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Highly directive and Gaussian far-field emission from “giant” photonic trumpets

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Photonic trumpets are broadband dielectric antennas that efficiently funnel the emission of a point-like quantum emitter—such as a semiconductor quantum dot—into a Gaussian free-space beam. After describing guidelines for the taper design, we present a “giant” photonic trumpet. The device features a bottom diameter of 210 nm and a 5 µm wide top facet. Using Fourier microscopy, we show that 95% of the emitted beam is intercepted by a modest numerical aperture of 0.35. Furthermore, far-field measurements reveal a highly Gaussian angular profile, in agreement with the predicted overlap to a Gaussian beam $M_g = 0.98$. Future application prospects include the direct coupling of these devices to a cleaved single-mode optical fiber. The calculated transmission from the taper base to the fiber already reaches 0.59, and we discuss strategies to further improve this figure of merit. © 2015 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4932574]

Photonic wire antennas have recently emerged as a powerful solution to shape the emission of a point-like quantum emitter into a directive Gaussian free-space beam. The integration of an isolated quantum dot (QD) in such structures opens appealing prospects for solid-state quantum optics, in particular, for the generation of non-classical states of light. Beyond the initial demonstration of bright single-photon sources,1–3 the broad operation bandwidth of these antennas is also a key asset to realize tunable single-photon sources4 or bright sources of entangled photon pairs.5 Specifically, nanowire antennas exploit the efficient spontaneous emission (SE) control provided by a single-mode high-index nanowire waveguide, whose far-field emission is tailored by a top taper.6 The taper can either take the shape of a sharp needle or the one of a “photonic trumpet.” So far, appreciable beam directivity has been demonstrated with both approaches, but collection optics with a numerical aperture (NA) that exceeds 0.7 are still mandatory to fully intercept the antenna output beam.1,3,4,7

Scaling up the dimensions of a photonic trumpet in order to enlarge its top facet represents a natural strategy to improve the output beam directivity. In this work, we first examine theoretically the relevance of this approach. We then report the realization of “giant” photonic trumpets with a 5 µm wide top facet. Using Fourier microscopy, we map their far-field emission and show that 95% of the emitted beam is intercepted by a numerical aperture of 0.35. Moreover, our measurements reveal a highly Gaussian angular profile, in agreement with the predicted overlap to a Gaussian beam $M_g = 0.98$. Extending the top facet also dramatically increases the overlap to the mode supported by a standard single-mode fiber (SMF), enabling an efficient direct coupling. The calculated transmission from the taper base to a cleaved fiber already reaches 0.59, and we discuss future improvement directions.

The structure under investigation is made of a dielectric material with a large refractive index $n_1 = 3.48$, in a low index environment ($n = 1$). As illustrated in Fig. 1(a), its bottom section features a diameter $d_0 = 230$ nm, which ensures single-mode operation (HE11) for a free-space operation wavelength $\lambda = 925$ nm. Moreover, this diameter choice ensures an optimal control over the SE of an embedded

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FIG. 1. (a) Geometry of the trumpet taper. Light is launched upward in the fundamental guided mode (HE11) at the taper base. $T$ is the total transmission to a collection lens with a numerical aperture NA = sin($\theta_{max}$), and $M_g$ is the far-field overlap to a Gaussian beam. (b) Calculated transmission to a Gaussian beam $T_g = M_g T$ in the $(d, h)$ plane for $d_0 = 230$ nm and $\lambda = 925$ nm. Each contour line corresponds to $T_g = 0.9$ for a given collection NA; the solid circles highlight the minimal taper dimensions compatible with those requirements. The cross corresponds to the taper described in Ref. 3, and the plus sign to this work.
point-like emitter.\(^8\) Indeed, for an on-axis optical dipole, 95\% of the SE is funneled into the HE\(_{11}\) modes, with symmetric contributions to the modes propagating upward and downward. Moving up along the structure, the wire diameter increases linearly (total opening angle 2\(\times\)) to induce a lateral expansion of the guided mode. The top facet is located at a distance \(h\) from the base and features a diameter \(d_t\). It is covered with a \(\lambda/4\) anti-reflection coating which is composed of Si\(_3\)N\(_4\) (refractive index \(n_0 = 1.99\)).

Qualitatively, the criterion for an adiabatic expansion of HE\(_{11}\) is determined from a comparison between \(x_0\), the diffraction angle of the mode inside the taper, and the sidewall tapering angle \(\alpha\) (Ref. 9). \(x_0 = \lambda/(\pi n_{\text{eff}} w_0)\), where \(n_{\text{eff}}\) and \(w_0\) are the effective index and waist\(^10\) of HE\(_{11}\). For the high contrast waveguide investigated here, as soon as the local diameter \(d\) exceeds 0.5 \(\mu\)m, \(n_{\text{eff}} \approx n_1\) and \(w_0 \approx 0.75(d/2)\).

Adiabatic transmission of HE\(_{11}\) is achieved when \(\alpha \ll x_0\). Larger taper angles, on the order of \(x_0\), result in the onset of conversion to higher order modes, with oscillations arising from interference effects. Finally, for \(\alpha \gg x_0\), one enters a deeply multimode regime: a large fraction of the electromagnetic energy is irreversibly transferred to higher order guided modes. At the taper base, \(x_0\) largely exceeds \(\alpha\). Moving up the taper, \(x_0\) decreases as \(d^{-1}\) to reach a minimum at the top facet level. The breakdown of adiabatic propagation occurs at a typical height \(h_0 = \lambda/(0.75\pi n_{\text{eff}}^2)\) which corresponds to \(x_0 = \pi\). If \(h \ll h_0\), the whole taper operates in the adiabatic regime, yielding large modal transmission for HE\(_{11}\). For larger tapers, light propagation involves several guided modes above \(h_0\).

We now focus on the taper output beam. In the following theoretical analysis, light is launched at the taper base into the upward HE\(_{11}\) mode, propagates along the taper, and is collected in free-space by an ideal thin lens with a NA. The parabolic dependence of \(h_0\) on \(d_t\) is reminiscent of the condition \(\alpha \approx x_0\) discussed above. For NA = 0.7, a very compact structure, with \(h_0 = 5 \mu\)m, is sufficient to ensure \(T_g = 0.9\). However, further improvements of the beam directivity become increasingly demanding in terms of taper height. As an example, \(h_0\) should be increased up to 24 \(\mu\)m in order to obtain the same transmisson into a NA of 0.35.

In the second part of the paper, we demonstrate the fabrication of such “giant” photonic trumpets and measure their far-field emission properties. Figure 2(a) is a scanning electron microscope image of a 26.8 \(\mu\)m high photonic trumpet that is supported by a pyramidal pedestal. At the connection with the pedestal, the waveguide supports a single guided mode \((d_b = 210 \text{ nm})\). The total tapering angle is \(2\alpha = 10.5^\circ\) and the top diameter \(d_t = 5.15 \mu\)m. For optical characterization, the device embeds self-assembled InAs QDs as an internal light source. The QDs are located ~150 nm below the connection with the pedestal. The structure is mostly composed of Al\(_{0.05}\)Ga\(_{0.95}\)As, except the dot section for which GaAs is used as barrier material. Compared to Ref. 3, the taper height and top diameter have been multiplied by more than a factor of 2 and 3, respectively. In brief, fabrication starts with the growth of a planar sample by molecular beam epitaxy. A hard etching mask is then defined using e-beam lithography, nickel deposition, and lift-off. The trumpets are etched in a reactive ion etching chamber, using a SiCl\(_4\)-Ar gas chemistry. Finally, the remaining Ni mask is removed using wet chemistry.

Optical characterization is performed in a cryogenic microphotoluminescence \((\mu\text{PL})\) setup. The sample is kept at


**FIG. 2.** Sample and microphotoluminescence spectra. (a) Scanning electron microscope image of the sample (tilted view). The horizontal scale bar represents 5 \(\mu\)m. (b) Top trace: Microphotoluminescence spectrum, acquired under pulsed excitation with a mean power \(P_{\text{exc}} = 200 \text{ nW}\) (vertically offset for clarity). Bottom trace: Isolation of a single QD line using additional interferometric filters. (c) Spectrally integrated CCD counts versus \(P_{\text{exc}}\) for QD lines 1 and 2. The solid lines show linear dependencies.
liquid helium temperature (~4 K) in a cold finger cryostat. The QD luminescence is excited by a pulsed laser beam (repetition rate 76 MHz) focused on the sample with a microscope objective (NA = 0.6). The excitation energy (En = 1.433 eV) is tuned below the GaAs and Al0.05Ga0.95As band gaps, in the absorption continuum of the QD’s wetting layer. The same objective collects the QD luminescence, and a low pass filter blocks stray laser light. For spectral analysis, the luminescence signal is directed towards a grating spectrometer equipped with a CCD camera.

A μPL spectrum is shown in Fig. 2(b) (top trace): it is composed of sharp lines, associated with the recombination of excitonic complexes trapped in individual QDs. At saturation, the brightest lines (for example, QD2) typically feature a spectrally integrated CCD count rate of ~100 kHz [Fig. 2(c)], which corresponds to a top extraction efficiency ε1 ~ 0.1. The isolated line QD1, that will be investigated later, features a twice lower ε1. In the open waveguide (no bottom mirror) investigated here, the theoretical maximum for ε1 is 0.47. It would be achieved for a QD with a stable charge state, located on the waveguide axis, above the collection with the pedestal. We stress that this reduced ε1 is not a concern for the main goal of this work, namely, the investigation of the taper far-field emission using Fourier microscopy.7,12

As illustrated in Fig. 3(a), the taper emission can be decomposed on a set of plane waves which leave the top facet with a direction defined by the polar and azimuthal angles θ and φ. These plane waves are focused on a point (ρ(θ), φ) of the objective back focal plane. After calibration of the objective response (function ρ(θ) and transmitted intensity versus θ), we image this plane with a CCD camera which yields the far-field intensity per unit solid angle dI/dθ(θ, φ). The objective calibration is detailed in the supplementary material.13 To a very good approximation, the function ρ(θ) is linear. The maximum imaging angle θmax = 37° is limited by the objective NA; this limit appears as a solid cone of opening angle θ = 2sin⁻¹(NA/2). The same linearity holds for the transmitted intensity. The upper panel is a profile measured along φ = 0°, and the right one is a profile measured along φ = 90° (“lateral” integration over 5 CCD pixels). The solid lines are fit to a Gaussian profile, yielding identical beam diffraction angle θb = 16° for both profiles. (c) Same measurement as in (b), without spectral filtering. All QDs contribute to the far-field map. (d) Collected fraction of the beam intensity versus the collection NA, determined from partial angular integration of the measurements shown in (b). The star marks a collected fraction of 95%.

We perform angle-resolved far-field measurements on a single QD embedded in the trumpet. We focus on the spectrally isolated line QD1, which can be filtered using a combination of bandpass interferometric filters [bottom trace in Fig. 2(b)]. As shown in Fig. 3(b), the trumpet under study emits a very directive beam which is fully intercepted by the objective. Moreover, as shown in Fig. 3(c), far-field measurements conducted on the QD ensemble yield an identical pattern, which is a direct proof of the single-mode nature of the bottom part of the waveguide. For quantitative analysis, we estimate the emission intensity intercepted within a cone of opening angle θ, Iint(θ) = ∫2π ρ(θ) sin θ dθ, yielding a beam divergence angle θb = 16°. Except for acquisition noise, the data do not show any deviation from the Gaussian law. This confirms simulation results, which predict an overlap to a Gaussian beam Mg = 0.98 for a 0.35 collection NA. Although the Gaussian character of the beam emitted by needle nanowires has recently been demonstrated7 and was predicted for trumpet tapers,3 we stress that the present...
nanowire antenna offers an unprecedented combination of directive and Gaussian emission. Beyond nanowire photonics, similar far-field characteristics are only offered by state-of-the-art micropillar cavities. These features simplify the efficient out-coupling to a single-mode fiber using free-space coupling optics, and, conversely, the in-coupling of an external Gaussian laser beam. In analogy with a symmetric micropillar cavity that embeds a QD, the structure investigated in this work is particularly well suited to explore optical nonlinearities at the single-photon level. Interestingly, the broadband nature of a waveguide approach enables multicolor nonlinearities based on complex emitter level schemes.

The “butt” coupling to a SMF constitutes another appealing perspective of this work. In particular, such a device would result in a practical, alignment-free source for the long-distance distribution of quantum light. As illustrated in Fig. 4(a), we first consider the coupling to the cleaved facet of a standard SMF (NA ≈ 0.1). Such a coupling has been recently demonstrated, using the first generation of trumpets presented in Ref. 3. In the following theoretical analysis, a perfectly matched anti-reflection layer with $n_{ar} = 2.25$ is inserted between the trumpet and the fiber cleaved facet. For a taper with a single-mode base, the transmission from the taper base to the fiber reads $T_f = T_{HE_{11}} \times T_{facet}$, where $T_{HE_{11}}$ is the HE$_{11}$ modal transmission of the taper, and $T_{facet}$ is the top facet to fiber modal transmission. The taper described in Ref. 3 offers an excellent $T_{HE_{11}} = 0.99$. However, the modest top facet diameter ($d_t = 1.6 \mu m$) leads to a poor overlap to the fiber mode and limits $T_{facet}$ to 0.11 [cross in Fig. 4(b)]. The “giant” trumpet demonstrated in this work features a much larger $T_{facet} = 0.74$ [plus sign in the figure]. Despite a slightly smaller $T_{HE_{11}} = 0.8$, $T_f$ is increased by a factor of 5 and reaches 0.59. Going beyond this result will require the simultaneous optimization of $T_{HE_{11}}$ and $T_{facet}$. An optimal $T_{facet} = 0.95$ is achieved for $d_t = 8.6 \mu m$. As shown in Fig. 4(c), a linear taper with this $d_t$ should feature a height $h > 118 \mu m$ to ensure $T_{HE_{11}} > 0.90$. Such structures could be defined in a thinned GaAs wafer, after a flip-chip step, and using a robust hard mask which can sustain very deep etching. Alternatively, an additional tapering of the fiber allows reducing the fiber mode size down to the micron range, thus decreasing a lot the constraints on $d_t$ and $h$.

To conclude, we have demonstrated “giant” photonic trumpets which funnel the emission of a single QD into a very directive and Gaussian output beam. Beyond free-space quantum optics experiments, these structures can also be directly coupled with high efficiency to a cleaved single-mode fiber. Envisioned applications include practical sources of quantum light, as well as recently proposed near-field QD-electrical field sensors and single-plasmon launchers.

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10$w_0$ is defined as the radial distance for which the amplitude of the dominant electric field component is divided by $e$.
13See supplementary material at http://dx.doi.org/10.1063/1.4932574 for (i) the calibration of the microscope objective response and (ii) the far-field emission of an InAs QD embedded in an unprocessed GaAs planar sample.