Continuous room-temperature operation of optically pumped InGaAs/InGaAsP microdisk lasers

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Abstract

Optically pumped InGaAs/InGaAsP multiple quantum well microdisk lasers wafer-bonded to sapphire lase continuously at room temperature. A threshold pump power of P_{th} = 1.1 mW at pump wavelength λ = 0.85 μm is measured for a 4.5 μm diameter disk with lasing emission wavelength near λ = 1.6 μm.

Continuous room-temperature lasing into a whispering gallery resonance at the periphery of an optically active semiconductor disk gain medium can occur only if temperature in this region is controlled within reasonable limits. Unfortunately, the poor thermal characteristics of small, optically pumped, microdisk lasers supported by a pedestal [1] does not meet the appropriate criteria and continuous lasing at room temperature has not been realized. The challenge is to overcome excessive heating without significantly degrading high confinement of the optical resonance. A solution is to use a disk active gain medium in intimate contact with a material of high thermal conductivity, low refractive index and low optical loss. Sapphire with thermal conductivity, $\kappa_{sapphire} = 0.4$ $Wcm^{-1}K^{-1}$ and relatively low refractive index, $n_{sapphire} = 1.78$ is a suitable material.

Figure 1 shows calculated temperature contour plots for a 5 μm diameter, 0.2 μm thick, microdisk with 5 mW of optical power uniformly incident from above. For the disk supported by a 3 μm diameter, 1 μm tall, pedestal we find that the periphery of the disk is $\Delta T = 62$ K above the substrate temperature. However, for the case of a microdisk in intimate contact with sapphire, the periphery of the disk is only $\Delta T = 5$ K above the substrate temperature (for glass $\kappa_{glass} = 0.014$ $Wcm^{-1}K^{-1}$ and $\Delta T = 80$ K).

The multiple quantum well epitaxial layer structure shown in Table I is grown by MOCVD. The quaternary InGaAsP and ternary InGaAs layers are lattice matched to InP and the quaternary has a energy bandgap corresponding to a wavelength of $\lambda_g = 1.1$ μm. After removal from the growth chamber, 10 μm wide grooves with 500 μm spacing are etched to a depth of 40 nm using $3HCl:H_20$ selective InP etchant. The epitaxial layer structure and sapphire are sandwiched together between graphite and wafer-bonded at 400 °C in a H_2 ambient [2]. Following wafer-bonding, the semiconductor is lapped down to 25 μm thickness and the remaining InP substrate is removed using $3HCl:H_2O$ etchant. The 100 nm thick InGaAs etch stop layer is then removed using a $H_2SO_4:H_2O_2:H_2O$ selective etchant. Amorphous SiN_x is then chemical vapour deposited at 325 °C. Standard photolithography and dry etching are used to define microdisks in the SiN_x layer. Electron Cyclotron Resonance (ECR) etching is used to transfer the pattern from the SiN_x layer to the semiconductor multiple quantum well active region. After removal of the SiN_x layer, the sample is ready for device characterization.

Light from a pump laser with emission at λ = 850 nm is focused onto the microdisk and emission from the disk is analysed using an optical spectrometer. Inset to Figure 2 shows a scanning electron micrograph (SEM) picture of a typical 4.5 μm diameter multiple quantum well microdisk laser wafer-bonded to sapphire. Figure 2 shows the dependence of measured output power, P_{out}, with absorbed power, P_{in}. Laser threshold power is P_{th} = 1.1 mW.

Figure 3 shows a three-dimensional plot of the measured continuous-wave optical spectrum for various absorbed pump powers. The linewidth of the lasing line centered at λ = 1599 nm is dominated by the 1 nm resolution of the spectrometer. A mode suppression ratio greater than 30 dB is observed when the spectrometer resolution is 0.2 nm and lasing wavelength is found to be independent of the absorbed power indicating lack of heating effects. Assuming lasing occurs in the lowest-order resonance radial number N = 1, the azimuthal number, M, is estimated using

$$\frac{n_{eff}(\lambda_2)}{\lambda_2} - \frac{n_{eff}(\lambda_1)}{\lambda_1} = \frac{(M+1)}{\pi D} - \frac{M}{\pi D} = \frac{1}{\pi D} \qquad (1)$$

In this expression, D is the diameter of the disk and $n_{eff}(\lambda)$ is the effective refractive index at wavelength λ of the slab waveguide [1] consisting of 0.2 μm thick semiconductor core and sapphire (air) as lower (upper) cladding. We obtain n_{eff} (λ_2 = 1.552 μm) = 2.759, n_{eff} (λ_1 = 1.599 μm) = 2.728, and D = 4.46 μm which compares well with the measured D = 4.5 μm. Our calculations indicate that the lasing resonance occurs at $M = \pi D n_{eff}(\lambda_2)/\lambda_2 = 24$.

In conclusion, we have shown continuous room-temperature lasing operation of microdisk lasers with lasing emission wavelength λ = 1599 nm. A threshold pump power of P_{th} = 1.1 mW at pump wavelength λ = 850 nm is measured for a D = 4.5 μm diameter InGaAs/InGaAsP multiple quantum well disk wafer-bonded to sapphire.

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References

[1] LEVI, A.F.J., McCALL, S.L., PEARTON, S.J., and LOGAN, R.A.: ‘Room temperature operation of submicrometre radius disk laser’, Electron. Lett., 1993, **29**, pp. 1666-1667

[2] HAISMA, J., SPIERINGS, G.A.C.M., MICHIELSEN, T.M., and ADEMA, C. L.: ‘Surface preparation and phenomenological aspects of direct bonding’, Philips Journal. Res., 1995, **49**, pp. 23-46.

Figure captions

Figure 1. **(a)** Calculated contour plot showing the thermal distribution for a 5 μm diameter and 0.2 μm thick microdisk laser when supported on a 3 μm diameter and 1 μm tall InP pedestal. **(b)** Same disk as (a) but wafer-bonded to sapphire. In both cases, 5 mW of heat flux is assumed to be incident uniformly on the top surface of the disk and contours are plotted for every $\Delta T = 2$ K. For ease of interpretation, only a quarter pie section of the disk is shown.

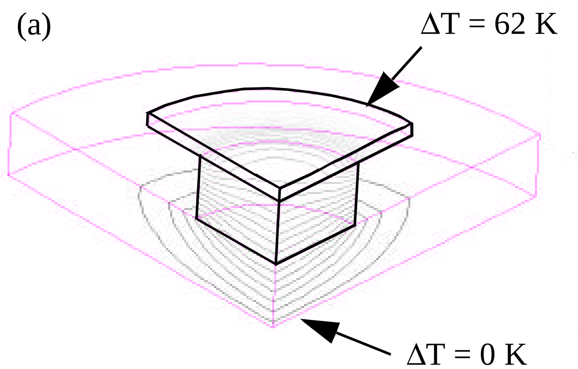
Figure 2. Measured continuous-wave collected power (P_{out}) at the lasing wavelength, $\lambda = 1599$ nm, versus the power absorbed by the disk (P_{in}) at pump wavelength $\lambda_{in} = 850$ nm, for a typical 4.5 μm diameter microdisk laser wafer-bonded to sapphire. Threshold power is $P_{th} = 1.1$ mW and resolution of the spectrometer is 10 nm. Inset shows the scanning electron micrograph picture of the 4.5 μm diameter wafer-bonded microdisk laser.

Figure 3. Three-dimensional plot showing the measured luminescence spectra of the microdisk laser used in Figure 2 for the indicated pump power levels, P_{in}. The linewidth of the resonances measured is limited by the 1 nm resolution of the spectrometer.

List of Tables

Table 1:

Material	Thickness (nm)	Doping
InP	40	i
InGaAsP	21	i
InGaAs	8	i
InGaAsP	5	i
InGaAs	8	i
InGaAsP	5	i
InGaAs	8	i
InGaAsP	5	i
InGaAs	8	i
InGaAsP	5	i
InGaAs	8	i
InGaAsP	5	i
InGaAs	8	i
InGaAsP	21	i
InP	40	i
InGaAs	100	i
InP	Substrate	$n = 4X10^{18}$ cm^{-3}



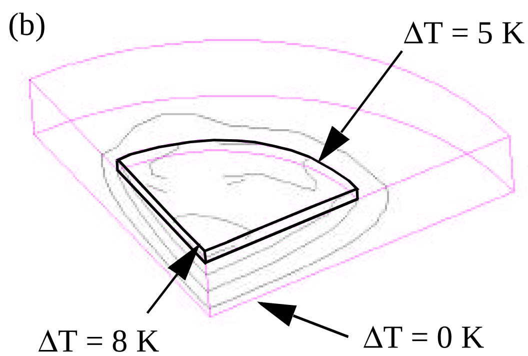
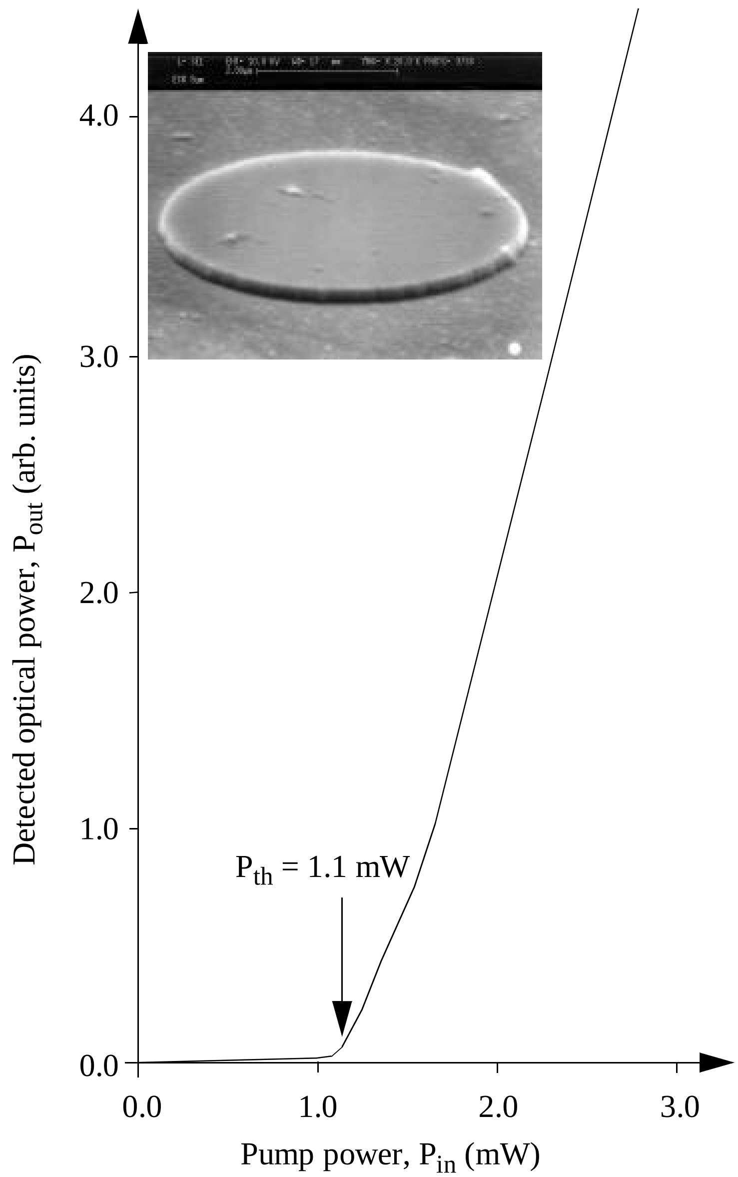
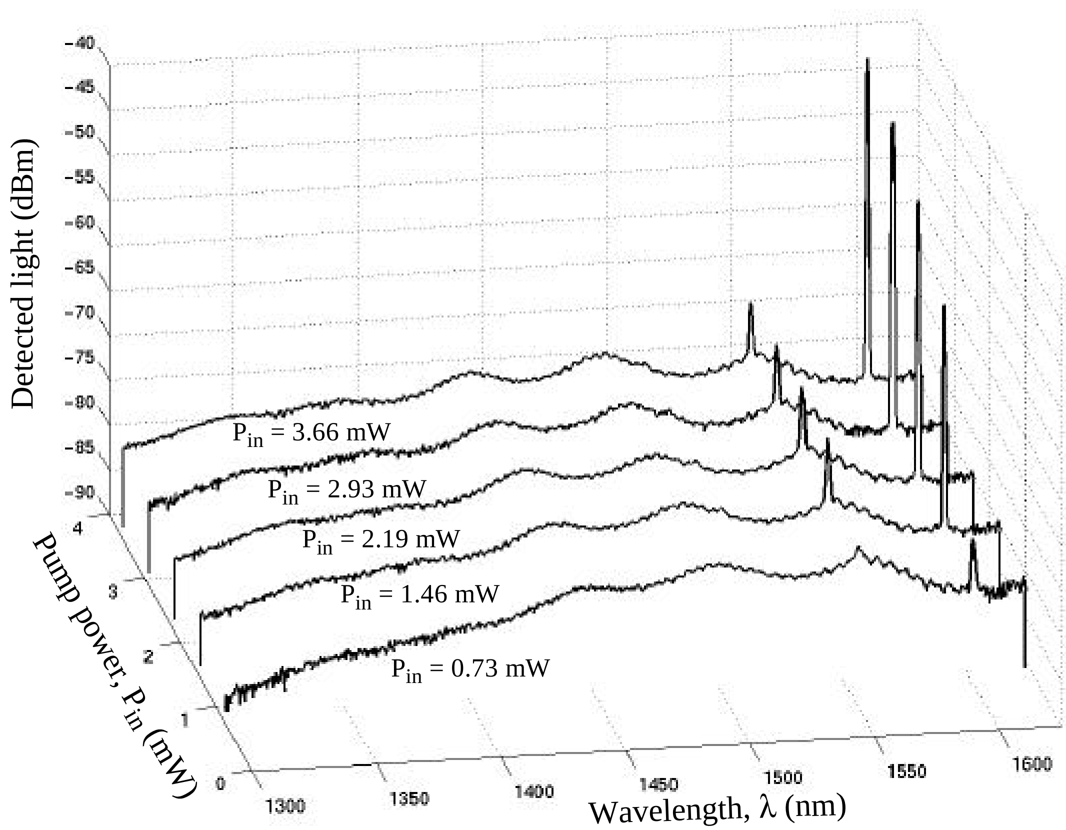


Figure 1.



4.0
3.0
2.0
1.0
0.0
Detected optical power, P_{out} (arb. units)
P_{th} = 1.1 mW
0.0
1.0
2.0
3.0
Pump power, P_{in} (mW)

Figure 2.



Detected light (dBm)
-40
-45
-50
-55
-60
-65
-70
-75
-80
-85
-90
Pump power, P_{in} (mW)
4
3
2
1
0
P_{in} = 3.66 mW
P_{in} = 2.93 mW
P_{in} = 2.19 mW
P_{in} = 1.46 mW
P_{in} = 0.73 mW
1300
1350
1400
1450
1500
1550
1600
Wavelength, λ (nm)

Figure 3.