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Y-coupled Terahertz Quantum Cascade Lasers

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Abstract: Two independently electrically driven terahertz quantum cascade lasers are optically coupled in a Y-configuration. Total peak output powers and emission spectra of this Y-system differ from those of either arm and from their linear sum.

OCIS codes: (250.0250) Optoelectronics; (140.5965) Semiconductor lasers, quantum cascade

1. Introduction

Adoption of terahertz quantum cascade lasers (THz QCL) as sources for real-world applications is currently hindered by a lack of electronically controlled single frequency tuning. Prior demonstrations of frequency control in THz QCLs have each had limitations: active region design (coarse gain tuning), waveguide gratings (rigid frequency selection) and opto-mechanical control mechanisms (limited switching speeds, high system complexity). Furthermore, many of the photonic engineering strategies employed to achieve electronic tuning at shorter wavelengths, such as sampled gratings, face practical difficulties related to large device sizes when scaled to THz wavelengths. One way to avoid very long waveguide structures is to employ lateral coupling between closely spaced laser cavities. In near-infrared solid state lasers, laterally coupled schemes have long been used to manipulate output powers, beam shapes and lasing frequencies [1]. In recent years some of these ideas have been transferred to mid-infrared QCLs [2], but to date demonstration of coupled THz QCL systems has been very limited. A notable exception was the fabrication of a phase-locked array of surface-emitting THz QCLs by Kao et al, using metal-metal waveguides, with highly curved linking sections between lasers [3]. However, this structure does not allow for facet emission of individual lasers and the curvatures required are not compatible with the semi-insulating single-plasmon (SI-SP) waveguides often used in THz QCLs. In this work, we employ an alternative coupling mechanism, making use of the large fraction of modal power in a SI-SP QCL which lies outside the active region thereby allowing the substrate to act as an optical-coupling channel between adjacent QCL ridges. The inset of Fig. 1(c) is a simulated cross-sectional mode intensity profile of two closely spaced SI-SP QCL waveguides, showing modal power within each ridge and a shared substrate lobe.

2. Fabrication and Testing

All Y-systems were fabricated from a single MBE-grown GaAs/Al0.15Ga0.85As wafer, with an active region based on reference [4]. Though the Y-structure brought the two 160 µm-wide, 11.7 µm-tall SI-SP QCL arms into close proximity, they were not physically merged and were independently electrically biased. The scanning electron microscope (SEM) image in Fig. 1(a) shows a packaged and wire-bonded device, its primary dimensions including the length L1 in which the ridge bases were separated by < 10 µm, symmetric arm S-bends, and final separation of 1 mm in length L2. The total device length, L TOTAL, was measured as the linear distance between (and perpendicular to) the cleaved laser facets. A 2 µm-deep by 2 µm-wide trench was focussed ion beam (FIB) milled between the arms, breaking the highly n+-doped GaAs layer beneath the active regions. Hence, the QCLs were electrically isolated. Devices were cooled in a Janis ST-100 continuous-flow helium cryostat and all measurements were performed in pulsed operation (1 % duty cycle, 1 µs pulse length). During Y-system operation the pulsers driving each arm were synchronised. Terahertz power was measured with a calibrated thermopile detector placed directly in front of the widely separated QCL facets. A Bruker Vertex 80 Fourier Transform Infra-red Spectrometer and helium-cooled bolometric detector were used to collect laser spectra with a resolution of 2.25 GHz (0.075 cm⁻¹).

3. Results and Conclusions

Examples of the electrical and optical characteristics of a Y-coupled THz QCL are given in Figs. 1 and 2, showing results from a device with L TOTAL = 6.23 mm, L1 = 520 µm and L2 = 3.36 mm. Under individual operation each arm displayed similar performance characteristics, with a lasing threshold of ~1.11 A and a peak pulsed power of ~4.8 mW. Fig. 1(b) shows the voltage-current (V-I) and light-current (L-I) data for arm A alone (red). Also shown (blue) are similar data recorded when arm B was driven at a fixed current (1.65 A), close to its peak output power. A total Y-system peak power of 10.4 mW was achieved compared to the linear sum of maximum individual arm powers of 9.6 mW, an increase of 10 %. In Fig. 1(c) we subtract the initial lasing power of arm B to show more
clearly the underlying increase in THz power levels relative to the baseline of arm A alone. The same effect was observed when the arms were interchanged. This global increase in system power was attributed to the higher modal gain possible due to the optical coupling; when both QCL active regions are above alignment bias each arm supports and amplifies the modal power of the other. However, no significant changes in the V-I characteristics were recorded. Further Y-coupled THz QCLs (not shown) displayed similar increases in total system powers.

Evidence of optically-coupled behaviour in the same Y-system was also observed in its emission spectra. Pulsed laser output collected from arms A and B (operated individually just above their respective lasing thresholds) are presented in Figs. 2(a) and (b), each showing multiple lasing modes. In comparison, the Y-system spectra in Fig. 2(c), recorded at the same driving currents, displays predominantly single-mode emission at 2.87 THz, with a side-mode suppression ratio of 13 dB. Modified Y-system spectra were also seen at other driving current combinations. For example, Figs. 2(d) and (e) show the individual spectra of arms A and B near their peak emission powers, Fig. 2(f) the corresponding Y-system. Once again the latter is not the result of a linear summation of the spectra of the individual arms. The most powerful mode falls at a frequency between those of A and B, at 2.89 THz. In addition, certain modes in Fig. 2(f) do not match precisely with Figs. 2(d) and (e), e.g. the mode at 2.89 THz lies ~1 GHz lower than the closest individual mode recorded from arm A.

We conclude that the optical link between the two arms provided by the Y-configuration has created a laser system distinct from either arm operated in isolation, i.e. a laterally coupled THz QCL system. The output powers and emission spectra of this Y-system are not reproducible by a linear summation of the characteristics of its constituent component lasers. This initial demonstration of SI-SP coupling in THz QCLs opens the door for more complex devices in which emission spectra may be varied in a user-defined manner, for instance by combining them with established photonic technologies. Even greater frequency flexibility might be achieved by increasing the number of coupled QCLs. Finally, this Y-system can be integrated with the novel photonic structures recently demonstrated by the authors [5]. This work was supported by EPSRC First Grant EP/G064504/1 and partly supported by HMGCC.

![Figure 1](image1.png)

![Figure 2](image2.png)

4. References

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