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Optical nanoantennae: bridging the far-field to the near-field

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Pairs of nanopatterned metallic ellipses form antennae that couple optical radiation with localized excitations and enhance fluorescence, with possible applications including biosensing and optoelectronic integration.

One's first experience with an antenna often involves nothing more than positioning one or two metal wires 'just right' to capture an invisible television signal. 'Rabbit ears' on top of televisions are simple dipole antennae that capture meter-long electromagnetic waves. Because Maxwell's equations are independent of length scale, the dipole antenna can be miniaturized to operate with shorter-wavelength radiation. Optical nanoantennae are small metallic particles that resonate at visible and near-IR frequencies. Analogous to conventional antennae, nanoantennae hold the promise of transferring optical radiation to and from nanosized structures and devices.

Light shining on a metallic nanoparticle can cause its electrons to oscillate in what is called a localized surface-plasmon resonance (LSPR). When two particles are close to each other, their dipole-like oscillations interact, creating a system analogous to the half-wave dipole antennae with a feed gap in the middle. Modern fabrication techniques let researchers create optical antenna systems with a desired resonance wavelength by controlling the particle size and shape, the distance between particles, and the choice of metal and host materials.[1] LSPRs also exhibit large electromagnetic-field enhancements, with the largest enhancement, for coupled particles, in the antenna gap.[2]

We make optical nanoantennae using electron-beam lithography, vacuum deposition of gold, and lift off.[3–5] The results are well-defined pairs of elliptical cylinders that are either regularly packed in an array, as show in in Figure 1, or isolated to permit study of a single pair. By selecting the geometry and host dielectric, we can choose the primary antenna resonance wavelength (for light polarized along the ellipses' common axis) anywhere from the red through the near-IR.

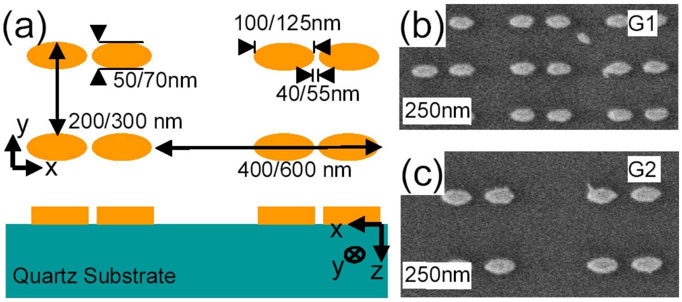

Figure 1. *(a) Schematic top and side views of an optical nanoantenna sample, showing dimensions for two geometries. (b) and (c) Electron microscope images for geometries denoted G1 and G2.*

The resonance properties of optical nanoantennae have been mapped with subwavelength resolution. Illumination mode near-field scanning optical microscopy (NSOM) has shown the resonance to depend strongly on polarization and particle geometry.[3] Finite-element modeling is used to complement our experiments, to explore field mapping beyond the experimental capabilities and to optimize geometries for field enhancement.[3,4] We have observed reciprocity in the nanoantenna response. Field enhancements around the antennae are similar for local, near-field excitation and for far-field excitation by plane waves.

Because future devices will integrate optical nanoantennae with localized emitters such as molecules (for biosensing) or quantum dots (for optoelectronics), it is important to study the interactions between the two.[5] We placed a fluorescent Rhodamine 800 dye (Rh800) inside a dielectric host in a thin film on top of a nanoantenna-array sample. The dye emission spectrum overlaps with that of the LSPR, and thus excites it. Feedback between the localized emitter (the dye in this case) and the LSPR results in enhanced fluorescence intensity. Figure 2(a) compares the far-field Rh800 fluorescence signal in the thin film away from any antennae with enhanced fluorescence when the film overlies antenna arrays with two different geometries. As a function of wavelength, the enhancement factor ranges from 20 to 100. Figure 2(b) and (c) shows near-field mapping of enhanced fluores-

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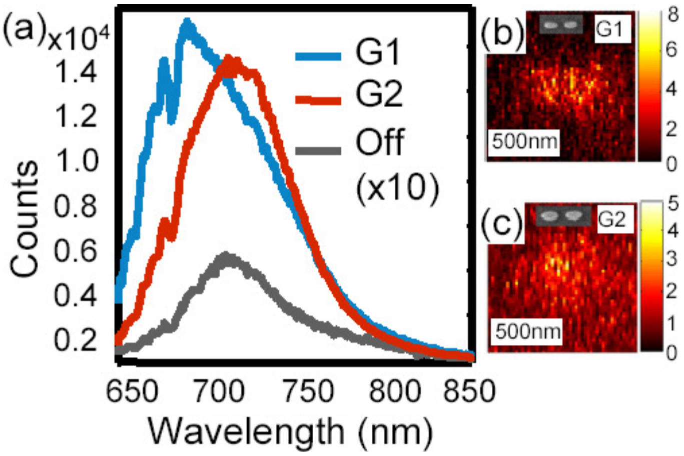

Figure 2. *Nanoantenna-enhanced fluorescence. (a) Far-field enhanced fluorescence as a function of wavelength, for a 633nm pump wavelength, for Rh800 dye interacting with arrays of antennas with G1 and G2, compared with nonenhanced fluorescence (Off, shown multiplied by 10). (b) and (c) Near-field mapping of enhanced fluorescence for an isolated antenna with G1 and G2, respectively. Insets show the antenna structure for reference.*

cence around isolated pairs. The localized enhancement is confined to a subwavelength area as small as $0.15\mu m^2$. Additional measurements show that the Rh800 excitation decays three times faster when it interacts with the LSPR, and that the enhanced emission is highly polarized along the primary antenna axis, as in a conventional antenna.

Optical nanoantennae hold great promise for bridging the divide between the nanoscale environment of current and future devices and optical wavelengths that are one or two orders of magnitude larger. Like a dipole antennae, the nanoantenna concentrates optical energy into a subwavelength volume, or alternatively allows localized energy to be efficiently radiated. Alongside localized photodetectors or emitters, nanoantennae will find applications in nanoscale integration of optoelectronics and biosensing devices. To help make such devices a reality, our future plans include improving the fabrication of nanoantennae to increase electromagnetic field enhancement and the resonance quality factor along with investigating different localized emitters such as quantum dots.

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