Double-metal waveguide terahertz difference-frequency generation quantum cascade lasers with surface grating outcouplers

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Double-metal waveguide terahertz difference-frequency generation quantum cascade lasers with surface grating outcouplers

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We report terahertz quantum cascade laser (QCL) sources based on intra-cavity difference-frequency generation processed into double-metal waveguides with surface-grating outcouplers. This configuration enables high confinement of the terahertz mode in the device active region and efficient surface extraction of terahertz radiation along the entire length of the waveguide. The devices operate at room temperature at 1.9 THz and produce over 110 µW of peak power output with the mid-infrared-to-terahertz conversion of 150 µW/W. The results represent at least a factor of 2 improvement in the performance compared to the best Cherenkov difference-frequency generation QCL devices operating below 2 THz. Published by AIP Publishing.

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The terahertz (THz) spectral range comprises a frequency band from 0.3 THz to 10 THz and hosts numerous applications in non-invasive imaging, chemical sensing, spectroscopy, and radio astronomy.1–4 Compact and mass-producible semiconductor lasers are desired to reduce the THz system size and cost for these applications. THz quantum cascade lasers (QCLs) are currently the only compact electrically pumped semiconductor sources operating in the 1–5 THz spectral region with a milliwatt-level power output, but their operation is still limited to cryogenic temperatures.5–7 THz QCL sources based on intra-cavity difference-frequency generation (DFG) in dual-wavelength mid-infrared (mid-IR) QCLs, referred to as THz DFG-QCLs, have recently been developed as an alternative to traditional THz QCLs.6,8 The active region of these devices is engineered to provide both mid-IR gain for pumps and giant second-order intersubband nonlinear susceptibility γ(2) for THz DFG in the same laser cavity.9 Since DFG is a nonlinear process that does not require the population inversion across a THz transition, THz DFG-QCLs can operate at room temperature.10

The waveguides of these devices were initially designed to support confined optical modes for both mid-IR pumps and THz DFG.9,10 However, the active region and waveguide doping in high-performance mid-IR QCLs result in very high absorption of the THz radiation in the laser waveguide, cf. Fig. 1(a). The Cherenkov phase-matching scheme was proposed to enable THz radiation extraction along the entire length of the THz DFG-QCL waveguides.6,8,11 Cherenkov THz DFG-QCL devices are grown on semi-insulating (SI) InP substrates that possess a large refractive index in the 1–6 THz range and small THz absorption, as shown in Fig. 1(b).11,12 The Cherenkov scheme dramatically improves THz radiation extraction into free space and enables broadband tuning THz DFG-QCLs.13 However, the use of the SI InP substrate requires lateral current extraction from the QCL active region using a heavily doped semiconductor layer.6,8,11,13 The lateral current extraction scheme increases Ohmic losses, reduces THz DFG efficiency, and adds complexity to device processing, particularly for continuous-wave laser operation.14–16

An alternative method to outcouple THz radiation along the DFG-QCL waveguide is to use a surface grating on top of the waveguide. This approach is similar to the one employed in THz QCLs (some examples are given in Refs. 17–19) and it can be implemented for THz DFG-QCLs grown on heavily doped substrates or devices processed into double-metal THz waveguides, similar to that of THz QCLs.17–19 THz DFG-QCLs with grating-outcoupling of THz radiation avoid the problems arising from the use of insulating substrates in the Cherenkov devices. Surface gratings further allow for direct outcoupling of THz radiation into air with higher THz transparency, compared to SI InP [cf. Fig. 1(b)], thus enabling THz extraction from very long (>3 mm) ridge-waveguide lasers.

![Absorption coefficients of doped InP as a function of THz frequency](image1)

![THz absorption of semi-insulating InP](image2)

FIG. 1. (a) Absorption coefficients of doped InP as a function of THz frequency. Calculations neglect the THz loss in intrinsic InP and include loss due to free electron plasma only. Calculations are shown for InP n-doped to 5 x 10^18 cm^-3 (solid black line) and 5 x 10^16 cm^-3 (dashed red line); other mid-IR QCL materials, namely, alloys of AlInGaAs, have free-carrier absorption coefficients similar to InP, within a factor of 2. (b) THz absorption of semi-insulating InP, after Ref. 12.
The first attempt to produce grating-outcoupled THz DFG-QCL devices was made in 2008 based on the concept of the second-order grating that outcoupled THz radiation normally from the laser waveguide. However, the lack of suitable waveguides for the THz mode, poor spectral selectivity of mid-IR pumps, and inefficient grating design resulted in a sub-microwatt-level device power output at cryogenic temperatures. Here, we report THz DFG-QCLs with grating-enabled surface outcoupling of THz radiation which provide power output at 1.9 THz that is approximately three orders of magnitude higher than that of the devices reported in Ref. and a factor of 2 higher than that of the state-of-the-art Cherenkov devices operating at similar frequencies.

The schematic of our device is shown in Fig. 2(a). The active region for the mid-IR pumps with integrated optical nonlinearity is sandwiched between InP mid-IR cladding layers and gold layers. The InP cladding layers provide low-loss dielectric confinement for the mid-IR pump modes and the gold layers provide low-loss plasmonic confinement for the THz mode, similar to that of THz QCLs with double-metal waveguides. High THz mode confinement in the laser waveguide enabled by the double-metal waveguide configuration increases the mode interaction with the grating; additionally, the bottom gold layer reflects THz power diffracted by the outcoupling grating towards the substrate and increases the overall grating outcoupling efficiency to air. COMSOL simulations show that a grating-outcoupled THz power for a device with a gold bottom waveguide cladding layer is nearly a factor of 3 higher compared to that for the device grown on a low-doped InP substrate (Si: 1.0 × 10^{17} cm\(^{-3}\)), assuming the same THz nonlinear polarization induced by the mid-IR pumps in the active region. Two 25-μm-wide cladding blocks made of SU-8 photoresist are introduced on both sides of the laser ridge to provide side-wall insulation and to prevent the interaction of the THz wave with the metal on the side of the ridge. To extract the THz DFG wave from the double-metal waveguide into free space, the k-vector of the THz nonlinear polarization wave driven by the mid-IR pumps in the waveguide (k\(_{\text{DFG}} = 2\pi \times n_g / \lambda_0\), where n\(_g\) ≈ 3.37 is the mid-IR pump group index\(^{11}\) and \(\lambda_0\) is the THz radiation wavelength in free space) and the wave vector of the THz radiation in air (k\(_{\text{air}}\) = 2\pi / \lambda_0) can be written as

\[
k_{\text{DFG}} = k_{\text{DFG}} + k_{\text{air}}.
\]

Unlike regular mid-IR and THz QCLs with grating-outcouplers, where the surface grating provides both outcoupling to free space and distributed feedback (DFB) that determines the optical field structure in the laser cavity, the surface grating outcoupler presented here only outcouples THz radiation and provides negligible feedback for the mid-IR pumps due to the large (~10 times) difference between the frequencies of the former and the latter in DFG-QCLs. This type of grating outcoupler can deliver a diffraction-limited single-lobe beam pattern without additional means to control the optical field structure in the laser cavity which is used in the DFB grating outcouplers, such as \(\pi\) phase-shift in the center of the second-order Bragg grating,\(^{18}\) third-order Bragg grating,\(^{19}\) dual-slit DFB grating,\(^{22}\) graded photonic heterostructures,\(^{23}\) plasmon-enhanced absorption of antisymmetric modes,\(^{24}\) and hybrid second- and fourth-order Bragg grating.\(^{25}\) However, unlike devices with DFB grating outcouplers, our devices need to have a separate structure to select the mid-IR pump frequencies. This is done by external diffraction gratings in the present work, but frequency-selection may also be achieved by implementing mid-IR DFB gratings in the device structure in addition to the THz outcoupling grating. We also note that, since separate structures are involved in the frequency selection and frequency outcoupling in our devices, the outcoupled THz beam in our lasers will steer as the THz frequency is tuned, unlike that in the devices with DFB grating outcouplers.

A second-order grating with k\(_{\text{gr}}\) = k\(_{\text{DFG}}\) has been one of the most popular structures for outcoupling of laser radiation from mid-IR\(^{26-29}\) and THz QCLs.\(^{17,18}\) However, the THz DFG field structure in our devices is determined by the mid-IR pumps that are not affected by the outcoupling grating, as discussed earlier. Depending on the phases of the mid-IR pumps, the phase of the forward- and backward-going nonlinear polarization waves relative to the grating structure may vary from 0 to 2\(\pi\), resulting in dramatic variation of the outcoupling efficiency in the devices. To avoid this situation, we decided to focus on gratings for outcoupling THz radiation from the waveguide in the forward and backward directions in a manner similar to the scheme used for THz QCLs in Ref.\(^{19}\) In this scheme, the left- and right-going DFG

![Image](https://via.placeholder.com/150)

**FIG. 2.** (a) Schematic illustration of the THz DFG-QCLs with the double-metal waveguide, SU-8 insulation layers, and a surface grating. (b) Simulation results of the power output from the 1.9 THz surface-emitting THz DFG-QCL with the surface gratings satisfying phase matching condition k\(_p\) = k\(_{\text{DFG}}\) + k\(_{\text{air}}\) (closed blue squares) and k\(_{\text{DFG}}\) = k\(_{\text{DFG}}\) - k\(_{\text{air}}\) (open red squares) as well as the simulated power output from the 1.9 THz Cherenkov THz DFG-QCL with the same active region (closed black triangles) as a function of the laser cavity length. Dashed lines are guides to the eye. (c) Three-dimensional COMSOL simulation of the THz wave out-coupled from the surface grating with k\(_{\text{DFG}}\) = k\(_{\text{DFG}}\) + k\(_{\text{air}}\) (the phase matching condition is depicted in the figure), obtained assuming the mid-IR pump waves propagating to the right of the figure. Terahertz radiation is outcoupled into a wave going to the left of the figure.
waves are outcoupled in different directions and do not interfere.

For forward direction outcoupling, there are two possible phase matching conditions, \( k_{gr} = k_{\text{DFG}} - k_{\text{air}} \) and \( k_{gr} = k_{\text{DFG}} + k_{\text{air}} \). The former condition makes the out-coupled THz wave propagate in the same direction as the THz wave in the waveguide, while the latter condition makes the out-coupled wave propagate in the opposite direction to the THz wave in the waveguide. Since the latter condition requires grating with higher density of diffracting elements per unit length, we expect that it may result in higher out-coupling efficiency of the THz wave.

To compare the out-coupling efficiencies between the two designs, we performed 3-dimensional electromagnetic simulations with COMSOL Multiphysics. DFG-QCL sections of different lengths were simulated. The schematic of the device considered in our analysis is shown in Fig. 2(a). The laser ridge width was assumed to be 28 \( \mu \)m and the waveguide structure consisted of a 6-\( \mu \)m-thick lower cladding layer (InP, Si: 1.0 \( \times \) 10\(^{10}\) cm\(^{-3}\)), a 6.732 \( \mu \)m-thick 90-period active region which is identical to that of the THz DFG-QCLs reported in Ref. 30, and a 5-\( \mu \)m-thick upper cladding layer (InP, Si: 1.5 \( \times \) 10\(^{10}\) cm\(^{-3}\)). We note that the waveguide structure that we considered in the simulations was nearly identical (slightly simplified) to the waveguide structure of the experimentally tested device described below. The thickness of the bottom gold layer is assumed to be 1 \( \mu \)m and the substrate is assumed to be semi-insulating InP, in agreement with experimental parameters. The 25-\( \mu \)m-wide SU-8 sidewall layers are placed besides the ridge. The refractive index of SU-8 was taken to be 1.85 from Ref. 31. The surface gratings (Au) are defined on top of the waveguide as shown in Fig. 2(a); we have assumed the top gold layer thickness of 1 \( \mu \)m and varied the grating duty cycle (defined as the ratio of the width of the metallized part of the grating and the grating period). The DFG process was modelled by introducing a forward-going terahertz polarization wave with the wave vector \( k_{\text{DFG}} \) in the device active region. The grating period was set for out-coupling of the forward-going THz wave at 1.9 THz (frequency relevant for radio-astronomical applications\(^{32,33}\)) from the laser waveguide into air in either the forward- or backward-going direction. Figure 2(b) shows the calculated THz power output in air for the two cases, assuming the same right-going polarization wave in the active region. As expected, the power output scales linearly with the device length and the surface gratings satisfying the condition \( k_{gr} = k_{\text{DFG}} + k_{\text{air}} \) provide higher performance. Our simulations further show that the highest efficiency may be obtained by out-coupling THz waves at a small angle \( \theta \approx 25^\circ \) to the device surface, with the grating period \( \Lambda \) determined by the equation

\[
k_{gr} = k_{\text{DFG}} + k_{\text{air}} \cos(\theta)
\]

(1)

to be 36.9 \( \mu \)m. The optimal grating duty cycle is 70% according to the simulations. Figure 2(c) shows simulated THz emission from a 562-\( \mu \)m-long section of a THz DFG-QCLs with a surface grating of 36.9 \( \mu \)m at a frequency of 1.9 THz. Our simulations further predict that the output power of the best-performing grating-outcoupled device is about 86% higher compared to the Cherenkov emission for the device with the same cavity length (800 \( \mu \)m) operating at the same 1.9 THz frequency as shown in Fig. 2(b). For the Cherenkov emission simulations, we assumed no metal layer below the QCL waveguide.

To experimentally verify the performance of the double-metal waveguide THz DFG-QCLs with the surface-grating outcouplers, we have processed and tested DFG-QCL devices based on the dual-upper-state (DAU) active region design which have been reported in Ref. 30. DAU active regions were originally developed for high-performance mid-IR QCLs\(^{34}\) but have recently been shown to provide high nonlinearity for THz DFG as well.\(^{30,35}\) The device heterostructure was grown on a 350-\( \mu \)m-thick semi-insulating InP substrate. The growth started with a 200-nm-thick heavily doped In\(_{0.53}\)Ga\(_{0.47}\)As etch-stop layer (Si: 1.0 \( \times \) 10\(^{18}\) cm\(^{-3}\)), followed by a 5.0-\( \mu \)m-thick InP cladding layer (Si: 1.5 \( \times \) 10\(^{16}\) cm\(^{-3}\)) and a 200-nm-thick In\(_{0.53}\)Ga\(_{0.47}\)As waveguide layer (Si: 1.5 \( \times \) 10\(^{16}\) cm\(^{-3}\)). Then, a 90-period active region which is identical to that of the THz DFG-QCLs reported in Ref. 30 was grown. On top of the active region, a 450-nm-thick In\(_{0.53}\)Ga\(_{0.47}\)As waveguide layer (Si: 1.5 \( \times \) 10\(^{16}\) cm\(^{-3}\)), a 6.0-\( \mu \)m-thick InP cladding layer (Si: 1.0 \( \times \) 10\(^{16}\) cm\(^{-3}\)), and a 15-\( \mu \)m-thick In\(_{0.53}\)Ga\(_{0.47}\)As capping layer (Si: 1.0 \( \times \) 10\(^{19}\) cm\(^{-3}\)) were grown.

For processing, the QCL wafer was cleaved into approximately 1 cm \( \times \) 1 cm pieces. The ep-side of these pieces and the epi-ready sides of similar pieces of heavily doped (n \( \approx \) 1 \( \times \) 3 \( \times \) 10\(^{18}\) cm\(^{-3}\)) InP substrate were coated with metal layers (Ti/Au: 20 nm/150 nm) by electron-beam evaporation. The metal-coated QCL wafer pieces were thermocompressively bonded, epi-side down, to metal-coated InP pieces at 320°C. The InP substrate of the bonded QCL pieces was then removed by selective etching in hydrochloric acid using the In\(_{0.53}\)Ga\(_{0.47}\)As layer as an etch-stop. The surface grating pattern was then transferred on the heavily doped In\(_{0.53}\)Ga\(_{0.47}\)As etch-stop layer, and this layer was removed in the areas of the grating openings. The 28-\( \mu \)m-wide ridge waveguides were then defined in alignment with the surface grating pattern in the etch-stop layer by optical lithography and dry etching. Then, approximately 16-\( \mu \)m-high and 25-\( \mu \)m-wide slabs of SU-8 photoresist were defined besides the laser waveguide by photolithography. The top metal contact (Ti/Au: 20 nm/600 nm) that included the grating pattern on top of the laser ridge was defined using the electron beam evaporation and lift-off. The metal grating pattern was aligned with the etch pattern on the heavily doped etch-stop layer so that the grating openings had no heavily doped

![FIG. 3. Scanning electron microscopy images of the processed device with grating outcouplers. (a) Device front facet with the layers of SU-8 and the bottom metal bonding interface indicated by an arrow and (b) top view of several devices on a laser bar.](image-url)
InGaAs material. Figures 3(a) and 3(b) show scanning electron microscopy images of the processed devices. The image of the device facet in Fig. 3(a) confirms high-quality metal-metal bonding and shows the SU-8 photore sist slabs on both sides of the laser ridge. The image of the top of the laser bar, Fig. 3(b), shows the top contact and the grating. The image confirms the grating period of 36.9 μm and the duty cycle of approximately 70%, in agreement with the design parameters.

The processed piece of wafer was cleaved into 1.5-mm-long laser bars. The relatively short cavity length of the lasers was determined by the limitations of the maximum current pulses that we can produce in our measurement setup. As shown in Fig. 2(b), we expect a linear increase in the THz power output from our lasers with the waveguide length. To enable single-frequency THz emission, the lasers were placed into a dual-grating external cavity setup36 to select the frequencies of the mid-IR pumps. The back facets of the laser bars were coated with a two-layer anti-reflection coating (YF3 and ZnSe) to suppress mid-IR feedback from the cleaved facets. The two mid-IR pump frequencies were spectrally selected by the external gratings to maintain THz difference-frequency around 1.9 THz. Devices were operated at room temperature with 200 ns current pulses at a repetition rate of 5 kHz. Figures 4(a)–4(c) report the device operation around 2 THz.36–38

![Image](image_url)

**FIG. 4.** Performance of a 1.5-mm-long DFG-QCL device with the grating outcoupler in the external cavity setup. (a) Emission spectra of the mid-IR pumps (top) and THz DFG (bottom). (b) Voltage and the peak power outputs of the two mid-IR pumps vs current. The blue dashed line and the red solid line refer to the power output of the short-wavelength and long-wavelength mid-IR pumps, respectively. (c) THz peak power output (blue solid line) and the mid-IR-to-THz conversion efficiency (red dashed line) of the device as a function of pump current. (d) THz far-field emission profiles of 1.90 THz (closed blue squares) and 1.93 THz (red open circles). The reference angle (0°) is defined as the beam direction perpendicular to the laser facet. The polarity of the angle is shown in the inset. The peak position of the far-field profile is at 32° in this case, in agreement with the Eq. (1) predictions of 32.6°. The full width at half maximum (FWHM) values of the far-field profiles at 1.90 and 1.93 THz are 17° and 16°, respectively. These values are in good agreement from the prediction from the Fraunhofer diffraction theory, assuming a uniform DFG wave intensity distribution in the QCL waveguide and using the effective emission aperture width L_{eff} = L \times \sin(\theta), where \theta is the emission angle and L = 1.5 mm is the device length. From the Fraunhofer diffraction theory, FWHM = 2 \sin^{-1} \left( \frac{0.443 L_0}{L_{eff}} \right) and we obtain the FWHM values of 13° and 10° for the emission at 1.9 THz and 1.93 THz, respectively.

characteristics of the device. The mid-IR pump powers were measured using a thermopile detector using two parabolic mirrors to collect light from the QCL and focus it to the bolometer. The mid-IR pump powers were corrected for the estimated 70% collection efficiency of our setup. THz peak power and the mid-IR-to-THz conversion efficiency [defined as the ratio of the THz peak power in Fig. 4(c) to the product of the mid-IR pump powers in Fig. 4(b)] as a function of current are plotted in Fig. 4(c). The THz power was measured using a calibrated liquid helium cooled Si bolometer using the same two parabolic mirrors that were used for mid-IR measurements. We note that, due to the uncertainty in the determination of the THz collection efficiency of our setup, the THz peak powers were not corrected for the collection efficiency which is estimated to be less than 50%. As shown in this figure, the maximum peak power output of the THz wave is 112.5 μW (not corrected for the collection efficiency) and the mid-IR-to-THz conversion efficiency at this power level is approximately 150 μW/W². The values of both THz power output and the mid-IR-to-THz conversion efficiency are a factor of 2 higher than that of the best-performing THz DFG-QCLs for operation around 2 THz.36–38
to the non-uniform (exponentially growing) intensity distribution of the forward-going mid-IR pump waves.

In conclusion, we report high-performance THz DFG-QCLs with THz radiation outcoupled from the active region by a surface grating. The power output and the mid-IR-to-THz conversion efficiency of our devices operating at 1.9 THz are at least a factor of 2 higher than that of similarly sized Cherenkov devices operating at similar frequencies. Our devices provide the highest peak THz power output for THz DFG-QCL sources operating below 2 THz reported to date.36–38 Similar grating outcoupling schemes can be implemented in high-performance buried-heterostructure THz DFG-QCLs grown on heavily doped substrates that are expected to be able to operate continuous-wave at room-temperature in the epi-side-up configuration, based on the reported performance of regular mid-IR QCLs.

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