Enhanced modulation bandwidth of GaAlAs double heterostructure lasers in high magnetic fields: Dynamic response with quantum wire effects

Y. Arakawa,[a] K. Vahala, and A. Yariv
California Institute of Technology, Pasadena, California 91125

K. Lau
Ortel Corporation, Alhambra, California 91803

(Received 1 July 1985; accepted for publication 9 September 1985)

The modulation bandwidth of GaAlAs double heterostructure (DH) lasers in high magnetic fields is measured. We found that the modulation bandwidth is enhanced by $1.4\times$ with a magnetic field of 20 T. This improvement is believed to result from the increase of the differential gain due to two-dimensional carrier confinement effects in the high magnetic field (quantum wire effects). A comparison of the experimental results with a theoretical analysis indicates that the intraband relaxation time $\tau_{\rm in}$ of the measured DH laser in the range of 0.1 to 0.2 ps.

The direct modulation bandwidth of conventional double heterostructure (DH) semiconductor lasers has been studied intensively because of its importance in applications of these devices to optical communications.[1-5] The practical direct modulation bandwidth f_r is set by the relaxation resonance frequency which is given by[3]

$$f_r = \frac{1}{2\pi}\left(\frac{g'(n,E_l)P_0}{\tau_p}\right)^{1/2}, \tag{1}$$

where P_0 is the steady-state photon density in the cavity, τ_p is the photon lifetime, $g'(n, E_l)$ is the differential gain [i.e., $g'(n, E_l) \equiv dg(n, E_l)/dn$], and E_l is the photon energy at which the laser oscillation occurs. Equation (1) expresses the modulation bandwidth as a simple function of three fundamental, independent parameters and shows that the increase of $g'(n, E_l)$ and P_0 or decrease of τ_p will increase the modulation bandwidth. P_0 and τ_p depend strongly on the laser geometry, and modulation speed enhancement based upon their control has been demonstrated.[3,4] The differential gain $g'(n)$, on the other hand, is an excitation-dependent material parameter. We have previously predicted that quantum confinement of electron motions in two-dimensional or one-dimensional active layers (1D or 2D AL; quantum well or quantum wire structures) should enhance this quantity and concomitantly the modulation speed.[6]

In this letter we report a successful demonstration of modulation speed enhancement through the above quantum wire effect. This was achieved by placing an GaAlAs DH laser in a high magnetic field thereby inducing quantum wire effects through the Lorentz force confinement of the carriers.[7] We compare these observed changes with the results of a simple calculation which is described below.

If we assume rigorous k-selection rules but take broadening effects due to intraband relaxation into consideration, the differential gain is given by[8]

$$g'(n, E_l) = \int C(\epsilon)\rho_{\rm red}(\epsilon)\left(\frac{df_c(n,\epsilon)}{dn} - \frac{df_v(n,\epsilon)}{dn}\right) \times \frac{\hbar/\tau_{\rm in}}{(E_l-\epsilon)^2 + (\hbar/\tau_{\rm in})^2}\,d\epsilon, \tag{2}$$

where $\rho_{\rm red}$, E, C, $f_c(f_v)$, and $\tau_{\rm in}$ are the reduced density of states, lasing photon energy, the dipole matrix element, the Fermi occupancy for electrons in the conduction band (valence band), and the intraband relaxation time (i.e., the T_2 time). The integration variable ϵ is the energy difference between conduction and valence-band states with identical crystal wave vectors. In Ref. 6 we have shown that a change in the density of states $\rho(\epsilon)$ due to the decrease of the dimension of the carrier motion is expected to lead to improvement of $g'(n, E_l)$. In a quantum wire structure, electrons are confined by a potential profile which reduces the number of degrees of freedom of motion to one. In these active layers the density of states comes to have a configuration with abrupt changes: $\rho(\epsilon)$ in a 1D AL is proportional to $1/\sqrt{\epsilon}$.[7] At the present time it is difficult to fabricate quantum wire structures. There is, however, an alternative way to realize quantum wire effects; this is by use of high magnetic fields.[7] When a high magnetic field B is applied along an axis z, electrons can move freely only along this axis. The motion of such electrons is quantized in the two transverse directions (x, y) and forms a series of Landau energy levels ϵ_c^j $(j = 0,1,2...)$ which can be related to the cyclotron frequency $\omega_c = eB/m_c$ as follows:

$$\epsilon_c^j = (j + \tfrac{1}{2})\hbar\omega_c + \hbar^2 k_z^2/2m_c, \tag{3}$$

where e, m_c, and k_z are the electron charge, effective mass, and the crystal wave vector parallel to the z axis. With this energy quantization in the x-y plane, the electrons behave as a quasi-1D gas and $\rho(\epsilon)$ can be expressed as

$$\rho(\epsilon) = \hbar\omega_c\left(\frac{2m^*}{\hbar^2}\right)^{3/2}\sum_{j=0}^{\infty}\frac{1}{\sqrt{\epsilon - (j+\frac{1}{2})\hbar\omega_c}}. \tag{4}$$

If we ignore the higher subbands $(j > 1)$, the result is a completely one-dimensional system.

We operated liquid phase epitaxially grown GaAlAs buried heterostructure lasers with a multimode optical fiber pigtail in stationary magnetic fields up to 20 T at room temperature. The test laser (ORTEL Corporation experimental model) had a $0.1\ \mu\text{m}\times 2\ \mu\text{m}\times 300\ \mu\text{m}$ active layer and a threshold current of 14 mA. The laser was mounted on a copper heat sink and the output light was coupled into a multimode optical fiber which was fixed by glue on a small base attached to the heat sink (core and classing regions of the fiber are 50 and 500 μm). The output of the optical fiber

[a] On leave of absence from the University of Tokyo, Japan.

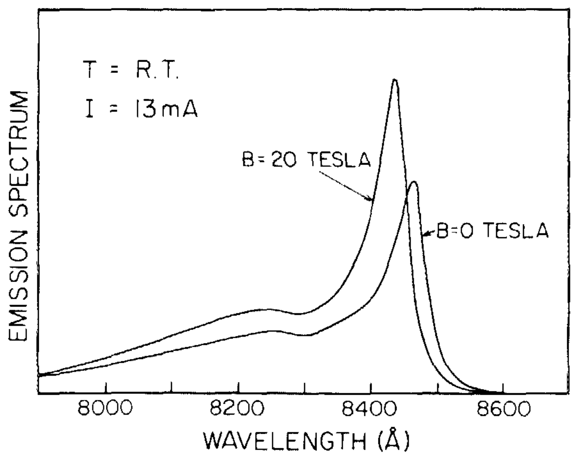

FIG. 1. Output spectrum just below threshold ($J/J_{th} \sim 0.9$) with and without high magnetic field of 20 T.

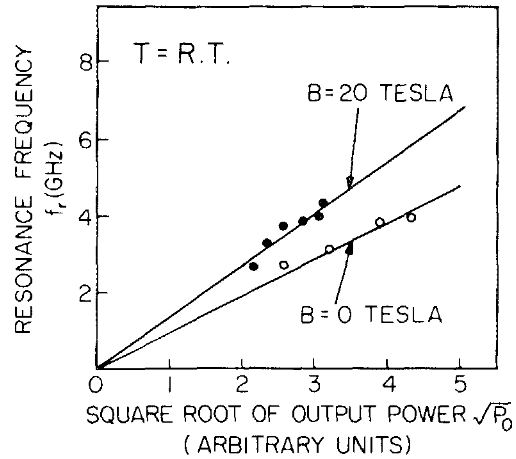

FIG. 2. Measured resonant frequency with and without magnetic fields as a function of the square root of the output power P_0. The open circle ($B = 0$) and closed circle ($B = 20$ T) indicate the measured f_r's.

was fed into a scanning Fabry–Perot interferometer with a resolution of 75 MHz. The modulation bandwidth f_r was measured by directly observing the small-signal modulation sidebands with the Fabry–Perot interferometer while sweeping the modulation frequency.

The Bitter magnet used in this measurement could generate stationary 20 T fields and had a 5 cm bore diameter. We placed the DH laser at the center of the Bitter coil where the magnetic field distribution is most nearly a constant. 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 emission spectrum of the DH laser with and without a magnetic field of 20 T. The injected current is 13 mA (below threshold). The observed spectral peak corresponds to the gain peak and was observed to shift with the application of the magnetic field. This shift results from a modification of the density of states function under application of the magnetic field. The calculated shift of the first Landau energy level ($1/2\ \hbar\omega_c$) under the magnetic field of 20 T is about 17 meV. The observed wavelength shift due to the magnetic field is about 40 A which corresponds to about 8 meV. This discrepancy can be explained by intraband relaxation effects.[9,10] The threshold current under application of the magnetic field was slightly lower (less than 5%) than the threshold current without magnetic field.

The measured relaxation resonance frequency with and without a magnetic field of 20 T is presented in Fig. 2 as a function of the square root of the output power P_0. Open circles ($B = 0$) and closed circles ($B = 20$ T) indicate the measured f_r. The straight lines in the figure are drawn by the least-squares error method. Since, as shown in Eq. (1), the resonant frequency is proportional to $\sqrt{P_0}$, the f_r should lie on straight lines. The variation of the slope of these lines will mainly reflect the changes in the differential gain g' which have resulted from the application of the magnetic field (τ_p changes only slightly). We notice that the f_r with $B = 20$ T is enhanced by 1.4× compared to the f_r with $B = 0$. From this change we can estimate that $g'(B = 20\ \text{T})$ is 1.9 times larger than $g'(B = 0)$.

The differences between the electronic states in the presence of magnetic fields and those in a 1D AL (i.e., a true quantum wire structure) are as follows. First, higher energy subband effects are different. With the magnetic field, the energy difference between adjacent bands is a constant which is equal to $\hbar\omega_c$, whereas in the 1D AL it is not {the subband energies being given by $(\hbar^2/2m^*)[(i\pi/L_y)^2 + (j\pi/L_x)^2]$, where L_x and L_y are the dimensions of the quantum wire and (i, j) are integers}. However, if both the thermal energy spreading kT and the energy spreading due to intraband relaxation $\hbar/\tau_{in}$ are much smaller than $\hbar\omega_c (kT, \hbar/\tau_{in} \ll \hbar\omega_c)$, we can ignore the higher subband effects. This condition is approximately satisfied for electrons in the conduction band when the magnetic field is greater than 15 T. Therefore, we can expect that the magnetic field strengths employed here constitute a fairly sufficient realization of the 1D AL structure. The second difference is that we cannot control the optical volume (optical confinement factor) of a DH laser with a magnetic field. In this case, the optical volume is regarded to be the same as that of the DH laser without the magnetic field. In the case of a true 1D AL laser one could presumably control this volume by varying the number of quantum wires.

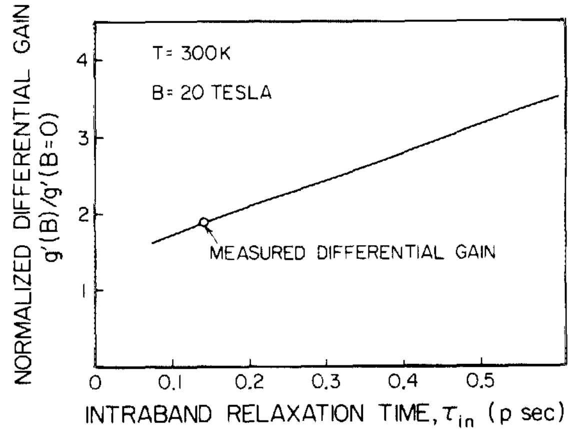

FIG. 3. Differential gain $g'(B = 20\ \text{T})$ divided by $g'(B = 0)$ as a function of the intraband relaxation time τ_{in}. The open circle indicates the measured $g'(B = 20\ \text{T})/g'(B = 0)$ on the basis of the results shown in Fig. 2.

Figure 3 shows the calculated results for the normalized differential gain $g'(B = 20\text{ T})/g'(B = 0\text{ T})$ as a function of the intraband relaxation time τ_{in}. In this analysis, the total loss is assumed to be 50 cm^{-1} and the confinement factor Γ is 0.5. We also assume that the total loss is independent of the magnetic field strength. This analysis indicates that the differential gain increases with the increase of τ_{in}. This can be expected since with the increase of τ_{in} the density of states function has a more peaked structure. Since the measured $g'(B = 20)/g'(B = 0)$ is ~ 1.9 as shown with a open circle in the figure, the τ_{in} in the DH lasers is estimated to be ~ 0.15 ps from the calculated results. This estimated τ_{in} is quite reasonable.

In this calculation, dependence of the coefficient $C(\epsilon)$, which is proportional to the square of the absolute value of the dipole matrix element, on the magnetic fields is also considered. As discussed in Refs. 6 and 12, in 1D AL laser, the $C(\epsilon)$ depends strongly on the direction of the polarization of the light propagating in the active layer against that of the quantum wire. It was found that the magnitude of the $C(\epsilon)$ at the subband edge becomes maximum (1.5 times larger than that of bulk crystal) when the wire is parallel to the direction of the polarization. In our experiment, as described before, the magnetic field is applied parallel to the cavity length. This geometry corresponds to the quantum wires perpendicular to the direction of the polarization of the light beam. Therefore, the $C(\epsilon)$ is not maximized under our condition, which leads to the reduction of the 1D effects. If we apply the magnetic field perpendicular to both cavity length direction and the current direction, the quantum wire, which is parallel to the direction of the polarization of the light beam, can be realized. This causes, however, the nonuniform distribution of carriers by the Hall effect, leading sometimes to the pulsation effects. The detailed discussion on the dipole matrix element with the magnetic field is described in a separate paper.[13]

In conclusion, we have investigated the modulation bandwidth of GaAlAs double heterostructure lasers in magnetic fields up to 20 T and have demonstrated significant enhancement of modulation bandwidth (1.4× at room temperature). This improvement results from the change in differential gain due to two-dimensional carrier confinement effects caused by the high magnetic field. If we place a quantum well laser in a high magnetic field, electrons are confined three dimensionally by both quantum well potential and Lorentzian force, which leads to the realization of quantum boxes (0D AL) effects.[11] The discussion of these fully quantized effects on the dynamic response will be presented in a separate paper.

Part of this work was performed while the authors were guest scientists at the Francis Bitter National Magnet Laboratory at MIT, which is supported by the National Science Foundation. The authors would like to express their sincere thanks to Dr. Larry Rubin and Bruce Brandt at the National Magnet Laboratory for their assistance in this experiment. This work was supported by the Air Force Office of Scientific Research, the Office of Naval Research, I.T.T. Corporation, and the Japanese Society for the Promotion of Science.

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