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Injection seeding and modelocking of metal-metal Terahertz quantum cascade lasers

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Abstract: Injection seeding of terahertz quantum-cascade-lasers with metal-metal waveguides is demonstrated at liquid nitrogen temperatures through injection of phase-locked terahertz pulses. Coherent detection and modelocking of the QCL are demonstrated with the generation of 11ps pulses.

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A recent development in Terahertz (THz) quantum cascade lasers (QCLs) is the coherent detection of its emission through injection seeding [1]. This is an important application for QCLs as it allows access to both the amplitude and phase of the emission on ultrafast timescales. It has permitted, 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 with THz time-domain spectroscopy (TDS) systems, which could allow the combination of a powerful, narrow-band QCL pump and a broadband THz probe. Until now, this technique for coherent detection has only been used with QCLs that use a single plasmon waveguide. This does not allow the technique to take full advantage of the highest performance THz QCLs, in terms of temperature and threshold current, that are obtained with a metal-metal (MM) waveguide. MM QCLs have not been used previously owing to the difficulty of injecting a THz seed pulse into the small modal volume of the sub-wavelength MM waveguide, as well as efficiently extracting the QCL emission. The high mode confinement results in MM QCLs having poor output powers and highly divergent beams. In this work [4], we present the realization of MM QCLs with integrated broadband horn antennas, enhancing the input and output coupling of the THz seed. The fabrication of these structures is greatly simplified and reproducible compared to the previous attempts to integrate horn antenna-like couplers with MM QCLs. We show that these devices are well suited to THz injection seeding, permitting the coherent detection of the MM QCL emission.

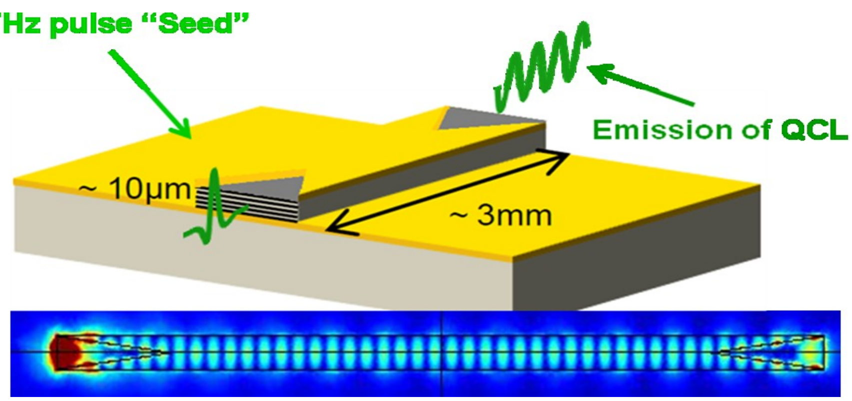

Fig. 1. Top: schematic of injection seeding of MM THz QCL with horn antennas that are realized by removing a ~150μm long V-shape metal from the top metal layer of waveguide at both facets of the QCL. Seed pulses are injected through one facet and the seeded QCL emission detected from the opposite facet. Bottom: electromagnetic simulations of the modal profile of the QCL emission and the effect of the integrated antenna

Figure 1 shows a schematic of the process. The planar horn antennas are realized on both facets via post processing through the use of focused ion beam etching that removes the top metal and doped layer. V-shape geometries with the length of the horn ~150μm are realized to adapt the confined mode to a free space mode, as shown in the electromagnetic simulations of figure 1. MM devices with horn antennas were fabricated from a 2.7 THz bound-to-continuum design, consisting of 90 repeat periods of a GaAs/AlGaAs heterostructure. The ridge width is 80μm with a cavity length of 3mm. Short THz pulses (~1ps), which are used as a seed, are focused onto the entry facet of the QCL [1]. At the exact moment the seed pulse is injected into the cavity, the QCL gain is switched on that allows to amplify the input pulse at the unclamped gain of the QCL and eventually seed the QCL emission i.e. laser action is initiated by the injected seed and not by the QCL's inherent spontaneous emission. In this case, the QCL emission is always fixed to the seed pulse permitting the coherent detection of the former. The seeded emission exits the cavity through the second facet.

Figure 2a shows the measured transmitted electric field of the input seed as a function of time at 10K. The input seed is amplified over ~200ps and eventually saturates indicating the QCL has been seeded by the short THz pulse. The detail of the electric field can be seen in figure 2b showing a quasi CW operation at ~2.7THz. As the measurement of the QCL emission in Figure 2 is coherent, taking the Fourier transform reveals the spectrum of the emitted radiation. This is shown in Figure 2c. To verify that the QCL emission is well seeded, we measure the emission amplitude dependence on the antenna voltage as shown in figure 2d (linearly proportional to the THz seed amplitude). We see that as the seed amplitude is increased, the signal we measure reaches an asymptotic maximum, consistent with emission that is well synchronized with the detection system.

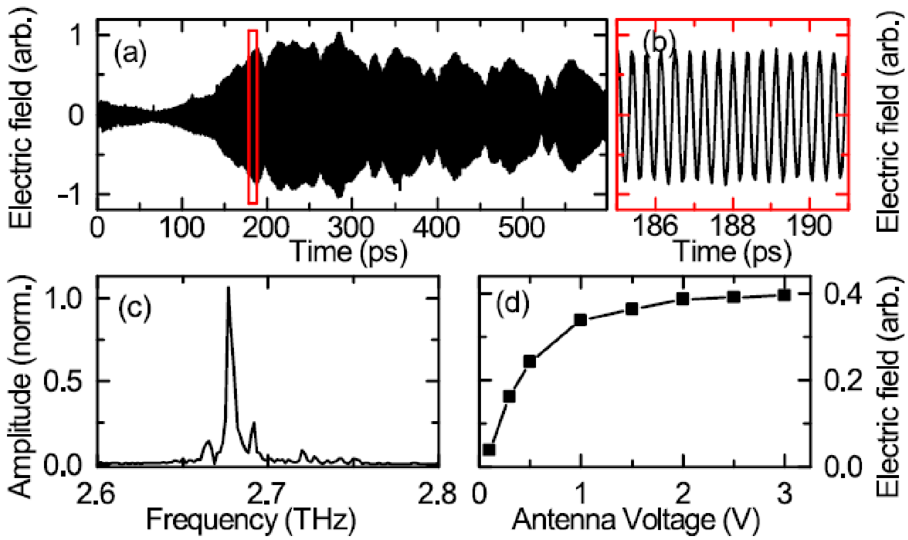

Fig. 2. Coherent detection of the MM QCL emission (a) Electric field emitted by the QCL in the first 600 ps after seed pulse arrives (b) Zoom of time window of 185–191 ps showing the electric field (c) Fourier transform of the time-domain electric field showing the emitted spectrum (d) Electric field amplitude emitted by the QCL at 550 ps as a function of antenna voltage.

This concept of planar horn antennas has also been applied to the injection seeding of a LO phonon-depopulation based MM QCL operating at 3.1THz. Indeed as these devices routinely operate up to relatively high temperatures compared to bound-to-continuum devices, we have demonstrated injection seeding at 77K (all previous measurements have been performed at 10K). Further as the gain bandwidth of these designs is greater we demonstrate injection seeding over a bandwidth of 600GHz for a 3mm long device. This much broader gain is of interest for the demonstration of short intense pulse generation and we show 11ps pulse generation from these devices via active mode locking.

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