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High-frequency modulation without the relaxation oscillation resonance in quantum cascade lasers

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Quantum cascade (QC) lasers, based on intersubband transitions in semiconductor quantum wells, are characterized by ultrafast (picosecond) carrier lifetimes. An important consequence of this unique property is the expected absence of relaxation oscillations in the transient response of these devices. Here, we discuss and experimentally verify this prediction by measuring the modulation response of several 8-μm-QC lasers, properly processed and packaged for high-speed operation, up to 10 GHz. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1411982]

Quantum cascade (QC) lasers[1,2] are midinfrared semiconductor light sources based on intersubband electron transitions in coupled quantum-well systems. A unique feature of these devices is their ultrafast carrier relaxation lifetime. Namely, electron equilibration between energy subbands is dominated by LO-phonon-assisted processes that occur on a picosecond time scale. For comparison, in conventional semiconductor lasers based on interband transitions the intrinsic carrier lifetime is on the order of a few nanoseconds; and even slower relaxation time constants are found in most other laser systems. This property makes QC lasers ideally suited for high-speed operation. In previous work, we have explored the use of these devices as ultrafast light sources, and demonstrated the generation of picosecond midinfrared pulses by gain switching and mode locking.[3–5] In this letter we investigate the high-speed modulation response of QC lasers; in particular, we demonstrate a unique feature of these devices that is directly related to their ultrafast carrier dynamics, namely the characteristic absence of relaxation oscillations.

It is well known that the transient response of any laser to a change in its pumping conditions (e.g., the drive current in a semiconductor laser) is determined by the interplay between the dynamics of the population inversion and that of the laser field.[6] In particular, both quantities respond to such a change by undergoing coupled damped oscillations towards their steady-state values, with the damping mechanism provided by stimulated emission and gain saturation. These so-called relaxation oscillations produce a resonance enhancement of the laser modulation response at their characteristic frequency f_R. Furthermore, the modulation response becomes increasingly weaker as the drive frequency is increased above this resonance, so that f_R provides a measure of the laser intrinsic modulation bandwidth.[6] The situation is radically different in QC lasers, because in these devices the relaxation of the carrier density to equilibrium is dominated by phonon scattering. Since this is an ultrafast mechanism, transient oscillations of the population inversion, and hence of the photon density, are overdamped, and no resonance will therefore appear in the frequency response. The modulation dynamics of QC lasers is to a large extent simply limited by their picosecond carrier lifetime, so that intrinsic bandwidths in excess of one hundred gigahertz can be expected.[7,8]

In order to put the above discussion in a quantitative framework, we first of all recall that the ‘‘textbook’’ laser modulation response is characterized by two poles at the following complex frequencies:[6,9]

$$\omega_{\pm}=\frac{i}{2}\left(\frac{1}{\tau_c}+\frac{cg_NP}{n}\right)\pm\sqrt{\frac{1}{\tau_p}\,\frac{cg_NP}{n}-\frac{1}{4}\left(\frac{1}{\tau_c}+\frac{cg_NP}{n}\right)^2},\tag{1}$$

where τ_c is the lifetime of the upper laser state, τ_p is the photon lifetime, c is the speed of light in vacuum, g_N is the differential gain, n the modal refractive index, and P the intracavity photon density in the lasing mode [the quantity $n/(cg_NP)$ is often referred to as the stimulated emission lifetime τ_{st}]. In interband semiconductor lasers, the second term in the square root is negligible, so that the two poles of Eq. (1) have a nonzero real part. Correspondingly, a resonance is introduced in the modulation response at the frequency $f_R=|\mathrm{Re}\{\omega_{\pm}\}|/(2\pi)$ (the relaxation oscillation frequency). In contrast, in QC lasers, due to their ultrashort carrier lifetime τ_c, the second term in the square root of Eq. (1) typically dominates, so that the two poles are pure imaginary and no such resonance exists.

The intrinsic cutoff frequency in QC lasers is then given by $f_{3\,\mathrm{dB}}=\mathrm{Im}[\omega_-]/(2\pi)$, and is maximized by decreasing the lifetimes τ_c, τ_p, and τ_{st}. The latter is inversely proportional

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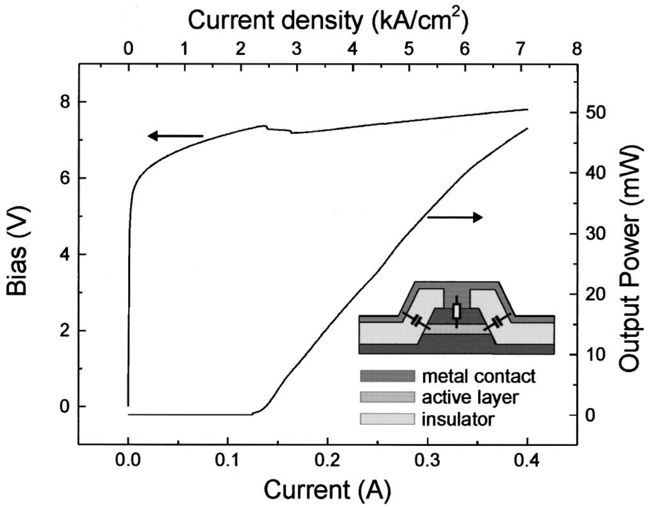

FIG. 1. cw bias-to-current and light output-to-current characteristics of one of the QC lasers tested at 20 K. The light is collected from one facet with 70% efficiency. Inset: schematic cross section of the QC laser waveguide. The shaded areas represent, in order of increasingly darker shading, the $Ge_{0.25}Se_{0.75}$ layer, the active material, the metal contact, and the cladding regions. The capacitance and resistance symbols indicate the main chip parasitics limiting the laser high frequency response.

to the output power, and therefore is minimized by operating the laser well above threshold. The photon lifetime τ_p is typically $\gtrsim \tau_c$, and can be decreased for instance by shortening the cavity length. An important limit is obtained in the case $\tau_p = \tau_c > \tau_{st}$, where $f_{3\ \mathrm{dB}}$ is equal to $1/(2\pi\tau_c)$. Using a typical calculated value[2] $\tau_c = 1.5$ ps, this gives $f_{3\ \mathrm{dB}} \approx 106$ GHz. Even larger bandwidths can be achieved by further decreasing the carrier lifetime, e.g., by increasing the wave function overlap between the upper and lower laser states, as in superlattice active regions.[2] Incidentally, while the above limit does not always apply to high-performance QC lasers, it happens to be valid for the devices used in this experiment, where τ_p, as estimated from the measured threshold current density (see Fig. 1) is also ≈ 1.5 ps.

Aside from the fundamental interest in the underlying device physics, semiconductor lasers with such a wide and flat frequency response are obviously attractive from a technological standpoint. In particular, high-speed midinfrared QC lasers could play an important role in the development of free-space optical communication links, an application that is attracting considerable interest in both the commercial sector, for high-capacity line-of-sight communications, and in the military, for secure battlefield transmission links. While impressive results have been demonstrated using 1.55 μm technology,[10] the use of midinfrared light for optical wireless can be advantageous[11] due to its lower atmospheric losses, particularly in the presence of fog and pollution. Furthermore, this intrinsically ultrafast response provides a major motivation to the present effort[12] to develop intersubband optoelectronic devices working at fiber-optic communication wavelengths.

In practice, parasitic effects in both the laser chip and package limit the modulation bandwidths of actual devices. For this experiment, these were minimized using previously developed approaches.[3,4] High-speed packaging was obtained by bonding the QC laser bar to a 50-Ω-microstrip line, and by using a cryogenic semirigid cable, connected to the stripline via the appropriate adapter, to deliver the radio frequency (rf) signal to the laser. Furthermore, we used a rather thick (5 μm) insulating layer underneath the laser top metal contact in order to reduce its bypass capacitance, which provides the main contribution to the chip parasitics (see inset of Fig. 1). A chalcogenide glass ($Ge_{0.25}Se_{0.75}$), deposited over the QC laser waveguide by pulsed laser ablation, was used for this purpose. This material was chosen because it was found to have all the required attributes,[4] including low absorption at midinfrared wavelengths (unlike the polymers that are commonly used for the same purpose with near-infrared lasers, such as polyamide). Incidentally, it should be mentioned that the use of these thick cladding layers also improves the overall laser performance,[13] by reducing the lateral waveguide losses and by providing increased thermal dissipation.

In this experiment, we measured the modulation response of several QC lasers, packaged and processed as just described, by driving them with the output of a synthesized signal generator, at a variable frequency ranging from ~0.1 to 10 GHz, combined with a dc bias above the threshold for cw operation. The light output was detected with a GaAs/AlGaAs quantum-well infrared photodetector (QWIP),[14] also packaged for high-speed operation, and the resulting photocurrent was amplified and fed to a microwave spectrum analyzer, where the modulation amplitude was measured. All the lasers used were grown by molecular beam epitaxy with the GaInAs/AlInAs material system, and are based on the "vertical" transition design in a three-coupled-quantum-well active region.[2] Their emission wavelength is near 8 μm, the wavelength of operation of the QWIP available in our lab. We emphasize however, that the high-speed properties discussed in this letter are quite general to all intersubband lasers, including different active-region designs, output wavelengths, and material systems, since they rely solely on the ultrafast carrier relaxation provided by phonon scattering.

In the following, we present results from two devices (from processing sample D2642BA), consisting of 1.25 mm long, 4.5 μm wide ridges; very similar data were measured from all other devices tested. In Fig. 1, we plot the light output and bias voltage versus current of one of these devices during cw operation at a temperature of 20 K. The corresponding threshold current densities of 2.4 kA/cm^2 are higher than in previously reported similar devices,[13] which can be attributed to details of the material growth and device processing.

Figure 2(a) shows exemplary modulation response traces of this device, for different values of the dc bias, and hence photon density, at a temperature of 20 K. These traces were normalized with the experimental frequency response of the receiver, so that they only reflect the modulation response of the QC laser. For that purpose, we measured the frequency response of the QWIP using the microwave rectification technique described in Ref. 14. The modulation response of a second laser measured at liquid nitrogen temperature is plotted in Fig. 2(b), showing identical behavior. Regarding the laser cutoff frequency, we notice first that the traces of Fig. 2 cannot be simply fit by a single-pole frequency response function, in particular because of the low-frequency shoulder observed in all these traces up to about 2 GHz. Aside from

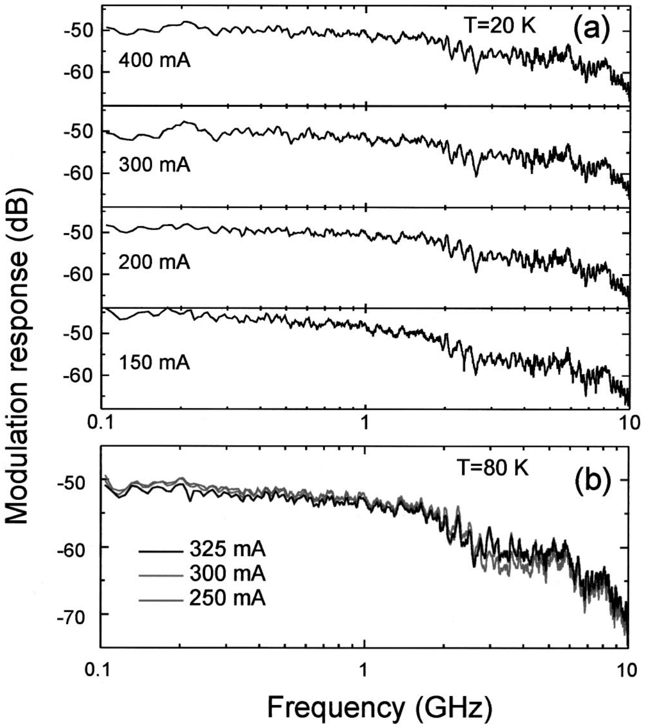

FIG. 2. (a) Exemplary high-frequency modulation response traces of an 8-μm-QC laser at 20 K, for different values of the drive current ranging from very near threshold (150 mA), up to over one order of magnitude higher photon density (400 mA). These traces were normalized with the experimental frequency response of the receiver and reflect only the modulation response of the QC laser. (b) High frequency modulation response of a different laser, for a set of values of the laser bias at 80 K.

this feature, which we ascribe to residual parasitic effects, the traces of Fig. 2 remain relatively flat up to roughly 7 GHz. Given the estimated capacitance across the chalcogenide layer, $C \approx 10$ pF, and the differential resistance of the laser above threshold, $R \approx 2\Omega$ (inferred from the data of Fig. 1), this indicates that the modulation response is still to a large extent RC limited.

In any case, the most striking feature of the data of Fig. 2, particularly if compared with the results of similar experiments with typical interband diode lasers, is the absence of any resonance peak. As previously discussed, in interband lasers relaxation oscillations introduce a resonance in the modulation response at their characteristic frequency. This frequency, given by the real part of Eq. (1), depends on the laser properties (most notably the differential gain and the photon lifetime), and varies roughly as the square root of the optical power; in typical diode lasers slightly above threshold, it is on the order of several tenths to a few gigahertz. In contrast, no such resonance is observed in any of the traces of Fig. 2. There are some features that resemble weak resonance peaks (e.g., near 6 and 8 GHz), but they remain exactly the same as the laser optical power is varied [by over one order of magnitude in Fig. 2(a)], in contrast with Eq. (1); once again we attribute these small features to parasitic effects, in particular in the laser package (the high-speed cryostat), given that they appear essentially unchanged in the frequency response of different lasers. It is also important to mention that no sign of relaxation oscillations was found over a wide range of dc bias, including values approaching the cw threshold (e.g., $P \rightarrow 0$), for which, no matter how fast the laser intrinsic response is, the relaxation oscillation frequency would eventually enter the relatively low-frequency range tested. We therefore believe that these results provide conclusive evidence of the absence of relaxation oscillations in QC lasers. We emphasize that this is a unique property of intersubband lasers that could prove quite important in the use of these devices as high-speed data sources, particularly in applications where linearity is important.

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