Sub-wavelength optical mode volumes for terahertz quantum cascade lasers

Y. Chassagneux, R. Colombelli, S. Dhillon, C. Sirtori, H. Beere, J. Alton, D. Ritchie

Abstract— **We demonstrate terahertz microcavity lasers at an emission wavelength of 112micron with ultra-low current thresholds (4 mA) and with sub-wavelength mode volumes. The properties of surface plasmons are exploited to confine the optical mode.**

Index Terms—**laser, terahertz, intersubband, microcavity.**

I. Introduction

Quantum cascade (QC) lasers are semiconductor injection lasers. However, in these devices electrons do not recombine with valence band holes, but instead undergo a quantum jump between quantized conduction band states, called subbands, of a suitably designed multi-quantum-well structure. The possibility of almost arbitrary design for the multi-quantum-well structure allows QC lasers to cover a wavelength range where few compact sources are available, i.e. the THz range (70 μm < λ < 200 μm) [1]. Currently, the best performance has been obtained using resonators where the mode confinement is provided by a double-sided metal waveguide [2]. In this geometry, the laser active core is directly sandwiched between two metal layers acting as contacts and confining layers simultaneously. Contrary to standard dielectric [3] or even one-sided surface plasmon waveguides, extensively used for mid-infrared (mid-IR) and THz QC lasers, metal-metal waveguides offer the opportunity of reducing to a minimum the active-region thickness without sacrificing the confinement factor, which remains always close to unity.

Reducing the thickness of the active region is interesting for several reasons. First, it eases the semiconductor growth, as 12-μm-thick epitaxial layers already push the MBE technology to its limit, and – in the long term – could constitute an obstacle to device commercialization. Secondly, surface emitting devices might represent a solution to the low power-extraction efficiency of metal-metal waveguides. In a double metal geometry, surface emission can be available with only a patterning of the metal [6]. Reducing the cavity thickness improve the effect of the geometry of the top metal allowing a more efficient extraction of light. Finally, thin active regions require a lower operating bias and they allow one to limit the total injected electrical power in the structure (current • bias voltage).

In the first part of our talk, we demonstrate THz QC lasers with an active-core thickness of 5.86 μm, i.e. approximately a factor of two lower than the typical thickness used so far [2]. Despite this considerable reduction in thickness, the performance in terms of threshold current density (J_{th}) does not degrade [4].

The next step consists in reducing the current threshold by reducing the device surface. We have fabricated THz QC lasers with low current thresholds in the mA range [5]. The laser resonator is based on a micro-cylindrical geometry (Fig. 1). Its effective mode volume is ≈ $0.7\cdot(\lambda/n_{eff})^3$, where λ is the free space emission wavelength (≈112 μm), and n_{eff} is the mode effective refractive index. The extreme confinement in the vertical direction is obtained using the thin metal-metal waveguide described above, while in the planar directions we make use of the guiding properties of surface plasmons.

In general, micro-cylindrical resonators rely on total-internal reflection on the cavity sidewalls in order to confine the light. We employ here a different principle: the mode is guided by the surface-plasmons, and its spatial extension is determined by the extension of the top metallization. The top metallic contact has in fact a smaller radius (r) than the micro-disk. Numerical simulations show that the optical mode is bound to the metal and it has a very low intensity at the resonator edge. The smallest microdisk laser devices (r=25

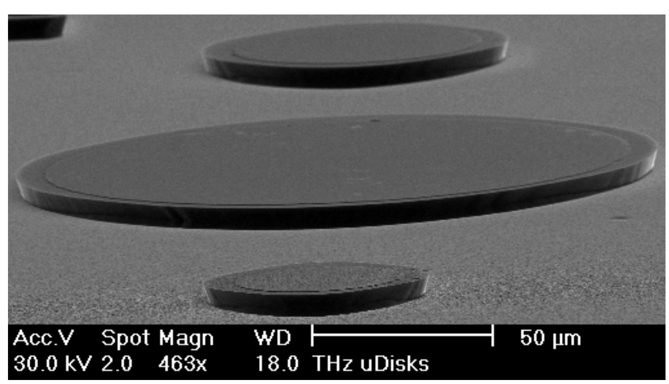

Fig. 1. Scanning Electron Microscope image of the fabricated micro-disks.

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µm) show a current threshold of ≈4 mA (Fig.2) at 10K, while the largest devices (r=87.5 µm) exhibit a current threshold of ≈21 mA (cf fig.2). All the lasers operate in continuous-wave mode up to 60K, and in pulsed mode up to 70K.

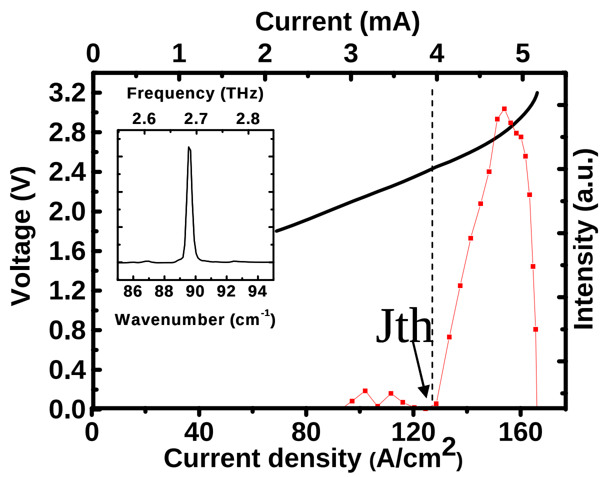

Fig. 2. *:* Light-voltage-current characteristics in continuous-wave of a typical microdisk with r= 25 µm at an operating temperature of 10K. *Inset*: spectrum of a typical device at 10K. The emission is peaked at λ≈ 112 µm.

The small (r=25 µm) and medium (r=37.5 µm) microdisk lasers show a single mode emission, as reported in the inset of Fig. 2. Comparison with finite-element numerical simulations allowed us to identify the resonator modes involved in the lasing process, and to elucidate the guiding properties of surface-plasmons in this system (Fig. 3).

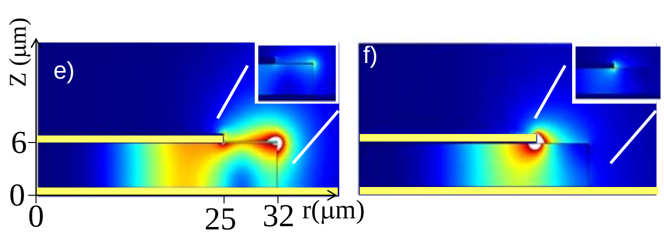

Fig. 3 Axisymmetric simulation of the mode involved in the lasing process prior (left) and after (right) removal of the n+ top doped layer. The electric field magnitude |E| is plotted. In the first case, the mode is guided by the top n+-layer up to the resonator edge. Without the n+ layer, the mode is bound to the top metallic contact.

It is important to mention that the demonstration of laser devices with sub-wavelength resonator volumes could open the way to the study of cavity quantum-electrodynamics phenomena in quantum cascade systems.

References

[1] C. Walther, G. Scalari, J. Faist, H. Beere, and D. Ritchie, "Low frequency terahertz quantum cascade laser operating from 1.6 to 1.8 THz", *Appl. Phys. Lett.* **89**, 231121 (2006).

[2] B. S. Williams, S. Kumar, Q. Hu, and J. L. Reno, "Operation of terahertz quantum-cascade lasers at 164 K in pulsed mode and at 117 K in continuous-wave mode," *Opt. Express* 13, 3331 (2005),

[3] C. Gmachl et al, IEEE J. Sel. *Topics Quantum. Electron*. 5, 808 (1999).

[4] Y. Chassagneux, J. Palomo, R. Colombelli, S. Barbieri, S. Dhillon, C. Sirtori, H. Beere, J. Alton, and D. Ritchie, "Low threshold THz QC lasers with thin core regions", *Electron. Lett.* 43, 285, (2007).

[5] Y. Chassagneux, J. Palomo, R. Colombelli, S. Dhillon, C. Sirtori, H. Beere, J. Alton, and D. Ritchie," Terahertz microcavity lasers with subwavelength mode volumes and thresholds in the milliampere range ", *Appl. Phys. Lett*. 90, 091113 (2007).

[6] J. A. Fan, M. A. Belkin, F. Capasso, S. Khanna, M. Lachab, A.G. Davies and E. H. Linfield,"Surface emitting terahertz quantum cascade laser with a double-metal waveguide", *Opt. Express* 14, 11672 (2006).