Direct imaging of a laser mode via mid-infrared near-field microscopy

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***Abstract*—The Fabry-Perot stationary waves inside a mid-infrared quantum cascade laser have been imaged using an apertureless scanning near field optical microscope. The laser devices emit at $\lambda \approx 7.7$ μm and they feature air-confinement waveguides, with the optical mode guided at the semiconductor-air interface. A consistent portion of the mode leaks evanescently from the device top surface and can be detected in the near-field of the device. Imaging of the evanescent wave across a plane *parallel* to the device surface allows one to directly assess the effective light wavelength inside the laser material, yielding the effective index of refraction. Imaging across a plane *perpendicular* to the device surface allows one to directly measure the electric field decay length, which is found in excellent agreement with the numerical simulations.**

***Index Terms*— Mid-infrared spectroscopy, near-field microscopy, quantum cascade laser.**

I. INTRODUCTION

THE mid-infrared (mid-IR, $5 \mu m < \lambda < 30 \mu m$) and terahertz (THz, $30 \mu m < \lambda < 300 \mu m$) ranges of the electromagnetic spectrum are extremely important for sensing applications [1]. Most molecules of chemical and biological interest exhibit roto-vibrational transitions in these wavelength ranges. Quantum cascade (QC) lasers [2,3], devices based on intersubband transitions in semiconductor heterostructures, efficiently cover these wavelengths and they are now becoming integrated as sources in commercial setups for trace gas detection. New possibilities also exist for novel QC laser-based sensing systems. For instance, the devices could be made sensitive to a material/liquid which contacts the QC laser surface. The laser would then react by detuning the emission wavelength, or by increasing the threshold current density [4-6].

Devices featuring an optical mode which leaks evanescently above the top surface have been implemented [7,8], and they are perfectly suited to such applications [5,6]. A near-field diagnostics of these devices is important in view of understanding and optimizing their properties. In addition, they provide an ideal playground for observations with mid-IR scanning near-field microscopes (SNOM) [9,10], offering the opportunity of imaging the light propagation *inside* a working (QC) laser.

We report here the direct imaging of the light confinement inside the cavity of a working semiconductor laser. The result is obtained by near-field imaging of the evanescent electric field on the surface of a specifically designed [5] mid-IR ($\lambda \approx$ 7.7 μm) QC laser. We directly observe the stationary waves inside the Fabry-Perot laser cavity, yielding the effective refractive index of the guided mode. We also give an experimental estimate of the electric field intensity at the surface. These devices behave as generators *"on demand"* of intense evanescent electric fields, controlled by the injected current.

II. EXPERIMENTAL RESULTS

In the first part of the talk we demonstrate that QC lasers employing waveguides based on air-confinement can be implemented on structures where the active region is located immediately at the device top surface, while previous devices featuring this architecture made use of thick top, doped semiconductor claddings to provide uniform current injection [1]. The lasers employ ridge-waveguide resonators with lateral electrical contacts, while a large, central top surface of the device is not covered by any metal layer (Fig.1.(a)). The peculiarity of this approach is that the same heterostructure can be processed as a surface-plasmon QC laser, if the metal contacts cover the whole surface of the device, or as an air-confinement device, if only lateral contacts are deposited and the top surface is left exposed. This device geometry therefore allows one to implement lasers supporting hybrid air- and surface-plasmon-confined modes. The lasers operate in pulsed mode, at $\lambda = 7.7$ μm and at room temperature. (Fig. 1(b)).

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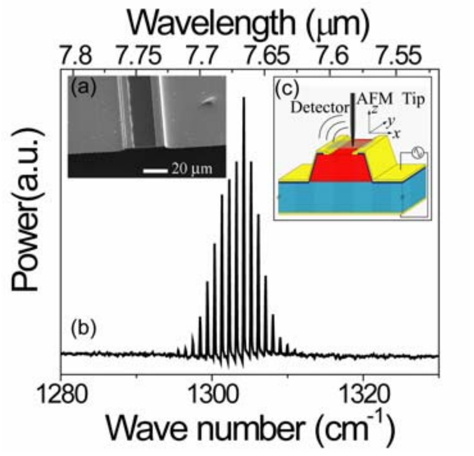

Fig. 1: (a) Pulsed emission spectrum at room-temperature of a typical laser device used for this work, (b): SEM image of a typical device, (c): Schematic of the apertureless SNOM setup. The semi-transparent green square corresponds to the typical area size scanned during a measurement run.

In the second part of the talk we present the imaging of the evanescent electric field at the device top surface performed with a mid-IR apertureless scanning near-field optical microscope (SNOM) [2]. A fraction of ≈ 0.9% of the total energy of the laser mode is located above the device. The a-SNOM measurements (Fig.1, right panel) reveal three operating regimes. At injection currents below laser threshold (panel (b), *thermal regime*) the near-field is dominated by the material thermal emission. At laser threshold (panel (c), *intermediate regime*), the thermal emission is still observable, but a clear near-field signal appears on the ridge top surface. The stationary waves of the Fabry-Perot resonator appear. Finally well above threshold (panel (d), *laser regime*) the intensity of the near-field signal increases by a few orders of magnitude, completely masking the thermal emission. A high resolution close-up (panel (e), 3D view) allows the clear observation of the stationary wave, whose periodicity is found to be ≈1.25 µm, in fair agreement with numerical simulations. The measurement of the evanescent field decay length gives a value of ≈ 500 nm, in excellent agreement with our simulations.

The presence of a strong evanescent electric field on the top surface of the devices suggests that they can be “surface” sensitive. For instance they should react to the deposition of a fluid on their surface, provided that the fluid exhibits an absorption line at the laser emission wavelength. Initial results will be shown.

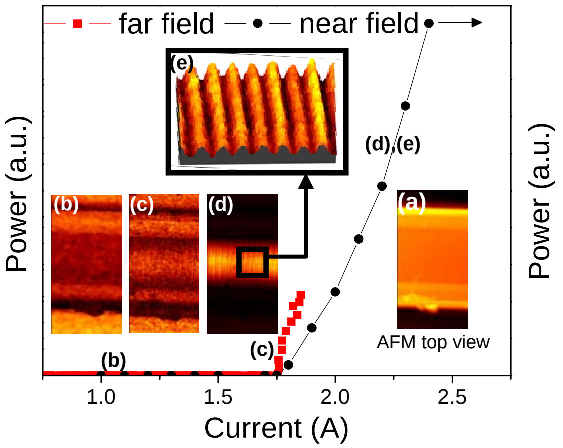

Fig. 2: Figure 2: Main panel: light-current characteristics of a typical device. Red dots: far-field emission from the laser facet. Black dots: near-field measurement. (a): AFM view of the laser ridge. The scanning range is 30x60µm, and it is identical for panels (a-d). The two lateral bright regions correspond to the lateral contact bands on top of the laser resonator, while the central, slightly darker region corresponds to the exposed semiconductor surface. (b): Near-field measurement below threshold: Only the thermal emission is present. (c): Near-field measurement at threshold: the stationary wave starts to emerge. (d): Near-field measurement well above threshold. (e): High resolution SNOM image of the stationary wave plotted in 3D.

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