Wavefront Engineering of Semiconductor Lasers Using Plasmonics

Nanfang Yu, Romain Blanchard, Jonathan A. Fan, Qi Jie Wang, Mikhail Kats, and Federico Capasso
School of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138, U.S.A.
E-mail: nyu@fas.harvard.edu, capasso@seas.harvard.edu

***Abstract*-Plasmonics involves manipulation of surface plasmons (SPs), which are collective oscillations of surface electrons in metal interacting with an electromagnetic field. Plasmonic structures provide compact and integrated optical processing, where planar metallic structures can be used to manipulate the amplitude and phase of SPs in two dimensions at the subwavelength level. By integrating plasmonic structures on active optical devices, one can engineer and fabricate devices with small footprints and special beam profiles in the near-field and/or in the far-field. This talk summarizes our recent work on building integrated plasmonic collimators, beam splitters, and polarizers for semiconductor lasers.**

I. Introduction

The manipulation of light using surface plasmons—known as plasmonics—has a wide range of applications in imaging, sensing, communications and optical manipulation. Unlike conventional optical components, plasmonic structures manipulate light at the sub-wavelength level in real space or over a wide range of k vectors in wave-vector space.

Our work explores the use of plasmonics for laser beam shaping based on monolithic integration. Currently, laser beams are manipulated externally using optical components such as lenses, beam-splitting polarizers and wave plates. These components are often bulky and expensive and don't provide the degree of flexibility and the range of new functionalities made possible by integrated optics.

Plasmonics could provide a compact and universal solution to beam shaping of semiconductor lasers and optical fiber based light sources. By fabricating in situ on their facet sub-wavelength metallic-dielectric structures researchers can design the near-field and far-field almost at will to achieve major performance improvements or to add new functionalities [1,2].

Semiconductor lasers now permeate our society, as key components in widespread commercial technologies such as optical fiber communications and CD and DVD players. However, their beams usually have a large divergence angle (of around tens of degrees) due to the significant diffraction caused by the small emission aperture of the devices. In addition, light output is mostly linearly polarized along a single direction, which is determined by the optical selection rules of the gain medium.

Clearly new beam-shaping schemes could improve myriad technologies by greatly reducing beam divergence and by making available a wide range of polarization states, such as circular polarization and linear polarization along different directions. In this paper we address some of these questions and demonstrate specific solutions in the model system of mid-infrared and far-infrared quantum cascade lasers (QCLs).

II. Wavefront Engineering of Quantum Cascade Lasers

A. *Plasmonic collimators*

Figure 1 shows one example of 2D collimation for a mid-infrared QCL. The plasmonic collimator works by transferring laser emission into SPs over a large area on the device facet and using gratings to coherently scatter their energy into the far-field, thereby breaking the diffraction limit set by the small emission area of the original laser. It was demonstrated that the beam divergence in the vertical and lateral directions can be reduced by more than one order of magnitude down to a few degrees without scarifying significantly the device power throughput [3-5].

A similar design can be employed for collimating the output of THz QCLs; see Fig. 2. Double-metal waveguide THz QCLs originally have broad emission profiles essentially over the half space in front of the lase facet. We demonstrated that by patterning a plasmonic grating consisting only a few grooves on the device facet, the far-field divergence angle was reduced to ~10^o and the power collection efficiency was correspondingly enhanced by a factor of 3 to 5.

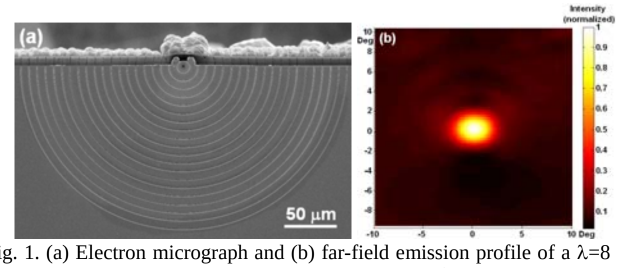
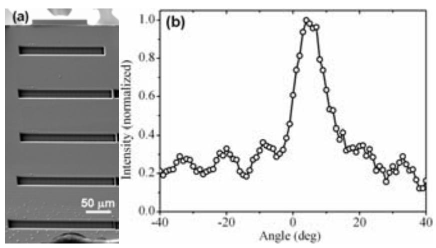


Fig. 1. (a) Electron micrograph and (b) far-field emission profile of a λ=8 µm QCL with a 2D plasmonic collimator patterned on the facet.



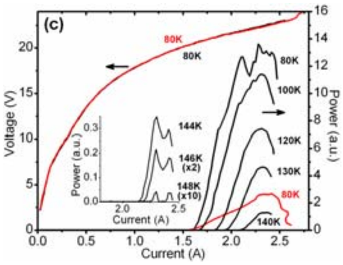


Fig. 2. (a) Electron micrograph and (b) measured vertical far-field mode profile of a λ=100 μm THz QCL patterned with a plasmonic collimator. (c) LIV characteristics measured for the same device with (black curves) and without (red curves) the plasmonic collimator.

B. Plasmonic Beam Splitters

We demonstrated integrated beam splitters based on plasmonics. Figure 3 shows that a single-wavelength QCL can be made to emit beams in two directions by defining on its facet two sets of plasmonic gratings with different periods [6].

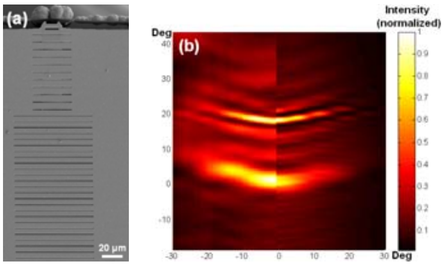


Fig. 3. (a) Electron micrograph and (b) far-field emission profile of a λ=8 μm QCL with an integrated beam splitter consisting of two gratings on the facet. The left and right half of (b) are, respectively, experimental and simulation results.

C. Plasmonic Polarizers

We demonstrated the plasmonic control of semiconductor laser polarization [7]. An integrated plasmonic polarizer can project the polarization of a semiconductor laser onto other directions. By designing a facet with two orthogonal grating-aperture structures, and introducing relative phase delay of SPs propagating on the two plasmonic structures, a polarization state consisting of a superposition of a linearly and circularly-polarized light was demonstrated in a QCL (Fig. 4); a first step toward a circularly polarized laser.

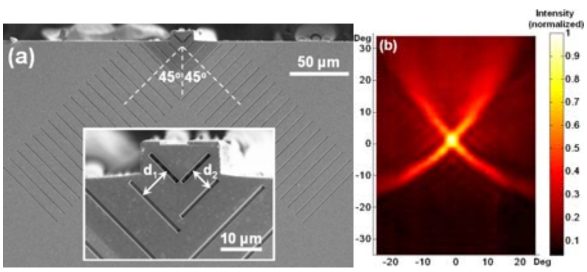


Fig. 4: (a) Electron micrograph and (b) far-field emission profile of a λ=9.9 μm QCL patterned with a plasmonic polarizer. The central region of the far-field profile contains circularly-polarized component.

III. CONCLUSIONS

In conclusion, we have demonstrated that the integration of a suitably designed 1D or 2D plasmonic structure on the facet of QCLs can lead to desirable far-field characteristics such as greatly reduced bean divergence and controllable polarization. By proper scaling of the plasmonic design according to wavelength and polarization, it can fit onto any type of semiconductor laser with a wide range of emitting wavelengths from visible to THz. We envision designing and building plasmonic nanostructures or metamaterials on the facet of many types of semiconductor lasers and also on fiber lasers to achieve complex wavefront engineering.

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