Y-coupled Plasmonic Terahertz Laser System

Owen P. Marshall\(^1\), Subhasish Chakraborty\(^1\), Md Khairuzzaman\(^1\), Harvey E. Beere\(^2\), David A. Ritchie\(^2\)

\(^1\) School of Electrical and Electronic Engineering, University of Manchester, Manchester, M13 9PL, UK.
\(^2\) Cavendish Laboratory, University of Cambridge, Cambridge, CB3 0HE, UK.

Abstract: We demonstrate a Y-coupled terahertz (THz) quantum cascade laser (QCL) system, consisting of two electrically independent surface plasmon guided lasers operating around 2.88 THz. Plasmon mode coupling is revealed in the Y-system emission: Measured output powers are up to 8% higher than the linear sum of the peak powers from the individual arms, with an emission frequency distribution distinct from that of either arm alone or from their linear combination.

Terahertz (THz) quantum cascade lasers (QCLs) are state-of-the-art electrically-driven semiconductor sources currently being studied in research laboratories worldwide\(^1\). Interest in these devices stems largely from their great promise for use in real-world THz applications, including medical and security-focused spectroscopic systems. They differ from other solid-state laser sources in a number of fundamental ways, including but not limited to their waveguiding mechanism. The very long wavelengths associated with THz radiation demand the use of an alternative to conventional refractive index waveguides. Terahertz QCLs make use of surface plasmons to satisfy this function, further increasing the appeal of these devices as they offer an ideal system in which to study the combination of plasmonic structures with an active gain media.

At present, there are two types of THz QCL plasmon waveguide in widespread use: semi-insulating surface-plasmon (SI-SP) and metal-metal (MM), each conferring particular performance advantages; SI-SP producing better output powers and beam shapes, MM giving improved temperature performance\(^1\). These plasmonic waveguides have formed the basis of a variety of device architectures, e.g. THz photonic crystal structures. However, some well-established concepts in shorter wavelength lasers based on guided-wave interconnects such as waveguide couplers and arrayed waveguide gratings (AWGs), remain undeveloped at THz frequencies, despite the promise of greater system control. The simplest device concept among them is the Y-coupling of two lasers, employed in more conventional semiconductor lasers for frequency, phase and beamshape control. To date, on-chip plasmonic coupling of THz QCLs has been limited. One notable exception was the report of lateral coupling in a MM system using tightly-curved linking waveguides\(^3\). In contrast, to the authors’ knowledge there has been no demonstration of plasmonic coupling between parallel SI-SP THz lasers. The approach in reference 3 is not applicable as the required linking section curvatures are incompatible with SI-SP waveguides. Conversely, the large fraction of modal power present in the substrate of an SI-SP QCL (Figs. 1a and b) offers a qualitatively different coupling...
mechanism. By placing a second plasmon waveguide close to the first we are able to tap into this substrate power reservoir, and by the same mechanism to influence it, resulting in a coupled system (Fig. 1c) with a new phase conditions. We employ this plasmonic coupling mechanism in a Y-configuration (Fig. 1d & 1e), bringing two electrically independent SI-SP THz QCL ridges into close proximity (without merging) over a short length, thereby enabling optical power transfer via their shared substrate. Electrical isolation was ensured by focused ion beam (FIB) milling a narrow 2 µm-deep trench through the highly doped contact layer lying above the substrate (Fig. 1e).

During individual operation, each laser arm of the Y-device displayed very similar performance. Fig. 2a shows the electrical and optical power characteristics of one arm (B), while the second arm (A) was turned off and held near its peak THz power (P_A). In the latter case P_A has been subtracted from the data to more clearly reveal the extent to which the total Y-system output power (P_TOT) exceeded the sum of the individual arm powers. The same effect occurred when the arms were interchanged, and was also observed in other Y-coupled THz QCLs. The global increase in P_TOT is attributed to the plasmon coupling mechanism described above, which allows the active region gain in one arm to support and amplify the modal power of the other due to the interaction of their plasmon modes. Further evidence of coupled behavior is observed in the Y-device emission spectra. Figs. 2b and 2c show pulsed laser spectra from arms A and B recorded in individual operation just above their respective lasing thresholds. Under these driving conditions each arm displays multiple lasing frequencies. However, when both arms are operated simultaneously (Fig. 2d) the result is single-frequency emission with a side-mode suppression ratio of 13 dB. Spectral modification is also seen at other driving condition combinations. For example, Figs. 2e and 2f contain spectra from A alone, and B alone at high driving currents, Fig. 2g the corresponding Y (A+B) spectra. The coupled-system mode distribution differs from either arm alone or their linear summation, whilst the specific lasing frequencies are also slightly red-shifted (< 1 GHz) compared to the results from A or B. The lasing modes in Figs. 2d and 2g may be considered supermodes, a product of the entire plasmonic Y-structure and not of either constituent component laser, thereby revealing the coupled system phase solutions.

In conclusion, elevated Y-system output powers and drastically modified lasing spectra provide strong evidence for plasmonic coupling between parallel SI-SP THz QCLs. This development can serve as a platform for more complex device architectures, for example using large numbers of plasmon guided lasers upon the same substrate, AWGs, or for integrating any of the host of available photonic structures for frequency control, such as the longitudinal holograms recently demonstrated by the authors. This work was supported by EPSRC First Grant EP/G064504/1 and partly supported by HMGCC.

References