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Generating ultrafast pulses of light from quantum cascade lasers

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S1: Maxwell Bloch simulations of the gain recovery time
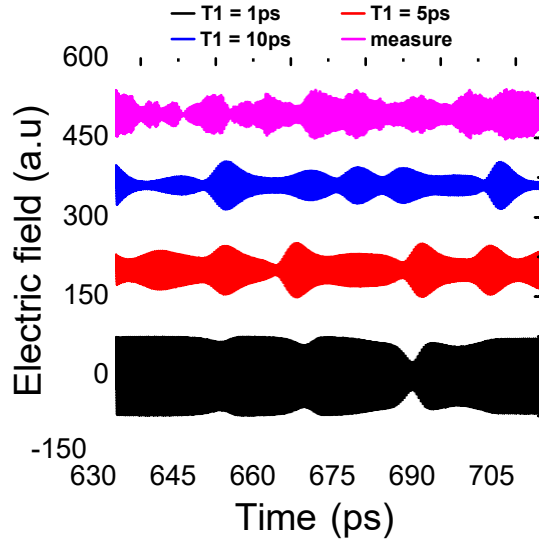

Figure S1. Calculated time domain profiles of QCL output emission over one round-trip period for gain recovery times of 1ps (black), 5ps (red) and 10ps (blue curve). The magenta curve corresponds to experimental data.

The gain recovery time, T1, was calculated using Maxwell-Bloch finite-difference time-domain simulations in a two level system. The procedure is detailed in-depth in ref. [1]. Here we have used a dephasing time of 0.6 ps from the full-width half-maximum of the gain and a total waveguide loss of 12 cm-1 from the first pass gain measurements [2] of the LO phonon depopulation based QCL. Figure S1 shows the calculated time response of the output electric field with different gain recovery times, compared to the experimental data over one round-trip period. The data shows a multiple pulses between a round-trip period of similar field values as the main pulses. For T1=1ps, the calculated time profile shows a quasi-CW behaviour while for T1= 10ps shows a more modulated behaviour with the intra-round trip peaks have a much lower field when compared to the main peaks. A time data with a gain recovery time of ∼ 5ps shows the best 'fit' with the data.

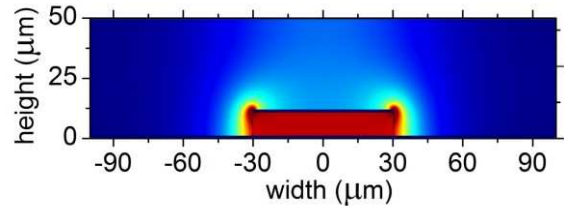## S2: Effective microwave index of metal-metal QCL

Figure S2. Modal profile at 12GHz of a 60 μm wide metal- metal QCL operating at a center frequency of 2.7THz.

The effective microwave refractive index of the QCL waveguide was calculated using COMSOL and the procedure described in ref [3], where a permittivity of 25 was used for the active region. The modal profile is shown in figure S2 for a ridge width of 60 μm and height of 10μm for a frequency of 12GHz. Owing to the large overlap of the mode with the surrounding air, a reduce effective index of 3.91 is determined.

References

1. J. R. Freeman, J. Maysonnave, S. Khanna, E. H. Linfield, A. G. Davies, S. S. Dhillon, and J. Tignon, Phys. Rev. A **87**, (2013).

2. N. Jukam, S. S. Dhillon, D. Oustinov, J. Madéo, J. Tignon, R. Colombelli, P. Dean, M. Salih, S. P. Khanna, E. H. Linfield, and A. G. Davies, Appl. Phys. Lett. **94**, 251108 (2009).

3. W. Maineult, L. Ding, P. Gellie, P. Filloux, C. Sirtori, S. Barbieri, T. Akalin, J.-F. Lampin, I. Sagnes, H. E. Beere, and D. A. Ritchie, Appl. Phys. Lett. **96**, 021108 (2010).