Optical localization of quantum dots in tapered nanowires

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***Abstract*—In this work we have measured the far-field emission patterns of InAs quantum dots embedded in a GaAs tapered nanowire and used an open-geometry Fourier modal method for determining the radial position of the quantum dots by computing the far-field emission pattern for different quantum dot locations.**

I. Introduction

InAs quantum dots embedded in a GaAs tapered nanowire have been shown to be a good candidate for realising an efficient single-photon source with a good coupling to a Gaussian field profile [1]–[3]. However, the efficiency of these structures rely on the radial position of the quantum dot and therefore it is important to be able to locate the quantum dots in a non-destructive way.

We use an inverse method for determining the position of the quantum dots by measuring the far-field pattern of quantum dots in a tapered nanowire, and then by optical simulations computing the far-field pattern for different emitter positions. By comparison between simulations and experiments we can determine the radial position of the quantum dots.

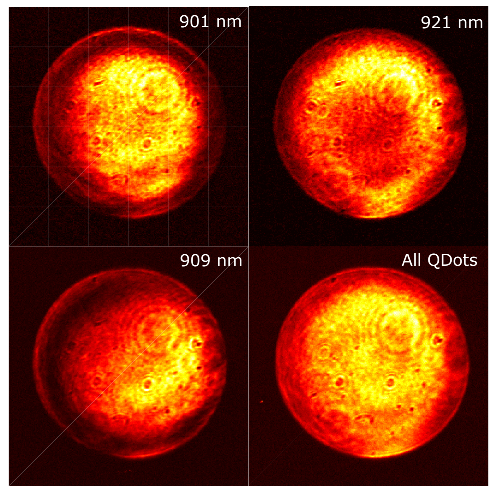

Fig. 1. Far field emission pattern of a tapered nanowire with a bottom diameter of 280 nm. Three quantum dots emitting at 901 nm, 909 nm and 921 nm are present in this sample. The far-field emission pattern are quite different indicating that the quantum dots are positioned differently in the nanowire.

II. Experiment

The tapered nanowires (needles) has been fabricated as in [1] and the far-field measurements has been performed by exciting the wetting layer of the quantum dots at 825 nm with a power of 6 μW. The emission pattern was recorded using a spectrally resolved Fourier imaging setup with a numerical aperture of 0.75. In Fig. 1 measurements of the far-field emission pattern are shown for three different quantum dots located in the same nanowire with a bottom diameter of 280 nm. As seen the far-field look very different indicating that the quantum dots are located at different radial positions in the nanowire.

In Fig. 2 a sketch of the structure is seen together with the normalised spontaneous emission rate for a dipole located 80 nm above the bottom mirror as function of the radial position for the two possible dipole orientations. As seen the emission rate into the two guided modes HE11 and TE01 depends strongly on the radial position of the quantum dot. Since the two modes have different field distributions in the nanowire the relative excitation of the modes will leave a footprint in the far-field of the quantum dot position. However, since the two modes interfere and have different propagation constants the far-field pattern will depend on the height of the nanowire. Therefore a good description of the exact geometry is important in order to have a good agreement between experiments and simulations. It should also be noted that the quantum dot only excites the TE01 mode if its dipole has a tangential component. For an in-plane isotropic emitter the total emission rate can be computed as the average: $\Gamma = (\Gamma_{\mathrm{radial}} + \Gamma_{\mathrm{tangential}})/2$, which means that the total emission rate into the TE01 mode is half of the rate shown in Fig. 2 [4].

III. Simulations

An open-geometry Fourier modal method [5] and the scattering matrix formalism [6] has been used for computing the near-field right outside the tip of the needle, and a near-field to far-field transformation [7] has been used to compute the far-field emission pattern. The normalised spontaneous emission

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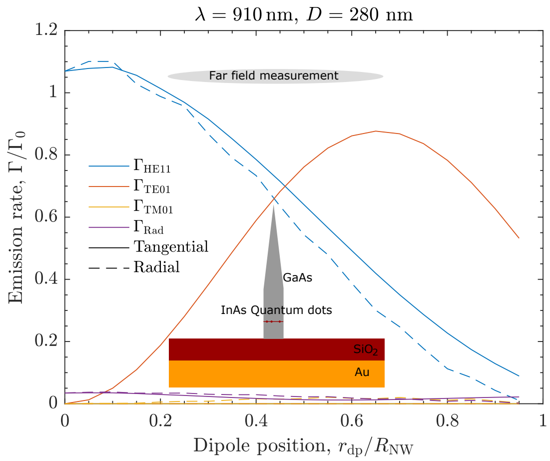

Fig. 2. The normalised spontaneous emission rate for a dipole with a wavelength of 910 nm located in a tapered nanowire with a diameter of 280 nm as illustrated in the sketch.

rate in Fig. 2 has been computed as in [5] by using the Lorentz reciprocity theorem [6].

As mentioned in the previous section the far-field pattern will depend on the height of the needle structure due to the different propagation constants for the HE11 and TE01 mode. At this moment we only have an approximate description of the actual needle geometry and therefore we do not have a final agreement between the simulated and measured far-fields. However, we do observe similar field patterns between the far-field measurements and the computed field in the nanowire, so we are confident that before the conference we will have more concluding results than we do at the moment. In Fig. 3 the far-field of a 2.5 μm long needle nanowire with a bottom diameter of 280 nm (approximately corresponding to the needle nanowire used for the measurements in Fig. 1) with a dipole emitter positioned off-axis by 0.6 R_{NW}, where the dipole couples to both the TE01 and the HE11 mode (see Fig. 2). This far-field pattern has similarities with the far-field produced by the 921 nm quantum dot in Fig. 1. Thus it is likely that this quantum dot is positioned off-axis by approximately 0.6 $R_{\text{NW}} = 84\,\text{nm}$. However, the far-field pattern is quite sensitive to the shape of the needle nanowire and therefore no final conclusion should be made before a more thorough investigation of the exact experimental geometry has been carried out together with additional simulations. The results presented here proofs the concept of localising quantum dots based on far-field measurements, but as discussed more work needs to be done before finally concluding on the quantum dot positions.

IV. Conclusion and Outlook

In this work we have shown the possibility of localising quantum dots in a needle nanowire based on their far-field emission pattern by comparison with simulations. Future work on this project will be to determine quantitative indicators in the far-field pattern, that changes with the quantum dot

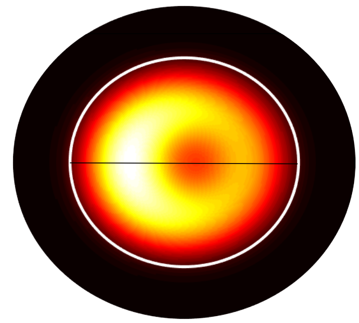

Fig. 3. Far-field pattern of the TE01 and HE11 mode in a nanowire, where the dipole is located at a radial offset of 0.6 R_{NW} to the right of the centre of the mirror symmetry line.

position in the nanowire. These indicators could be the offset of the maximum power in the far field, the ratio between the bright and the dark spot in Fig. 1(top right) and Fig. 3, and the width of the far-field pattern if it looks Gaussian as in Fig. 1(top left). This is under investigation and the results will be presented at the conference. When we are confident on the positions of the quantum dot we plan to cross-check our findings with a structural visualisation technique such as TEM as in [8] or by imposing a strain as in [9].

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