Demonstration of high wall plug efficiency THz QCLs: investigation of the optical, electronic and thermal performance

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***Abstract*— We demonstrate high wall-plug efficiency bound-to-continuum THz quantum-cascade lasers, operating at 2.83 THz, in both pulsed and continuous wave (cw) and emitting a maximum peak optical power of ~ 100 mW at 4K. The cw total power conversion-efficiency (η_w) is extracted via an innovative experimental approach based on the micro-probe photoluminescence measurement of the lattice temperature as a function of the electrical power. A detailed analysis of the device electronic and thermal performance under both cw and pulsed operation is reported.**

***Index Terms* — THz quantum cascade lasers, photoluminescence, thermal properties, electronic properties**

Qunatum cascade lasers (QCLs) working in the THz spectral range, lasing up to 164 K in pulsed mode and 117 K in continuous wave (cw) [1], in the spectral range 4.4 THz – 1.2 THz [2] have been recently demonstrated, with the use of surface-plasmon or double-metal optical waveguides. In this spectral range, while room-temperature operation still remains a priority, the production of devices yielding low power consumption and W- level of optical powers is highly attractive for a wide range of technological applications, such as imaging, spectroscopy and sensing. At the present stage of development the maximum output powers of THz QCLs are still limited at values as low as ~ 248 K in resonant-phonon (RP) structures [3] and ~ 90 mW in bound-to-continuum (BTC) devices with a high reflectivity coating evaporated on one facet. [4] This together with the rather high dissipated electrical powers and the limitation induced by the device thermal management limits the power conversion efficiencies (η_W) of THz QCLs at values ~ 0.6 % and ~ 2 % in RP and BTC QCLs, respectively. [3,4]

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The η_W values reported up to now, have been extracted via the measurement of the ratio $\eta_W = P_o/P$ between the emitted optical peak power (P_o) and the total electrical power in the device (P). However, these direct optical measurements of η_W are not enough accurate in THz QCLs mostly due to the high optical divergence of the emitted optical beam that limits the collection efficiency (ηc) of the optical power at values as low as $\eta_c \sim 0.3$. This implies that the extracted η_W values had to be considered as a lower limit.

We will report on the demonstration of high power conversion efficiency THz QCLs and propose an alternative experimental approach to determine simultaneously the wall-plug efficiency, the thermal resistance (R_L) and the subband electronic temperatures in QCLs operating in continuous wave (cw). The above information has been obtained using micro-probe band-to-band photoluminescence that allows the investigation of the laser front facet down to a spatial resolution of ~ 1 μm. [5,6]

We will present a high performance $GaAs/Al_{0.15}Ga_{0.85}As$ THz QCLs grown by molecular beam epitaxy (MBE) by a commercial provider. The devices are based on a bound-to-continuum scheme and have been fabricated on a surface-plasmon optical waveguide. Laser action at 2.83 THz with a threshold current density J_{th} = 140 A/cm^2 at 4 K, and a maximum collected peak optical power P_o = 100 mW has been demonstrated with maximum operating temperatures of 85 K in pulsed mode and 55 K in cw. From the collected P_o and P values we extracted a wall plug efficiency per facet η_W = 2.3 % at a heat sink temperature T_H = 4K. [7]

An alternative approach to extract the total power conversion efficiency in QCLs, based on the measurement of the active region temperature (T_L) increase with P will be presented. This experimental approach allow to correlated the power conversion efficiency to the device thermal resistance (R_L) via the equation $\Delta T/P = (1-\eta_w) \times R_L$, with $\Delta T = T_L - T_H$. [8]

We measured a maximum total wall plug efficiency η_w = (5.5 ± 0.4) % and a device thermal resistance R_L = 8.37 K/W in cw at T_H = 4K.

The simultaneous measurement of a non-equilibrium hot electron distribution is reported.

Finally, we present a thermal analysis of the device during both cw and pulsed operation. The device thermal behaviour under pulsed operation will be investigated by means of a time resolved PL analysis based on an innovative intensified CCD system of detection. We extracted the cross-plane component of the active region thermal conductivity and the thermal boundary resistance at the interfaces and studied the heat flow dynamics related to the generation of heat pulses via electrical methods.

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