Integrated Two-State AWG-Based Multiwavelength Laser

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Abstract—An integrated InP–InGaAsP two-state coupled-laser device for use in optical packet switching and signal processing is presented. The two states are identified by distinct lasing wavelengths. Single-mode lasing occurs in both states and the contrast ratio between the two states is 35 dB. Switching between states with optical pulses is demonstrated. The use of an arrayed waveguide grating (AWG) and ring laser configuration permits monolithic integration without the need for cleaved facets. How the AWG can be used to obtain partial isolation between multiple interconnected devices is also discussed.

Index Terms—Arrayed waveguide grating (AWG), optical bistability, optical logic, optical memory, photonic integrated circuits, semiconductor laser.

I. INTRODUCTION

RECENT work in all-optical packet processing of telecommunication data has demonstrated a need for optical memory, logic, and threshold functions [1], [2]. Future digital optical processing systems will require that many of these functions be integrated and interconnected on a single photonic integrated circuit. Coupled lasers exploiting gain quenching can provide the required functions [3], [4], and the flexibility of the concept allows implementation in various configurations and technologies. Here we present an integrated InP–InGaAsP coupled laser device based on gain quenching. An arrayed waveguide grating (AWG) multiplexer is used in the device as a frequency selective element for the two coupled ring lasers. Ring lasers are chosen because no cleaved facets are required to form laser mirrors.

The AWG also acts to isolate device inputs from outputs, and provides isolation between interconnected devices when used in a larger system. These isolation benefits, ring laser configuration, plus the stable well-controlled laser frequencies, give the device significant advantages compared to previous designs based on absorptive or dispersive bistability in laser diodes [5]. These advantages are particularly important when

Fig. 1. (a) Mask layout for two-state multiwavelength laser. (b) Operation of device showing Laser A, suppressing lasing in Laser B. (c) Diagram showing the AWG connections.

larger monolithic integrated systems comprising of multiple interconnected bistable elements are required. Furthermore, the use of two lasers and gain quenching permits optical set and reset operation [3]. Optical set and reset operation has also been recently demonstrated in devices based on absorptive bistability [6].

II. OPERATION AND DESIGN

A picture of the device waveguide and metallization mask layouts is given in Fig. 1(a); the thin black lines indicate the device waveguides. A device schematic diagram is shown in Fig. 1(b). The device is constructed from the following components: A 4×4 (4 input/4 output) AWG multiplexer [7], two semiconductor optical amplifiers (SOAs), an 80/20 splitting ratio multimode interference (MMI) coupler, and two 72/28 splitting ratio MMI couplers [8]. The couplers employed tapered access waveguides for accurate coupling ratios and low excess loss [9].

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The device consists of two coupled ring lasers, Laser A and Laser B. The laser cavity for Laser A is indicated by the solid thick black line in Fig. 1(b), and consists of SOA A, the AWG, the 80/20 coupler, and the upper 72/28 coupler. Laser light flows in both clockwise (CW) and counterclockwise (CCW) directions in the cavity. Laser B is formed with a similar cavity consisting of SOA B, the AWG, the 80/20 coupler, and the lower 72/28 coupler.

The dashed thick black line in Fig. 1(b) shows the Laser A CCW light being coupled via the 80% branch of the 80/20 coupler, into the Laser B cavity. This light passes through the gain medium of Laser B (SOA B), suppressing the gain in Laser B below threshold, and preventing Laser B from lasing [3]. This amplified Laser A light is routed via the AWG to a device output. Due to the symmetric arrangement of Laser A and B, the system has another possible state: When Laser B lases and injects light into SOA A, via the coupler 80% branch, to suppress Laser A.

To obtain bistable operation, more light needs to be coupled between the lasers than is fed back to an individual laser [4]. For the bidirectional ring lasers implemented here, only one of the CW or CCW lasing directions couples into the other laser. Thus, assuming equal lasing in both ring laser directions, a minimum interlaser coupler asymmetry of 67/33 is required for bistability [4]. Imperfections in the waveguide structures, and also spontaneous emission from the SOA not involved in lasing, can cause unequal levels of lasing light in the CW and CCW directions. To ensure correct operation in the presence of undesirable inequality in the CW and CCW light levels, a significantly more asymmetric coupler (80/20) than the minimum required was chosen. A detailed explanation of the operation of two coupled lasers as either a memory or threshold function can be found in [3] and [4].

As shown by the dotted thick black line in Fig. 1(b), the Laser A CW light leaves the device via the 28 percent branch of the 72/28 coupler. Apart from providing an extra output, the 72/28 couplers serve as wavelength-independent inputs. Light input via a 72/28 coupler into the dominant laser can suppress lasing in this laser, allowing the other laser to become dominant, thus causing a change of state [3].

The 4×4 AWG employed had a design channel spacing of 2 nm, a free spectral range (FSR) of 8 nm, and a design center wavelength of 1550 nm. The 2-nm channel spacing was chosen because previous AWG-based lasers had shown single-mode lasing with channel spacings in this range [10]. The excess loss through similar test AWGs constructed on the chip was 4 dB, and the channel crosstalk was -15 dB. The connections to the AWG are shown in Fig. 1(c). The bottom and top in Fig. 1(c) refer to the bottom and top AWG sides in Fig. 1(a) and (b). The ports highest in Fig. 1(c) are closest to the outside of the AWG; some AWG ports are not employed. Fig. 1(c) shows the path and direction light takes through the AWG, when Laser A is dominant (solid lines), or when Laser B is dominant (dashed lines). With these connections, Laser A lases at the AWG center wavelength plus 4 nm, while Laser B lases at the center wavelength plus 2 nm. The lasers can also lase at other wavelengths, one or more AWG FSRs away from their design wavelengths. The particular connection scheme of Fig. 1(c) was chosen as it provides

the correct functionality, with a minimum number of waveguide crossings in the design.

The AWG serves two functions: First, it acts as narrow bandwidth filter which sets the laser frequency, and aids single-mode lasing. Second, it routes the amplified light from the dominant laser which passes through the suppressed laser, to an output. This second function provides a form of isolation between two interacting devices, and between the device input and output, in the following way: Light from a second device impinging back on the output of the first device, cannot pass through the AWG to the source laser, unless it has the same wavelength as the light from the first device. Furthermore, light input to a device will not propagate to an output, provided the frequency of the input light is different from the device laser frequency. Such directional decision flow and isolation is a key requirement for devices employed in larger integrated digital systems [11]. Strong directional decision flow and isolation requires AWGs with low channel crosstalk [7], and an appropriate choice of operating frequencies for the interconnected devices.

III. DEVICE FABRICATION

The device was fabricated on a InP-InGaAsP epitaxial wafer, which contained bulk active areas with 1550-nm emission wavelength InGaAsP for the device SOAs. Furthermore, passive waveguides for the other device components were fabricated in 1250-nm emission wavelength InGaAsP areas. A deep/shallow double etch process was employed to construct the waveguides. Deep etching permitted small radius waveguide bends, typically 100- μ m radius, and thus, small device dimensions (2.1×0.7 mm). Details on the wafer growth and device fabrication can be found in [10].

IV. EXPERIMENTAL RESULTS

To permit measurements, the processed wafer was cleaved to expose the input-output waveguides [Fig. 1(a)]. An antireflection coating was applied to the cleaved facet, and an array of lensed fiber tips [12] permitted simultaneous access to the inputs and outputs. The coupling loss between the fiber tips and device waveguides was estimated to be in the order of 6 dB [12]. The device was mounted on a Peltier cooled copper chuck. All measurements were taken at 25 °C.

Laser A had a threshold current of 101 mA, and that of Laser B was 130 mA, for continuous wave operation. In operation Lasers A and B were biased at 145 and 191 mA, respectively, both approximately 1.5 times the threshold current. Here the device serves as a memory function, by biasing the lasers approximately equally [3], [4]. The spectra of the two stable device states are shown in Fig. 2. Laser A had a wavelength of 1555.15 nm and Laser B, 1561.2 nm. These wavelengths are consistent with the chosen AWG design and connection scheme. Laser B has a wavelength one AWG FSR minus one AWG channel spacing longer than Laser A. The AWG center wavelength 1551.2 nm, is shifted slightly from the design center wavelength of 1550 nm. The spectral full-width at half-maximum of each laser peak was less than 60 pm, limited by the spectrum analyzer resolution, indicating single longitudinal

Fig. 2. Spectra for the two device states. (a) Laser A is dominant. (b) Laser B is dominant.

Fig. 3. Switching between the two states of the multiwavelength laser. Pulses of 1 ns at the device inputs switch the device between the states. The filtered outputs of the device are shown.

mode laser operation. The contrast between the optical power at the laser wavelengths is over 35 dB in each state (Fig. 2).

Fig. 3 shows the dynamic switching between device states. One nanosecond wide pulses are sent into the input ports of the dominant laser. The device outputs are amplified, filtered, then detected by a photodiode and recorded by an oscilloscope. The power levels shown in Fig. 3 are those estimated at the chip input–output waveguides.

The power levels from the outputs and in particular Output B were somewhat low (20 μ W). We believe that this may be due to losses in the AWG or a small radius bend (40 μ m) in the output path. Power levels output from the IN A/B waveguides were considerably higher, approximately 0.6 mW.

The switching times were approximately 2 ns. The switching time consisted of the time required to turn OFF the dominant laser, time for the suppressed laser gain to recover, and time for the laser oscillation to build up again.

V. DISCUSSION AND CONCLUSION

The speed of the device was primarily limited by the large laser cavity length, 4.5 mm of InP–InGaAsP ridge waveguide.

Furthermore, the lasers were not pumped far above threshold. The relaxation oscillation frequency of the individual lasers was slightly less than 1 GHz, leading to laser light rise and fall times of between 0.5 and 1 ns (Fig. 3). The device speed could be improved by reducing the laser cavity size. Employing other device architectures and frequency selective elements [3], instead of the ring lasers and AWG presented here, may reduce device size. The device speed can also be improved by pumping further above threshold, which will increase the laser response speed. Lasers which can be pumped far above threshold are possible by reducing excess losses in the circuit, and perhaps employing more advanced gain mediums such as quantum well or dot material.

In summary, we have demonstrated an integrated two state multiwavelength laser which functions as a one-bit optical memory. An AWG was used in a novel way to provide well controlled laser frequencies and permit monolithic device integration. The AWG can also function to provide partial device isolation, and directional decision flow, important issues when multiple devices are used in monolithic integrated systems. The device serves as a step toward large scale monolithic integrated optical logic and memory devices, and will be useful in itself for further experiments in all-optical packet switching [2].

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