



UNIVERSITY OF LEEDS

This is a repository copy of *Reshaping the emission of a THz quantum cascade laser frequency comb through an on-chip graphene modulator*.

White Rose Research Online URL for this paper:
<https://eprints.whiterose.ac.uk/180273/>

Version: Accepted Version

Proceedings Paper:

Di Gaspare, A, Pogna, EAA, Balci, O et al. (8 more authors) (2021) Reshaping the emission of a THz quantum cascade laser frequency comb through an on-chip graphene modulator. In: 2021 Conference on Lasers and Electro-Optics Europe & European Quantum Electronics Conference (CLEO/Europe-EQEC). 2021 Conference on Lasers and Electro-Optics Europe & European Quantum Electronics Conference (CLEO/Europe-EQEC), 21-25 Jun 2021, Munich, Germany. IEEE . ISBN 978-1-6654-4804-8

<https://doi.org/10.1109/cleo/europe-eqec52157.2021.9542356>

Reuse

Items deposited in White Rose Research Online are protected by copyright, with all rights reserved unless indicated otherwise. They may be downloaded and/or printed for private study, or other acts as permitted by national copyright laws. The publisher or other rights holders may allow further reproduction and re-use of the full text version. This is indicated by the licence information on the White Rose Research Online record for the item.

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.



eprints@whiterose.ac.uk
<https://eprints.whiterose.ac.uk/>

Reshaping the emission of a THz quantum cascade laser frequency comb through an on-chip graphene modulator

Alessandra Di Gaspare¹, Eva A. A. Pogna,¹ Osman Balci², Sachin M. Shinde², Lianhe Li,³ Cinzia di Franco⁴, A. Giles Davies,³ Edmund Linfield,³ Andrea C. Ferrari², Gaetano Scamarcio⁴ and Miriam S. Vitiello¹

1. NEST, CNR-NANO and Scuola Normale Superiore, Piazza San Silvestro 12, 56127 Pisa, Italy

2. Cambridge Graphene Centre, Cambridge, 9 JJ Thomson Avenue, CB3 0FA, United Kingdom

3. School of Electronic and Electrical Engineering, University of Leeds, Woodhouse Lane, Leeds LS2 9JT, United Kingdom, UK

4. CNR-IFN and Dipartimento Interateneo di Fisica, Università degli Studi di Bari, Via Giovanni Amendola, 173, I-70126 Bari, Italy

Graphene possesses a peculiar potential for the development of optoelectronic components capable to actively manipulate infrared light [1]. Its electrostatically tunable optical conductivity, band structure and transport characteristics, and the possibility to be grown over large areas, offer an intriguing playground for engineering, at the nanoscale, amplitude modulators, spatial light modulators and switches, combining high efficiency ($> 50\%$) intensity modulation, reasonably high speeds ($> \mu\text{s}$ response times), and spectral tunability in the underexploited high (> 1.5 THz) terahertz-frequency range [2], where frontier applications in quantum communications, quantum computing, adaptive and quantum optics are still at their infancy.

We devise a single layer graphene-on-polyimide modulator [3] with a tunable-by-design optical bandwidth, in which the electrostatic gating of the single layer graphene conductivity, achieved through a metamaterial grating gate coupler patterned on a $\lambda/4$ -polyimide layer on Au waveguide cavity, allows 90% modulation efficiency, combined with a 20 KHz electrical bandwidth in the 1.9-2.7 THz frequency range (see Figure 1).

The graphene modulator is then exploited as a dispersion compensator of a THz-frequency, broadband semiconductor heterostructure laser [4]. To this purpose, we integrate our modulator, on-chip, with a quantum-engineered multimode THz quantum cascade laser (QCL). Adjusting, by-design, the modulator operational bandwidth, we demonstrate that the SLG modulator can compensate the QCL cavity dispersion, resulting in an integrated laser behaving as a stable optical frequency comb synthesizer over a record dynamic range of 35% [3].

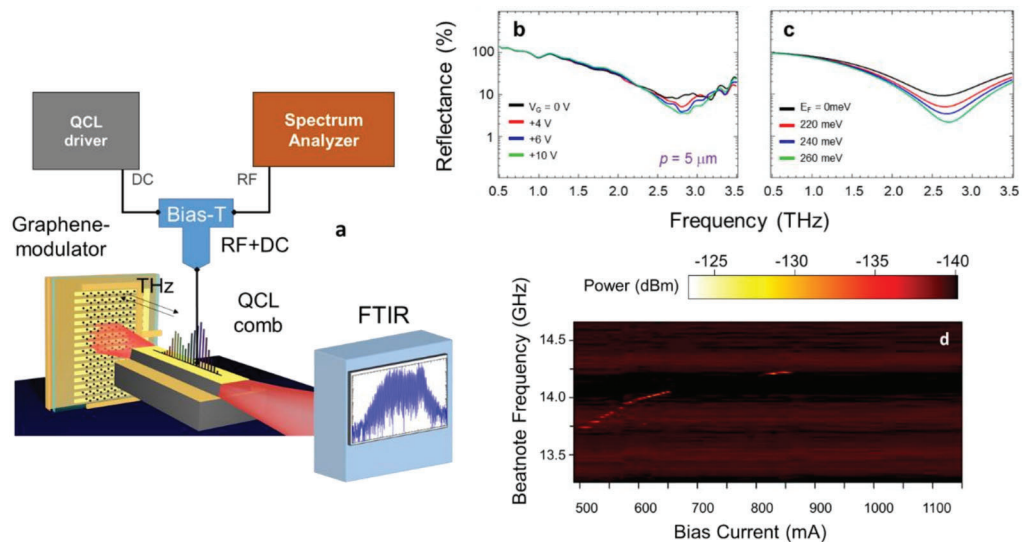


Fig. 1(a) schematic layout of the experimental setup, with the graphene modulator is positioned on a moving piezoelectric stage in close proximity of the back facet of the THz QCL frequency comb. (b) total reflectance measured as a function of the gate bias with a time domain spectrometer on the modulators with grating periodicity $p = 5 \mu\text{m}$; (c) Calculated reflectance for the same grating of panel (b) at different Fermi energies; the Fermi energies chosen to reproduce the experimental data. (d) Intermode beatnote map as a function of the continuous wave driving current measured at 15 K in the QCL-modulator system shown in (a) ($p = 5 \mu\text{m}$).

References

- [1] M. Romagnoli, et al. Graphene-based integrated photonics for next-generation datacom and telecom. *Nat. Rev. Mater.* **3**, 392 (2018)
- [2] P. Gopalan, B. Sensale-Rodriguez, 2D Materials for Terahertz Modulation. *Adv. Opt. Mater.* **8**, 1 (2020)
- [3] A. Di gaspare et al, Tunable, Grating-Gated, Graphene-On-Polyimide Terahertz Modulators, *Adv. Funct. Mater.*, 2008039 (2020)
- [4] Garrasi, K. et al. High Dynamic Range, Heterogeneous, Terahertz Quantum Cascade Lasers Featuring Thermally Tunable Frequency Comb Operation over a Broad Current Range. *ACS Photonics* **6**, 73 (2019).