Proceedings Paper:

Strupiechonski, E, Blanchard, R, Genevet, P et al. (7 more authors) (2014) Enhancing the gain by quantum coherence in terahertz quantum cascade lasers. In: CLEO: 2014, OSA Technical Digest. CLEO: QELS_Fundamental Science, June 8-13, 2014, San Jose, California United States. OSA . ISBN 978-1-55752-999-2

https://doi.org/10.1364/CLEO_QELS.2014.FTu3D.1

Enhancing the Gain by Quantum Coherence in Terahertz Quantum Cascade Lasers

E. Strupiechonski[(1,2)], R. Blanchard[(2)], P. Genevet[(2,4)], Y. Wang[(4)], A. Belyanin[(4)], L. H. Li[(3)], E. H. Linfield[(3)], A. G. Davies[(3)], F. Capasso[(2)] and M. O. Scully[(1,4)]

(1) Baylor University, Waco, Texas 76706, USA

(2) School of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138, USA

(3) School of Electronic and Electrical Engineering, University of Leeds, Leeds LS2 9JT, UK

(4) Texas A&M University, College Station, Texas 77843, USA

estrup@seas.harvard.edu

Abstract: We propose and study GaAs/$Al_{25}Ga_{75}As$ terahertz frequency quantum cascade lasers in which mid-infrared radiation is used as a coherent drive for enhancing the terahertz gain.

1. Active region design

We propose and present an experimental study of terahertz (THz) frequency quantum cascade lasers (QCLs) in which an external mid-infrared radiation source is used as a coherent drive for enhancing THz gain. An example of the active region design is shown in Fig. 1, where the calculated GaAs/$Al_{25}Ga_{75}As$ conduction band diagram is shown for two identical modules under an alignment bias of 14.6 kV.cm^{-1}.

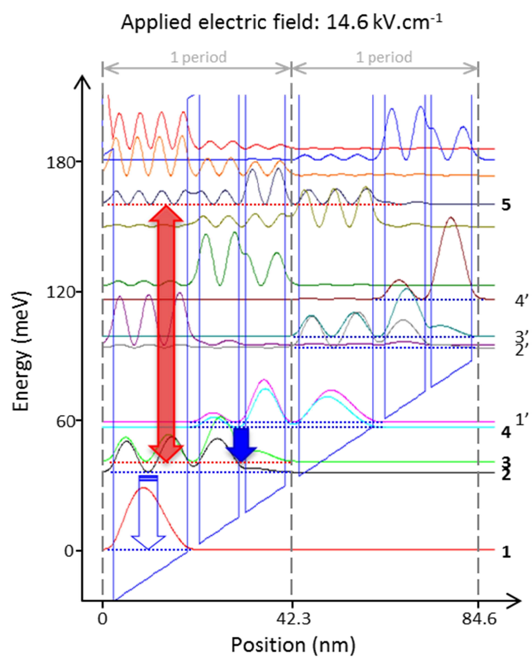

Figure 1 - Schematic bandstructure diagram showing coherent enhancement of the gain in a THz QCL. Arrows: terahertz laser transition (blue); LO-phonon emission (white); mid-infrared pump (red)

The design is based on a "resonant-phonon" active region scheme [1], in which a mid-infrared transition is also engineered. In this structure, electrons are injected into both states 1' and 4, with an injection efficiency that is tunable with applied bias. State 3 stays empty owing to resonant LO-phonon scattering into the ground state (cf. Fig. 1, white arrow). As a result, the transition 4-3 is inverted, and lasing is observed as in a standard THz QCL. Coherent radiation at a mid-infrared wavelength of λ=10.2 µm, resonant to transition 3-5 (red arrow), generates quantum coherence between states 5 and 4, hence enhancing the THz gain for radiation resonant to transition 4-3 (blue arrow).

2. Fabrication and characterization

In order to investigate systematically the effects of a mid-infrared pump on the gain in a THz QCL, three different GaAs/$Al_{25}Ga_{75}As$ structures have been designed and grown by molecular beam epitaxy on an insulating GaAs substrate. This material system has been chosen for its large value of conduction band discontinuity (223.5 meV), allowing good confinement of the high order states involved in the mid-infrared transition.

The active regions have been processed into metal-metal and single-plasmon Fabry-Perot waveguides, and characterized in an FTIR spectrometer using a CO_2 laser and a QCL master-oscillator power-amplifier (MOPA) [2] as external mid-infrared sources.

3. Gain enhancement by quantum coherence

The maximum gain is reached when both optical fields are at exact resonance with the corresponding transitions. Under these conditions, the gain for the THz transition is given by:

$$g_{\mathrm{THz}} = \frac{4\pi\omega_{43}e^2}{hc\mu_{43}} \frac{d_{43}^2}{\gamma_{43}+\frac{|\Omega_d|^2}{\gamma_{54}}}\left[(n_4 - n_3) + \frac{|\Omega_d|^2\,(n_3-n_5)}{\gamma_{54}\gamma_{53}}\right] \quad (1)$$

where d_{43} is the dipole moment of the THz transition, μ_{43} is the refractive index of the THz mode, n_i is the population on the i^{th} subband, γ_{ij} is the linewidth of the transition $i-j$, and Ω_d is the Rabi frequency of the mid-infrared drive field E_d, defined as $\Omega_d = d_{53}E_d/h$. The mid-infrared driving field enhances the gain in two ways: first, by depopulating the lower laser state 3, and second, by introducing the last term (in the brackets), which is proportional to the drive intensity and due directly to quantum coherence effects.

This presentation will report the design and modeling of the laser performance. The fabrication process, characterization apparatus, and experimental results will then be presented and discussed.

[1] H. Luo, S. R. Laframboise, Z. R. Wasilewski, G. C. Aers, H. C. Liu, J. C . Cao, “Terahertz quantum-cascade lasers based on a three-well active module”, Applied Physics Letters, **90**, 041112 (2007).

[2] P. Rauter, S. Menzel, A. K. Goyal, B. Gökden, C. A. Wang, A. and Sanchez, G. W. Turner, F. Capasso, “Master-oscillator power-amplifier quantum cascade laser array”, Applied Physics Letters, **101**, 261117 (2012).