Reduction of the field spectrum linewidth of a multiple quantum well laser in a high magnetic field—spectral properties of quantum dot lasers

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The field spectrum linewidth of a multiple quantum well laser immersed in a high magnetic field is measured at room temperature and at 165 K. The low-temperature measurements show a decrease of linewidth with increasing magnetic field. We believe this behavior results from the formation of a totally discrete electronic state space. Measurements of the low-temperature luminescence spectrum show that the emission is split into two peaks by the high field with the higher energy peak responsible for lasing action.

Conventional semiconductor lasers are finding widespread use in optical communication systems employing silica fiber and in certain sensing systems. In the future a number of more exotic communication and sensing systems may replace these systems where increased channel capacity or improved sensitivity is required.[1] These future systems require semiconductor lasers which drastically outperform those that are now commercially available. These new lasers must be highly single mode and have much narrower field spectrum linewidths. Use of external-cavity systems is one way to narrow the linewidth, and practical external-cavity systems have been demonstrated.[2] A sacrifice is made here, however, since compactness and the potential for monolithic integration are compromised.

In this letter we investigate an alternate approach which maintains these properties. In this approach we alter the laser's linewidth by modifying certain active layer material properties that are of central importance in determining its size. The linewidth of a semiconductor laser is given by the expression[3-5]

$$\Delta\omega = \frac{\theta}{2P}(1+\alpha^2)\,, \tag{1}$$

where θ is the spontaneous emission rate into the lasing mode, P is the number of photons in the lasing mode, and α is the linewidth enhancement factor resulting from the strongly detuned gain spectrum. In an external-cavity semiconductor laser the decreased spatial overlap of the gain with the field decreases θ, and the increased modal volume increases P thereby reducing linewidth. In the present approach, we reduce the linewidth by simulating quantum dot effects through the application of high magnetic fields to a multiple quantum well structure. By doing this the electronic state space of the laser active layer should be modified in a way that causes reduction of the linewidth enhancement factor α.

To understand why this should happen, consider the expression for α in terms of optical gain $g(n)$ and resonant refractive index $\mu(n)$[5]:

$$\alpha = \frac{\omega}{2\mu_0}\frac{\mu'}{g'}\,, \tag{2}$$

where ω is the lasing frequency, μ_0 is the nonresonant contribution to the refractive index, and μ' (g') is the derivative of the refractive index (gain) with respect to carrier density n. In a bulk active layer α is typically -5, thereby causing a degradation of spectral purity by a factor of 26 times [see Eq. (1)]. That α is nonzero and large in semiconductor lasers results from μ' being significant. This happens for two reasons. First, the laser gain spectrum is highly detuned, causing a strong contribution to $\mu(n)$ by the carriers at the lasing frequency. Second, band filling causes the gain and refractive index spectra to shift in frequency when the carrier density is disturbed. For these reasons, μ' in Eq. (2) is sizable (and in turn so is α) and it gives a measure of differential changes in μ that result from detuning and band filling.

In an ideal quantum dot laser the situation would be very different. In such a device the active layer would consist of an array of structures (the quantum dots) having a characteristic size of 100 Å (ideally of the same shape and size). These structures would be fabricated from a low band-gap material and would be imbedded in a high band-gap material (e.g., GaAs in AlGaAs). Electrons and holes residing in these structures would have highly localized wave functions and the state space in each dot would be discrete as opposed to the quasicontinuum of the bulk. In the ideal quantum dot laser the contribution to gain from each dot would arise from a pair of two level systems (one for each electron spin). The overall active layer would be very much like a gas laser in which the dots are likened to the atoms in the gas. In addition to a number of other differences, α in this ideal case would be zero provided the emission line is symmetrical and that lasing occurs at the peak of the emission line.

Many of the characteristics we ascribe to this ideal device seem unattainable at the present time. Problems stem from the technological difficulties involved in fabricating quantum dots. A means of testing the ideas discussed above without actually fabricating quantum dots does exist, however. This is to apply high magnetic fields normal to the plane of a quantum well laser.[6,7] By doing this we can achieve confinement of carriers in two directions via the Lorentz force and in the third direction from the quantum well barrier. Previously, we have employed this technique in bulk active layers to study quantum wire effects in semiconductor lasers.[8]

In this experiment we used an Hitachi GaAs/AlGaAs multiple quantum well laser similar to that described in Ref. 9. The room-temperature threshold current was 42 mA and the lasing wavelength was 792.0 nm. The laser was mounted in a sample holder which could be evacuated and inserted

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into a cryostat (see Fig. 1). The entire assembly, sample holder and cryostat, rested on a conventional Bitter magnet with the portion of the cryostat containing the sample residing in the bore of the Bitter coil. This magnet was capable of generating a cw magnetic field as high as 19 T. The temperature of the sample was controlled with a heating element and monitored with a thermal couple. The light emission from the front facet of the laser was reflected from a right-angle mirror and collimated for transmission through the column of the sample holder. The beam exited the sample holder through a window. Thereafter it was split for measurement of power and spectra. Optical power was also measured directly at the sample with a detector stationed at the back facet of the laser. The laser emission spectrum was measured in two ways. Low-resolution measurements were made using a grating spectrometer, and field-spectrum linewidth measurements were made using a high-resolution scanning Fabry–Perot étalon having an instrumental bandwidth of 10 MHz. Feedback effects to the laser were controlled by slightly misaligning optics, windows, and the Fabry–Perot étalon.

Measurements were conducted at room temperature and at 165 K. The lower temperature was selected by using current-voltage characteristics to monitor the onset of carrier freeze-out effects. At a given temperature, linewidth versus output power data were taken for various magnetic field strengths. Zero field measurements were conducted at both the beginning and the end of a run at a given temperature to ensure that the experimental setup had not misaligned itself during application of the high field. Measurements at room temperature of linewidth versus power showed no observable dependence on magnetic field strength.

Measurements at 165 K are presented in Fig. 2. In this case there is an observable reduction of the linewidth as the magnetic field is increased. The reduction is as large as $2\times$ for a field strength of 19 T. We believe this reduction is the result of emission from quantum-dot-like states in the active layer. The reduction is probably diluted by scattering, and we believe the absence of any observable reduction at room temperature is due to intense carrier scattering. Another effect that could also weaken the observable reduction is the presence of other dot states in the spectral proximity of the states which are responsible for lasing action. This would tend to detune the system and hence lead to field spectrum linewidth broadening as discussed earlier.

The presence of other states was confirmed in measurements of luminescence which were performed on this device at 165 K. At low field strengths the luminescence had a single peak. At high field strengths, however, the spectrum had the dual peak structure shown in Fig. 3. This figure shows a sequence of spectra measured at a field strength of 19 T for different pump currents to the laser. In the spectra the low-energy peak is excited first. With increasing pump current the second peak is excited and eventually provides the gain necessary for lasing action in this device. As the field was reduced these peaks merged into one another, eventually becoming indistinguishable below 15 T. The maximum separation of the peaks was 26 meV at 19 T. Although it is possible that additional structure is hidden at these temperatures by scattering, we believe these peaks can be interpreted as transitions between Landau energy states in the conduction and valence bands of the quantum wells (i.e., simulated quantum dot states). Spectra similar to these have been observed at much lower temperatures in GaAs quantum wells which are subjected to high magnetic fields.[10]

In conclusion, we have discussed the potential advantage of a quantum dot semiconductor laser with regards to achieving a narrow field-spectrum linewidth. Such a device would have an active layer which would be similar to a gas laser in that its luminescence spectrum would result from

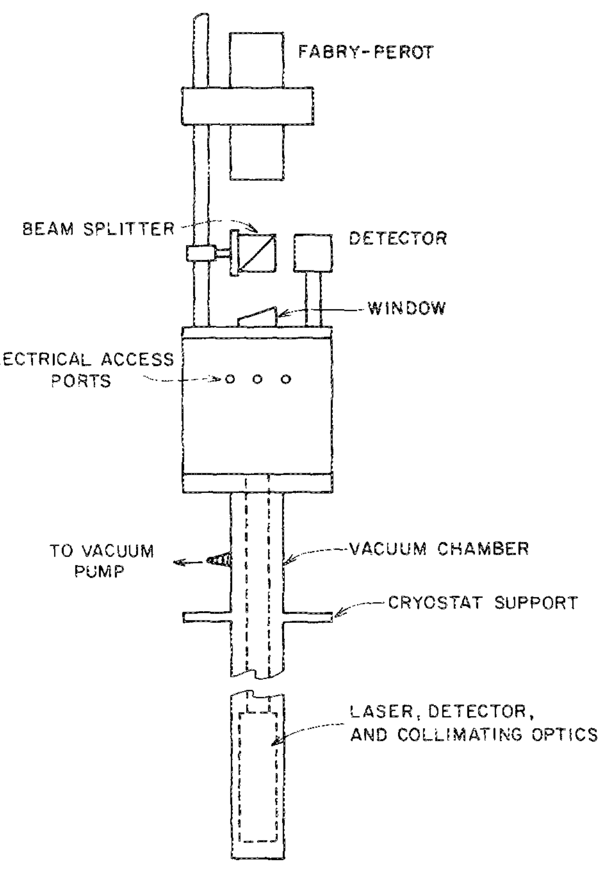

FIG. 1. Sample holder and measurement apparatus.

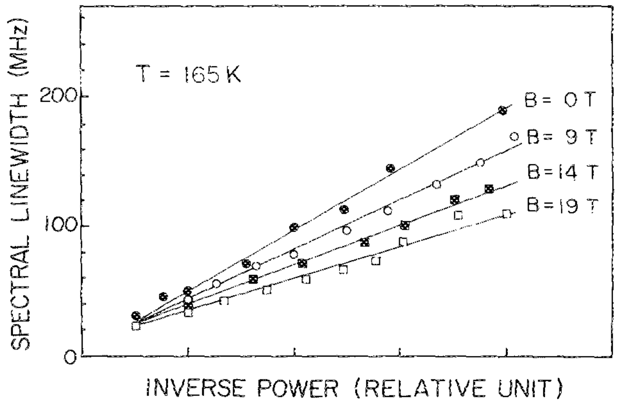

FIG. 2. Measured field spectrum linewidth vs inverse output power in relative units at several magnetic field strengths.

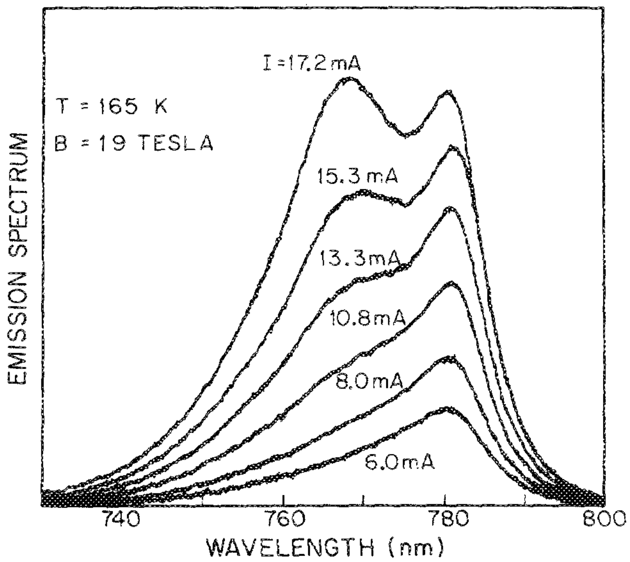

FIG. 3. Measured emission spectrum from a multiple quantum well laser in a 20-T magnetic field for several injection current levels below threshold.

discrete states. To test these ideas we have presented measurements of a multiple quantum well semiconductor laser immersed in a high magnetic field. It is well known that when the magnetic field direction is normal to the quantum well plane this system becomes discrete in the sense mentioned above and may simulate a quantum dot system. Linewidth versus power measurements were taken at room temperature and indicated that the device under test was broadened by spontaneous emission. No linewidth dependence on magnetic field was observed at room temperature, however. At 165 K the linewidth was observed to decrease as the field was increased. We believe this is the result of a discrete set of electronic states setting up in the laser active layer (i.e., dotlike states). Room-temperature measurements were probably diluted by scattering and subsequent broadening of the transition. Measurements of the luminescence spectrum at high field strengths indicated the presence of two peaks. The higher energy peak was responsible for lasing action in the device tested.

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