Room temperature, single-mode 1.0 THz nonlinear quantum-cascade laser

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***Abstract*—We demonstrate a single-mode 1.0 THz non-linear quantum-cascade laser based on long wavelength dual-upper-state (DAU) active region. The DAU structure enables to obtain high power output in the long-wavelength mid-infrared range in which very high nonlinear susceptibility can be realized. As a result, we have improved their device performance on the low frequency side and have recently demonstrated multi-mode sub-terahertz nonlinear quantum cascade lasers at room temperature. In this paper, we fabricate a device with two-section buried distributed feedback grating configuration, and it operates in a single-mode at a frequency of 1.03 THz. Besides, a THz peak output power of 18 μW is obtained at room temperature.**

I. INTRODUCTION

Terahertz quantum-cascade laser sources based on intra-cavity nonlinear mixing (THz NL-QCL) [1] are only electrically driven monolithic semiconductor light sources capable of operating at room temperature in the terahertz spectral range. Due to the enormous design flexibility of QCL active region structures, THz NL-QCL can be engineered to have giant second order nonlinear susceptibilities, these devices have expanded spectral coverage that extend over nearly the entire 0.6-6 THz range [2-5]. However, the performance of THz NL-QCLs on the low frequency side (<2 THz) has been significantly limited in terms of THz output power; this is because the outcoupled THz radiation is principally limited by the high absorption in the waveguide and the reduction of the THz conversion efficiency from two mid-infrared (MIR) pumps. Thus, the performance of THz NL-QCLs operating below 2 THz has not been sufficiently developed so far. Recent efforts in the wavefunction engineering using dual-upper-state (DAU) active region [6] led to a significant improvement in terms of device performance as well as the optical nonlinearity of the active region for efficient THz generation. As a result of this approach, we expand the frequency range down to the sub-THz region [5]. In our previous work, multi-mode THz generation has been demonstrated based on high-power, long-wavelength QCLs with the DAU active region that reduces optical absorptions and enhances nonlinear susceptibility, simultaneously. However, from a practical point-of-view, single mode operation is also required for several important applications, such as local oscillators for heterodyne detection. Here, we report a 1.03 THz single mode NL-QCL based on long wavelength DAU active region. The NL-QCL with two-section buried distributed feedback grating (DFB) configuration produces a THz peak output power of 18 μW at room temperature.

II. RESULTS

All the layer structures were grown on a semi-insulating (SI) InP substrate by the metal organic vapor phase epitaxy technique. The active region in our devices consisted of identical DAU structure with 70 stages, which possesses a broadband gain bandwidth, is designed for long-wavelength (λ~13.7 μm) and the details of the nonlinear active region design are described in ref. 5.

Figure 1(a) shows a Cherenkov waveguide with a schematic of two-section buried DFB configuration for THz NL-QCL via two-color MIR nonlinear mixing. THz emission Cherenkov angle to substrate θ_c defined as $\cos^{-1}(n_g / n_{sub})$, where n_g is the group index of the MIR pumps of this device and n_{sub} is the refractive index of the SI InP substrate, is estimated to be ~11° in our device, where we assume n_g~3.46 [5] and n_{sub}~3.52 [7]. The front facet of the device substrate was polished at ~20° in order to avoid total internal reflection of the Cherenkov wave and allow for THz outcoupling to the air. Figure 1(b) shows the result of a COMSOL simulation of a 1 THz NL-QCL with Cherenkov emission scheme. The nonlinear THz polarization waves are modeled by the difference frequency generation in which two MIR pumps (λ_1=13.6 μm and λ_2 =13.0 μm) are propagated in the active region. In this model, we define a propagation constant of nonlinear THz polarization wave (β_{THz}), $\beta_{THz} \sim n_g \omega_{THz}/c$, where ω_{THz} is the THz different-frequency and c is the light speed. The simulated result clearly shows that THz radiation is propagated in the forward direction from the device.

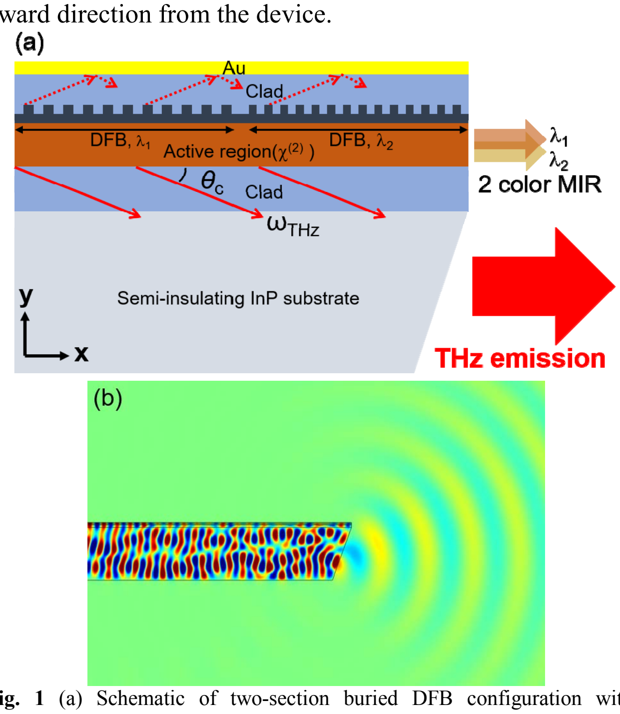

Fig. 1 (a) Schematic of two-section buried DFB configuration with a Cherenkov waveguide for non-linear THz-QCL. (b) Two-dimension COMSOL simulation of magnetic field (Hz) of the THz output from the device to the air.

Figure 2 shows the pulsed current-voltage-light output (I-V-L) characteristics of a 14 μm-wide, 3 mm-long device for THz and MIR at room temperature. THz output power collected by high-resistivity hyperhemispherical Si lens was detected using a liquid helium-cooled Si bolometer. The MIR output power was gathered by two off-axis parabolic mirrors and measured with a calibrated thermopile detector. Despite the long wavelength MIR range, the QCL device exhibits a MIR peak power of 0.75 W at room temperature (combined power of the λ_1 and λ_2 pumps). Simultaneously, a peak THz power of approximately 18 μW was obtained together with the inferred MIR-THz power conversion efficiency of ~270 μW/W^2; this is significantly improved, compared with the results of single mode THz NL-QCLs below 2 THz [8].

Spectral measurement results using a Fourier transform infrared (FTIR) spectrometer for THz and MIR are shown in figure 3. A narrow linewidth, single-mode operation is obtained around 1 THz at room temperature. Two single-mode MIR emissions at λ_1 of 13.6 μm (733.2 cm^{-1}) and λ_2 of 13.0 μm (767.6 cm^{-1}) with a frequency spacing of 1.03 THz (34.4 cm^{-1}) were observed. The frequency of the single-mode THz spectrum was in very good agreement with the spacing of the two MIR pump spectra. The side mode suppression ratio (SMSR) of the THz emission was achieved ~25 dB.

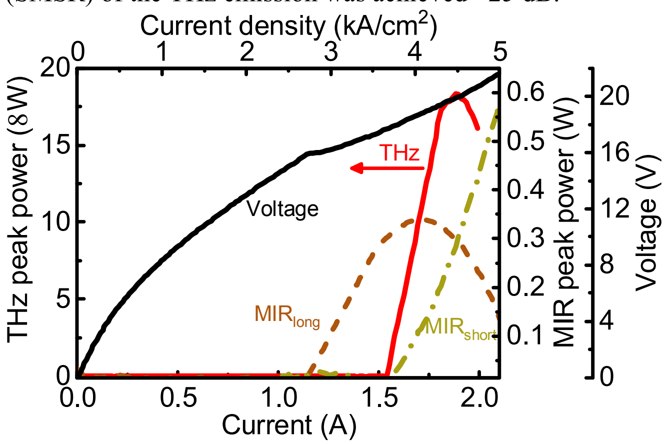

Fig. 2 Pulsed current-voltage-light output characteristics of a 3.0 mm-long, 14 μm wide device for THz and MIR peak power at room temperatures.

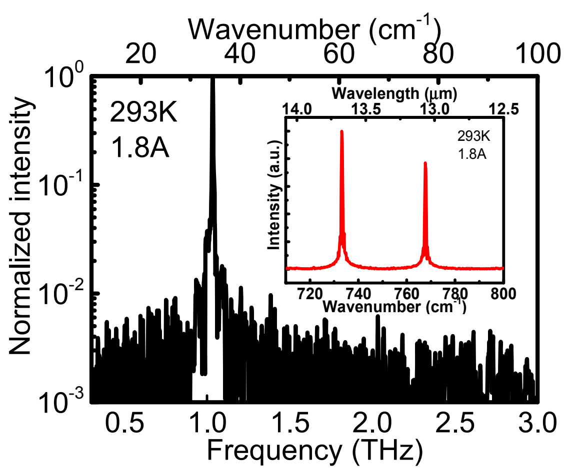

Fig. 3 The THz emission spectrum at room temperature. Inset shows room temperature MIR emission spectrum.

III. CONCLUSION

In conclusion, we demonstrated room temperature single mode THz emission around 1.0 THz from a NL-QCL with a long wavelength DAU active region. In the results, room temperature, single-mode operation with a THz peak of ~18 μW was achieved at room temperature with a SMSR of ~25 dB. The narrow free-running linewidth (LW) of ~1 kHz has been measured for THz NL-QCL, using high-resolution heterodyne technique with THz frequency comb [9]. Such THz single-mode spectrum is highly suitable for the use of local oscillators for heterodyne detection, when CW operation will be achieved. In the future, further improvement in performance can be achieved by the adoption of some efficient THz extraction schemes [10, 11], which would produce THz sub-mW output power at room temperature. These high-performance THz NL-QCLs will open up a new opportunity for many THz applications.

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REFERENCES

[1] M. A. Belkin, F. Capasso, A. Belyanin, D. L. Sivco, A. Y. Cho, D. C. Oakley, C. J. Vineis, and G. W. Turner, "Terahertz quantum-cascade-laser source based on intracavity difference-frequency generation," *Nature Photonics*, vol. 1, pp. 288-292, 2007.

[2] M. A. Belkin and F. Capasso, "New frontiers in quantum cascade lasers: high performance room temperature terahertz sources," *Phys. Scr.* vol. 90, 118002, 2015

[3] M. Razeghi, Q. Y. Lu, N. Bandyopadhyay, W. Zhou, D. Heydari, Y. Bai, and S. Slivken, "Quantum cascade lasers: from tool to product," *Opt. Express* vol. 23, no.7, pp8462-8475, 2015.

[4] K. Fujita, S. Jung, Y. Jiang, J. H. Kim, A. Nakanishi, A. Ito, M. Hitaka, T. Edamura, and M. A. Belkin, "Recent progress in terahertz difference-frequency quantum cascade laser sources," *Nanophotonics*, vol. 7, no. 11, pp. 1795–1817, 2018.

[5] K. Fujita, S. Hayashi, A. Ito, M. Hitaka, T. Dougakiuchi, "Sub-terahertz and terahertz generation in long-wavelength quantum cascade lasers," *Nanophotonics*, vol. 8, no. 12, pp. 2235–2241, 2019.

[6] K. Fujita, M. Hitaka, A. Ito, T. Edamura, M. Yamanishi, S. Jung, and M. A. Belkin, "Terahertz generation in mid-infrared quantum cascade lasers with a dual-upper-state active region," *Appl. Phys. Lett.* vol. 106, pp. 251104, 2015.

[7] L. N. Alyabyeva, E. S. Zhukova, M. A. Belkin, and B. P. Gorshunov, "Dielectric properties of semiinsulating Fe-doped InP in the terahertz spectral region," *Scientific Reports* vol. 7, 7360, 2017.

[8] Y. Jiang, K. Vijayraghavan, S. Jung, F. Demmerle, G. Boehm, M. C. Amann, and M. A. Belkin, "External cavity terahertz quantum cascade laser sources based on intra-cavity frequency mixing with 1.2-5.9 THz tuning range," *J. Opt.,* vol. 16, pp. 094002, 2014.

[9] L. Consolino, S. Jung, A. Campa, M. De Regis, S. Pal, J. H. Kim, K. Fujita, A. Ito, M. Hitaka, S. Bartalini, P. De Natale, M. A. Belkin, and M. S. Vitiello, "Spectral purity and tunability of terahertz quantum cascade laser sources based on intracavity difference-frequency generation," *Sci. Adv.* vol. 3, e1603317, 2017.

[10] J. H. Kim, S. Jung, Y. Jiang, K. Fujita, M. Hitaka, A. Ito, T. Edamura, and M. A. Belkin, "Double-metal waveguide terahertz difference-frequency generation quantum cascade lasers with surface grating outcouplers," *Appl. Phys. Letters* vol. 113, 161102, 2018.

[11] S. Jung, J. H. Kim, Y. Jiang, K. Vijayraghavan, and M. A. Belkin, "Terahertz difference-frequency quantum cascade laser sources on silicon," *Optica*, vol. 4, no. 1, pp. 38-43, 2017.