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Analysis of Gain-Switching Characteristics Including Strong Gain Saturation Effects in Low-Dimensional Semiconductor Lasers

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The effects of gain nonlinearities on gain-switched short-pulse-generation characteristics are analyzed via rate equations assuming a nonlinear-gain model including a gain saturation parameter g_s to quantitatively describe the strong gain-saturation nonlinearity in low-dimensional semiconductor lasers at high carrier densities. It was found that the minimum pulse width and the delay time are mainly determined by g_s rather than a differential gain coefficient g_0 and a gain compression factor ε. By tracing the temporal evolution of carrier density, photon density, and material gain during gain switching, distinctly different effects of g_s, ε, and cavity lifetime τ_p on pulse generation were clarified.

Gain nonlinearities in semiconductor lasers can be categorized into two types, gain saturation[1,2] and gain compression,[3–5] which depend explicitly on carrier density and optical field intensity, respectively. Short-pulse generation by gain switching[3–6] has often been simulated qualitatively via rate equations including a gain compression factor ε[3–5] while neglecting gain saturation. A recent study on low-dimensional semiconductors, however, has revealed strong gain-saturation nonlinearity.[7,8] To quantitatively simulate their gain-switching characteristics, we need to include the strong gain saturation into gain models.

In this paper, we introduced a gain model saturating to g_s at high carrier densities, and analyzed gain-switching characteristics via rate equations. We demonstrated that the delay time and the minimum pulse width of gain-switched output pulses are dominantly determined by the saturated gain g_s rather than the low-density differential gain coefficient g_0 and gain compression factor ε. In addition, we graphically depicted gain dynamics to assist with in-depth understanding of the gain-switched operation.

We start with the following rate equations:

$$\frac{dn^{2D}}{dt} = n^{2D}_{pump}\zeta(t) - \frac{\Gamma}{m} v_g g \frac{s^{2D}}{1+\varepsilon s^{2D}} - \frac{n^{2D}}{\tau_r}, \qquad (1)$$

$$\frac{ds^{2D}}{dt} = \Gamma v_g g \frac{s^{2D}}{1+\varepsilon s^{2D}} - \frac{s^{2D}}{\tau_p} + m\beta \frac{n^{2D}}{\tau_r}, \qquad (2)$$

for s^{2D} [two-dimensional (2D) photon density for all active layers], n^{2D} (2D carrier density per single active layer), n^{2D}_{pump} (time-integrated injected carrier density per single active layer), $\zeta(t)$ (normalized time trace of pumping pulse), m (active layer number), Γ (confinement factor), v_g (group velocity), g (material gain), τ_r (carrier lifetime), τ_p (photon lifetime), ε (gain compression factor), and β (spontaneous coupling factor).

We introduce a gain model defined by g_s (saturated gain), g_0 (differential gain coefficient), and n^{2D}_0 (transparency density) as

$$g = g_0(n^{2D} - n^{2D}_0)\left[1 + \frac{g_0(n^{2D} - n^{2D}_0)}{g_s}\right]^{-1} \approx \begin{cases} g_0(n^{2D} - n^{2D}_0) & n^{2D} - n^{2D}_0 \ll g_s/g_0 \\ g_s & n^{2D} - n^{2D}_0 \gg g_s/g_0 \end{cases}. \qquad (3)$$

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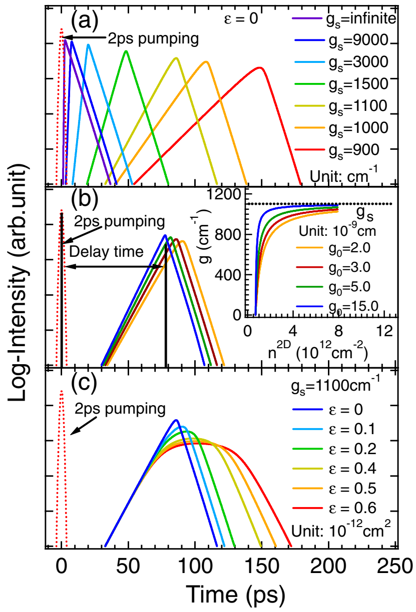

Fig. 1. (Color online) Log plots of waveforms of output optical pulses, for (a) g_s varied from 900 cm^{-1} to infinite, $g_0 = 3.0 \times 10^{-9}$ cm, and $\varepsilon = 0$, (b) g_0 varied from 2.0 to 15.0 $\times 10^{-9}$ cm, $g_s = 1100$ cm^{-1}, and $\varepsilon = 0$, (c) ε varied from 0 to 0.6 $\times 10^{-12}$ cm^{-2}, $g_0 = 3.0 \times 10^{-9}$ cm, and $g_s = 1100$ cm^{-1}. The insert in (b) shows the corresponding gain curves.

Note that g_s is determined by the density of states, distribution functions, many body carrier–carrier interactions, and filling factors, and should be around 10^3–10^4 cm^{-1} at 300 K for quantum-well lasers[2] depending on their structures and materials. Quantum-dot and quantum-wire lasers typically have smaller g_s, because the densities, or filling factors, of dots and wires in an active layer are low. In the numerical calculations below, we assumed $n^{2D}_0 = 0.7 \times 10^{12}$ cm^{-2}, $\tau_r = 1.0$ ns, $\tau_p = 3.7$ ps, $m = 2$, $\Gamma = 4.9 \times 10^{-2}$, $v_g = 8.57 \times 10^{-3}$ cm/ps, $\beta = 5.0 \times 10^{-5}$, and $n^{2D}_p = 8.0 \times 10^{12}$ cm^{-2}. A Gaussian function with a pulse duration of 2 ps is assumed for $\zeta(t)$.

The effects of g_0, g_s, and ε on gain-switched pulse generation are investigated first. Figure 1(a) shows that g_s significantly affects the delay time and rise time (or slopes of the delay part and rise part of the pulses) but has almost

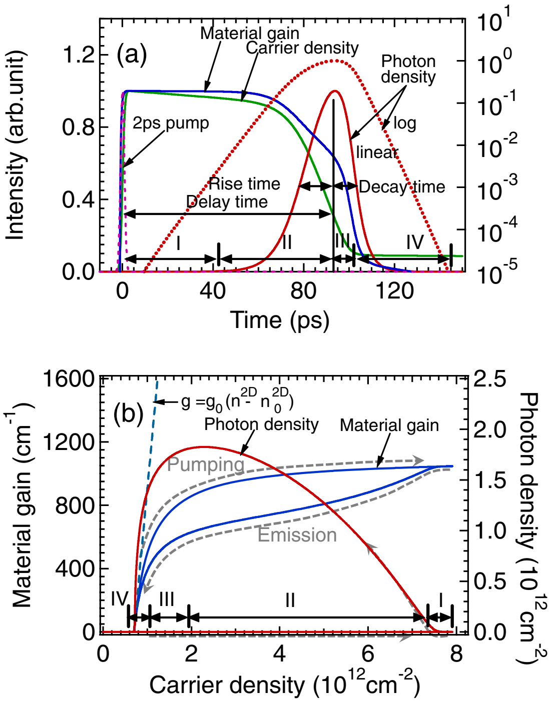

Fig. 2. (Color online) (a) Typical evolution of carrier density, material gain, and photon density (linear plot and log plot) during a cycle of pulse generation after a 2-ps optical pulse pumping, parameters $g_0 = 3.0 \times 10^{-9}$ cm, $g_s = 1100\,\mathrm{cm}^{-1}$, and $\varepsilon = 0.2 \times 10^{-12}\,\mathrm{cm}^{-2}$ were used for simulation. (b) Replots of material gain and photon density against carrier density. The four dashed arrows indicate the temporal evolution directions of material gain and photon density. According to the different temporal effects of ε and g_s on material gain and photon density, carrier density is divided into four regions. The photon-density evolutions of each region in (b) are correspondingly indicated in the time region in (a).

no effect on decay time, and monoexponential fittings suggest that the decay times are actually the photon lifetime in a cavity. Figure 1(b) shows that the pulse shape hardly changes with varying g_0 when g_s is fixed. Figure 1(c) shows that ε suppresses the pulse peak but has almost no obvious effect on the rise time. Therefore, the effects of g_s and ε on the pulse characteristics are very different: g_s significantly affects the delay time and rise time, and changes the pulse width, while ε compresses the pulse peak profile and changes the pulse width. Accordingly, for quantitative simulation of pulse generation, both of the parameters g_s and ε are necessary.

Next, graphical analysis of gain dynamics in the presence of g_s and ε was performed. Figure 2(a) shows typical time evolutions of carrier density, material gain, and photon density during a cycle of gain-switched pulse generation. In Fig. 2(b), the transient material gain and photon density are replotted against the corresponding carrier density. During the 2 ps pumping process, no effects of ε appear, since the developed photon density s^{2D} is negligible. The significant deviation of the gain curve from a linear relation shown by the dashed line is only due to the modulation of g_s for high carrier densities. The emission process is divided into four regions for convenience in analysis. In region I, almost no photons are generated, and still no effects of ε are reflected in the gain curve; therefore, both the increase and decrease of material gain follow the same gain curve modulated by g_s. In this region, g_s determines the rate of photon generation, as shown by the straight dashed line of photon density in the log plot in this region in Fig. 2(a), and determines the delay time. In region II, photon density increases to maximum rapidly, and the increase in photon density makes τ_p and ε start to work. The log plot of photon density in Fig. 2(a) then starts to bend, and the gain curve marked by "Emission" deviates from the one marked by "Pumping" in Fig. 2(b). The separation of the two gain curves is caused by ε. However, the gain value is still not very far from g_s, and the effect of ε is rather weak. In region III, the material gain is further decreased with decreasing carrier density, and approaches the linear gain relation. The effect of g_s on gain is weakened, while the effect of ε remains, since photon density is still high. This explains the reason for the modulation of decay time mainly by ε. In region IV, photon density is decreased, and gain becomes linear. Thus, the effects of g_s and ε disappear, and the decay time is determined only by photon lifetime, as shown by the straight lines of the log plot of photon density in Fig. 2(a) and those in Fig. 1. In short, g_s completely controls region I, where the delay time of the generated output pulse is produced. In region II, although both ε and g_s affect the rise time, the effect of g_s is dominant. The decay time is determined in regions III and IV, where ε and photon lifetime, respectively, are dominant. If the value of ε is very large, region III will be expanded, and the decay time will be mainly determined by ε. In contrast, if ε is small, photon lifetime basically determines the decay time in region IV.

In summary, we quantitatively demonstrated the effects of gain nonlinearities on gain-switched short-pulse-generation characteristics in low-dimensional semiconductor lasers. The results showed that the value of the saturated gain g_s has a strong impact, rather than differential gain g_0, gain compression factor ε, and cavity photon lifetime τ_p, on the gain-switched-pulse characteristics, where a small value of g_s results in a long delay time and a long pulse width. The gain dynamics during pulse generation was depicted graphically, and the above results are supported consistently. For compensation of the small value of g_s to realize short pulses experimentally, it should be helpful to increase the confinement factor Γ and the active layer number m, and to use higher subbands.

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