Antennas to collect nearly every single photon from an emitter

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Planar antennas have achieved near-unity collection of single photons, which may open many applications in opto-electronics, quantum optics, spectroscopy, imaging, and metrology.

Single-photon sources have been discussed as the building blocks of a variety of technologies, including quantum cryptography, optical quantum computation, spectroscopy, and metrology. However, these proposals depend on having single-photon sources that are bright and have a constant flux. These requirements imply a need for near-unity efficiency in collecting photons. We have designed planar antennas to achieve this goal.

In a recent publication,1 we reported on a scheme that uses a layered dielectric antenna for tailoring the angular emission of a single oriented molecule such that a commercially available microscope objective can collect more than 96% of the emitted photons. As a result, we demonstrated record photon count rates of about 50MHz. Figure 1(a) shows our antenna design. A vertically oriented molecule is embedded at a specific position in a dielectric layer and emits photons, which are collected by an objective lens. To provide an intuitive explanation of how this antenna works, we start by considering a structure that consists of a lower output substrate with refractive index \( n_1 \) in contact with the upper medium that contains the emitter and has an index \( n_2 < n_1 \). To avoid feeding photons into large angles, we set the distance \( h \) between the emitter and the interface to be larger than a characteristic evanescent length. This arrangement ensures that the radiation of the emitter in the downward direction couples to angles less than \( \sin^{-1}(n_2/n_1) \) in the substrate. However, the part of the emission that is parallel to the interface or in the upward direction would be lost.

To remedy this problem, we limit the thickness of the emitter’s layer, topping it with a third medium that has refractive index \( n_3 < n_2 \). This construction channels the emission of the molecule into quasi-waveguide modes of the middle layer. These modes then leak into the substrate below at well-defined angles of less than \( \sin^{-1}(n_2/n_1) \), as sketched in the polar plot of Figure 1(b).

Figure 1. Design and performance of a planar dielectric antenna. (a) An oriented molecule is embedded at height \( h \) in a dielectric medium of refractive index \( n_2 \). An upper layer with refractive index \( n_3 \) helps to channel photons in the middle layer, where they leak down to a lower output layer of index \( n_1 \) to be collected by an objective lens. \( t \): Thickness of the green layer. (b) Polar plot of calculated emission pattern (red line) of a vertically oriented molecule in an antenna with these parameters: \( n_1 = 1.78 \) (sapphire), \( n_2 = 1.5 \) (polyvinyl alcohol), \( n_3 = 1 \) (air), \( t = 350 \text{nm} \), and \( h = 200 \text{nm} \). Blue area shows angles covered by objective lens. (c) Back focal plane image obtained in experiments. Red arrows indicate the polarization.

In contrast to plasmonic antennas (another approach to single-photon collection), our antenna design is wavelength insensitive, lossless, and easy to make (no lateral patterning is needed). Furthermore, as shown in Figure 1(c), the output mode is well behaved (in this case, very close to a radially polarized doughnut mode) and can be converted into other modes such as the fundamental mode of an optical fiber with high fidelity.

In the above work, loss to the upper half-space limited the collection efficiency to 96%, and the emitter’s electric dipole had to be oriented vertically. In a new report,2 we have analyzed a design, shown in Figure 2(a), that lifts these restrictions to get more than 99% collection efficiency for arbitrary dipole orientation. A metallic mirror on top of the antenna brings the small upward emission back to the output half-space.

An example of this antenna scheme could use a single-photon emitter such as a nitrogen-vacancy color center in a diamond nanocrystal. For instance, the nanocrystal could be embedded in a polymer layer \( n_2 = 1.5 \) on a bulk substrate of cubic zirconia with \( n_1 = 2.2 \), which would also act as a solid immersion lens.

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Figure 2. Antenna design with improved efficiency. (a) A metal mirror on top reflects upward emission back toward the lower layers. The output layer is shaped to form a solid immersion lens (SIL). (b) Theoretical collection efficiency (the fraction of the photons collected if the objective lens captures all light within angle $\theta$) as calculated for a horizontally or vertically oriented diamond nitrogen-vacancy center as the emitter. HED: Horizontal electric dipole. VED: Vertical electric dipole.

The upper spacer layer could be air or aerogel ($n_3 \approx 1$), supporting a metallic mirror. Calculations for this example—graphed in Figure 2(b)—show that for both horizontal and vertical orientations of the emitter’s dipole, losses to the upper half-space are negligible, and the emission to the output half-space is confined within an angle that is accessible by commercial air objective lenses. Indeed, more than 99% of all the emitted photons can be collected in this simple scheme. We are currently working on experiments to demonstrate this level of efficiency with the new antenna design.

In conclusion, we have shown that planar antennas can be used for strongly tailoring the emission pattern of a single-photon emitter such as a molecule, semiconductor quantum dot, color center, or solid-state ion to achieve near-unity collection efficiency. Our approach is wavelength insensitive and compatible with both cryogenic and room-temperature operation. We expect such antennas to find applications in many areas of science and technology.

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References