1.3.1 Terahertz photonics

Quantum cascade (QC) lasers [1] are semiconductor devices in which radiation is generated by electronic transitions within an artificial crystal, a so-called heterostructure. This heterostructure consists of alternating layers of two semiconductor materials, with the layer thickness determining the electronic states inside the crystal, and thereby the frequency of the emitted light as well as the electrical transport. The operation of QC lasers in the range of frequencies 1-10 THz was demonstrated and patented at Laboratorio NEST, by employing superlattice active material and developing a waveguide concept based on interface modes called surface plasmons [2]. Here we present recent results in the implementation of THz QCLs into advanced photonic structures and novel applications, as well as in the investigation of the fundamental limits of the emission linewidth. Furthermore, THz research at NEST has evolved towards new concepts in the detection of radiation exploiting nanowire and graphene nanostructures.

The present high level of interest in THz laser sources is driven by their many potential applications. These are found in fields such as gas sensing and spectroscopy, the provision of local oscillators for heterodyne detection in astronomy and in advanced imaging techniques. Although each specific application has its own set of associated performance requirements, the majority require single mode laser light, with good beam quality and high powers. The Fabry-Perot cavities commonly used for THz QCLs tend to be intrinsically multimode and, equally important, their precise emission frequency cannot be determined a priori by device construction.

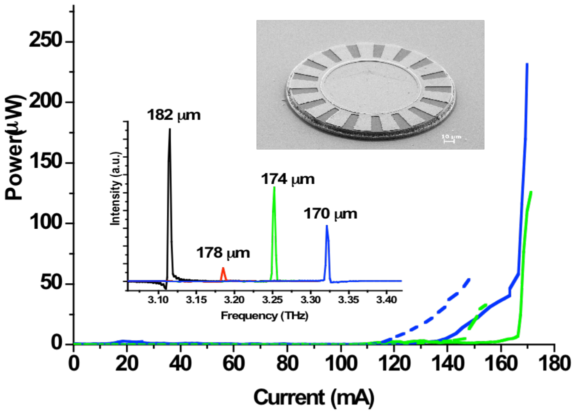

Figure 1. Light-current characteristics of ~ 3.2 THz microdisk DFB lasers. Solid lines refer to disks with 17 grating periods, dashed lines to 16. The insets show a SEM picture of the finished device and single-mode emission spectra for disks with different diameter.

Distributed feedback (DFB) resonators were realized in recent past to achieve stable and predictable single mode emission. A number of different approaches were developed, all based on inserting a grating right at the top metal - semiconductor interface [3,4]. Surface-plasmon waveguides, in fact, present the nice feature of having the mode intensity peaked at the surface; any patterning of this interface is then bound to heavily affect the propagating mode. The use of higher order gratings is especially interesting for vertically emitting devices, which would otherwise be impossible, owing to the intersubband selection rules. This aspect is of relevance also to enhance the extraction of light from double-metal waveguides, which is typically quite low due to the impedance mismatch between the guided mode and free space. We have now applied this concept to whispering gallery microdisk lasers, as exemplified in Fig. 1. By defining a circular second-order metal grating along the circumference, a single lasing whispering gallery mode can be selected and light collected in the vertical direction. Furthermore, the use of gratings with prime number circular symmetry forces the device to operate on the mode with highest vertical outcoupling, providing efficient vertical emission. The measured slope efficiency of 50 mW/A is in fact the largest observed to date for vertically emitting THz QC lasers. The beam profile is also circularly symmetric, which is an important feature for practical use in optical set-ups, and its divergence is mainly determined by the disk size [5]. To optimize this aspect, we have then modeled and fabricated THz QCLs in a ring DFB resonator of much larger diameter [6]. A second order grating with a double slit configuration was found to offer the best compromise between electrical and optical properties of the top electrode. Figure 2 shows the L-I characteristics and the measured far-field of a fabricated device. Even without collection optics employed, the devices show peak powers up to 10 mW, with a slope efficiency of ~25 mW/A, demonstrating the good radiative efficiency of this resonator and the directionality of the emitted power.

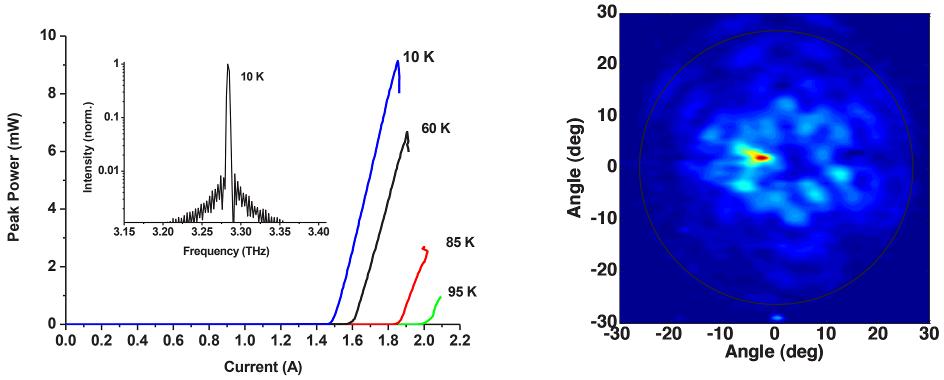

Figure 2. Left: Light-current characteristics of a ring device at different temperatures. The inset shows the spectrum of the same device on a logarithmic scale at 1.8A. Right: Measured far-field of another ring device. The black circle corresponds to the cryostat window.

An alternative concept being investigated is based on quasi-periodic linear gratings generated with a deterministic rule [7]. Single-mode THz lasers have been realized employing a specially designed Fibonacci sequence. High-power collimated emission is achieved at an angle of nearly 50° from the surface normal, and can be tailored by grating design.

Tuning of the emission line is also an important aspect for spectroscopic applications. We have recently demonstrated the first THz QC lasers operating in an external cavity. A simple configuration with a controllable end mirror placed near the laser facet without collimating optics was adopted, and the emission tuned by changing the cavity length [8]. Typical performances are reported in Fig. 3 for a 4.7 THz laser. At the moment this configuration, while simple, allows tuning ranges of ~ 2 % of the emission frequency. A different approach we have developed is instead based on using a movable-microcavity coupled with a laser through a second-order grating [9].

Interestingly, a similar set-up was also used for the first measurement of the linewidth enhancement factor in a THz QC laser using a self-mixing technique [10]. The gain dynamics within the active region of THz QC lasers was further studied through time-resolved pump-probe measurements of the gain recovery time. These were performed at the FELIX free electron laser source, monitoring the time evolution of the photocurrent induced by the THz pulses in a saturation regime of the transition [11]. The results are consistent with estimates of electron transit times in the QC superlattice.

On the other hand, we have investigated the fundamental limits to the laser emission linewidth, by analyzing its frequency noise spectrum. At high frequencies, where the 1/f contribution becomes negligible, a plateau is found, corresponding to a base floor < 100 Hz compatible with the Schawlow-Townes formula, corrected to include the contribution of thermal photons [12]. Finally, an important portion of THz research at NEST is now devoted to the development of practical applications of the THz quantum cascade technology through their implementation in sensing and imaging (including near-field) systems [13-14].

On the detection side, we have pioneered the use of field-effect nanotransistors as THz sensors, in which the rectification of the incoming signal originates from the non-linearity of the transfer characteristics. Both InAs nanowires [14-16] and graphene detectors [17-18] have been developed, with room-temperatures performances already competitive with commercial devices.

References

[1] Quantum cascade laser, Science **264**, 553 (1994). J. Faist *et al.*

[2] Terahertz semiconductor-heterostructure laser, Nature **417**, 156 (2002). R. Köhler, A. Tredicucci, F. Beltram, H. E. Beere, E. H. Linfield, A. G. Davies, D. A. Ritchie, R. C. Iotti, F. Rossi.

[3] High performance operation of single mode terahertz quantum cascade lasers with metallic gratings, Appl. Phys. Lett. **87**, 181101 (2005). L. Mahler, A. Tredicucci, R. Köhler, F. Beltram, H.E. Beere, E.H. Linfield, D.A. Ritchie.

[4] Finite size effects in surface emitting terahertz quantum cascade lasers, Opt. Express **17**, 6703 (2009). L. Mahler, A. Tredicucci, F. Beltram, C. Walther, H. E. Beere, and D. A. Ritchie.

[5] Vertically emitting microdisk lasers, Nature Photonics **3**, 46 (2009). L. Mahler, A. Tredicucci, F. Beltram, C. Walther, J. Faist, B. Witzigmann, H. E. Beere, and D. A. Ritchie.

[6] Distributed feedback ring resonators for vertically emitting terahertz quantum cascade lasers, Opt. Express **17**, 13031 (2009). L. Mahler, M. I. Amanti, C. Walther, A. Tredicucci, F. Beltram, J. Faist, H. E. Beere, and D. A. Ritchie.

[7] Quasi-periodic distributed feedback laser, Nature Photon. **4,** 165 (2010). L. Mahler, A. Tredicucci, F. Beltram, C. Walther, J. Faist, H. E. Beere, and D. A. Ritchie.

[8] Tunable terahertz quantum cascade lasers with an external cavity, Appl. Phys. Lett. **91**, 121104 (2007) J. Xu, J. M. Hensley, D. B. Fenner, R. P. Green, L. Mahler, A. Tredicucci, M. G. Allen, F. Beltram, H. E. Beere, and D. A. Ritchie.

[9] Tuning a distributed feedback laser with a coupled microcavity, Opt. Express **18**, 19185 (2010). L. Mahler, A. Tredicucci, F. Beltram, H. E. Beere, D. A. Ritchie.

[10] Linewidth enhancement factor of terahertz quantum cascade lasers, Appl. Phys. Lett. **92**, 071106 (2008). R. P. Green, J. Xu, L. Mahler, A. Tredicucci, F. Beltram, G. Giuliani, H. E. Beere, and D. A. Ritchie.

[11] Gain recovery dynamics of a terahertz quantum cascade laser, Phys. Rev. B **80**, 075303 (2009). R. P. Green, A. Tredicucci, N. Q. Vinh, B. Murdin, C. Pidgeon H. E. Beere, and D. A. Ritchie.

[12] Quantum-limited frequency fluctuations in a terahertz laser, Nature Photon. **6**, 525 (2012). M. S. Vitiello, L. Consolino, S. Bartalini, A. Taschin, A. Tredicucci, M. Inguscio, P. De Natale.

[13] Terahertz confocal microscopy with a quantum cascade laser source, Opt. Exp. **20**, 21924 (2012). U. Siciliani de Cumis, J. Xu, L. Masini, R. Degl'Innocenti, P. Pingue, F. Beltram, A. Tredicucci, M. S. Vitiello, P. Benedetti, H. E. Beere, D. A. Ritchie.

[14] Room temperature Terahertz detectors based on semiconductor nanowire field-effect transistors, Nano Letters **12**, 96 (2012). M. S. Vitiello, D. Coquillat, L. Viti, D. Ercolani, F. Teppe, A. Pitanti, F. Beltram, L. Sorba, W. Knap, and A. Tredicucci
[15] Semiconductor nanowires for highly sensitive, room-temperature detection of Terahertz quantum cascade laser emission, Appl. Phys. Lett. **100**, 241101 (2012). M. S. Vitiello, L. Viti, L. Romeo, D. Ercolani, G. Scalari, J. Faist, F. Beltram, L. Sorba, and A. Tredicucci.
[16] Terahertz detection by heterostructured InAs/InSb nanowire based field effect transistors, Appl. Phys. Lett. **101**, 141103 (2012). A. Pitanti, D. Coquillat, D. Ercolani, L. Sorba, F. Teppe, W. Knap, G. De Simoni, F. Beltram. A. Tredicucci, M.S. Vitiello.
[17] Graphene field-effect transistors as room-temperature terahertz detectors, Nature Mat. **11**, 865 (2012). L. Vicarelli, M. S. Vitiello, D. Coquillat, A. Lombardo, A. C. Ferrari, W. Knap, M. Polini, V. Pellegrini, A. Tredicucci.
[18] Photocurrent-based detection of terahertz radiation in graphene, Appl. Phys. Lett. **103**, 211120 (2013). A. Tomadin, A. Tredicucci, V. Pellegrini, M. S. Vitiello, M. Polini.