Hybrid resonators for light trapping and emission control

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Humans were shaped by light. Sight is our most versatile tool to perceive our surrounding, and thus to survive. Our very appearance is determined by light. The colour of our skin derives from its ability to protect us from sunlight, and our eyes combine beauty with a breathtaking capability to detect light intensities between a single photon [1] and bright sunlight (more than $10^{16}$ photons per second). While vision forms our natural connection to light, daily life in a modern society is impacted by light in many more ways. Light carries energy, which can be harvested in a solar panel or used to cut through steel. It also carries information, used in the optical fiber network that spans the globe and forms the backbone of the internet [2]. Its interaction with matter allows remarkably precise measurements, for example of individual viruses, antibodies or proteins [3, 4]. Imaging systems such as microscopes and telescopes are used to understand both the extremely distant — stars and galaxies — and the extremely close, such as cells, skin tumors or bacteria. Owing to the recent developments in computer processing power, imaging is expanding its impact on our lives by facilitating for example self-driving cars and automated face recognition. This increase in processing power, in turn, would not have been possible without light, as advances in optical lithography drive the exponential miniaturization of the elements on computer chips.

Despite everything we can do with light, there is still more we cannot do. The interaction between light and matter is extremely weak. Visible light has a wavelength around 500 nm, and the diffraction limit [5] prevents focusing it to a spot smaller than half this wavelength. Electrons, on the other hand, which form the part of matter that interacts mostly with light, are typically localized on the scale of an atom or molecule: $\sim 1$ nm or less. This enormous size mismatch makes the probability of light absorption or emission very low, limiting for example the miniaturization of light sources and detectors. It also prevents optical non-linearities at low power, a requirement for all-optical
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information processing which could make computers much faster and more energy-efficient [6]. Such practical applications aside, a whole realm of fascinating new physics is accessible only with stronger light-matter interaction.

Luckily, light-matter interaction can be enhanced. One can either make the light pass the atom (or whatever it needs to interact with) multiple times, or squeeze the light to sizes below the diffraction limit. The first is achieved by an optical cavity [7] — a resonator that traps light for many oscillation periods — while the second can be done through plasmonics [8–10], which couples the light to free electrons in a (noble) metal to create extremely confined fields.

Although both cavities and plasmonic structures have enjoyed great successes, each is troubled by fundamental limitations, as we will discuss further in this chapter. To unlock the full potential of strong light-matter interactions, alternative methods are required. This thesis concerns alternative strategies to store and confine light, based on hybrid resonators. These resonators combine two or more coupled optical resonances, and the resulting hybrid system can have unique properties that are unavailable with the individual constituents.

In this chapter, we first discuss how light-matter interaction strength can be quantified and compare figures of merit for various applications. We then briefly discuss the current state of the art in controlling interaction strength using optical cavities or plasmonic antennas. The bulk of this thesis deals with combinations of such cavities and antennas. We therefore provide an overview of the work done on such hybrid antenna-cavity systems. We conclude with a motivation and outline of this thesis.

1.1 Quantifying light-matter interaction

One of the most common light-matter interactions is the absorption or emission of a photon by a small particle, for example an atom or a molecule. The energy of a photon is transferred via an optical transition to an excited state in the particle, or vice versa. To quantify light-matter interaction strength, let us consider such a system of an emitter — treated as an ideal two-level system — coupled to a light field, using the formalism of cavity quantum electrodynamics (CQED) [11]. This will deliver several fundamental figures of merit that govern the interaction strength. We will find that these figures of merit are applicable not just for typical situations studied in CQED, but for other physical processes and applications as well.

The interaction strength between light and a small emitter is determined by the electric dipole interaction Hamiltonian $\hat{H} = -\hat{\mu} \cdot \hat{E}$, where $\hat{\mu}$ is the dipole moment operator of the optical transition, and $\hat{E}$ is the electric field operator [11, 12]. If the electric field is that of a single, empty optical mode, we can write $\langle i | \hat{H} | f \rangle = \hbar g$, with $g = \mu \sqrt{\omega/(2\hbar V \epsilon_0 \epsilon)}$ the emitter-field coupling rate from the Jaynes-Cummings Hamiltonian and $\mu = |\mu| = |\langle g | \hat{\mu} | e \rangle|$ the dipole moment of the transition from electronic excited state $|e\rangle$ to ground
1.1 Quantifying light-matter interaction

state $|g\rangle$ [12, 13]. Here, $V$ represents the volume occupied by the optical mode, and $\epsilon = n^2$ is the relative permittivity of the material embedding the emitter. From this we recognize that the coupling rate $g$ depends both on purely electronic properties of the emitter, captured in $\mu$, and on the confinement of the optical mode, captured in $V$. Thus, it is possible to modify light-matter interactions by shaping the photonic environment. This has been the main endeavour in the field of CQED since 1946 [14, 15]. These efforts have greatly improved our understanding of both light and matter, and have been lauded with many awards including the 2012 Nobel prize for Haroche and Wineland.

The manner in which the coupling rate $g$ affects an emitter depends on the losses in the system. If we assume that the emitter losses are negligible, losses are determined by the decay rate $\kappa$ of the optical mode, or its quality factor $Q = \omega/\kappa$. Two distinct regimes can be considered — the weak coupling regime, with $2g < \kappa$, and the strong coupling regime, with $2g > \kappa$. We discuss them here briefly.

1.1.1 Weak coupling — Spontaneous emission and the Purcell effect

If $2g < \kappa$, energy in the optical mode is lost more rapidly than it is exchanged between the mode and the emitter [13]. This is known as the weak coupling regime, and it renders the process of spontaneous emission irreversible. The rate of spontaneous emission is then determined by Fermi’s Golden Rule, which prescribes that the transition rate from an initial (excited) state $|i\rangle$ to a set of final states $|f\rangle$ with energy difference $E_i - E_f = \hbar\omega$ is [12]

$$\Gamma = \sum_f \frac{2\pi}{\hbar} \left| \langle i | \hat{\mathcal{H}} | f \rangle \right|^2 \delta(E_i - E_f).$$  \hspace{1cm} (1.1)

Importantly, $|i\rangle$ and $|f\rangle$ are states of the complete emitter-radiation system. Hence, even if there is only one electronic ground-state for the emitter to decay to, the summation in Eq. (1.1) should nevertheless be taken over all possible photonic states at frequency $\omega$. Equation (1.1) applies in any photonic system, whether dominated by a single cavity mode, or characterized by a continuum. We can rewrite Eq. (1.1) as [12]

$$\Gamma = \frac{\pi \omega}{3\hbar \epsilon_0} |\mu|^2 \rho_\mu(\omega, r),$$  \hspace{1cm} (1.2)

where we introduced $\rho_\mu(\omega, r)$, the optical local density of states (LDOS) [17]. This represents the density per unit volume and unit frequency range of optical states at frequency $\omega$, available to an emitter at position $r$ and with a dipole orientation $\mu$. Although spontaneous emission is

*For a derivation including finite emitter losses and dephasing, see [16].
an inherently quantum-mechanical process, the LDOS can be calculated classically [12, 18] and depends only on the photonic environment. In a homogeneous medium, $\rho(\omega, r) = \omega^2 n/(\pi^2 c^3)$ for any dipole orientation (see Fig. 1.1) [12]. LDOS is a convenient figure of merit in photonics, as it quantifies the photonic contribution to the spontaneous emission rate. In contrast, the electronic contribution is commonly quantified by the oscillator strength $f = 2\mu^2 m\omega/(\hbar e^2)$ of a transition, with $e$ and $m$ respectively the electron charge and mass [13].

The LDOS can in principle be found for any optical environment, including an optical cavity supporting a single mode. In this case, the LDOS at cavity resonance can be found by inserting $\langle i|\hat{H}|f \rangle = \hbar g$ into Eq. (1.1) and using the energy density of states $2/(\pi\hbar\kappa)$ of a single cavity mode at cavity resonance to replace the sum by an integral over photon energy and remove the delta function [13]. This yields a cavity LDOS $\rho_c = 6/(\pi\kappa V)$ (see Fig. 1.1) and decay rate $\Gamma_c = 4g^2/\kappa$. Normalizing $\Gamma_c$ to the emitter decay rate $\gamma$ in a medium of index $n$ yields the famous Purcell factor:

$$F_P = \frac{\Gamma_c}{\gamma} = \frac{4g^2}{\gamma\kappa} = \frac{3}{4\pi^2} \frac{Q}{V} \left( \frac{\lambda}{n} \right)^3.$$ (1.3)

This expression was first derived in 1946 by Purcell [14], who was the first to realize that the probability of a spontaneous transition mediated by a photon

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1The terms LDOS, Purcell enhancement, emission enhancement and Purcell factor are often (confusingly) used interchangeably in literature. In this thesis, LDOS refers to $\rho_\mu$ as used in Eq. (1.2). By Purcell enhancement, emission enhancement or relative LDOS we mean $\rho_\mu$ relative to that in a homogeneous medium (usually vacuum). The Purcell factor exclusively refers to the peak value of the Purcell enhancement due to a particular resonance.
could be modified by the environment. In his case, this involved radiative transitions of nuclear magnetic moments at radio frequencies, which he found could be strongly accelerated by coupling to a resonant electric circuit. In the late 1960’s, this fact was first observed experimentally at optical frequencies by Drexhage [19], not using a cavity but instead by modifying LDOS through the distance of emitters to a mirror. For completeness, we note that the photonic environment not only modifies the emitter decay rate, but also its resonance frequency, although this so-called ‘Lamb shift’ is typically very small [12, 20].

Spontaneous emission control has proven useful in several important applications. Enhancing the emission rate of light-emitting diodes (LEDs), which are currently limited to switching speeds of \(\sim 100 \text{ MHz}\), would make these ideally suited as light sources in optical interconnects on a microprocessor, which could dramatically decrease the power consumption of microcomputing [21, 22]. Moreover, enhancing the spontaneous emission rate additionally provides control over where the light is going [23], which enables, for example, directional emission or efficient collection of the light from such on-chip LEDs. Reciprocity guarantees that a strongly directional emitter also has a directional absorption pattern, which has been proposed as a key parameter enabling nano-scale solar cells to surpass the Shockley-Queisser efficiency limit [24]. LDOS enhancements can also benefit the development of small, low-threshold lasers. Spontaneous emission and stimulated emission are intimately linked through the Einstein coefficients. It is therefore not surprising that the pump power required to reach the lasing threshold is proportional to \(V/Q\), with \(Q\) and \(V\) the quality factor and mode volume of the laser cavity mode [25]. Hence, improving \(Q/V\) decreases the minimal operation power of a laser, which can lead to a reduction of energy usage in optical communication [22, 25]. A fact that is surprising, is that the Purcell factor can also influence processes that are not related to emission at all. Optical resonators can be used to sense small particles such as single viruses or molecules [3, 26]. The detection sensitivity is determined by \(\Delta \omega / \kappa\), with \(\Delta \omega\) the resonator lineshift induced by the particle. Cavity perturbation theory [27] states that, for a single small particle perturbing a resonator, \(\Delta \omega \propto V^{-1}\). As a consequence, sensitivity is directly proportional to the Purcell factor. Going beyond currently available technologies, an hotly pursued outstanding challenge is the development of a quantum network, which would enable quantum-secure communications, quantum information processing and quantum simulations [28–31]. Photons are one of the preferred candidates to transport quantum information between the nodes in this network, due to their high speed and low-noise properties at optical frequencies. An essential component of such a network would be a fast, deterministic and efficient source of single photons [30]. Quantum emitters such as atoms, molecules or quantum dots could be at the heart of such a source [32]. However, their intrinsic decay rates are typically around 100 MHz, preventing high-frequency operation, and emission patterns are isotropic, which is detrimental to achieve a high collection efficiency [33].
Coupling these emitters to an optical resonator solves both issues — emission rates are enhanced and emission is redistributed into the resonator with efficiency $F_P/(1 + F_P)$ [23].

1.1.2 Strong coupling — Photon-photon interaction

If the Purcell factor is increased to the point where the emitter decay rate $\Gamma = F_P \gamma$ approaches the cavity linewidth $\kappa$, such that $2g \approx \kappa$, one enters the regime of strong coupling. If $2g > \kappa$, energy is exchanged between emitter and optical mode more rapidly than it decays. Emitted light can thus be reabsorbed and re-emitted several times before it is lost, leading to the well-known vacuum Rabi oscillations — the probabilities of finding an excitation in the emitter or in the optical mode are periodically exchanged. The Purcell effect no longer holds in this regime — stronger coupling rates $g$ increase the exchange rate between cavity and emitter, yet the total decay rate of the system is fixed at $\kappa$ (or to $\kappa + \gamma + 2\gamma^*$, if emitter decay $\gamma$ and dephasing $\gamma^*$ are not neglected [13, 16]). Whereas in the time domain, strong coupling is marked by Rabi oscillations, in the frequency domain this corresponds to a splitting of the emission peak known as vacuum Rabi splitting.

Single-emitter strong coupling to an optical cavity mode has been one of the major goals in CQED [34], and was first observed at radio frequencies by Rempe et al. in 1987 [35], and at optical frequencies by Thompson et al. in 1992 [36]. This fascinating phenomenon shows that not just decay rates, but even the eigenstates of matter depend on the photonic environment. In the strong coupling regime, these eigenstates become so-called dressed states — hybridized states of light and matter excitation. This effect can be used to coherently manipulate the emitter through entanglement with single photons, and to establish an effective interaction between two photons. Another key component of the quantum photonic network mentioned in the previous section would be the node that processes the quantum information carried by single photons. However, information processing requires interaction between signals. Although photons normally do not interact, a cavity strongly coupled to an emitter responds very differently to a single photon than to two photons [6, 37]. As a consequence, whether a photon is transmitted or reflected by the cavity depends on the presence of another photon, which corresponds to an effective interaction between the photons and allows quantum logical operations with single photons [23].

1.2 Optical cavities

Historically, the first attempts to reach high Purcell factors or strong coupling have focused on obtaining very high $Q$ by using optical cavities [7]. Typically, very high reflectivity mirrors or lossless dielectrics are used, which have
1.2 Optical cavities

enabled quality factors up to $Q \approx 8 \cdot 10^9$ [38]. Mode volumes, however, are limited approximately to $(\lambda/(2n))^3$ because cavities rely on interference effects [39]. Here, we summarize the current state of the art for cavities in the context of emission enhancement and strong coupling. Because most applications require on-chip integration, we focus mainly on cavities in the solid state.

Optical cavities can be subdivided (see Fig. 1.2a-d) into (1) Fabry-Perot cavities, which trap light between two metallic or Bragg mirrors, (2) whispering-gallery-mode cavities, where waves circulate in a microsphere, -disk or -toroid, trapped by continuous total internal reflection at the walls, and (3) photonic crystal cavities, which use the band gap of a periodic dielectric to trap light in a defect [7, 40]. The first cavities at optical frequencies were Fabry-Perot cavities based on highly reflective metallic mirrors (Fig. 1.2a), which enabled the first observations of cavity Purcell enhancement [41] and strong coupling [36] at optical frequencies. Such cavities have reached $Q$ up to $4.4 \cdot 10^7$ [42], but typically have large mode volumes [40]. Microposts (Fig. 1.2c) form a solid-state version of the Fabry-Perot cavity and have delivered, for example, single-photon sources with high brightness and indistinguishability [43, 44], record-high single-photon emission rates of 4 MHz [45] and the first single-emitter strong coupling in the solid state [46]. Whispering-gallery-mode cavities (Fig. 1.2b) can reach record $Q$ [38, 47] for large diameter, and mode volumes of a few cubic wavelengths [48] for small-diameter microdisks. Single-emitter strong coupling was reached in a high-index microdisk [48, 49], and high-$Q$ microtoroids were used, among others, for low-threshold lasers [50] and single-particle biosensing [3]. Photonic-crystal cavities (Fig. 1.2d) combine very high $Q$ (up to $1.1 \cdot 10^7$ [51]) with near-diffraction limited mode volumes ($\sim 1(\lambda/n)^3$ [51, 52]). Single-emitter strong coupling [37, 53–56], very low-threshold lasers [57–59] and — to our knowledge — the highest experimental cavity Purcell enhancement of 75 [60] have been reported using photonic-crystal cavities.

Cavities, however, suffer from important drawbacks that prevent the realization of a large-scale quantum photonic network. Because $V$ is fundamentally limited, $Q$ must be very high to achieve large Purcell enhancement or strong coupling. This necessitates cryogenic temperatures of 10 K or lower, since only then are emitters available with such narrow linewidths. Furthermore, in a network, all elements must operate at the same wavelength, which implies that the cavities have to be kept in tune to within their ultra-small bandwidth — an unscalable challenge. Finally, response times of the nodes are limited to the inverse cavity bandwidth. High $Q$ thus limits the speed of switching operations and addressing of the nodes for loading or retrieving quantum information.
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Figure 1.2: Cavity and antenna designs. (a) Fabry-Perot cavity. (b) Whispering-gallery-mode (microdisk) cavity. (c) Micropillar cavity, the solid-state analogue of the Fabry-Perot cavity. (d) Photonic crystal cavity. (e) Phased array (Yagi-Uda) antenna. (f) Dipole antenna. (g) Dimer (bow-tie) antenna. (h) Nano-patch antenna. The cavities and antennas are ordered according to their typical mode volumes. The red dots represent a usual location for the emitter.

1.3 Plasmonic antennas

At the interface between a metal and a dielectric, strong interaction of the free-electron gas in the metal with light can lead to hybridized light-matter waves named plasmon polaritons [12]. Their wavelengths can lie far below that in free-space. Therefore, plasmonic antennas — finite-size metallic structures that act as cavities for plasmon polaritons — can confine light to mode volumes far below the diffraction limit.\(^\ddagger\) Ohmic absorption in the metal, however, typically limits \(Q\) to \(\sim 5 - 20\). Hence, compared to cavities, plasmonic antennas operate at the other extreme of \(Q\) and \(V\), offering high LDOS over a very broad bandwidth. This makes them ideally suited for coupling to emitters at room temperature, which typically have severely broadened linewidths [65].

Because in antennas, radiative processes have to compete with non-radiative Ohmic decay, it is crucial to verify that high LDOS is accompanied by a high radiative efficiency. This requires the use of low-loss (noble) metals, but it also depends on antenna geometry. Plasmonic structures which support large LDOS while maintaining a reasonably high radiative efficiency can be categorized (see Fig. 1.2e-h) [66] into dipole antennas [67], patch or nano-patch antennas [68–70] and phased-array antennas [71, 72]. First works focused on dipole antennas (Fig. 1.2f) such as spheres or nano-rods.

\(^\ddagger\)Note that the conventional definition of the mode volume, discussed further in Chapter 2 and applicable to high-\(Q\) cavities, does not apply to low-\(Q\) plasmonic resonators [61]. Although an analytical expression for plasmonic mode volumes is beyond the scope of this thesis, we note that a possible solution is offered by the use of quasi-normal modes [62–64].
In such resonators, increasingly high LDOS is obtained when the emitter is placed closer to the metal interface [18]. Radiation efficiency, however, drops sharply at distances of a few nanometers due to quenching by non-radiative processes in the metal. It was long believed that this limited the attainable Purcell factors to a few hundred, if radiative efficiencies above 50% were to be maintained [13]. However, recently it was realized that quenching can be overcome by placing the emitter inside a nano-gap between two metals. Such structures support highly confined ‘gap plasmons’, which can couple efficiently to radiation. Importantly, both the emitter decay rate into the gap mode and the quenching rate depend on gap thickness $d$ as $d^{-3}$ [73]. Hence radiation efficiency is roughly independent of the gap size, while the Purcell enhancement grows sharply with decreasing gaps. This forms the working principle of (nano-)patch or ‘particle-on-mirror’ antennas (Fig. 1.2h), which have shown record LDOS enhancements of 1800 for a silver nanowire on a silver substrate [74] and ~1000 for a silver nanocube on a gold mirror [68], with claimed radiative efficiencies above 50%. Not just patch antennas but also antenna dimers (Fig. 1.2g) enjoy this gap enhancement, and LDOS enhancements up to ~750 in a gold sphere dimers [75] (at >50% efficiency) and ~760 in a bow-tie antenna [76] (at ~25% efficiency) have been demonstrated. Very recently, two works have observed first signatures of plasmonic strong-coupling with a gold nanosphere on a gold mirror [70] and a gold nano-slot waveguide antenna [77]. Additional field confinement can be created through the ‘lightning-rod effect’, which leads to strong fields at sharp metal tips. This partly underlies the good performance of the bow-tie antenna and that of the nano-cone antenna, for which experimental LDOS enhancements of ~100 [78] were found at efficiencies above 60%, while theory predicts that enhancements around 5000 are possible at similarly high efficiency [79, 80]. Most of these antennas have dipolar, that is, almost isotropic, radiation patterns. Even a bow-tie or a small particle on a mirror, despite their complex near-field patterns, show a simple dipolar coupling to propagating waves, as long as they are small compared to the wavelength. Phased array antennas (Fig. 1.2e), on the other hand, such as Yagi-Uda [71, 81] or bulls-eye [72] antennas, can have more directional emission patterns, which can improve the collection efficiency. Purcell factors are typically lower in these antennas, due to decreased confinement.

These results show that plasmonics can bring the fascinating physics of cavity quantum electrodynamics into the domain of extremely high coupling rates $g$, possibly allowing the generation of single photons and coherent manipulation of emitters at >10 THz rates. However, the large bandwidth and Ohmic losses of plasmonics still pose major challenges. For one, bandwidths are so large as to make switching of the device — which requires a resonance shift of approximately the linewidth — practically impossible. Moreover, high photon generation, transport and collection efficiencies are key to scaling the current systems to a multi-node quantum network [23, 82]. For example,
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The generation of \( n \)-manifold single photons in a network scales as the total single-photon source efficiency to the power \( n \) [32]. It is not clear how significant efficiency improvements of current plasmonic antennas should be obtained.

1.4 Antenna-cavity hybrids

![Figure 1.3: Phase diagram of cavity and antenna \( Q \) and \( V \).](image)

Data are shown from several state-of-the-art cavities (1: [46], 2: [53], 3: [37], 4: [49], 5: [48]) and antennas (6: [70], 7: [77], 8: [68]). We indicate whether \( V \) was obtained from simulations, from observed Rabi splitting \( 2g \) or from the Purcell factor \( F_P \). Simulated \( V \) were always cross-checked with observed Rabi splitting. Dashed lines show constant Purcell factor \( F_P \), and the coloured curves mark the separation between strong (left of the curves) and weak coupling, given by the condition \( 2g = \kappa + \gamma_e \) [16], with \( \gamma_e = \gamma + 2\gamma^* \) the emitter linewidth. We assume an emitter at 800 nm emission wavelength with oscillator strength \( f = 100 \) (typical for epitaxially grown quantum dots [49]), and linewidths \( \Delta \lambda_e \) of 0 (blue), 1 (green) and 10 (red) nm. At room temperature, most emitters have \( \Delta \lambda_e \geq 10 \) nm. Hybrid systems could occupy the intermediate region between cavities and antennas.

As we have seen, both cavities and antennas suffer from fundamental constraints, particularly limiting the scaling of single photon sources and quantum logic gates into a larger network. Hence, alternative methods to trap and confine light are required. In this thesis, we study how combinations of different resonators provide such alternatives. The first of such combinations, is a hybrid system composed of a high-\( Q \) cavity coupled to an antenna. Intuitively, one might expect that, by storing the light partially in a cavity and partially in an antenna, such a system could combine the small mode volumes of a plasmonic antenna with the high quality factors of a cavity. In Fig. 1.3, we summarize the best cavities and antennas from literature through
1.5 Motivation and outline

their quality factors and mode volumes. Cavities are located at one extreme in this diagram — at high $Q$ and high $V$ — whereas antennas are found at the opposite extreme. Hybrids could potentially reach high $Q$ and low $V$, but more realistically could fill the gap between these two extremes, working at intermediate, practical $Q$ and $V$. This could alleviate antenna losses, offer linewidths compatible with those of realistic emitters and allow switching operations. Moreover, this intermediate regime offers ‘sweet spots’ where strong coupling could be achieved with a realistic emitter, even if a high-$Q$ cavity or low-$Q$ antenna with the same Purcell factor would not reach it.

Hybrid systems were first studied in 1999 [83] and have since been proposed for a great variety of applications. In the context of (bio-)sensing, systems that were typically based on whispering-gallery-mode cavities functionalized with metallic particles have been experimentally studied [84–89], with notable successes including the detection of such small particles as single ions in solution [90]. Hybrid systems have furthermore been studied in the context of optical trapping [91–94], surface-enhanced Raman scattering [95, 96], nano-scale lasers [97, 98] and interfaces between on-chip propagating signals and far-field radiation [99–103]. Naturally, the promise of combining small mode volumes with high quality factors renders hybrid systems highly interesting for emission enhancement or strong coupling. This has prompted several theoretical works to predict very high LDOS [104–106], and even the possibility of strong coupling [107–109] for a number of different antenna-cavity geometries. Experimentally, only few works [110, 111] have studied spontaneous emission in a hybrid system. Thus far, no clear evidence was found for large LDOS effects, partially due to the difficulty of separating pump enhancement, changes in the collection efficiency and LDOS effects [66]. Finally, although this is not a route to large single-emitter emission enhancement, we should note that there is also an active field of research into hybrid plasmonic-photonic systems with one-dimensional confinement, such as antenna arrays in a Fabry-Perot etalon [112–116].

1.5 Motivation and outline

This thesis concerns two types of hybrid resonances, each of which offers exciting opportunities unavailable with the underlying individual components. The first are resonances in hybrid antenna-cavity systems, and the second are bound states in the continuum.

Antenna-cavity hybrids

Hybrid antenna-cavity systems could combine the best of cavities and of plasmonics, to benefit applications ranging from single-particle sensing to quantum information processing. Although a number of specific geometries have
been studied, many important questions remain unanswered. These could be summarized into three main questions: (1) Could we find fundamental limits that govern the LDOS or optical responses of any hybrid system, regardless of cavity or antenna geometry? (2) If so, under what conditions could those limits be approached? (3) Experimentally, how can we make these systems, and deterministically load them with emitters? This thesis addresses these questions both theoretically and experimentally.

Theory

Chapter 2 discusses a simple and intuitive theoretical model to describe the interaction between a cavity and an antenna, as well as LDOS in such systems. Unlike previous works, the model is generic to any geometry. This chapter serves as an introduction to the physics of antenna-cavity hybrids and provides the theoretical basis for several subsequent chapters.

In Chapter 3, we theoretically demonstrate that hybrids can support larger LDOS than their bare constituents. We elucidate how interference lets these systems break a fundamental limit governing the LDOS for a single antenna, and show how cavity-antenna frequency detuning can serve as a tuning mechanism to achieve $Q$ and $V$ anywhere in between those of the cavity and of the antenna. Importantly, we show that photon collection efficiency can be high, despite plasmonic losses.

In Chapter 4 we regard hybrid systems from an electrical engineering perspective by deriving a circuit analogy for these systems. First, we review two different circuits from literature, which describe a nano-antenna, and show that the two are equivalent. The well-known maximum power transfer theorem from circuit theory is then used to find a second fundamental bound on antenna scattering and LDOS. We show how a hybrid system can be viewed as a conjugate-matching network between antenna and radiation load, allowing these systems to reach this fundamental bound.

Experiments

In Chapter 5 we present the deterministic fabrication of hybrid antenna systems consisting of whispering-gallery-mode microdisk cavities and aluminium antennas. A novel method is demonstrated for high-precision placement of fluorescent quantum dots in these systems.

Chapter 6 builds upon the developed fabrication method to study the perturbation of our microdisk cavities by the antennas. Through a combination of tapered-fiber spectroscopy and free-space microscopy, we measure antenna-induced linewidth broadening and shifts for antennas and disks of various sizes. These measurements reveal that changing antenna length can lead to a linewidth tuning of more that two orders of magnitude, in good agreement with cavity perturbation theory. Such extreme flexibility in linewidth makes hybrid systems very attractive as single-photon sources.
Chapter 7 discusses fluorescence measurements of the hybrid systems loaded with quantum dots. This reveals striking asymmetric resonances in the fluorescence spectra, corresponding to the hybrid modes. Linewidth and shape show excellent agreement to theory, and give evidence of a strongly boosted LDOS at the hybrid mode, as compared to the bare antenna. Fluorescence decay rate measurements show a strong increase of decay rate, which we attribute mainly to the antenna.

In Chapter 8 we go beyond systems with a single antenna, and experimentally study an antenna lattice instead, coupled to an ultra-high-$Q$ microtoroid cavity. The cavity is shown to induce a strong suppression of the antenna polarizability, demonstrating that cavities and antennas need not always work symbiotically. The lattice, however, does lead to interesting new phenomena that are absent for a single antenna, such as an antenna-cavity coupling that depends on angle of incidence.

**Bound states in the continuum**

The last Chapter 9 is concerned with an alternative strategy for trapping light, involving a very different hybrid resonance. Recently, it was discovered that an otherwise leaky mode inside a photonic crystal slab could become perfectly confined (i.e. with infinite $Q$) at one particular wavelength. We experimentally demonstrate that such a state, known as a bound state in the continuum (BIC), is associated with a polarization vortex in momentum-space. This implies that the state is topologically protected, making it robust against small variations in geometry. At first sight, it may appear that there is little connection between these resonant states and the hybrid antenna-cavity resonances studied in the earlier chapters. However, we show that similar physics is at work — both are in fact hybrids of two distinct resonances. While the coupling between an antenna and a cavity (usually) occurs in the near field, a BIC arises due to coupling of resonances via far-field interference. We show that such far-field coupling between an electric and a magnetic dipolar resonance inside the crystal unit cell can lead to a BIC if complete destructive interference is obtained.