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Injection seeding of metal-metal Terahertz quantum cascade lasers

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Abstract— **We show the coherent detection of the laser emission from seeded terahertz (THz) quantum cascade lasers (QCL) with metal-metal waveguides using free-space coupling of a THz pulses to the sub-wavelength waveguide. We implement a simple, monolithic planar horn antenna design on the metal-metal waveguide that reduces the impedance mismatch to the waveguide. The laser emission is seeded and coherently detected using electro-optic sampling. Injection seeding of metal-metal waveguides with a LO phonon depopulation design at liquid nitrogen temperatures is also demonstrated.**

I. INTRODUCTION

A recent development in THz QCLs is the coherent detection of its laser emission using electro-optic sampling [1]. It has allowed, for example, the demonstration of modelocking [2] as well as bringing insights into the QCL's ultrafast dynamics [3]. It also allows QCLs to be integrated within THz time-domain spectroscopy (TDS) systems. Until now, this coherent detection technique has only been used in QCLs with single plasmon waveguides, whereas the highest performance THz QCLs, in terms of temperature and threshold current, are obtained with a metal-metal (MM) waveguide. The major difficulty of injecting a MM QCL is the small mode volume of the sub-wavelength MM waveguide. In this work [4], we present the realization of MM QCL waveguides with enhanced broadband freespace–waveguide coupling through the use of planar horn antennas integrated onto the ridge of the QCL.

II. EXPERIMENT AND RESULTS

MM devices were fabricated from a 2.7 THz bound-to-continuum GaAs/AlGaAs design (90 periods) with a 3mm long and 80µm wide ridge. V-shape geometries of ~150µm are realized [4] to adapt the confined mode to a free space mode on both facets (focused ion beam etching of top metal and doped layer). Short THz seed pulses (~1ps) are focused onto entry facet of the QCL [1], which is maintained at 10K. The QCL gain is switched on exactly when the seed pulse is injected into the cavity, so that the later initiate the laser emission, which is then always locked to the seed pulse and thus permits its coherent detection. Figure 1a shows the measured transmitted electric field of the input seed as a function of time. As the seed amplitude is increased the signal we measure reaches an asymptotic maximum (figure 1d), consistent with emission that is well synchronized with the detection system.

This concept of planar horn antennas has also been applied to the injection seeding of a 3.1THz LO phonon-depopulation based MM QCL. Indeed as these devices routinely operate up to relatively high temperatures compared to bound-to-continuum devices, we have demonstrated injection seeding at 77K. Further, as the gain bandwidth of these designs is larger, we demonstrate injection seeding over a bandwidth of 600GHz for a 3mm long device.

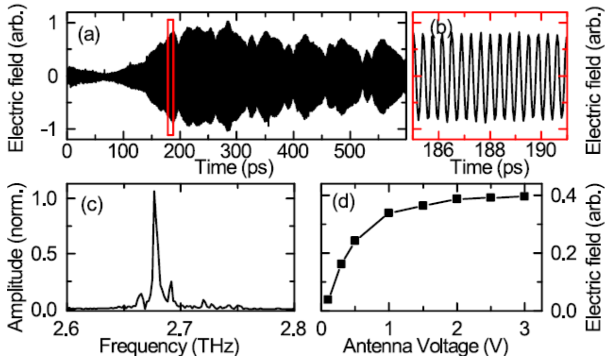

Fig. 1. Coherent detection of the MM QCL emission (a) The time domain electric field emitted by the QCL in the first 600 ps after the seed pulse arrives (b) Detail of 185–191 ps showing the electric field (c) The Fourier transform of the time-domain electric field showing the emitted spectrum (d) The electric field produced by the QCL at 550 ps as a function of antenna voltage.

III. SUMMARY

We have performed injection seeding in a MM QCL and coherently detected its emission by electro-optic sampling, using a planar horn antenna design. It has been performed up to 77K temperature for a LO phonon-depopulation based design, with a 600 GHz gain bandwidth. This much broader gain is of interest for the demonstration of short intense pulse generation via active mode locking.

REFERENCES

[1]. D. Oustinov et al, "Phase seeding of a terahertz quantum cascade laser" *Nature Comm*, **1**, 69 (2010), DOI: 10.1038/ncomms1068.

[2]. J. R. Freeman *et al*, "Electric field sampling of modelocked pulses from a quantum cascade laser", *Opt. Express* **21**, 16162 (2013).

[3]. J. R. Freeman et al, "Laser-seeding dynamics with few-cycle pulses: Maxwell-Bloch finite-difference time-domain simulations of terahertz quantum cascade lasers", *Phys. Rev. A*. **87**, 063817 (2013).

[4]. A. Brewer *et al*, "Coherent detection of metal-metal terahertz quantum cascade lasers with improved emission characteristics" *Appl.Phys. Lett.*, **104**, 081107 (2014).