Double-disk structure for output coupling in microdisk lasers

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We report our experiment on the use of a double-disk structure to couple light output from a microdisk laser which allows us to maintain a high Q value of the microdisk resonator. The small photon leakage rate from the lower lasing disk to the top waveguiding disk can be carefully controlled by choosing the distance between the two disks. Various structures can be fabricated on the top disk to couple the light out. In this letter, a simple opening in the top disk is used for output coupling. © *1994 American Institute of Physics.*

The whispering-gallery-mode microdisk lasers based on different material systems have been demonstrated at liquid nitrogen and room temperatures.[1–5] In these lasers, the optical mode is strongly confined in the direction perpendicular to the thin disk. This enables most of the spontaneous emission to couple into the lasing mode, which is the lowest-order transverse electric (TE) mode.[6] Thus, the spontaneous emission factor β of the microdisk lasers, defined as the spontaneous emission rate into the lasing mode divided by the total spontaneous emission rate,[7] can be close to the theoretical maximum value of unity.[8] It turns out that the lasing threshold of a laser is determined by a sum of two factors. One factor is the transparency pumping rate of the gain medium. Another factor is the cavity factor with a value proportional to β. In the case where one has a laser gain medium with a low transparency pumping rate, the cavity factor will dominate. In that case cavities with high β values such as the microdisk structure can be used to realize lasers with low lasing threshold.[9] For example, because of their high cavity β values, the semiconductor microdisk lasers fabricated recently have threshold power in the range of microwatts limited mainly by the transparency pumping rate of the quantum wells in the microdisks.

Although these microdisk lasers can be made to lase, there is no directional coupling of light out from these lasers. In fact the photons are strongly confined inside the disk structure. For useful applications, a directional coupling of light out is necessary. Recently Levi *et al.* demonstrated that by introducing an asymmetric point in the circular microdisk structure, it is possible to enable an increased amount of light to leak out from the point of asymmetry.[10] It has also been suggested that grating may be fabricated on the disk to couple the light out. Although in principle, it is possible to fabricate various structures directly on the disk to couple light out, in practice because of the small size of the microdisk, it is not easy to control the deteriorating effect of the output coupling structures on the Q value of the cavity. Such a deteriorating effect is particularly bad for microdisk structures because of their high Q values (around 100–1000). In this letter, we explore a method that will allow us to fabricate various output coupling structures without the worry of affecting the high Q value of the cavity. The method makes use of a double-disk structure.

A regular microdisk laser has a disk with a multiple quantum well (MQW) which is suspended in air via a pedestal on the substrate. The double-disk structure, as shown in Fig. 1, has a second disk on top of the MQW microdisk with the same diameter supported by another pedestal between the two disks. The top disk is basically a passive material for guiding purpose. The photons generated in the MQW microdisk slowly leak out into the top guiding disk via resonant waveguide coupling. The coupling efficiency between the MQW microdisk and the top disk can be carefully controlled by choosing the distance of separation between the two disks. The larger the separation between the disks, the less the coupling efficiency. Figure 2 shows an estimate of the coupling percentage per roundtrip length versus the coupling length for a 0.65 μm separation between two disks.[11] The coupling length is the roundtrip length of the photons propagating around the circumference of the disk, given approximately by πD, where D is the disk diameter. As can be seen from Fig. 2, about 0.1%–1% coupling efficiency was estimated for a disk diameter ranging from 5 to 20 μm. This double-disk method enables the MQW disk resonator to maintain a perfect disk shape with high Q value, while various structures can be placed on the top disk to couple the light out. In our initial experiment, we made an opening on

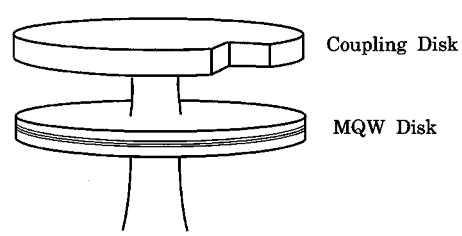

FIG. 1. Schematic of the double-disk structure of the InGaAs/InGaAsP microdisk laser in our experiments. The top disk, basically a passive guiding disk, receives lasing light from the bottom MQW disk structure through resonant waveguide coupling. The opening on the top guiding disk provides a leaking source and directs the lasing light out from the double-disk structure.

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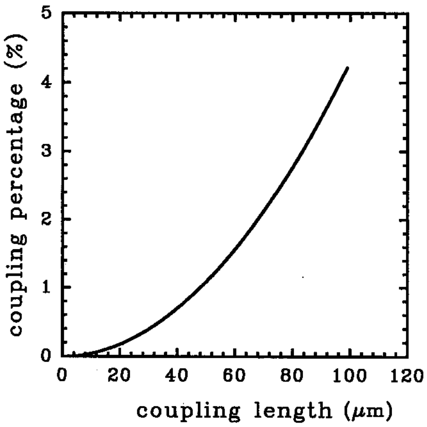

FIG. 2. The calculated coupling efficiency per roundtrip length of a two-disk structure vs the coupling length, which is approximately the circumference of the disk structure. The separation between the two disks is assumed to be 0.65 μm.

the top guiding disk (as shown in Fig. 1) to direct the light out from the double-disk structure.

The layer structure of the double-disk microdisk laser used in our experiment was grown by molecular beam epitaxy with the InGaAs/InGaAsP material system. First, an $In_{0.84}Ga_{0.16}As_{0.33}P_{0.67}$ etch stop layer was grown on the top of the semi-insulating (100) InP substrate, then, a 1.0-μm-thick InP pedestal layer followed by a 0.2-μm-thick MQW disk layer was grown. Inside the MQW disk layer, three $In_{0.53}Ga_{0.47}As$ quantum wells (~100 Å) were sandwiched by $In_{0.84}Ga_{0.16}As_{0.33}P_{0.67}$ barrier layers (~100 Å) with end caps (~700 Å) on both sides. A second InP pedestal layer with 0.65 μm in thickness was grown on the MQW layer, which is followed by a 0.2-μm-thick $In_{0.84}Ga_{0.16}As_{0.33}P_{0.67}$ passive layer as the top guiding disk.

Multistep photolithographic techniques were used to fabricate the double-disk lasers with 3 and 10 μm in diameter. The openings were patterned first using an AZ-1350J photoresist and etched down around 0.4 μm using reactive ion etching without etching the MQW disk layer. After removing the photoresist the circular disks were patterned and carefully aligned with the openings. Then reactive ion etching was used again to etch the circular patterns down vertically (~1.2 μm) into the bottom pedestal layer to form the cylinders. In both reactive ion etching steps we used a gas mixture of methane, hydrogen, and argon with a ratio of 5:17:8. A highly selective HCl etchant was then used to clear the remaining pedestal layers horizontally to form two supporting pillars. Figures 3(a) and 3(b) show the images of a 10-μm-diam double-disk microdisk laser taken from a scanning electron microscope. The InP pillar is rhombus shaped because of the anisotropic etch.

The lasing characteristics of the double-disk microdisk lasers were analyzed by optical excitation using a Nd:YAG laser at 1064 nm. The pump laser was modulated by an acousto-optic modulator with a varying duty cycle and focused to a spot size covering the entire area of the microdisk laser. The microdisk samples were cooled down to liquid nitrogen temperature. The emission from the microdisk laser

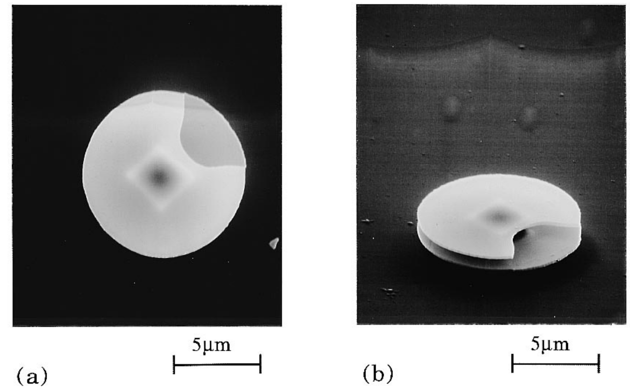

FIG. 3. Scanning electron microscope images of a fabricated double-disk microdisk laser with 10 μm in diameter. (a) top view; (b) side view.

was collected by an objective lens dispersed by an optical grating spectrometer and detected using a lock-in technique and a liquid-nitrogen cooled germanium detector.

Figure 4 shows the lasing spectra obtained from a double-disk microdisk laser with 10 μm in diameter at and above threshold. The threshold is where the peak pump laser power is approximately 500 μW with a 1 μs pulse width and 1% duty cycle to reduce the heating. In our experiment, a 10-μm-diam double-disk microdisk laser without any opening on the top disk was also fabricated for comparison. Due to the lower loss on the top disk, the double-disk laser without opening has a lower threshold (~300 μW). This is also the typical threshold value for a single-disk microdisk laser with the same material composition and diameter as the bottom disk. The lasing threshold of a 3-μm-diam double-disk microdisk laser is about 25 μW, which is almost the same as that of a single-disk microdisk laser with the same diameter. It shows that the double-disk laser remains a high Q cavity without deteriorating the lasing threshold.

The directional lasing output from the opening of the top

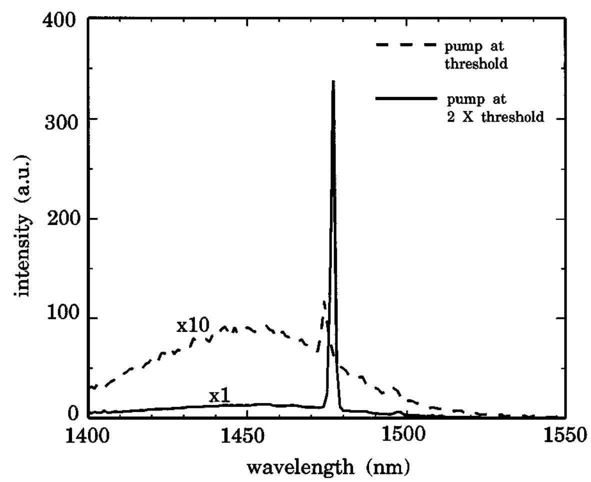

FIG. 4. Measured spectra of the 10-μm-diam double-disk microdisk at 85 K. Excitation is by a Nd:YAG laser at the wavelength of 1064 nm. The solid curve is for the case where the pump power is above threshold and the dashed curve is for the case where the pump power is at threshold. The resolution of the spectrometer is 1 nm.

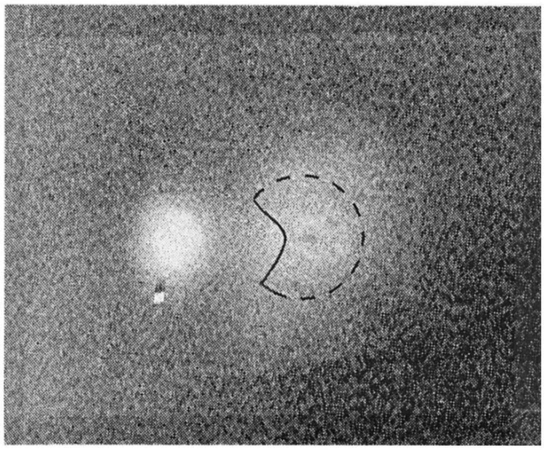

FIG. 5. An edge-emitting lasing output from the opening of a 10 μm top disk at the wavelength of 1.5 μm. The location of the microdisk laser and its top opening were retraced using a dashed line. The bright dot on the image is due to a burned spot on the infrared imaging tube.

disk of a double-disk laser can be imaged using an infrared imaging tube. The image is shown in Fig. 5. In the figure, we can see the lasing light scattered from the disk itself as well as a strong edge-emitting spot from light escaping the opening and hitting the substrate at around 10 μm away from the opening. This image was taken at a pumping power two times above threshold. In order to obtain the image, the pump laser had to be strongly attenuated with filters before the infrared camera. Due to the focusing difference between the output spot on the substrate and the disk itself, we have to refocus to see the opening on the disk and retrace the top view of the double-disk structure using a dashed line in Fig. 5. The figure clearly shows that the opening on the top guiding disk provides a leaking source of the lasing photons and directs the lasing light out from the double-disk laser.

In summary, we have demonstrated using a notch on the top guiding disk of a double-disk structure to couple the lasing light out horizontally from the top disk, while the bottom lasing disk maintains a high cavity Q value. For useful applications, such as optoelectronic interconnects, a vertical-emitting structure is desirable. Based on our double-disk design, we are currently pursuing various methods capable of achieving vertical coupling, including the use of grating or opening with 45° edge on the top guiding disk. Further research would be needed to incorporate a p-n junction structure to realize injection current pumping.

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