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Three-well terahertz frequency quantum cascade lasers with a common LO-phonon extraction and injection stage

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1. Introduction

Terahertz-frequency quantum cascade lasers (THz QCLs) are promising sources for many applications including THz spectroscopy, remote sensing and THz imaging.[1,2] However, cryogenic cooling is needed for THz QCLs, limiting their practical use in many applications outside the laboratory environment. In order to improve the temperature performance, an extraction-controlled design was proposed, based on an indirect pumping scheme, where LO-phonon scattering replaces resonant tunnelling for carrier injection.[3] Here, we present a three-well design, in which one diagonal phonon-scattering process is employed to realize both the carrier extraction and injection simultaneously. Its simplicity makes it an ideal platform to investigate the scattering injection process for high temperature operation of THz QCLs.

2. Design of active region

The conduction band profile and the squared moduli of the electronic wavefunctions of two periods of our GaAs/$Al_{0.15}Ga_{0.85}As$ structure at the design bias are shown in Fig. 1. Levels 2 and 1 are the laser states for the emission of THz radiation; level 3 then behaves as the injection level of the same period and simultaneously as the extraction level of the previous period. The energy separation between levels 3 and 2 is designed to be equal to the LO-phonon energy, enabling fast resonant LO-phonon scattering to transport electrons from level 3 to level 2. The electrons in level 1 are extracted rapidly via resonant tunnelling and subsequently by LO-phonon scattering. This leads to a short lifetime for level 1, and hence a population inversion between laser-levels 2 and 1.

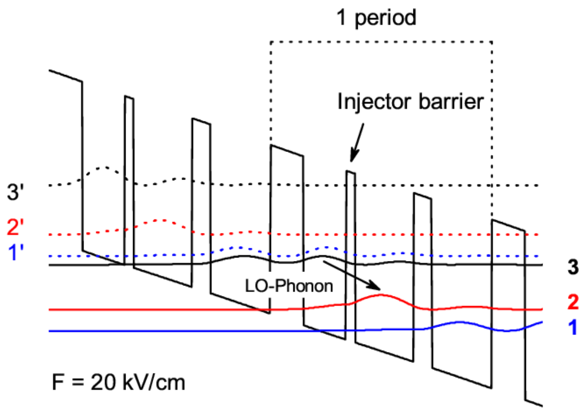

Fig. 1: Calculated conduction band diagram and squared moduli of the electronic wave functions of a three-well design in GaAs/$Al_{0.15}Ga_{0.85}As$ at an electric field of 20 kV/cm.

3. Experimental results

The sample was grown by molecular beam epitaxy. The QCL structure consisted of a 10-µm-thick stack containing the periodic three-well active module, which was embedded between two n^+-GaAs layers ($n = 5.0\times10^{18}$ cm^{-3}). Devices were fabricated using a gold–gold waveguide configuration, and the laser ridges were defined by wet-chemical etching. For the light intensity–current–voltage (*L–I–V*) and spectral characterization, the devices were operated in pulsed mode with 2-µs-long pulses at a repetition rate of 10 kHz and the laser emission was detected using a cooled Ge:Ga bolometer. The output power was calibrated with an absolute THz power meter (Thomas–Keating Instruments).

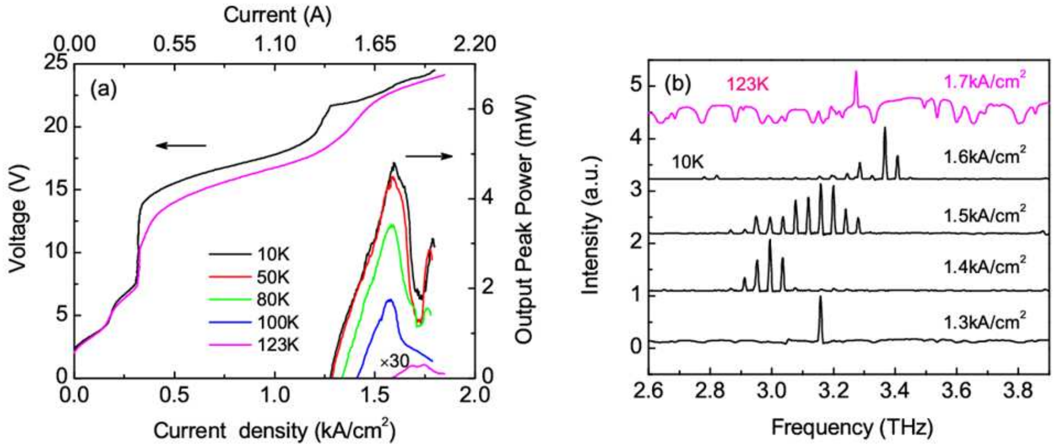

Fig. 2: (a) *L–I–V* characteristics at various temperatures. (b) Spectra at 10 K and 123 K. The device was 1000 µm long and 110 µm wide, processed into a gold–gold waveguide configuration.

The *L–I–V* curves and the measured spectra at various biases are shown in Fig. 2(a) and Fig. 2(b), respectively. The device lased up to 123 K in pulsed mode. At a temperature of 10 K, the threshold current density is 1.32 kA/cm^2 and the peak output power is 4.8 mW. The emission frequency was centred at ~3.1 THz at biases close to threshold. With increasing bias, the spectra broadened and multi-mode lasing behaviour over the range 2.9 to 3.4 THz was observed. The large threshold current density and the temperature performance will be analysed based on a density matrix model.

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