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Intracavity near-field optical imaging of a mid-infrared quantum cascade laser mode

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Abstract

We report the direct imaging of Fabry–Pérot standing waves inside the cavity of a mid-infrared quantum cascade laser *via* apertureless scanning near-field optical microscopy. The quantum cascade devices employed present an evanescent wave at the top surface, whose magnitude is directly proportional to the cavity mode intensity in the device core region. Apertureless scanning near-field optical microscopy measurements provide experimental results about the nature of this evanescent field in good agreement with calculations (effective index and electric field decay length).

Keywords: SNOM; Near-field microscopy; Semiconductor lasers; Quantum cascade lasers; Evanescent fields

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1. Introduction

In less than three decades, the scanning near-field optical microscope [1] (SNOM) has become an important instrument to probe the optical properties of devices and materials. It allows now one to perform imaging with a resolution well beyond the diffraction limit [1]. The SNOM has been successfully applied at visible [2], infrared [3], terahertz [4], and gigahertz [5] frequencies, producing optical images with a resolution which is sometimes as high as a few hundredths of the observation wavelength. Such resolution offers the possibility to probe the material optical properties far beyond what is achievable with classical far-field microscopy. SNOM microscopy measures the spatial distribution of electromagnetic fields at the surface of a sample. It has been extensively used to study and characterize localized or propagating [6,7] surface plasmons or surface phonon polaritons [8]. SNOMs have also been used to perform spatially resolved studies of absorption [9], Raman scattering [10,11], luminescence [12] or fluorescence [13] on a nanoscopic scale and to characterize passive or active devices [14,15].

In this paper, we report a study using scanning near-field optical microscopy on a mid-IR quantum cascade (QC) laser in operation [16–18]. The QC laser is a semiconductor laser which employs electrical injection. Stimulated light emission results from intersubband transitions in the semiconductor heterostructure which forms the active region of the laser. Thanks to electronic band engineering, QC lasers now can cover the spectral range of mid-IR ($2.9\,\mu m < \lambda < 24\,\mu m$) and THz ($60\,\mu m < \lambda < 200\,\mu m$). Such devices are already used as infrared sources to detect species of chemical and/or biological interest *via* their fingerprint absorptions in the mid-IR [19].

The QC lasers implemented for this study feature an optical mode which leaks evanescently on the top surface [20–22]. For this reason, they are referred hereafter as air-confinement QC lasers. They behave as generators of intense evanescent electric fields whose intensity is electrically controlled [18]. In addition, metallic nanostructures could be deposited on the device top surface for plasmonic applications, meant for instance to launch surface plasmons in a plasmonic circuit. These potential applications motivate the study and the accurate characterisation of

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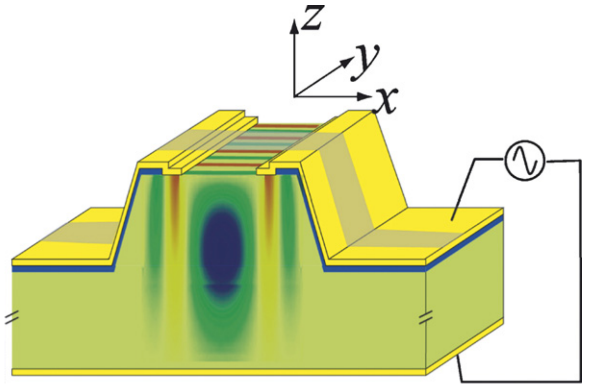

Fig. 1. Scheme of an air-confinement quantum cascade laser. The 2D optical mode ($|E_z|$) is obtained by 2D finite element simulations. The scanning zone is represented in grey. The laser emits from the facets, obtained by cleaving the semiconductor chip. An evanescent electric field is expected to appear on the device top surface.

the optical near-field produced at the surface of air-confinement QC lasers.

2. Device fabrication

The semiconductor growth was performed by metal-organic vapor phase epitaxy (MOVPE). Details of the structure are reported in Ref. [18] and references therein. No semiconductor top claddings were grown, so the mode guiding can be achieved either with a metallic layer (surface–plasmon guiding), or by air-claddings. In this work, the lasers used a Fabry–Pérot ridge resonator with two lateral metallic top contacts for the current injection. Fig. 1 represents the geometry of the devices, on which the result of a 2D finite elements calculation of the optical mode is superimposed. In order to achieve optical guiding, the active region of the QC laser exhibits an interface with air at the device top surface between the top contacts. When the laser is in operation, most of the electromagnetic field inside the cavity is confined in the active region core. Yet, part of it leaks evanescently into the air-claddings above the device and between the metallic top electrodes. The Fabry–Pérot cavity geometry induces the presence of standing waves inside the resonator. The lateral spatial distribution of the evanescent field at the air/active region interface is expected to be the same as that of the standing waves inside the active region. These devices are studied in more details in Ref. [22].

The devices operate at room temperature under pulsed excitation and emit at a wavelength $\lambda \approx 7.7\ \mu\text{m}$. The laser ridge widths vary from 26 to 41 μm. The central region on each ridge where the active region is directly in contact with air is typically 10 μm narrower than the ridge itself.

3. Infrared apertureless SNOM: experimental set-up

The development of high transmission optical fibers in the mid-IR spectral range is still in its infancy, and their use in optical fiber SNOMs to map the near-field at wavelengths beyond 5 μm have been so far limited to a few attempts [23]. Apertureless SNOM (aSNOM) based on the scattering of the near-field by the tip apex of an atomic force microscope (AFM) does not require any optical guiding through a fiber. Hence, this technique has proven its ability to map mid-IR near-fields with a resolution as high as 10 nm [3]. For this study, we used a home made aSNOM, employing a quartz tuning fork, which can be operated across a very large range of the optical spectrum, from visible to infrared frequencies [24].

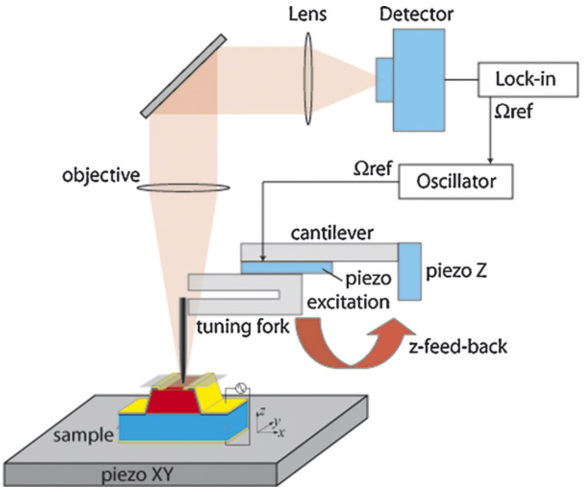

Fig. 2. Schematic view of the experimental set-up. The tungsten tip is mounted at the extremity of the tine of a quartz tuning fork. The piezoceramic plate is controlled with an ac voltage at frequency Ω_{ref} from an oscillator, which produces the mechanical excitation of the tuning fork; this induces a sinusoidal oscillation of the tip at the same frequency. Measuring the voltage on the tuning fork electrodes with a lock-in amplifier allows one to determine the tip oscillation amplitude. A feedback on the piezo Z maintains it at a preset value. Recording the feedback voltage during the lateral scans of the sample under the tip results in a topographic image of scanned area. During its oscillatory movement, the tip apex periodically scatters the evanescent field at the QC laser top surface. A microscope objective collects the scattered field modulated at Ω_{ref}, which is then focused on an HgCdTe infrared detector. The aSNOM signal is obtained by demodulating the signal from the infrared detector at frequency Ω_{ref}. Thus, the aSNOM allows one to record simultaneously a near-field mid-infrared image and a topographical image of the scanned area of the device. The scanned area is represented in grey on the figure.

Our aSNOM is coupled with an AFM whose tip oscillates orthogonally to the sample surface in *tapping-mode*. The tip is made of electrochemically etched 50-μm-diameter tungsten wire placed at the extremity of one arm of a quartz tuning fork. In turn, the tuning fork is glued sideways on a piezoceramic plate, as schematically depicted in Fig. 2. The piezoceramic plate is fed with a sinusoidal voltage at fixed frequency Ω in order to excite a mechanical resonance of the tuning fork. The amplitude of the oscillatory movement of the tip above the surface is monitored *via* the ac voltage on the tuning fork electrodes using a lock-in amplifier. The tip taps periodically onto the sample surface. An electronic feedback is implemented on the piezoelectric stage which controls the average height of the tip above the surface, in order to maintain the oscillation amplitude at a preset value. Thus, by measuring the feedback voltage while scanning the sample under the tip we are able to record the surface topography.

When an electromagnetic field is present at the surface, the tip scatters periodically the near-field at a frequency Ω. The scattered field is collected by a large numerical aperture infrared