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# Terahertz quantum cascade lasers with >1 W output powers

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Terahertz (THz) frequency quantum cascade lasers emitting peak powers of >1 W from a single facet in the pulsed mode are demonstrated. The active region is based on a bound-to-continuum transition with a one-well injector, and is embedded into a surface-plasmon waveguide. The lasers emit at a frequency of ~3.4 THz and have a maximum operating temperature of 123 K. The maximum measured emitted powers are ~1.01 W at 10 K and ~420 mW at 77 K, with no correction made to allow for the optical collection efficiency of the apparatus.

*Introduction:* Terahertz (THz) frequency radiation has many potential applications, ranging from imaging and chemical sensing through to telecommunications [1, 2]. However, one of the principal challenges is to develop compact, low-cost, efficient THz sources. In this respect, the development of the THz quantum cascade laser (QCL) has provided a potential solid-state solution [3]. Nonetheless, for many remote sensing and imaging applications, high optical powers are desirable, in part owing to the significant attenuation of THz radiation by water vapour in the atmosphere. Recently, the THz QCLs have been demonstrated with peak pulsed output powers ($P_{peak}$) of up to 470 mW per facet, using a direct wafer-bonding technique to stack two separate THz QCLs together, thereby increasing the active region and waveguide thickness [4]. This approach, however, requires the QCL to have a symmetric active region, limiting the widespread applicability of the technique. In general, increased output powers can be obtained, in the conventional interband semiconductor lasers and mid-infrared QCLs [5–7], by using longer and broader area cavities, with a $P_{peak}$ of up to 120 W achieved in the broad area mid-infrared QCLs [7]. In this Letter, we demonstrate the broad area high-power THz QCLs operating in the pulsed mode with an emission frequency of around 3.4 THz. The devices deliver a $P_{peak}$ of up to 1.01 W from a single facet at 10 K. This is the first demonstration of THz QCLs with $P_{peak}$ exceeding 1 W.

*Experimental details:* The QCL active region design is based on a bound-to-continuum transition with a one-well injector, and is similar to that reported in [8]. It consists of an $Al_{0.16}Ga_{0.84}As/GaAs$ heterostructure with a layer sequence of **52**/103/**17**/107.5/**36**/88/**39.5**/<u>172</u> (starting from the injector barrier) where the thicknesses are in Å, $Al_{0.16}Ga_{0.84}As$ barriers are in bold, and the Si-doped layer ($3 \times 10^{16}$ cm$^{-3}$) is underlined. For the designed electric field of 7.6 kV/cm, lasing is expected at ~3.4 THz.

The QCL structure was grown by solid-source molecular beam epitaxy on a semi-insulating GaAs substrate. The complete structure consists of a 250 nm undoped GaAs buffer layer, an undoped 300 nm $Al_{0.5}Ga_{0.5}As$ etch-stop layer, a 600 nm Si-doped GaAs layer ($3.5 \times 10^{18}$ cm$^{-3}$), 180 periods of the active region and a 50 nm heavily Si-doped ($5 \times 10^{18}$ cm$^{-3}$) GaAs contact layer. Immediately prior to the QCL growth, the GaAs and AlAs growth rates were measured using an *in situ* kSA BandiT spectrometer to calibrate precisely the growth layer thicknesses and aluminium composition [9]. Based on high-resolution X-ray diffraction measurements, this growth protocol, along with a growth rate self-compensation during the 10 h growth period, allows the structure thickness to be controlled to within 0.5% of the designed values.

The THz QCLs were processed into the surface-plasmon ridge waveguide structures using standard photolithography and wet chemical etching techniques. Ridges with widths ($w$) ranging from 145 to 425 μm were formed, and the substrate was thinned to ~180 μm by wet chemical etching. For measurement, the devices were cleaved and indium-soldered to copper submounts.

The THz QCLs were characterised in the pulsed mode, with a repetition rate of 10 kHz and a duty cycle of 2%, in a liquid-helium continuous-flow cryostat equipped with 1.5 mm-thick polyethylene windows. The radiation was collected from a single facet and the power was measured using an absolute terahertz power meter (Thomas Keating), which was butted against the cryostat window. Unlike earlier reports of high-power THz QCLs [10, 11], neither a light-pipe nor a Winston core was used here despite a separation of ~3.5 cm between the power meter and the device facet. Furthermore, no correction to the collection efficiency is applied to any of the powers reported in this Letter.

*Results:* Fig. 1 shows the dependencies of the measured $P_{peak}$ on both the ridge width and the cavity length for the as-cleaved devices at a heatsink temperature of 10 K. The power scales linearly with the ridge width, similar to the observations in [7]. For the devices with a cavity length of 1.5 mm, the scaling factor $dL/dw$ ~0.98 mW/μm, where $L$ is the emitted power, whereas for the devices with a cavity length of 1 mm, the scaling factor is ~0.60 mW/μm. The effective mirror losses from the device facets, which scale inversely with the cavity length, are likely to be responsible for this difference. Similarly, the emitted power scales with the cavity length. A $P_{peak}$ of up to ~780 mW was obtained from a device with a 3 mm-long cavity and a 425 μm-wide ridge.

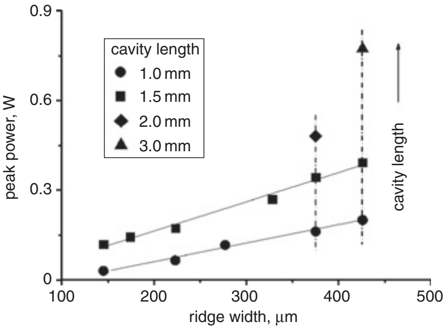


**Fig. 1** *Dependencies of measured power on ridge width and cavity length for as-cleaved devices at heatsink temperature of 10 K*

Fig. 2 shows the typical output power–current–voltage ($LIV$) characteristics of the 3 mm × 425 μm device against heatsink temperature. A maximum operation temperature of 123 K was obtained. At 77 K, the device still delivered a $P_{peak}$ of ~420 mW. Fig. 2 (inset) shows the dependence of the $P_{peak}$ on the distance from the cryostat window (in a nitrogen-purged atmosphere). A linear fit was observed empirically, suggesting that if the power meter was positioned closer to the laser facet (similar to [4]), a further increase in the single-facet power would be expected. Nevertheless, by taking the radiation from both the facets into account, a value for the $P_{peak}$ of ~780 mW at 10 K leads to a wall-plug efficiency of ~1.4% and a slope efficiency of $dL/dI \simeq 435$ mW/A. This slope efficiency is equivalent to a differential quantum efficiency of ~31 photons per injected electron – a factor of ~1.7 larger than that reported in [11], which is likely to be a result of the different active region design and/or the optimised device growth.

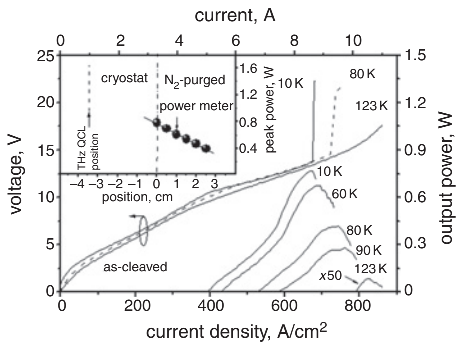


**Fig. 2** *Typical current–voltage–output power characteristics of as-cleaved device (3 mm × 425 μm)*

Inset: Dependence of $P_{peak}$ on distance from device (nitrogen-purging is used outside the cryostat)

To increase the emitted power from a specific facet, a high-reflectivity coating can be applied to the opposite facet [6]. We coated the rear facet with $SiO_2$(150 nm)/Ti(10 nm)/Au(150 nm)/$SiO_2$(200 nm), deposited by an electron beam evaporator. Fig. 3 shows the output power against current density from a 425 μm-wide, 4.2 mm-long, facet-coated device. A $P_{peak}$ of ~1.01 W (at 10 K) is obtained from the front facet, at a frequency of ∼3.4 THz (Fig. 3, inset), and the device operated to a maximum heatsink temperature of 118 K. With the increasing current, the lasing spectra show a multimode behaviour, and both broaden significantly and shift to higher frequencies. Owing to the wide ridges, the lateral modes are also present in the lasing spectra. It should be noted that this lasing frequency is ∼0.5–1 THz lower than the THz QCLs reported in [4, 11]. An increase in the emitted power would be expected if the QCL design was scaled to higher frequencies [12], and indeed the highest reported peak powers for THz QCLs operating at ∼3.1 THz are only ∼110 mW to date [13].

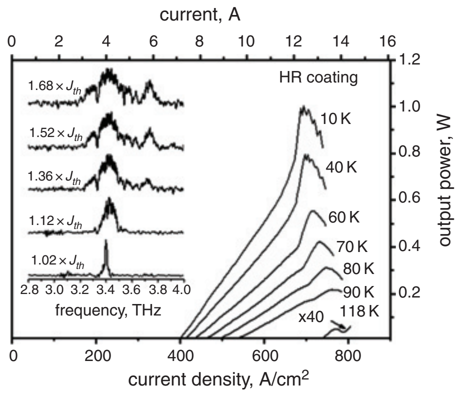


**Fig. 3** *Output power against current from rear facet-coated device (4.2 mm × 425 μm)*

Inset: Typical lasing spectra for different device current densities at 10 K

*Conclusion:* We have realised broad area high-power THz QCLs with $P_{peak}$ exceeding 1 W at 10 K from a single facet, uncorrected for the collection efficiency of the measurement apparatus. Furthermore, at 77 K, a $P_{peak}$ value of ∼420 mW was obtained.

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