Optical Nano-Antennas

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Over the past few years, an exciting development in nano-optical research has set in with the recognition that metallic nanoparticles with their plasmon resonances may be used in a fashion very similar to the way electrical engineers of the twentieth century have developed radio-frequency (RF) antennas. This introduces the concept of optical nano-antennas. Following many of the same rules that apply to RF antenna design, also the properties of optical nano-antennas can be tailored to fulfill desired functions.

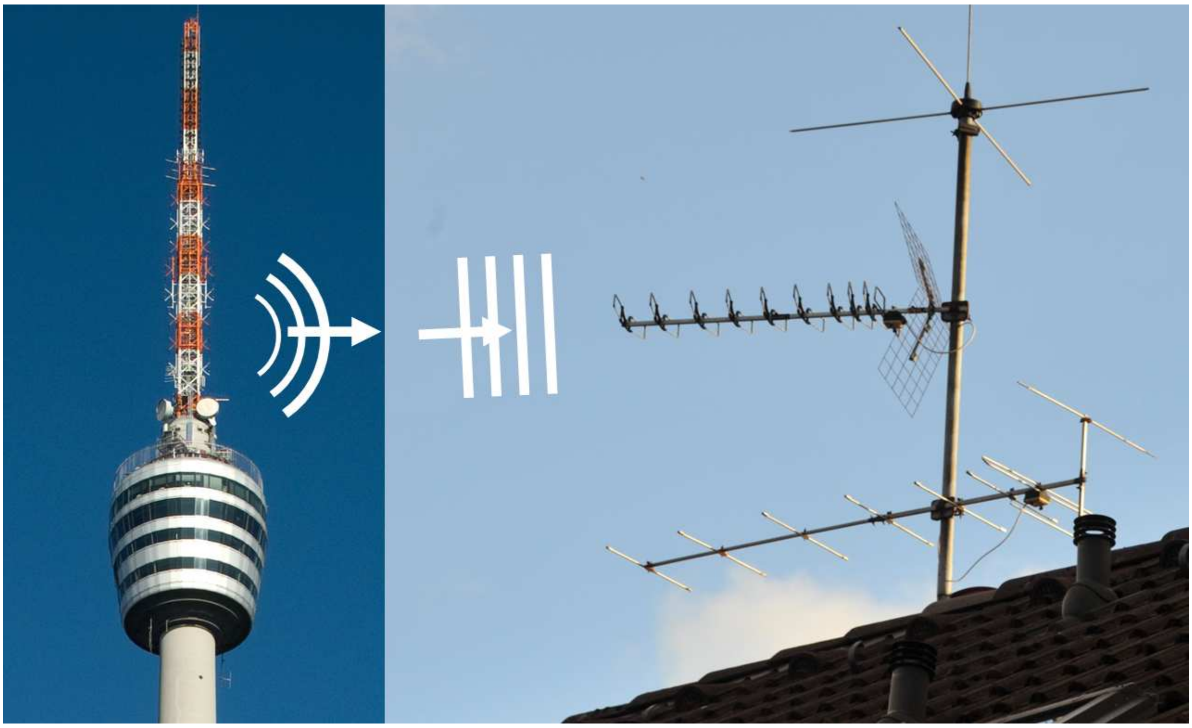

Figure 1: The conventional scheme for Radio-Frequency (RF) communication achieved by RF antennas. A popular type of receiving antenna is the Yagi-Uda antenna. On the right, two such antennas are displayed, pointing in different directions. Both consist of one active element (a folded-dipole), a passive reflector, and several passive director elements. Their line of sight indicates the direction towards an emitting radio tower, such as the famous radio tower of Stuttgart, Germany, seen on the left.

Like their RF counterparts, nano-optical antennas may be seen as impedance matching devices between free space radiation and the radiation/photon source. In receiving mode the antenna is able to confine free space radiation to a subwavelength region in the vicinity of the structure. With the control of emission rates and directions of quantum emitters like individual molecules or quantum dots at the nanoscale – enabling efficient coupling to more conventional optical technologies – could have technological applications in building single photon detectors on the nanoscale. This is especially interesting for the development of the sources needed in quantum cryptography.

A particularly promising geometry for tailoring the emission pattern is the Yagi-Uda antenna design, named after Shintaro Uda and Hidetsugu Yagi from Tohoku University, Japan, who patented their concept in 1926. Yagi-Uda antennas used to be ubiquitous sights in urban landscapes. Being the most popular choice in terrestrial TV and radio broadcasting systems, nearly every rooftop featured one or more of these devices (Figure 1). To this day, they are widely used in RF communication because of their high maximal directivity.

Operational implementations of nano-optical antennas have only recently been demonstrated in emission mode. Antenna directionality was nicely proven in these works by far-field spectroscopic imaging of the reciprocal space. In our work we investigate experimentally the properties of nano-optical antennas in reception mode with a near-field microscope. This allows us to draw direct conclusions about the exact antenna mode of operation, which may otherwise only be inferred from simulations mimicking experimental results. Having studied individual antenna elements in the past [1], we recently began fabrication and characterization of a variety of Yagi-Uda antennas [2,3]. In Figure 2 we show representative results from measurements with our cross-polarization apertureless Scanning Near-field Optical Microscope (aSNOM).

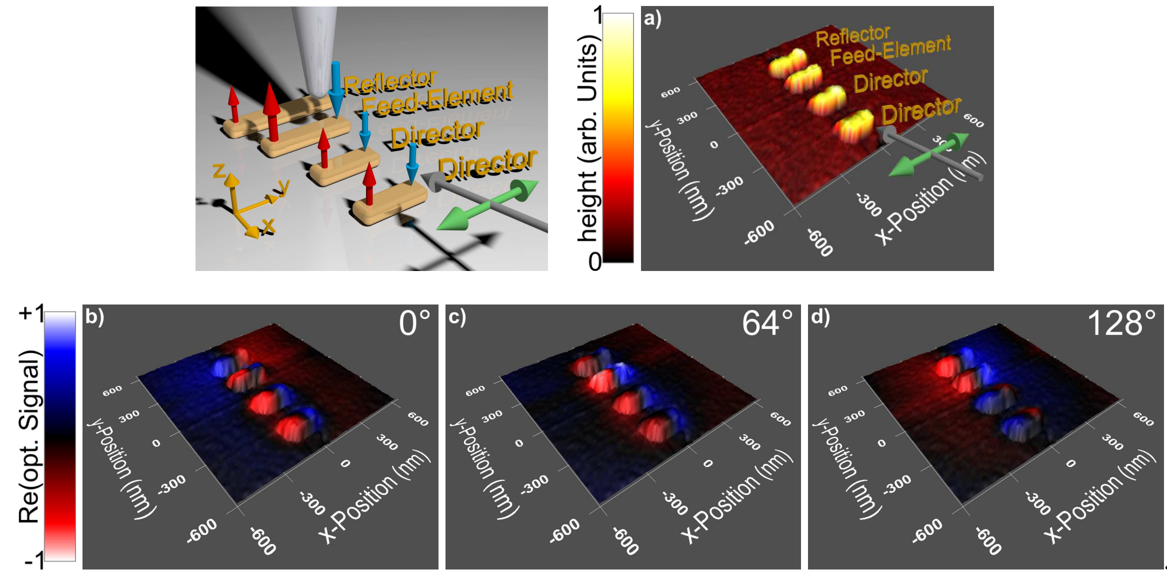

Figure 2: (a) Composition of a nano-optical Yagi-Uda antenna and experimental setup: The nanoantenna is fabricated on a glass substrate and illuminated by a weakly focused s-polarized (green arrow) radiation (λ = 1064 nm) under an oblique incident angle (grey arrow). The normal components of the near-fields surrounding the antenna elements (blue and red arrows) can couple to a mode of a sharp AFM tip. They are scattered back and recorded in the far-field. The measured 3D-topography is shown on the right. (b-d) real part of the optical signal superimposed onto the topography at different incidents of time: (b) 0° phase, (c) 64° phase, (d) 128° phase.

With the aSNOM being able to measure both amplitude and phase, we can reconstruct the field evolution of the time-harmonic reception processes. Figure 2b-d show the real part of the E-fields measured above the antenna at different snapshots in time. The electric field strength at the specific incident of time is color coded as texture on top of the 3D topography shown in Figure 2a. Figure 2b shows the fields at the incident of time that we denominate with the phase of 0° where the two directors light up. The two directors show one positive and one negative field lobe with a field node in between them. The feed element shows a rather weak field amplitude, indicating that the fields are close to the point in time where the sign of the field amplitude flips. Interestingly, the reflector shows a dipole pointing in the opposite direction with respect to the directors. Figure 2c shows the situation 64 phase degrees later in time. All antenna elements show the same color scheme, indicating that the dipole moments have the same orientation. The feed element is at its maximum field strength, brighter than all the other elements at any time. Finally, Figure 2d shows the E-fields another 64° later where the reflector reaches its maximum. The field strength of the feed element is already declining and the dipole moments of the upstream lying directors have already flipped.

The far-field directivity of an antenna emission can also be studied by nearfield optical microscopy. It is quantified by the expression

$$D(\theta,\phi) = 4\pi \frac{P(\theta,\phi)}{\int P(\theta,\phi) d\Omega}$$

which is the power $P(\theta,\phi)$ per unit solid angle emitted in a given direction divided by the emitted power per solid angle by an isotropic source of equal total radiated power. Thanks to the Rayleigh-Carson reciprocity theorem, a highly directive emission antenna is also able to collect radiation efficiently from defined directions. Thus, by investigating a given antenna under illumination from different directions, the directivity can be mapped out.

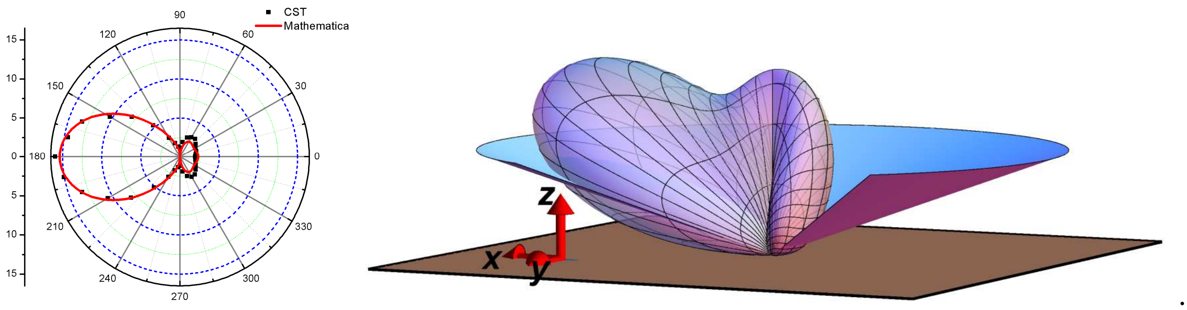

Figure 3: The emission pattern of a substrate supported Yagi-Uda nanoantenna coupled to a dipole emitter. Left: Horizontal cut through the emission pattern of Yagi-Uda antenna on the air side of the substrate under the angle accessible to our aSNOM. Right: 3D plot of the emission pattern. The cone indicates the illumination angle of our setup.

Figure 3 shows a typical directivity plot. Our oblique incident illumination scheme gives us access to a cone-shaped part of the radiation pattern with an opening angle of approximately 140° as indicated on the right. The conical cut through the emission pattern shown on the left exhibits a strong directionality. When we extract the reception characteristic for illumination under varying angles, taking the supporting substrate into account, we observe excellent qualitative agreement.

In summary, we have experimentally observed the detailed function of nano-optical Yagi-Uda antennas in the nearfield. Such structures show strong directionality in receiving mode. In the phase channel of our near-field images we observe the capacitive coupling of the director elements and the inductive coupling of the reflector element. Upon forward illumination of the antenna, the constructive interference of scattered light by these elements leads to a strong field enhancement at the position of the feed element.

The interpretation of amplitude and phase dynamics of the Yagi-Uda nanoantenna elements is analogous to their RF counterpart. This suggests that modification of existing RF antenna theories should make it possible to transfer most of the RF engineering design rules also to nanoantennas.

References:

[1] Dorfmüller, J.; Vogelgesang, R.; Weitz, R. T.; Rockstuhl, C.; Etrich, C.; Pertsch, T.; Lederer, F.; Kern, K. *Nano Lett.* **2009**, *9*, 2372–2377.

[2] Dorfmüller, J.; Dregely, D.; Esslinger, M.; Khunsin, W.; Vogelgesang, F.; Kern, K. *Nano Lett.* **2011**, *11*, 2819–2824.

[3] Dregely, D.; Taubert, R.; Dorfmüller, J.; Vogelgesang, R.; Kern, K.; Giessen, H. *Nat. Commun.* **2011**, *2*, 267.

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