High-power terahertz quantum-cascade lasers

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Introduction: Terahertz quantum-cascade lasers (QCLs) have now been demonstrated at frequencies of 1.9–5.0 THz (λ = 60–160 μm) [1–3], and are important additions as compact, coherent sources in a spectral region that has long lacked convenient and efficient sources. In particular, these continuous-wave (CW) lasers are well suited for use as local oscillators (LO) in heterodyne receivers [4, 5]; this is significant because harmonic multipliers, commonly used as LO sources above 300 GHz, cannot deliver more than microwatt power above 2 THz. Molecular gas lasers are also used to provide tens of milliwatts of CW power at various fixed frequencies sprinkled throughout the terahertz region, but they are somewhat large and unwieldy and require some effort to maintain their stability. While single-pixel heterodyne systems do not require much more than a milliwatt of terahertz LO power, imaging or spectroscopy applications that involve illuminating many pixels, or that require significant material penetration or travel through air would benefit tremendously from much higher power terahertz sources. Resonant-phonon terahertz QCLs have recently been demonstrated up to temperatures of 164 K in pulsed mode and 117 K in CW mode [6] with the use of ‘metal–metal’ waveguides. Because of their subwavelength size in the transverse and lateral dimensions, these waveguides tend to have large facet reflectivities (0.7–0.9, depending on the dimensions relative to the wavelength [7]), which leads to relatively low output powers (<10 mW). The terahertz QCLs which have displayed the largest peak output powers (~90 mW) have been based on bound-to-continuum active region designs, and have used semi-insulating (SI) surface-plasmon waveguides [8, 9], which are characterised by a larger transverse mode profile (confinement factor Γ ~1–0.5) and do not appear to exhibit enhanced facet reflectivity [7]. In this Letter, we report the demonstration of terahertz QCLs which emit 248 mW peak power in pulsed operation at ~4.4 THz, and up to 138 mW of power in CW operation.

Design and fabrication: The lasers described in this Letter are based upon the resonant-phonon active region design, in which a combination of resonant tunnelling and fast longitudinal-optical phonon scattering selectively depletes the lower radiative state [10]. The active region design is similar to that described in [6] which lased at 2.9 THz. The thicknesses of the eight layers in a module are (with the barriers in bold) 48/82/17/68/40/164/34/90 Å in the A and the 164 Å well is bulk doped with Si at 1.9 × 1012 cm–3. Along with some modifications to the injector, the major change was to thin the 25 Å radiative barrier to 17 Å, which increased the energy separation (anticrossing) between the two radiative states to obtain a larger photon energy (calculated as 19.0 mV). This laser was intended to emit near the neutral oxygen line at 4.7 THz, which is the primary coolant of interstellar dust and therefore of great interest to the astrophysics community.

The structure, labelled FL183R-2 (EA1229), was grown in the GaAs/Al0.15Ga0.85As material system by molecular beam epitaxy with 183 capped contacts. The waveguides process consisted of SI surface-plasmon waveguide ridge structures as described in [10], with the exception that the heavily doped layer under the active region was 0.4 μm thick and doped at n = 3 × 1018 cm–3, and the ridges were dry etched to obtain nearly vertical sidewalls. An undoped 100 nm Al0.35Ga0.65As etch-stop layer was grown underneath the doped contact to allow the option of metal–metal waveguide processing. Finally, the devices were lapped to a substrate thickness of ~170 μm, ridges were cleaved, and an Al2O3/Ti/Au/AlOx high-reflectivity (HR) coating was evaporated on the rear facet of selected devices. The mode was calculated using a one-dimensional Drude model solver (Fig. 1), which gave a value of x0 = 3.9 cm–1 for the waveguide loss and a confinement factor of Γ = 0.26. A two-dimensional finite-element solver gave similar values of x0 = 3.0 cm–1 and Γ = 0.21 for the fundamental mode in a 200-μm-wide ridge [7].

Results: A 198 μm-wide, 1.21 mm-long, HR-coated ridge was mounted in a vacuum cryostat and a Winston cone was used to collect light from the laser facet and bring it to the polycrystalline Dewar window. The device was biased with pulse trains of 200 ns pulses repeated at 100 KHz, modulated by a 1 KHz square wave for an overall duty cycle of 1%. The output power was measured with a pyroelectric detector, with the peak level calibrated by a thermopile power meter (ScienTech model AC2500H). The collected peak output power against current is shown in Fig. 2, along with several typical spectra. At 5 K, Jth = 530 A/cm2 in pulsed mode with a maximum peak power of 248 mW, and lasing was observed up to 105 K. Because of the large power dissipation in this device, the maximum power observed in CW operation was reduced to 138 mW, and lasing ceased at a heatsink temperature of 35 K. Somewhat more efficient CW performance was obtained from a 98 μm-wide, 2.15 mm-long HR coated structure, as the narrower ridge provided a more efficient geometry for heat removal (see Fig. 3). A maximum CW power of 123 mW was collected at 10 K (wall-plug efficiency ~0.5%) compared to a peak pulsed power of 135 mW, and lasing continued up to a maximum temperature of 40 K. The slightly higher CW operating temperature is significant for practical applications. Using a closed-cycle pulsed tube cryocooler with a few watts of cooling power at 30 K (Cryomech PT60), this laser produces ~50 mW of power, which is essential for real-time imaging using focal-plane array cameras [11]. Although Jth in these devices is significantly larger than in bound-to-continuum QCLs [9], these devices also have a large dynamic current range of ~400–500 A/cm2 above threshold, which results in large output powers.

In pulsed mode, the slope efficiency was measured to be dL/dI = 300 mW/A, or a value of ~340 mW/A after accounting for the 85–90% transmission of the Dewar window. This is equivalent to a differential quantum efficiency (DQE) of approximately 18 photons per injected electron. The DQE is more than a factor of three larger than that observed from the best metal–metal waveguide devices [6]. This is a result of the larger out-coupling factor for the SI-surface-plasmon...
waveguide, calculated to be $a_m/(a_m + a_w) = 0.6$ (using a mirror loss of $a_m = 4.7 \text{ cm}^{-1}$). Although metal–metal waveguides have similar or better values for the scaled waveguide loss $a_m/\Gamma$ (which determines threshold gain), they exhibit a larger loss $a_m$ (because $\Gamma \sim 1$), and smaller $a_w$ (because of their high facet reflectivity), and thus typically display $a_m/(a_m + a_w) \sim 0.1$. If we consider these calculated loss values, along with an approximate value of $\eta = 0.5$ for the internal quantum efficiency [6], we find that the measured slope efficiency is still a factor of three less than we might expect. While it is likely that we have underestimated the power somewhat owing to non-ideal collection efficiency, this result suggests that the waveguide losses in the SI-surface-plasmon waveguides may be larger than calculated. This conclusion is bolstered in that, when devices from this wafer were fabricated into metal-metal waveguide ridges (not shown), they exhibited typical thresholds of $J_{th} = 370 \text{ A/cm}^2$, which reflects the larger scaled waveguide and mirror losses $(a_m + a_w)/\Gamma$ in the SI-surface-plasmon waveguides. In any case, improvements in waveguiding, output mode coupling, and reduction in lasing thresholds should enable terahertz QCLs with even higher output powers and efficiencies in the future.

**Fig. 3** Voltage against current at 10 K and collected CW light against current characteristics for HR coated 98 $\mu$m x 2.15 mm ridge at various heatsink temperatures

**Acknowledgments:** This work is supported by AFOSR, NASA, and NSF. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the US Department of Energy under contract no. DE-AC04-94AL85000.

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8 November 2005

Electronic Letters online no: 20063921
doi: 10.1049/el:20063921

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**References**