Multi-Watt high-power THz frequency quantum cascade lasers

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Multi-Watt high-power terahertz (THz) frequency quantum cascade lasers are demonstrated, based on a single, epitaxially grown, 24-μm-thick active region embedded into a surface-plasmon waveguide. The devices emit in pulsed mode at a frequency of ∼4.4 THz and have a maximum operating temperature of 132 K. The maximum measurable emitted powers from a single facet are ∼2.4 W at 10 K and ∼1.8 W at 77 K, with no correction being made for the optical collection efficiency of the apparatus, or absorption by the cryostat polyethylene window.

Introduction: Terahertz (THz) frequency radiation has many potential applications, ranging from imaging, bio- and chemical-sensing, and non-destructive testing, through to security scanning, industrial process monitoring, and 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) provides a potential solid-state solution [3]. Nevertheless, for many remote sensing and imaging applications, for example, real-time measurement using a THz camera, high optical powers are desirable [4]. In addition, a high-power THz source is attractive for the investigation of non-linear physics at THz frequencies.

In general, increased output powers can be obtained, in both conventional interband semiconductor lasers and mid-infrared QCLs, by using broader area cavities [5]. Relying on this strategy, we previously demonstrated 1.01 W peak output powers (P_{peak}) from a broad-area THz QCL [6]. However, scaling the device area to an even larger value leads to difficulties in managing the significant Joule heating and random filamentation [5]. As an alternative, the power can be increased by increasing the active region thickness, i.e. the number of cascade periods [7]. Indeed, THz QCLs with P_{peak} of up to 470 mW per facet at 5 K have been demonstrated, using a direct wafer-bonding technique to stack two separate 10-μm-thick THz QCLs together, thereby increasing the active region thickness [8]. This approach, however, requires the QCL to have a symmetric active region, limiting widespread applicability of the technique. In this Letter, we demonstrate multi-Watt high-power THz QCLs with a 24-μm-thick active region, grown in a single epitaxial growth. The devices operate in pulsed mode with emission at a frequency of ∼4.4 THz and deliver P_{peak} up to ∼2.4 W at 10 K and ∼1.8 W at 77 K.

Experimental details: The QCL active region design is similar to that reported in [6, 9] but with rescaled layer thicknesses to enable higher frequency emission. The 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 (3.5×10^{18} cm^{-3}) GaAs layer, 410 periods of the active region, and a 50 nm heavily Si-doped (5×10^{18} cm^{-3}) GaAs top contact layer. Half way through the active region, a 50 nm highly Si-doped (5×10^{18} cm^{-3}) AlAs layer was inserted. The function of this thin AlAs layer is two-fold: Firstly, it re-sets the pyrometric oscillations for growth rate monitoring [10], and secondly, it enhances the optical confinement factor [8]. After growth, the QCL wafer was processed into surface-plasmon ridge waveguide structures using photolithography and dry etching. To improve heat dissipation, the substrate was thinned to ∼180 μm by wet chemical etching.

For measurement, devices were cleaved, wire bonded and indium-soldered to copper submounts. In order to increase the emitted power from the front facet, some of the devices were coated on the rear facet by SiO_2(150 nm)/Ti(10 nm)/Au(150 nm)/SiO_2(200 nm) high-reflectivity (HR) layers, deposited using an electron beam evaporator. The details of the device measurements can be found in Ref. [6]. To reduce Joule heating, a duty cycle of 1% (pulse width of 1 μs) was used here, which is the only difference from the experimental approach in [6], where a 2% duty cycle was used. We emphasise that neither a light-pipe nor a Winston core was used to enhance the light collection efficiency. Furthermore, no correction for the optical collection efficiency of the apparatus or the transmission of the cryostat polyethylene window (measured separately to be 79%) was applied, although these factors have been considered elsewhere [11–13].

Results: Fig. 1 shows the typical output power–current–voltage (LIV) characteristics of an as-cleaved device (of lateral dimensions 4.2 mm × 425 μm) as a function of heat sink temperature. At 10 K, the device delivered a P_{peak} of ∼2.3 W (single facet), limited to an injection current density of 1180 A/cm^2 by the power supply used. Smaller devices reached maximum power at a current density of 1280 A/cm^2, suggesting a higher value of P_{peak} ought to be possible. Nevertheless, taking account of the radiation from both facets and the polyethylene window absorption, a total output power >5.7 W could be anticipated. Around the maximum injection current, a slope efficiency of ∼1.64 W/A is obtained, which is equivalent to a differential quantum efficiency of ∼90 photons per injected electron – a factor of ∼3 larger than that reported in [6], which is most likely to be a result of increasing the number of cascade periods by a factor of 2, compared with ref. [6].

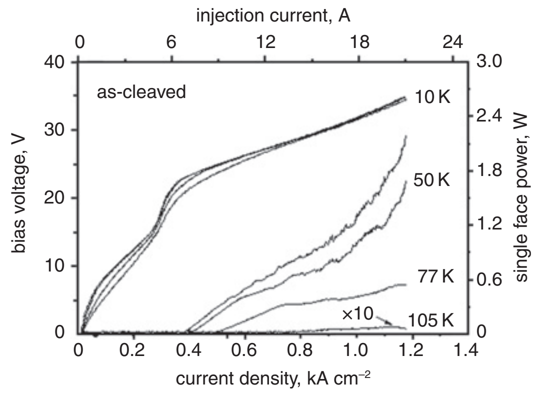

Fig. 1 *Typical LIV curves of as-cleaved device (4.2 mm × 425 μm)*

Fig. 2 shows the output power as a function of injection current density from a 425-μm-wide, and 3.6-mm-long, HR facet-coated device. A P_{peak} of ∼2.4 W at 10 K and ∼1.7 W at 77 K is obtained from the front facet. This is the first demonstration of Watt-level THz QCLs at 77 K. The devices operated to a maximum temperature (T_{max}) of 125 K, at a frequency of ∼4.4 THz (see Fig. 2, inset). At 10 K, the threshold current density (J_{th}) was measured to be 359 A/cm^2. With increasing injection current density, the lasing spectra show multi-mode behaviour, and the spectral emission both broadens significantly and shifts to higher frequencies. Owing to the wide ridges, lateral modes are also present in the lasing spectra. These observations are very similar to those in the previously reported broad-area devices [6].

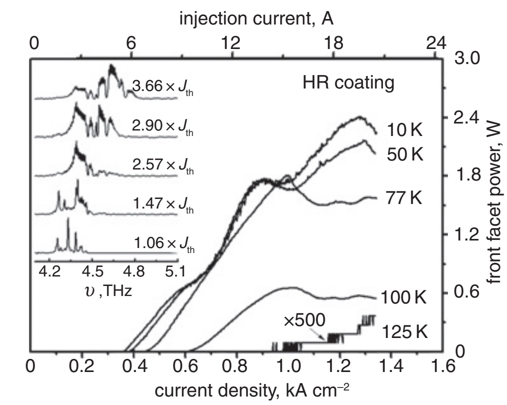

Fig. 2 *Output power as function of current density from rear-facet-coated device (3.6 mm × 425 μm). Inset: typical lasing spectra for different device current densities at 10 K*

Table 1 summarises the performances of devices with different configurations, i.e. dimension and/or HR coating. Most of the broad-area devices deliver >2 W output power at 10 K. Even for a smaller area device (1.5 mm × 150 μm), a P_{peak} of ∼460 mW at 10 K is obtained. This value is compared with that obtained from a wafer-bonded device with similar dimensions (2.5 mm × 120 μm), reported in [8], where the absolute output power was determined by a calibrated thermopile detector mounted inside the cryostat. In that case, the polyethylene window absorption does not reduce the measured power. It is notable that T_{max} and P_{peak} at 77 K are both significantly enhanced with the HR coating present, but there is relatively little enhancement of P_{peak} at 10 K. We tentatively attribute this phenomenon to a highly saturated gain at lower temperatures for these broad-area devices which results in mirror losses having only a small effect on the output power. The maximum T_{max} of 132 K and maximum P_{peak} of ~1.8 W (at 77 K) are both obtained from an HR-coated device with a ridge width of 375 µm and a cavity length of 3.8 mm.

Table 1: Summary of performance of devices with different dimensions, with and without HR facet coating

Device	Length, mm	Width, µm	HR coating	T_{max}, K	P_{peak} (10 K), W	P_{peak} (77 K), W
D1	4.2	425	no	105	2.25	0.62
D2	3.6	425	yes	125	2.40	1.69
D3	3.8	375	no	100	2.01	1.01
D4	3.8	375	yes	132	2.08	1.78
D5	2.6	325	no	130	1.67	0.98
D6	1.5	150	no	123	0.46	0.30

Conclusion: We have realised multi-Watt high-power THz QCLs (based on a 24-µm-thick active region) with P_{peak} up to 2.4 W at 10 K from a single facet, uncorrected for the collection efficiency of the measurement apparatus or absorption of the cryostat polyethylene window. Furthermore, at 77 K, a maximum P_{peak} value of ~1.8 W was obtained.

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One or more of the Figures in this Letter are available in colour online.

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