Extraction-controlled quantum cascade lasers

Wacker, Andreas

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Since their first realization,1 quantum cascade lasers (QCLs) have turned into versatile devices. While the first lasers operated in the infrared region above the optical phonon frequency (around 9 THz in the most common III/V semiconductor materials used), terahertz (THz)-QCLs, operating below this frequency, could be achieved later.2 However, the operation of these THz-QCLs has only been established for temperatures up to 186 K yet.3 The achievement of almost two orders of magnitude in frequency from 1.2 THz to 250, based on a single concept QCLs operate over a range of different cooling techniques. Based on a simple two-well design for terahertz quantum cascade lasers is proposed which is based on scattering injection and the efficient extraction of electrons from the lower laser level by resonant tunneling. In contrast to existing designs this extraction also controls the positive differential conductivity. The device is analyzed by calculations based on nonequilibrium Green’s functions, which predict lasing operation well above 200 K at a frequency of 2.8 THz. © 2010 American Institute of Physics. [doi:10.1063/1.3483764]
possible solution of this problem is the development of scattering injection designs. Such a structure was recently shown to exhibit improved temperature performance in the THz region. In these structures a tunneling resonance is included in the current flow before the electrons reach the injector state in order to guarantee PDC.

Here a design based on scattering injection is proposed where this tunneling resonance is skipped, see Fig. 1(b). Instead, the tunneling resonance from the lower laser level to the extraction level controls the current. The idea is that for biases below the designed operation point the carriers are essentially located in the lower laser level. At the design bias the extraction level removes these carriers effectively. Simultaneously, this level serves as the injection level for the upper laser level of the next period via phonon scattering. Thus this structure is a simplified combination between the resonant phonon extraction and the scattering injection scheme, where both features are provided by the same levels. This allows a design with only two wells per period and thereby increases the number of possible periods in the waveguide. (Two-well designs have been already established for the conventional tunneling injection design.)

The design of the structure was optimized by calculations within the nonequilibrium Green’s function model described in Refs. 8, 18, and 19 using an improved treatment of acoustic phonon scattering and including alloy scattering, see Ref. 20 for details. This model allows for a consistent treatment of coherent evolution and scattering including level broadening, and has been recently used by other groups as well. Here the following issues were found to be of relevance for the final design: (i) at the operating bias, the extraction level is in resonance with the lower laser level and located about one optical phonon energy above the upper laser level of the subsequent period. (ii) The higher levels do not provide further level spacings comparable to the lasing transitions in order to avoid reabsorption at higher temperatures, when they are partially filled. (iii) Increasing doping enhances the number of carriers in the gain transition but also strengthens impurity scattering associated with a larger linewidth and a shorter lifetime of the upper laser state. The chosen doping was found to provide the strongest gain. (iv) Compensation effects reduce the width of the gain spectrum if the same doping atoms affect both laser levels. Thus, the placing of the doping in the barrier between the lasing states is advantageous.

Figure 2(a) shows the calculated current-voltage characteristics for different temperatures for the optimized structure. The currents are of the same magnitude as in the design in Ref. 3 and thus the same thermal management should work. The gain spectrum, see Fig. 2(b), shows a peak around 12 meV (2.8 THz). At 200 K the gain maximum is 76/cm which is almost twice as large as the calculated value for the structure in Ref. 3 (42/cm at 17 meV for 200 K). Given the fact that the latter sample exhibited laser operation until 186 K, laser operation well above 200 K can be expected for the proposed design. At 300 K the peak gain is reduced to 22/cm, which is most likely not sufficient to overcome the waveguide losses.

In order to understand the operation, the energetically and spatially resolved carrier density is shown in Fig. 3. At 37 mV per period, the extraction level is aligned with the upper laser level, which causes a pronounced current peak, while a significant part of the electrons is trapped in the lower laser level. Increasing the bias, the lower laser level is emptied at 48 mV due to its alignment with the extraction level. For low temperatures (e.g., 100 K) the scattering lifetime of the upper laser level is long and thus almost all electrons are collected in this level, see the data given in Table I. Thus the current is determined by the tunneling from the upper laser level into the extraction level which causes NDC at the bias of 48 mV per period. With increasing temperature, scattering becomes stronger leading to a higher occupation of the lower laser level, so that the contribution of the tunneling resonance between lower laser level and the extraction level is of larger importance. This provides PDC for each period as observed at 200 and 300 K and required for stable operation. Thus the scattering from the upper to the lower laser level, which reduces the inversion (see Ref. 23 for a detailed discussion), is actually required for the device.
In conclusion, a design for THz-QCLs has been proposed based on the efficient depopulation of the lower laser level, which also ensures the PDC. Lasing operation above 200 K is predicted.

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