Controlling the emission profile of a nanowire with a conical taper

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The influence of a tapering on nanowire light-emission profiles is studied. We show that, for nanowires with divergent output beams, the introduction of a conical tapering with a small opening angle reduces the beam divergence and increases transmission. This results in a dramatic increase in the collection efficiency of the detection optics. For a realistic tapering and a modest NA, the collection efficiency is enhanced by more than a factor of 2. This improvement is ensured by the adiabatic expansion of the guided mode in the tapering.

In recent years, research into semiconductor nanowires has intensified owing to their numerous promising properties [1]. The nanowire is a 1D single-crystalline structure with a typical radius between 20 and 200 nm, featuring a high refractive index enabling tight optical confinement. By embedding a quantum dot (QD) inside the nanowire, single photons can be generated [2], and by modifying the material composition the wavelength can be tuned [3] from the IR to the near-UV.

Potential nanowire applications include lasers [4], high-efficiency light-emitting diodes [3] and single-photon sources (SPSs) [2,5,6]. For all these applications, high efficiency is desired, but obtaining a total efficiency of ~100% is still a challenge. In any photon source, the product of two parameters governs the total efficiency. The first is the ratio $\beta$ of decay into the relevant guided mode, and the second is the collection efficiency $\gamma$, which is the ratio of the power detected by the collection optics and the power of the guided mode. The influence of $\beta$ and $\gamma$ on the total efficiency in various SPS designs was thoroughly studied in [6]. In micropillars, a $\beta$ near 1 can be achieved using a high-$Q$ cavity, and for nanowires a $\beta$ of ~1 is obtained automatically simply by choosing the correct wire radius for a radially oriented emitting dipole [5,7]. Emission diagrams for a standard nanowire were presented in [8,9], revealing that output beam profiles for nanowires are generally divergent, leading to a small $\gamma$.

One procedure for improving $\gamma$ is by modifying the nanowire geometry. In this Letter, we examine the influence of a conical tapering, similar to those used in scanning near-field optical microscopy (SNOM), on the collection efficiency $\gamma$. However, where SNOM tapers are used to achieve a field enhancement in a specific point, our tapering is used for the opposite purpose, namely, to exploit adiabatic mode expansion to efficiently couple the guided mode to a low-divergence output beam. Adiabatic mode expansion has previously been used to obtain efficient coupling between a ridge waveguide and a fiber [10]. Also, the nanowire design must ensure a strong coupling to the active medium, i.e., the QD. We demonstrate that the implementation of realistic conical tapers increases the collection efficiency $\gamma$ to ~65%, using a lens with a NA of only 0.5.

The parameter $\beta$ depends on the position and the orientation of the dipole emitter [9]; however, in the following, we study $\gamma$ under the assumption that $\beta$ is ~1. Even for $\beta=1$, there is only a 50% probability that the excited mode is traveling forward, but we shall here assume that the backward-traveling contribution is reflected forward, e.g., by implementation of a Bragg reflector below the QD. We can thus justify the simplifying assumption that all radiation goes into a forward-propagating mode.

We investigate the nanowire geometries sketched in Figs. 1(a)–1(c) with a QD positioned at the center of the wires. Following [8,9], we restrict our studies to a homogenous material with dielectric constant $\varepsilon=\varepsilon^2=6$, which is close to that of GaN at optical wavelengths. We consider a guided mode traveling forward in the topmost nanowire layer. At the top, the mode is partly reflected back into the nanowire and partly transmitted into free space, and we compute the ratio of the power of the emitted radiation over that of the guided mode.

Because of the small size and the large refractive index, approximate methods for calculating the diffraction at the top of the nanowire cannot be used. It is necessary to perform a full 3D vectorial simulation, and we have employed the eigenmode expansion technique [11] with perfectly matched layers. In this technique, the structure is split into layers along the propagation axis, and the field is expanded on the eigenmodes of these layers. At the interfaces, the fields are connected using the transfer-matrix formalism. The tapers illustrated in Figs. 1(b) and 1(c) are modeled using a staircase approximation [12], where the number of staircase steps is increased until convergence is obtained. For the ideal conical
taper only eight staircase steps were necessary, and this suggests a tolerance toward fabrication imperfections. However, a quantitative study of this tolerance is beyond the scope of this Letter. Finally, the emission into the far field is computed by employing equivalent surface currents [13].

We first study the geometry illustrated in Fig. 1(a) as function of nanowire radius $R_{nw}$. We employ dimensionless units, however, as an example of typical length scales, for a QD emitting at 950 nm; $\omega R_{nw}/c = 1$ corresponds to $R_{nw} \sim 150$ nm. The emitted power $P(\theta)$ is illustrated in the far-field emission diagrams of Fig. 2(a) for the two polarizations $\varphi = 0$ and $\varphi = \pi/2$. The integration over the azimuthal angle $\varphi$ is included in $P(\theta)$ such that the total emitted power $P_t$ is

$$P_t = \int_0^\pi P(\theta) d\theta.$$  

Comparing the profiles, we observe that the modes for $\omega R_{nw}/c = 1$ and 2 are well confined with a narrow waist, leading to a broad emission profile. For $\omega R_{nw}/c = 0.75$ and 6, the mode waists are wide, resulting in narrow-emission profiles. We remark that the wide-mode profile for $\omega R_{nw}/c = 0.75$ is due to a deteriorating confinement as $R_{nw} \rightarrow 0$.

To facilitate the analysis, we have computed the total transmission into free space as well as the collection efficiency $\gamma$ of a lens with numerical aperture equal to 0.5 in Fig. 2(c). For large nanowire radii, the light detected by the lens increases with $R_{nw}$ toward a maximum of $\sim 82\%$, corresponding to the plane-wave transmission coefficient given by $1 - (n-1)^2/(n+1)^2$. However, a large nanowire radius should be avoided, as it allows for spontaneous emission into higher-order guided modes with divergent emission profiles.

For very small $R_{nw}$, the amount of light collected by the 0.5 NA lens does approach 100% as the radius is decreased; however, for these small radii the fraction $\beta$ tends toward zero [5,7]. This can be understood by inspecting the mode profiles in Fig. 2(b). For small radii, the modes are pushed out of the waveguide, resulting in large-mode volumes and weak coupling with the QD at the center. Figure 2(b) indicates that the best QD-mode coupling is obtained for $\omega R_{nw}/c = 1$; however, for $\omega R_{nw}/c = 1$, $\gamma$ is only $\sim 29\%$.

Fixing $\omega R_{nw}/c = 1$, we now modify the nanowire geometry by implementing the conical taper with tip opening angle $\alpha$ sketched in Fig. 1(b). The corresponding emission diagrams and the total emission and collection efficiency as function of $\alpha$ are given in Figs. 3(a) and 3(b). As an example of length scales, if $R_{nw} = 150$ nm the taper height for $\alpha = 5^\circ$ is $\sim 3.4$ $\mu$m.

For large opening angles, the collection efficiency is not improved by the taper, but we observe that when $\alpha$ approaches zero, $\gamma$ increases dramatically, reaching 87% for $\alpha = 1^\circ$. This high collection efficiency can be attributed to an adiabatic expansion of the guided mode with two beneficial effects. First, the adiabatic expansion eliminates the reflection at the semiconductor–air interface, increasing the total transmission to 100%. And second, the guided-mode profile is expanded such that the divergence of the output beam is reduced. These two effects ensure a high collection efficiency without compromising the good QD-mode coupling. The adiabatic expansion can be improved by reducing the opening angle even further, resulting in $\gamma \rightarrow 1$. 

\begin{equation}
\int \varepsilon |\mathbf{E}|^2 d\mathbf{r} = 1.
\end{equation}
To validate the feasibility of such sharp tips, preliminary fabrication attempts have been performed by focused ion-beam etching. Figure 1(d), which displays a scanning-electron micrograph of a GaAs tip etched in a FEI Strata 400 etching system (Ga+ ions, 30 keV energy), confirms that tip angles as small as 4° and a very smooth surface can be processed.

The experimental fabrication of conical tapers with very small opening angles could prove difficult because of the fragility of the outermost tip. To examine the importance of obtaining a perfect conical taper, we have studied the truncated geometry illustrated in Fig. 1(c). The influence of the truncation parameter $L/L_0$ on the total transmission and collection efficiency for an opening angle $\alpha=5^\circ$ is illustrated in Fig. 3(c). We observe a rapid increase in $\gamma$ reaching 65% for $L/L_0=0.5$, which is only 4% less than the collection efficiency for an ideal taper and represents an improvement of more than a factor of 2 compared with a standard nanowire tip. A perfect taper is thus not required to obtain the improvement in $\gamma$ from the adiabatic mode expansion. We can understand this by inspecting the field profiles for the ideal taper and the truncated taper shown in Fig. 4. The field strength in the upper part of the taper shown in Fig. 4(a) is very weak. The absence of the top part of the tip thus has little influence on the emission, and the field profile for the truncated geometry shown in Fig. 4(b) is almost identical to the ideal case. The profile for the standard nanowire is included in Fig. 4(c) for comparison.

In conclusion, we have shown that the divergence of the nanowire output beam can be greatly reduced and the total emission can be increased to $\sim100\%$ by the introduction of a conical taper. The opening angle of the taper should be below $\sim10^\circ$ to obtain a major effect, and since the taper does not need to be perfectly conical, the adiabatic effect should be experimentally realizable. In nanowire light emitters, the taper permits control of the emission profile, and in single-photon sources it allows for a strong QD-field coupling and a high collection efficiency to be obtained simultaneously.

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References