GHz sideband generation with THz quantum cascade lasers

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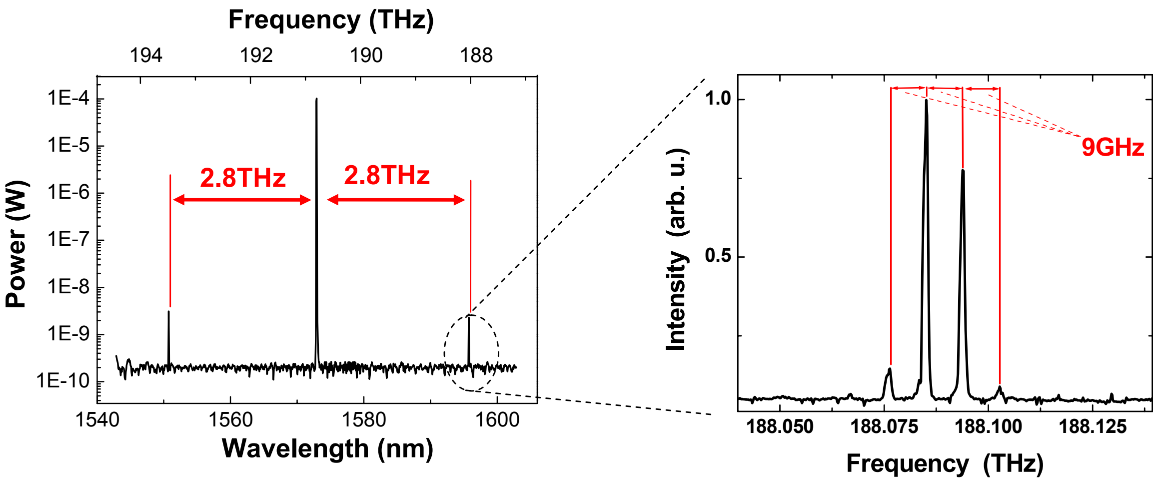
Abstract

Quantum cascade lasers (QCLs) are inherently fast devices thanks to intersubband lifetimes of the order of the ps, leading to the absence of relaxation oscillations [1]. In this work we modulate the bias-voltage of a single-mode, double-metal waveguide, 2.8 THz QCL by using a frequency-tunable RF-synthesizer [2]. By increasing the amplitude of the modulation signal (P_{RF} = 20 dBm) we observe the appearance of multiple GHz sidebands (SBs) in the emission spectrum of the laser, with a spacing that can be continuously tuned from ~12.5 down to 2 GHz and below.

In order to clearly resolve the SBs we exploited a non-linear up-conversion technique recently demonstrated by us, where a near infrared carrier at 1.55 μm is injected inside the cavity of a double-metal waveguide QCL driven above threshold [3]. As a result of the non-linear mixing, the intracavity THz field is upconverted into the near-IR, giving rise to THz SBs on both sides of the optical carrier (see the left panel of the Figure). As displayed in the right panel of the Figure, the ultrafast modulation applied to the bias voltage generates additional GHz SBs that can be clearly observed thanks to a high resolution optical spectrum analyser ($\delta\nu$ < 1 GHz). The fact that the GHz and THz SBs have comparable amplitudes indicates a strong depth of modulation, which in this case is obtained without any impedance adaptation between the laser and the microwave coaxial line. Beyond ~ 12.5 GHz we observe a rapid fall off of the SBs amplitude. According to our calculations this cut-off is purely limited by the device wiring/mounting.

As the RF frequency approaches the round trip frequency of the THz QCL waveguide (~12.2 GHz) the modulation depth augments, resulting into a substantial increase in the number of generated SBs (>10, not shown). We interpret this effect as an indication that the THz cavity roundtrip time and the period of the RF wave propagating into the QCL waveguide are close to resonance. Further work to clarify this point is under way.

Finally we note how the concurrent generation of THz and GHz SBs onto an optical carrier at 1.55 μm, shows the potential of THz QC lasers as wide band all-optical wavelength shifters and ultra-fast modulators for wavelength division multiplexing applications.



Left panel. Near infrared spectrum (fibre coupled) from the double-metal waveguide, 2.8 THz QCL. The central intense line corresponds to the optical carrier at 1571nm (190.9 THz). Clearly visible are the 2 sidebands at 191 +/- 2.8 THz. Right panel. Blow up of the right THz sideband. Clearly visible are 4 additional sidebands spaced by 9GHz, corresponding to the frequency of the RF synthesiser. Without RF modulation only one line is observable, given by the up-converted single longitudinal mode of the THz QCL.

REFERENCES

[1] R. Paiella, R. Martini, F. Capasso, C. Gmachl, H. Y. Hwang, E. A. Whittaker, and H. C. Liu,"High frequency modulation without the relaxation oscillation resonance in quantum cascade lasers", Appl. *Phys. Lett.* **79**, 2526-2528 (2001)

[2] S. Barbieri, J. Alton, H. E. Beere, J. Fowler, E. H. Linfield, and D. A. Ritchie, "2.9 THz quantum cascade laser operating up to 70K in continuous wave", *Appl. Phys. Lett.* **85**, 1674 (2004)

[3] S. S. Dhillon, C. Sirtori, S. Barbieri, A. de Rossi, M. Calligaro, H. E. Beere, and D. A. Ritchie, "THz sideband generation at telecom wavelengths in a GaAs-based quantum cascade laser", *Appl. Phys. Lett.* **87**, 071101-1 - 3 (2005). S. S. Dhillon, C. Sirtori, J. Alton, S. Barbieri, A. de Rossi, H. E. Beere, and D. A. Ritchie, "THz transfer onto a telecom optical carrier", *submitted to Nature Photonics (February 2007)*.