APPLIED PHYSICS LETTERS VOLUME 80, NUMBER 17 29 APRIL 2002

Unidirectional bistability in semiconductor waveguide ring lasers

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(Received 22 October 2001; accepted for publication 1 March 2002)

Large-diameter ridge-guided semiconductor lasers weakly coupled to a straight output waveguide show unidirectional operation and directional bistability at currents up to about twice the threshold. The direction of lasing in the ring may be controlled by biasing contacts at either end of the coupled guide. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1474619]

Bistable laser diodes may find application in photonic systems for all-optical switching, gating, and wavelength-conversion functions. Besides, electrically controlled bistabilty effects are interesting for digital signal modulation. Some monolithic semiconductor ring lasers exhibit unidirectional operation,[1–4] and unidirectional bistability in a triangular cavity laser has been recently reported.[5] We have observed similar unidirectional bistability in circular waveguide InGaAs/InGaAsP semiconductor lasers. In addition, we show that directional switching can be controlled by current injection into terminal contacts of a straight waveguide weakly coupled to the ring. This effect leads to dual-output bistable complementary spatial switching, which can be of interest for optical modulation, both electrically and optically driven.

A diagram of the lasing ring and coupled waveguide, with the positions of the various contacts made to the structure, is shown in Fig. 1. There are two 500-μm-long contacts on the coupled guide, at either end. The gap between the ring and the output waveguide is 1 μm, providing a theoretical power coupling of 10%.[6] The guide is terminated by the cleaved facets of the laser chip, and thus feedback can occur modified by the coupling loss to the ring and the bias applied to the waveguide contact. Some of the devices have been made with the cleavage plane set at 5° to the normal to the straight waveguide axis reducing the reflection to about 0.1% to 0.3%. The devices were fabricated in standard five-quantum well lattice-matched InGaAs/InGaAsP laser material emitting at 1.55 μm. The waveguide is a single-mode 2 μm wide ridge structure fabricated by CH_4/H_2 reactive ion etching. The ring diameter is 1.2 mm and the total length of the coupled waveguide is 1.6 mm.

The device which measurements are reported in the present work, was operated at continuous wave at room temperature exhibiting a current threshold of 125 mA and a corresponding threshold current density of 1.66 kA/cm^2. Figure 2 shows the light output as a function of the ring current I_R; the data were obtained by measuring the integrated photodiode current from the reverse biased output waveguides and were confirmed by external photodiode measurements. The optical outputs were simultaneously measured at port 1 and port 2 of the straight waveguide, and are a measure of the counter clockwise (CCW) and clockwise (CW) power in the ring. There are three distinct regions of operation. At and just above threshold, region I in Fig. 2, from 125 to 135 mA, both modes oscillate. From 135 to 220 mA, region II, unidirectional operation occurs, either in one direction or the other, and the laser output switches from one to the other output as the laser ring current is increased. At the nonlasing output, only spontaneous emission is observed, and the unidirectional mode extinction ratio is larger than 30 dB. Above 220 mA, region III, operation is unstable—the laser light switches from one output to the other in a random and noisy fashion.

Wavelength spectra of the CW mode in region II are shown in Fig. 3, illustrating the change in the output as the current increases and a bistable transition occurs. At 160 mA, the CW output consists of amplified spontaneous emission. At a ring current of 175 mA, the CW mode is active and a single longitudinal resonance of the ring dominates (the resonances are spaced at about 0.166 nm, corresponding to the free spectral range of the ring resonator). The unidirectional regime favors single-longitudinal mode operation more strongly than the bidirectional regime, due to cancellation of the spatial hole burning.[7] Besides this, a narrowing of the linewidth is expected, the measurement of which is under development.

The $L-I$ curves of Fig. 2 are taken with a rising laser

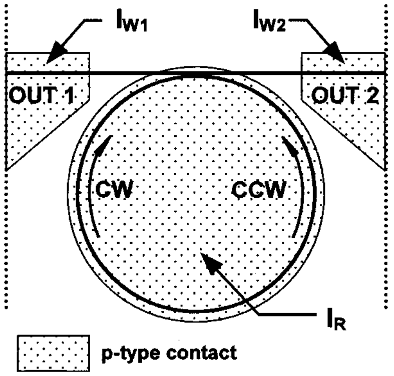

FIG. 1. Geometry of the device showing the contact layout; I_R, I_{W1}, I_{W2} indicate the current biases applied to the ring and to the two output waveguide contacts, respectively. The ring radius is 600 μm and the output waveguides are 800 μm long.

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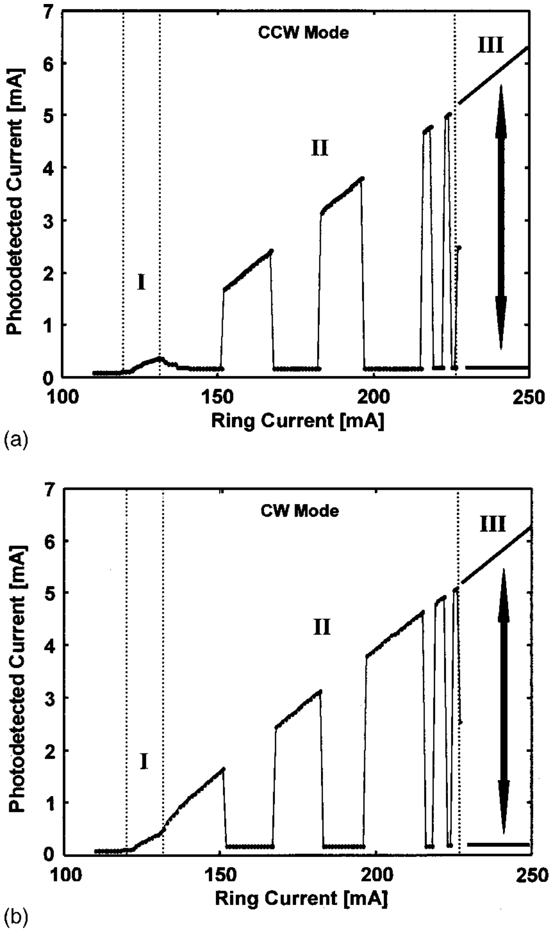

FIG. 2. Photodetected output waveguide current vs increasing ring laser current I_R for the CCW mode (a) and the CW mode (b). Three distinct regimes of operation can be identified: bidirectional (I), bistable (II), and unstable (III).

current; if the current is held constant at a particular value in region II, the output direction is stable, and if the current is reduced, the direction of rotation is maintained at that of the peak current, as illustrated in Fig. 4 for both high and low output states. Hence, in region II, the system is bistable and it exhibits memory, as it holds on to the state reached just before the ring current is decreased.

The reported bistable operation is consistent with the analysis proposed by Sargent[8] for semiconductor lasers operating near threshold in quasiequilibrium conditions. According to his theory, bidirectional continuous wave operation in semiconductor ring lasers is not likely to occur, due to spatial hole burning effects. Single-mode operation is still the most probable situation and bistable operation should be observed.

In the following, we investigate the effects on the ring lasing direction when the output waveguide contacts are forward biased. Applying forward bias to the output contacts affects laser operation and unidirectional mode selection can be achieved. Applying a current bias I_{W1} on port 1 larger than 30 mA, the amplified power fed back into the ring is sufficient to entirely suppress the CCW mode and direct the unidirectional laser output to port 2, i.e., on CW mode. This is shown in Fig. 5, which reports CW power for increasing ring current and for two different current bias values I_{w1}. The situation is not unlike the S-shaped unidirectional laser

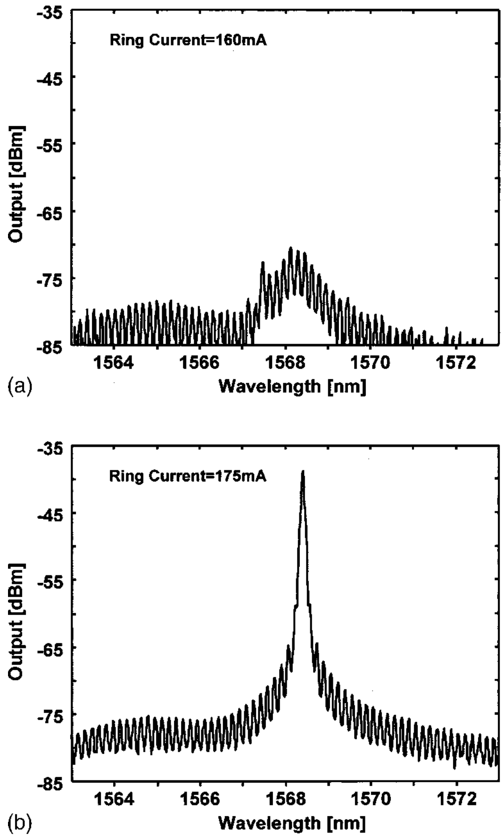

FIG. 3. Emission spectra of the CW mode for ring laser currents of 160 mA (a) and 175 mA (b), showing single-longitunal mode operation and a switching extinction ratio larger than 30 dB. The resolution of the optical spectrum analyzer is 0.1 nm.

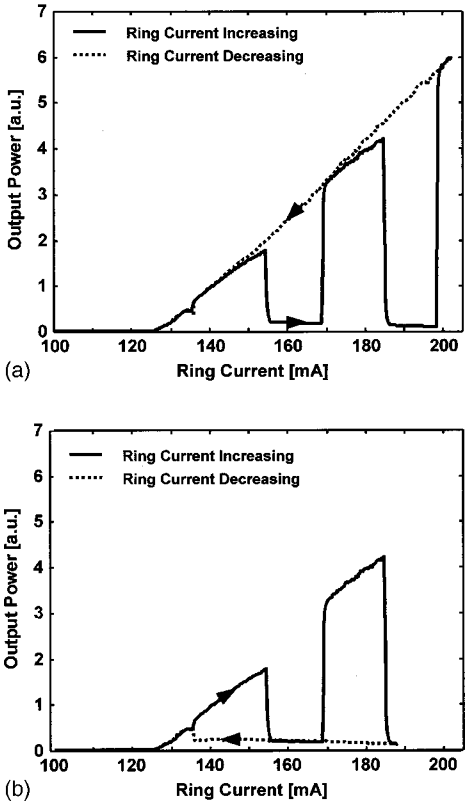

FIG. 4. Output power of the CW mode as the laser current I_R is increased and decreased. When the laser current is decreased, the ring mode direction is maintained.

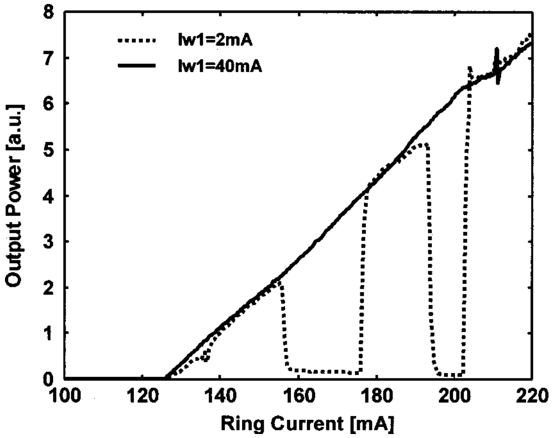

FIG. 5. CW mode output power vs increasing ring current I_R for output waveguide 1 currents (I_{w1}) of 2 mA (dashed line) and 40 mA (solid line).

of Hohimer *et al.*,[2] where crossover waveguides introduce an asymmetric coupling between the ring counterpropagating modes.

The effects of varying the bias current I_{w1} at port 1 were also investigated, and results are reported in Fig. 6. The ring laser was driven by a constant current I_R of 190 mA and the output from port 2 recorded. The laser was initially in CCW mode, so the output from port 2 was zero. When I_{w1} was increased to 7 mA, the laser switched to CW operation, and remained in that mode as I_{w1} was further increased and then reduced down to zero. This demonstrates that control of the laser direction can be performed through one of the external electrical contacts. The biased output waveguide amplifies the spontaneous emission and the reflected laser output at that port, feeding them back into the opposite direction, inducing the switch to CW operation.

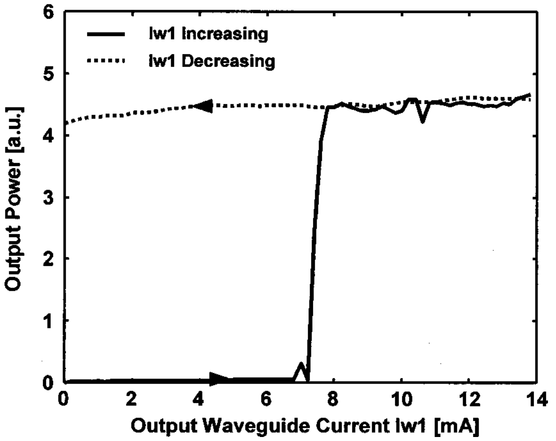

FIG. 6. CW mode output power vs output waveguide 1 current (I_{w1}). Direction switching is observed as the current I_{w1} is increased (solid line); the new direction is maintained when I_{w1} is subsequently decreased (dashed line). The laser ring is biased at a constant current I_R = 190 mA.

The bias current does not have to be applied continuously to control the oscillation direction. In fact, if the laser is operated in region II and, for example, CCW is active, then a forward current pulse applied to contact 1 will reverse the laser oscillation direction immediately and CW mode will be activated. The original direction may be restored by applying a current pulse to contact 2. This mode of operation offers effective control of the laser output direction, and also confirms that the system is bistable and does not rely on the particular phase conditions of feedback from the coupled guide to determine the direction of oscillation in the ring.

In summary, we have observed bistable operation in waveguide InGaAs/InGaAsP semiconductor ring lasers with coupled output waveguides; the biasing conditions of the output guides can set the particular direction of oscillation of the ring laser. Contacts on the output guide act as "set–reset" control inputs to the laser bistable when fed with short current pulses.

The authors would like to acknowledge the assistance given by the technical staff of the Nanoelectronics Research Center and the Dry Etching group in the Department of Electronics and Electrical Engineering at Glasgow. One of the authors (M.S.) would like to thank the European Union for the financial support of a Marie Curie fellowship under Contract No. HPMF-CT-1999-00083.

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