Optical nano-antennas as a key-connection between the nanoscale and optical fibers.

T. Grosjean

FEMTO-ST Institute, UMR CNRS 6174, Besançon, France
thierry.grosjean@univ-fcomte.fr

The wavelength is a central parameter in optics. Besides its direct relationship with colors and photon energy, it defines the limit between two different optical regimes. Optics at scales larger than the wavelength is directly perceived with our eyes. It involves free space propagating light (under the form of plane waves, spherical waves, etc.) and is nowadays involved in an extremely broad panel of scientific, medical and industrial researches and applications ranging from astronomy to microscopy. Optics at subwavelength scale involves another type of optical waves, called “evanescent waves”, which are bound to object surfaces and cannot leave them to propagate in free space. They are thus undetectable with lenses and cameras. These non-radiative waves originate a large panel of extraordinary optical phenomena that only exist at subwavelength scale [1].

With the advent of scanning near-field optical microscopies (SNOM), the eighties witnessed a turning point in the investigation of the subwavelength scale optics [2]. SNOM enabled to overcome the resolution limit of microscopy (half the wavelength, i.e. about 200 nm), thus resolving deeply subwavelength size objects and unraveling the extraordinary phenomena of sub-diffraction optics. Breaking down diffraction barrier has been rendered possible by replacing the objectives of conventional microscopy by sharp tip probes, whose apexes were positioned very close to the sample surface to either detect or generate evanescent waves in a raster scan mode. Rapidly, “near-field” tips extended their initial role of pure imaging elements to become systems capable of measuring and structuring the matter on the nanometer scale. Nano-optics emerged from these pioneering researches, and can thus be seen as the direct continuation of the near-field optics.

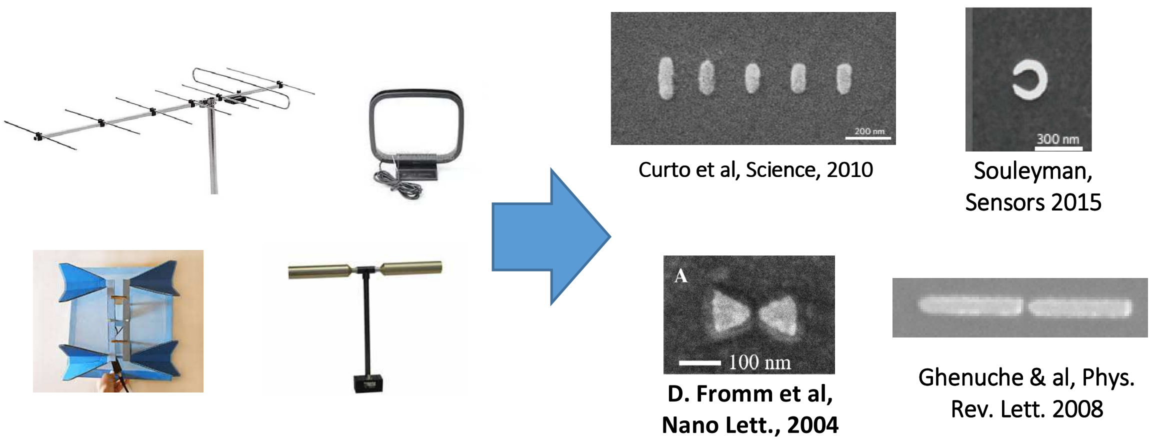

Figure 1: Four examples of antennas operating at radiofrequency and microwave regimes (left panel) and their optical counterparts (called nano-antennas) (right panel).

Research in nano-optics is aimed at understanding the optical phenomena at the subwavelength scale. It essentially relies on the ability to control light-matter interaction on the nanometer scale with specifically designed nanostructures. The improvement of nanoscale fabrication technologies in the past decades has for instance allowed the investigation of giant optical phenomena on metallic nanoparticles, leading to the concept of nano-antennas [3].

Nano-antennas are the result of the extension to optics of the well-known concept of electromagnetic antennas used at lower frequencies (radio and microwave frequencies) (Fig.1). As their low frequency counterparts, nano-antennas are aimed at efficiently interconnecting free-space propagating electromagnetic waves (here, light) with highly localized sources and fields. They provide interfaces to make the nanoworld efficiently communicate and interact with the macroscale. The ability of nano-antennas to concentrate light on the nanometer scale is for example widely exploited to locally enhance inherently weak optical effects and to control the emission from fundamental light sources, such as fluorescent molecules, quantum dots, fluorescent particles, etc. Remarkably, nano-antenna's optical properties can be finely tuned by slightly changing the shape and size of their constitutive metallic parts. Such a property enables the accurate engineering of light-matter interaction and its ultimate control well beyond the diffraction limit, thus impacting vast scientific and potentially economic domains.

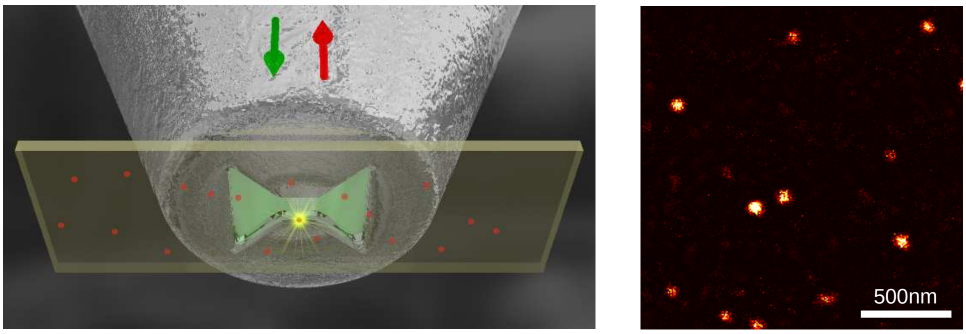

Figure 2: First imaging of single PbS colloidal quantum dots emitting at telecommunication wavelengths. The SNOM nanoprobe is a double resonance bowtie aperture nano-antenna at the end of a fiber tip (left panel). It is positioned close to a sample consisting of PbS colloidal quantum dots deposited on a microscope cover slip. The quantum dots (point-like emitters) are represented by red dots. During raster scan, the nano-antenna locally illuminates the quantum dots (in-fiber illumination) and locally collects the fluorescence photons (in-fiber collection). The green and red arrows illustrate this fully fibered imaging process and the related nanoscale two-way communication channel provided by the nano-antenna. Right panel: image of single PbS quantum dots emitting at telecommunication wavelengths (λ=1.5 µm) [7].

Bulky optics (objectives, lenses, microscopes) are usually unavoidable to deliver light from a macroscopic external source to nano-antennas, or to collect and transfer outcoupled signals from nano-antennas to a remote detector. Another option is to graft a nano-antenna at the end of an optical fiber, the nano-antenna becoming an optical interface between the nanoscale and fiber networks [4]. Engineering a nano-antenna at the apex of a SNOM fiber tip holds promise of nanoscale optical systems free from bulky optics.

I will first introduce the concept of nano-antenna. I will present the significant contribution of nano-antennas to SNOM, but also what SNOM techniques have brought to the investigation of light-matter interaction with nano-antennas. The integration of nano-antennas at the apex of SNOM fiber tips enabled the implementation of a new generation of nano-probes capable of extracting a more intense and richer signal from the "nano-world", thus significantly extending and improving our "optical" vision at extremely small scales (Fig. 2) [5-7]. Reciprocally, SNOM techniques allowed the integration of nano-antennas into ultra-compact, mobile and turnkey optical benches for the fabrication and manipulation of tiny objects [8]. New concepts of fiber integrated sensors also emerged from the combination of optical antennas and optical fibers [9,10]

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