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Operation of a 1.8-THz Quantum-Cascade Laser Above 160 K

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Abstract: The maximum operating temperature of previously reported terahertz quantum-cascade lasers (QCLs) has empirically been limited to a value of $\sim \hbar\omega/k_B$. Here, we report a new design scheme for terahertz QCLs and achieve 163-K operation for a 1.8-THz QCL, which is a factor of 1.9 larger than $\hbar\omega/k_B$.

OCIS codes: (140.5965) Semiconductor lasers, quantum cascade; (140.3070) Infrared and far-infrared lasers

Terahertz quantum-cascade lasers (QCLs) operate on the principle of intersubband optical transitions and now provide spectral coverage from $\nu \sim 1.2-5.0$ THz ($\lambda \sim 250-60$ μm) with optical power output in the tens of milli-Watt range, and are poised to become one of the most important types of terahertz radiation source [1]. For these devices to be practicable, the foremost requirement is to improve their operating temperatures to that accessible by the present day thermoelectric coolers ($\gtrsim 240$ K), and ultimately to room temperature.

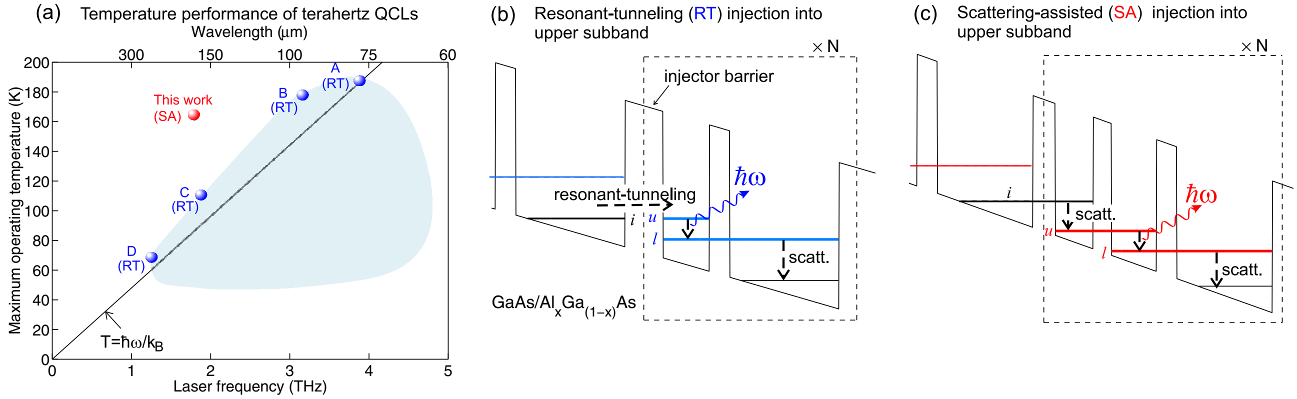

Fig. 1. (a) Maximum operating temperature ($T_{\max}$) versus frequency survey chart for terahertz QCLs (that operate without the assistance of a magnetic field), where the shaded area corresponds to a variety of reported designs [1]. The best reported terahertz QCLs in terms of $T_{\max}$ are indicated by markers A, B, C, D corresponding to Refs. [2, 3, 4, 5] respectively. All of the previously reported terahertz QCLs employ a resonant-tunneling (RT) assisted injection scheme as compared to a scattering-assisted (SA) injection scheme demonstrated in the present work. Illustrative band diagrams for both schemes are shown in (b) and (c) respectively, where the radiative transition is from subband $u \rightarrow l$, and i is the injector subband where most carriers are localized during operation.

The injector region in a QCL has a significant bearing on its quantum-transport and thereby critically affects the QCL's performance parameters. All the previously reported terahertz QCLs rely on *resonant-tunneling* (RT) as a means to inject carriers into the upper laser subband. A wide variety of designs have been reported, which, incidentally, have a common characteristic in that the maximum temperature of operation $T_{\max}$ has been empirically limited by $\sim \hbar\omega/k_B$ across all the operating frequencies as is shown in Fig. 1(a). Correspondingly, $T_{\max}$ for low-frequency ($\nu < 2$ THz) QCLs is typically much worse than the highest value of 186 K recently reported for a 3.9-THz QCL [2]. This behavior could be qualitatively understood from an illustrative band diagram for the RT assisted injection mechanism as shown in Fig. 1(b). At low-frequencies, the laser-level separation E_{ul} ($\sim \hbar\omega \sim 8$ meV for $\nu \sim 2$ THz) becomes similar to the typical energy broadening of the subbands (few meVs). Hence, it becomes difficult to selectively inject from $i \rightarrow u$ where i is the injector subband and u is the upper laser subband. The injector barrier is typically kept thick for low-frequency designs to limit $i \rightarrow l$ leakage-current, which, however, reduces the obtainable dynamic range in current for the laser and consequently its maximum operating temperature [4, 5]. In

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this paper, we show that this problem could be circumvented by utilizing a unique *scattering-assisted* (SA) injection mechanism as shown illustratively in Fig. 1(c). In this case, the cascade-structure is designed to maximize current flow at a bias much higher than that for the $i - u$ alignment. Consequently, potential barriers need not be made very thick to limit current flow that directly determines the amount of population inversion that could be established.

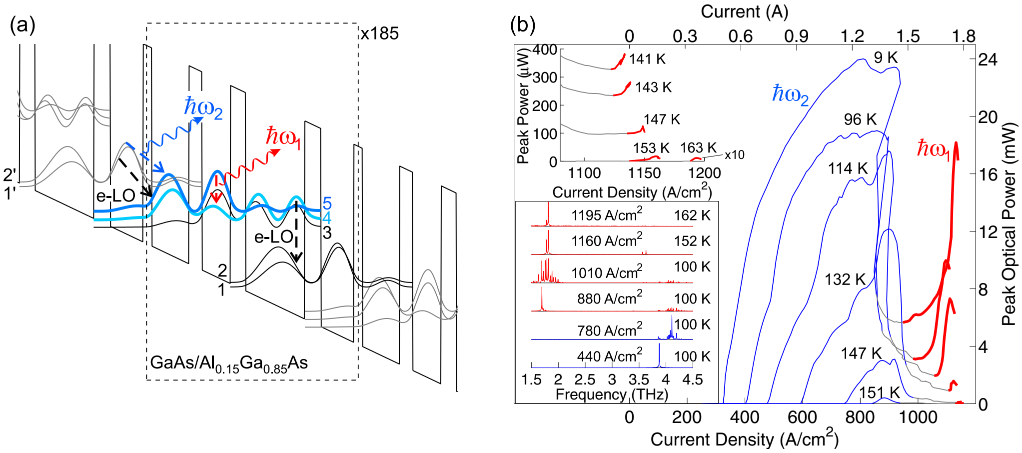

Fig. 2. (a) Operating-bias band diagram for the designed terahertz QCL structure with SA injection mechanism. The desired radiative transition is from $5 \rightarrow 4$. Subband 5 is populated from injector levels $1', 2'$ primarily through electron-longitudinal-optical (e-LO) scattering. Subband 4 is depopulated by the resonant-phonon [6] mechanism back into the injector levels. For this particular design, the $(1', 2') \rightarrow 5$ transitions also achieve population inversion and lasing as seen from the experimental results and an electrically switchable dual-color laser is realized. (b) Pulsed light-current (L-I) characteristics measured from a 120 μm $\times$ 1.3 mm metal-metal ridge laser. Details of device fabrication and characterization are similar to that in Ref. [2]. This device shows dual-color lasing at 4 THz and 1.8 THz respectively, which correspond to the radiative transitions as indicated by curvy arrows in (a). Thin lines in blue represent predominantly 4 THz optical power whereas bold lines in red correspond to the 1.8 THz photon energy, as is also evident from spectra shown in the bottom inset for some specific data points on the L-Is. The upper inset shows expanded version of the high-temperature L-Is.

A mid-infrared QCL has already been reported with a SA injection scheme [7]. However, the present report is the first time such a scheme has been implemented for terahertz QCLs. Details of the design and experimental results in pulsed operation are shown in Fig. 2(a) and Fig. 2(b) respectively. A wide variety of SA-injection designs are possible; our specific design has two-injector levels that are at resonance at the operating bias and prevent current flow at low-bias. As shown Fig. 2(b), this design in-fact achieves dual-color lasing at 4 THz ($T_{\max} \sim 151$ K) and 1.8 THz ($T_{\max} \sim 163$ K). The high frequency lasing is due to large carrier localization in the injector levels that develops a population inversion between the said levels and the upper subband of the low-frequency radiative transition (i. e. $(1', 2') \rightarrow 5$ as indicated by $\hbar\omega_2$ in Fig. 2a).

In conclusion, we report a new design scheme for terahertz QCLs to surpass the empirically observed limit $T_{\max} \sim \hbar\omega/k_{\mathrm{B}}$ and obtain much higher operating temperature than previously reported for a $\nu < 2$ THz QCL. Our particular design also demonstrates dual-color lasing at two widely different frequencies that are electrically controllable. Both of these developments are highly relevant for applications in terahertz spectroscopy, sensing, and imaging. This work is supported by AFOSR, NASA, and NSF. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the U.S. Department of Energy under Contract DE-AC04-94AL85000.

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