Room temperature operation of a sub-micron radius disk laser

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Abstract

An InGaAs/InGaAsP quantum well disk laser $0.8mm$ in radius and $0.18mm$ thick is operated at room temperature in the $M = 5$ whispering mode at wavelength $l = 1.542mm$ using $l = 0.85mm$ optical pumping. Because approximately 20% of the spontaneous emission feeds into lasing modes, the output is superlinear with pump over a wide range. A narrow luminescent peak at $1.690mm$ wavelength is identified with the $M = 4$ whispering mode.

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Very small gain volumes and high-Q cavities may be simultaneously achieved using microdisk laser geometries. Continuous operation at reduced temperatures using optical pumping [Ref. 1] and pulsed operation at room temperature using current injection [Ref. 2] have been demonstrated for such lasers. We report here room temperature lasing action in a very small InGaAs/InGaAsP quantum well microdisk of radius $R = 0.8 \pm 0.05 mm$ and thickness $L = 0.18 mm$.

Figure 1 shows a scanning electron micrograph of a laser similar to the one operated. Viewed from above the disk is quite circular so that scattering losses [Ref 3] which limit the finesse of high-Q modes should be small. Sample growth and etching procedures are as described in reference 1. The disk is composed of six 120Å thick quantum wells of InGaAs material lattice matched to InP. Five barriers 120Å thick of InGaAsP separate the quantum wells, and InGaAsP caps 240Å thick enclose the quantum well-barrier structure. The InGaAsP material has a band-edge corresponding to $1.1 mm$ wavelength radiation.

An AlGaAs/GaAs laser diode provides $l = 0.85 mm$ wavelength power for the optical pump which is focused onto the disk laser top surface using a 0.5 numerical aperture (N.A.) lens, so that at best only about 80% of total incident pump light is intercepted by the $R = 0.8 mm$ radius disk. The total incident pump power, P_{ex} is delivered during an 8 ns period at a repetition period of 100 ns. Heating becomes significant for pulse widths of 30 ns (30% duty cycle) or greater as evidenced by a decrease of both laser and total light output. Light for analysis is collected by the same 0.5 N.A. lens, and directed to a spectrometer. The 5 nm resolution spectra shown in Fig. 2 have a luminescent background, a lasing line at $l = 1.542 mm$, and a resonance at $l = 1.690 mm$. Fig. 3 shows lasing power scattered by disk imperfections into the vertical direction versus total incident pump power, P_{ex}.

It should be noted that output lasing power is superlinear with input. This is expected according to simple models for very small semiconductor lasers because in such models a relatively large fraction of total spontaneous emission is emitted into the lasing mode. This fact is most readily explained by considering the steady state intensity, S, in the lasing mode. $S = r_{sp}^{\mathrm{mode}} / (k - g^{\mathrm{mode}})$ where r_{sp}^{mode} is the spontaneous emission rate into the lasing mode, k is the optical loss rate in the cavity and g^{mode} is the modal gain. For S to reach a given threshold intensity S_{th} when r_{sp}^{mode} is small requires a much smaller value of $(k - g^{\mathrm{mode}})$ than when r_{sp}^{mode} is relatively large. Hence, superlinear behavior extends over a larger range of pump power for r_{sp}^{mode} large, because the rate of change in S with P_{ex} around S_{th} is larger when r_{sp}^{mode} is small.

Microwave measurements [Ref. 4] of sapphire disks indicate that whispering mode frequencies w_M may be calculated to an accuracy of a few percent by solving the equation $2pwn_{eff}(w)R = x_M^1\, c$, where c is the speed of light in vacuum, R is the disk radius, $n_{eff}(w)$ is the (two-dimensional) effective refractive index, and x_M^1 is the smallest positive root of $J_M(x) = 0$, where J_M is the usual Bessel function with integer index M. Larger roots are denoted by x_M^L. The effective refractive index is found from the relation [Ref. 5]

$$\tan(pL\sqrt{e - n_{eff}{}^2}\ /\ l) = \sqrt{(n_{eff}{}^2 - 1)/(e - n_{eff}{}^2)}$$

where e is the real part of the semiconductor dielectric constant, L the disk thickness, and l the free-space wavelength corresponding to optical frequency w. We use

$$e = [3.456 + 0.333(\hbar w - 0.75eV)]^2 .$$

obtained from data in reference 6 to find values w_M as solutions to the above, and corresponding wavelength l_M. In particular, we find $l_5 = 1.480mm$ and $l_4 = 1.634mm$. The small discrepancy between the calculated and experimentally measured values of l_M ($l_5 = 1.542mm$, $l_4 = 1.690mm$) is in part due to uncertainties in the exact physical dimensions of the disk.

The spontaneous emission rate into a mode may be expressed as

$$r_{sp}{}^{\mathrm{mod}\,e} = \int r_{sp}(w)\Gamma(w)\,dw$$

where

$$\Gamma(w) = \frac{g(w)/p}{(w - w_C(w))^2 + g(w)^2}$$

is the cavity function and $g(w)$ describes the line shape of the resonance centered at $w_C(w)$. For simplicity we consider the case where both w_C and g are independent of w. For g small, Γ is a d-function so that $r_{sp}^{\mathrm{mod}\,e} = r_{sp}(w_C)$. Although the cavity linewidth g may be small and the spontaneous emission into the mode originates from the frequency interval $w_C \pm g$, such emission is enhanced by $1/g$ so that the principle of mode partition is preserved. However, when g becomes larger than the luminescence width, $r_{sp}^{\mathrm{mod}\,e}$ is usually reduced below $r_{sp}(w_C)$ by an overlap factor.

Spontaneous emission within a dielectric slab of the disk's thickness ($0.4 \times l$ in the material) and composition is about 75% into trapped transverse electric modes (evanescent above and below the dielectric), 10% tranverse magnetic modes and about 15% into free modes propagating outside the dielectric [Ref. 7]. Very little goes into trapped transverse magnetic modes because most of the corresponding modal energies are outside the dielectric. We believe these properties also apply to disks. Consequently, about 75% of spontaneous emission is into two-dimensional disk modes of transverse electric character describable by scalar forms $J_M(n_{eff} wr / c)e^{iMq}$, where q is the polar coordinate angle and r is the radial coordinate. There are four roots x_M^L of Bessel functions J_M between $x_6^1 = 9.936$ and $x_4^1 = 7.588$, namely $x_5^1 = 8.771$ (corresponding to the $M = 5$ whispering-gallery mode lasing emission measured at $l_5 = 1.542mm$), $x_0^3 = 8.654$, $x_2^2 = 8.417$, and $x_3^2 = 9.761$. Thus, there are about (2 + 2.5) modes in an interval centered on the $M = 5$ whispering mode with endpoints halfway to the adjacent whispering modes. The factor 2.5 is from counting half of the 5 modes corresponding to x_0^3, x_2^2, and x_3^2, taking into account the degeneracy factor of two for $M > 0$. The factor 2 is from x_5^1 and its degeneracy of two. The separation of the $M = 4$ and $M = 5$ whispering modes is about 150 nm and the measured luminescence width (full-width-half-maximum) is about 220 nm for $P_{ex} = 1mW$. Including the 75% factor mentioned above, we estimate that the fraction of spontaneous emission which goes into one of the $M = 5$ whispering gallery modes is $b(P_{ex} = 1mW) = (150 \times 0.75)/(220 \times 4.5) = 0.106$, or 0.212 into both $M = 5$ whispering modes.

This result appears to be inconsistant with the spectra of Fig. 2. However, it should be noted that in an ideal disk geometry, radiation from whispering modes is emitted into directions near the plane of the disk, not towards the vertical direction and into the detection apparatus. In addition, the measured smooth luminescence background has a substantial and perhaps dominant contribution from free modes. Furthermore, below transparency, light emitted into whispering modes is substantially absorbed before it escapes the laser structure and is detected. Overall, these effects reduce the apparent b value as determined by casual inspection of the vertically emitted emission spectrum.

In summary, room temperature lasing action in a very small InGaAs/InGaAsP quantum well microdisk of radius $R = 0.8mm$ and thickness $L = 0.18mm$ has been realized. Approximately 20% of the spontaneous emission feeds into the $M = 5$ whispering-gallery modes at wavelength $l = 1.542mm$. It should be possible to fabricate even smaller structures which lase into the $M = 4$ whispering-gallery mode.

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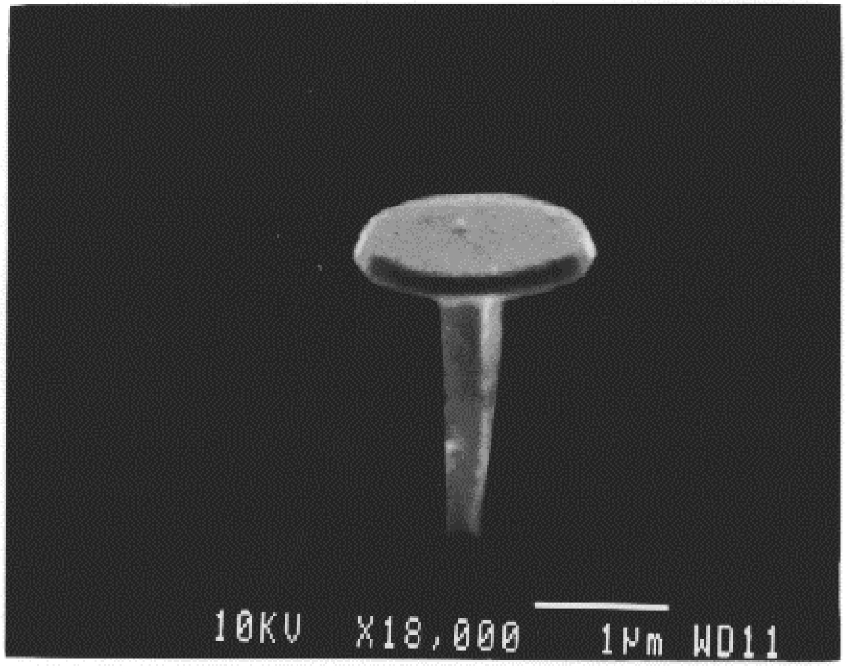

Figure 1 - Scanning electron micrograph of an InGaAs/InGaAsP multiple quantum well microdisk laser with $R = 0.8mm$ and $L = 0.18mm$. The $1mm$ bar provides a scale.

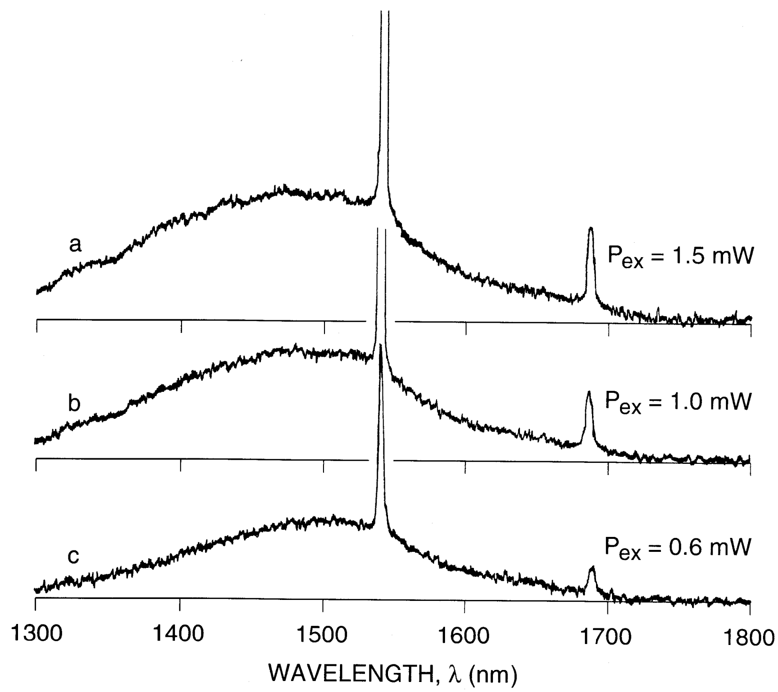

Figure 2 - Room temperature photoluminescence spectra of a $R = 0.8mm$ radius microdisk laser. Excitation is by a pulsed AlGaAs/GaAs laser diode emitting at $l = 0.85mm$. Pump power incident on the device is P_{ex}.

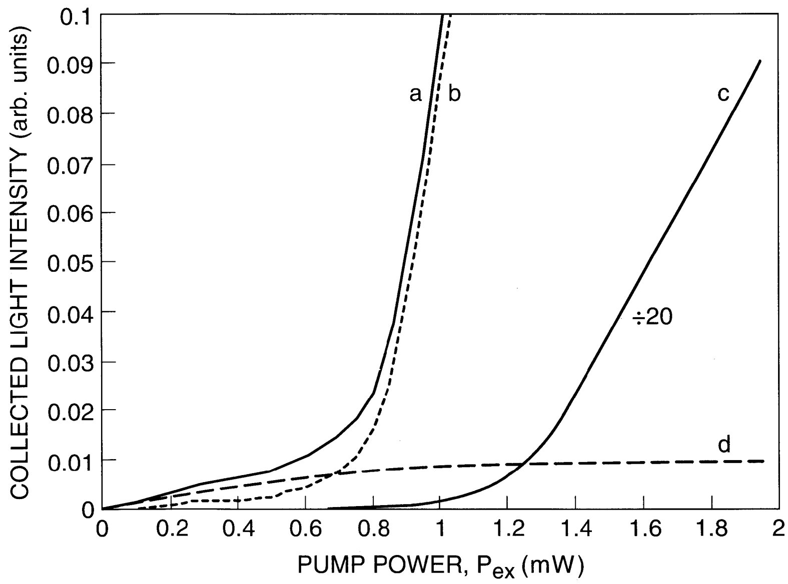

Figure 3 - (a) Room temperature power at the lasing wavelength versus incident pump power, P_{ex}, for the $R = 0.8mm$ microdisk laser of Fig. 1 and 2. (b) Power in the lasing line versus pump power. (c) Power at the lasing wavelength versus pump power. Vertical scale is divided by 20. (d) Power in the spontaneous emission background at the lasing wavelength versus pump power. Resolution is 5 nm.