# Difference-Frequency Generation Terahertz Quantum Cascade Lasers with Surface Grating Outcouplers

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**Abstract:** We report terahertz quantum cascade laser sources based on intra-cavity difference-frequency generation processed into double-metal waveguides with surface-grating outcouplers. Over 112 μW of peak power output is produced at room temperature at 1.9 THz. 

**OCIS codes:** (140.5965) Semiconductor lasers; (140.3570) Lasers, single-mode

## 1. Introduction

The terahertz (THz) spectral region, from 0.3 THz to 10 THz, has numerous applications such as chemical sensing, non-invasive imaging, radio astronomy, and spectroscopy. THz quantum cascade lasers (QCLs) based on intra-cavity difference-frequency generation (DFG) [1], referred to as THz DFG-QCLs, are currently the only electrically-pumped semiconductor laser sources operating at room temperature in the THz spectral region. By implementing the waveguides with the Cherenkov phase-matching scheme on InP substrate [2] and Si substrate [3], a dramatic improvement in their performance has been demonstrated. However, Cherenkov THz DFG-QCLs require growth on semi-insulating substrate and processing with lateral current extraction, which make the fabrication of high-power devices a challenge. THz DFG-QCLs grown on doped substrates or transferred on metal-coated substrates with the THz radiation extracted along the entire laser waveguide via a surface-grating [4] offer an appealing solution for advancing the power output of THz DFG-QCLs.

Here we demonstrate a room-temperature THz DFG-QCLs with a surface grating designed to efficiently outcouple the THz from the waveguide to air in the forward direction. Our device generates over 112 μW of THz power output at 1.9 THz with the mid-IR-to-THz conversion efficiency in the range of 140-300 $\mu W/W^2$, depending on the operating point. This represents the highest performance for THz DFG-QCLs operating below 2 THz.

## 2. Surface gratings design and simulation result

Metal gratings are widely used for light outcoupling from THz QCLs. A second-order grating that outcouples light from the waveguide in vertical direction is one of the most popular structure due to its vertical emission property. However, the uncertainty of the phases of the THz contributions from forward- and backward-going nonlinear polarization waves in THz DFG-QCLs leads to unpredictable THz power output. As a result, here we focus on gratings for light outcoupling in forward direction.

The gratings should be designed to satisfy the phase matching condition between the outcoupled wave and the nonlinear polarization wave in the laser waveguide [4]. For forward direction out-coupling, there are two possible phase matching conditions, $k_{wg} = k_{gr} + k_{air}$ and $k_{wg} = k_{gr} - k_{air}$. Here, $k_{wg}$, $k_{gr}$, and $k_{air}$ are the wave vector of the nonlinear polarization wave inside of the laser waveguide, that of a grating, and that of a THz wave propagating in the air, respectively. From simulation results, we found that the grating structure satisfying latter equation shows better out-coupling efficiency and our devices were processed in this configuration.

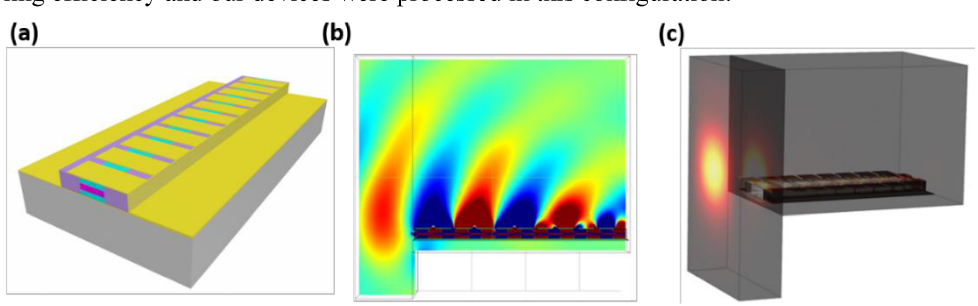


Fig. 1. (a) Schematic of the device structure. Gold is shown in yellow, laser active region is shown in red, the upper and lower InP cladding layers are shown in blue, the substrate is shown in grey, and the SU-8 layers are shown in purple. (b) COMSOL simulations of the THz outcoupling from the laser waveguide. (c) COMSOL simulations of a typical far-field profile of a THz DFG-QCLs with the grating outcoupler.

The device structure is shown in Fig. 1(a). Double-metal waveguide was used to reduce the loss of the THz mode in the laser cavity. To further reduce THz loss, the laser ridge waveguide was planarized with the SU-8 photoresist that also served as a spacer that isolates the THz mode from the side metal contact. In future devices, similar configuration may be achieved by growing QCLs on a heavily-doped substrates and applying buried heterostructure processing. The grating structure was designed for 1.9 THz radiation outcoupling, that corresponds to the atomic fine structure lines of singly ionized carbon and may be of interest for radio astronomy [5]. For the optimal performance, the grating period was chosen to be 36.35 μm and the duty cycle is 0.8. Figure 1(b) shows the forward-going propagation of the outcoupled THz wave, computed with COMSOL. Fig. 1(c) shows the simulation result for typical far-field pattern from the surface gratings. COMSOL simulations further predict that our device should have 1.11 times higher THz power output, compared to the standard Cherenkov THz DFG-QCL devices, assuming the same polarization wave in the active region and a 200 μm laser waveguide length. We note that the waveguide length in simulations was limited by the computing constrains and typical QCL waveguides are 2-5 mm in length. For these longer devices, the grating-outcoupling method has significantly higher performance, compared to Cherenkov devices, since the THz radiation has significant absorption in InP even when semi-insulating substrates are used [6].

## 3. Fabrication and experimental results

The laser active region design is identical to that of the THz DFG-QCLs reported in Ref. [7]. The ridge is defined to have 28 μm width and 25-μm-wide SU-8 spacers are defined besides the laser waveguide as shown in Fig. 1(a). The metal grating is defined using lift-off process. The processed wafer is cleaved into 1.5-mm-long laser bars. Devices were tested in pulsed mode at room temperature in a dual-grating external cavity setup reported in Ref. [8].

Figure 2(a) shows the mid-IR and THz emission spectra of a typical device. The THz DFG peak at 63.4 $cm^{-1}$ (1.9 THz) is determined by the mid-IR pump frequency difference. Figure 2(b) shows the L-I-V characteristics of the mid-IR pumps. The THz power output and the mid-IR-to-THz conversion efficiency of our device as a function of pump current is shown in Fig. 2(c). The maximum recorded THz peak power is nearly 112.5 μW, and the conversion efficiency varies between 300 and 140 $\mu W/W^2$. This conversion efficiency is 2.96 times higher than that of the buried-hetero structured Cherenkov THz DFG-QCL device with the same active region, 12 μm ridge width, and 3 mm cavity length. Future efforts will include the improvements in the device grating design, and implementing the same outcoupling scheme in buried heterostructure devices grown on heavily-doped substrates.

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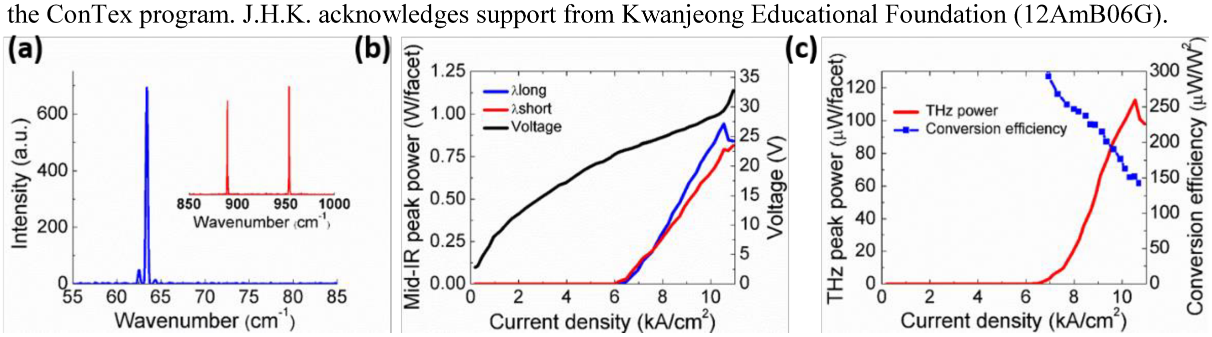


Fig.2 (a) The THz emission spectrum of the device at pump current of 3.65 A. Inset: the mid-IR emission spectrum at the same operating condition. (b) L-I-V characteristics of the mid-IR pumps. (c) THz power output and the mid-IR-to-THz conversion efficiency of the device as a function of pump current. The device was tested at room temperature with 200 ns current pulses at 5 kHz repetition frequency.

## 4. References

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