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Intraband carrier kinetics and picosecond pulse shaping in field-enhanced bulk semiconductor absorbers

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Picosecond pulse propagation through a field-enhanced waveguide bulk semiconductor saturable absorber is studied numerically. Fast switching from unsaturated absorption to delayed strong saturation and gain, as well as the predicted dependence of saturation energy on electric field, is based on intraband carrier kinetics and electric-field dynamics in the absorber and can lead to improved, controllable pulse shaping. © 1998 Optical Society of America

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Intraband carrier kinetics in semiconductor lasers has attracted much attention because of its importance in defining and limiting high-speed performance. A great deal of attention has focused on the effects of spectral hole burning and carrier heating in short-pulse propagation through amplifying media.[1–4] In some ultrashort-pulse lasers, such as mode-locked and Q-switched lasers, semiconductor saturable absorbers play a principal role,[5] so intraband carrier kinetics can also influence the characteristics of these devices. Complicated saturation dynamics based on intraband carrier kinetics have been demonstrated for bulk[6,7] as well as for quantum-well saturable absorbers.[6,8] Femtosecond pump–probe experiments[6,7] on reverse-biased, p–i–n heterostructure saturable bulk absorbers have shown that carrier heating that is due to the electric field is significant in such absorbers and together with the dynamics of the electric field can have a dominant influence on the saturation dynamics.

In this Letter we study theoretically the propagation of picosecond pulses through waveguide bulk semiconductor absorbers with both built-in and externally applied electric fields. We show that intraband carrier kinetics—carrier heating by the electric field and subsequent carrier cooling owing to carrier–phonon interaction and by photogenerated cold carriers—can lead to improved shaping of picosecond pulses compared with those in conventional saturable absorbers when the intraband dynamics are negligible. This research is based on an extension of the model for femtosecond saturation dynamics in field-enhanced bulk absorbers, which has been shown to agree with experiments.[6,7]

Figure 1 shows schematically an energy-band diagram of the absorber under study. The x axis is normal to the waveguide structure, and the z axis is the direction of pulse propagation. In the absorbing region ($0 < x < W$) the energy bandgap is smaller than the bandgap in the barriers ($x < 0$, $x > W$). The electric field $\mathbf{E}_0$ (the built-in field in a p–i–n heterostructure plus the field that is due to any externally applied voltage) is assumed to be constant throughout the structure.We calculate the pulse propagation characteristics by using the propagation equation for the photon density $S(z, t)$:

$$\frac{\partial S}{\partial t} + v_g \frac{\partial S}{\partial z} = -\Gamma v_g \left[\frac{1}{W} \int_0^W \mathrm{d}x\, \alpha(z, x, t) \right] S, \quad (1)$$

where Γ is the confinement factor in the x direction, v_g is the group velocity, and $\alpha(z, x, t)$ is the absorption coefficient. The dynamics of α can be evaluated through the rate equations

$$\frac{\mathrm{d}\bar{n}_i}{\mathrm{d}t} = S v_g \frac{1}{W} \int_0^W \mathrm{d}x\, \alpha(z, x, t) + R_n{}^i, \quad (2)$$

$$\frac{\mathrm{d}\bar{u}_i}{\mathrm{d}t} = S v_g \frac{1}{W} \int_0^W \mathrm{d}x\, \alpha(z, x, t) [\epsilon_{i0} + (\mp q) \varphi(x)] - \frac{\bar{u}_i - \bar{u}_{Li}}{\tau_{ui}} + R_u{}^i, \quad (3)$$

where $i = c, v$. $\bar{n}_c$ and $\bar{n}_v$ are, respectively, the electron and hole densities, averaged across the absorbing

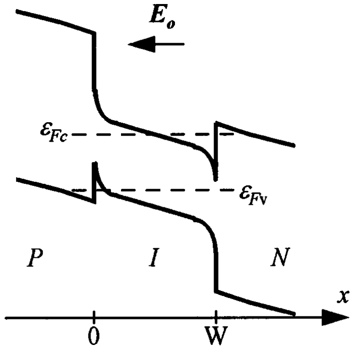

Fig. 1. Band diagram of the absorber considered (a waveguide p–i–n heterostructure). Absorption takes place in the region $0 < x < W$. The initial field $\mathbf{E}_0$ comprises the built-in field of the p–i–n structure, the externally applied voltage, or both. The dashed lines show the quasi-Fermi levels for electrons (ϵ_{Fc}) in the conduction band and for holes (ϵ_{Fv}) in the valence band.

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region:

$$\bar{n}_i = \frac{1}{W}\int_0^W \mathrm{d}x n_i(x),$$

$$n_i(x) = 2\left(\frac{m_i k_B T_i}{2\pi\hbar^2}\right)^{3/2} F_{1/2}\left[\frac{\epsilon_{Fi} - (\mp q)\varphi(x)}{k_B T_i}\right], \tag{4}$$

and $\bar{u}_c$ and $\bar{u}_v$ are the averaged energy densities for electrons and holes, respectively:

$$\bar{u}_i(x) = \frac{1}{W}\int_0^W \mathrm{d}x\left\{3k_B T_i\left(\frac{m_i k_B T_i}{2\pi\hbar^2}\right)^{3/2} \times F_{3/2}\left[\frac{\epsilon_{Fi} - (\mp q)\varphi(x)}{k_B T_i}\right] + (\mp q)\varphi(x) n_i(x)\right\}. \tag{5}$$

The first term in Eq. (5) is the kinetic energy; the second term is the potential energy. The minus in Eqs. (3)–(5) refers to the electrons ($i = c$), and the plus refers to the holes ($i = v$). Electrons (holes) are pumped into the conduction (valence) band with kinetic energy $\epsilon_c{}^0$ ($\epsilon_v{}^0$) and potential energy $(-q\varphi)$ $[(+q\varphi)]$ [see Eq. (3)]. m_c (m_v) is the electron (hole) effective mass.

The potential $\varphi(x)$ can be written as

$$\varphi(x) = E_0 x + \tilde{\varphi}(x), \tag{6}$$

where the screening potential $\tilde{\varphi}(x)$ is calculated from Poisson's equation

$$\frac{\partial^2\tilde{\varphi}}{\partial x^2} = \frac{q}{\epsilon\epsilon_0}[n_c(x) - n_v(x)]. \tag{7}$$

ϵ_{Fc} (ϵ_{Fv}) and T_c (T_v) are the Fermi level and temperature, respectively, for the electrons (holes). Here (in contrast to Ref. 7) we neglect the time taken to establish thermal equilibrium across the absorber on a picosecond time scale [the time is of subpicosecond scale and can be estimated as the thickness of the absorber (~100 nm) divided by the saturation carrier velocity in strong electric fields, $\sim 2 \div 3 \times 10^5$ m/s] and assume that the carrier distributions across the absorbing region are established instantaneously. It supposes that quasi-Fermi levels and temperatures are independent of x. The approximation allows one to avoid solving a carrier transport equation and to evaluate carrier kinetics with rate equations (2) and (3) alone.

At $\varphi = 0$ Eqs. (2)–(5) are reduced to the usual models[2] used for semiconductor optical amplifiers. In fact, Eqs. (2)–(5) can be considered a generalization of the previous model for the case of a nonzero electric field in the active region of the device.

The second term in Eq. (3) describes energy relaxation that is due to carrier–phonon interactions.[2,7] $\bar{u}_{Lc}$ ($\bar{u}_{Lv}$) is the energy density of electrons (holes) at the lattice temperature T_L. $R_n{}^i$ and $R_u{}^i$ in Eqs. (2) and (3) are the removal rates of carriers and energy, respectively, from the absorbing region that are due to thermionic emission and tunneling through barriers and can be expressed in terms of the carrier distributions near the boundaries ($x = 0, W$) and the transmission coefficient of the barriers.[7] The absorption coefficient α can be written as[7]

$$\alpha = \alpha(z, x, t) = \alpha_0(1 - f_c{}^0 - f_v{}^0)/(1 + \epsilon_{\text{sup}}S). \tag{8}$$

Here α_0 is the unsaturated absorption coefficient, ϵ_{sup} is an absorption suppression factor, and $f_c{}^0$ and $f_v{}^0$ are Fermi functions given by

$$f_i{}^0 = \left\{1 + \exp\left[\frac{\epsilon_i{}^0 + (\mp q)\varphi(x) - \epsilon_{Fi}}{k_B T_i}\right]\right\}^{-1}. \tag{9}$$

The results of our calculations are shown in Fig. 2. Figure 2(a) shows the dynamics of the gain ($-\alpha$) at several initial electric fields E_0, and Fig. 2(b) shows calculated output pulses together with the input pulse. For comparison, the results of calculations for the classical model, in which the carrier temperature and field dynamics are neglected, are also given in Fig. 2.

The calculations have been done for a GaAs/AlAs structure because relatively large barriers (0.49 eV for electrons and 0.24 eV for holes) are feasible with these materials. The thickness W of the absorbing region is 100 nm. The duration of the input pulse is

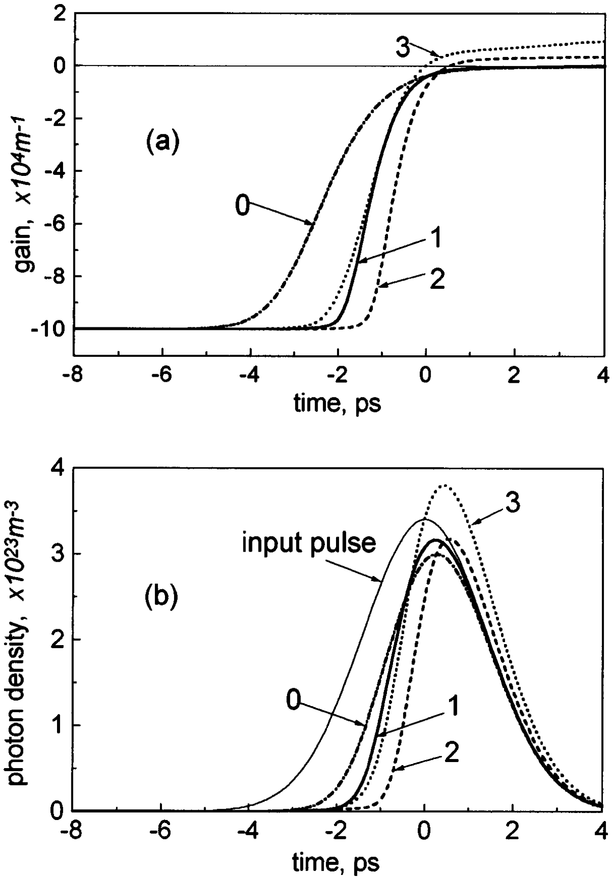

Fig. 2. (a) Temporal dynamics of the gain ($-\alpha$). (b) Input and output photon densities. Curves 0, temperature and field effects are neglected; curves 1, $E_0 = 3 \times 10^7$ V/m; curves 2, $E_0 = 4.5 \times 10^7$ V/m; curves 3, carrier removal from the absorbing region is neglected.

3.3 ps. The photon density at the peak of the input pulse is $3.4 \times 10^{23}\ \mathrm{m}^{-3}$. The length of the absorber is 40 μm. The absorption coefficient is $\alpha_0 = 10^5\ \mathrm{m}^{-1}$; $\epsilon_{\mathrm{sup}} = 2 \times 10^{-24}\ \mathrm{m}^3$.[7] The carrier energy relaxation times in Eq. (3) are $\tau_{uc} = 1$ ps and $\tau_{uv} = 0.5$ ps.[2,7]

Before the pulse there are few carriers in the absorbing region, and field screening is practically absent. Carriers generated by the pulse are accelerated (i.e., heated) by the electric field and can reach temperatures of approximately 2000–3000 K.[7] Obviously, these hot carriers are off resonance with the incoming photons and cannot saturate the absorption. Curves 1 and 2 in Fig. 2(a) demonstrate the suppression of saturation during the initial stage of absorption in comparison with the classical model (curve 0): clearly, delayed saturation takes place. Accordingly, the absorption of the front of the pulse is much stronger than in the classical model [curves 1 and 2 versus curve 0 in Fig. 2(b)].

As the photogenerated carriers accumulate, the field is screened, reducing carrier heating by the field. Hot carriers generated previously begin to cool. Two mechanisms contribute to the cooling. The first one is carrier-phonon scattering, which leads to cooling of hot carriers to the lattice temperature. The second mechanism is the pumping of cold carriers by the pulse. In fact, the pulse generates electrons and holes near the edges of the conduction and valence bands with energies $\epsilon_c{}^0$ and $\epsilon_v{}^0$, respectively, which are smaller than the characteristic lattice thermal energy $k_B T_L$. The hot carriers share their energy with the cold carriers, leading to effective cooling. The cooled carriers fill the bottom of the appropriate band, and the absorption saturates quickly [curves 1 and 2 in Fig. 2(a)]. The duration of the transition from unsaturated absorption to strong saturation is defined by the rate of carrier cooling and is much shorter than in the classical model of saturation. The moment of the transition (or time delay in saturation) is defined by the initial electric field E_0. For larger initial fields more carriers must be generated to screen the field and start saturation of the absorption. Thus the transition between unsaturated absorption and strong saturation occurs at later times for larger initial fields [curves 1 and 2 in Fig. 2(a)]. In other words, larger fields need larger pulse energy to saturate the absorption. That is, the saturation energy in the absorbing medium depends on the electric field E_0, which in turn depends on the applied bias voltage—an externally controllable parameter. This is intuitively obvious, and we have demonstrated it numerically.

If a sufficient carrier density is generated during the period of unsaturated absorption, positive gain can be obtained after carrier cooling [curve 2 in Fig. 2(a)]. Thus, in absorbers with applied or built-in electric fields, a transition from absorption to gain can be achieved. In this case the tail of the output pulse is amplified [curve 2 in Fig. 2(b)].

By comparison with the calculated output pulse when field and temperature dynamics are neglected [curve 0 in Fig. 2(b)], we see that the application of an electric field in absorbers leads to stronger shortening of the input pulse. This effect of improved field-induced pulse shaping could be used in passively mode-locked and Q-switched lasers.

It is worth noting that carrier heating by the electric field also leads to fast carrier removal from the absorbing region through thermal emission of carriers above the barriers, and it renders more difficult the accumulation of carriers to achieve gain. Suppression of the carrier emission, for instance, by increasing barrier heights in the heterojunctions, would allow one to produce gain with weaker pulses. Curves 3 in Fig. 2 are obtained if removal of photogenerated carriers is completely neglected [$R_n{}^i = R_u{}^i = 0$ in Eqs. (2) and (3)] and at $E_0 = 4.5 \times 10^7$ V/m. Clearly substantial gain after cooling and hence amplification of the trailing edge of the pulse take place.

In summary, a new mechanism for pulse shaping in waveguide reverse-biased bulk semiconductor absorbers has been proposed and described. The dependence of the saturation energy on the electric field in the absorber, and the phenomenon of ultrafast switching from unsaturated absorption to gain, can be useful for pulse generation and reshaping in short-pulse lasers. These novel phenomena are based on the effects of the built-in (or externally applied) electric field on intraband carrier kinetics.

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