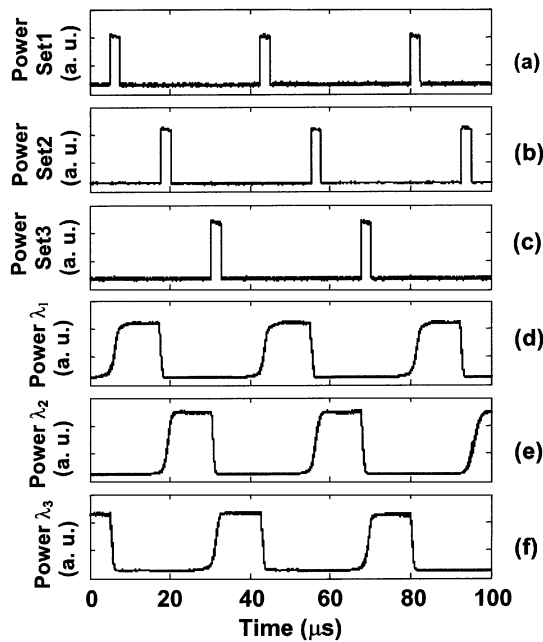


Fig. 3. Dynamic output of the memory showing switching between each states every $12.7 \mu\text{s}$. The upper panels (a), (b), and (c) are the traces of the external optical pulses. The lower panels (d), (e), and (f) are the dynamic output of memory at each wavelength (λ_1 , λ_2 , λ_3).

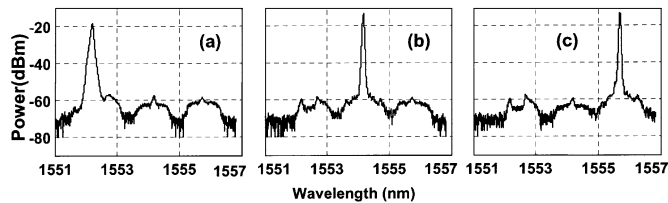


Fig. 4. Spectral output at each state of the memory. (a) Represents state 1 (λ_1 dominant). (b) Represents state 2 (λ_2 dominant). (c) Represents state 3 (λ_3 dominant).

two lasers (0.2 nm). However, a better experiment result can be obtained if the filters are identical.

The SOAs used in the experiment are polarization insensitive. Hence, external light of arbitrary polarization can switch the state of the memory, ensuring that the optical memory is polarization independent.

IV. CONCLUSION

A three-state all-optical memory based on coupled ring lasers has been demonstrated. The state of the memory is determined

by the wavelength of the memory's light output. In each state, only one wavelength is dominant. This all-optical memory implementation has separate inputs to set the memory in a particular state, and the contrast ratio between output states of the memory is over 40 dB.

The speed of this memory is determined by the cavity length of the ring laser and the propagation distance between each laser. The experimental setup was constructed from standard commercially available fiber pigtailed components, thus each laser has a cavity lengths of around 16 m and approximately 13 m of fiber is used between each lasers, which implies that about several microseconds are required to change the states of the memory. However, in integrated versions of the memory, the laser would have a cavity length of several millimeters and the distance between each laser would be reduced to several millimeters, indicating that integrated versions of the memory could attain speeds in the gigahertz range.

The concept of this three-state memory can be extended to create all-optical memories with a larger number of states. However, the operating speed of the extended multistate memory will slow down since the distance between the coupled lasers will increase. Furthermore, more optical switching power and more amplification of the combined light (the role of SOA 4 in Fig. 1) are required, due to the increasing coupling loss in the extended multistate all-optical memory.

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