Rectangular Ring Lasers Based on Total Reflection Mirrors and Three Waveguide Couplers

Doo Gun Kim, Jae Hyuk Shin, Cem Ozturk, Jong Chang Yi, Youngchul Chung, and Nadir Dagli, *Fellow, IEEE*

***Abstract*—Novel rectangular ring lasers containing active and passive sections are fabricated and characterized. The rectangular laser cavity is formed using four low-loss total internal reflection (TIR) mirrors and an output coupler made out of passive three coupled waveguides. The fabrication process is exactly the same as for other active and passive devices except for one deep etch step for TIR mirror fabrication. Two different lasers having active section lengths of 250 and 350 μm and total cavity lengths of 580 and 780 μm are fabricated. For both devices, lasing thresholds of 38 mA are obtained at room temperature and under continuous-wave operation. Lasing is predominantly single-mode with a sidemode suppression ratio better than 20 dB. The power loss of a single TIR mirror is also determined to be about 0.5 dB. Such low-loss TIR mirrors enabled lasers with very small footprints.**

***Index Terms*—Rectangular ring laser, total internal reflection (TIR) mirror, three waveguide coupler, microring resonator.**

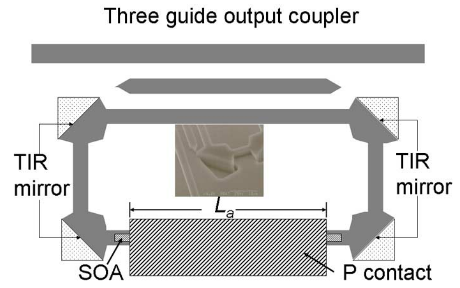

Fig. 1. Top schematic of the ring laser fabricated using four TIR mirrors, an SOA, and a three-guide coupler. The inset shows the SEM picture of the three-guide coupler, TIR mirrors with self aligned input and output waveguides.

I. INTRODUCTION

RING lasers are very desirable sources for photonic integration. They do not require cleaved facets and are easily attached to optical waveguides. They can be made very compact by folding their cavity. If unidirectional oscillation can be achieved, spatial hole burning effects seen in Fabry–Pérot and distributed feedback lasers can be avoided. Furthermore, the ring cavity offers advantages for mode-locked operation. Because of these attractive features, ring lasers have been topics for many different studies. Ring lasers with circular [1], triangular [2], square [3], and disk [4] geometries have been reported. For proper operation, the design of coupling between the ring laser cavity and output waveguide is very important. Previous output coupling schemes included laterally coupled Y junctions [1], multimode interference couplers [5], branching grooves [3], and vertical directional couplers [4]. Most of these demonstrations used the same active material for the laser cavity, output coupler, and output waveguide. For such designs, the properties of the output coupler also change as the current applied to the device changes. This difficulty can be eliminated to a large degree by making the output coupler entirely passive, which requires active–passive integration. Furthermore, for high integration densities, the area occupied by the ring cavity should also be reduced. In circular geometries, the device area is mainly determined by the radius of curvature of the cavity. However, increased radiation loss becomes an issue as radius of curvature decreases. The device area can be reduced significantly by folding the cavity using total internal reflection (TIR) mirrors.

In this letter, we report on rectangular cavity ring lasers having a folded cavity using four TIR mirrors. Active and passive materials are integrated within the folded cavity and output coupler is made out of an entirely passive three-guide coupler [6]. Coupling is done laterally and the exact same material growth–regrowth and the fabrication steps used in the fabrication of the lasers can be used in the fabrication of other devices such as semiconductor optical amplifiers (SOAs), modulators, ring resonators, and photodetectors. As a result, such lasers can be the key components for high-density photonic integrated circuits (PICs).

II. DEVICE DESCRIPTION AND FABRICATION

Fig. 1 shows the top schematic of the ring laser. It is formed using four TIR turning mirrors that fold regular straight ridge waveguides into a rectangular cavity. The ridge waveguide on one side of the rectangular cavity contains active material and forms the SOA. The rest of the device is made out of passive material. Fig. 2 shows the cross-sectional profile of the active and passive waveguides. They are 3-μm-wide ridge waveguides etched 1.8 μm deep. The core of the waveguides is a 0.35-μm-thick quaternary material with a photoluminescence peak of 1.4 μm. It is grown on 1.8-μm-thick n InP on an n+ InP substrate. On top of the core there is 1.8-μm-thick

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D. G. Kim is with the School of Electronic and Electrical Engineering, Chung-Ang University, Seoul 156-756, Korea (e-mail: emblemdo@gmail.com).

J. H. Shin and N. Dagli are with the Electrical and Computer Engineering Department, University of California, Santa Barbara, CA 93160 USA (e-mail: jhshin@engr.ucsb.edu; dagli@ece.ucsb.edu).

C. Ozturk is with Engineering and Natural Sciences, Sabanci University, Istanbul 34956, Turkey (e-mail: cemozturk@sabanciuniv.edu).

J. C. Yi is with School of Electronics and Electrical Engineering, Hong Ik University, Seoul 121-791, Korea (e-mail: wave@hongik.ac.kr).

Y. Chung is with the Department of Electronics and Communications Engineering, Kwangwoon University, Seoul 139-701, Korea (e-mail: ychung@kw.ac.kr).

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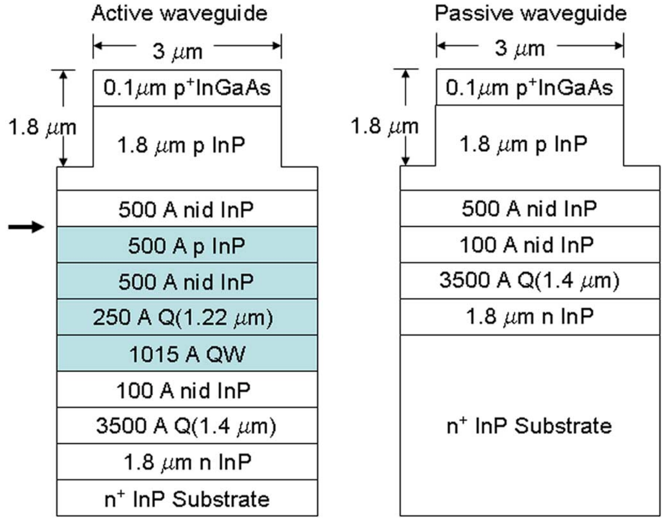

Fig. 2. Cross-sectional profile of the active and the passive waveguides used in the experiment.

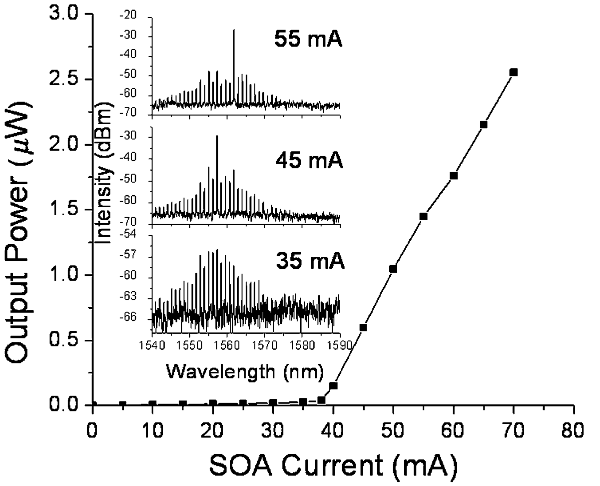

Fig. 3. Light output versus current characteristics of a ring laser diode with a total cavity length of 580 μm and SOA length of 250 μm. The inset shows the output spectrum at different bias currents.

p InP capped by a 0.1-μm-thick p+ InGaAs contact layer. The active waveguide contains a 0.1-μm-thick multiquantum-well (MQW) region on top of the core. MQW has seven wells and eight barriers [7]. The well and barrier widths are 75 and 80 A, respectively. Since TIR mirrors are used in forming the cavity, there is no need to use deeply etched curved waveguides to reduce the radiation loss. Hence, there is no excess scattering loss and no need to etch through the active material. The active waveguide is the same as a standard ridge waveguide laser structure. Furthermore, the area of the laser can be minimized by making the sides of the rectangle short. This helps to increase the integration density significantly. However, this requires low-loss mirrors to keep the round-trip loss low, which can be achieved by proper design and processing. This typically requires a self-aligned process and a vertical and smooth mirror etch. In our previous work, we demonstrated such mirrors with excess loss of about 0.7 dB per mirror [8]. These mirrors were also used in a compact ring resonator band stop filter [9]. Another design criterion is to have deterministic coupling that does not change depending on operating conditions. Since the output section is made out of passive material, a simple directional coupler could be sufficient, but, in practice, this is hard to realize due to the presence of TIR mirrors. If the waveguide inside the resonator and output waveguide are placed in closed proximity to allow coupling, the deeply etched edge of the mirror will perturb the output waveguide generating undesired reflections and significant additional loss. Alternatively, two waveguides of the directional coupler can be bent in and out of the resonator using TIR mirrors, but it is very difficult to place two good mirrors on two waveguides in very close proximity without significant additional loss. This additional loss can be reduced by increasing the gap of the coupler, but coupling reduces significantly. We found a compromise solution using three coupled waveguides as shown in Fig. 1. This approach separates the resonator and output waveguides significantly, hence, the mirror edge is not a problem. However, coupling between three waveguides is still less than the coupling in a directional coupler of the same waveguide width, gap, and length. In this design, the price paid is the loss of the power remaining in the middle waveguide and low output coupling. We tapered the ends of the middle waveguide to reduce back reflections and help the radiation of the light at the end of this waveguide into substrate. In our design, we kept the gap between the waveguides 1.5 μm due to practical considerations. Since the entire coupler is passive, its transmission T and output coupling C can be analyzed accurately. Beam propagation method simulations yield $T_1(L_{a1} = 250\ \mu\text{m}) = 0.82$, $C_1(L_{a1} = 250\ \mu\text{m}) = 0.01$, $T_2(L_{a2} = 350\ \mu\text{m}) = 0.68$, and $C_2(L_{a2} = 350\ \mu\text{m}) = 0.03$. Even though 17% (0.8 dB) and 29% (1.48 dB) of the power out of the cavity is lost for 250- and 350-μm-long couplers, simulations indicate that loss of this arrangement is less than the loss obtained using two mirrors and a directional coupler for the same level of output coupling due to reasons outlined earlier.

The details of the fabrication are reported in [8] and [9]. The scanning electron microscope (SEM) picture of a corner of the device showing three-guide coupler and two self-aligned mirrors is shown in Fig. 1. The sidewalls of etched mirrors show excellent uniformity and smoothness.

III. RESULTS AND DISCUSSION

Fig. 3 shows the current versus light output of a ring laser diode under continuous-wave (CW) operation for a total cavity length of 580 μm and for an SOA length of 250 μm. The output waveguides are terminated with cleaved facets. The lasing threshold current at 20 °C is around 38 mA. The output spectrum at different bias currents is also shown in the inset of Fig. 3. The adjacent peaks are due to resonator modes and their separation is about 1.12 nm. This agrees well with the free-spectral range (FSR) of the resonator calculated using $\Delta\lambda = \lambda^2/(nL)$, with $\lambda = 1.55\ \mu\text{m}, L = 580\ \mu\text{m}$, and $n = 3.7$. The sidemode suppression ratio (SMSR) is 21 dB at 1.3 times threshold. Fig. 4 shows the CW current versus light output for another ring laser diode for a total cavity length of 780 μm and an active waveguide length of 350 μm. In this case, the lasing threshold current at 20 °C is again around 38 mA.

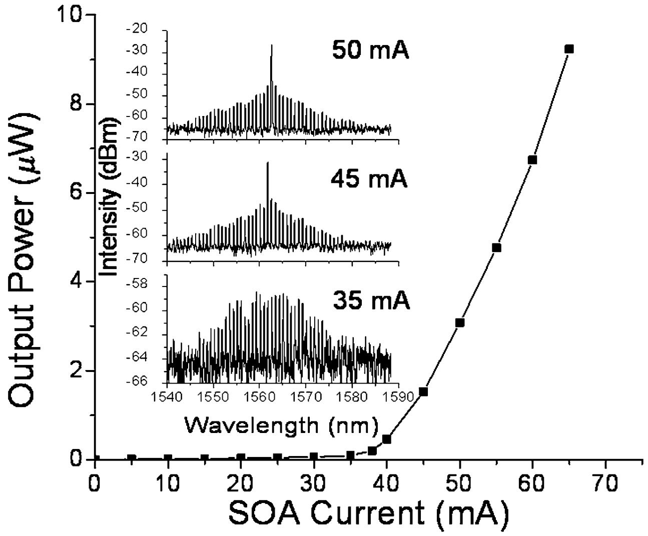

Fig. 4. Light output versus current characteristics of a ring laser diode with a total cavity length of 780 μm and SOA length of 350 μm. The inset shows the output spectrum at different bias currents.

The output spectrum at different bias currents is also shown in the inset of this figure. The separation between adjacent peaks is about 0.847 nm which agrees well with the FSR of the resonator calculated using the above formula and values except for $L = 780$ μm. The SMSR is 23 dB at 1.8 times threshold. In both cases below threshold, the spectrum envelop is very similar to the spectral shape of the SOA spontaneous emission and the resonances are dominated by the resonances of the cavity. Hence, we get filtered spontaneous emission. This shows that other effects due to facets and the power left in the middle waveguide of the output coupler are negligible. Above threshold, a lasing mode near the gain peak of the SOA is observed. In both cases, the low output power is due to low output coupling. In the experiment, the laser was integrated with an external SOA sharing the same output waveguide. There was another laser with the same layout and dimensions on the other side of this SOA. Due to the presence of this SOA, the lasing output of a single laser in both directions could not be measured. But the lasers on both sides of the SOA had the same characteristics even though their outputs were due to lasing in opposite directions. This suggests that the lasing is bidirectional.

There is a slight change in the threshold current when the active waveguide length and total cavity length are increased. In such a laser, the threshold current can be expressed as

$$I_{\text{th}} = K_0 + K_1\left[\alpha_a + \alpha_p\frac{L_p}{L_a} + \frac{1}{2L_a}\ln\left(\frac{1}{TR^4}\right)\right]$$

where K_0 and K_1 are constants related to the material, α_a and α_p are the loss coefficient of active and passive sections of length L_a and L_p, respectively. T is the power transmission coefficient of the three-guide coupler and R is the power reflection coefficient of a single TIR mirror. Increased active waveguide length reduces the effective loss coefficient of the TIR mirrors and increases the optical gain. But increased cavity length increases the loss of the passive waveguide sections and makes the coupler longer. Increased coupling length decreases the transmission through the three-guide coupler and round-trip cavity loss increases. In general, all the parameters in this equation can be determined if there are many different L_a values, which is not the case in the present experiment. However, the difference between the threshold currents of both devices is very small, i.e., $I_{\text{th}1} - I_{\text{th}2} \approx 0$. Furthermore, α_p is less than 10 cm^{-1} and $\alpha_p(L_{p1}/L_{a1} - L_{p2}/L_{a2}) < 1$ cm^{-1}, i.e., very small. Hence, to a very good approximation $1/L_{a1}\ln(1/T_1R^4) \approx 1/L_{a2}\ln(1/T_2R^4)$. Using previously given T_1 and T_2 values, we obtain $0.92 \leq R \leq 1$ or mirror loss less than 0.5 dB. This value agrees very well with other independent measurements of R using either direct measurements [8] or a resonator using TIR mirrors [9]. This analysis also shows that low-loss TIR mirrors are possible.

IV. CONCLUSION

We have fabricated and characterized novel rectangular ring lasers containing active and passive sections. The output coupler was made out of passive three coupled waveguides and the rectangular cavity was formed using four low-loss TIR mirrors. Two types of lasers with active section lengths of 250 and 350 μm were fabricated. The total cavity lengths of these lasers were 580 and 780 μm, respectively. Lasing thresholds for both types were 38 mA at room temperature, and under CW operation and lasing spectra were predominantly single-mode with SMSR better than 20 dB. The power loss of a single TIR mirror was found to be about 0.5 dB. Such low-loss TIR mirrors enabled lasers with very small footprint. The fabrication technology and process used were exactly the same as for other active and passive devices except for one deep etch step for TIR mirror fabrication. As such, it enables a platform for compact PIC.

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