QSS11 - Arno Rauschenbeutel - Questions & Answers

Arno Rauschenbeutel

Bill Phillips: You emphasized that for nanophotonics you need a full vector treatment. Certainly. But are there other approximations that must be abandoned for nanophotonics?

ARNO: In order to compute the modes in nanophotonics, we solve, without approximations, Maxwell's equations for the boundary conditions imposed by the structure. We represent the latter by a spatially varying permittivity. This approximation, also used in bulk or fiber optics, continues to be valid in nanophotonics with dielectrics. When it comes to the interaction of an atom with a nanophotonic mode, we continue to use the dipole approximation in quantum nanophotonics. However, because of large transverse intensity gradients, the rate of higher order multipolar transitions may be somewhat higher than for a paraxial wave with the same intensity and polarization.

Bill Phillips: The correlated photon description is Mollow-like. For multi-level atoms there is another broadening mechanism that, I think, predates Mollow. This gives a width related to the excitation rate, not the spontaneous rate. Did you take this into account?

ARNO: Thank you very much Bill, for pointing me towards this work, which I did not know. However, in our case, the atoms scatter light on a cycling transition. Thus, while we deal with a multi-level atom, it effectively behaves like a two-level atom. We therefore expect Mollow's treatment to apply.

Bill Phillips: In seeing the atom where it is not, you compared to the physical size of the atom—what about the size of the center-of-mass wavefunction of the atom?

ARNO: After Doppler cooling the ion, the spatial extension of the motional atomic wave packet was ~ 36 nm, i.e., about 4 times smaller than the apparent shift of the ion's position.

Bill Phillips: The story of the Darwin-predicted emission seems to involved an ill-defined separation of spin and orbital angular momentum of the light. Is that right?

ARNO: In dipolar emission, the spin and angular momentum components of the light field are coupled and their expectation values for a $\sigma\pm$-polarized dipole are $\langle Sz\rangle=\pm 2\hbar\cos^2(\theta)/(1+\cos^2(\theta))$ and $\langle Lz\rangle=\pm 2\hbar\sin^2(\theta)/(1+\cos^2(\theta))$, respectively, where θ is the angle between the quantization axis (with its origin at the position of the emitter) and the direction of observation. In the xx-yy-plane (θ=90∘), the photons carry exclusively orbital angular momentum with expectation value $\pm\hbar$, while the spin angular momentum vanishes, corresponding to linear polarization. This is an example of spin–orbit coupling of light, which gives rise to Darwin's prediction: When a photon of linear momentum $\hbar$k carries $\pm\hbar$ orbital angular momentum, it has to come from a position $\Delta y=\pm k^{-1}=\pm\lambda/2\pi$ away from the origin. I hope that this answers your question, Bill.

Bill Phillips: For the Cs directional spontaneous emission, what are you taking as the quantization axis?

ARNO: The quantization axis is orthogonal to the fiber axis and to the radius vector that connects the fiber axis and the atomic position. The origin is located at the position of the emitter.

Bill Phillips: For directional emission, it seems that there should be something that breaks time-

reversal-symmetry, perhaps something that looks like a magnetic field. Is this right?

ARNO: Yes, you are right. It is the spin of the spin-polarized atom that changes sign when time is reversed (like a magnetic field) and that breaks time-reversal-symmetry.

Bill Phillips: Also, presumably there is plenty of emission into free space and not into the nanofiber. Does that change anything?

ARNO Indeed, in our case, most of the emission goes into free space, while the high directionality has been observed for the emission into the nanofiber-guided modes. Nevertheless, even if we consider all the emitted light – both into the waveguide and into free space – the theory still predicts a finite directionality with respect to the emission into the two half-spaces that are separated by the plane that contains the atom and that is orthogonal to the nanofiber-axis. In other words, upon spontaneous emission of a $\sigma+$ or $\sigma-$ polarized photon, the atom experiences a net recoil momentum that has a component along the nanofiber. Moreover, studying photonic crystal waveguides, it has been shown that it is possible to simultaneously realize a high β-factor and a high directionality. Finally, in our experiments on single-atom cavity quantum electrodynamics with whispering-gallery-mode microresonators, we observe the same high directionality for the emission into the counterpropagating whispering-gallery-modes, and this emission dominates over free-space emission because the system operates in the strong-coupling regime. Summarizing, a high β-factor and a high directionality are not mutually exclusive.

Jonathan Kunjummen: The gold nanoparticle directionality (40:1) was greater than the cesium directionality (10:1). Is this from multilevel effects, the fact that you use many cesium atoms together, or something else?

ARNO: The photons that are emitted by the atoms are either linearly polarized along the quantization axis or circularly polarized in the plane that contains the atomic position and the nanofiber axis. However, the forward and backward propagating nanofiber-guided modes are elliptically polarized at the position of the atoms. The directionality is therefore limited by the non-vanishing polarization overlap of, e.g., the backward propagating fiber mode with $\sigma\sigma+$ polarization. In the gold nanoparticle experiment, the ellipticity of the polarization of the induced dipole could be continuously tuned and, thus, be made "more orthogonal" with, e.g., the backward propagating mode. While this also reduces the polarization overlap with the forward propagating mode, it allows one to increase the directionality beyond what one gets for a circularly polarized emitter.

David Nadlinger: When you say the minima are above/below the waveguide, is that because of linear polarisation in the nanofibre? Could you move them by adjusting the polarisation?

ARNO: Yes, you are right. We break the azimuthal symmetry by using linearly polarized trapping field (the red- and blue-detuned trapping fields are orthogonally polarized). If we turn the linear polarizations of both fields by the same angle, the minima move azimuthally by that angle.

Followup question: Could you then rotate the polarization very quickly and generate toroidal traps?

ARNO: Yes, that could be done. Alternatively, one could simply use circularly polarized trapping fields. They preserve the azimuthal symmetry and result in toroidal traps.

Gaby Slavcheva: Have you looked at the directionality of second-order coherence in the previous section of your talk? Does it exhibit bunching or anti-bunching?

ARNO: I assume that you are referring to the experiment on "Correlating Photons Using the Collective Nonlineary of Weakly Coupled Atoms". There, the observed modification of the photon statistics occurs in the forward direction only, because it stems from the interference of the pump field with the scattered field. In the backward direction, only the scattered component is present. Moreover, unless the condition for Bragg reflection is fulfilled, the amplitude of this component is not collectively enhanced. Therefore, while we did not measure the photon statistics for the

backscattered light, I assume that it will exhibit slight antibunching as expected for free-space fluorescence of a small ensemble of atoms.

Gaby Slavcheva: How strong is the pump? Is it not similar to the Mollow triplet spectrum for strongly-dressed states?

ARNO: The saturation parameter was 0.02. The Rabi frequency is therefore much smaller than the linewidth and we do not deal with strongly dressed states. Thus, the spectrum we observe corresponds to the Mollow triplet in the unresolved sideband regime, i.e., the splitting of the sidebands (or of the dressed states) is much smaller than their width.

David Nadlinger: For the last section of the talk, is there a simple explanation for why the "two-photon" scatter is broader in frequency than the absorption that "scoops out" the middle part?

ARNO: The two-photon component has the same spectral width as the atomic absorption. Still, if one filters a Lorentzian spectrum with a Lorentzian of the same width and center frequency in the limit of high optical depth, two symmetric bumps remain because the off-resonant optical depth is smaller than the resonant optical depth.