Quantum cascade lasers with facet-patterned nano-antennas for near field vibrational spectroscopy

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***Abstract*—We report the design and development of metallic nano-antenna structures fabricated on the end facets of semiconductor quantum cascade lasers (QCLs) for use in near-field vibrational microscopy. Finite difference time domain (FDTD) simulations are employed to design optimum antenna structures with large (~50x) near field enhancements relative to the same size aperture. We use focused ion beam milling to fabricate antennae on high-reflectivity coated QCL facets. Apertureless mid-IR SNOM imaging is used to evaluate the near-field signal showing significant variations in the local enhancement of the field, in line with simulations. Full 3-dimensional FDTD simulations allow us to investigate how the SNOM measurements are influenced by the tip-surface interation.**

***Index Terms*—**

I. Introduction

Quantum cascade lasers (QCLs) have now reached a high level of technological maturity, providing wide tunability and complete control over wavelength and emission linewidth at mid-infrared (mid-IR) wavelengths. They are therefore ideally suited to mid-infrared spectroscopy, which is a highly sensitive tool for identifying and characterizing molecular bonds. In particular, mid-IR spectroscopy has several advantages over other techniques (such as Raman and fluorescence spectroscopy) for studying biomolecular samples, including the lack of additional probe molecules and absence of problems associated with background fluorescence or light scattering. The power of vibrational *microscopy* is that it allows spatial distinction between regions of different chemical composition in almost any material. However, in conventional mid-IR microscopy the best spatial resolution obtainable is of the order of a few micrometers, a well-known consequence of the Abbe diffraction limit.

Our approach to overcome this limit is to make use of a nano-antenna defined on the gold-coated QCL facet (Fig. 1 a) using focussed ion beam milling. This results in an enhancement the near-field intensity in the small (10-200nm) antenna gap region, providing a powerful platform for mid-infrared vibrational microscopy beyond the diffraction limit. As shown in Fig. 1 b, our finite difference time domain simulations predict large (>50x) enhancements in the near field intensity. These simulations take into account the real and imaginary parts of the metal (gold) refractive index and also the underlying dielectric layer. Several designs have been investigated, with particular emphasis on bow tie and inverse bow tie designs due to the well-defined alignment geometry with the TM-polarized QCL output.

The apertureless SNOM [1] is an ideal instrument for imaging in the mid-IR region, providing an ultrahigh resolution which is wavelength independent. In the conventional SNOM technique, light passes through a subwavelength aperture which is scanned across the surface of a sample, limiting the achievable resolution to about a tenth of the wavelength of the light. In contrast, the apertureless method involves detection of the scattered radiation from oscillating probe, with the scattering from the tip apex collected for imaging. In our configuration, the λ~8µm QCL is used as the source and the apertureless SNOM tungsten tip is scanned across the fib-milled facet, allowing for topographic AFM analysis and direct near field imaging of the antenna during operation. As shown in Fig. 1 c, we measure a strong enhancement of the scattered near field signal at the antenna centre, consistent with our FDTD simulations.

3D FDTD simulations have also shown an intensity enhancement as a function of tip – antenna separation and position (Fig. 2 a-c) during the a-SNOM measurements, so modifications to the scattered signal are expected [2].

In further studies we plan to functionalise the facet allowing (bio)chemical binding and study the scattered QCL radiation as a function of the a-SNOM tip position to provide compositional information on a nm-lengthscale [3]. Chemical identification with high spatial resolution is expected to have a major impact in many diverse areas such as compositional studies of cell membranes and the development nanoscale organic electronics.

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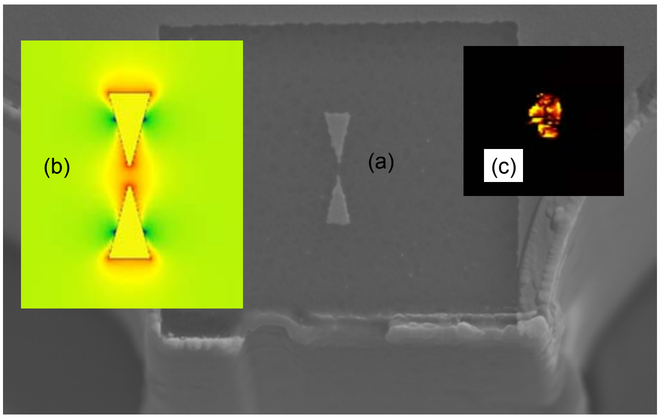
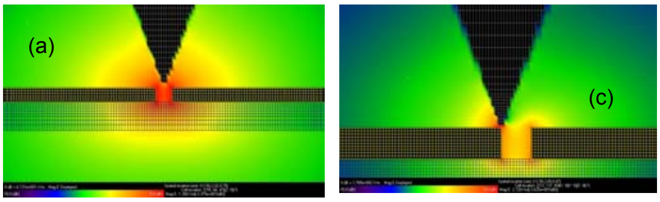


Fig. 1. (a) SEM image of fib-milled QCL facet. (b) FDTD simulation of bowtie antenna. (c) a-SNOM image of facet with bow tie antenna



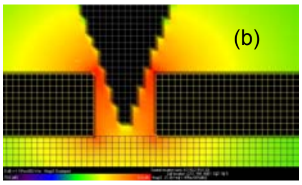


Fig. 2. (a – c) 3D FDTD simulations of tip – antenna interaction

REFERENCES

[1] Zenhausern, Y. Martin, H.K. Wickramasinghe, “Scanning Interferometric Apertureless Microscopy: Optical Imaging at 10 Angstrom Resolution”, Science, 269, pp 1083-1085, August 1995

[2] B. Knoll, F. Keilmann, “Enhanced dielectric contrast in scattering-type scanning near-field optical microscopy”, Optics Commumincations 182, pp 321-328, August 2000

[3] A. Cricenti et al, “Chemically Resolved Imaging of Biological Cells and Thin Films by Infrared Scanning Near-Field Optical Microscopy”, Biophys. J. 85, pp 2705-2710, 2003