Ultrafast switch-off of a vertical-cavity semiconductor laser

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(Received 3 October 1996)

It is shown that perturbation of an electrically pumped semiconductor vertical-cavity surface emitting laser by means of a short optical pump pulse may lead to a transient switch-off of the laser emission, provided that the pump pulse has a significantly higher photon energy than the semiconductor laser. This behavior is opposite to the commonly expected increase in emission for any laser. The unusual response is explained in terms of a transient heating of the carrier distributions, leading to a transient reduction in population at the laser mode, hence to a switch-off. Switching time constants as fast as 3 ps are observed, which is much faster than could be expected from the inverse relaxation frequency. [S0163-1829(97)04115-5]

The modulational response of semiconductor lasers is usually considered to be limited by the relaxation frequency. Such limitation is understood within the rate-equation approach,[1] the basic assumption of which is that the shape of the carrier distribution functions adiabatically follows the carrier density. Experiments up to tens of gigahertz modulation frequency have confirmed this picture.[2,3] On a time scale comparable with characteristic electron-electron or electron-phonon scattering processes, however, this basic assumption is not valid and physically different behavior may arise. Recent theoretical predictions[4] have in fact shown that the dynamic response of a semiconductor vertical-cavity surface emitting laser (VCSEL) may largely be influenced by dynamic changes in the shape of the carrier distribution functions. Perturbing an electrically pumped VCSEL at room temperature by means of a short optical pulse can thus result in an unusual rapid switch-off of the emission, which is opposite to common expectation. Here we report the observation of this phenomenon and compare the observations with simple but quantitative model calculations.

The commercially available VCSEL devices[5] are operated under ambient conditions. They exhibit a threshold current of 2.9 mA and their diameter is 8 μm. The emission is single mode with about 1 mW of cw-output power at 850-nm wavelength (corresponding to 1.459 eV photon energy) for a 5.0-mA injection current. More technical details of such GaAs-based VCSEL's containing four quantum wells in the cavity can, e.g., be found in Ref. 6. The devices are perturbed by optical femtosecond pulses, which are focused onto the VCSEL's under normal incidence by means of a microscope objective. The photon energy of the femtosecond pulses exceeds the photon energy of the microlaser emission by more than 200 meV, which is significantly higher than the spectral width of the femtosecond pulses (15 meV). In the following, this difference between the two photon energies will be termed *excess energy*. The resulting pump spot size is chosen to be roughly twice the diameter of the elements in order to ensure homogeneous excitation. The transient emission is collected by the same microscope objective, which has an aperture sufficiently large to collect the entire emission. It is time resolved via sum-frequency generation with a fraction of the femtosecond pulses delayed in time, by employing a 1-mm-thick crystal of $LiIO_3$. Spectral filters are introduced into the beam in order to separate the VCSEL emission from the reflected pump beam. The signal at the sum frequency is detected by a photomultiplier using standard lock-in techniques. By up-converting the reflected beam we have ensured that the temporal resolution of the entire setup is only limited by the autocorrelation width of the femtosecond pulses, having an actual full width at half maximum (FWHM) of 120 fs.

The parameter space, consisting of the stationary electrical injection current, the pump photon energy, and the pump pulse energy, has been investigated systematically. One example for large pump photon energies ($\hbar\omega_p = 1.73$ eV) is depicted in Fig. 1. Following the optical pump pulse at $t=0$, a switch-off of the VCSEL emission is observed for moderate injection currents. The period in time until the emission increases again becomes shorter with increasing injection current. Hence the switch-off gradually vanishes for larger injection currents [Fig. 1(a)]; the laser appears to be more robust. At 5-mA injection current the switch-off has disappeared. With decreasing pump pulse energy [Fig. 1(b)] or decreasing photon energy [Fig. 1(c)], the switch-off behavior gradually disappears.

Notice that under the present conditions the relaxation frequency is always less than 10 GHz, which is deduced from data on a longer time scale. This is much slower than the initial switch-off observed in Fig. 1.

It is important to discuss an undesired and trivial mechanism that at first seems like a possible explanation of the observed behavior: If a fraction of the pump pulse were absorbed by the Bragg mirrors, the resulting reduction in refractive index of the low-band-gap material would lead to a reduction in reflectivity, hence to a transient switch-off. We do not see any reason, however, why this mechanism should depend on the electric injection current, a behavior that is clearly seen in the experiment [Fig. 1(a)]. Consequently, we can rule out this parasitic as the dominating contribution. On the other hand, there may be certain corrections to the simple picture oulined in the following, which is based on transient carrier heating.

The switching mechanism is schematically depicted in Fig. 2. Consider the stationary operating semiconductor laser [Fig. 2(a)] with Fermi-distributed carriers. Two simplifications are employed for clarity: Only electrons are shown and

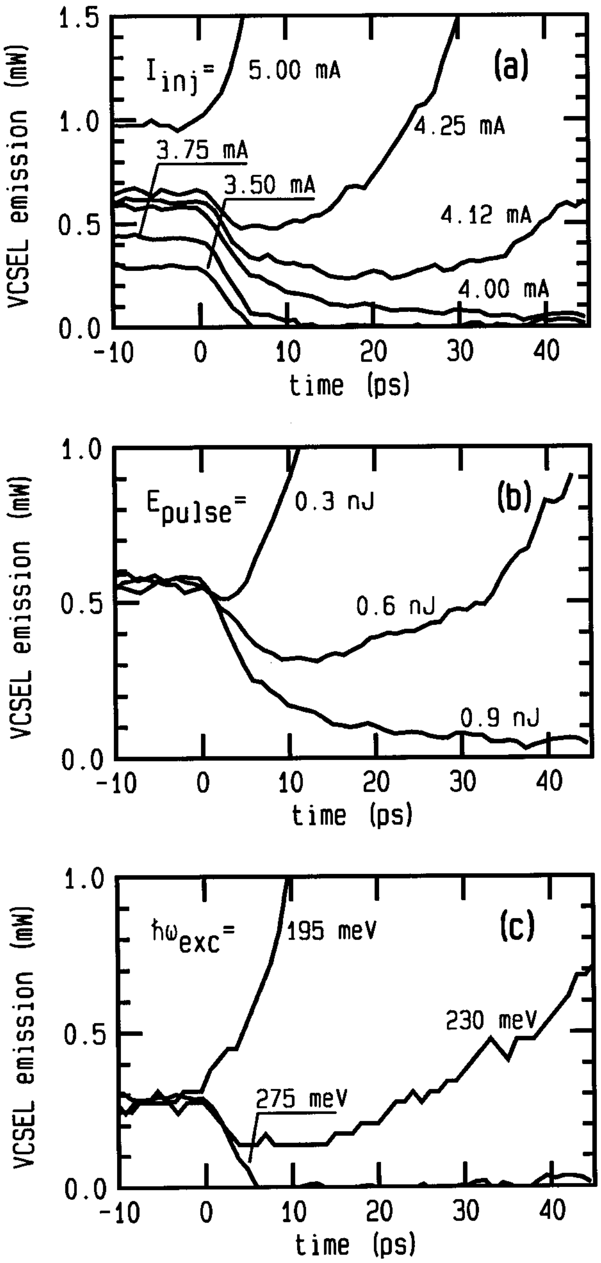

FIG. 1. Experiment. Transient VCSEL emission after perturbation with an optical pulse at $t=0$. (a) For a fixed pulse energy of 0.9 nJ and fixed excitation at 1.73 eV photon energy (corresponding to an excess energy of 0.275 eV), the stationary electrical injection current I_{inj} is a parameter; (b) for a fixed injection current of 4.0 mA and excitation at 1.73 eV photon energy, the pulse energy is a parameter; and (c) for 3.5 mA injection current and a pulse energy of about 0.9 nJ, the excess photon energy is a parameter.

spectral holes are neglected. At time $t=0$ the additional pump pulse is applied [Fig. 2(b)], thus increasing the number of excited carriers in the conduction and the valence band, respectively. Since carriers are added at an energy above the average, both the number of carriers and their mean energy are increased. Due to efficient carrier-carrier scattering, the electron and hole distributions will relax towards new Fermi functions, which are characterized by higher temperatures [Fig. 2(c)]. As a consequence, the occupation numbers at the spectral position of the lasing mode will decrease, which

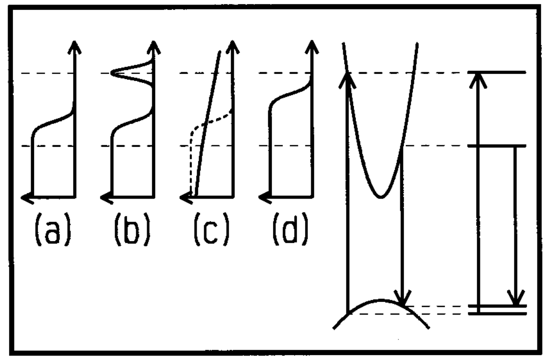

FIG. 2. Schematic band diagram and evolution of the carrier distribution functions: (a) before the arrival of the additional pump pulse, (b) at the arrival, (c) after thermalization of the carriers among themselves, and (d) after the subsequent cooling. The four-level system depicted on the right-hand side is unable to explain the experimental evidence.

results in a reduced modal gain and eventually in the switch-off. Inelastic scattering with LO phonons will cool down the carrier system while conserving the number of carriers [Fig. 2(d)]. This process is somewhat slowed down by the heating of the phonon system itself, and inversion will be recovered after several picoseconds. The time scale for the subsequent switch-on is governed by the comparatively low gain in a microcavity containing only four quantum wells as the active material. Furthermore, Fig. 2 clarifies why this mechanism cannot be explained by a simple four-level model: Going from Fig. 2(b) to 2(c), the occupation probability decreases for the levels that correspond to the four-level system. Consequently, the sum of the occupations of these four levels will decrease as well. In the four-level system, however, the sum of the occupations has to be constant.

Modeling the data, we closely follow along the lines of Refs. 7 and 8. The basic assumption is that carrier-carrier scattering is fast and leads to Fermi-distribution functions. The corresponding density and temperature are computed as a function of time. The application to quantum wells, which are approximated as two-dimensional sheets, is straightforward. It leads to the following extended rate equations for the photon density n_p (photons per volume), the electron-hole pair density n_{eh} (carriers per area), the carrier temperature T_{eh} (same for electrons and holes), and the Bose factor of hot LO phonons[9] $N(T_{LO})=1/[\exp(\hbar\omega_{LO}/k_B T_{LO})-1]$:

$$\frac{dn_p}{dt}=+\beta\Gamma_{spont}+\Gamma_{stim}-\Gamma_{loss}, \tag{1}$$

$$\frac{dn_{eh}}{dt}=-\Gamma'_{spont}-\Gamma'_{stim}+\Gamma_{pump}, \tag{2}$$

$$\frac{dT_{eh}}{dt}=+\Gamma_{heat}-\frac{\hbar\omega_{LO}}{k_B}\frac{N(T_{eh})-N(T_{LO})}{\tau_{eh\text{-}LO}}, \tag{3}$$

$$\frac{dN(T_{LO})}{dt}=+\frac{N(T_{eh})-N(T_{LO})}{\tau_{eh\text{-}LO}}-\frac{N(T_{LO})-N(T_0)}{\tau_{LO}}, \tag{4}$$

with the rate for stimulated emission $\Gamma_{stim}=\overline{gn}_p$ ($\Gamma'_{stim}=\Gamma_{stim}L_z/N_{QW}$), c the velocity of light in the medium at the photon energy of the laser mode $\hbar\omega$, L_z the quantum-well width, and N_{QW} the number of quantum wells. The average gain coefficient in the cavity $\overline{g}=gN_{QW}L_z/L$ is related to the gain g approximated by $g(\hbar\omega,n_{eh},T_{eh})=g_0\Theta(\hbar\omega-E_g)(f_e+f_h-1)$. $f_e(\hbar\omega,n_{eh},T_{eh})$ and $f_h(\hbar\omega,n_{eh},T_{eh})$ are the Fermi-distribution functions of electrons and holes, respectively, L is the cavity length, Θ is the Heaviside step function, and E_g is the band-gap energy. β is the coupling coefficient of spontaneous emission into the laser mode. The rates for spontaneous emission $\Gamma_{spont}=n_{eh}/\tau_{eh}$ ($\Gamma'_{spont}=\Gamma_{spont}L_z/N_{QW}$), losses of the cavity $\Gamma_{loss}=n_p/\tau_p$, cooling of the carriers due to emission of LO phonons, and the decay of LO phonons leading to an equilibrium with the lattice temperature T_0 are assumed to be exponentials with respective time constants τ_{eh}, τ_p, $\tau_{eh\text{-LO}}$, and τ_{LO}. As an immediate result of energy conservation, the carrier distribution functions are heated via the pump process and due to stimulated emission[7,8] (the latter is of minor importance here):

$$\Gamma_{heat}=\left(+\left[\frac{T_{eh}}{n_{eh}}+\frac{\pi\hbar^2}{m_ek_B}\right]-\frac{\hbar\omega-E_g}{n_{eh}k_B}\right)\Gamma'_{stim}+\left(-\left[\frac{T_{eh}}{n_{eh}}+\frac{\pi\hbar^2}{m_ek_B}\right]+\frac{\hbar\omega_{exc}^{cw}}{n_{eh}k_B}\right)\Gamma_{pump}^{cw}+\left(-\left[\frac{T_{eh}}{n_{eh}}+\frac{\pi\hbar^2}{m_ek_B}\right]+\frac{\hbar\omega_{exc}^{pulse}}{n_{eh}k_B}\right)\Gamma_{pump}^{pulse}, \quad (5)$$

$$\Gamma_{pump}=\Gamma_{pump}^{cw}+\overline{\Gamma}_{pump}^{pulse}\exp\left[-\left(\frac{t}{\tau}\right)^2\right], \quad (6)$$

with $\tau=\mathcal{F}/2\sqrt{\ln 2}$ (where $\mathcal{F}$ denotes the FWHM); m_e is the effective electron mass; the hole mass does not enter at this point as the Boltzmann approximation has been applied for the hole distribution function.[8] $\hbar\omega_{exc}$ is the excess energy of electron-hole pairs injected via the pump process. For the optical pump process $\hbar\omega_{exc}$ is simply given by $\hbar\omega_p-E_g$.

The parameters of the following numerical calculations correspond to the experiment and are given by $m_e=0.067$, $m_h=0.22$, $E_g=1.448$ eV, $\hbar\omega_{LO}=36$ meV, $\hbar\omega=1.458$ eV, $\tau_p=5$ ps, $\tau_{eh}=1$ ns, $\tau_{eh\text{-LO}}=1$ ps, $\tau_{LO}=2.45$ ps (see Refs. 7, 10, and 11), $g_0=10^4$ cm^{-1}, $N_{QW}=4$, $L_z=10$ nm, $L=1$ μm, $T_0=300$ K, $\beta=10^{-4}$, $c=c_0/n_b$ with the background refractive index $n_b=3.3$ and the vacuum velocity of light c_0, $\hbar\omega_{exc}^{cw}=0.3$ eV (injection from the barrier material), $\hbar\omega_{exc}^{pulse}=0.275$ eV (see experiment, Fig. 1), $\Gamma_{pump}^{cw}=1.4\times10^9$ cm^{-2}ps^{-1}, $\overline{\Gamma}_{pump}^{pulse}=6.0\times10^{11}$ cm^{-2}ps^{-1}, $\mathcal{F}=120$ fs (see experiment).

Figure 3 shows one example of the simulations, the full line correponds to the complete model, the dashed line neglects hot phonons ($T_{LO}=T_0=300$ K), and the dotted line reflects the standard rate-equations ($T_{eh}=T_{LO}=T_0=300$ K). Under cw-lasing conditions, the carrier density is 1.1×10^{12} cm^{-2}. After the short pump pulse the carrier density increases by about 7%. Due to the excess energy of the carriers (here 275 meV), which is way above $k_BT_{eh}\approx26$ meV, the carrier temperature experiences a substantial increase. For large excess energies the resulting decrease in gain due to the increase in carrier temperature overcompensates the increase in gain due to the increase in carrier density and the system can even switch into the absorptive regime. This leads to a rapid switch-off of the laser emission. Carriers, however, quickly cool on a time scale of $\tau_{eh\text{-LO}}=1$ ps due to emission of LO phonons and the experimental data cannot be explained without the effect of hot phonons (see the dashed line in Fig. 3), which clearly inhibit rapid cooling of the carriers over several picoseconds. Using the well-known literature parameters for the phonon lifetime,[10,11] we obtain a match of the involved time scale without any fit parameters.

As expected, the initial switch-off gradually disappears for smaller excess energies (see Fig. 4), which is also observed in the experiment [Fig. 1(c)]. The dependence on injection current [Fig. 1(a)] could be understood if the carrier density showed a substantial increase with injection current. In that case, the additionally introduced hot carriers would lead to a smaller increase in temperature of the entire carrier

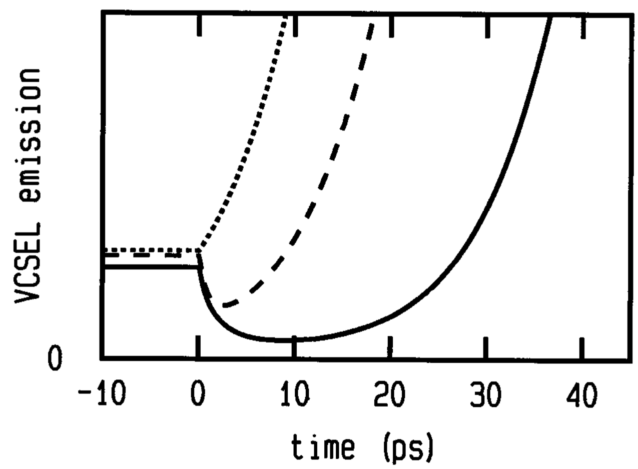

FIG. 3. Model. Transient VCSEL emission after perturbation with a short pump pulse at $t=0$. Complete calculation including carrier heating and hot phonons (solid line), hot phonons neglected (dashed line), and the standard rate equations (dotted line).

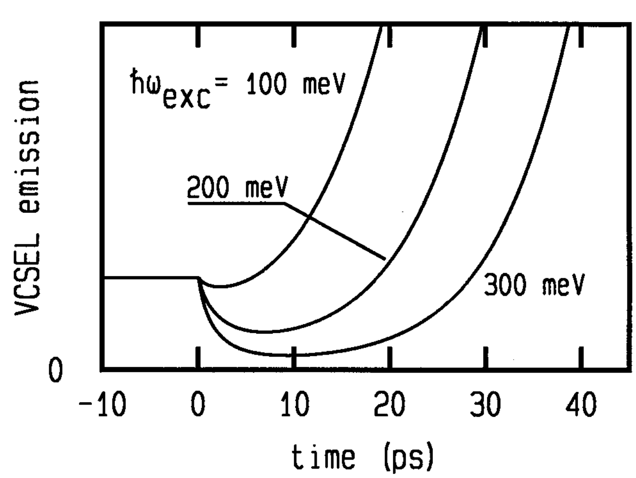

FIG. 4. Complete model (see Fig. 3), with the excess energy as a parameter. This result has to be compared with the experiment, Fig. 1(c).

system, hence at large injection currents to an increase in emission rather than to a switch-off. The above simple modeling, however, does not reproduce this trend in detail as the carrier density is still essentially pinned. Transverse effects and spectral hole burning, which are not included in the model, would further relax the carrier pinning and could explain the observed behavior as a function of injection current. The dependence on pump pulse energy [Fig. 1(b)] is currently not well understood. It would be very interesting to compare the experimental data with microscopic theories such as Refs. 4 and 12, however, with the effect of hot phonons incorporated.

In conclusion, we have presented experimental evidence for ultrafast switch-off of semiconductor vertical cavity lasers after impulsive excitation. The unusual switch-off is interpreted in terms of a transient carrier heating due to the excitation process, a many-body effect that is particular for *semiconductor* lasers. This type of switching might prove to be useful for ultrafast modulation of semiconductor lasers well above the usual relaxation frequency.

The research of M.W. has been supported by the Krupp-Stiftung. We acknowledge support through the DFG-SPP ‘‘Optische Signalverarbeitung.’’ Stimulating discussions with S. W. Koch and F. Jahnke are gratefully acknowledged.

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