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Coherent single-photon absorption by single emitters coupled to 1D nanophotonic waveguides

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Abstract: We have derived an efficient model that allows calculating the dynamical single-photon absorption of an emitter coupled to a waveguide. We suggest a novel and simple structure that leads to strong single-photon absorption.

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It was pointed out by Cirac *et al.* [1] that a time-reversal symmetric photon wavepacket can be used to efficiently transfer quantum states among distant nodes consisting of Λ -type atomic media. The interesting concept of time-reversal symmetry was also applied to two-level atoms, showing that it is indeed possible to perfectly invert an atomic qubit using photon wavepackets that are spatially and temporally the inverse of the photon wavepacket emitted by a qubit through spontaneous emission [2]. However, realizing this prediction requires highly non-trivial pulse shaping, especially at the single-photon level. A very promising route towards realizing single-photon absorption with unit probability is to use recent advances in nanophotonics that enable the funneling of almost all single-photon emissions into a single mode [3–5]. It has been shown that these one-dimensional (1D) or quasi-1D waveguides can be used to efficiently control the spontaneous emission (SE), see sketch in Fig. 1. Inversely, reciprocity in classical electrodynamics predicts efficient coupling of (single) photons with an emitter, provided the incoming (single-photon) wavepacket is fed through the same channel which is associated with a high SE rate. To optimize the atomic excitation probability, a time dependent treatment is required to predict which photon wave packets have optimal temporal and spatial profiles for atomic excitation.

We have recently developed a time-dependent model [6], which enables calculating the dynamical properties of single-photon absorption and quantifies the atomic excitation efficiencies that can be reached using practically achievable single photon wavepackets in 1D waveguides. As sketched in Fig. 1, we consider a single-photon wavepacket propagating along a 1D waveguide, interacting with a single emitter. We explore the possibility of maximizing the single-photon absorption by the emitter via engineering the photonic environment of the emitter, and by shaping the pulse of the input single-photon wavepacket through waveguide dispersion. In particular, we propose a terminated metallic nanowire to aid the single photon absorption. By placing the emitter at an optimal position from the termination of the wire, we can obtain a significant improvement of the atomic excitation when illuminating the atom using a single Gaussian single-photon wavepacket from one side.

In most realistic cases, an emitter coupled to a 1D waveguide will still have a residual coupling to free space modes that are not guided by the wire. For such a quasi-1D waveguide, the spontaneous emission β -factor into the forward plus backward propagating waveguide modes will have a value less than 100%. Also, a break in symmetry in the geometry might imply that emission into forward and backward propagating waveguide modes is unbalanced. In these cases, where the pumping channel funneling the incident single-photon wavepacket has a spontaneous emission β -factor of β_0 , the equation of motion for the atomic excitation becomes,

$$\frac{dC_0^e(t)}{dt} = -i \int_{-\infty}^{\infty} dk C_k^g(0) \sqrt{\frac{\beta_0 \Gamma}{2\pi}} v_g e^{-i(\omega_k - \omega_0)t} - \Gamma C_0^e(t)/2. \quad (1)$$

where g_k is the coupling strength, $C_0^e(t)$ is the probability amplitude of the excited atomic state, Γ is the spontaneous emission decay rate, v_g is the group velocity of propagating mode, $C_k^g(0)$ is the initial wavepacket defined in k-space.

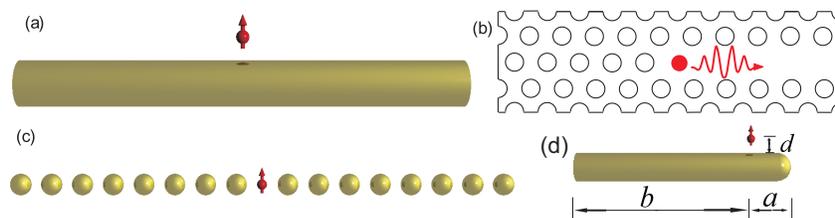


Fig. 1. Possible realizations of a 1D waveguide coupled to a single emitter: (a) a metallic nanowire, (b) a photonic crystal waveguide (c) an infinitely long plasmon particle chain, and (d) a terminated metallic nanowire. The wire radius in (d) is 20 nm, the distance of the emitter to the wire surface and the wire termination are given by $d = 10$ nm, $a = 190$ nm, respectively.

It should be remarked that the first term of the rhs in Eq. (1) is simply the pulse shape in absence of light-matter coupling, assuming that the coupling strength g_k is constant in the narrow frequency interval given by the pulse width.

For an infinitely long 1D waveguide excited by a single pulse, the maximum SE β factor possible for the pumping channel is 50%. Considering the case of a single Gaussian pulse, we find that maximum value for the atomic excitation is around 40% for such an infinitely long waveguide. This value may be pushed closer to the limit of 50% by not using Gaussian pulses, but rather the inverting pulses proposed by Rephaeli et al. [2]. However, to go beyond the limit of 50% will invariably require illuminating the emitter from two sides with a proper phase relation between the two input pulses. However, we find show that instead of increasing the complexity of illumination by using two pulses, it is possible to significantly increase the excitation probability by engineering the photonic environment of the emitter in order to break the symmetry.

Specifically, we study a terminated metallic nanowire coupled to an emitter, as shown in Fig. 1(d). On the right-hand side, the metallic nanowire is terminated with a spherical endcap of radius R (equal to the radius of the nanowire). On the left-hand side, the nanowire is infinitely long. By properly choosing the position of the emitter, we found that 91% of the emission can be funneled into the left-hand propagating mode. Due to this large spontaneous emission β -factor, one expect that the maximum atomic excitation may be enhanced significantly. Indeed, we found that the maximum of the atomic excitation probability is 72% for such a terminated metallic nanowire. We further explore whether waveguide dispersion could aid single-photon absorption by pulse shaping. For a Gaussian input wavepacket, we find that the absorption efficiency can be improved by a further 4% by engineering the dispersion.

We envisage that our time-dependent model for the atomic excitation can be useful for the analysis of different nanophotonic structures, and aid in interpreting ongoing experimental activities that focus on coupling a freely propagating photon to an atom, quantum dot, or NV center. Our method of engineering the photonic environment to enhance the maximum atomic excitation is demonstrated by the example of studying the single photon absorption by single emitters coupled to the terminated metallic nanowire.

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