Near-field Mapping of Infrared Optical Antennas

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Abstract: The near-field distribution of linear optical antennas is measured with phase-contrast scattering-type near-field microscopy (*s*-SNOM). A distinct scaling behavior with antenna length is observed for different structures with and without gap.

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The developments in nanoscale fabrication techniques have enabled the creation of individual structures small enough to interact with light in much the same way as classical antennas interact with radio frequency (RF) electromagnetic waves [1,2]. In this regard, optical antennas can provide subdiffraction limited control of the spatial light localization providing new tools for sensing and microscopy applications and becoming indispensable components for radiation coupling into nanophotonic waveguides and devices.

The targeted design of optical antennas with desired functionality, however, has remained challenging and the near-field and radiative characteristics of the different structures proposed are not completely understood. This is because classical antenna concepts are not directly applicable due to design approximations that fail in the optical frequency range making the scaling of RF antenna theory difficult. This includes the common RF assumption of perfect conductivity, i.e., zero skin depth, of the antenna elements in contrast to the finite conductivity and thus light penetration into the structure. Likewise linear RF antennas may often be assumed to have negligible thickness with respect to the wavelength – a condition not only difficult to obtain experimentally in the optical regime but also undesirable due to an associated increase in ohmic loss. In contrast, the possibility for the excitation of the geometry dependent surface plasmon modes in the optical regime permits new resonant conditions.

In order to provide a systematic understanding of the optical antenna resonances and their dimensional scaling we investigate the optical near-field using scattering-type scanning near-field optical microscopy (*s*-SNOM). *s*-SNOM provides ultrahigh spatial resolution down to 10 nm and give access to the vector field distribution including the optical phase by homodyne detection and polarization selective excitation and probing. With the in general high sensitivity with respect to the structural details of the antenna geometry, here, we focus on the mid infrared spectral region.

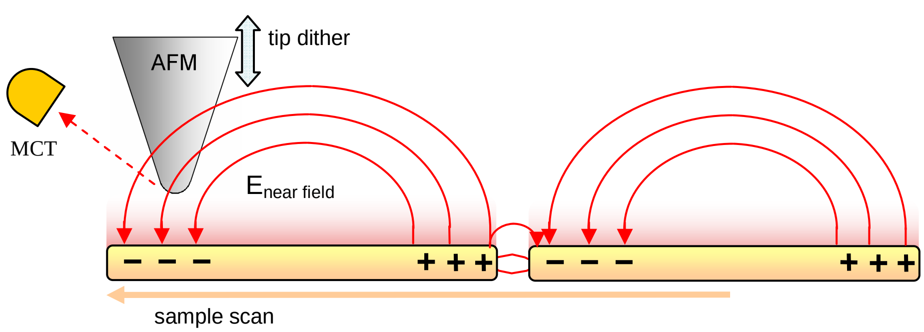

Fig. 1. A schematic of the atomic-force microscope based scattering-type near-field probing (*s*-SNOM) of the antenna near-field distribution with nanometer spatial resolution and optical phase, amplitude and polarization resolution.

Linear antennas were designed with lengths varying from 1.5 to 7.0 μm with and without center gaps of different width in the 100 nm range. They were fabricated by electron beam lithography with a 70 nm gold layer on silicon with a 5 nm seed layer of titanium. For the *s*-SNOM measurements the antennas are illuminated with 10.6 μm CO_2-laser radiation polarized parallel or perpendicular with respect to the long axis of the antenna. As shown schematically in Fig. 1, the tip-scattered near-field light by the atomic force microscope probe is detected by a mercury-cadmium-telluride (MCT) detector. The near-field signal of the antenna is discriminated from the far-field background by signal demodulation at the first- and second-harmonic of the cantilever tip-sample dither frequency using lock-in detection.

Fig. 2 shows the second-harmonic *s*-SNOM image and topography (beneath each) from three linear Au rods of length 1.6 μm (a), 3.35 μm (b), and 4.5 μm (c). The data are normalized with respect to the maximum and minimum near-field signal of each structure. The different signal levels within each scan represent a different relative optical phase. It is evident that a pure dipolar behavior is supported up to a critical length of < 3.4 μm which corresponds to $\lambda_{eff}/2$ with λ_{eff} ~6.8 μm (i.e. λ_{eff} < 10.6 μm). Beyond this critical length the antennas exhibit multipolar modes as seen in Fig. 2c).

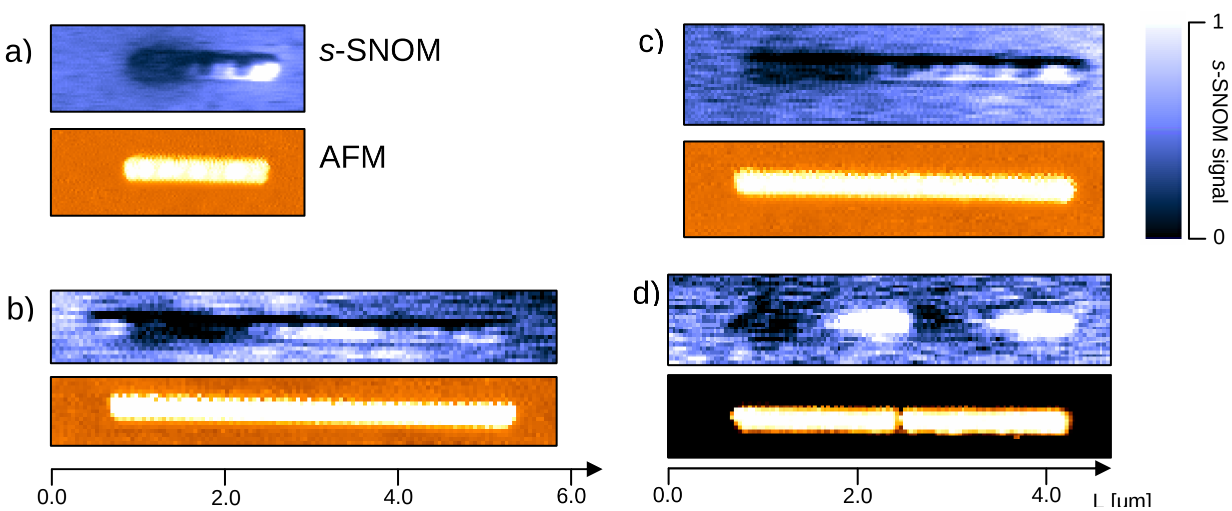

Fig. 2. Phase sensitive second-harmonic *s*-SNOM signal at $\lambda_{incident}$ = 10.6 μm from linear Au rods of length 1.6 μm (a), 3.35 μm (b), and 4.5 μm (c) for parallel polarization. Up to a critical length the rods support a dipolar excitation (a and b) giving way to a multipolar pattern for longer rods (c). With the introduction of a gap into the 3.35 μm structure the dipolar pattern disappears with the response resembling that of two short coupled dipoles (d). Note: lighter versus darker regions in the optical images represent different relative optical phase. No corresponding resonant behavior is observed for perpendicular polarization.

In contrast Fig. 2d) shows the *s*-SNOM near-field images of a 3.35 μm (total length) antenna, this time with a center gap of width 150 nm. Notably, the optical response does not correspond to a single optical dipole but instead resembles that of two (coupled) individual optical dipoles of shorter length equivalent to the one shown in Fig. 2a).

While the gap itself gives rise to an enhanced local field – useful in its own right for sensing applications – the data show that the gap presents a disruption of the current flow and thus a reduced radiative efficiency of the antenna as suggested previously [3]. Just like in RF linear dipole antennas, where the circuitry of the transmitter or receiver compensate for the gap through impedance matching, for radiative coupling to nanophotonic devices, similar concepts need to be developed for optical antennas.

References:

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