Terahertz quantum cascade laser based on LO-phonon-scattering assisted depopulation.

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In a recent breakthrough,[1] we have developed the longest wavelength quantum cascade laser to date, at λ = 87.2 μm corresponding to 3.44 THz or 14.2 meV photon energy. The laser is based on $GaAs/Al_{0.15}Ga_{0.85}As$ multiple quantum well structures, and it utilizes resonant LO-phonon scattering for depopulation of the lower radiative level to achieve population inversions. The core structure, a four-well module, is shown within the dashed box in Fig. 1. The radiative transition takes place between levels 5 and 4, highlighted by thicker lines. 175 nominally identical such modules are cascade connected in series. Under designed bias, the ground level 1' of a previous module is aligned with level 5, selectively injecting electrons to this upper level. The lower level 4 is at resonance with a level in the adjacent well, where very fast LO-phonon scattering (~0.5 ps) takes place, keeping this level mostly empty.

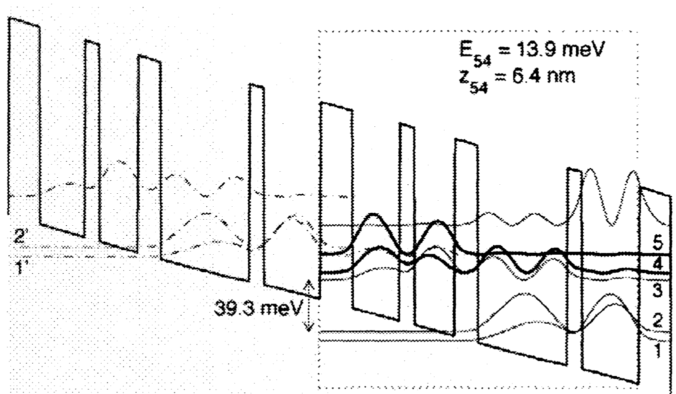

Figure 1. Conduction band profile of the THz quantum cascade laser structure under a bias of 64 mV/module, corresponding to a total bias voltage of 11.2 V.

Lasing at 3.437 THz (λ = 87.2 μm) was obtained in this device at a threshold current density of 840 A/cm^2 at 5 K heat sink temperature. Typical emission spectra above threshold are shown in Fig. 2. The emission frequency corresponds to a photon energy of 14.2 meV, close to the calculated value of 13.9 meV. For much of the bias range, the emission is dominated by a single mode, and the spectrum shifts towards higher energy longitudinal modes with increasing bias (inset, Fig. 2) due to Stark shift.

Measured optical power versus current (P-I) curves at low duty cycle are plotted in Fig. 3(a). Lasing is observed up to 64 K with a power level of 25 μW, compared to the 2.5 mW observed at 5 K. Fig. 3(b) displays the voltage versus current, as well as several P-I curves taken at different duty cycles. The peak power remains largely unchanged for duty cycle below 1%, and gradually drops to 0.5 mW at 50% duty cycle.

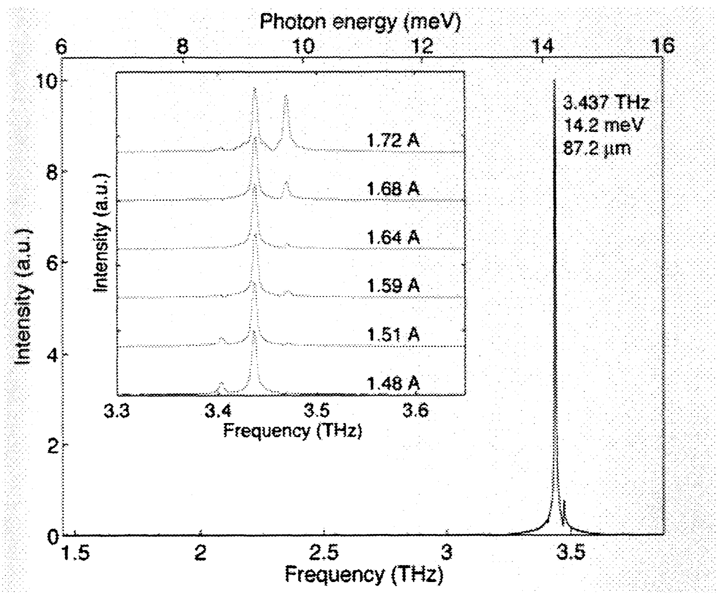

Figure 2. Emission spectrum above threshold biased at 1.64 A at 5 K. The inset shows an expanded view of spectra at various bias points, offset for clarity.

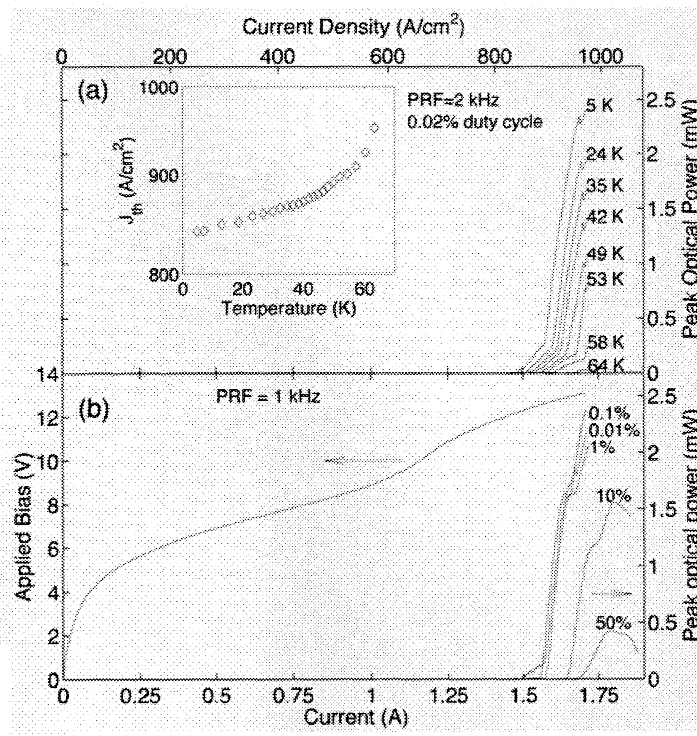

Figure 3. (a) Emitted power versus current at various heat sink temperatures with a 0.02% duty cycle. (b) Applied bias voltage and peak emission power versus current, collected at various duty cycles and heat sink temperature from 8 K to 15 K.

The performance of this device is quite promising, as a first attempt to develop THz quantum cascade lasers based on LO-phonon assisted depopulation and at this long wavelength. Minor improvements such as fabrication of narrower ridges and improved heat sinking should lead to CW operations. Further refinement of the injector design should improve efficiency and reduce the threshold current density. We believe that resonant LO-phonon assisted depopulation is a robust scheme that will enable operation at even higher temperatures and still longer wavelengths. We are currently developing quantum cascade lasers for the important 2.5-THz frequency range based on the same operating principle. Given the remarkable success at 3.4 THz, we are optimistic about the outcome of this new development. The resulst will be presented at the symposium.

1. B. S. Williams, H. Callebaut, S. Kumar, Q. Hu, and J. L. Reno, to be published in Appl. Phys. Lett., Febuary 24 (2003).