# Optical Antennas for Vector Near-field Imaging

**Robert L. Olmon[1,2], Laxmikant Saraf[3], Peter. M. Krenz[4], Glenn Boreman[4], Markus Raschke[1]**
*[1]Department of Chemistry, University of Washington, Seattle, Washington*
*[2]Department of Electrical Engineering, University of Washington, Seattle, Washington*
*[3]Pacific Northwest National Laboratory, Richland, Washington*
*[4]Center for Research and Education in Optics and Lasers (CREOL), University of Central Florida, Orlando, Florida*
*E-mail: raschke@chem.washington.edu*

**Abstract:** A new method for nano-engineering the optical antenna properties of scanning probe tips by combining focused ion beam milling with nano-CVD is presented. We demonstrate the capabilities by probing specific vector-field components of plasmonic nanostructures.

**OCIS codes:** (180.4243) Near-field microscopy; (220.4241) Nanostructure fabrication

## 1. Introduction

Efficient design and optimization of nanoscale photonic and plasmonic devices for use in such applications as optical circuits, plasmonic waveguides, metamaterials and molecular spectroscopy relies on the complete characterization of the optical response of the devices. Measurement of the optical vector near-field through scanning probe methods is therefore highly desirable as it reflects the surface optical polarization density, and thus the source term for the optical response that represents the functionality of the device. Investigations have been conducted utilizing atomic force microscope (AFM) tips as local scattering probes or antennas for projecting the highly localized near-field amplitude and phase information of optical nanostructures into the far-field for detection, giving insight into inhomogeneous polarization distributions with spatial variations on nanometer length scales [1], resonant mode patterns in infrared (IR) optical antennas [2], the spatial confinement of enhanced fields [3], and standing wave patterns of surface plasmon polaritons [4], for example.

However, the complete characterization of optical vector fields of nanoscale structures has remained difficult, since with high-resolution optical scanning probe techniques (e.g. scattering-type scanning near-field optical microscopy, or *s*-SNOM), the detected near-field signal is highly dependent on the polarizability of the probe tip and the tip-sample coupling which are a function of the geometric and material parameters of the tip [4].

Here we present a new technique for creating a scanning probe capable of measuring specific vector near-field components by optimizing the optical antenna properties of the probes. This enables full characterization of the optical field of the system of interest. Specifically, combining focused ion beam (FIB) milling [5] with metallization by electron beam induced chemical vapor deposition (nano-CVD) we adapt existing FIB fabrication methods to systematically optimize the probe parameters with respect to scattering efficiency, spectral characteristics, and polarization selectivity.

To demonstrate the capabilities of this technique, we engineer the scattering properties of a silicon probe to gain systematic access to the near-field component polarized perpendicular to the tip axis. This allows for the first time to systematically probe the elusive in-plane field component of the coupled dipole optical antenna [1,3] in the mid-IR. By 3D tomographic near-field imaging we find a significant spatial extent of both the in-plane and out-of-plane field components above the antenna gap which has implications for nanofocusing applications where the gap field is to be used as a highly confined light source.

## 2. Experiment and Results

The scattering optical probe tip is engineered from a forward pointing silicon AFM tip by FIB milling to create a 120 nm wide plateau at the apex. A platinum layer typically 50-80 nm thick and 80-120 nm wide is then grown at the end of the probe by CVD to enhance the scattering efficiency for field components polarized perpendicular to the tip axis, while diminishing the scattering efficiency for tip-parallel excitation. Figure 1(a) illustrates the general fabrication process showing SEM images for the original probe (left), milled probe (middle), and the probe after deposition (right) with color overlayed to delineate platinum regions (yellow) from silicon regions (red).

To demonstrate the functionality of the probe, linear gold dipole antennas 1.6 µm long, 80 nm high and approximately 200 nm wide were fabricated with a 5 nm titanium adhesion layer on a silicon substrate by electron beam lithography. The antennas were arranged as collinear dimers with gaps of approximately 100 nm to take advantage of the highly localized in-plane capacitive field between adjacent antennas. Amplitude and phase information is extracted by homodyne detection using *s*-SNOM with illumination from a 10.6 µm $CO_2$ laser polarized along the antenna axis as indicated in Fig. 1(b). Detected light is demodulated at the second harmonic of the AFM tip-sample dither frequency by a lock-in amplifier to discriminate the desired signal from the background.

Figure 1(c) shows the antenna topography (top) with corresponding optical images of the $E_y$ field component measured by a modified probe (middle) and the $E_z$ field component measured by an unmodified platinum coated probe (bottom). Optical contrast is produced by both the intensity variation of the near-field as well as interference of the near-field with the homodyne reference field. This phase contrast is seen in the $E_z$ image as the antenna surface polarization interferes constructively (white regions) and destructively (black regions) with the reference field as shown previously [2]. The experimental results are in excellent agreement with simulations of the optical antenna response to a 10.6 μm plane wave performed using HFSS (Ansoft Corp.), as shown in Fig. 1(d) for an incident electric field amplitude of 1 V/m.

The technique shown here of tuning the optical response of probe tips by nano-machining and -lithography is generally applicable to probe any desired near-field component even for complex antenna geometries, arrays, or photonic crystals. It is advantageous over the conventional approach using unmodified or tips with isotropic nanoparticles as scattering probes, providing enhanced sensitivity, controlled tip-sample coupling, and in principle spectral selectivity and even directivity for the scattered near-field for improved signal detection.

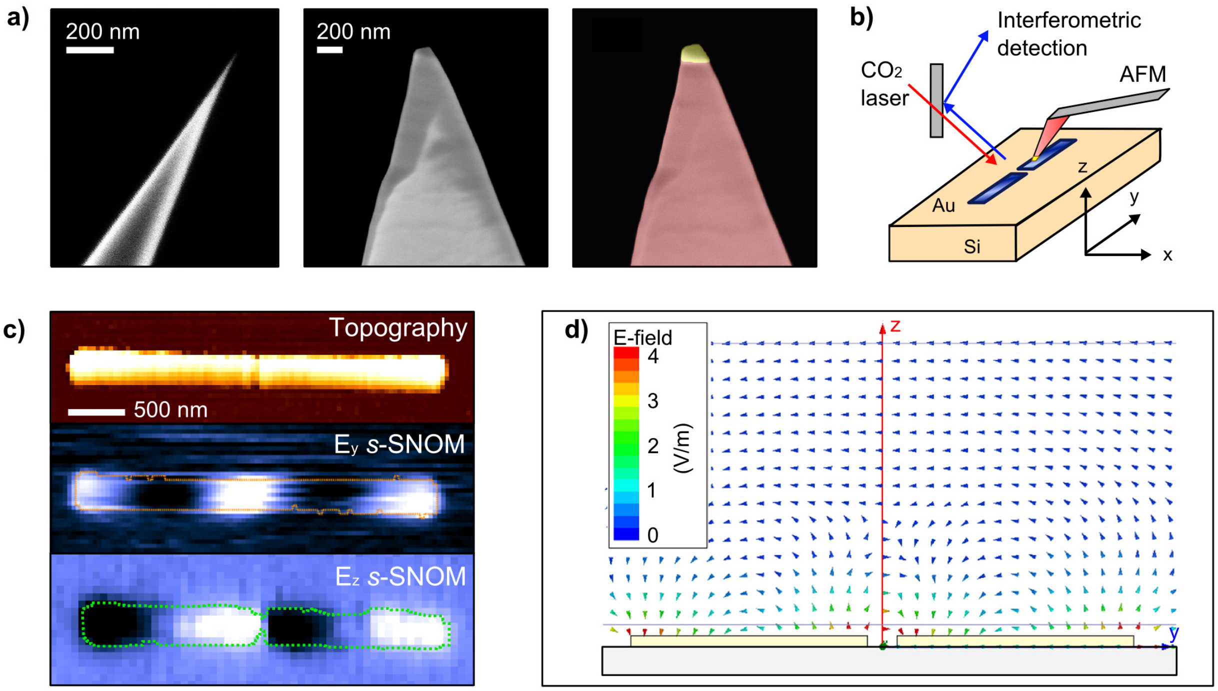

Fig. 1. Probe engineering process (a) showing the original probe (left), the FIB milled probe (middle) and the probe after platinum deposition (right) colored to indicate platinum growth (yellow) and silicon (red). (b) A schematic diagram of the experimental setup. (c) Antenna topography (top), and *s*-SNOM signals of the $E_y$ (middle) and $E_z$ (bottom) near-field components probed with a modified tip and an unmodified tip, respectively. (d) Simulated electric field vectors near an excited coupled dimer antenna.

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