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Detailed Terms
High-temperature performance and broad continuous tunability of terahertz quantum-cascade lasers

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ABSTRACT

We demonstrate a terahertz quantum-cascade laser (QCL) operating significantly above the temperature of $h\nu/k_B$, which had so-far been been an empirical limitation for the maximum operating temperature of these devices. With a design that employs a new scattering-assisted injection scheme, a 1.8 THz QCL operating up to a temperature of 1.9$h\nu/k_B$ (163 K) is realized with more than 3 mW of peak optical power output at 150 K. We also demonstrate continuous tunability over a frequency range of 137 GHz of a single-mode QCL operating at 3.8 THz in metal-metal waveguides. A unique concept of altering the lateral mode profile of the “wire laser” waveguide geometry was implemented to achieve tuning despite the strong mode confinement of metal-metal waveguides at terahertz frequencies.

Keywords: terahertz, intersubband, tunable, quantum-cascade laser, tunable, phonon scattering

1. INTRODUCTION

High-power sources of terahertz radiation are required for applications in terahertz sensing, imaging, and spectroscopy such as identification of interstellar molecular species (in astronomy), remote monitoring of earth’s atmosphere, biomedical imaging, detection of concealed weapons, drugs, and explosives and so-forth.\textsuperscript{1–4} There have been significant advances in terahertz science and technology in the recent years.\textsuperscript{5, 6} From the various available sources of radiation, terahertz quantum-cascade lasers\textsuperscript{7} (QCLs) are the most promising among solid-state technologies. Terahertz QCLs are semiconductor lasers in which optical emission is due to intersubband transitions in the conduction band of semiconductor heterostructures (GaAs/AlGaAs or InGaAs/InAlAs). These devices now provide continuous-wave (cw) spectral coverage in the frequency range of 1.2 THz\textsuperscript{8} ($\lambda \sim 250 \mu m$) through $\nu \sim 5$ THz ($\lambda \sim 60 \mu m$) with optical power output in the tens of milliWatt range.\textsuperscript{9} In terms of optical power output, frequency linewidth, and frequency stability they are arguably at par with the much bigger and expensive molecular gas lasers. Additionally their emission frequency could be artificially adjusted by band-structure engineering, which makes them attractive for a variety of applications. However, cryogenic cooling is required for their operation which is the primary hindrance towards making a terahertz QCL available in a compact and inexpensive instrument.

The primary challenge for terahertz QCLs is to improve their maximum operating temperatures across the entire frequency range. A higher maximum operating temperature indicates a more robust QCL active medium with large gain, which is important for large output power or for robust temperature performance of the single-mode distributed feedback (DFB) lasers. Whereas pulsed operation above the technologically important liquid-Nitrogen temperature of 77 K has been demonstrated across the entire frequency range of 1.2 – 5 THz, single-mode cw operation above 77 K has only been demonstrated for $\nu \sim 3$ THz QCLs in which case the optical power output reduces to the order of 1 mW at 77 K.\textsuperscript{10, 11} Further improvement in design of the active regions is therefore necessary to be able to realize single-mode lasers with tens of milliWatt of optical power output at high temperatures for such sources to be practically useful.
Figure 1. (a) Maximum operating temperature ($T_{\text{max}}$) versus frequency for different terahertz QCLs across the frequency spectrum that operate without the assistance of a magnetic field. Previously reported terahertz QCLs relied on a resonant-tunneling (RT) assisted injection into the upper laser level, for which $T_{\text{max}} \sim h\nu/k_B$ is typically observed. However, a new scattering assisted (SA) injection scheme has comprehensively surpassed such a temperature limit and a 1.8-THz QCL operating up to $T_{\text{max}} \sim 1.9 \ h\nu/k_B$ has been realized. (b) Design bias conduction band diagram of the 1.8 THz QCL in GaAs/Al$_{0.15}$Ga$_{0.85}$As material system with scattering-assisted injection. The radiative transition is from $u \rightarrow l$ ($E_{ul} \sim 7.7$ meV). Electrons are injected into the upper laser level $u$ by electron-phonon scattering from the injector levels $i_1$ and $i_2$. The lower laser level $l$ is emptied by the resonant-phonon depopulation scheme.

A wide variety of terahertz QCL designs have been reported in literature. All the previously published terahertz QCLs rely on a resonant-tunneling (RT) injection scheme to populate the upper laser subband, for which the maximum temperature of operation $T_{\text{max}}$ scales approximately linearly with the design frequency, and has so-far empirically followed the relation $T_{\text{max}} \sim \nu k_B$ across different designs and operating frequencies as highlighted in Fig. 1(a). Consequently the best temperature performance is obtained at higher frequencies with $T_{\text{max}} \sim 186$ K for a 3.9 THz QCL. We recently surpassed the $T_{\text{max}} \propto \nu$ scaling behavior with a new scattering-assisted (SA) injection mechanism to obtain high-temperature operation even for the low-frequency designs. A 1.8-THz QC laser operating up to a value of $T_{\text{max}} \sim 163$ K $\sim 1.9 \ h\nu/k_B$ was realized and will be described subsequently in this article.

The best temperature performance for terahertz QCLs are obtained in metal-metal cavities, which provide optimum low-loss waveguiding for the terahertz optical mode and are compatible with the TM polarization requirement of the quantum-cascade lasers. However, owing to their sub-wavelength dimensions at terahertz frequencies, it has been very difficult to implement optical feedback from outside the resonator cavity, which is typically how frequency tunability is achieved for semiconductor lasers. Continuous frequency tunability of single-mode output is one of the primary requirement for high resolution sensing techniques such as heterodyne spectroscopy. Toward this goal, we have implemented a new tuning mechanism for terahertz QCLs which has allowed us to realize continuous frequency tunability in the range of 3.6 $\%$ of the center frequency for a 3.8 THz QCL, which is also described subsequently in this article.

2. SCATTERING-ASSISTED INJECTION DESIGN SCHEME

Terahertz QCLs with resonant-tunneling injection are typically designed with thick injector barriers with injection anticrossing $2\hbar\Omega$ kept in the range of 1 – 2 meV for optimum performance. This is in part due to the requirement of minimizing the parasitic current flow at low bias to prevent an early occurrence of negative-differential resistance (NDR) in the current-voltage ($I$-$V$) characteristics, since such a low-bias parasitic current flow constitutes a significant fraction of the overall current in such designs. This design limitation results in the current transport across the injector barrier being incoherent. Consequently the current depends sensitively
Figure 2. (a) Numerical computation of a three-well 3 THz QCL design similar to that in Ref. 18 with resonant-tunneling injection for different thicknesses of the injector barrier, where $2\hbar\Omega$ corresponds to injection anticrossing splitting energy. The current-density versus voltage curves are highlighted in red color (thick lines) in the bias region with positive population inversion prior to the occurrence of the negative-differential resistance. The results in (b) are similar to (a) except that the numerical results are now computed for the 1.8 THz scattering-assisted injection design of Fig. 1(b) for different values of intra-injector anticrossings (i.e., the energy splitting between the injector levels $i_1$ and $i_2$). Design parameters such as overall doping and the radiative oscillator strength are kept the same for calculations in (a) and (b) for a valid comparison.

Figure 3. (a) Pulsed light-current-voltage characteristics versus temperature for a 1.3 mm × 120 μm metal-metal ridge cavity QCL measured with a He-cooled InSb hot-electron bolometer, which has a high-frequency detection roll-off for $\nu > 2$ THz. Whereas the QCL predominantly emits at $\nu \sim 1.8$ THz (characterized by red color and bold lines), it also lases at $\nu \sim 4$ THz at low-bias due to an undesired radiative transition from $i \rightarrow u$ (shown in blue, attenuated by a factor of $\sim 20$ due to the detector roll-off). Absolute power is calibrated with a thermopile power-meter. The inset shows the threshold current density $J_{th}$ as a function of temperature $T$ for the low-frequency emission. (b) Normalized spectra of the same device measured with a He-cooled broadband Silicon bolometer with linear scans using a Nicolet Magna 850 Infrared spectrometer.
on dephasing scattering and hence is prone to be adversely affected by faster scattering rates at high temperatures. The scattering-assisted injection method shown illustratively in Fig. 1(b) avoids such a limitation on the thickness of the current limiting barrier (in this case, the intra-injector barrier) since the cascade-structure is designed to maximize current flow at a bias much higher than that for the $i-u$ alignment. Consequently, the resonant-tunneling current transport across the current limiting barrier is kept coherent even at higher operating temperatures, leading to higher gain in the active region. Fig. 2 shows numerical computation of $I-V$s for representative designs with (a) resonant-tunneling and (b) scattering-assisted injection respectively, where it could clearly be seen that a larger injector anticrossing leads to an early NDR only for resonant-tunneling injection scheme.

The designed QCL structure with scattering-assisted injection (labeled OWI185E-M1) was grown by molecular beam epitaxy with 185 cascaded periods, and a standard growth scheme yielding a $\sim 10 \mu m$ thick active region. In Fig. 1(b), starting from the injector barrier, the layer thicknesses in nm are $4.2/8.5/2.3/9.6/3.4/7.3/4.0/15.3$ with the barriers indicated in bold fonts. The widest well was n-doped to $2.05 \times 10^{16} \text{cm}^{-3}$ yielding an average doping of $5.7 \times 10^{15} \text{cm}^{-3}$ per QCL period. Metal-metal ridge lasers were fabricated and characterized as outlined in Ref. 13. Pulsed light-current-voltage characteristics and spectra for the QCL are shown in Fig. 3. The device lased predominantly at a frequency of 1.8 THz up to a maximum operating temperature of 163 K ($\sim 1.9 \hbar \nu/k_B$). 28 mW of peak optical power was detected at 10 K that reduced to $\sim 0.65$ mW at 160 K. The results in the power output and operating temperature for this QCL are significantly better than previous terahertz QCLs operating at similar frequencies$^{22,23}$ that are based on the resonant-tunneling injection mechanism, which is likely due to the large gain in this active medium.

The observed threshold current-density $J_{th}$ for 1.8 THz QCL, as plotted in the inset of Fig. 3, remains independent of the heat-sink temperature $T$ approximately up to 110 K, which is a significantly higher turn-on temperature than that for any of the previously reported terahertz QCLs. The weak temperature dependence of $J_{th}$ with temperature attests to the robust temperature performance of this design scheme, which is likely due to the fact that the intra-injector anticrossing for this design was $2\hbar \Omega \sim 3$ meV to keep the resonant-tunneling transport across the cascade structure coherent. Upon further optimization we expect further improvements in the maximum operating temperature of the design. This demonstration should be promising for future improvements in the active region of terahertz QCLs since it shows that variations in the quantum design can significantly alter the device performance. For example, a new extraction controlled quantum design was recently proposed that might promise further improvements in the temperature performance of terahertz QCLs.$^{24}$

Figure 4. (a) Schematic diagram of a metal-metal resonator cavity for terahertz QCLs. The vertical height of the cavity is typically 10 $\mu m$ and is much smaller than the wavelength of the guided optical mode. (b) An example finite element calculation for the two-dimensional propagating electromagnetic mode in a 13 $\mu m$ wide and 10 $\mu m$ tall metal-metal waveguide with GaAs semiconductor active region. At 3 THz the cavity dimensions are much smaller than the wavelength of the optical mode, and yet $\approx 80$% of the electromagnetic energy density is confined within the semiconductor.

3. CONTINUOUS TUNABILITY OF A TERAHERTZ WIRE LASER

Tunable terahertz QCLs are highly desired for applications in sensing and spectroscopy. For these applications, mode-hop-free continuous tuning is required, which is usually achieved by using an external-cavity grating. At terahertz frequencies, it is difficult to couple the beam diffracted from the grating back into the gain medium due to the long wavelengths associated with the terahertz frequencies compared to the sub-wavelength dimension of...
the emitting aperture. The difficulty is further exacerbated by the required cryogenic operation. As a result, continuous frequency tuning using an external-cavity grating has yet to be achieved. In addition, alternative electrical tuning by changing the refractive index due to temperature or due to a cavity-pulling effect only produces a relatively small fractional tuning (< 1%).

Metal-metal waveguides for terahertz QCLs have near unity mode confinement even for lateral dimensions much smaller than the wavelength, owing to a severe mode-mismatch for propagation inside the waveguide and in the free-space. Whereas this waveguide characteristic makes it difficult to implement external feedback into the cavity to implement conventional tuning techniques, it allows a lateral access to the waveguided mode by making the dimensions much smaller than the wavelength as shown in Fig. 4, without impacting the mode confinement severely. Such a laser device could essentially be called a “wire laser” whose transverse dimension $w \ll l$ the length. Recently, we implemented a unique method to tune the resonant-cavity mode of a terahertz wire laser, thereby realizing broad continuous frequency tunability for a terahertz QCL for the first time.16

![Figure 5. (a), (b) Device configuration for tuning a terahertz “wire laser”. A narrow metal-metal waveguide has a corrugation on one side to implement first-order distributed-feedback for single-mode operation. The resonant cavity mode is tuned by laterally moving a silicon plunger and a metallic plunger respectively towards the cavity. The electric-field profile at the device facet is shown at the narrowest cross section of the DFB structure. (d) Tuning results from a representative device. In the upper part, the threshold current-densities of the device at different frequencies are plotted. The lower part shows broadband tuning of this device over a frequency range of 137 GHz.](image)

In a uniform gain medium, the lasing frequency for a particular resonant mode is determined by its $\omega - k$ dispersion relation $k_z^2 + k_{\perp}^2 = \omega^2 \mu \epsilon$, where $k_z$ ($k_{\perp}$) is the component of the $k$-vector in the longitudinal (transverse) direction, $\omega$ is the frequency, $\mu = \mu_0$ is the vacuum permeability, and $\epsilon$ is the dielectric constant. The lasing frequency, $\omega = \omega_0$, of an already fabricated device can be tuned by changing the values of $k_z$, $k_{\perp}$, or $\epsilon$. Out of these three parameters, very little effort has been made to change $k_{\perp}$. This is because for most solid-state and semiconductor lasers, $\lambda$ is comparable, or often smaller than the transverse dimension of the cavity $w$. Consequently, little mode
leaks out in the transverse directions and very little change can be made to \( k_\perp \). However, terahertz QCLs based on metal-metal waveguides can be made with deep sub-wavelength widths, allowing manipulation of \( k_\perp \).

In a previous work,\textsuperscript{28} unexpected radiation patterns are attributed to a substantial fraction of the mode that travels outside of the wire laser. This unusual feature allows tuning of the lasing frequency by changing \( k_\perp \), which is realized by moving either a dielectric or a metallic “plunger”, close to the wire laser, as shown in Fig. 5. If a dielectric plunger is used (silicon in this case), as it is pushed towards the laser, it extracts the mode from the gain medium, effectively expanding the mode profile in the transverse direction, as shown in Fig. 5(a). Consequently, the value of \( k_\perp \) decreases and red-shift tuning is achieved. Similarly, if a metal plunger is used (gold in this case), \( k_\perp \) increases as the plunger is pushed towards the laser as the mode approaches cut-off in the transverse dimension as shown in Fig. 5(b), which then results in blue-shift tuning.

Figure 5 shows the schematic of the device design and the experimental results for a 3.8 THz QCL. In order to assure a continuous tuning of a single lasing mode, an asymmetric corrugation structure is used,\textsuperscript{29} with the flat side facing the plunger. The laser ridge had 12.5 \( \mu \text{m} \) average width, 3 \( \mu \text{m} \) sinusoidal grating modulation, 30 periods and a grating period of \( \Lambda = 13.7 \text{ \mu m} \). In the same fabrication process that defined the DFB laser ridges, rails perpendicular to the laser ridges to guide the plungers were also fabricated. During operations, the plunger was pressed down and could only be pushed forward towards the laser ridge. A red-shift tuning of 57 GHz and a blue-shift tuning of 80 GHz was achieved as shown in Fig. 5(d) resulting in a combined tuning of 137 GHz, or 3.6% of the 3.8 THz center frequency. The threshold current-density at different plunger positions is also plotted, which exhibits a moderate increase as either silicon or a metal plunger is pushed towards the laser ridge. Hence, a robust technique to realize continuous-frequency tuning of a single-mode terahertz QCL has been demonstrated. Future work will involve improvements to the mechanical design by designing a micro-electromechanical system based movable plunger for a more precise control of the plunger movement, which will allow broader tuning range than described here.

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