This chapter discusses possible applications inspired by this thesis. In particular, a large part of this thesis was devoted to waveguide-integrated plasmonic antennas to combine the local field enhancement of plasmon antennas with lossless propagation in integrated optics. As demonstrated in chapter 2 and 3 the system composed by antennas on waveguides allows us to measure scattering out of plane from antennas with a very low background signal. Because of this dark field character one can measure scattering spectra of single nano-rod antennas with a very low integration time on a common silicon detector. Also by measuring the transmission through the waveguide we could determine how the antenna scattering affects the waveguide transmission spectrally. Both characteristics depend on the scattering resonance of the antenna and therefore can be controlled by the antenna design. A depiction of these properties is shown in Fig. 9.1. This figure also shows that resonances of the antennas create strong confinement in small volumes of high electromagnetic fields (hot-spots). The properties of low-background efficient detection by out of plane detectors, and the possibility of completely waveguide-integrated excitation and detection of plasmon resonances spur a varied number of possible applications.

9.1 Chemical and biological detection fluidic environment

By functionalizing gold antennas on waveguides and integrating the system in a fluidic environment one can envision the detection out of plane as well as through waveguides of chemical and biological samples in very small volumes and very low concentrations. During our work for this thesis we developed PDMS fluidic cells that can be pressed
on top of the waveguide so that the effect of different fluids as well as solutes dissolved in the fluid could be measured, for instance by monitoring transmission through the waveguide. Also fluidic cells integrated with on chip waveguides are commercially available from LIONIX BV for "lab-on-chip" applications. These cells provide the means to bring liquid carrying analytes close to the antennas on waveguides. The presence of a chemical or biological sample that is brought in close proximity to the antenna can be detected in different ways. One method is based on fluorescence of the analyte. In this case the analyte can be optically pumped though the waveguide or with an excitation beam perpendicular to the substrate and the signal could be measured through the waveguide. This signal is therefore seen as an increase in intensity on a spectrally filtered photodetector integrated on or with the waveguide. A difficult challenge to overcome when performing both the addressing and the readout through the waveguide in a completely integrated fashion, is that fluorescence from the waveguide material itself can obscure the analyte signal. In our investigations we observed that when measuring transmission through LPCVD deposited Si$_3$N$_4$ waveguides with milliwatts of CW laser illumination this effect was not important. Nevertheless when measuring with a pulsed laser with $\lambda = 640$ nm, 80 picosecond pulse length and an average power in the milliwatts regime and repetition rates of tens of MHz then fluorescence from the waveguide became apparent. The second method is based on the fact that the scattering properties of a nano-antenna change as function of refractive index changes in the medium surrounding the antenna, particularly in the volume of enhanced near-field. Analytes with a different refractive index (or polarizability per volume) than the solvent would thereby cause a fluctuating optical signal as they diffuse into, and out of, the antenna near field. This change in $n$ in the antenna near field causes two different effects that could be measured. On the one hand in a phased array antenna a $\Delta n$ would change the directionality of the scattered light out of the guided mode. Thus, this signal can be measured through an intensity change on a photodetector. On the other hand this signal could be seen in transmission both by measuring the spectra through the waveguide and by a change in intensity of a
monochromatic source spectrally positioned at a flank of the spectral feature created by
the presence of the antenna. This method may provide a measurement device capable
of measuring the presence of single molecules as demonstrated in Ref. [1] but with the
advantage of being based on an integrated on-chip platform.

9.2 Antennas and single emitters

A concept that is taking increasingly more importance in the field of quantum informa-
tion is the quantum internet [2]. The idea is to connect objects or systems that behave
quantum mechanically. Connections between these objects should, in a reversible
way, be able to convert quantum states from one system to the quantum states of
another system. These quantum interconnections would allow the distribution and
teleportation of quantum states among the different nodes of the network and have a
multi-node entanglement across the network. A candidate for such an interconnect is
based on the coupling of single photons and single degrees of freedom in matter, such as
electron spin, or electronic excitation in atoms, molecules, or quantum dots. One of the
problems of this idealized system is that photons interact weakly with matter as already
explained in chapter 1 of this thesis. In order to overcome this issue, many efforts are
directed towards photonic crystal waveguides and coupled photonic crystal cavities in
III-V semiconductors [3, 4], while for use of other emitters plasmonic nanowires have
been proposed [5–7]. As alternative to the highly lossy transport of light in nanowires,
we propose to exploit plasmonic antennas on waveguides. This system, on the one
hand, would increase the interaction between photons and matter due to the strong
field confinement of the antennas in the vicinity of strategically positioned atoms, NV-
centers, molecules or quantum dots. On the other hand by using waveguides for this
network photons could be transported losslessly between nodes. We have theoretically
shown in chapter 3 that by positioning single atoms, NV-centers, molecules or quantum
dots in the vicinity of an antenna on a waveguide it is possible to couple the emitted
light from the single quantum emitter into the waveguide and direct it towards an
integrated detector. The directional coupling to the waveguide was experimentally
demonstrated in chapter 3 of this thesis. Also, the theory with which we understand
and design these antennas was used to understand the response of Yagi-Uda antennas
due to a very localized excitation similar to the one produced by a single emitter
(chapter 4). Thus, we believe phased array antennas as well as quadrupolar antennas
in combination with waveguides could find an application in the efficient coupling of
single photons into integrated optical chips. One of the main problems for this idea is
that with gold antennas the emission incoupling into the waveguide was theoretically
predicted to be around 60% which is far from ideal for scalability of the system and
which therefore would be far from the read-out efficiencies of 84% achieved for cavity
systems (Ref. [8]). Nevertheless we believe that arrays of quadrupolar antennas may
increase this coupling due to the strong near field gradients and better matching to
the waveguide modes. Furthermore, hybrid structures of plasmon antennas coupled
to moderate Q-cavities could alleviate the drawbacks of plasmonics while removing
the scaling problems that ultra high Q resonators suffer due to their sensitivity to fluctuations in environment and fabrication.

## 9.3 On-chip integrated Coulomb-blockade photon sources

Hot electrons are electrons in a material with energy in excess of the Fermi energy [9]. These electrons can be created or injected into a material in different ways, for instance by the absorption of a photon or by tunneling electron transport. Hot electrons are drawing attention lately in the field of plasmonics, for instance for their use in plasmon based detectors [10], but also for the generation of photon sources by injection of hot electrons into metal antennas [11]. We propose to use hot electrons to create a single photon source introducing single hot electrons into the metallic feed element of a Yagi-Uda antenna by using an intermediate step employing small (<5 nm) metallic islands between electrical contacts and the feed element of the antenna. Due to the Coulomb charging effect one could envision that only a single electron at a time tunnels, resulting in the possibility of single photon generation, where single photons would be expected to appear, matched to the antenna resonance. Alternative to the hot electron generation process, one could imagine immobilizing a single quantum dot or molecule in the gap [12–14]. Due to the directionality of this antenna we would also attain control over the emission direction of these photons. See Fig. 9.2 for a sketch of the concept.

![Figure 9.2: Artist impression of an on-chip integrated Coulomb-blockade photon source based on a Yagi-Uda antenna.](image)

Some of the main problems that should be resolved to assess the feasibility of this approach are firstly to assess if multi-photon emission probabilities are indeed low, and secondly if deterioration of devices due to electrical driving can be avoided. To avoid that multiple photons are produced one can enhance the radiative LDOS by the use of a proper designed antenna for wavelengths close in energy to the energy of the hot electrons. To avoid deterioration due to electrical driving one could imagine
working in a vacuum environment or by embedding the system in a properly chosen high-k dielectric medium. This technology would need to compete with single photon production of $10^3$ photons/second/nm achieved with NV center based commercially available single photon sources e.g. [http://qcVictoria.com/] or $10^6$ photons/s/nm achieved with spontaneous parametric down conversion [15].

9.4 Design of antennas with asymmetrical scattering capabilities

Finally we review possible applications of one of the main results of this thesis, namely the asymmetries in terms of the differential scattering cross section and its polarization dependence that arise due to magnetic, magnetoelectric, and quadrupolar effects. Usually plasmonic antennas like for instance rod antennas, due to their small size, are seen as objects that scatter light equally whether they are excited in the forward or backward direction along a certain orientation. That is, these antennas usually scatter light symmetrically under a spatial inversion in the direction of excitation. This symmetrical scattering can be understood from the point of view that scatterers considerably smaller than the wavelength can be well described as electrical dipolar scatterers. Therefore, the only driving input for the scattering process is the electric field ($E$). This input does not change (up to a phase factor) upon an inversion between forward or backward excitation direction. In contrast, in this thesis we found examples of antennas for which an asymmetrical forward-backward scattering was present due to the appearance of higher order modes like magnetic dipolar and electric quadrupolar modes. For these modes, as explained in chapter 7, the excitation is also given by the magnetic field ($H$) and the symmetric electric field gradient ($\vec{E}$). With $E$, $H$ and $\vec{E}$ as driving for the scattering process it is easy to see that the scattering can not be symmetric under inversion, since even for a plane wave excitation $E$, $H$ and $\vec{E}$ must change relative phase and sign under such an inversion. This can be condensed in the following statement: if the superpolarizability tensor contains cross coupled terms there will be an asymmetry in the forward-backward excitation scattering, which also implies that for every axis with a broken geometrical symmetry a cross coupled term will be obtained.

Applications of these asymmetries fall apart in two classes: control over polarization degrees of freedom, and control over the spatial distribution of scattered light. As regards the first, in Chapter 6, we discussed the fact that magneto-electric scatterers, such as split rings, show a strongly handed response to incident light. In other words, the coherence relation between the electric and magnetic dipole moment that can be simultaneously induced in a split ring ensure a large difference in extinction depending on handedness of the incident light, at least for particular incidence directions, and viceversa a strong handedness of scattered light for particular scattered wave vectors. Moreover, we demonstrated that this effect can be significantly boosted by placing scatterers in arrays, in such a way that the scattering patterns narrows around the wave vectors for which reradiated light is strongly handed. An interesting possibility is to use
such antennas to create directional emitters that radiate handed light. More precisely, such antenna proposed in Chapter 6 is shown to radiate the emission of a source close by the antenna in the forward direction with right handed elliptical polarization, while it will radiate in the backward direction left handed elliptically polarized light. This type of correlation between direction and spin angular momentum has been already investigated in e.g. the photon spin Hall effect introduced by Bernevig et al. [16] as well as in the work of le Feber et al. [17]. The coupling between photon angular momentum and photon pathway could be used as an implementation of flying q-bits. Also, this type of antenna might be used for an on-chip enantioselective discrimination of chiral molecules like the ones found in pharmaceutical complexes [18, 19].

Regarding the second class of antennas, with which we can control the spatial distribution of scattered light, we return to the nano-pyramid antennas discussed in Chapter 7. These structures possess a strong asymmetric scattering created by the interference of the electric dipolar and the magnetic dipolar and electric quadrupolar modes sustained in these structures. Specifically when these structures are illuminated, with light at a wavelength centered around 660 nm, from the top with linearly polarized light, high field intensity zones are created on the bottom of the antenna, while when illuminated from the bottom such local hot spots are created on the top of the antenna. We propose together with Said R.K Rodriguez that this vertical asymmetry in scattering and in field confinement close to the antenna is based on the interference between the dipolar and quadrupolar modes which creates this special scattering asymmetry. By understanding the basic elements of this type of scattering one could optimize in a single or in a multi-element structure this interference effect. Having a strongly asymmetric scattering object could be used for lighting applications using LEDs. In particular, for white light generation there is a large demand for efficient conversion of blue LED light into other colors by a phosphorescent layer. Asymmetric scattering structures could aid both the absorption and the emission process. Moreover, for particular lighting applications in, e.g., automotive or projection devices, directional emission could be useful. Also, near-field asymmetric scattering might be used for enhancing solar cell absorption. This enhancement is possible since near field excitation could be concentrated only where required, for instance at the active layer of the solar cells.
References

REFERENCES


