Rapid modulation of interband optical properties of quantum wells by intersubband absorption

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Intersubband absorption of radiation by a two-dimensional electron gas can be used to control the electron temperature and effect a significant modulation of the interband optical properties of the semiconductor in the quantum well. We discuss the implementation of a fast modulator of infrared radiation for fiber-optical communications as well as the formation of powerful and short single-mode infrared pulses.

It is well known that the interband (IB) absorption coefficient g in a degenerate semiconductor is a strong function of the electron temperature T_e. It has been proposed[1] to use this effect for a rapid control of the semiconductor-laser gain by driving a lateral electron-heating current through the active region. The present letter deals with effects that can be obtained in a multiple quantum-well (MQW) waveguide with no external pumping current.

We shall discuss the situation in which T_e is varied by irradiating the MQW by infrared photons $\hbar\omega$ (e.g., from a CO_2 laser, $\hbar\omega = 124$ meV) nearly resonant (within $\Delta\omega$) with the intersubband (ISB) energy. The proposed waveguide structure is illustrated in Fig. 1. The IB radiation propagates along x and the ISB along y directions. The ISB radiation in the waveguide is assumed TM polarized and its photon flux inside a QW will be denoted by Φ_ω. In a steady state, T_e is determined by the balance equation

$$k\Delta T_e = w\tau_E\hbar\omega, \tag{1}$$

where τ_E is the energy relaxation time of QW electrons, $\Delta T_e \equiv T_e - T$, and w is the ISB transition rate. Evaluating w by the Golden rule,[2] we have

$$w = \frac{e^2 f}{2\gamma}\frac{R_0}{m\bar{n}}\Phi_\omega\frac{\gamma^2}{(\Delta\omega)^2+\gamma^2}, \tag{2}$$

where $R_0 \equiv 377\ \Omega$ is the vacuum impedance, m the electron effective mass, and $\bar{n}$ the refractive index; $f \approx 1$ is the oscillator strength and γ the width of the ISB resonance. The typical power flux density 10 kW/cm^2 of a CO_2 laser corresponds to $\Phi_\omega \approx 5\times 10^{23}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. We shall be considering the case of an InGaAs QW ($m = 0.041\ m_0$). Taking $\hbar\gamma \approx 4$ meV (from the data[3] in GaAs QW at 300 K) and $\tau_E \approx 6$ ps (from the energy loss rate of 7 meV/ps measured[4] in InGaAs/InP QW at $T_e = 500$ K for high carrier densities), Eq. (1) gives $\Delta T_e \approx 260$ K at resonance. The relatively long energy relaxation time[5] is usually explained by hot photon effects

A desired variation of T_e can be accomplished by varying either the intensity Φ_ω or the frequency $\Delta\omega$. It is possible and preferable to vary the detuning $\Delta\omega$ at constant CO_2 power and frequency—by Stark shifting the ISB resonance. For this purpose, we need means for applying an electric field in the z direction. To minimize the loss of ISB power by free-carrier absorption in the contact layers controlling the electric field, the use of doped bulk regions should be avoided. Instead, we propose to make the contact layers out of multiple quantum wells, doped or modulation doped to a high conductivity and narrow enough that the intersubband resonance in the contact QWs is far above the ISB photon energy $\hbar\omega$.

Device length L_ω in the y direction should be chosen short enough that Φ_ω be approximately uniform, $\alpha L_\omega < 1$, where α is the ISB absorption coefficient,

$$\alpha = \frac{r\Gamma_\omega n_S}{d_{\mathrm{QW}}}\frac{w}{\Phi_\omega} = \frac{\Gamma_\omega n_S}{d}\frac{e^2 f}{2\gamma}\frac{R_0}{m\bar{n}}\frac{\gamma^2}{(\Delta\omega)^2+\gamma^2}, \tag{3}$$

$d = d_{\mathrm{QW}} + d_{\mathrm{B}}$ is the MQW period, $d_{\mathrm{QW}} \equiv rd$ the QW thickness, n_S the electron sheet concentration per period, and Γ_ω the confinement factor for the ISB radiation intensity. For an efficient operation of the modulator it is important that the steady-state density p_S of holes generated by the IB radiation be small compared to $n_S = n_0 + p_S$. The equilibrium electron density n_0 (introduced by doping) is limited

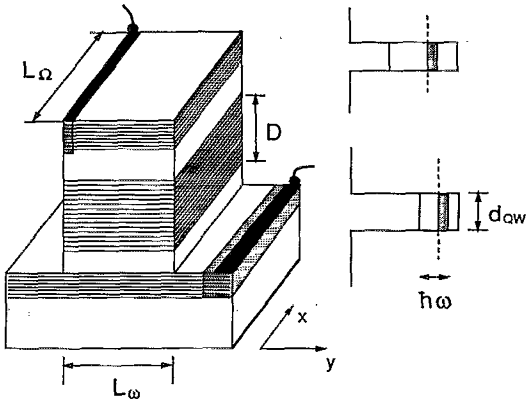

FIG. 1. Schematic diagram of the modulator. Typical dimensions, considered in this work: $L_\Omega = 500\ \mu$m, $L_\omega = 3\ \mu$m, and $D = 1.5\ \mu$m. The quantum-well width $d_{\mathrm{QW}} \approx 100$ Å in the core (D) layers is chosen so that the intersubband separation is nearly resonant with $\hbar\omega$. The equilibrium sheet-electron concentration in the core QW s is denoted by n_0. The width of contact QWs (top right) is narrow enough to avoid absorption of TM-polarized ISB radiation.

by the requirement that the Fermi level be less than the ISB separation, $E_F < \hbar\omega$. At $n_0 = 2\times 10^{12}\ \mathrm{cm}^{-2}$ in the range of 300 to 500 K one has $E_F \approx 115$ meV. Higher n_0 would result in a diminishing efficiency of carrier heating due to increasing population of the second subband.

The modulator length L_Ω in the x direction should be chosen so as to achieve a desired modulation depth of the transmitted IB beam $e^{r\Gamma_\Omega g L_\Omega}$, where Γ_Ω is the waveguide confinement factor for the IB radiation intensity. The gain function g is of the form

$$g(T_e, T_h, n_S, p_S, \hbar\Omega) = (f_e + f_h - 1) g_{\max}, \tag{4}$$

where f_e and f_h are the Fermi functions of electrons and holes, respectively, at energies selected by incident photons $\hbar\Omega$ inducing transitions between the heavy hole and the lowest electron subbands. The value of $g_{\max}$ in an InGaAs QW is, typically,[6] $g_{\max} \approx 10^3\ \mathrm{cm}^{-1}$. For transitions at the fundamental absorption edge in the QW, the Fermi factors are given by

$$f_e(n_S, T_e) = 1 - e^{-\pi\hbar^2 n_S/mkT_e}; \tag{5a}$$

$$f_h(p_S, T_h) = 1 - e^{-\pi\hbar^2 p_S/m_h kT_h}; \tag{5b}$$

where $m_h \approx 0.5 m_0$ and T_h are the heavy-hole effective mass and temperature, respectively. The modulator can be expected to perform up to frequencies limited by the inverse energy relaxation time τ_E, provided the slower processes associated with carrier generation by the IB radiation make negligible contribution to g. At a given value of n_0 the latter requirement puts a limit on the IB flux that is modulated.

To estimate this limit and calculate the temperature dependence of g in a steady state, we consider the rate equations:

$$\frac{dp_S}{dt} = -\bar{c}gS - R_S n_S p_S; \tag{6a}$$

$$\frac{dS}{dt} = (r\Gamma_\Omega)(\bar{c}g)S + \frac{S_0 - S}{\tau_{\mathrm{ph}}}. \tag{6b}$$

Here S is the photon density per unit area in a single QW, $S_0 \equiv \Phi_\Omega d_{\mathrm{QW}}/\bar{c}$, where Φ_Ω is the incident IB photon flux, $\bar{c} \equiv c/\bar{n}$ is the speed of light, and $\tau_{\mathrm{ph}} = L_\Omega/\bar{c}$. The quantity $R_S \equiv B/d_{\mathrm{QW}}$ where $B \approx 10^{-10}\ \mathrm{cm}^3/\mathrm{s}$ is the radiative recombination coefficient.[6]

Figure 2 shows the stationary gain as a function of incident power, calculated from Eqs. (6) at several carrier temperatures,[7] assuming $n_S = n_0 + p_S$ with $n_0 = 2\times 10^{12}$ cm^{-2} and $\tau_{\mathrm{ph}} = 5$ ps ($L_\Omega \approx 500\ \mu\mathrm{m}$). We see that for $S_0 \lesssim 10^8\ \mathrm{cm}^{-2}$ carrier-generation effects can be neglected. The total modulation power $\mathscr{P}_\Omega = \Gamma_\Omega^{-1} \mathscr{A} \Phi_\Omega \hbar\Omega$ is related to S_0 by

$$r\Gamma_\Omega\, \mathscr{P}_\Omega = N L_\omega \hbar\Omega \bar{c} S_0,$$

where $\mathscr{A} = D \times L_\omega$ is the MQW core cross-sectional area, D the core thickness, and $N = D/d$ the number of periods. Taking $n = 50$, $r\Gamma_\Omega \approx 0.3$, and $L_\omega \approx 3\ \mu\mathrm{m}$, we find that the maximum modulated power is about 6 mW. For $\mathscr{P}_\Omega \approx 1$ mW, the steady-state g varies from $g \approx -9\ \mathrm{cm}^{-1}$ at $T_e \approx 300$ K to $g \approx -61\ \mathrm{cm}^{-1}$ at $T_e = 500$ K. For $L_\Omega = 0.5$ mm and $r\Gamma_\Omega \approx 0.3$, this corresponds to a 3.5 dB modulation.

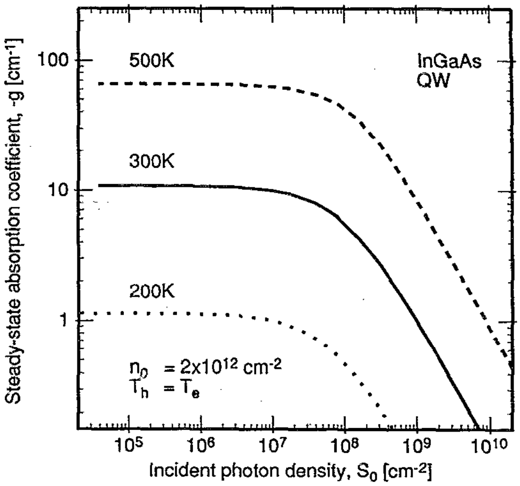

FIG. 2. Dependence of the steady-state gain on the photon density S_0 of incident interband radiation at different carrier temperatures. The assumed parameters: $g_{\max} = 10^3\ \mathrm{cm}^{-1}$, $r\Gamma_\Omega = 0.3$, and $R_S = 10^{-4}\ \mathrm{cm}^2/\mathrm{s}$.

At a higher power (or lower n_0) the modulator efficiency suffers from self-induced transparency effects associated with the accumulation of holes. As we shall now discuss, these effects can be used advantageously for the formation of short high-power IB radiation pulses. For this purpose, the MQW need not be doped and in what follows we let $n_0 = 0$.

Consider the situation arising at a high S_0 in the presence of ISB absorption.[7] In the steady state there is a large number of electrons and holes $p_S(S_0\ T_e)$, readily evaluated from Eqs. (6). In this state the gain has a small negative value $g(S_0, T_e)$. If the carrier heating is now abruptly terminated (by chopping Φ_ω or by shifting the ISB resonance with an external electric field), then T_e rapidly goes down to the ambient temperature and the gain function becomes temporarily positive. The excess carriers undergo stimulated recombination accompanied by a large pulse in the IB photon density. An example of such a pulse is shown in Fig. 3(a). The pulse shape is calculated from Eqs. (6), assuming that the initial electron heating is stopped at $t = 10$ ps and the carrier temperature relaxes from $T_e = 500$ K to $T_e = 300$ K, according to $\Delta T_e(t) = \Delta T_e e^{-t/\tau_E}$ with $\tau_E = 6$ ps. At longer times t the carrier density and the gain approach their new steady-state values $p_S(S_0, T)$ and $g(S_0, T)$, respectively.

The pulse shown in Fig. 3(a) has a full width at half maximum $\Delta t_{\mathrm{FWHM}} = 15$ ps and a peak photon density of $4\times 10^{10}\ \mathrm{cm}^{-2}$—corresponding to a power of 2.4 W (the pumping level is only 60 mW). Variation of the peak versus the pump power is plotted in Fig. 3(b). Note that the peak power varies only by 30% over the decade $10^9 \lesssim S_0 \lesssim 10^{10}\ \mathrm{cm}^{-2}$. The width Δt_{FWHM} is practically constant over the same range. As discussed below, increasing S_0 in this range mainly leads to a faster device recovery in preparation for the next pulse.

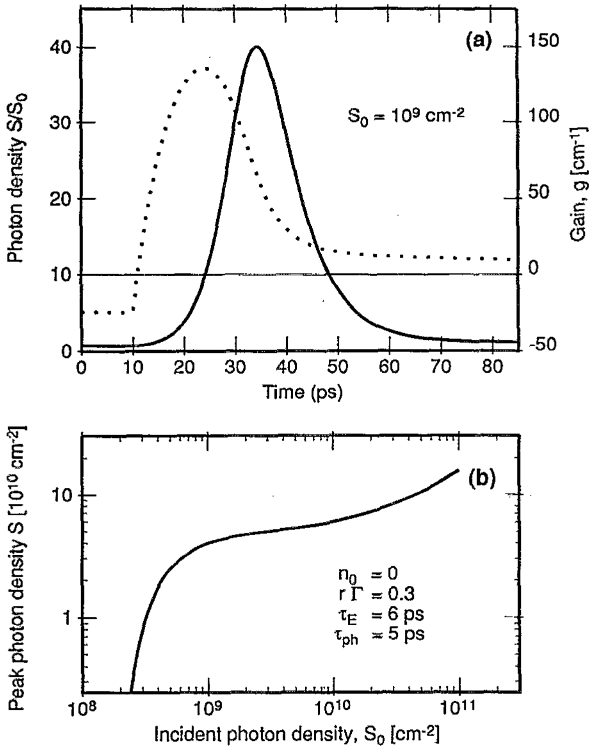

FIG. 3. Formation of short pulses by abrupt termination of carrier heating. In the presence of both IB and ISB radiations, the device is allowed to reach a steady state with assumed carrier temperature $T_e = 500$ K. At $t = 10$ ps, the ISB absorption terminates abruptly and T_e relaxes to the ambient temperature $T = 300$ K. (a) Incident photon density $S_0 = 10^9$ cm^{-2}. The full width of the pulse at half maximum is 15 ps. Dotted curve shows the variation of gain $g(t)$. (b) Variation in the peak photon density with the varying pump intensity.

Indeed, when the carrier heating is turned on, the negative gain function temporarily increases in magnitude. This results in an enhanced absorption of IB radiation and the number of carriers increases back toward the steady-state value $p_S(S_0, T_e)$. During this relatively slow process, the power is stored for the next pulse. The storage time depends on the incident power and scales approximately as $1/S_0$ for $S_0 \gtrsim 10^9$ cm^{-2}. Figures 4(a) and 4(b) plot the evolution of the photon density S assuming that the initial electron heating is stopped at $t = 10$ ps and then resumed at $t = 110$ ps. Although the log-log representation of the pulses in Fig. 4(a) looks "ugly," it shows clearly the trends upon variation in the incident density S_0. Figure 4(b) replots two of the examples in a linear scale. In this plot, the area under the absorption curve equals that under the peak, since our model neglects nonradiative recombination processes. This implies that for a given value of S_0 and a given swing in the carrier temperature, the peak power is inversely proportional to its duration.

An important advantage of the pulse former and the

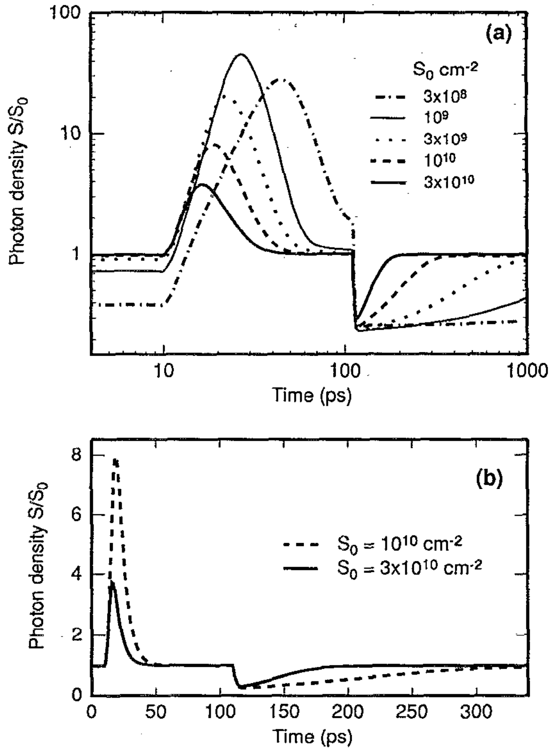

FIG. 4. Pulse shape at several incident photon densities. The ISB absorption terminates abruptly at $t = 10$ ps and resumes at $t = 110$ ps. (a) Double logarithmic plot. In the range $8\times 10^8 \leqslant S_0 \leqslant 5\times 10^{10}$ cm^{-2}, the pulse full width at half maximum is practically constant, 15 ps. The highest peak ratio $S_0/S \approx 50$ occurs at $S_0 \approx 5\times 10^8$ cm^{-2}, but at this level Δt_{FWHM} increases to 19 ps. (b) Two pulses replotted in a linear scale.

modulator described in this letter is the fact that the mode content of IB radiation is not changed since the feedback from our device to the laser source would be typically small. This means that the modulator can be expected to be free of additional errors due to chirp. Moreover, ultrashort pulses of single-mode radiation can be formed in the described fashion.

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