Design and simulations of highly efficient single-photon sources

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Abstract— The realization of the highly-efficient single-photon source represents not only an experimental, but also a numerical challenge. We will present the theory of the waveguide QED approach, the design challenges and the current limitations. Additionally, the important numerical challenges in the simulations of sources with in-plane emission will be discussed.

1. INTRODUCTION

Within optical quantum information processing, deterministic generation of single indistinguishable photons on demand is a key functionality. An optically or electrically excited quantum emitter, e.g. a semiconductor quantum dot, embedded inside a solid-state semiconductor host material represents an attractive platform for such a single-photon source. However, for an emitter in bulk material, the symmetry of the system leads to a collection efficiency of only 1-2 %, and efficient light extraction thus poses a major challenge in single-photon source engineering. [1]

Several approaches have been proposed to control the light emission and ensure an efficient coupling to the collection optics. Within waveguide quantum electrodynamics, the quantum dot is placed inside a waveguide. By carefully tailoring the waveguide dimensions, the relative coupling of the spontaneous emission (SE) to the fundamental waveguide mode, known as the SE β factor, can reach 0.95 in uniform GaAs waveguides. This high β is obtained thanks to a suppression of the SE contribution to radiation modes due a screening effect. [2] Furthermore, in photonic crystal waveguides the β additionally benefits from increased SE into the fundamental mode near the band edge, thus enabling an experimentally measured β above 0.98. [3]

Such near-unity coupling to a waveguide relies critically on correct engineering of the dimensions, which in turn requires accurate numerical simulation of SE in the considered waveguide. This simulation represents an extremely demanding task. Whereas determination of the SE contribution to the fundamental mode is straightforward, the contribution to the radiation modes must be evaluated for a waveguide placed in an open system. The difficulty lies in that most computational methods require that the computational domain be limited to fit in memory, leading to parasitic reflections from the surrounding wall. Here, an absorbing boundary condition can be employed to reduce the influence of the size of the computational domain, and to compute the correct SE contribution the absorbing boundary condition must perfectly mimic the open geometry system.

State-of-the-art methods to compute the SE will be discussed with emphasis on the influence of the size of the computational domain. We will show that proper convergence towards an open boundary limit is generally not obtained, representing a major numerical challenge in optical engineering of high-efficiency single-photon sources.

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