Directional light coupling from microdisk lasers

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We describe methods for directional coupling of light output from whispering-gallery mode microdisk lasers. Patterned asymmetries in the shape of microdisk resonators provide control of both direction and intensity of light output without dramatically increasing laser thresholds.

Recently we have investigated the possibility of fabricating optically active microstructures which may potentially be of use in future photonic or optoelectronic circuits. As a first step in this direction we demonstrated the concept of a whispering-gallery mode microdisk laser.[1,2]

The device makes use of optical modes at the edge of a thin semiconductor dielectric disk which is 2–10 μm in diameter and suspended in air or low refractive index material such as SiO_2. Optical gain is provided by one or more optically or electrically pumped InGaAs quantum wells in the plane of the disk. The disk thicknesses are approximately $\lambda/4n_{\rm eff}=0.15$ μm for a wavelength $\lambda=1.5$ μm. The effective[1] disk index of refraction corresponding to this thickness is $n_{\rm eff}=2.55$. The high index contrast ratio between the disk and its surroundings is a key feature since it strongly confines active optical modes to the plane of the disk thereby ensuring large modal overlap with the quantum well gain region. The high index contrast ratios also enhance the Q value and mode selectivity of the microcavity. Our initial experiments[1] and all of the results described here use optical pumping at liquid nitrogen temperatures to achieve lasing. However, we have also recently demonstrated lasing action in similar microdisk structures using electrical pumping at room temperature.[2]

An ideal microdisk laser of the type described above emits radiation in a radially symmetric pattern which is confined to a small range of angles centered on the plane of the disk. However, to be of practical use, we believe that it is necessary to control both the direction and intensity of light output both in the disk's plane and in the vertical direction perpendicular to the disk plane. The purpose of this letter is to report results of our initial experiments aimed at achieving this goal. For larger semiconductor whispering-gallery mode lasers with diameters in the 100 μm range, Y-couplers[3,4] or cleaved faces[5] can be used as output couplers. For the microdisk case these more traditional couplers cannot be fabricated at present.

First consider the high quality microdisks that we have fabricated using photolithography and selective etching techniques.[1,2] These disks are very nearly circular but do exhibit some edge roughness in the form of variations in radius as large as 0.1 μm with a scale length around the disk of $\sim$0.2 μm. A second major deviation from circular symmetry is the nearly square InP support post that can act as an effective grating scattering light out of whispering-gallery modes. This post can also introduce coupling between the whispering-gallery mode nearest the edge and lower order modes that penetrate further into the interior of the disk. It also damps the lower order modes that overlap the post region. It is convenient to parameterize the degree of damping in a given mode by its quality factor[6] Q.

The Q values for our microdisks with absorbing InGaAs quantum wells are typically between 100 and 750 as measured from the shape of the low power InGaAs photoluminescence spectrum near a microcavity resonance. As may be seen in Fig. 1, $Q=\lambda/\Delta\lambda\simeq 1.5$ μm/10 nm$\simeq$150, corresponding to a cavity finesse of $F=$FSR/$\Delta\lambda\simeq 10$ where the free spectral range is FSR$\simeq$100 nm for a 2.2 μm diam disk. These data are taken with optical excitation power as low as a factor of 25 below the laser threshold. In this regime we expect the Q value to be representative of that for the passive disk resonator, limited by both the quantum well absorption and losses from the optical cavity. In the absence of absorption and losses, ideal radiation from the whispering-gallery mode at the disk edge is estimated to limit the passive Q to approximately

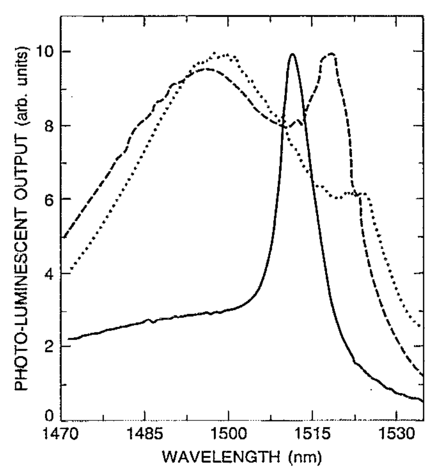


FIG. 1. Measured photoluminescence spectrum of a 2.2 μm diam microdisk on a substrate cooled to liquid nitrogen temperatures. Excitation is by $\lambda=638$ nm HeNe radiation at total incident power levels of 4 μW (dotted curve), 30 μW (dashed with vertical scale divided by 12) and 75 μW (solid with vertical scale divided by 65). Only a fraction of the incident power, probably near 0.5, strikes the disk. The bump evident in the dotted data at 1.52 μm is an enhancement of the photoluminescence due to whispering-gallery modes at the edge of the disk. This bump remains at nearly constant width ($\Delta\lambda=10$ nm) and intensity relative to the photoluminescent background at excitation powers below 10 μW. The spectrometer resolution is 1 nm. All of the spectra shown here are obtained below the 100 μW pump power threshold for this laser. All laser thresholds are obtained by a linear extrapolation from the light output as a function of pump power in the range from 200 μW to 1 mW. A major portion of the broad luminescence peak originates from the central region of the disk over the InP supporting post where any mode structure is expected to be strongly damped.

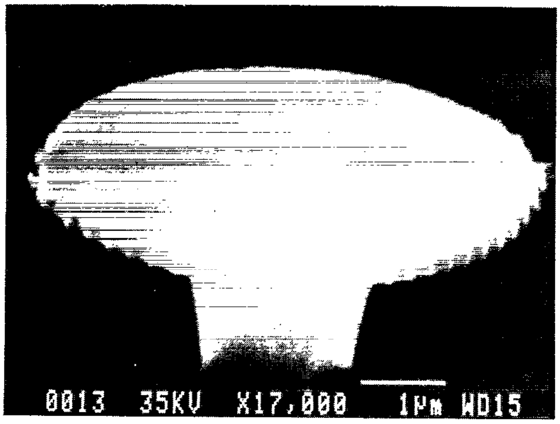
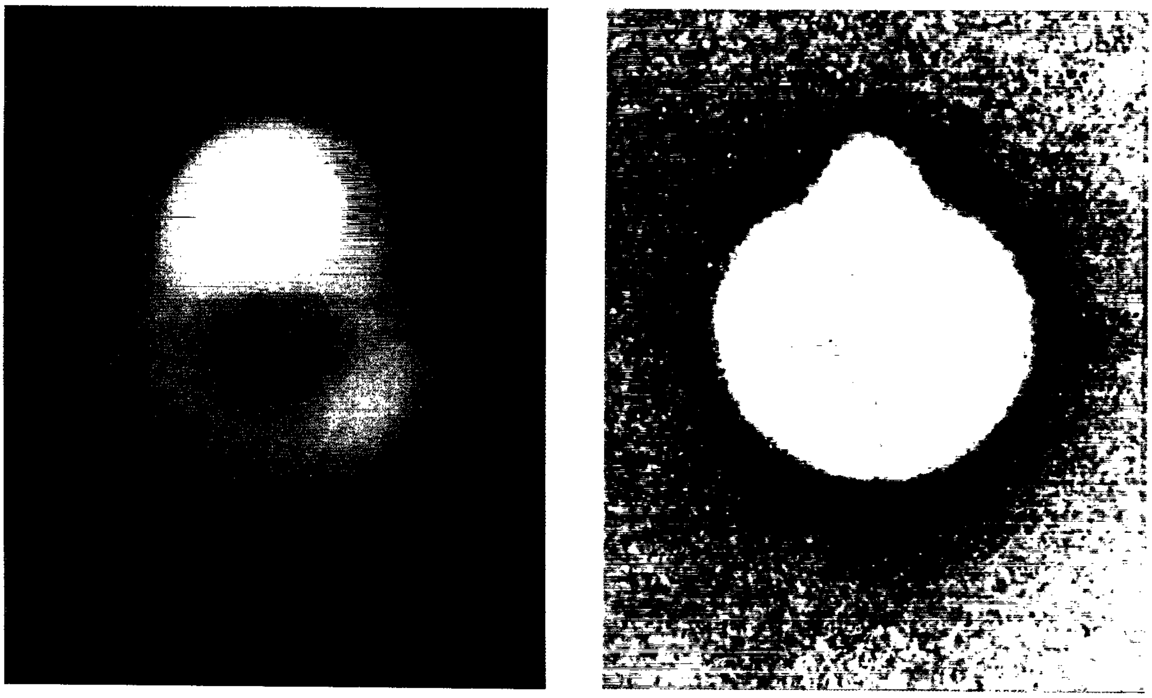


FIG. 2. Scanning electron microscope picture of a microdisk with an *e*-beam patterned grating at the edge.

24 000 for a 2.2 μm diam disk 0.15 μm thick. For data shown in Fig. 1 an absorption constant of 10^3 cm^{-1} at $\lambda = 1.52$ μm is required to reduce the mode's Q from the zero absorption estimate of 24 000 to the measured value of 150. This is consistent with an estimate of the absorption constant at the spectral position of the lasing mode (well to the long wavelength side of the absorption peak) for the six InGaAs quantum wells in this disk and a mode/quantum-well overlap factor of approximately 0.3. Ideally, the whispering-gallery mode Q varies exponentially with the radius. However, even at small disk diameters near 2 μm, asymmetries or imperfections can limit the Q values and probably contribute to the degraded Q measured from the data in Fig. 1. Scattering due to imperfections at the disk edge is not as strong as one might first think because the whispering-gallery optical mode intensity peaks approximately 0.2 μm in from the edge.

Patterned asymmetries can provide control of the direction and intensity of optical output from the disk without dramatically decreasing Q or increasing the lasing threshold. An obvious patterned output coupler is simply a grating around the circumference of the disk as shown in Fig. 2. This linear grating was produced by raster-scan electron-beam lithography and has a modulation depth of approximately 100 nm, approximately a quarter wavelength in the material. Naturally, the period of such a linear grating varies with position on the disk's circumference. These microdisks lase with thresholds approximately twice that of our best circular disks. The laser mode pattern viewed from above for a disk similar to that shown in Fig. 2 is dominated by 2, 4, or 6 bright spots on the circumference, approximately symmetrically placed. In all cases, two of these bright spots are located at the two points, 180° apart, where the grating period is maximum



(a) (b)

FIG. 3. Measured vertically emitted intensity pattern of $\lambda = 1.56 \pm 0.1$ μm radiation from a 4 μm diam microdisk with a tab on the circumference is shown in (a). The pump power is near 1 mW. The vertical laser emission and photoluminescence are viewed vertically through a numerical aperture 0.5 microscope objective that images the light on an infrared sensitive video tube. This image is shown with its grey scale converted to a red temperature scale. A microscope image taken with visible light is shown in (b) with the same spatial scale as in (a). Note that the support post (dark "square" inside the disk) is slightly asymmetric and extends toward the tab due to the chemical etching process used to obtain the undercut disk.

and small tabs are formed in the photolithographic process. Other symmetrically placed bright spots are expected on the circumference where the grating period is roughly half a whispering-gallery mode wavelength in the disk ($\simeq 0.2\ \mu$m). Gratings can in principle be formed at any point around the circumference to couple out a particular amount of light in a specific pattern. However, the electron-beam lithography required to produce these gratings is not practical at present for large numbers of such structures.

The effective whispering-gallery mode reflectivity is predicted to decrease rapidly with decreasing radius of curvature at the disk edge. This leads to the idea of a cavity with the shape of the cross section of an egg for coupling the light out of the edge in a preferred direction, in this case, the "tip of the egg." The whispering-gallery mode should follow the disk edge if the change in curvature is adiabatic; i.e., the length scale for changes in the radius of curvature should be long compared to $\lambda/2\pi n_{\text{eff}} \simeq 0.1\ \mu$m. We have fabricated a series of microdisks whose shape ranges from an appropriately adiabatic egg shape to a relatively long waveguide or tab abruptly intersecting the circumference and extending out several wavelengths along a radius. These asymmetric disks lase with thresholds in the range between 100 and 500 μW and exhibit bright vertical emission at the point of reduced radius of curvature as shown in Fig. 3. Spectra taken through an aperture, approximately one-third the disk diameter, centered on the tab indicate that the bright spot shown in Fig. 3(a) is dominantly laser emission into a single line with a wavelength near 1.55 μm. A similar spectrum taken with the aperture at the edge of the disk opposite the tab showed a reduction in the laser line intensity relative to that at the tab by a factor of between 6 and 10. This demonstrates that the dominant laser vertical output coupling is at the tab.

The measured vertical emission in Fig. 3 includes only a small portion of the total tab emission in all directions. The differential quantum efficiency for light emitted into the vertical cone collected by the microscope objective used in these experiments is only 0.1%–0.2%. If the tab radiation intensity as a function of angle from the vertical direction is peaked in the plane of the disk, as expected for the thin disk geometry, one hopes to obtain much higher quantum efficiencies for coupling from the tab into waveguides in the plane of the disk.

The lasing spectrum of a 4 μm diam tabbed laser is compared in Fig. 4 with that of a 4μm diam circular disk laser located 10 μm away on the same wafer. The pump power is the same in both cases and is approximately an order of magnitude above threshold. For the circular disk a single mode lases over the entire pumping power range up to several milliwatts where heating effects begin to decrease the laser output. The tabbed laser also begins lasing

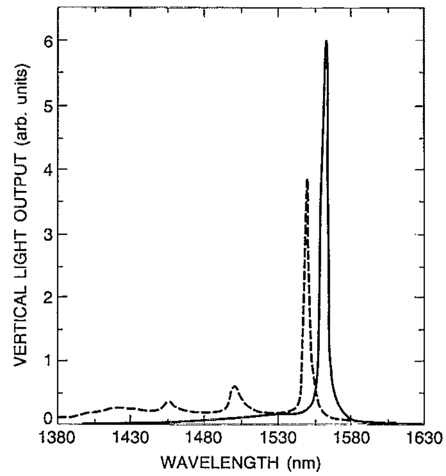


FIG. 4. Spectrum of photoluminescence and laser emission lines for a 4 μm diam circular disk (solid line) and a 4 μm diam disk with a tab (dashed line) similar to that shown in Fig. 3(b). Excitation is by 1 mW of $\lambda = 638$ nm HeNe radiation. The threshold pump power is near 100 μW for the circular microdisk and 200 μW for the microdisk with a tab. These threshold values are probably high by at least a factor of 2 since all of the incident power does not strike the disk.

in a single mode although at a threshold roughly twice that of the circular disk. However, with increasing pump power the lasing output from the tabbed laser soon begins to shift into other whispering-gallery modes. The mode spacing apparent in Fig. 4 is approximately that expected for whispering-gallery modes at the edge of a 4 μm diam disk.

Optimization of light coupling techniques will require some further work. We are, for example, studying the feasibility of using chemical vapor deposited SiO_2 which can form microlenses on the tab and act as bridges between microdisk lasers and waveguides. Patterns on top of the disk can optimize the vertically emitted radiation while minimizing the associated degradation of the Q value.

The experiments described here also indicate a tolerance for asymmetries and imperfections in these microdisks that is much larger than initially expected. This is good news for large scale applications such as laser arrays and microphotonic circuits where high yields are required.

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[6] The quality factor Q is defined by the temporal decay of the stored energy U where $U = \exp(-\omega_0 t/Q)$, where ω_0 is the angular resonant frequency of the mode.