Semiconductor Microlaser Linewidths

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Semiconductor microdisk laser linewidths are measured for cavity volumes near a cubic wavelength. The linewidths remain near the subthreshold values for pump powers well above threshold in agreement with a microscopic theory that includes the coupled dynamics of the optical emission and the nonequilibrium electron-hole gas in the cavity.

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Microlasers are excellent laboratories for the study of the fundamental laser and semiconductor carrier phenomena since their volumes can be reduced to the point where there is only one optical resonator mode within the gain medium spectral bandwidth. In general the physics of the hot, dense, often nonequilibrium electron-hole gas obtained in a lasing semiconductor is not well understood. The strong interaction of this gas with a single microlaser laser line is an interesting new probe of semiconductor carriers under lasing conditions. In particular the linewidth of a microlaser mode is an important measure of phenomena that are expected to occur in the small volume limit where a large fraction β of the spontaneous emission from the gain region is emitted into the laser mode [1,2]. As β approaches unity the light output from a microlaser becomes a nearly linear function of the pump power, i.e., the laser threshold appears to vanish. However, there are a number of measurable properties of the microlaser that are expected to clearly indicate threshold behavior [2] including changes in the lasing linewidth, amplitude fluctuations in the emitted light, and carrier density pinning in the case of semiconductor gain material. We study the case of a semiconductor microdisk laser where large β values between 0.1 and 0.2 have been measured [3]. A simple model [4,5] predicts that the coupling of the refractive index fluctuations associated with carrier fluctuations in the gain medium adds a factor $(1 + \alpha^2)/2$ to the linewidth near the threshold. The gain-refractive-index coupling factor α has values that typically range between 2 and 5. Above threshold the simple model predicts that the linewidth decreases inversely with the light level in the cavity, i.e., the usual Schawlow-Townes behavior. We find instead that the measured linewidths for β values above 0.05 are much larger than expected and remain nearly constant as the light levels increase to well over an order of magnitude above threshold. These measurements agree with the predictions of a microscopic theory [6] of the interacting carrier-photon system in the microcavity resonator. The underlying physics is that the spontaneous and stimulated emission rates increase with β and become comparable to the carrier equilibration rates. This results in nonequilibrium carrier energy distributions that increase the system noise and lasing linewidths.

The microdisk lasers [3] used for our linewidth measurements are fabricated from layered semiconductors grown by metal-organic chemical-vapor deposition (MOCVD). A thin dielectric disk supported by a dielectric post is photolithographically patterned and etched into this layered semiconductor. The large dielectric contrast between the disk and the surrounding air confines electromagnetic field modes to the edge of the disk where high-Q whispering-gallery modes propagate. These high-Q modes persist even when the disk diameter is reduced to dimensions of the order of a wavelength resulting in only a few well-isolated field modes within the luminescent bandwidth of the quantum well active region of the disk. The β values can be varied [3] from 0.04 to 0.2 using disk diameters between 5 and 2 μm.

Experimentally we compare the laser linewidth power dependence for two microdisks with diameters of 2.2 and 5 μm. Both disks are fabricated from a layered quantum well structure with six 100 Å InGaAs quantum wells separated by 50 Å InGaAsP barriers with an energy gap corresponding to a wavelength of 1.1 μm. The total disk thickness is approximately 0.15 μm corresponding to a third of a wavelength in the composite semiconductor. The light output as a function of pump power has been studied in detail [3] near threshold for these two microdisks. Continuous optical pumping with a spatially uniform HeNe laser at a wavelength of 632 nm results in a single lasing mode in each disk with threshold pump powers of 25 and 45 μW for the 2.2 and 5 μm diameter disks, respectively. β values for the 2.2 μm disk are a function of pump power and range between 0.23 below threshold to 0.1 well above threshold. These β values are obtained [3] both by fits to the light output as a function of pump power and as the measured ratio of the emission into the laser cavity linewidth to the total spontaneous emission. The β values decrease inversely with the disk volume to the range between 0.05 and

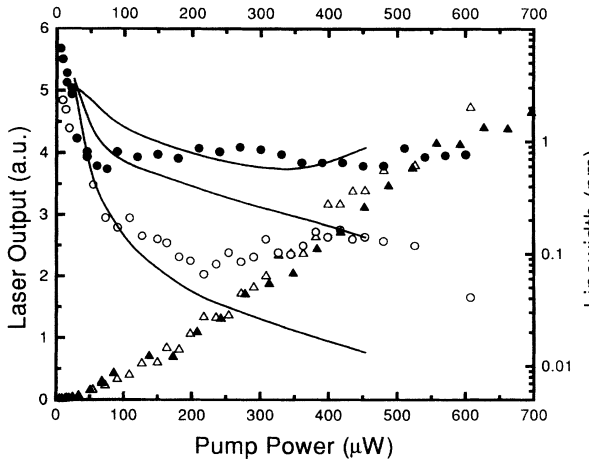

FIG. 1. Experimental and theoretical (solid lines) linewidths are shown as a function of pump power. The solid and open triangles show the laser light output for the 2.2 and 5 μm diam microdisks, respectively. The theoretical curves correspond to β values of 0.4, 0.1, and 0.01 in order of decreasing linewidth. The pump power at threshold for the 2.2 μm diameter disk is approximately 25 μW and the 5 μm disk pump powers have been multiplied by a factor of 0.55 so that they appear to have the same threshold for comparison with the theory.

0.02 for the 5 μm diameter disk. Radiative losses from imperfections at the disk edges limit the empty cavity Q's to 260 $\pm$ 50 and 500 $\pm$ 100 for the 2.2 and 5 μm diameter disks, respectively ($Q = \lambda_0/\Delta\lambda_0$, where λ_0 is the cavity resonance center frequency and $\Delta\lambda_0$ is the width with a transparent active medium). This difference in Q's and the volume ratio of 5 can approximately account for the difference in threshold pump powers. Note that the smaller Q of the 2.2 μm diameter microdisk means that its threshold pumping rate per unit volume is significantly larger than that for the 5 μm diameter disk which leads to larger nonequilibrium carrier effects.

The single mode microlaser linewidths and light outputs measured for the two microdisks are shown in Fig. 1 as a function of pump power. A grating spectrometer with a resolution of 0.07 nm was used to measure the full width at half maximum widths $\Delta\lambda$. The pump powers for the 5 μm disk have been multiplied by a factor of 25/45 so that the light output thresholds for the two microdisks appear at the same pump power. Below threshold both microdisk linewidths increase due to absorption in the cavity with decreasing pump power. It was surprising to find that the linewidth for the large β, 2.2 μm diameter laser decreased only slightly above threshold and remained at a comparatively large value for pump powers nearly a factor of 50 above threshold.

Larger volume semiconductor lasers with β's in the range from 10^{-3} to 10^{-5} exhibit linewidths that decrease inversely with pump power to values well below 100 MHz. By comparison, the linewidths near 80 GHz for our high-β laser are surprisingly large. Decreasing the β by a factor of 5 to 10 with the increased volume of the 5 μm diameter laser results in a decreased linewidth, however there is still a plateau before the linewidth begins to decrease at pump powers nearly a factor of 10 above threshold.

We monitored the lattice and carrier temperatures by measuring the logarithmic slope of the high frequency tail of the luminescence from the quantum wells (carrier temperature) and the InP support pedestal (lattice temperature). The lattice temperature remained constant within 5 °C of the liquid nitrogen cooled substrate temperature of 85 K while the carrier temperature increased from 85 to 135 K for the 2.2 μm disk over the range of pump powers shown in Fig. 1. The constant lattice temperature ensures that there are no heat sinking problems and the increase in carrier temperature can be compared with our theoretical model.

The power dependence and magnitude of the measured linewidths implies that the amplitude or spectrum of the underlying noise source must increase as the lasing power and β increase. This variation in the noise source is not expected in the simple model of a low-β laser with a homogeneously broadened gain spectrum. In this simple model the carrier density and the associated index of refraction are pinned at threshold, i.e., they remain constant above threshold because of the dominant stimulated emission rates. Carrier pinning stops any increase in linewidth due to index fluctuations of the gain media that cause a $(1 + \alpha^2)/2$ linewidth increase near threshold. In order to explain our results we need a mechanism that increases the noise in the light output as β increases and as the total emission rate increases. Our analysis shows that the large linewidths originate in the delicate interplay of the β-enhanced optical rates and the reduced gain-loss compensation.

Experimental evidence of deviations from the simple model are found by measuring the integrated photoluminescence and lasing wavelength as a function of pump power as shown in Fig. 2 for the high-β microdisk. The carrier density, approximately proportional to the measured integrated photoluminescence shown in Fig. 2, continues to increase above threshold. This increase in photoluminescence is in part due to carriers at high energies as seen from the spectra shown in Fig. 3(a). Above threshold the photoluminescence near the lasing frequency increases gradually, but it increases more rapidly at higher energies. This indicates nonequilibrium heating of the carrier system, i.e., a nonequilibrium state of the carriers relative to the lattice as well as carrier depinning. The shift in lasing wavelength seen in Fig. 2 is additional clear evidence of carrier depinning since it corresponds to an increase in the effective refractive index approximately porportional to the increase in carrier density. In contrast, the carrier density for the lower β disk remains nearly pinned at the threshold value, as demonstrated by

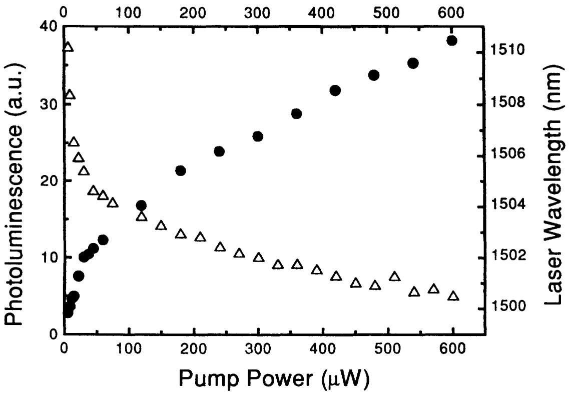

FIG. 2. The integrated photoluminescence (left axis, solid circles) and lasing wavelength (right axis, open triangles) are shown as a function of pump power for a 2.2 μm microdisk. The threshold pump power is approximately 25 μW.

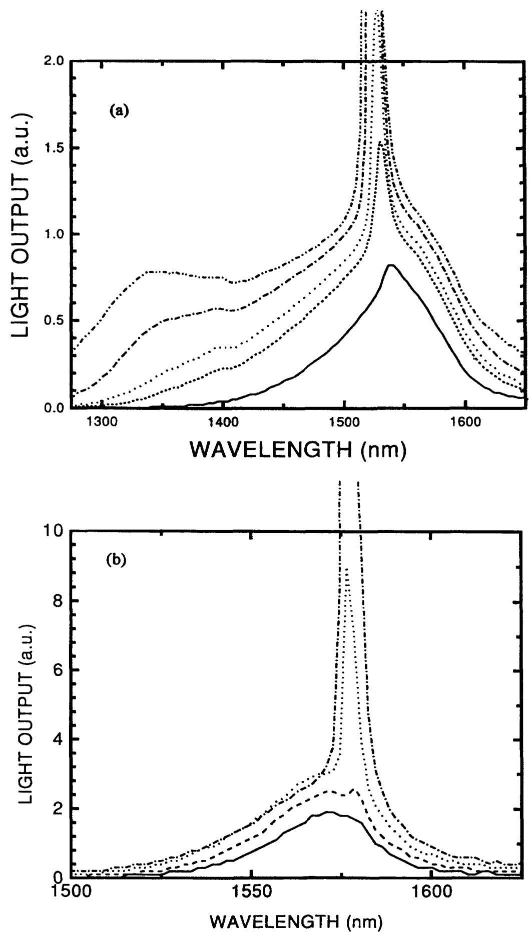

FIG. 3. The photoluminescence spectrum of a 2.2 μm diameter disk is shown for a series of pump powers in the range near threshold in (a) and a similar series is shown in (b) for the 5 μm diam disk. The small dotted curve is near threshold for both (a) and (b). The pump powers in (a) are 8 μW (solid curve), 18 μW (dashed), 22 μW (dotted), 37 μW (dash-dotted), and 84 μW (dash-double-dotted). The pump powers in (b) are 18 μW (solid), 30 μW (dashed), 54 μW (dotted), and 164 μW (dash-dotted).

the similarity of the photoluminescence spectra for pump powers at and above threshold shown as the dotted and dash-dotted curves in Fig. 3(b), respectively. The lasing wavelength for the lower β disk is also measured to be constant above threshold.

A detailed microscopic theory of the carrier dynamics in microlaser environments has been developed including carrier scattering, nonequilibrium carrier distributions, and collective effects [6,7]. The theoretical model leads to frequency dependent rate equations describing the buildup of light intensity $I(\omega)$ in the resonator,

$$\frac{\partial}{\partial t} I(\omega) = I(\omega)[g(\omega) - \kappa] + W(\omega) S_p(\omega), \quad (1)$$

where ω is the frequency, $g(\omega)$ is the gain, including stimulated emission and absorption, and κ is the optical resonator loss. The spontaneous emission rate is $W(\omega)$ and the additional factor $S_p(\omega)$ describes the connection between κ and ω. The gain and spontaneous emission rate depend on the carrier occupation and are modified by many body effects. The nonequilibrium carrier dynamics are described by a Boltzmann equation for the occupation probabilities $f_{e,h}$ of the state with momentum κ,

$$\frac{\partial}{\partial t} f_{e,h}(k) = \left[\frac{\partial}{\partial t} f_{e,h}(k)\right]_{\text{pump}} + \left[\frac{\partial}{\partial t} f_{e,h}(k)\right]_{\text{relax}} + \left[\frac{\partial}{\partial t} f_{e,h}(k)\right]_{\text{photon}}, \quad (2)$$

where the subscripts on the right hand side indicate rates due to (1) the optical pumping process, (2) relaxation rates including carrier-carrier Coulomb scattering and carrier-phonon scattering, and (3) rates due to the carrier-photon interactions including stimulated and spontaneous emission. All of these equations are derived microscopically. In this model the scattering times for stimulated and spontaneous emission are no longer free parameters. Instead they are computed self-consistently from the spectral light intensity and the actual carrier distribution functions.

The solid curves in Fig. 1 are predictions from the theoretical model using parameters that approximate the InGaAs gain material and the optical microcavity. The theoretical curves agree reasonably well in both the magnitude and power dependence if one interpolates between the plotted β values of 0.4, 0.1, and 0.01 to the measured β values near 0.15 for the 2.2 μm diameter disk and 0.05 for the 5 μm diameter disk. The theoretical curves are normalized to the data in the region near the threshold pump powers. It is difficult to make an exact comparison between the theory and the experiment since there are many approximate parameters in the model, e.g., the spectral position of the lasing mode with respect to carrier momentum distribution, the different Q values for the two disks, and the subband structure of the quantum wells.

Several other predictions of the theoretical model can be checked experimentally including the rise in the carrier temperature, predicted to be 80 °C for the high-β disk at pump powers an order of magnitude above threshold. This prediciton agrees reasonably well with the value of 50 °C measured from the high frequency luminescent spectral profile. The dominant contribution to the large, power independent linewidths predicted by the model at large β arise from increased spontaneous emission and index fluctuations associated with nonequilibrium carriers generated above threshold and the reduced gain-loss compensation. Experimentally the nonequilibrium distribution can be seen in Fig. 3(a) as the increasing luminescence near 1325 nm as a function of pump power. At pump powers well above threshold [dash-double-dotted curve in Fig. 3(a)], there is a dip in the luminescence spectrum between 1325 nm and the lasing line. When this spectrum is compared to a similarly pumped nonlasing structure, where the luminescence peaks near 1530 nm, a spectral "hole" at the position of the laser line is clearly seen in the photoluminescence of the lasing disk with an approximate width corresponding to the scattering time of 40 fsec predicted by our model. At lower β values the stimulated and spontaneous emission rates decrease. As a result the carrier scattering rates dominate and establish an equilibrium system at all energies described by a quasi-Fermi level. As this equilibrium is approached, carrier pinning sets in at threshold along with the increased gain-loss compensation leading to the normal linewidth behavior above threshold predicted by the simple model.

A number of other contributions to the laser linewidth anomalies may arise under various conditions. Vahala and Yariv [8] considered a mechanism that can produce a constant linewidth at large pump powers due to fluctuations as the carriers approach equilibrium. In fact their predicted linewidths increase at small volumes and are in order of magnitude agreement with our experimental results. However, the present model predicts scattering and equilibration times that do not allow the approximations required by the Vahala-Yariv model. The present model does not predict the constant linewidths at low β's and high pump powers observed in some experiments with stripe lasers [8]. A more complete description of microlaser linewidths clearly requires further studies.

In summary, we have studied semiconductor microlaser linewidths in the limit of large β and found anomalously large linewidths which persist to pump powers much more than an order of magnitude above threshold. A microscopic model of the nonequilibrium carrier dynamics in the microlaser cavity predicts that these large linewidths arise from spontaneous emission and index fluctuations that continue to increase above the laser threshold and the associated reduction in gain-loss compensation (depinning of the nonequilibrium carrier density). The anomalous linewidths are an excellent probe of the nonequilibrium dynamics of the hot, dense electron-hole gas in the cavity. The single mode structure of the cavity modes in the high β limit allows a clear comparison between theory and experiment. Laser linewidths are important in a number of potential microlaser applications. For example, in communications applications much smaller linewidths than those observed in the high-β microlasers described here are required. Our results indicate that very large Q values (>2000) and the associated reduction in pump rates will be required to achieve significantly narrower linewidths for high-β semiconductor microlasers.

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