Laser emission at 830 and 960 GHz from quantum cascade structures

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***Abstract*—Laser emission at 830 GHz and 950 GHz is demonstrated from two different quantum cascade structures based on an intra-well optical transition. Laser action is induced by applying a perpendicular magnetic field to the plane of the layers.**

The THz quantum cascade laser (QCL) [1] is a semiconductor laser based on intersubband transitions in quantum wells. It presently covers a wide spectral window ranging from 4.9 THz to 1.39 THz [2]: possible applications in imaging [3], spectroscopy and astronomy [4] push the extension of the frequency range towards lower frequencies. A control over the in-plane degree of freedom of the electron may be an essential element to obtain population inversion and optical gain at very low THz frequencies, where the broadening of the states becomes very close to the photon energy (h$\nu < 4$ meV). In this work we present results obtained on low frequency THz QCL immersed in strong magnetic field. This class of devices, based on a intra-well optical transition, exhibit extremely low threshold currents (1 A/cm^2 and below) due to the reduction of the non-radiative scattering processes obtained via the magnetic field-induced in-plane confinement [2], [5].

The new structure (sample A3913) proposed here relies on magnetically enhanced population inversion and shows laser action at about 960 GHz. The structure, grown in the $Al_{0.1}Ga_{0.9}As$/GaAs material system, is based on an intra-well excited state optical transition in a very wide (76.5 nm) GaAs quantum well. The designed optical transition is a second excited to first excited state transition at 4.1 meV. The structure exploits the same kind of large active well already presented in our previous studies [5], but the injector part has been modified, replacing the chirped superlattice with a system of three coupled quantum wells. The resulting structure counts now four quantum wells. The devices, grown by MBE and processed in double-metal ridge waveguides, display laser action starting from an applied magnetic field of 5.9 T (Fig.1a). A typical spectrum of the emitted laser radiation is reported in the inset of Fig. 1a. The spectrum, measured with an home made FTIR spectrometer, is centered around a frequency of 955 GHz ($\lambda \simeq 314$ μm, h$\nu = 3.95$ meV). The threshold current density reaches its minimum value of 8 A/cm^2 for an applied magnetic field of 12 T.

Laser action is observed up to a temperature of at least 40 K. Experiments are still under way to assess the temperature limit. The transport at constant applied bias together with its second derivative in respect to the magnetic field is plotted in

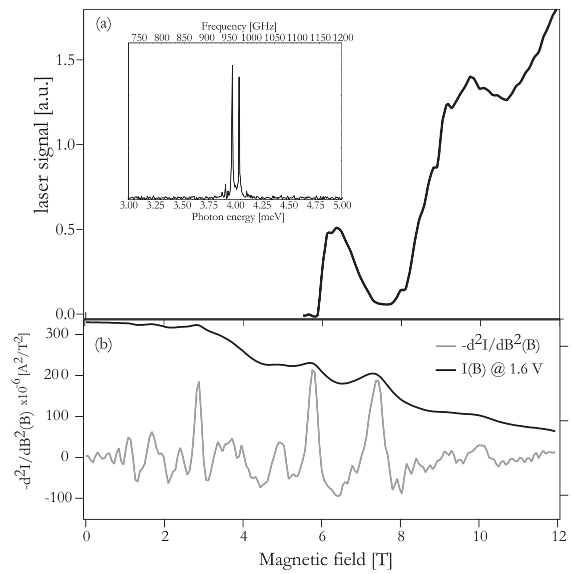

Fig. 1. (a): Laser emission as a function of applied magnetic field for sample A3913 for an injected current of 90 mA. Inset: laser spectrum for an applied magnetic field of 6.4 T. (b): Transport for structure A3913. Current as a function of magnetic field at a constant bias of 1.6 V (just below threshold) and second derivative of the current in respect to magnetic field to highlight the observed resonances.

Fig.1b as a function of the applied magnetic field. It shows extremely pronounced features (peaks in the -d^2I/dB^2 plot) attributable to magneto-intersubband resonances related to single and two-electron scattering events [5]. The same features are also present in light emission (Fig.1a). Some of the oberved resonances are clearly attributable to intersubband Landau resonances between the 3 states of the large quantum well: nevertheless a significative discrepancy is observed between the resonances that can be attributed to the lasing transition ($3 \longrightarrow 2$, E_{32}=4 meV) and the observed peaks in the current that correspond to an energy spacing of 4.95 meV. The tight mode confinement provided by the two metals on both sides of the epilayer allows the fabrication of small devices where the modal volume is well below one cubic wavelength [7]. For example, laser action is observed in a 400 μm long, 70 μm wide ridge, for an epilayer thickness of 16.2 μm. The resulting threshold currents lie in the milliampere range.

Another structure (sample A3912), still based on intra-well

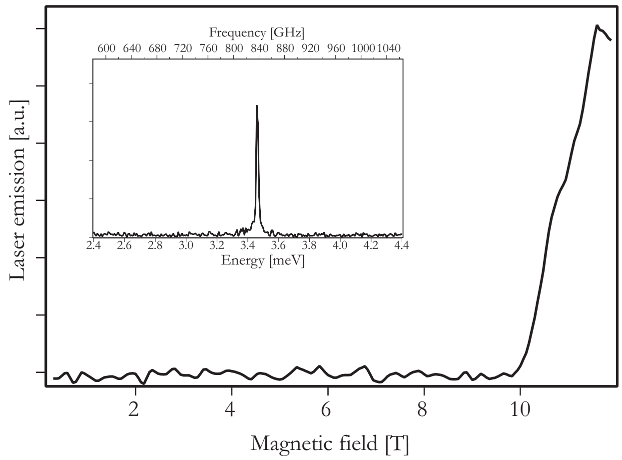

Fig. 2. Laser emission as a function of applied magnetic field for sample A3912. Inset: laser spectrum for an applied magnetic field of 11 T.

optical transition, shows laser action at 832 GHz ($\lambda \simeq 359$ μm, h$\nu = 3.45$ meV) starting from an applied field of 10 T. Typical laser emission as a function of the applied magnetic field recorded at constant injected currentis reported in Fig.2 together with an emission spectrum recorded at 11 T.

In conclusion we demonstrate laser action in the GHz range from quantum cascade structure with magnetically assisted gain. The investigated structures show the possibility to selectively inject carriers and achieve population inversion between closely spaced subbands and extend the spectral window accessible to the quantum cascade technology which now spans more than two orders of magnitude in wavelength (359 μm-3.05 μm [8]). The good L-B characteristics of the investigated samples open the possibility to observe laser action at even lower frequencies, approaching the microwave range.

REFERENCES

[1] R. Köhler, A. Tredicucci, F. Beltram, H. Beere, E. Linfield, A. Davies, D. Ritchie, R. Iotti, and F. Rossi, Nature **417**, 156 (2002).
[2] G. Scalari, C. Walther, J. Faist, H. Beere, and D. Ritchie, Appl. Phys. Lett. **88**, 141102 (2006).
[3] S. Kim, F. Hatami, J. Harris, A. Kurian, J. Ford, D. King, G. Scalari, M. Giovannini, N. Hoyler, J. Faist, et al., Appl. Phys. Lett. **88**, 153903 (2006).
[4] J.R Gao, N.H. Hovenier, Z.Q. Yang, J.J. Baselmans, A. Baryshev, et al., Appl. Phys. Lett. **86**, 244104 (2005).
[5] G. Scalari, S. Blaser, J. Faist, H. Beere, E. Linfield, D. Ritchie, and G. Davies, Phys. Rev. Lett. **93**, 237403 (2004).
[6] K. Kempa, Y. Zhou, J. Engelbrecht, P. Bakshi, H. Ha, J. Moser, M. Naughton, J. Ulrich, G. Strasser, E. Gornik, et al., Phys. Rev. Lett. **88**, 226803 (2002).
[7] L.A. Dunbar, G. Scalari, L. Sirigu, M. Giovannini, R. Houdré, and J. Faist, Appl. Phys. Lett. , in press (2007).
[8] D. Revin, J. Cockburn, M. Steer, R. Airey, et al., Appl. Phys. Lett. **90**, 021108 (2007).