Terahertz difference frequency generation in quantum cascade lasers on silicon

Seungyong Jung*,a, Jae Hyun Kim,a, Yifan Jiang,a, Karun Vijayaraghavanb, and Mikhail A. Belkin*a

aDepartment of Electrical and Computer Engineering, The University of Texas at Austin, 10100 Burnet Road, Austin, Texas, USA 78758;
bATX Photonics, 10100 Burnet Road, Austin, Texas, USA 78758
*Email: sejung@utexas.edu (S. J.), mbelkin@ece.utexas.edu (M.A.B.)

ABSTRACT

We demonstrate that an application of a III-V-on-silicon hybrid concept to terahertz (THz) Cherenkov difference frequency generation (DFG) quantum cascade laser (QCL) sources (THz DFG-QCLs) can dramatically improve THz output power and mid-infrared-to-THz conversion efficiency. Completely processed THz DFG-QCLs grown on a 660-µm-thick native InP substrate are transfer-printed onto a 1-mm-thick high-resistive Si substrate using a 100-nm-thick SU-8 as an adhesive layer. Room temperature device performance of the reference InP and hybrid Si THz DFG-QCLs of the same ridge width (22 µm) and cavity length (4.2 mm) have been experimentally compared. The target THz frequency of 3.5 THz is selected for both devices using the dual-period first order surface gratings to select the mid-infrared pump wavelength of 994 cm⁻¹ and 1110 cm⁻¹. At the maximum bias current, the reference InP and hybrid Si devices produced THz power of 50 µW and 270 µW, respectively. The mid-infrared-to-THz conversion efficiency corresponds to 60 µW/W² and 480 µW/W², respectively, resulting in 5 times higher THz power and 8 times higher conversion efficiency from the best-performing hybrid devices. A hybrid Si device integrated in a Littrow external-cavity setup showed wavelength tuning from 1.3 THz to 4.3 THz with beam-steering free operation.

Keywords: Quantum cascade lasers, terahertz, difference frequency generation, photonic integration

1. INTRODUCTION

The terahertz (THz) spectral region from 0.3 THz to 10 THz has many applications such as chemical sensing, biomedical diagnosis, non-invasive imaging and spectroscopy [1, 2]. For efficient and compact THz applications, using a THz source with room temperature operation, electrical pumping, high power, and wide tunability is highly desired. THz difference frequency generation quantum cascade laser sources (THz DFG-QCL) are currently the only monolithic electrically-pumped semiconductor devices that can produce laser-like THz emission at room temperature [3]. Active regions of THz DFG-QCLs are designed to provide both optical gain for mid-IR pumps and giant second-order nonlinearity (χ(2)) for efficient generation of THz waves inside of the laser cavity [4]. Since the DFG process does not involve population inversion for the THz transition, THz DFG-QCLs can produce coherent THz emission at room temperature.

Significant improvement in THz output power and tunability of THz DFG-QCLs has been made after the implementation of the Cherenkov emission scheme for THz extraction [5, 6]. The initial version of the Cherenkov THz DFG-QCLs used a semi-insulating (SI) InP substrate whose refractive index in the 1-6 THz range is higher than the effective index of the THz nonlinear polarization wave propagating in the QCL active region. Such leaky THz waveguide configuration makes the DFG-QCL to emit THz waves generated in the active region into the SI InP substrate that provides significantly lower THz loss than that of the QCL active region. As a result, Cherenkov DFG-QCLs produced over one order of magnitude higher THz power compared to that of edge-emitting DFG-QCLs [7]. An automatic phase-matching condition provided by the Cherenkov scheme allowed for demonstrating widely tunable THz DFG-QCL sources with a tuning range of 4.5 THz in an external cavity setup [8] and a tuning range of 0.6 THz ~ 2.5 THz in various monolithically-tunable configurations [9-11]. By using epi-down mounting on diamond heat spreaders, Cherenkov DFG-QCLs can now produce over ten micro-watt of continuous-wave THz.
power at room temperature [11, 12]. However, our simulation result shows that, for a typical 3-mm-long THz DFG-QCL on the SI InP substrates, only less than 20% of THz waves produced in the active region is out-coupled to free space due to significant THz absorption in the SI InP. In addition, the relatively high refractive index in the SI InP introduces a wide cone angle of Cherenkov radiation limiting the efficiency of the THz out-coupling from the front facet of the device.

In this paper we demonstrate that the THz power and out-coupling efficiency of Cherenkov THz DFG-QCLs can be dramatically improved by implementing the III-V-on-Si hybrid laser concept to the DFG-QCLs. Experimentally, our best-performing 4.2-mm-long Cherenkov THz DFG-QCLs transfer-printed on high-resistivity float-zone (HR-FZ) Si produced THz peak power of 270 µW and have the mid-IR-to-THz conversion efficiency of 480 µW/W² at 3.5 THz at room temperature. The THz peak power of the best devices on Si was 5 times higher and the mid-IR-to-THz conversion efficiency was 8 times higher than that of the best reference devices with the same dimensions on the SI InP substrate. An external-cavity DFG-QCL on HR-FZ Si showed beam-steering-free wavelength tuning of 3 THz - from 1.3 to 4.3 THz. The tuning range is primarily limited by the residual mid-IR reflectivity at the device facets due to imperfection of anti-reflection coating.

2. THEORETICAL ANALYSIS

Cherenkov emission of THz DFG-QCLs occurs when the phase velocity of the THz wave in the device substrate is faster than the phase velocity of the nonlinear polarization wave in the device active region. The propagation angle of the Cherenkov THz emission with respect to the QCL cavity is defined as, \[ \theta_c = \cos^{-1}(n_g / n_s), \] where \( n_g \) and \( n_s \) are the group index of mid-IR pumps and the index of the substrate, respectively. Since the mid-IR group index in QCLs shows a nearly constant value of \( \approx 3.37 \) over the 8-12 µm [13], any substrate with a THz refractive index higher than \( \approx 3.37 \) can fulfill the condition of Cherenkov DFG emission.

Previously, SI InP substrates were used for Cherenkov THz DFG-QCLs since high performance mid-IR QCLs with InGaAs/AlInAs active regions can be grown on InP. However, SI InP has relatively high THz absorption loss that limits the propagation length of Cherenkov emission to below 1 mm. It also exhibits a relatively large THz refractive index that results in the Cherenkov DFG emission cone angle of \( \approx 20 \) °. The Cherenkov emission will then experience the total internal reflection at the semiconductor-air interface, unless the substrate facet is polished. A conical-shape substrate aperture would be ideal to out-couple Cherenkov emission into free space but it is generally impractical to fabricate. Thus, polishing the InP substrate facet into a wedge shape with an angle between 20 ° and 30 ° is typically used to out-couple part of the central Cherenkov beam into free space.

The HR-FZ Si substrate of Cherenkov DFG-QCLs provides many advantages over the SI InP substrate. The HR-FZ Si has the value of the refractive index \( n_s = 3.4 \) that matches well with the group index \( n_g = 3.37 \) to fulfill the Cherenkov condition over the entire THz range with the small Cherenkov cone angle of about 10 °. Since the critical

![Figure 1. The refractive indices (a) and optical absorption (b) of FZ HR Si (red) and SI InP (blue) as a function of frequency.](http://proceedings.spiedigitallibrary.org/proceedings perder/10123316-2)
angle at the substrate facet/air interface is 16 °, the DFG-QCLs on Si substrates do not require the substrate facet polishing and are expected to increase out-coupling efficiency by enhanced extraction of the lateral portion of the Cherenkov beam. Furthermore, extremely low THz loss in HR-FZ Si (see Fig. 1) enables a long extraction length of THz waves. For example, the absorption length in FZ-Si at 3.5 THz is longer than 5 cm compared to less than 1 mm for SI InP. In addition, very small THz refractive index dispersion of HR-FZ Si offers beam-steering-free wavelength-tuning operation in DFG-QCLs [8].

Figure 2. (a, b) 3-dimensional COMSOL simulation of the THz power intensity out-coupled from the SI InP device to air (a) and the HR-FZ Si device to air (b). The yellow lines are the power streamlines indicating propagation direction of THz power out-coupled to equal points on the air monitor. All simulations assume uniform mid-IR pumps intensity in the laser cavity. The substrate of the SI InP device is assumed to be polished at 20 °, while the substrate of the HR-FZ Si device was assumed to be polished at 10 °. (c) The ratio of THz power of the HR-FZ-Si-hybrid device to THz power of the SI InP reference device at different cavity lengths.

Figure 2(a, b) shows 3-dimensional COMSOL simulation results obtained from a 203-µm-long Cherenkov THz DFG-QCL operating at 3.5 THz on a SI InP substrate (Fig. 2(a)) and a HR-FZ Si substrate (Fig. 2(b)). The nonlinear-polarization sources in the QCL active region are modeled by setting dipoles to radiate forward-propagating waves (direction to the facet) at a fixed frequency of 3.5 THz in TM polarization (oscillating across the layers). The substrate facet polishing angle of 20 ° for the InP substrate and 10 ° for Si substrate are used in the simulation. The facet out-coupling efficiency of each case is estimated by comparing the incoming THz power onto the substrate facet to the out-coupled THz power on the air screen as shown in the Fig. 2. Our simulations show that the facet out-coupling efficiency of the device with the SI InP substrate is about 30 % and that with the HR-FZ Si is about 45 %.

Figure 2(c) displays the ratio of the THz power of a 3.5 THz DFG-QCL on the HR-FZ Si to that on the SI InP for different cavity lengths. The expected power output from longer devices (P_{THz}) is obtained by scaling the above simulation results as,

\[ P_{THz} = \eta_{ext} I_0 \int_{0}^{L_{cav}} e^{-\alpha_{sub} x} \cos \theta \, dx, \]  

where \( \eta_{ext} \) and \( I_0 \) are, respectively, the out-coupling efficiency of the Cherenkov cone through the facet and the linear power density (W/m) of the THz Cherenkov wave emitted from the laser waveguide into the substrate as determined from the COMSOL simulations, \( L_{cav} \) is the laser cavity length, and \( \alpha_{sub} \) is the absorption coefficient of the substrate. The power output of the SI InP device virtually stops increasing after the length of the laser cavity exceeds the absorption length of the THz radiation in the SI InP substrate (<1 mm in the 3-5 THz range). In contrast, the power output of the hybrid device continuously increases with the cavity length, owing to the extremely long THz absorption length (>5 cm) in HR-FZ Si.

3. DESIGN AND FABRICATION

The laser structure was grown on a 660-µm thick semi-insulating InP substrate by a commercial foundry (IQE Inc.). The active region of our DFG-QCL is designed based on the bound-to-continuum transition scheme [14] and its waveguide structure is similar to that of the device reported in Ref. [7]. The growth started with a 200-nm-thick
In$_{0.53}$Ga$_{0.47}$As current injection/etch-stop layer followed by a 3-µm-thick InP cladding layer and a 200-nm-thick In$_{0.53}$Ga$_{0.47}$As waveguide layer. Then, two 25-repetition stacks of active regions, the bottom one designed for the peak gain at 8.5 µm and the top one designed for the gain peak at 9.5 µm, were grown with In$_{0.53}$Ga$_{0.47}$As/In$_{0.52}$Al$_{0.48}$As superlattices. The active regions were capped with a 300-nm-thick In$_{0.53}$Ga$_{0.47}$As waveguide layer, a 3-µm-thick InP cladding layer, a 100-nm-thick InP contact layer, and finally a 10-nm-thick In$_{0.53}$Ga$_{0.47}$As capping layer.

A piece of the grown wafer was processed into distributed feedback (DFB) lasers with the side current injection scheme [5] following conventional dry-etched ridge waveguide fabrication steps. The first-order surface gratings with two sections for selecting two mid-IR pump frequencies were formed using e-beam lithography and dry etching. The grating pitches for the 9.02 µm short wavelength ($\lambda_{\text{short}}$) and the 10.08 µm long ($\lambda_{\text{long}}$) wavelength pumps are 1.408 µm and 1.584 µm, respectively. The completely processed wafer die was cleaved into two sections, one section for the characterization of the reference devices on the Si InP substrate and the second section for transfer to the HR-FZ Si.

The second section of the completely processed QCL wafer was transfer-printed on HR-FZ Si using the following steps [15]. We have first photolithographically defined 50-µm-wide 8-µm-tall SU-8 epoxy supporting elements next to each ridge on the processed wafer in order to prevent epi-layer damage during the wafer-bonding process. The wafer was then attached to a piece of glass slide with laser ridges facing the glass using crystal glue (Crystalbond 509). The InP substrate was then selectively removed using an HCl-based wet etchant, with the InGaAs current injection layer used as an etch stop. The exposed surface of the current injection layer was then bonded to a 1-µm-thick HR-FZ Si wafer coated with a 100-nm-thick SU-8 layer. The bonding was performed in the AML wafer bonding machine at a pressure of 1 MPa and a temperature of 180 °C for 15 min. Finally, the glass slide was removed by dissolving the crystal glue with acetone and the hybrid QCL-on-Si wafer was diced into laser bars using a dicing saw. The front facets of the Si-hybrid and reference InP devices were polished in 15 ° and 30 °, respectively, to out-couple THz Cherenkov emission in the direction parallel to the laser cavity.

![Figure 3. Scanning electron microscope images of the reference InP device (a) and the Si device (b).](image)

Figure 3 shows the scanning electron microscopy images of the facets of the devices on InP and Si substrates. The somewhat roughened surface of the facet of the QCL-on-Si originates from the dicing process (devices on Si InP were cleaved). The thickness of the SU-8 bonding layer is estimated from Fig. 3(b) to be about 100 nm. According to our simulations, a 100-nm-thick SU-8 layer has about 90 % transmission of the THz Cherenkov radiation into the Si substrate. Devices were indium-soldered to copper blocks in the episide-up configuration and wire bonded.

### 4. Experimental Results

The mid-IR power output was measured using a thermopile detector with a metal power collecting pipe while the THz power output was measured using a two parabolic mirror setup and a calibrated liquid helium cooled Si bolometer. Both mid-IR and THz power outputs were not corrected for the collection efficiency. A long-pass filter with the cut-on frequency of 1000 cm$^{-1}$ was used to separate the two mid-IR pump powers. The spectra were measured using a Fourier transform infrared spectrometer equipped with a deuterated triglycerine sulfate detector (for mid-IR measurements) or the Si bolometer (for THz measurements). Devices were driven in pulsed mode using 40 ns current pulses at 15 kHz repetition frequency at 20 °C of a heat sink temperature.

Proc. of SPIE Vol. 10123 1012316-4
Figure 4(a) displays the mid-IR and THz spectra measured from the Si-hybrid device. Stable dual single-mode mid-IR pump operation was obtained at the peak wavelengths of 994 cm⁻¹ and 1110 cm⁻¹. The peak positions of the mid-IR pumps are identical for devices on Si and InP. THz emission frequency of both devices is 3.48 THz in agreement with the frequency separation of the mid-IR pumps. Figure 4(b) shows the mid-IR power output for each pump. To compare the performance of the InP and Si devices, a best-performing device of each type with the identical dimensions (22-µm-wide width and 4.2-mm-long cavity length) was selected. Both devices show nearly the same threshold current of 4.5 A for the short wavelength pump while the long wavelength pump of the hybrid device starts lasing at 6.5 A. Overall, the performance of the Si-transferred devices was similar to that on InP for pulsed operation used in this work [15]. The bias voltage of the Si device is about 5 V higher than that of the InP device, likely due to the reduced thickness of the current injection layer during substrate etching, which can be overcome in the future by using a thicker current injection layer.

Figure 5(a) The mid-IR spectra and mid-IR pump powers of the DFB mode (red squares) and the EC mode (blue circles) of the external-cavity (EC) DFG-QCL on the HR-FZ Si operating at fixed bias current of 5.2 A under pulsed mode at room temperature. (b) THz peak power (blue circles) and conversion efficiency (red squares) of the EC DFG-QCL on the HR-FZ Si operating at the same bias condition as in (a).

THz peak power and the mid-IR-to-THz conversion efficiency of both devices are plotted in Fig. 4(c). THz power of the reference InP device is as high as 50 µW with the conversion efficiency of 60 µW/W² while that of the Si-hybrid device reaches 270 µW with the efficiency of 480 µW/W² at the maximum bias current, resulting in a factor of 5 improvement in THz power and a factor of 8 improvement in the conversion efficiency. The power improvement is
in excellent agreement with the simulation result, shown in Fig. 2(c). The ratio of the THz power of the hybrid device to that of the reference device remains nearly constant over the measured current range.

Tunability of a 2-mm-long, 22-µm-wide Si-hybrid device has been tested in a Littrow-type external-cavity (EC) setup (see Ref. [8] for the details of the setup). One of the mid-IR pumps was fixed at the wavelength at 995 cm\(^{-1}\) by the surface DFB grating integrated on the EC-Si-hybrid device while the other pump has been selected by controlling the angle of a gold-coated diffraction grating that provides EC feedback to the QCL device. The back facet of the device is coated with an anti-reflection coating to suppress FP mode and the front facet left uncoated is polished with an angle of 15° to direct THz beam parallel to the laser cavity. Figure 5(a) shows the mid-IR spectra of the DFB mode and the EC mode measured at different angles of the diffraction grating while the device was biased at fixed current of 5.2 A. The wavelength of the EC mode was tuned from 1045 cm\(^{-1}\) to 1145 cm\(^{-1}\), the tuning range of which is primarily limited by residual facet reflection due to imperfection of the antireflection coating [8].

Total power of the mid-IR pump powers of the device was maintained to about 2 W over the tuning range but significant power fluctuation of each pump is observed due to the gain competition between the DFB mode and the EC mode. Figure 5(b) shows corresponding THz performance of the EC HR-FZ Si device. The total tuning range of 3 THz from 1.3 THz to 4.3 THz is obtained. THz power of the device was increased from 20 µW at 1.3 THz to over 500 µW at 4.3 THz and the conversion efficiency was increased from 50 µW/W\(^2\) at 1.3 THz to 550 µW/W\(^2\) at 4.3 THz. Note that the EC device was 2.1 times shorter than the DFB device reported in Fig. 4, which lead to lower THz power output and conversion efficiency at 3.48 THz of the EC device, compared to the DFB device.

![Figure 6](image_url)

Figure 6. The transverse far field of the EC DFG-QCL on Si measured at different wavelengths indicated in the figure. The inset shows the schematic of the device indicating the orientation of angle polarity.

As we mentioned earlier [8], the Si-hybrid device can offer the beam-steering-free operation due to very low THz refractive index dispersion of HR-FZ Si. This has been confirmed by characterizing far fields of the HR-FZ Si device operating in the EC setup at different THz wavelengths. Figure 6 displays the far field profiles of the EC device measured in the transverse direction. The peak far-field intensities are maintained at nearly the same direction of approximate -10° with a full width at half maximum of 12°.

5. SUMMARY

We have demonstrated that the use of HR-FZ Si substrates instead of Si InP substrates in THz DFG-QCLs results in a dramatic improvement in the THz power output and the mid-IR-to-THz conversion efficiency in the devices. The 22-µm width and 4.2-mm-long ridge-waveguide THz DFG-QCLs transfer-printed on HR-FZ Si produced the peak THz power output of 270 µW with the mid-IR-to-THz conversion efficiency of 480 µW/W\(^2\) at 3.48 THz while the reference InP device with the same dimensions and operating frequency produced 50 µW with the conversion efficiency of 60 µW/W\(^2\) at the maximum bias current. We also demonstrated that the EC-Si-hybrid device is tunable from 1.3 THz to 4.3 THz without any significant THz beam steering.
This work was supported by National Science Foundation (NSF) ECCS-1150449 (CAREER), ECCS-1408511, and IIP-1448707 (SBIR); the Army Research Office (ARO) W911NF-15-1-0630 (STIR); J.H.K. acknowledges the support from Kwanjeong Educational Foundation (KEF) (12AmB06G).

REFERENCES