



*Optical Antennas on Substrates and Waveguides*  
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## Summary

Currently our society faces two large challenges: a challenge in information technology where a growing number of people request access to increasingly large internet bandwidths, and a challenge in energy, i.e., to sustainably provide for the world energy consumption without dependence on fossil fuels. For both these problems possible solutions are sought in the efficient manipulation and control of light. For information technology, light has the large advantage that signals can be multiplexed by encoding information in different wavelengths, allowing a single fiber to carry up to Terabytes/s of information. As regards energy, if we would be able to harvest just 0.02% of the solar energy incident on the entire earth yearly, this would completely fulfill our energy demands. Both challenges require exquisite control over how light propagates, and over how light interacts with matter through emission, absorption and scattering. This control has been vastly improved in the last decade by recently developed new design ideas and fabrication possibilities for nanophotonic structures. In order to contribute to science in this specific direction, in this thesis, we explore ways in which we can more intuitively understand and design complex nanophotonic structures that are composed of metal scatterers embedded in dielectric structures. Metal scatterers are currently studied very intensively in the field of “plasmonics”. Especially structures made of noble metals can act as very strong “antennas” that strongly scatter and confine light. In this work we specifically target the question how antennas can be integrated with dielectric structures such as waveguides which can losslessly carry information, which, could be the next step of the revolution in information technology started by optical fibers.

Chapter 2 reports on scattering experiments on single rod plasmonic nano antennas fabricated on top of a single mode  $\text{Si}_3\text{N}_4$  ridge waveguide. This study was carried out to assess how strongly light propagating in guided modes interact with plasmon antennas, with the ultimate goal to provide an on-chip plasmon building block for interconversion between guided modes and strongly localized fields that could, for instance, interact with active materials. We found that when placed on a single mode dielectric waveguide, the response of plasmonic rod antennas can be simplified to that of electric dipolar scatterers placed on a multilayer system. When driven in resonance these small antennas scatter out of the waveguide up to 20% of the light from the guided mode, showing the strong interaction of plasmonic antennas with the waveguide mode. To gain control over the scattering process we use this building block as a base for more complex antennas. Therefore, we continue this research in chapter 3 by studying the system of a multi-element phased array plasmonic antenna plus dielectric waveguide.

In this chapter we characterize the scattering processes created by a phased array antenna positioned on a waveguide. We find that phased array antennas on a waveguide couple very strongly to the guided mode. We also find that the interference, occurring due to the scattering from the different elements of the antenna, endow the system with directional scattering both out of the waveguide mode and into the waveguide mode. To complement the study performed in chapter 3, regarding the incoupling of light from point sources, we continue with chapter 4 by studying phased array antennas under localized excitation. For this purpose we used a cathodoluminescence measurement set-up to generate nanometric position controlled point sources on Yagi-Uda antennas. By using point dipole theory and a statistical analysis we explain the features appearing in the acquired spatial excitability maps. We conclude that Yagi-Uda antennas are highly robust when it comes to providing directivity, but exquisitely sensitive to disorder as regards to the enhancement in radiative power provided by the antenna.

In chapter 5 we change focus and work on developing analytical theory tools that allow us to understand and design optical nano antennas. In this chapter we present a numerical tool with which the polarizability tensor of any optical antenna with an arbitrary geometry can be retrieved. This tool is based on either an expansion of the scattered fields in vector spherical harmonics (VSH) or on the integration of the effective surface currents driven on the scatterers. We compare both routines and we find that the VSH tool is more accurate than the effective currents approach, although the latter allows for the retrieval of the polarizability tensor for scatterers on surfaces and in close proximity to other scatterers. In chapter 6 we use the retrieval tool to explain the behaviour of one of the most iconic optical antennas, the split ring resonator. We find that the split ring has a strong magneto optical coupling that amounts to 27% of the electric polarizability. We proceed to use the multipolar expansion of this magneto electric antenna to design a novel split ring based multi-element antenna with very interesting characteristics as a directive radiation source of elliptically polarized light from a localized point source. The ellipticity of the radiated light can be increased by using magnetoelectric scatterers with a stronger cross coupling than the obtained with the split ring.

In chapter 7 we expand the point dipole model to include electric quadrupolar moments. We use this extended theory to analyze the behavior of two types of antennas. The first of these is the so-called “dolmen” antenna that was reported in literature to support a very strongly quadrupolar mode. In particular, we quantify the claim made in earlier reports that narrow features in the dolmen extinction spectrum known as “Fano interference” or “plasmon-induced transparency” (PIT) are attributable to a quadrupolar response. We find that in fact the PIT is not only due to the quadrupolar mode but that a commonly disregarded magnetic dipolar mode is also present and contributes as much as the quadrupolar mode in the interference process. The second of these antennas concerns nanopillars made out of aluminium. Through optimization of their simultaneous electric dipole, magnetic dipole, and electric quadrupole response these nanopillars are shown to be suitable for vertical asymmetric field confinement that could be used for enhancing LED illumination and solar cells. Finally, in chapter 8 we show how to use the extended point quadrupole-dipole theory in the presence

of a substrate. We explain measurements of nano cylinders with strong quadrupolar moments, measured in a cathodoluminescence setup, which are capable of strongly directing light by the interference of its different multipolar moments. These "nano lighthouses" have the characteristic that they are capable of strongly directing scattered light although the antenna is composed of one single element.