An efficient, optical fiber-based waveguide interface to a single quantum dipole

Marcelo Davanço[1,2] and Kartik Srinivasan[1]

[1] *Center for Nanoscale Science and Technology, National Institute of Standards and Technology, Gaithersburg, MD*
[2] *Maryland NanoCenter, University of Maryland, College Park, MD, 20742*
* *Corresponding author: mdavanco@nist.gov*

Abstract: We theoretically investigate a single emitter embedded in a hybrid optical waveguide that proves highly efficient, optical fiber access to the dipole transition. A photoluminescence collection efficiency above 70 % and a ≈ 15dB transmission contrast upon resonant excitation are predicted.

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The successful realization of a number of proposed applications in areas such as classical and quantum information processing [1] and single emitter spectroscopy [2] requires efficient and accessible dipole excitation and emission channels. In this work, we theoretically investigate a nanophotonic system that provies a highly efficient interface to a single emitter embedded in a semiconductor channel waveguide. Our system (Fig. 1) consists of a suspended GaAs semiconductor channel waveguide (WG) that hosts a single InAs quantum dot [3] and is evanescently coupled to an optical fiber taper WG. The taper WG is a single mode optical fiber whose diameter at half its length is adiabatically and symmetrically reduced to 1 μm. Fiber taper and channel WGs form a directional coupler of length L_c, such that power may be transferred between the two guides. This allows excitation signals injected at the fiber input to reach the dipole, and, conversely, fluorescence to be outcoupled through both fiber ends, as indicated in Fig.1(b).

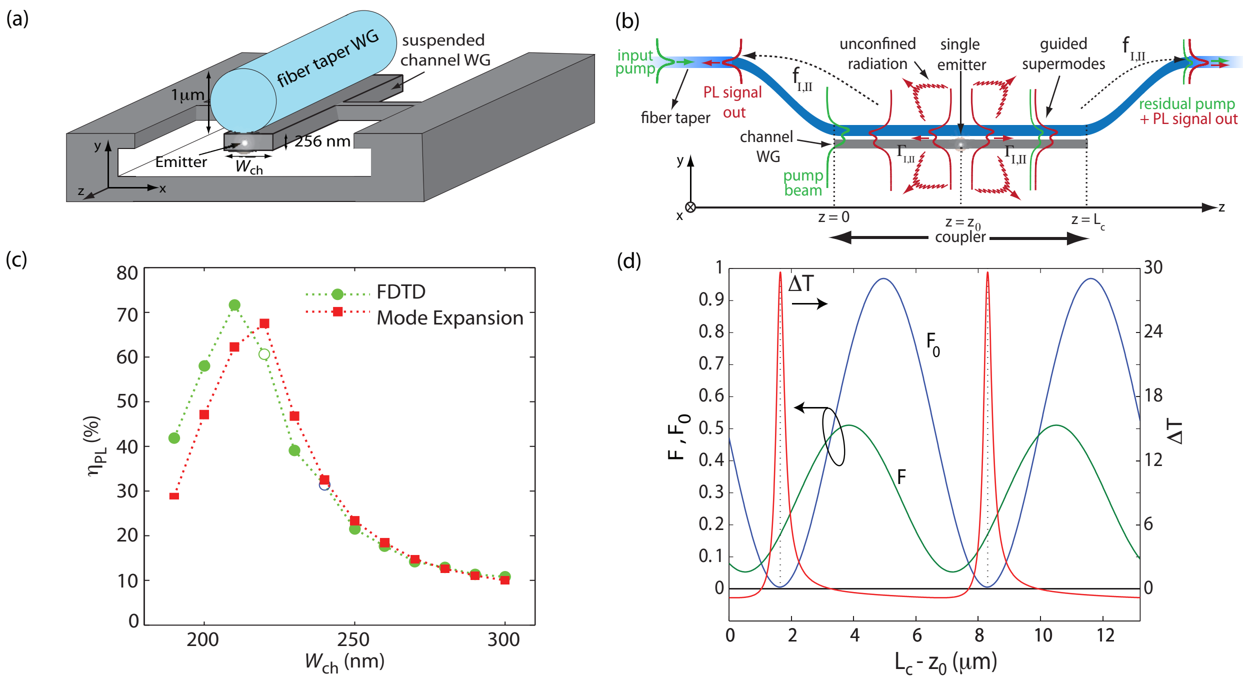

Fig. 1. (a)-(b) Fiber taper/channel waveguide directional coupler scheme. (a) 3D schematic showing cross-section of the hybrid waveguide. (b) Non-resonant single dipole PL collection configuration. (c) Maximum spontaneous emission collection efficiency calculated with FDTD and supermode expansion methods. (d) Normalized transmission as a function of separation from a single dipole located at z_0, on- (F) and off- (F_0) resonance, for $W_{ch} = 220$ nm. The transmission contrast $\Delta T = (F - F_0)/F_0$ is also plotted.

Finite difference time domain (FDTD) simulations were used to determine the photoluminescence (PL) collection efficiency into the fiber, η_{PL}, for a x-oriented dipole embedded in a 256 nm thick channel and radiating at $\lambda = 1.3\,\mu$m (the same material system used in Ref. [3]). As shown in Fig. 1(c), η_{PL} displays a maximum of $\gtrapprox 70\%$ for a channel width $W_{\rm ch} \approx 220\,$nm, where we have considered collection from both the forward and backward direction of the optical fiber. Based on the methodology of Refs. [4, 5], we determined that this highly efficient collection is due to the emission into two coupler hybrid supermodes (I and II) that simultaneously exhibit high spontaneous emission coupling factors ($\beta_{\rm I} \approx 30\%$ and $\beta_{\rm II} \approx 10\%$) and efficient coupling ($\approx 50\%$) to the fiber taper waveguide mode.

The availability of supermodes with high β furthermore allows strong modification of the transmission between the input and output fiber ports by the single embedded dipole. The transmission contrast through the fiber, defined as $\Delta T = (F - F_0)/F_0$, where F and F_0 are the photon flux levels on and off resonance with an x-polarized dipole moment located at $z = z_0$, is plotted in Fig.1(d). Calculation of ΔT is described in Ref. [4], and is based upon the interaction of a single two level atom with a quantized electromagnetic field, using the standard quantum optics input-output formalism of Ref. [6] and the formulation employed by van Enk in describing the coupling of a dipole to a free-space beam [7]. We see that F can be significantly enhanced or suppressed relative to F_0, depending on the distance $L_{\rm c} - z_0$ between the dipole and coupler termination: at $Lc - z_0 \approx 1.65\,\mu$m, F is ≈30 times larger than F_0 (increasing from $< 1\%$ to $\approx 20\%$); at $L_{\rm c} - z_0 \approx 5.0\ \mu$m, it is 2.4 times smaller (decreasing from $\approx 96\%$ to $\approx 40\%$). A judicious choice of coupler length thus produces fiber-coupled structures in which a single dipole can have a strong effect on the transmitted photon flux.

The efficient spontaneous emission collection and the dipole's ability to significantly influence light transmission through the coupling fiber indicates that the system described here can serve as an efficient optical interface to a single embedded quantum dot. This is of relevance to a class of experiments in information processing [8] and spectroscopy [2] in which the coherent quantum regime of strong coupling in cavity QED [1, 3] is not necessary. Of additional appeal are the relaxed fabrication requirements of a channel WG in comparison to high quality factor cavities, made resonant at specific wavelengths. An experimental implementation of this hybrid waveguide-quantum dot system has been initiated. Our latest efforts in the fabrication and characterization of these devices will be reported.

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