A mid-infrared Lab-on-a-Chip: Generating, Guiding and Detecting Light in a Monolithic Device

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Abstract: We present a fully integrated mid-infrared sensor. The laser and detector are fabricated from a bi-functional quantum cascade structure, connected through a dielectric-loaded surface plasmon waveguide, which acts as interaction zone and provides high coupling.

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1. Introduction

Mid-infrared spectroscopy is one of the main techniques for chemical sensing and medical diagnosis. A challenging task is to make such systems accessible in remote areas, requiring the development of more compact and cost-effective sensing systems. So far, all miniaturized concepts have been demonstrated with external lasers or detectors. In our work, we demonstrate a integrated mid-infrared sensor, comprising a laser, a plasmonic waveguide and a detector on the same substrate. In order to reach this goal, we combine two major technologies customized for monolithic integration: quantum cascade structures and plasmonics.

2. Bi-functional quantum cascade laser/detector

Quantum cascade lasers are one of the most important compact coherent light sources in the mid-infrared, offering high power, engineerable emission wavelengths, room-temperature operation etc [1]. Going one step further, QCLs can be designed with detection functionality [2, 3]. Simply by changing the applied bias, this bi-functional quantum cascade laser/detector (QCLD) switches between laser and detector operation. Although such devices are limited due to wavelength matching, the further optimized device works at room temperature with a pulsed laser emission of 200 mW and a superior detection performance, compared to discrete quantum cascade detectors (one order of magnitude higher responsivity). The integrated detector has a responsivity of 45 mA/W (30% of the theoretic maximum), extremely low noise and does not saturate at QCL power levels, enabling high dynamic range sensing.

3. Dielectric-loaded surface plasmon polaritons in the mid-infrared

We utilize surface plasmon polaritons (SPPs) to efficiently guide light from the laser to the detector and to enhance the interaction with the evanescent decay into the environment, e.g. fluid. In the visible and near-infrared, plasmonics have already solved many fundamental problems in sensing, imaging and on-chip communication [4]. In this work, we focus on the mid-infrared region, enabling the direct observation of specific molecular resonances. As in this wavelength region metals have a large negative permittivity, mid-infrared SPPs are commonly very weakly confined. Their practical use requires special techniques to increase their confinement. Previously, this has been solved by patterning sub-wavelength resonant grooves into the metal surface. Here, we present an alternative way. By applying a thin (200nm thick) dielectric layer on top of an unpatterned metal surface, the propagation properties of the SPP can be modified in such a way, that the SPP is strongly bound to the interface [5]. This increased confinement enables an efficient end-fire coupling to the dielectric waveguide of the laser and the detector via spatial mode matching. As an additional advantage, the thin dielectric layer can be used to reduce the waveguide loss in narrow SPP waveguides. Commonly, SPP waveguides are fabricated as metal stripes to provide lateral guiding. Due to scattering on the metal edges the propagation length drops with decreasing stripe width. The obvious solution is to eliminate these metal edges, which can be achieved by patterning the thin dielectric layer as a strip on top of unpatterned gold. With this structure, we observe a coupling efficiency of up to 50%.

4. On-chip sensing of chemical fluids

In order to prove the function of our on-chip sensor, we put the entire device into a testing fluid consisting of two substances with a low and a high absorption coefficient at the laser emission wavelength. For this purpose we use ethanol (low absorption) and distilled water (high absorption). Figure 1 (right) shows the detector signal versus the ethanol concentration of the fluid. For specific applications, the quantum cascade structure and waveguide can be designed to cover the absorption lines of various chemical substances, which are then selected by DFB gratings. An on-chip spectrometer can den be fabricated with an array of these lasers with different grating periods.

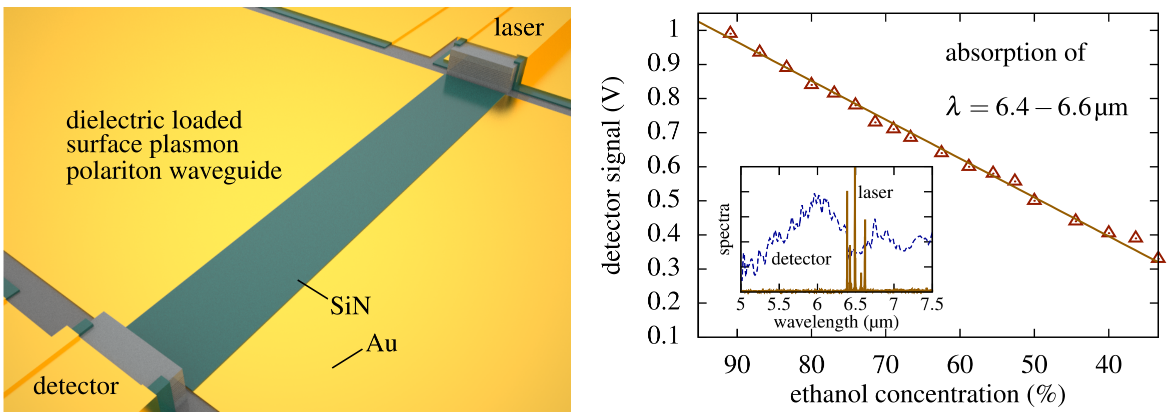

Fig. 1. Sketch of the fabricated device (left). Experiment measuring the absorption of a testing fluid (ethanol/water) with different concentrations (right). The inset shows the laser and detector spectra of the device.

5. Conclusion

We demonstrate a fully integrated mid-infrared sensor for high dynamic range sensing. A bi-functional quantum cascade laser/detector structure is used to generate and detect mid-infrared radiation. A dielectric loaded surface plasmon polariton waveguide is used to enhance the interaction with a fluid and in parallel provide a high coupling efficiency. Due to this high coupling and the good room-temperature performance of the quantum cascade structure, we observe detector signals around up to 1 V at 200 mW laser power, without amplification. As no additional fabrication technique is required, the entire device can be built with the same processing and costs as the mid-infrared laser alone.

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