Directional Light Output from Photonic-Wire Microcavity Semiconductor Lasers

J. P. Zhang, D. Y. Chu, S. L. Wu, W. G. Bi, R. C. Tiberio, C. W. Tu, and S. T. Ho

***Abstract*— We have obtained directional light output from a recently realized InGaAsP photonic-wire microcavity ring lasers. The output was achieved by fabricating a 0.45-μm-wide U-shape waveguide next to a 10-μm diameter microcavity ring laser. The laser has a threshold pump power of around 124 μW when optically pumped at 514 nm. It is comparable to the former structure without output coupling. The output coupling efficiency can be controlled carefully by choosing the spacing between the laser cavity and the waveguide.**

I. INTRODUCTION

RECENTLY, we have achieved lasing in a microring resonator with a photonic-wire structure [1], which we referred to as a photonic-wire ring laser. Photonic-wire structures are strongly-guided one-dimensional waveguides with tightly confined mode area. The photonic-wire ring laser realized (with a 4.50-μm diameter ring) has a very small cavity mode volume of 0.27 μm^3, and a low lasing threshold of 95 μW when optically pumped at 514 nm. As discussed in our previous work [1], the low lasing threshold and small cavity volume of the photonic-wire lasers can be understood as follows. In a photonic-wire structure, the photonic density of states is strongly modified, which enables the lasing mode to capture a large percentage (about 35%) of the spontaneous emissions in the structure [2]. The fraction of spontaneous emission captured by the lasing mode is called the spontaneous emission coupling factor β. Since spontaneous emission and stimulated emission are related, a large β value also means a high gain for the lasing mode in the cavity. The large β value makes it possible to achieve lasing in a small cavity and to attain low lasing threshold. Besides low-lasing threshold, other laser properties including the population inversion, modulation rates, and carrier dynamics such as their decay rates and response times, are also strongly modified in the photonic-wire structures.

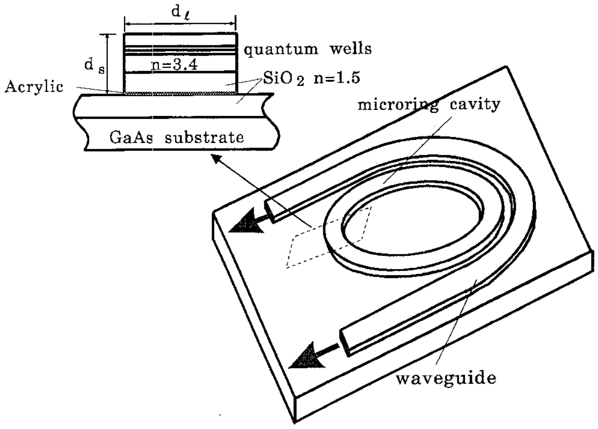

Fig. 1. Schematic diagram of InGaAs–InGaAsP microring semiconductor laser. The MQW microring is half surrounded by a U-shape waveguide, which couples lasing light out from the ring cavity.

In our first demonstration of photonic-wire laser, the laser structure is a circular ring cavity without directional output for the lasing light [1]. In order for these lasers to be useful for applications, it is necessary to obtain directional light output. In this letter, we demonstrate a structure to obtain directional output from our photonic-wire lasers effectively. The structure involves coupling the light in the tiny cavity to an adjacent waveguide through resonant waveguide coupling.

II. LASER STRUCTURES

Fig. 1 shows a schematic diagram of the waveguide-coupled photonic-wire laser. The diameter of the ring cavity is 10 μm. As described in our previous work, the ring cavity is a 0.45 μm × 0.19 μm (width × height) strongly guided semiconductor waveguide, which is made up of InGaAsP material with refractive index of $n = 3.3$. The waveguide is surrounded above and below by air ($n = 1$) and SiO$_2$ ($n = 1.5$), respectively, which gives a large refractive index difference between the guiding region and the cladding region. The large refractive index difference results in tightly confined waveguide modes, and leads to a large amount of spontaneous emission to be channeled into the lasing mode [2].

As shown in Fig. 1, the microring cavity is half surrounded by a U-shape waveguide. The U-shape waveguide has the same waveguide width as the waveguide that forms the ring cavity.

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This allows photons in the ring cavity to escape to the U-shape waveguide via resonant photon tunneling. The percentage of photon escaping from the ring cavity to the U-shape waveguide per photon round trip in the cavity is called the output coupling efficiency. This output efficiency is dependent on the width of the gap between the ring cavity and the U-shape waveguide as well as the perimeter of the ring. For example, in the case of a 10-μm diameter ring cavity, a coupling efficiency of 0.4% can be achieved with a 0.6-μm gap width. In our experimental realization, we have fabricated structures with various gap width ranging from 0.3 μm to 1 μm. As described in our previous work, these microring resonators have a quality factor (Q value) of a few hundreds. For example, with $Q = 300$, the energy loss per round trip will be around 2%. The output coupling efficiency is designed to be less than 1% so as not to drastically affect the Q value of the cavity.

III. EXPERIMENTS

The layered InGaAs–InGaAsP waveguide structure used in our experiments is grown by molecular beam epitaxy (MBE). A 0.2-μm InP buffer layer is first grown on top of a semi-insulating (100) InP substrate, followed by the waveguide layer. Within the waveguide layer, three (100 Å) $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}$ quantum wells are separated by (100 Å) $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}_y\mathrm{P}_{1-y}$ barrier layers. They are sandwiched by two 0.07-μm $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}_y\mathrm{P}_{1-y}$ layers. The total thickness of the waveguide layer is 0.19 μm [1].

Etching of the structure is done by nanofabrication techniques involving electron-beam (E-beam) lithography, reactive ion etching (RIE), plasma-enhanced chemical vapor deposition (PECVD) and bonding-etching techniques [1]. PMMA is spun on the top of 800-Å $\mathrm{SiO_2}$ to act as an electron beam resist. The laser patterns are then written on the PMMA with JEOL JBX 5DII e-beam writer. Subsequently RIE is used to transfer the patterns down to the $\mathrm{SiO_2}$ film, and the PMMA is then removed. RIE technique is then used again to etch pattern down vertically into the InP substrate. To place the thin ring cavity and waveguide-coupling structures on a low-refractive-index material, the substrate is removed via the following techniques. The RIE etched chip is deposited with 0.7-μm-thick $\mathrm{SiO_2}$ after the second RIE step. A piece of GaAs substrate covered with 0.75-μm-thick $\mathrm{SiO_2}$ is then prepared using PECVD. The two samples are $\mathrm{SiO_2}$ face-to-face bonded together with acrylic. Finally, highly selective etchant is used to remove the InP substrate. Fig. 2 show the scanning electron microscope (SEM) images of a waveguide-coupled 10-μm diameter micro-ring laser. Note that a disk-shape structure is left behind at the center of the ring. This is done to reduce e-beam writing area, because large e-beam writing area can increase the roughness on the ring's side walls (due to the accumulation of many Gaussian beam tails from the e-beam). Note that we are careful to introduce slots in the center disk to prevent lasing in the center disk.

The experimental set up is similar to the one we used before [3]. The waveguide-coupled micro-cavity lasers are cooled down to 85 K in a vacuum chamber. The micro-cavity lasers are pumped with a 514-nm argon-ion laser. The pump light is modulated by an acousto-optic modulator with 100:1 duty cycle and focused to a spot size covering the whole ring laser cavity. The scattered light from the laser structure is collected by an objective lens. The emission spectrum is detected and measured with a spectrometer, a liquid-nitrogen-cooled germanium detector, and a lock-in amplifier.

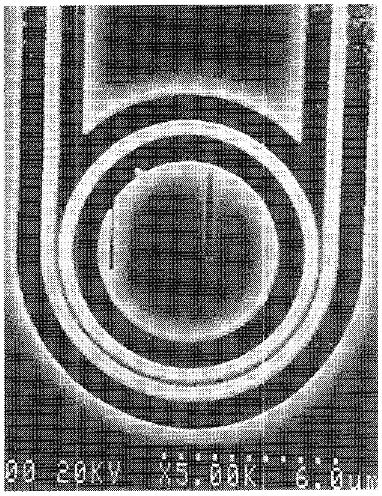

Fig. 2. Scanning electron microscope (SEM) image of a waveguide coupled photonic-wire ring laser fabricated with a 10-μm ring diameter.

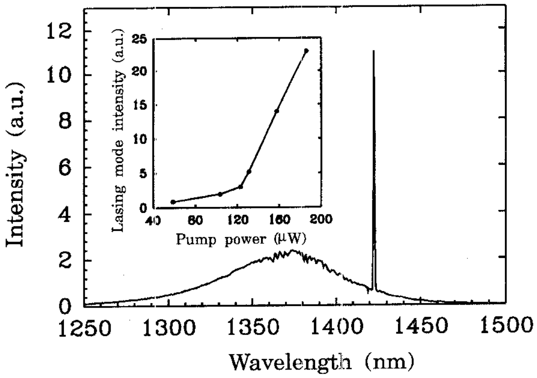

Fig. 3. Emission spectra of a 10-μm diameter photonic-wire ring laser with 0.45-μm ring width at 85 K. The curve is for the case where the pump power is about 1.5 times above the threshold. The spectrumeter's resolution was set to 1 nm. The inset is the intensity versus pump power at the lasing wavelength. The threshold pump power is 124 μW.

Fig. 3 shows the lasing spectrum of a waveguide-coupled micro-ring laser with 10-μm diameter and 0.45-μm ring width at 1.5 times above the lasing threshold. The figure inset shows the light intensity versus pump power at the lasing wavelength of 1422 nm. Under high-pump power condition, we observed multimode operation. One of the lasing modes is near the center of the spontaneous emission center. Imperfect quantum well fabrication probably results in the lasing mode being away from the spontaneous emission peak. The typical threshold pump power is 124 μW for the 10-μm micro-ring lasers with 0.45-μm ring width. The 124 μW is the power estimated to be absorbed by the ring structure at threshold. The output-coupling waveguide absorbs light to make it transparent. However, the coupling coefficient is designed to be less than

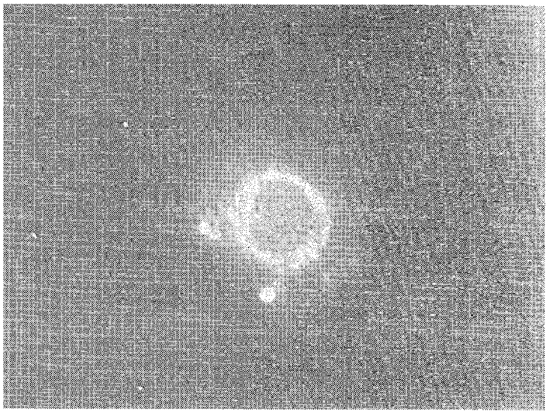

Fig. 4. The infrared image of a photonic-wire ring laser at 1.5 threshold pump power. We cand see a faint ring pattern and two bright emitting spots at the ends of the U-shape waveguide.

1%. The effects of output-coupling waveguide is minimal. The lasing characteristics of the photonic-wire ring lasers with and without U-shape waveguide are found to have similar threshold pump power. This shows that the coupling to the output U-shape waveguide has minimal effects on lasing in the microring resonator. We also double checked that the lasing light was not from the center disk by refocusing the pump beam only on the center disk. In that case lasing ceased.

Output light at the ends of the U-shape waveguide is imaged using an infrared camera as shown in Fig. 4 at 1.5 threshold pump power. A silicon filter is used in front of the camera to block the 514-nm pump light so as to make sure that the image observed is actually the lasing light and not the pump. The two bright spots in Fig. 4 are light scattered from the two ends of the U-shape waveguide. We can see a faint ring pattern that is formed by the laser light scattered out of the ring cavity due to the roughness on the cavity's side walls. At just below lasing threshold we could still see a very faint ring pattern but we could not see any bright spots at the end of the U-shape waveguide, which re-affirms that the two bright spots are from the lasing light.

IV. CONCLUSION

We have realized an output-coupling structure for an InGaAsP photonic-wire microcavity ring laser with a 10 μm diameter. Using such a structure lasing light is coupled out while the laser resonator maintains a high-cavity Q value. This enables the lasers to maintain low lasing threshold. The coupling of the laser light into a waveguide makes it potentially possible to integrate the ring laser with other devices, such as modulator, detector, and couplers.

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