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Reduction of the spectral linewidth of semiconductor lasers with quantum wire effects—Spectral properties of GaAlAs double heterostructure lasers in high magnetic fields

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The spectral linewidth of a GaAlAs double heterostructure laser placed in a high magnetic field is measured at 190 K. It is found that the power-dependent spectral linewidth is reduced by a factor of 0.6 in a magnetic field of 19 T. This reduction is believed to result mainly from the reduction of the linewidth enhancement factor α due to a quasi-one-dimensional electronic system formed by the high magnetic field (i.e., by quantum wire effects).

Recently, the spectral linewidth of single mode semiconductor lasers has received considerable attention.[1–4] This quantity gives a direct measure of the phase noise in the output of a semiconductor laser and is therefore an important consideration in certain system applications of these devices. Our recent theoretical analysis predicted that this linewidth can be substantially reduced through a modification of the material using the quantum well structure [i.e., two-dimensional (2D) electronic system] or the quantum wire structure (i.e., 1D electronic system).[5–7] These improvements result from the change in the complex electric susceptibility of electrons and holes brought about by the modified electronic density of states. In this letter we report a successful experimental demonstration of the reduced linewidth in semiconductor lasers with quantum wire effects by placing a conventional double heterostructure laser in a high magnetic field. In this case a quasi-1D electronic system is formed by the Lorentzian force confinement of the carriers to tight cyclotron orbits.[8,9]

A GaAlAs buried heterostructure laser grown by liquid phase epitaxy was operated in a stationary magnetic field of up to 19 T at 190 K. The test laser (an ORTEL Corporation experimental model) had a 0.15 μm active region thickness, a 3 μm stripe width, and was 300 μm long. Its threshold current was 10 mA at room temperature (6 mA at 190 K). The laser was mounted on a copper heat sink and was placed inside the sample holder which was evacuated for the measurement. The sample holder was immersed in liquid nitrogen and the temperature of the sample was controlled by a heater. The laser light output was first collimated in the same sample holder and directed through a window. The beam was then split into two parts: one fed into a scanning Fabry–Perot interferometer with a resolution of 25 MHz for measuring the linewidth, and the other fed into a photodetector for monitoring laser output power.

The Bitter magnet used in this measurement could generate stationary 19 T fields and had a 5 cm bore diameter. We placed the laser at the center of the Bitter coil where the magnetic field distribution is most uniform. The laser was placed so that the cavity length direction was parallel to the magnetic field. Since the transverse width of the active layer is less than 2 μm, the nonuniformity of the carrier distribution in the transverse direction due to the Lorentz force can be neglected.

Figure 1 shows the measured spectral linewidth at 190 K for various magnetic fields ($B = 0$, 11, 16, 19 T) as a function of the reciprocal mode power $1/P$. As shown in the figure the measured linewidth for each magnetic field varies linearly with the reciprocal mode power. Such a variation indicates the linewidth results from quantum broadening (spontaneous emission). The experimental results indicate that this power-dependent linewidth is substantially reduced with the increase of the magnetic field. At 19 T, the linewidth decreases by a factor of 0.6 compared to the linewidth without a magnetic field. This improvement of the power-dependent linewidth is believed to be mainly due to quantum wire effects through the formation of a quasi-1D electronic system as discussed below. Figure 1 also shows that the high power limit of the linewidth converges to almost the same linewidth for each magnetic field. This power-dependent

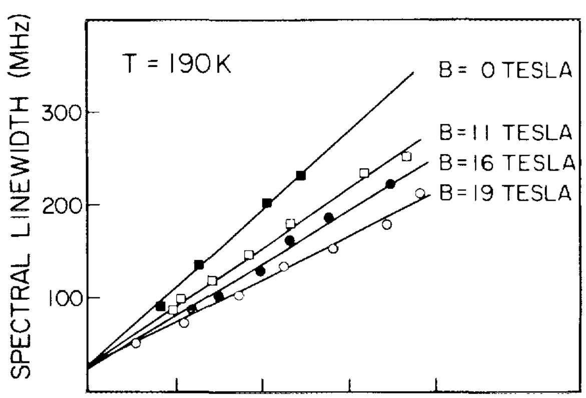

FIG. 1. Measured spectral linewidth as a function of the reciprocal of output power (in relative unit) for magnetic fields of $B = 0$, 11, 16, and 19 T at 190 K.

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linewidth results from the instrumental resolution of the Fabry-Perot interferometer and a number of mechanisms intrinsic to the device ($1/f$ noise, occupation fluctuation, mode competition). The result suggests that the intrinsic contribution to the power-independent linewidth is not crucially affected by the magnetic field.

The power-dependent spectral linewidth $\Delta\nu$ can be expressed by[2]

$$\Delta\nu = \frac{v_g h\nu(\Gamma g) R_m n_{sp}}{8\pi P}(1+\alpha^2), \tag{1}$$

where R_m, v_g, $h\nu$, Γ, g, n_{sp}, and P are the mirror loss, the group velocity of light, the photon energy, the optical confinement factor, the bulk gain at threshold, the spontaneous emission factor, and the laser output power, respectively. Expression (1) differs from the well known Schawlow-Townes linewidth formula through a linewidth enhancement factor involving the quantity α which is given by[3]

$$\alpha = \frac{\partial\chi_R(E_l, n)/\partial n}{\partial\chi_I(E_l, n)/\partial n}, \tag{2}$$

$$\chi(E_l, n) = \chi_R(E_l, n) + \chi_I(E_l, n), \tag{3}$$

where χ, E_l, and n are the complex susceptibility, the photon energy at laser oscillation, and the carrier concentration. α reflects a strong amplitude phase coupling of the lasing field in a semiconductor laser resulting from the highly detuned optical gain spectrum. This coupling causes a phase noise (linewidth) enhancement which was only observed recently.[1] $\chi(E,n)$ is related to the reduced electronic density of states $\rho(\epsilon)$ as shown in the following equation:

$$\chi(E,n) = \int A(\epsilon)\rho(\epsilon)(f_c - f_v)\hat{\chi}(E-\epsilon)d\epsilon, \tag{4}$$

where $A(\epsilon)$, f_c (f_v), and $\hat{\chi}(\epsilon)$ are the dipole matrix element, the Fermi–Dirac function for electrons in the conduction (valence) band, and the complex susceptibility of an electron-hole pair having energy difference ϵ. In a 1D electronic system the density of states $\rho(\epsilon)$ is proportional to $1/\sqrt{\epsilon}$, which has a peaked structure in contrast to the density of states of the 3D electronic system. These structures lead to smaller calculated α's[5] (intuitively, the gain spectrum becomes more tuned). Improvements in $\Delta\nu$ over the conventional device are thus expected in devices employing quantum wire active layers.

A quasi-quantum wire effect in a semiconductor laser can be realized through the use of high magnetic fields[8,9] in which case electrons can move freely only in the direction of the magnetic field. The motion of such electrons is quantized in the two transverse directions (x,y) forming a series of Landau energy subbands. The density of states for electrons in the conduction band $\rho_c(\epsilon)$ can be expressed as

$$\rho_c(\epsilon) = (\hbar\omega_c)\left(\frac{2m_c}{\hbar^2}\right)^{3/2} \sum_{j=0}^{\infty} \frac{1}{\sqrt{\epsilon - (j+\frac{1}{2}\hbar\omega_c)}}, \tag{5}$$

where ω_c and m_c are the cyclotron corner frequency and the effective mass of electrons. When $\hbar\omega_c$ is large enough (i.e., the B field is large enough) only the first Landau subband is occupied, resulting in a true 1D electronic system.

Figure 2 shows theoretical calculations of the power-

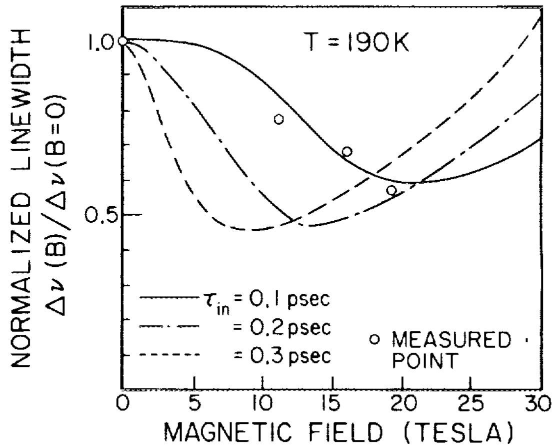

FIG. 2. Measured and calculated spectral linewidth as a function of magnetic field. The open circles represent the measured data on the basis of Fig. 1. The solid curves give the theoretical linewidth $\Delta\nu$ for various τ_{in}.

dependent linewidth in the magnetic field normalized by the linewidth without the magnetic field, i.e., $\Delta\nu_{norm}(B) = \Delta\nu(B)/\Delta\nu(B=0)$ plotted as a function of the magnetic field B for various intraband relaxation times τ_{in}. In this calculation the necessary modal gain for laser oscillation is assumed to be 50 cm^{-1}. The open circles represent the measured results on the basis of Fig. 1. The comparison between the experimental result and the calculated result suggests that the τ_{in} of the measured laser is about 0.1 ps. The theoretical results indicate that $\Delta\nu_{norm}(B)$ decreases with the increase of B initially and then begins to increase again, leading to the existence of a magnetic field B_{min} which minimizes the $\Delta\nu_{norm}(B)$. Such a minimum exists because, in addition to the B field dependence of α in Eq. (1), one other quantity, n_{sp}, also varies with the B field. These quantities vary in an opposing fashion as illustrated in Fig. 3 where α and n_{sp} are calculated as a function of magnetic field assuming a τ_{in} of 0.1 ps.

Although the theoretical analysis shows that the $\Delta\nu_{norm}(B)$ is reduced only by a factor of 0.5–0.6 B_{min}, this does not imply that the smallest attainable $\Delta\nu_{norm}(B)$ of the

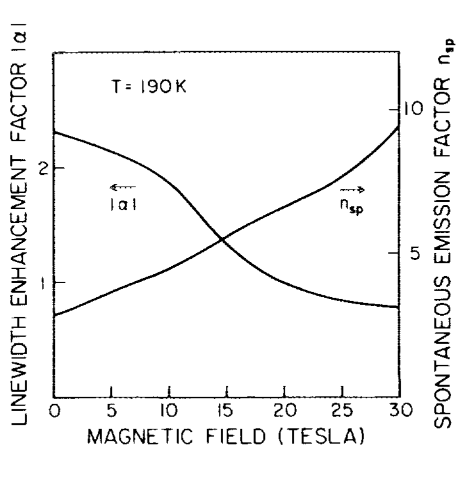

FIG. 3. Calculated linewidth enhancement factor α and spontaneous emission factor n_{sp} as a function of magnetic field. In this calculation τ_{in} is assumed to be 0.1 ps.

quantum wire laser is limited to this value. One important difference between "true" quantum wire structures and the magnetic field quasi-quantum wires is that the optical confinement factor for true quantum wire structures can be controlled by varying the number of quantum wires. Theoretical predictions indicate that a higher Fermi energy level for laser oscillation leads to lower α and n_{sp}.[7] Therefore, in the true quantum wire case, it should be possible to decrease n_{sp} and α by reducing the number of quantum wires while maintaining the 1D electronic properties. This would allow one to reap the benefits of quantum wires in terms of smaller α's without paying a penalty in n_{sp}. The overall reduction of linewidth, $\Delta\nu$, would then be much larger than demonstrated.

In conclusion, the improvement of the semiconductor laser spectral linewidth due to 1D (quantum wire) effects was successfully demonstrated using a high magnetic field. The results correspond to a reduction of the linewidth by a factor of 0.6 at a magnetic field of 19 T.

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