# Plasmonic Laser Antennas and Infrared Molecular Sensors

**E. Cubukcu**

Department Material Science and Engineering
University of Pennsylvania
3231 Walnut St, Philadelphia, PA, 19104, USA
Fax: +1-215-8987975; email: cubukcu@seas.upenn.edu

**Abstract**

In this paper we describe two potential applications for plasmonic nanoantennas. The first application we discuss relies on the ability of optical nanoantennas to confine light to subwavelength dimensions. This property is utilized by directly integrating a nanoantenna on the facet of a commercial semiconductor laser. As a second application, we capitalize on the large local field enhancements offered by optical antennas to significantly increase the detection sensitivity of infrared absorption spectroscopies.

## 1. Introduction

The concept of the antenna has been widely explored in the microwave domain. However, their analogues for light, namely, the plasmonic or optical nanoantennas have been overlooked until recently for controlling and manipulating the flow of light. In optics, we use large diffraction limited components such as lenses to manipulate light beams. With the advent of nanofabrication techniques in the past decade, it is now possible to fabricate antennas for light. Optical antennas are expected to be nanoscale commensurate with the shorter optical wavelengths [1-4]. In addition, plasmonic nanoantennas have a different length scaling than their microwave counterparts (i.e. antenna length equals half the free space wavelength) due to the kinetic inductance of electrons at optical frequencies[2]. Plasmonic nanoantennas offer two key features, which are crucial for various applications including sensors, photovoltaics, and light-emitting devices. These are the field localization and the resonant field enhancement. When an optical antenna is excited resonantly with light, i.e. the wavelength is twice the effective antenna length, a dipole moment will be induced in the nanoantenna. The dipole field decays very fast away from the nanoantenna resulting in localized near fields. Near the nanoantenna the total field is the incident field plus the dipole field. When excited resonantly the dipole field can be many orders of magnitude larger than the incident field, which is the origin of the near field enhancement.

In recent years, a variety of schemes taking advantage of localized near fields generated by metallic nanoparticles have been proposed to use them as optical nanoantennas [1]. Optical or plasmonic nanoantennas consisting of nanometer size metallic particles can be used as a transducer to improve the size mismatch between the diffraction limited spot of the excitation light and molecules that are much smaller than the excitation wavelength.

In this section, we discuss a photonic device, the plasmonic laser antenna, which is essentially a semiconductor laser with a resonant optical antenna integrated on its facet. This device relies on the localized SP resonances of the optical antenna. Such a compact laser source with subwavelength spatial resolution provides distinct advantages in a number of applications including microscopy, spectroscopy, optical data storage, lithography, and laser processing. A schematic of the device is shown in Fig. 1(a). We fabricated, by focus ion beam (FIB) direct lithography, a coupled nanorod optical antenna structure that comprises a pair of gold nanorods separated by 30 nm on a facet of a commercial edge-

ISBN 978-952-67611-2-1

emitting laser diode operating at a wavelength of 830 nm. Since the output of the laser diode is polarized parallel to the quantum wells, the optical antenna was oriented accordingly to achieve resonant excitation.

Apertureless near-field scanning optical microscopy (a-NSOM) setup has been utilized for the mapping of the optical near-field distribution in the fabricated devices. In this technique, a sharp gold-coated atomic force microscope (AFM) tip with a typical radius of curvature of ~20 nm scatters the light from the near-field as it scans over the sample while simultaneously measuring the surface topography (Fig. 1(b)). Results of our NSOM measurements are displayed in Fig. 1(e). We determine the full width at half maximum of the central peak of the near-field intensity distribution to be 40 nm in the x direction and 100 nm in the y direction. Our device is capable of generating an intense optical spot that is localized within an area that is 50 times smaller than what one would obtain with conventional diffraction limited optics such as lenses. This is in addition to the large intensity enhancement that also occurs as predicted by finite difference time domain (FDTD) simulations (Fig. 1(c)).

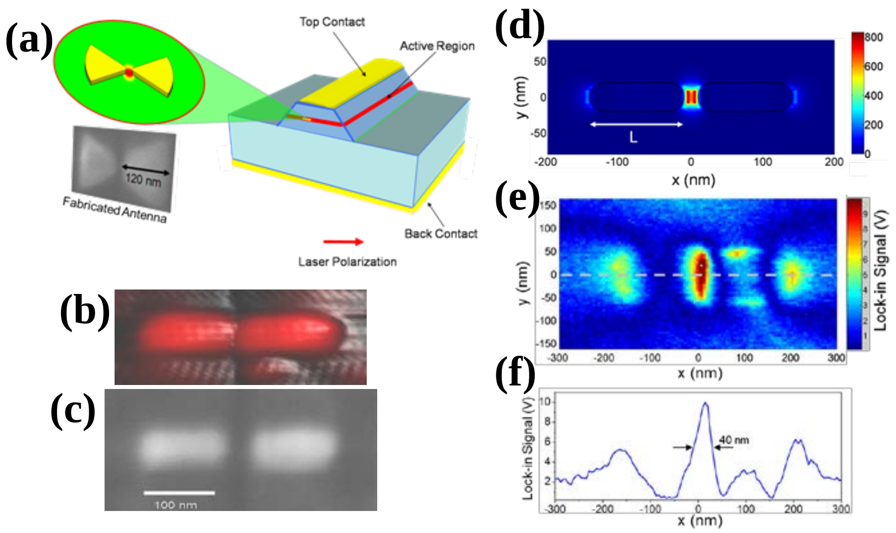


Fig. 1: (a) Standard configuration for the plasmonic laser antenna. (b) AFM topography of the characterized nanoantenna. (c) SEM image of the fabricated coupled nanorod antenna (d) FDTD calculation of the total near-field intensity generated by the nanoantenna. (e) Apertureless-NSOM image of the nanoantenna on the laser facet. (f) Line-profile of the near field measurement along the nanoantenna axis shown in (e). From Ref. 4.

Our approach is universal in the sense that the plasmonic laser antenna concept can be easily extended to mid-IR wavelengths using a quantum cascade laser. The mid-IR plasmonic laser antenna that provides a subwavelength optical spot would be significant for resolving nanometric features of biological and chemical specimen in the "fingerprint region" and for performing absorption spectroscopy with high spatial resolution.

Recently, a new approach for and surface enhanced infrared absorption spectroscopy (SEIRA)[5] that relies on Fano like resonances due to resonant coupling between optical nanoantennas and a monolayer of molecules has been introduced many authors[6, 7]. To this end, we report on use of split ring resonator, the building block for metamaterials due to their artificial magnetic properties, as optical nanoantennas for infrared detection of small number of molecules [8]. Here, we are interested in their ability to enhance electric fields in the near zone as plasmonic nanoantennas with a compact C-shaped footprint compared to their linear optical antenna counterparts. The split ring nanoantenna resonance occurs when the perimeter of the SRR loop is a half integer multiple of the wavelength of optical current circulating in the metal. Therefore the split ring nanoantenna resonance can be tuned by changing the radius and in turn the perimeter of the SRR. The other advantage of using split ring nanoantennas as opposed to regular nanorod antennas is that split ring nanoantennas naturally have a gap offering potentially larger nearfield enhancements, which is crucial for sensors.

 

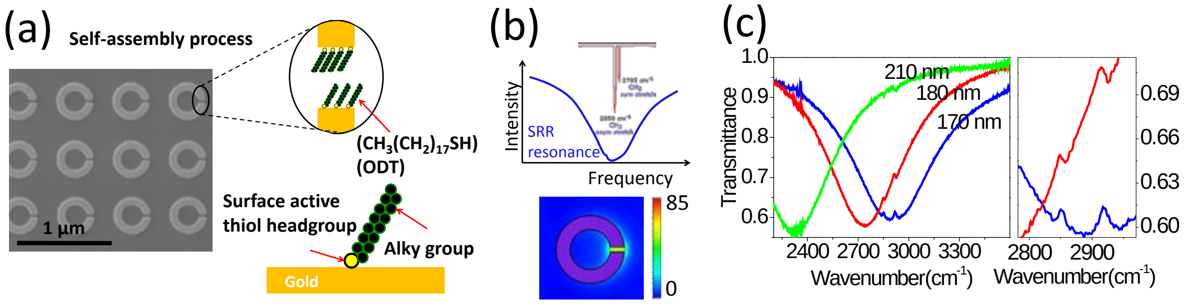


Fig. 2: (a) SEM image of the C-shaped nanoantennas and the schematic of the molecular self-assembly process. (b) Strong spectral overlap between the molecular vibration modes and the nanoantenna resonance. The bottom panel shows the calculated near-field amplitude profile. (c) Measured infrared transmission spectra for three different nanoantenna arrays with the molecules adsorped on the gold surface. The panel on the right is a close up view of the region that contains the stretching modes of the ODT molecule. From Ref. 8.

We fabricated arrays of C-shaped nanoantennas with different radii. When the resonance of the nanontenna matches the vibrational stretching modes of the self-assembled molecules, the incoming infrared radiation can be efficiently delivered to the molecules facilitating the absorption process. For the case of strongest resonant coupling (r=170 nm), the contrast between the maximum and the minimum transmittance at the antisymmetric vibrational frequency is about 1.9% corresponding to ~20,000 molecules per nanoantenna (Fig. 2(c)).

In summary, we demonstrated that optical nanoantennas can be utilized in two different applications for their ability to enhance and localize electromagnetic radiation. Plasmonic laser antennas relying on the strong confinement offer sub-100 nm optical spots enable new potential application the microscopy and data storage. Split ring resonator sensors that offer infrared detection of ~20,000 per element take advantage of strong light-matter interaction facilitated by strongly enhance electromagnetic fields. By utilizing an infrared detection with a higher signal to noise ratio, detection of single molecules can be possible.

**References:**

[1] L. Novotny, and N. van Hulst, “Antennas for light,” Nature Photonics, 5(2), 83-90 (2011).
[2] L. Novotny, “Effective wavelength scaling for optical antennas,” Physical Review Letters, 98(26), 266802 (2007).
[3] P. Muhlschlegel, H. J. Eisler, O. J. F. Martin *et al.*, “Resonant optical antennas,” Science, 308(5728), 1607-1609 (2005).
[4] E. Cubukcu, N. F. Yu, E. J. Smythe *et al.*, “Plasmonic Laser Antennas and Related Devices,” Ieee Journal of Selected Topics in Quantum Electronics, 14(6), 1448-1461 (2008).
[5] J. Kundu, F. Le, P. Nordlander *et al.*, “Surface enhanced infrared absorption (SEIRA) spectroscopy on nanoshell aggregate substrates,” Chemical Physics Letters, 452(1-3), 115-119 (2008).
[6] F. Neubrech, A. Pucci, T. W. Cornelius *et al.*, “Resonant Plasmonic and Vibrational Coupling in a Tailored Nanoantenna for Infrared Detection,” Physical Review Letters, 101(15), (2008).
[7] R. Adato, A. A. Yanik, J. J. Amsden *et al.*, “Ultra-sensitive vibrational spectroscopy of protein monolayers with plasmonic nanoantenna arrays,” Proceedings of the National Academy of Sciences of the United States of America, 106(46), 19227-19232 (2009).
[8] E. Cubukcu, S. Zhang, Y.-S. Park *et al.*, “Split ring resonator sensors for infrared detection of single molecular monolayers,” Applied Physics Letters, 95(4), (2009).

 