Carrier-induced phase shift and absorption in a semiconductor laser waveguide under current injection

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The effects of injected carriers on the refractive index of an AlGaAs/GaAs semiconductor laser waveguide are investigated through measurements of the carrier-induced phase shift and free-carrier absorption of a guided probe laser beam at a wavelength below the band gap of the GaAs waveguide. The carrier densities and carrier lifetimes at various injection current levels can be deduced directly from these measurements. A carrier-induced phase shift of more than $\pi/2$ is observed.

The injected carrier density in a semiconductor laser is usually determined from measurement of the carrier lifetime[1,2] which generally proceeds with injection of a short current pulse and subsequent observation of the decay of the optical response.[3,4] The carrier lifetime is a complicated nonlinear function of the carrier density, usually expressed in an expansion $\tau^{-1} = A + BN + CN^2$, where τ and N are carrier lifetime and carrier density, respectively. The coefficients in this expansion depend strongly on the individual device parameters.[4] Detailed knowledge of the radiative and nonradiative recombination rates and the ionized impurity concentration in the device is needed[4] before the carrier density can be deduced from lifetime measurement. However, the injected free carriers change the index of refraction of the semiconductor waveguide. In this letter we study the effects induced by the injected carriers and deduced the carrier density from these measurements.

The free carriers reduce the real part of the refractive index in a semiconductor because of carrier-induced dispersion in the dielectric constant. The imaginary part is increased because of free-carrier absorption. If the semiconductor is probed with a beam at a wavelength far below the band gap of the semiconductor, the imaginary part of the refractive index is negligibly small in comparison to the real part, n, and the carrier-induced change in n can be approximated by[5]

$$\Delta n = -\frac{1}{2n}\frac{4\pi N e^2}{\omega^2 m^*}, \qquad (1)$$

where N is the carrier density, ω is the angular frequency of the probe light, and m^* is the reduced electron-hole optical effective mass. Because the probe wavelength is far below the band gap of the semiconductor, interband transitions of the electrons do not contribute to the imaginary part of the refractive index at this wavelength. To the extent that scattering is negligible, free-carrier absorption is solely responsible for the absorption of the probe light.

In our experiment, a cw laser beam at 1.064 μm from a Nd:YAG laser was used to probe a single-mode AlGaAs/GaAs buried heterostructure (BH) semiconductor laser waveguide. The semiconductor laser has a lasing threshold current of 18 mA and a lasing wavelength at 8462 Å, which corresponds to a band gap of 1.465 eV in the active region. The dimensions of the active waveguide region are 3 μm$(w) \times 0.15$ μm$(d) \times 300$ μm(l). The index step of the symmetrical BH waveguide is $n_a - n_c = 0.2$, which gives a confinement factor[6] $\Gamma = 0.35$ for the 1.064-μm probe beam coupled through the waveguide. When carriers are injected into the waveguide, changes in the real part of the refractive index cause phase changes in the 1.064-μm probe beam which travels through the waveguide. The induced phase shift is given by[6]

$$\Delta\phi = \Gamma \Delta n (2\pi/\lambda) l, \qquad (2)$$

where λ is the probe wavelength *in vacuo* and l is the length of the waveguide. On the other hand, changes in the imaginary part due to carrier absorption reduce the output intensity of the guided probe beam by $e^{-\Gamma\alpha l}$, where α is the absorption coefficient.

Consider the GaAs waveguide probed at 1.064 μm. The electron and hole optical effective masses are $m_e^* = 0.069 m_0$ and $m_h^* = 0.52 m_0$, respectively,[7] at 300 K at a carrier density around 1×10^{18} cm^{-3}. The reduced effective mass is $(m^*)^{-1} = (m_e^*)^{-1} + (m_h^*)^{-1} = 0.061 m_0$. Equation (1) then gives a carrier-induced change of the refractive index at $\lambda = 1.064$ μm,

$$\Delta n = -2.388 \times 10^{-21}\ N\,\mathrm{cm}^3. \qquad (3)$$

The free-carrier absorption coefficient of GaAs[7] at 1.064 μm is $\alpha = \sigma N$, where $\sigma = \sigma_e + \sigma_h$ is the free-carrier absorption cross section. Both Δn and α are linearly proportional to N under the conditions considered in this experiment. The electron absorption cross section[7] is $\sigma_e = 6 \times 10^{-18}$ cm^{-2} and the hole absorption cross section[7] is estimated to be twice as large, $\sigma_h \sim 12 \times 10^{-18}$ cm^{-2}, due to intervalence-band absorption. Under current injection, the refractive index also changes in response to the increase of the junction temperature. For GaAs[7]

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$$\frac{1}{n}\frac{dn}{dT}=4.5\times 10^{-5}.$$

Under the typical conditions where the injected carrier density is on the order of 10^{18} cm^{-3}, the junction temperature increase is on the order of 1 K. The thermally induced changes in the refractive index is at least one order of magnitude smaller than the change induced by the carriers. Because the probe wavelength is well below the band gap, the slight increase of the junction temperature does not induce any increase in the absorption of the probe light either. Combining Eqs. (2) and (3), we have

$$N=7.077\times 10^{15}(\Delta\phi/l\Gamma)\ \text{cm}^{-2}, \tag{4}$$

from measurement of the carrier-induced phase shift. From the free-carrier absorption, we have

$$N=5.56\times 10^{16}\,\frac{1}{l\Gamma}\ln\frac{P(0)}{P(I)}\ \text{cm}^{-2}, \tag{5}$$

where $P(0)$ and $P(I)$ are the intensities of a fixed portion in the center of the output probe beam at 1.064 μm when the waveguide is injected with no current and a current I, respectively.

A Mach–Zehnder interferometer was set up to measure the current-induced phase shift of the probe beam. The cw probe beam at 1.064 μm was split into two beams with a beamsplitter. One traveled through free space. The other was coupled with a microscope objective into the single-mode AlGaAs/GaAs semiconductor laser waveguide which is under dc current injection. A pinhole was placed after the output of the waveguide to block the stray light and to pass only the guided light. This beam was then collimated with another microscope objective of the same magnification and was combined with the free-space-traveling beam with a second beamsplitter. The individual intensities of these two beams at the output were well balanced. They traveled through a roughly equal distance. The accurate relative traveling distance was fine tuned with a piezoelectric micropositioner of 100 Å resolution to determine the relative phase difference between them. Two independent correction lenses were used to adjust their wave fronts as close to the plane wave front and as close to each other as possible for the convenience of phase measurement. Adjustment of the wave fronts and alignment for perfect collinear overlapping of their wave fronts were monitored with a camera and a TV screen until the line fringes and ring fringes disappeared completely. Then a small portion of the expanded combined beam was selected with an iris diaphram. Its intensity was detected with a large-area Ge detector and the signal was measured with a lock-in amplifier. Several filters were used to prevent the spontaneous and stimulated emission of the semiconductor laser from being detected by the Ge detector.

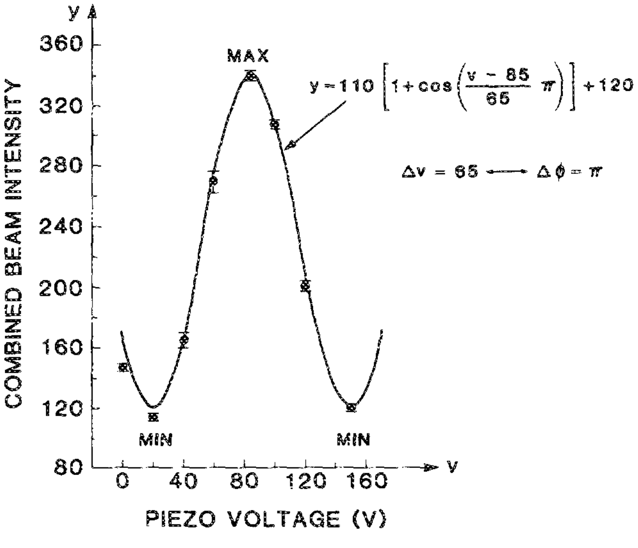

FIG. 1. Combined intensity of the guided beam and the free-space-traveling beam vs the voltage on the piezoelectric micropositioner which controls the relative traveling distance of these two beams. A change of 65 V corresponds to a relative phase change of π between these beams.

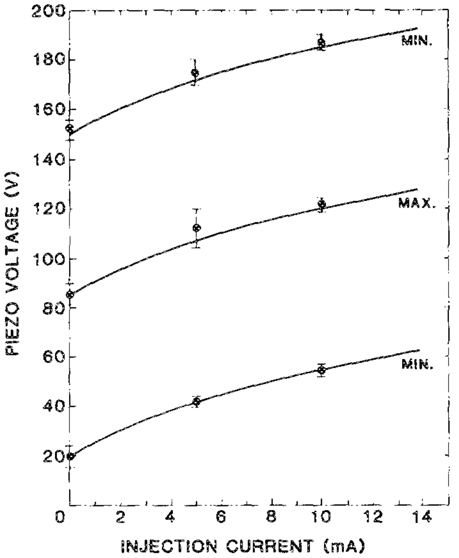

FIG. 2. Voltage applied on the piezoelectric micropositioner for tracking the maximum and minimum combined intensity of the guided and free-space-traveling beams vs the current injected in the waveguide which induces phase changes in the guided beam. The solid curves are calculated from the curve in Fig. 3.

The intensity of the combined beam changed sensitively in response to variations in the injection current level. However, the absolute value of the current-induced phase shift in the guided probe beam cannot be easily deduced from the absolute or relative changes of the combined beam intensity because the injected carriers change both the phase and the absolute intensity of the guided beam, as is discussed above. We therefore measured the phase shift by fixing the injection current at each level and adjusting the phase of the free-traveling reference beam with the piezoelectric micropositioner to track the maxima (constructive interference) and minima (destructive interference) of the combined beam intensity. Thus the phase shift of the guided beam can be measured independently of its intensity changes caused by free-carrier absorption. With no injection current, the relative phase change of the two beams caused by changing the relative traveling distance with the micropositioner can be used to calibrate the piezoelectric reading with respect to the phase change, as is shown in Fig. 1. When the semiconductor laser waveguide was injected with a current, the voltage of

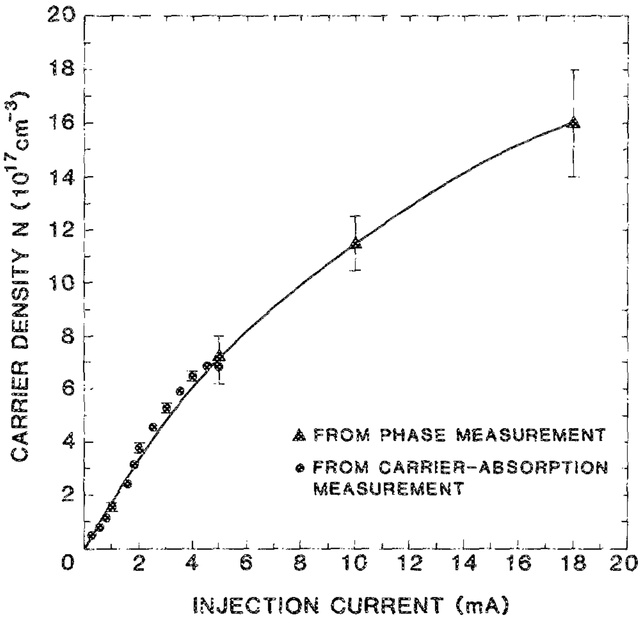

FIG. 3. Carrier density as a function of the injection current derived from measurements of carrier-induced phase shift and free-carrier absorption of the guided probe beam. The curve is a fit of the data with a linear expansion of the carrier lifetime in terms of the carrier density.

the piezoelectric controller was adjusted and the changes of the applied voltage required for tracking the maximum and minimum output intensities of the combined beam at various injection current levels were recorded. The measured data are shown in Fig. 2. From Fig. 2 it is determined that the waveguide shifts the phase of the guided beam by $\pi/3$ and $7\pi/13$ with a current of 5 and 10 mA, respectively. At the lasing threshold of 18 mA, the phase shift is about $3\pi/4$. It is clear that the phase shift is nonlinear with the injection current and the differential change decreases at high current levels. From Eq. (4), the injection carrier density at these current levels can be deduced, which are shown in Fig. 3. The carrier density at the lasing threshold is estimated to be $(1.6 \pm 0.2) \times 10^{18}$ cm^{-3}. At low injection current levels, accurate measurement of the carrier-induced phase changes is very difficult because of the small changes in the phase, although it is observable. We therefore tried to deduce the carrier density from the carrier-induced absorption. In this measurement, the same experimental setup was used except that the free-space-traveling beam was blocked. Relative changes in the output intensity of a small central portion of the guided beam were measured. The carrier density as a function of the injection current at low current levels was then deduced with Eq. (5). The results are also shown in Fig. 3. It is clear that the results are consistent with those obtained from the phase measurement. If we apply the steady-state equation $N = I\tau/lwd$, the carrier lifetime can also be deduced. The results are $\tau = 3.1$, 2.5, and 1.9 ns at $I = 5$, 10, and 18 mA, respectively. The data in Fig. 3 can be fitted with a curve described by $\tau^{-1} = A + BN + CN^2$ with $A = (2.4 \pm 0.12) \times 10^8$/s, $B = (8.0 \mp 2.6) \times 10^{-11}$ cm^3/s, and $C = (5.1 \pm 1.6) \times 10^{-29}$ cm^6/s, as is shown in the figure. From this curve, changes in the applied voltage needed to track the maximum and minimum interference at various injection current levels can be calculated. They are displayed as the curves in Fig. 2. We did not try to model from A, B, and C the radiative and nonradiative recombination rates because, as is discussed earlier, modeling will not generate reliable information unless more detailed knowledge of the impurity concentration is available.[4]

In conclusion, injection carrier-induced changes in the refractive index of a semiconductor laser waveguide are studied with a probe beam at a wavelength below the band gap. Carrier-induced phase shift and free-carrier absorption of the probe beam are measured carefully. The carrier density and carrier lifetime can be deduced from these measurements. With a longer waveguide, a phase shift of π in the guided beam can be achieved with current injection.

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