Temperature dependence of pulse duration in a mode-locked quantum-dot laser

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The authors demonstrate, experimentally and theoretically, that in a mode-locked two-section quantum-dot laser, the pulse duration decreases with temperature. The primary cause is the increase of carrier capture/escape rates with temperature that leads to faster absorption recovery. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2711291]

Due to the nature of their density of states, quantum-dot (QD) semiconductors are exciting materials for realizing low threshold and high characteristic temperature lasers.[1] In addition, mode-locked QD lasers can be used to generate ultrashort pulses at high repetition rates.[2] If this high-speed performance is proven to be resilient to temperature variations, QD lasers can become the next-generation sources for ultrafast optical communications because the removal of thermoelectric coolers would lead to reduced cost and complexity. In this context, we have reported recently the stable passive mode locking of an InGaAs QD laser over a relatively broad temperature range.[3] To meet the requirements for high-speed communications, it is also important to investigate the temperature dependence of the pulse duration. For instance, in communication systems with transmission rates of 40 Gbits/s or more, the temporal interval between pulses is less than 25 ps. If follows that the duration of the optical pulses should be substantially below this value at any operating temperature.

In this letter, we show experimentally that, perhaps counterintuitively, the pulse duration and the spectral width decrease significantly as the operating temperature is increased up to 70 °C. We performed simulations that reproduce this trend where the temperature dependence of the carrier capture and the escape rates from the quantum dots were taken into account.

The QD laser used in this work was a two-section device with a total length of 2.1 mm (saturable absorber length of 0.3 mm), similar to that described in Ref. 3. The active region containing five self-organized QD layers was grown by molecular beam epitaxy on a GaAs (100) substrate. One facet coating provided high reflectivity, while the other was antireflection coated. The device was mounted *p* side up on a copper heat sink, and a Peltier-based cooler was used to control the operating temperature. The gain section of the laser was electrically pumped on a continuous wave bias.

By using a background-free autocorrelation technique based on second-harmonic generation, the pulse durations were measured at several values of operating temperature, ranging between 20 and 70 °C. Figure 1 depicts the decrease in pulse duration with temperature, while keeping a constant injection current of 190 mA and adjusting the reverse bias to achieve the minimum duration at each temperature setting. It was also observed that the spectra became narrower and were redshifted as the temperature was increased. The combination of these effects resulted in a sevenfold decrease in the duration-bandwidth product, as indicated in Fig. 1. (The pulses are still strongly frequency chirped due to the strong dispersion in the semiconductor material.) This observed decrease in bandwidth as a function of temperature has been investigated extensively elsewhere and several possible rea-

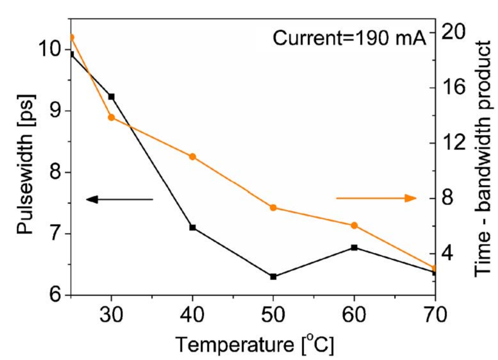

FIG. 1. (Color online) Experimental results. Dependence of the minimum pulse duration and duration-bandwidth product with temperature at a constant injection current (with optimized reverse bias for each temperature).

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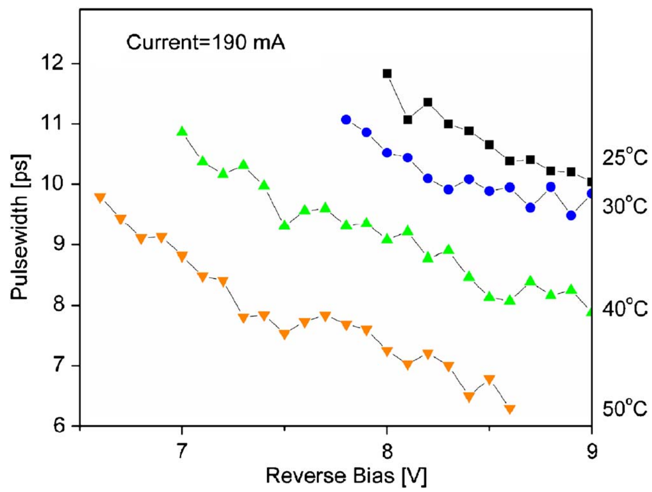

FIG. 2. (Color online) Experimental results. Dependence of the pulse duration on reverse bias at a constant injection current for several temperatures.

sons have been suggested. One implies an increase in the homogeneous linewidth,[4] but another is that a decrease in population inversion over the entire gain spectrum due to thermal coupling to the wetting layer would reduce the number of modes that reach threshold.[5]

The experimental dependence of pulse duration with increasing reverse bias for several fixed values of temperature is presented in Fig. 2. The possibility of obtaining even shorter pulses at higher temperatures was limited by the shift from ground-state to excited-state emission, as the reverse bias was increased and the ground-state gain saturated.

To account for the decrease in pulse duration with increasing operating temperatures, we used the model for mode locking in QD lasers described in Ref. 6. Thus,

$$\gamma^{-1}\partial_t A(t) + A(t) = \sqrt{\kappa}e^{(1-i\alpha_g)G(t-T)/2-(1-i\alpha_q)Q(t-T)/2}A(t-T), \quad (1)$$

$$\partial_t \rho_g = -\gamma_g \rho_g + F_g(\rho_g, N_g) - e^{-Q}(e^G - 1)|A|^2, \quad (2)$$

$$\partial_t \rho_q = -\gamma_q \rho_q + F_q(\rho_q, N_q) - s(1 - e^{-Q})|A|^2, \quad (3)$$

$$\partial_t N_g = N_{g0} - \Gamma_g N_g - 2F_g(\rho_g, N_g), \quad (4)$$

$$\partial_t N_q = N_{q0} - \Gamma_q N_q - 2F_q(\rho_q, N_q). \quad (5)$$

$A(t)$ is the normalized complex amplitude of the electric field, the variables $\rho_g(t)$ and $\rho_q(t)$ describe the occupation probabilities in a dot located either in the amplifier or in the absorber section, respectively, and the variables $N_{g,q}(t)$ describe the carrier densities in the wetting layers, scaled to the QD carrier density. The variables $G(t)=2g_gL_g[2\rho_g(t)-1]$ and $Q(t)=2g_qL_q[2\rho_q(t)-1]$ are the dimensionless saturable gain and absorption. The parameters $g_{g,q}$, $\Gamma_{g,q}$, and $\gamma_{g,q}$ are, respectively, the differential gains, the damping rate in the wetting layers, and the carrier relaxation rates in the dots, γ is the dimensionless bandwidth of the spectral filtering section, and α_g (α_q) are the linewidth enhancement factors in the gain (absorber) section. The time delay T is equal to the cold cavity round-trip time. The attenuation factor $\kappa < 1$ describes total nonresonant linear intensity losses per cavity round-trip. The dimensionless parameters N_{g0} and N_{q0} describe pumping processes in the amplifier and the absorber sections. The parameter s is the ratio of the saturation intensities in the gain and absorber sections. The functions $F_{g,q}(\rho_{g,q}, N_{g,q}) = B_{g,q}N_{g,q}(1-\rho_{g,q}) - R^{\text{esc}}_{g,q}\rho_{g,q}$ describe the carrier exchange rate between the wetting layers and the dots. $B_{g,q}=\tau^{-1}_{g,q}$ and $R^{\text{esc}}_{g,q}=(\tau^{\text{esc}}_{g,q})^{-1}$ are temperature-dependent coefficients defining carrier capture and escape from the dots to the wetting layer.

The two main processes to that can be influenced and that must be considered with temperature change are (i) the capture and (ii) the escape times to/from the quantum dots. Experimentally, the relative contribution of these processes cannot be disentangled, but our modeling indicated that the capture/escape processes in the absorber are dominant. The increased capture rate at high temperature was measured experimentally.[7,8] The carrier capture and escape times depend on the availability of phonons. We assumed that their temperature dependence can be described by the Bose-Einstein distribution, such that

$$\tau_{g,q}, \tau^{\text{esc}}_{g,q} \sim e^{(E_{\text{wl}}-E_{\text{gs}})/kT} - 1, \quad (6)$$

where E_{wl} and E_{gs} are the energy levels corresponding to the quantum well and to the ground state of the quantum dot. The choice of a Bose-Einstein distribution is consistent with the property that capture and escape are instantaneous processes ($\tau_{g,q}=\tau^{\text{esc}}_{g,q}=0$) if $E_{\text{wl}}=E_{\text{gs}}$. We found that this ansatz leads to predictions that match well the experimental results. A similar distribution was discussed in Refs. 7 and 9. In the numerical simulations, we assumed a carrier capture time of $\tau_g=10$ ps for the gain section and $\tau_q=50$ ps for the absorber section, at 20 °C and $E_{\text{wl}}-E_{\text{gs}}=230$ meV.

The modeling of the escape processes is more tentative, less investigated, and related to the impact of the first excited state. Our model does not take the first excited state into account as it will lead to significant additional complexity due to the electron-hole energy exchange asymmetry between the ground and excited states at elevated temperatures.[10] Instead, we examined just the general trend and considered the most important case in which the capture is either much faster than the escape ($\tau_g \ll \tau^{\text{esc}}_g$) in the gain section or it is much slower than the escape ($\tau_q \gg \tau^{\text{esc}}_q$) in the absorber section. In the gain section, the ratio $\tau_g/\tau^{\text{esc}}_g$ can be estimated from the quasiequilibrium condition $\tau^{\text{esc}}_g \sim \tau_g e^{(E_{\text{gs}}-E_{\text{wl}})/kT}$.[11] For these small values of escape rate ($\tau_g/\tau^{\text{esc}}_g < 0.1$), the escape process becomes essentially negligible. In the absorber section, quasiequilibrium conditions cannot be applied, and the thermal escape time at room temperature was arbitrarily considered to be 5 ps, which satisfies $\tau_q \gg \tau^{\text{esc}}_q$ and is close to the estimate in Ref. 12.

In our numerical simulation, plotted in Fig. 3, the objective was to match qualitatively the pulse duration dependence. The trends observed experimentally are well described by our model and it can be seen that the pulse durations decrease smoothly by about two times for temperature increases over the 25–50 °C latitude. This temperature range is arbitrary and has been used solely to demonstrate the trends. The actual temperature of the carriers is of course higher than the temperature of the lattice, which was measured experimentally. The difference between the carrier temperature and the temperature of the lattice is due to the carrier heating caused by carrier injection and short energy pulses circulating in the cavity. It is, however, rather difficult to estimate this difference.

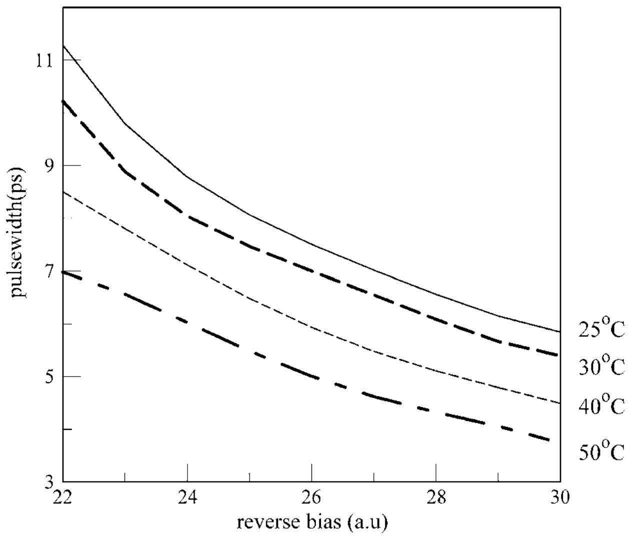

FIG. 3. Numerical simulations. Dependence of the pulse duration with reverse bias at a constant injection current for several temperatures. The parameters for the numerical simulation are $\kappa=0.2$, $T=5$, $\gamma=10$, $\gamma_g=\gamma_q=\Gamma_g=0.01$, $\Gamma_q=1$, $\alpha_g=\alpha_q=2$, $2g_gL_g=2.4$, $2g_qL_q=13.5$, $s=30$, and $N_{g0}=10$.

Experimental results demonstrate an even faster decrease of the pulse durations with temperature than that implied by the results of Fig. 3. This can be attributed to the higher temperature of the carriers together with the complexity of multiple-phonon scattering[7] that is not accounted for in the simple assumptions made for the capture and escape rates in Eq. (6).

It follows from our modeling that the role of the temperature-dependent capture and escape processes in the gain section is relatively minor. Indeed, it is more likely that the duration of a mode-locked pulse is determined primarily by the capture and escape rates in the absorber section of our device. In our model, both capture and escape rates increase with temperature, but in the numerical analysis the dominant role of the capture rates in the pulse shortening with temperature is emphasized within the model. (The identical temperature dependence for the capture and the escape rates simply demonstrates the trend.) It can be expected that the actual dependence of the escape rates on temperature could be quite different and yet still lead to the same qualitative results.

In conclusion, we have investigated the influence of temperature on the mode-locking performance of a two-section QD laser. It has been shown experimentally that both the pulse duration and the spectral width decrease as temperature was increased, resulting in an overall decrease of the time-bandwidth product. A model has been developed to simulate this behavior for passive mode locking in quantum-dot lasers, where the temperature dependence is linked to the capture and escape rates into the quantum dots. We believe that this provides an important insight into the specific carrier mechanisms that have an impact on the mode-locking performance of quantum-dot lasers.

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