Single Rod Antenna on a Dielectric Waveguide

For the purpose of using plasmonics in an integrated scheme where single emitters can be probed efficiently, we experimentally and theoretically study the scattering properties of single nano-rod gold antennas placed on one-dimensional dielectric silicon nitride waveguides. Using real space and Fourier microscopy correlated with waveguide transmission measurements, we quantify the spectral properties, strength and directivity of scattering. The scattering processes can be well understood in the framework of the physics of dipolar objects placed on a planar layered environment with a waveguiding layer.

2.1 Introduction

A highly promising development in nanophotonics is the use of plasmonic antennas to interface near fields and far fields [1–4]. As opposed to conventional dielectric optics that are bound by the diffraction limit, plasmonic structures can confine electromagnetic fields to very small volumes, essentially by packing energy in a joint resonance of the photon field and the free electrons in the metal. As a consequence, plasmonic structures are currently viewed as ideal structures to interface single emitters and single photons [5–16], as well as to realize many types of field-enhanced spectroscopies, such as Raman spectroscopy [17–20], SEIRA [19, 21–24], and fluorescence correlation spectroscopy [25]. Currently, most workers in the field of nano-antennas target the basic understanding and use of antennas in essentially index-matched surroundings. We propose that all the exciting properties of plasmonic nano-antennas can be used in even more versatile ways, if it would be possible to excite and interrogate the antennas efficiently in integrated photonic circuits. Dielectric waveguides, such as high index
ridges on low index substrates, represent a common and mature photonic integration technology. [26, 27] We envision local integration of plasmonic antennas as a promising route to enhance conventional dielectric photonic circuits, and to achieve excitation and detection of plasmonic antenna resonances in an integrated fashion. In order to ultimately apply this combination of structures it is important to understand exactly how antennas interact with waveguides, i.e., how the antenna scatters the waveguide modes, and conversely how the waveguide affects the antenna resonance frequencies, resonance profiles, and directivity. In view of these exciting possibilities, it is highly desirable to comprehensively quantify first how strongly single plasmon building blocks couple to waveguide modes, and how strongly waveguide modes couple to radiation channels outside the waveguide. Such a comprehensive experimental study can then in a second step be used as input to a toolbox for designing phased array antennas. In this chapter we focus on the first part, i.e. the comprehensive quantification of the scattering by single rod antennas on dielectric waveguides. This study will be used in chapter 3 for the design of phased array antennas.

2.2 Experimental setup and methods

In order to study antennas coupled to dielectric waveguides, we employ a setup that combines a fiber-coupled end-fire setup with a confocal microscope as seen in figures 2.1a and 2.1b. The setup can be used in two configurations, as further highlighted in the sketches presented on the left side of the figures. In the first configuration of the setup shown in Fig. 2.1a light is coupled from one end facet into the waveguide using a cleaved fiber (Nufern S630_HP) that carries excitation light from a Fianium supercontinuum light source (SC-450-PP, with the spectrum after the fiber ranging from 650 to 900 nm, max. power at 725 nm of 0.680 mW when measured through bandpass filter 700 nm FWHM 50 nm). Light is coupled into the waveguide and transmitted into a second fiber for spectral analysis on an Avantes peltier cooled Si CCD array spectrometer (AvaSpec-2048TEC-USB2-2). To quantify the scattered light spectrally, spatially and in terms of wave vector content, a home built microscopy system is placed with its optical axis perpendicular to the sample substrate. We use an Olympus 100x, NA 0.95 M Plan IR objective to collect the scattered light, which is then directed through a tube lens to a CCD camera (The Imaging Source DMK21AU04) for imaging, or to a Thorlabs galvo scanner system. This galvo system scans the scattered light collected from the sample plane over a 50 μm core multimode fiber which acts as a confocal pinhole (sample-to-fiber magnification 228 times). This fiber brings out-of-plane scattered light onto a second channel of the same Avantes spectrometer. This confocal scanning configuration for out-of-plane scattering allows us to retrieve images of the sample as well as the spectral content of light scattered from different parts of the antenna. As further functionality, we can flip in a so-called Fourier or Bertrand lens that allows conoscopic imaging. In other words, when flipping in the Fourier lens we retrieve the intensity distribution of scattered light over all wave vectors in the objective NA, essentially through imaging the back focal plane (BFP) of the
2.2 Experimental setup and methods

![Diagram of experimental setup](image)

Figure 2.1: Schematic overview of the experimental setup [a) and b)] together with the representation of the two main working modes. In panels c) and d) the pictures present a schematic view of the sample used together with a scanning electron micrograph of a typical result of a fabricated Si$_3$N$_4$ waveguide with a deposited Au antenna.

imaging objective [25, 28–35]. By using a pinhole system at a distance equal to the focal distance $f_{\text{Fourier}}$ from the Fourier lens we spatially filter the scattered light prior to wave vector imaging, so that we collect radiation patterns only from those parts of the sample that we are interested in, namely the antennas. The Fourier image can again be collected panchromatically on the CCD, or through the galvo scanning mirrors by the fiber, which allows us to spectrally resolve the differential scattering cross section. To conclude, with this configuration of the setup we can study the effect of the antenna on the waveguide transmission (channel 3 in Fig. 2.1a) and scattering of the antenna into the air side (channel 2 in Fig. 2.1a). Given the thickness of the quartz substrate
used for the samples (≈ 600 µm), a home made solid immersion lens system (SIL) was required in order to also access scattering into the substrate side (depicted as channel 4 in Fig. 2.1a), as the Olympus objective lacks the required working distance. This SIL system that employs a BK7 glass hemisphere of diameter 2 mm, allowed us also to collect light that was scattered by the antennas into angles that exceed the total internal reflection angle of the substrate, however, only with spherical and chromatic imaging aberrations too large to allow diffraction limited and Fourier imaging.

The second configuration of the microscope in Fig. 2.1b is designed to study the converse interaction, i.e., rather than coupling in through the waveguide and collecting scattered light, we study how light coming from free space (channel 2 in Fig. 2.1b) is coupled into the waveguide mode. This configuration is achieved by swapping the spectrometer-coupled detection fiber that is placed after the galvo system with the combination of a pinhole system and free space collimated supercontinuum light from the Fianium source. The light scattered into the waveguide and detected through the fibers at the end facets is sent to the spectrometer to quantify the "forward" and "backward" waveguide in-coupling spectra. In absence of the Bertrand lens, we couple in light locally using real space focusing at the diffraction limit. When we flip the Bertrand lens in so that the incident beam is focused in the objective back aperture, we couple light in over a large area, yet at a well-defined incident angle that can be freely varied over the entire objective NA.

**Normalization of the scattering excited via the waveguide**

A particularly difficult problem is how to quantitatively normalize the spectrum of light scattered by the antennas to the spectrum that is offered through the waveguide to the antenna. The only possible references we have access to are the spectra measured in transmission through nominally identical blank waveguides (i.e., without antennas) as a measure for the incident spectrum, and spectra obtained from scattering centers that appear comparatively close to the antenna, due to roughness of the waveguide. In the first case, artifacts may occur due to the fact that the spectrum may vary between alignments and between waveguides, due to chromatic effects in coupling to the waveguide, and for the 1 cm long waveguides due to the integrated effect of unexpected small defects and impurities that change the spectrum along the length of the waveguide. In the second approach, the advantage is that spectra are taken from a region very close to the structure. However, one here relies on the assumption that the scattering centers have no strong frequency dependence, and one does not obtain a quantitative signal strength comparison, as opposed to when using waveguide transmission. In practice no large difference between the two approaches is found when spectrally locating the resonance. Here we present data using the second method (normalization to nearby scattering centers), preferring spectral fidelity over an absolute scale.
2.2 Experimental setup and methods

Sample fabrication

The samples used for the experiments are composed of gold antennas fabricated on top of silicon nitride waveguides by aligned electron beam lithography. A sketch of the structures used is shown in Fig. 2.1c. As we ultimately target visible light spectroscopy applications, we consider silicon nitride waveguides. Fused silica wafers ($n=1.45$) of 100 mm diameter were covered with 100 nm thick Si$_3$N$_4$ using a LPCVD process. This process [Lionix BV, The Netherlands] ensures low loss Si$_3$N$_4$ at manageable stress levels for postprocessing. In order to define 1D waveguide ridges, we perform e-beam lithography using a Raith e-line machine. The waveguides together with positioning markers that are used at a later stage were defined in MaN2403 negative resist (200 nm thickness) with an electron beam lithographic step [dose 235 $\mu$C/cm$^2$, 35 nm spot size, current 0.14 nA and a fixed beam movable stage (FBMS) step size of 0.01 $\mu$m].

The pattern was then transferred into the Si$_3$N$_4$ by dry etching (Oxford Plasmalab, 50 sccm CHF$_3$ and 5 sccm O$_2$, 100 W forward RF power, 5 min etching time). In a second electron beam lithography step the antennas were defined on top of the waveguides, using alignment markers fabricated in the Si$_3$N$_4$ for precise positioning. In this step ZEP-520A positive resist (125 nm thick, exposed with a line dose of 200 pA s/cm, 29 nm spot size, current 0.03 nA) was used to define a liftoff mask for thermal vapor deposition of gold. To mitigate the very poor adhesion of gold on Si$_3$N$_4$, in the evaporation step we first deposited a thin chromium adhesion layer of $\sim 3$ nm, prior to the deposition of $\sim 30$ nm of gold. A typical final result is shown in Fig. 2.1d.

In this chapter we discuss only one type of antenna namely the single rod 100 nm long antennas. This antenna is composed of 1 element with a length of 100 nm and a height of 30 nm as controlled by the gold evaporation. While we have studied antennas on various waveguide widths, all the data presented here are for waveguide widths of 1000 nm and 1500 nm. The strip height is 100 nm. We estimate the electron beam alignment accuracy of antennas to waveguides to be $\sim 40$ nm, i.e., far below any typical feature of the waveguide mode structure as shown in the insets of Fig. 2.2 a and b. The dispersion relations of these waveguides as well as their mode profiles at different wavelengths are shown in Fig. 2.2. In this figure we present the dispersion relation for both type of waveguides as calculated using a finite element mode solver. Figures 2.2a and b show the profile of the waveguide modes at 750 nm and 850 nm, which, as we will see later in chapter 2 and 3, are the center wavelength of the resonances of the antennas discussed in both chapters. At these two wavelengths the waveguides present single transverse electric (TE) mode behaviour. Due to the polarization of the in-coupled light we excite only the TE modes of the waveguides. For the widest of the two waveguides shown (1500 nm width), the second TE waveguide mode has its cutoff wavelength at around 600 nm. Choosing even wider waveguides than 1500 nm would hence imply multimode behavior in the spectral window of the plasmon resonance.
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**Figure 2.2:** a) and b) show the dispersion relations of silicon nitride ridge waveguides on top of a fused silica substrate. The dispersion relations are calculated for waveguides of 1000 nm (a) and 1500 nm (b) width and a guiding layer thickness of 100 nm. The light lines for the silica substrate and the Si₃N₄ are the plotted black lines while the first three modes m=1, 2 and 3 are plotted with color lines. In c) we plot the mode profile for a 1000 nm wide waveguide at 750 nm wavelength. The inset of this graph shows two cuts of the profile, one through the y axis and the other along the x-axis at 15 nm from the top surface of the waveguide. This is the expected position of the center of the antennas deposited over the waveguides.

### 2.3 Scattering of guided modes by single element antennas

We first discuss measurements on single rod antennas excited through the 1000 nm width waveguides. These measurements are intended to obtain the resonance frequency of the single rod antennas. In order to obtain this information, TE polarized light is sent in through the waveguide (channel 1 in Fig. 2.1a), and light scattered by the antenna into the air-half space is collected and resolved on the spectrometer (channel 2). Fig. 2.3b (continuous black line) shows the spectrum of light scattered into the air side...
of the sample by a 100 nm rod antenna normalized to the input intensity with which it is excited through the waveguide according to the normalization method presented in section 2.2. The antenna spectrum shows a clear peak centered around 750 nm, with a bandwidth of around 55 nm (FWHM). The resonance frequency is comparable to resonance frequencies previously found for rods on simple glass substrates [36–39]. When collecting light scattered by the antenna into the substrate underlying the waveguides using the (SIL) solid immersion lens system, we find that the resonance frequency is almost identical (Fig. 2.3b (dashed red line)). However, when comparing the intensity of the light emitted into the different media for quantitative reference, we find that a signal approximately 2 times stronger is found into the quartz substrate than into air, consistent with the fact that a higher scattering intensity towards the high index medium is expected from the radiation of dipoles on top of a high index layered system [40]. We conclude from our measurements that waveguide-addressing of plasmon antennas allows for high signal-to-noise ratio dark-field spectroscopy of single plasmon antennas both using collection of light from the air side, and from the substrate side. This conclusion is promising for integrated applications of plasmonic antennas in sensing using integrated optics. Even more promising is that detection in such a sensing scheme could also occur via the waveguide itself. We estimate that a single nanorod antenna removes approximately 20% of the intensity in the waveguide mode out of the transmission channel (as can be seen in Fig. 2.4) and redistributes it over waveguide reflection, absorption in the metal, and out-of-plane scattering. This estimate results from transmission spectra normalized to nominally identical blank waveguides shown in Fig. 2.4.

To obtain a more comprehensive understanding of how plasmon antennas scatter waveguide modes, we analyze the scattered light further in terms of polarization and directionality. In the remainder of this chapter we focus on collection of light on the air side of the sample, as the quality of our imaging system is far superior in this configuration. Polarization analysis shows that more than 90% of the light is scattered in the polarization direction parallel to the direction of the antenna (y direction in the reference frame depicted in Fig. 2.1a). We have also studied 100 nm rod antennas fabricated at various rotation angles relative to the waveguide axis. As the antenna is rotated from 90°, 45° to 0° angle relative to the waveguide axis, we consistently find strong polarization of scattered light collected on the air side of the sample along the antennas axis.

We have access to the directionality of scattering by the single rod antennas using Fourier microscopy, i.e., by insertion of a Bertrand lens into our imaging system. While the 100 nm line rod antennas appear as diffraction limited points in spatial imaging, interesting information is obtained when looking at the scattered light by imaging the back focal plane of the objective in this manner. At the air side (channel 2 in Fig. 2.1a), the radiated pattern appears to be distributed over a wide range of angles (up to $\sin \theta = 0.7$) relative to the sample normal (Fig. 2.3c and 2.3d). Upon polarization analysis with a linear polarizer in detection we find a large contrast in integrated intensity. In addition, the weak cross-polarized radiation pattern is clearly distinct from the co-polarized pattern in that it consists of four separate lobes. Similar results were
Figure 2.3: Sketch of the experimental geometry relevant for panels (b-f), in which we collect out-of-plane scattering due to the antenna that is excited through the waveguide. 

b) Spectrum of the scattered intensity for a 100 nm long rod antenna on a 1000 nm width waveguide (continuous black line) taken from the air side of the sample. (dashed red line) taken from the glass side of the sample with a SIL. The spectrum is normalized to the light offered to the antenna, measured by integrating light scattered from roughness of the waveguide adjacent to the antenna. Both peaks show that the scattering of guided modes happens through a resonant process. 

c) and d) Graphs of the measured radiation pattern for the 100 nm rod antenna, analyzed through a vertical c) and horizontal d) linear polarizer. The white circle indicates the NA of the Olympus objective (N.A=0.95). The integration time for the vertical polarization is 1.45 s and 30 s for the horizontal polarization. 

e) and f) Graphs of the simulated radiation pattern analyzed through a vertical e) and horizontal f) linear polarizer. Field values are calculated at the position of the microscope objective, i.e., 1.8 mm from the sample plane. The fields are normalized to $E_y = 1.7 \times 10^{-9}$ V/m, given a guided mode strength of 1 V/m. Graphs c) to f) demonstrate that a 100 nm rod antenna located over a multi-layer substrate behaves as an electric dipolar scatterer.

reported in [28] for antennas excited using total internal reflection (TIR) on a prism. Clearly, waveguide excitation is an efficient alternative to TIR for dark-field Fourier
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microscopy. We note that the fact that the radiation pattern extends somewhat outside the NA of our objective indicates that diffraction by the spatial selection pinhole blurs the measured radiation pattern. The radiation pattern found in the two polarization channels for the 100 nm rod antenna in Fig. 2.3c and 2.3d bears the clear signature of an in-plane y-oriented dipole placed on top of a Si$_3$N$_4$-SiO$_2$ substrate. In high-NA imaging, such a y-oriented dipole generates cross polarized fields at very large angles due to the huge refraction angles in the aplanatic imaging system. The measured radiation pattern for the 100 nm rod antenna, as shown in Fig. 2.3c and 2.3d is in excellent agreement with the theoretical radiation pattern that is expected for a dipolar scatterer positioned 30 nm above a 2D layer system consisting of quartz and silicon nitride as shown in Fig. 2.3e and 2.3f. These theoretical radiation patterns are calculated by using the analytically known far-field expansion of the Green’s function of a multilayered system, as explained in Ref. [40]. In this type of calculation the substrate is an infinitely extended multilayered system composed of Air-Si$_3$N$_4$-SiO$_2$, thereby ignoring the finite width of the 1D waveguide on SiO$_2$. In this 2D waveguide geometry, we can perform quantitative scattering calculations of antenna particles excited by waveguide modes that we obtain by solving for the propagation constants and mode fields of guided modes that are bound to the Si$_3$N$_4$ waveguide. In this approach, the polarizability of scatterers is taken as the electrodynamically corrected quasi-static polarizability of a prolate spheroid [41]. The dynamical correction used in the calculations for the polarizability is [42]

$$\frac{1}{\alpha} = \frac{1}{\alpha_{\text{static}}} - Im[G_{\text{interface}}(r_0, r_0)]. \quad (2.1)$$
Here $\alpha_{\text{static}}$ is the static polarizability of a prolate spheroid and $G_{\text{interface}}(r_0, r_0)$ is the Green’s function of the layered system as found in [43] evaluated at the position of the scatterer $r_0$. The satisfactory correspondence between the measured radiation patterns for antennas on 1D guides, and the theoretical figures for 2D guides implies that the finite width of 1 $\mu$m of the waveguide used does not strongly alter the angular distribution of light scattered out-of-plane. Arguably, close inspection of the data shows that angular emission is narrowed in $k_y$ by the 1D waveguide compared to the 2D system.

### 2.4 In-coupling by a single dipole antenna

As a complementary experiment on the antenna-waveguide system, we have also performed the reverse, i.e., excitation from the far field and detection through the waveguide (see Fig. 2.1b). In this experiment a diffraction limited focused spot is scanned over the antenna and the light in-coupled into the 1500 nm wide waveguide is acquired through the aligned optical fibers at the waveguide end facets. The inset of Fig. 2.5 shows a plot of the maximum in-coupled intensity for different positions of the scanned beam. The 2D grayscale plot, which could be viewed as a confocal raster scanning graph, barring the fact that collection is through the waveguide, and not through any objective, indicates that the light is being coupled into the waveguide from a point that is approximately equal in size, or less, than the diffraction limit. By calibration of the spot to a white light image of the fabrication markers, we ensured that the center of the maximum in-coupled intensity coincides strictly with the antenna position. At each position we furthermore collect spectral information, as the incident beam has a broad spectrum and the detected light is coupled into the spectrometer. Fig. 2.5 shows the spectrum at the location of maximum in-coupling determined from the 2D spatial raster scan. We find a maximum coupling from free space into the waveguide at a wavelength around 750 nm across a bandwidth of 65 nm (FWHM). The excellent correspondence of the in-coupling resonance frequency with the scattering resonance we observe when illuminating through the waveguide, indicates that resonant in-coupling into the waveguide occurs at the same wavelength as scattering of the waveguide mode by the antenna out of the waveguide. Also, the bandwidth agrees reasonably well with the measured bandwidth in the out-coupling experiment. However, the spectrum in the in-coupling experiment has a tail towards the near infrared wavelengths due to the red shifted cutoff frequency of the 1500 nm wide waveguides compared to the 1000 nm wide waveguides used to obtain Fig. 2.3.

We now attempt to estimate the in-coupling efficiency of light into the waveguide from the data measured in Fig. 2.5. In this experiment coupling from the waveguide to the spectrometer used a metallized tapered fiber tip at the waveguide end facets, in order to reduce stray light contributions such as grazing light coupled to the SiO$_2$ substrate. Unfortunately, the use of this metallic tip makes it difficult to find a quantitative coupling efficiency of antenna to waveguide, as the waveguide-to-fiber efficiency is imprecisely known. On basis of in-coupling intensity data of 10 kcts/s at 750 nm, knowing that...
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the irradiance factor for our spectrometer is \(12.86 \text{ (kcts/s)/(}\mu\text{W/cm}^2/\text{nm})\) at 750 nm, we can calculate an in-coupled irradiance of \(0.77 \mu\text{W/(cm}^2\cdot\text{nm})\) in the spectrometer; when using a free space focused beam with an irradiance of \(1.56 \times 10^8 \mu\text{W/(cm}^2\cdot\text{nm})\), an estimated fiber collection efficiency of \(10^{-4}\), an efficiency in the single mode to multi mode fiber coupling of 10%, and a loss in the waveguide of \(10^{-2}\). With this data we estimate in-coupling efficiencies on the order of 1%, for diffraction limited in-coupling beams. Unfortunately, the experimental uncertainties especially regarding the in-coupling of the signal into the detection fibers, imply that our experimental estimate is not more accurate than approximately one order of magnitude. To obtain an independent, and possibly more precise estimate, we turn to theory.

We use the model of a dipolar scatterer on top of a 2D waveguide as explained before. We find the efficiency with which such a scatterer couples light into the waveguide in two steps. First, we find the extinct power, \(i.e.,\) the power that is removed from a plane wave incident from the air due to the presence of the scatterer. The extinct power is defined as

\[
P_{\text{ext}} = \frac{\omega}{2} \text{Im}(\mathbf{p} \cdot \mathbf{E}_o^\ast).
\]

Furthermore, the power that the induced dipole moment radiates into the far field \textit{barring} the waveguide mode can be calculated from the dyadic Green’s function far field expansion that can be found in Ref. [40]. The difference in extinct power and far field radiated power equals the power coupled into the waveguide, plus the power absorbed by the particle due to losses. We find (assuming a plane wave excitation) that the coupling efficiency strongly depends on the height of the single rod antenna with respect to the waveguide as shown in Fig. 2.6 (green curve). This dependence reflects
the strong spatial dependence of both the guided mode contribution, and radiative mode contribution to the local density of states of stratified waveguide systems. We predict a maximum incoupling+absorption of $\sim 48\%$ for particle heights 30 nm from the waveguide. This in-coupling decays exponentially with distance from the waveguide and stabilizes at 30% at distances around 2 $\mu$m from the waveguide. Since significant incoupling is not expected for such large distances we estimate that those 30% correspond to absorption in the particle. Taking that as a measure for absorption, we conclude that a particle just above the waveguide will couple approximately 20% of the light that it harvests from the input beam into the waveguide. The remaining 80% is split between far field (50% of extinct power) and absorption (30% of extinct power). It is important to notice that these numbers indicate the efficiencies with which the power is distributed in the different radiation channels relative to the total power that couples to the dipolar scatterer. To convert these relative efficiencies to actual cross sections, one needs to determine what the absolute extinction cross section of the particle is. The overall extinction cross section is anticipated to be at most $0.16 \, \mu$m$^2$, i.e., 1.2 times smaller than the diffraction limit, as calculated from full wave simulations. To conclude, a single particle illuminated by a diffraction limited beam can couple approximately 20% of the incident energy into the waveguide, in accord with the crude measured estimate.

![Figure 2.6](image.png)

**Figure 2.6:** Results of a calculation where a plane wave is sent towards the antenna from the air side and the efficiency of absorption plus scattering into the waveguide mode is reported. The axis show the ratio between guided plus absorbed power to extinction power for plane wave excitation of the antenna found for a single rod antenna element at different ‘z’ distances from the waveguide at 755 nm.

The constraint of fairly large absorption (30%), which in our system is due both to the gold and to the underlying Cr adhesive layer, can be mitigated by shifting the operation range further to the NIR using larger particles, or by swapping Au for silver. In this case a protective dielectric could be required to avoid particle degradation. Such capping is expected to also be beneficial optically, as it would pull the waveguide mode up towards the particle, thereby likely enhancing the coupling efficiency.
2.5 Conclusions

To conclude, we have fabricated plasmonic antennas precisely aligned to dielectric waveguides, and quantified their properties for applications in waveguide-integrated plasmonics. We found that single rod antennas scatter light as electric dipoles on top of a multi-layer system. As a first step, we have quantified how single plasmonic antennas couple to waveguide modes, in particular quantifying how strongly, and into which directions, antennas out-couple waveguide modes. Conversely, we have argued that a single plasmon antenna can already couple up to 20% of a diffraction limited input beam into the waveguide mode. These electric dipolar scatterers coupled to dielectric waveguides can therefore be used as couplers of light from localized sources to waveguide modes, or as phase controlled scatterers that can be addressed through individual waveguides. Finally the understanding of these antennas and how we can treat them analytically as electric dipole scatterers opens a way to design multielement antennas in an analytical fashion without resorting to full wave simulations.
References


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