Integrating THz Quantum Cascade Lasers to Flexible Dielectric-Metallic Waveguides: Moving beyond Free Space Optics

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The terahertz (THz) quantum cascade laser (QCL) holds great potential in a whole host of applications including laboratory spectroscopy, imaging, sensing and particular astrophysics. QCLs are both compact and robust, exhibiting high power emission (1W in pulsed and 100mW in *cw*mode) with a frequency and bandwidth which can be tailored by suitable device design.However, a number of technological issues still hinder the full exploitation of this class of THz source; like temperature of operation, use of free-space optics, and non-Gaussian beam profiles.

In this work, we present a novel approach that simultaneously targets the latter two issues by developing a THz fibre based approach. The choice of THz waveguide (WG) is critical, since traditional approaches exhibit high material losses in this frequency range (>5dB/m). This work utilises a hollow flexible polystyrene-lined silver waveguide (PS-MWG) as it demonstrates broadband transmission with low dispersion, relatively low losses (<1dB/m), and the ability to support fundamental low order Gaussian-like modes. A key challenge is to efficiently couple the QCL output beam, from the cryostat, to the THz waveguide, external to the cryostat. We adopted an integrated metallic waveguide (MWG) *in-cryo* approach as it demonstrates robust mechanical stability and ease of alignment. Additionally, the diameter can be tailored to allow the spatial beam distribution to be readily matched to that of the *ex-cryo* PS-MWG.

Far-field measurements from the MWG coupled to a metal-metal (MM) THz QCL (*in-cryo* approach) showed a reasonable degree of beam divergence (half angle ~20°) and evidence of the formation of the TE_{11} mode from the Gaussian-like power profile. This is significantly better than the highly diffracted far-field pattern observed from a typicalMM QCL (half angle >30° with strong interference patterns). The coupling efficiency was estimated to be ~70%, with negligible reduction in QCL performance observed. The PS-MWG is a 1mm diameter fused silica capillary with a ~600nm layer of silver deposited on the inner walls. Onto this, a 10μm thick layer of polystyrene (PS) is deposited which determines the transmission band of the structure, centred around 3THz. Simulations show a significant spatial overlap between the TE_{11} mode of the MWG and the HE_{11} mode of the PS-MWG at a separation of 3 mm, for the case of a 1mm diameter for each WG. The resulting measured profile confirmed the excitation of a low divergence (~7°) HE_{11} Gaussian-like beam at a distance >500mm from the facet of the QCL. A high coupling efficiency (>90%) was achieved between the internal MWG and external PS-MWG without the use of any additional optical components, compared to just ~15% between a bare MM QCL and PS-MWG directly. Additionally, a beam cleaning effect was observed, whereby a sub-optimal, multi-lobed beam exiting the cryostat reverts to the single-lobed HE_{11} mode after transmission through the PS-MWG. Comparison with another commonly used collimating technique, a high resistivity silicon lens attached to the laser facet, was also investigated.This was shown to excite a higher order, non-Gaussian mode in the PS-MWG, with a lower coupling efficiency (~70%).