It should also be noted that only DC conditions have been addressed and further design modifications may be necessary to prevent latch-up in both on- and off-states under dynamic conditions.

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ROOM TEMPERATURE OPERATION OF SUBMICROMETRE RADIUS DISK LASER

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Indexing terms: Lasers, Semiconductor lasers

An InGaAs/InGaAsP quantum well disk laser 0·8 μm in radius and 0·18 μm thick is operated at room temperature in the $M = 5$ whispering mode at wavelength $\lambda = 1{\cdot}542$ μm using $\lambda = 0{\cdot}85$ μm optical pumping. Because ~20% of the spontaneous emission feeds into lasing modes, the output is superlinear with pump over a wide range. A narrow luminescent peak at 1·690 μm wavelength is identified with the $M = 4$ whispering mode.

Very small gain volumes and high-Q cavities may be simultaneously achieved using microdisk laser geometries. Continuous operation at reduced temperatures using optical pumping [1] and pulsed operation at room temperature using current injection [2] have been demonstrated for such lasers. We report room temperature lasing action in a small InGaAs/InGaAsP quantum well microdisk of radius $R = 0{\cdot}8 \pm 0{\cdot}05$ μm and thickness $L = 0{\cdot}18$ μm.

Fig. 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 [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 120 Å thick quantum wells of InGaAs material lattice matched to InP. Five barriers 120 Å thick of InGaAsP separate the quantum wells, and InGaAsP caps 240 Å thick enclosure the quantum well-barrier structure. The InGaAsP material has a band edge corresponding to 1·1 μm wavelength radiation.

An AlGaAs/GaAs laser diode provides $\lambda = 0{\cdot}85$ μm wavelength power for the optical pump which is focused onto the disk laser top surface using a 0·5 numerical aperture (NA) lens, so that at best only ~80% of total incident pump light is intercepted by the $R = 0{\cdot}8$ μm 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 NA lens, and directed to a spectrometer. The 5 nm resolution spectra shown in Fig. 2 have a luminescent background, a lasing line at $\lambda = 1{\cdot}542$ μm, and a

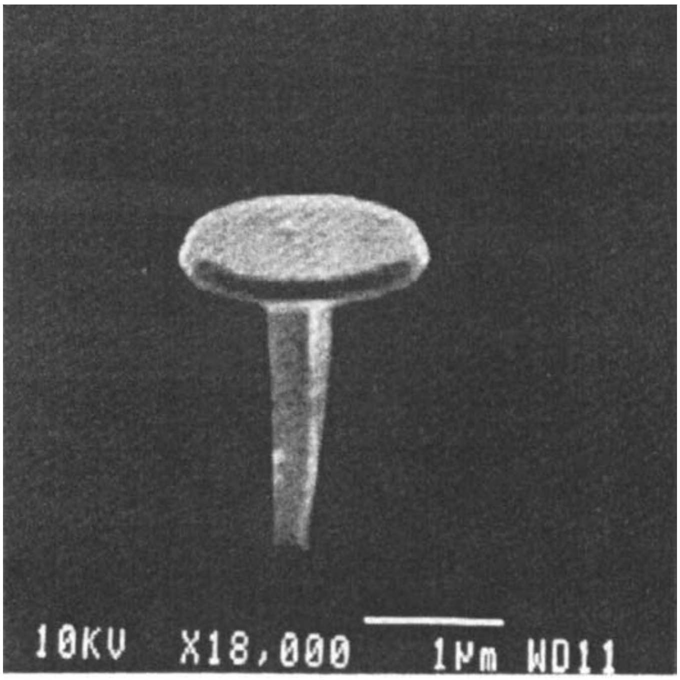

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Fig. 1 *Scanning electron micrograph of InGaAs/InGaAsP multi-quantum well microdisk laser with $R = 0{\cdot}8$ μm and $L = 0{\cdot}18$ μm*

The 1 μm bar provides a scale

resonance at $\lambda = 1{\cdot}690$ μm. Fig. 3 shows lasing power scattered by disk imperfections into the vertical direction against 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

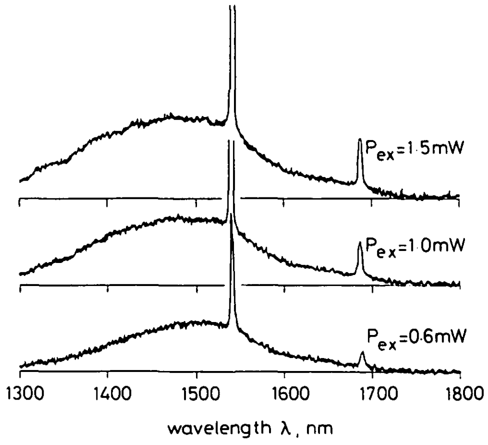

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Fig. 2 *Room temperature photoluminescence spectra of $R = 0{\cdot}8$ μm radius microdisk laser*

Excitation is by a pulsed AlGaAs/GaAs laser diode emitting at $\lambda = 0{\cdot}85$ μm; pump power incident on the device is P_{ex}

emitted into the lasing mode. This fact is most readily explained by considering the steady state intensity S in the lasing mode. $S = r_{sp}^{mode}/(\kappa - g^{mode})$ where r_{sp}^{mode} is the spontaneous emission rate into the lasing mode, κ 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 $(\kappa - g^{mode})$ than when r_{sp}^{mode} is relatively large. Hence, superlinear behaviour extends over a large 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 [4] of sapphire disks indicate that whispering mode frequencies ω_M may be calculated to an accuracy of a few percent by solving the equation $2\pi\omega n_{eff}(\omega)R = x_M^1 c$, where c is the speed of light in a vacuum,

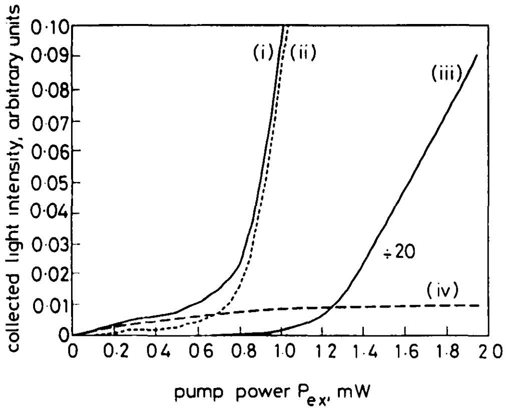

Fig. 3 *Lasing power scattered by disk imperfections into the vertical direction against total incident power P_{ex}*

(i) room temperature power at lasing wavelength against incident pump power P_{ex} for $R = 0.8\,\mu m$ microdisk laser of Figs 1 and 2
(ii) power in lasing line against pump power
(iii) power at lasing wavelength against pump power; vertical scale is divided by 20
(iv) power in spontaneous emission background at lasing wavelength against pump power
Resolution is 5 nm

R is the disk radius, $n_{eff}(\omega)$ 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 [5]

$$\tan(\pi L\sqrt{(\varepsilon - n_{eff}^2)}/\lambda) = \sqrt{[(n_{eff}^2 - 1)/(\varepsilon - n_{eff}^2)]}$$

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

$$\varepsilon = [3{\cdot}456 + 0{\cdot}333(\hbar\omega - 0{\cdot}74\ \text{eV})]^2$$

obtained from data in Reference 6 to find values ω_M as solutions to the above, and corresponding wavelength λ_M. In particular, we find $\lambda_5 = 1{\cdot}480\,\mu m$ and $\lambda_4 = 1{\cdot}634\,\mu m$. The small discrepancy between the calculated and experimentally measured values of λ_M ($\lambda_5 = 1{\cdot}542\,\mu m$, $\lambda_4 = 1{\cdot}690\,\mu m$) 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

$$r_{sp}^{mode} = \int r_{sp}(\omega)\Gamma(\omega)\,d\omega$$

where

$$\Gamma(\omega) = \frac{\gamma(\omega)/\pi}{(\omega - \omega_C(\omega))^2 + \gamma(\omega)^2}$$

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

Spontaneous emission within a dielectric slab of the disk's thickness ($0{\cdot}4 \times \lambda$ in the material) and composition is ~75% into trapped transverse electric modes (evanescent above and below the dielectric), 10% transverse magnetic modes and ~15% into free modes propagating outside the dielectric [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, ~75% of spontaneous emission is into two-dimensional disk modes of transverse electric character describable by scalar forms $J_M(n_{eff}\,\omega r/c)e^{iM\theta}$, where θ is the polar coordinate angle and r is the radial co-ordinate. There are four roots χ_M^L of Bessel functions J_M between $x_6^1 = 9{\cdot}936$ and $x_4^1 = 7{\cdot}588$, namely $x_5^1 = 8{\cdot}771$ (corresponding to the $M = 5$ whispering-gallery mode lasing emission measured at $\lambda_5 = 1{\cdot}542\,\mu m$), $x_0^3 = 8{\cdot}654$, $x_2^2 = 8{\cdot}417$, and $x_3^2 = 9{\cdot}761$. Thus, there are about $(2 + 2{\cdot}5)$ modes in an interval centred on the $M = 5$ whispering mode with endpoints halfway to the adjacent whispering modes. The factor 2·5 is from counting half of the five modes corresponding to x_0^3, x_2^2, and x_3^2, taking into account the degeneracy factor of 2 for $M > 0$. The factor 2 is from x_5^1 and its degeneracy of 2. The separation of the $M = 4$ and $M = 5$ whispering modes is ~150 nm and the measured luminescence width (full-width half-maximum) is ~220 nm for $P_{ex} = 1$ mW. 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 $\beta(P_{ex} = 1\ \text{mW}) = (150 \times 0{\cdot}75)/(220 \times 4{\cdot}5) = 0{\cdot}106$, or 0·212 into both $M = 5$ whispering modes.

This result appears to be inconsistent 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 β 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 $R = 0{\cdot}8\,\mu m$ and thickness $L = 0{\cdot}18\,\mu m$ has been realised. Approximately 20% of the spontaneous emission feeds into the $M = 5$ whispering-gallery modes at wavelength $\lambda = 1{\cdot}542\,\mu m$. It should be possible to fabricate even smaller structures which lase into the $M = 4$ whispering-gallery mode.

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