UNIVERSITY OF LEEDS

This is a repository copy of *In-plane surface plasmonics integrated with THz Quantum cascade lasers for high collimation*.

White Rose Research Online URL for this paper:
https://eprints.whiterose.ac.uk/82603/

Version: Accepted Version

Proceedings Paper:

Liang, G, Dupont, E, Fathololoumi, S et al. (8 more authors) (2014) In-plane surface plasmonics integrated with THz Quantum cascade lasers for high collimation. In: Optics InfoBase Conference Papers. CLEO: Science and Innovations, 08-13 Jun 2014, San Jose, California United States. Optical Society of American (OSA) . ISBN 9781557529992

https://doi.org/10.1364/CLEO_SI.2014.STh1F.2

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.

White Rose
university consortium
Universities of Leeds, Sheffield & York

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

In-plane surface plasmonics integrated with THz Quantum cascade lasers for high collimation

Guozhen Liang,[1] Emmanuel Dupont,[2] Saeed Fathololoumi,[2,3] Zbigniew R. Wasilewski,[3] Dayan Ban,[3]
Siu Fung Yu,[1,7] Lianhe Li,[5] Alexander Giles Davies,[5] Edmund Linfield,[5]
Hui Chun Liu,[6] Qi Jie Wang,[1,7]

[1] *School of Electrical and Electronic Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798 Singapore.*
[2] *National Research Council, Bldg. M-50, 1200 Montreal Rd, Ottawa, Ontario K1A0R6, Canada*
[3] *Department of Electrical and Computer Engineering, Waterloo Institute for Nanotechnology, University of Waterloo, 200 University Ave. West, Waterloo, N2L3G1, Ontario, Canada.*
[4] *Department of Applied Physics, Hong Kong Polytechnic University, Kowloon, Hong Kong.*
[5] *School of Electronic and Electrical Engineering, University of Leeds, Leeds LS2 9JT, UK.*
[6] *Key Laboratory of Artificial Structures and Quantum Control, Department of Physics, Shanghai Jiao Tong University, Shanghai 200240, China.*
[7] *CDPT, Centre for Disruptive Photonic Technology, School of Physical and Mathematical Sciences, Nanyang Technological University, 639798, Singapore*
qjwang@ntu.edu.sg

Abstract: We report planar integration of tapered Terahertz (THz) quantum cascade lasers (QCLs) with spoof surface plasmon (SSP) structures. The SSP structure consists of one plasmonic coupler and periodically arranged scatters. The resulting surface-emitting THz beam is highly collimated with a beam divergence as narrow as 3.6°×9.7°. As the beam divergence is inverse proportional to the light emission area, this low divergence indicates a good waveguiding property of the SSP structure, while the low optical background of the beam implies a high coupling efficiency of the THz wave from the laser cavity to the SSPs. Since all the structures are in-plane, this scheme provides a promising platform where the well-established SP techniques can be employed to engineer the THz QCL beam with high flexibilities.

1. Introduction

With the flexibility of confining and manipulating the optical wave at a subwavelength level by structuring the metallic surface, surface plasmons (SPs) have boosted numerous studies in compact photonic circuits [1], enhanced light-matter interactions [2], near-field imaging system [3] and beam shaping [4–6], etc. However, in the terahertz (THz) region, flat metal surface cannot support bound surface modes. Fortunately, it has been recently found that metal surface corrugated at subwavelength scales can support tightly confined THz surface waves, just like the SPs behavior at shorter wavelength [7]. Such surface waves are hence called “spoof” surface plasmons (SSPs). SPP structure has been fabricated on the facet of THz QCLs for collimation purpose, achieving a beam divergence of ~11.7°×16° [8]. The drawbacks of this scheme are the limited area of the laser facet and the incompatibility of the fabrication with conventional optical lithography, all of which limit the further application of the SSP structure.

In this work, we report the planar integration of tapered THz QCLs with SSP waveguides, which are further processed into unidirectional SSP out-couplers by introducing periodically arranged scatterers. The resulting surface-emitting THz beam is highly collimated with a beam divergence as narrow as 3.6°×9.7°. More importantly, since all the structures are planar, this scheme provides a platform where an integrated THz photonic circuit may be built by integrated other optoelectronic devices like Schottky diode THz mixer [9], graphene modulator and/or graphene detector.

2. Results

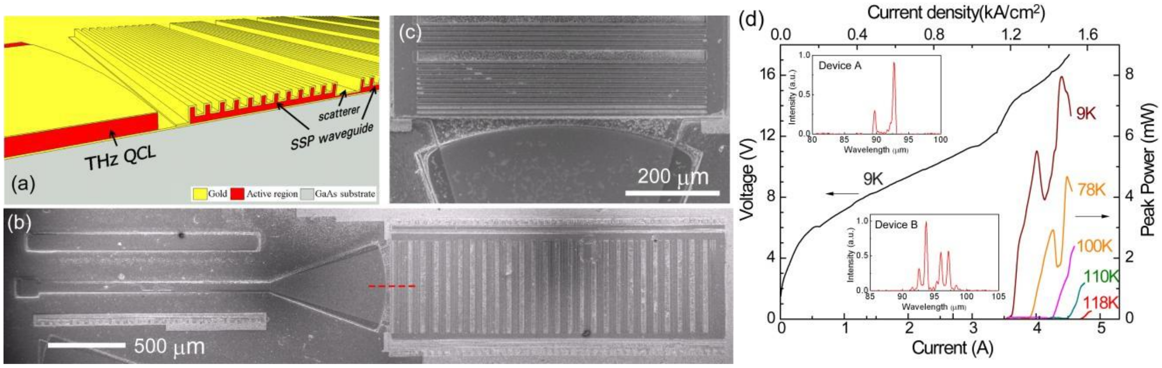

Fig. 1. (a) 3D schematic cross-section view of our device along the red dashed line in (b). (b) Scanning electron microscope (SEM) image of a fabricated device. Also shown is a ridge laser fabricated by the side of the device. (c) Enlarged view of the central region of the device. (d) Pulsed light-current-voltage (LIV) characteristics of the laser under different heat sink temperatures. Inset: laser spectra of devices A and B at 4.3 A and 9 K, where their far-field patterns were measured.

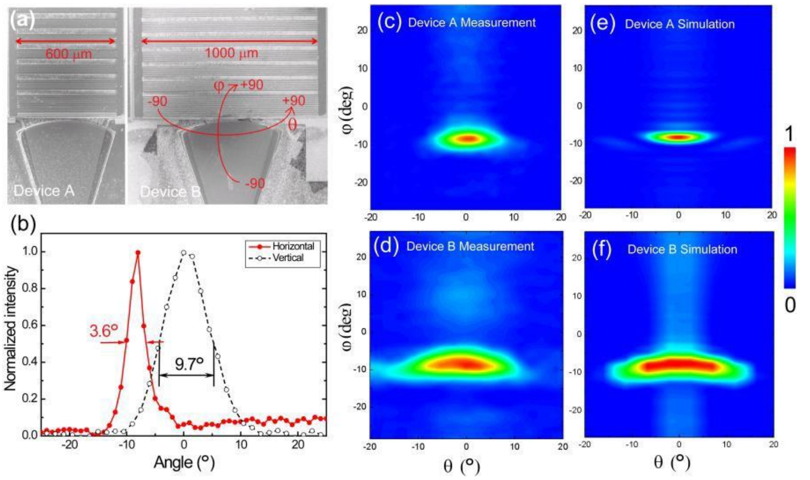

Fig. 2. (a) SEM images of the device A and B showing that the groove width of device A is 600 μm and that of device B is 1000 μm. (b) horizontal and vertical line scans of the far-field pattern in (c) across the peak value. (c), (d) Measured far-field patterns of devices A and B, respectively. (e) Simulated far-field pattern of device A at 94 μm wavelength. (f) Simulated far-field patterns of devices B considering the multi-mode emission from 92 μm to 98 μm.

References

[1] T. W. Ebbesen, C. Genet, and S. I. Bozhevolnyi, "Surface-plasmon circuitry," Phys. Today **61**, 44 (2008).

[2] B. Ng, J. Wu, S. M. Hanham, A. I. Fernández-Domínguez, N. Klein, Y. F. Liew, M. B. H. Breese, M. Hong, and S. a. Maier, "Spoof Plasmon Surfaces: A Novel Platform for THz Sensing," Adv. Opt. Mater. **1**, 543–548 (2013).

[3] A. J. Huber, F. Keilmann, J. Wittborn, J. Aizpurua, and R. Hillenbrand, "Terahertz near-field nanoscopy of mobile carriers in single semiconductor nanodevices.," Nano Lett. **8**, 3766–70 (2008).

[4] L. Li, T. Li, S. Wang, C. Zhang, and S. Zhu, "Plasmonic Airy Beam Generated by In-Plane Diffraction," Phys. Rev. Lett. **107**, 1–4 (2011)

[5] H. J. Lezec, A. Degiron, E. Devaux, R. A. Linke, L. Martin-Moreno, F. J. Garcia-Vidal, and T. W. Ebbesen, "Beaming light from a subwavelength aperture.," Science **297**, 820–2 (2002).

[6] N. Yu, Q. J. Wang, and F. Capasso, "Beam engineering of quantum cascade lasers," Laser Photon. Rev. **6**, 24–46 (2012). [7] J. B. Pendry, "Mimicking Surface Plasmons with Structured Surfaces," Science **305**, 847–848 (2004).

[8] N. Yu, Q. J. Wang, M. A. Kats, J. A. Fan, S. P. Khanna, L. Li, A. G. Davies, E. H. Linfield, and F. Capasso, "Designer spoof surface plasmon structures collimate terahertz laser beams.," Nat. Mater. **9**, 730–735 (2010).

[9] M. Wanke, E. Young, and C. Nordquist, "Monolithically integrated solid-state terahertz transceivers," Nat.Photonics. **4**, 565–569 (2010).