Integrating THz quantum cascade lasers with flexible dielectric-lined hollow metallic waveguides: Moving beyond free space optics

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***Abstract*—We demonstrate a THz optical delivery system capable of supplying a low divergence HE_{11} Gaussian beam at a distance of >500mm from the facet of a THz quantum cascade laser. This is achieved by optimising the optical coupling to an external hollow flexible polystyrene-lined Ag waveguide, by utilising a monolithically integrated cylindrical metal waveguide in the laser mounting block. This is shown to achieve >80% coupling efficiency between the two waveguides, whilst maintaining the spectral integrity of the laser. A comparison with other excitation geometries, such as bare laser excitation, as well as a laser with a facet coupled silicon lens, is also analysed.**

I. INTRODUCTION

THE terahertz (THz) quantum cascade laser (QCL) [1] has become integral to a wide range of applications requiring compact, robust and high power emission, including imaging, spectroscopy, and sensing. However, a primary challenge for its implementation is the ability to produce well collimated, repeatable, Gaussian-like emission over useful distances (>10s mm), external to the housing cryostat. To date, this has proved elusive without the need for multiple free space optical components, which can be time consuming to implement, introduce unnecessary absorption and reflection losses, and are susceptible to alignment errors. With the maturity of many types of THz waveguide in recent years, an alternative approach has been envisaged, whereby waveguided QCL power replaces free space guiding, producing a simple, controlled, 'plug and play' optical delivery system.

In general, material losses in the THz range are non-negligible, and as such, traditional solid core fibres on the whole perform poorly in terms of intrinsic losses. To overcome this, various alternative fibres have been demonstrated, including photonic bandgap, porous and hollow core designs [2]. Of these, the dielectric lined hollow core designs stand out as having a number of strengths; broadband transmission with low dispersion (~6ps/THz·m at 2 THz [3]), relatively low losses (1 dB/m for a 2.2 mm diameter [4]), and the ability to support fundamental low order Gaussian-like modes, such as the HE_{11} mode. The implementation of this class of THz waveguide with the high power THz QCL would constitute a powerful shift in methodology, which mimics the hugely influential implementation of 1.55µm fibre-laser based systems in recent decades. In this work, we demonstrate the delivery of a low divergence Gaussian-like beam at a distance of >500mm from the facet of a THz QCL via coupling to an external hollow flexible polystyrene-lined Ag waveguide (PS-MWG). A maximum coupling efficiency was achieved by building on previous in-situ beam shaping techniques [5] to produce a monolithically integrated cylindrical metal waveguide (MWG) in the mounting block, in order to couple to the external PS-MWG. A comparison with other excitation geometries, such as direct QCL excitation, as well as a QCL with a facet coupled silicon lens, is also presented.

II. RESULTS

QCLs from two different active region designs, a bound-to-continuum design emitting at 2.85THz [6] and a bound-to-continuum with a single quantum well phonon extraction-injection stage emitting at 3.2-3.4THz [7] respectively, were fabricated in both metal-metal (MM) and single plasmon (SP) laser geometries using a standard wet etching chemical process. The waveguide chosen for THz delivery outside the cryostat was a previously characterised, 555mm long PS-MWG with 1mm bore diameter, and a 10µm inner coating of polystyrene [8]. These types of waveguides support a Gaussian-like HE_{11} mode, which simulations suggest would couple to the TE_{11} mode of a 1mm diameter MWG with an efficiency greater than 80% if brought to within a 2-3mm separation. The integrated MWG was fabricated with a length of 6.8mm in a copper mounting block such that the central axis of the cylindrical MWG aligned with the QCL. Devices were mounted in a continuous-flow He cryostat, with a specially designed 1.35mm wall thickness cylindrical HDPE window, to achieve the optimal waveguide separation distance of ~2 mm (Fig. 1a).

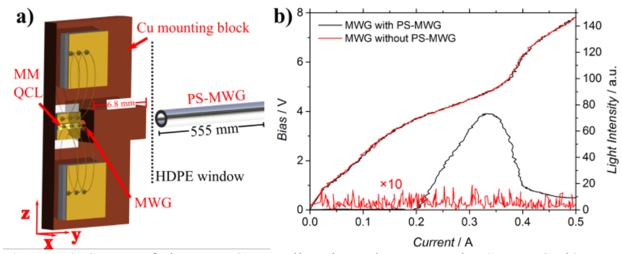

Fig. 1. a) Setup of the MWG coupling into the external PS-MWG. b) LIV characteristics as measured 560mm from the end of the THz QCL with and without the use of the PS-MWG.

The coupling between the MM QCL and the integrated MWG was estimated by comparing the measured output power from the rear laser facet and the MWG directly, using parabolic mirrors and a large area pyro-electric detector. This yielded a coupling efficiency value of 70 ± 5% for the laser to the internal waveguide. The coupling efficiency into the PS-MWG was then estimated by comparing the power output from the MWG before and after transmission through the PS-MWG. This gave a maximum waveguide-waveguide coupling efficiency of 80 ± 5%, accounting for the 5 dB/m loss of the PS-MWG, and without correcting for atmospheric loss. This compares to a coupling efficiency of only 16 ± 5% achieved when using a MM QCL or 45 ± 5% when using a SP QCL as the sole exciting element to the PS-MWG. The improved coupling efficiency is ascribed to the high degree of optical mode matching between the two waveguides. This is confirmed when analysing the emission beam profiles from the rear (i.e. QCL facet) and front of the MWG device, and the end of the PS-MWG (Fig. 2); which shows the conversion of the bare laser emission into a TE_{11} like mode in the MWG and then its conversion into a HE_{11} like mode in the PS-MWG.

To demonstrate the capability of the setup, LIV measurements were taken with and without the PS-MWG, with the detector held a fixed distance of 560mm from the exciting element. In the absence of the PS-MWG power delivery was completely quenched (Fig. 1b), demonstrating the necessity of a waveguided delivery system over these longer distances.

The output beam profile from the MM QCL (Fig. 2a), as measured by the back facet, displays a high degree of divergence (half angle >30°) in both spatial directions. The profile divergence is better than typically observed for MM QCLs, most likely as a result of back-plane reflection from the mounting block. Upon passing through the MWG, a clear improvement is demonstrated [Fig. 2(b)], with the degree of divergence reduced (half angle ~23° in the x and ~20° in the z direction), and evidence of the formation of the TE_{11} mode of the structure observed from the Gaussian-like power profile. The higher degree of divergence in the x direction is most likely due to the asymmetry of the laser facet geometry. The final beam profile from the PS-MWG shows a Gaussian like HE_{11} mode, with a beam waist of 1.00mm [Fig. 2(c)].

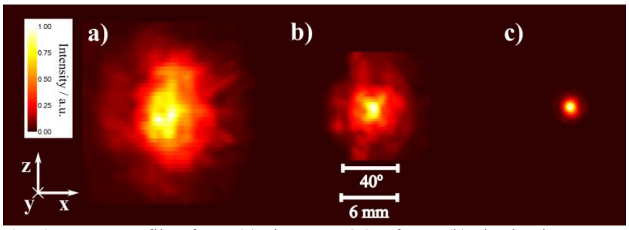

Fig. 2. Beam profiles from (a) the MM QCL facet, (b) the in-situ ~7mm MWG, and (c) the ~555mm PS-MWG, as measured by a Golay cell detector.

Beam cleaning was also observed for sub-optimal, multi-lobed excitation beams, produced by deliberately misaligning the QCL with the MWG. In this case, the Gaussian like HE_{11} mode was retained upon transmission through the external waveguide. The excitation of the HE_{11} mode was also shown to be extremely robust upon MWG excitation, being measured even with a deliberate 1mm lateral misalignment between MWG and PS-MWG [9].

To investigate the spectral integrity of this THz delivery approach, spectra were measured from the MM QCL facet, the MWG, and the PS-MWG, for two different classes of THz QCL (Fig. 3). This shows that all the frequency modes from the original lasers are preserved through both waveguides. Furthermore it highlights the capability of the PS-MWG as a low loss, broadband transmission waveguide.

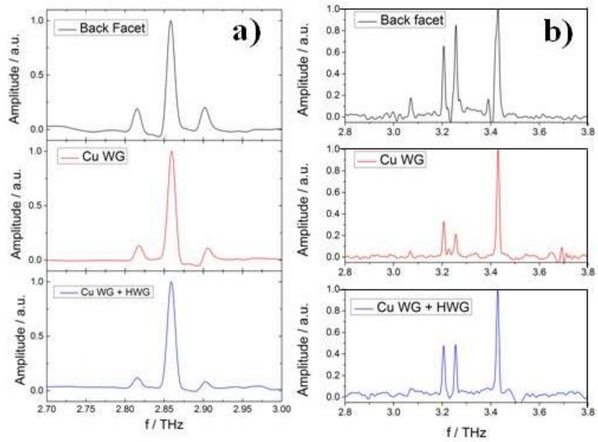

Fig. 3. Representative spectra measured from the MM QCL facet, MWG, and PS-MWG combination for a, (a) 2.85THz bound-to-continuum QCL and (b) 3.2-3.4THz bound-to-continuum with phonon extraction stage QCL.

A comparison to the most commonly employed QCL beam shaping technique, a silicon lens, was investigated [10]. A 3mm diameter hyper-hemispherical high resistivity silicon lens with a 0.6mm spacer was attached to the facet of a 2.85THz MM QCL. With the addition of the lens, the output power from the laser increased fourfold, which is consistent with previous work. The device was mounted in the cryostat to achieve the ~2mm optimal separation to the PS-MWG. Accounting for waveguide loss, a coupling efficiency of 70 ± 5% was calculated, unadjusted for atmospheric absorption. However, the beam profile exiting the PS-MWG showed a bi-lobed higher order mode, with a larger degree of beam divergence compared to the HE_{11} mode [9]. This suggests an optical mode mismatch between this excitation configuration and the HE_{11} mode of the waveguide. Although the coupling efficiency is good, the excitation of any higher-order modes can be detrimental from an application standpoint.

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