Load Effects on Quantum Dots Antennas Connected with Nanowires

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Abstract

This paper analyzes the performance of antennas made by quantum dots, by studying the effects of the transition element (a nanowire) posed between the antenna and the final load. The analysis is performed in the frame of the circuit theory, in the long wavelength and weak field limits. It is highlighted a huge effect related to the quantum parameters of the nanowire, dramatically affecting the performance in terms of power delivered to the load.

1. Introduction

Quantum dots (QDs) are quantum heterostructures in which electrons are confined within an atomic scale region that can be controlled by electromagnetic fields. These structures can enable quantum technology paradigms, such as, for instance, qubits and quantum gates [1]. They also provide a promising practical implementation of the concept of quantum antennas (*e.g.*, [2]).

As the possibility of using QDs for such an application is being experimentally proven (*e.g.*, [3]), the focus is now moving towards a system-level analysis aimed at assessing the overall performance of a transmitting or receiving system embedding such antennas.

In this view, here we analyze the reference problem illustrated in Fig.1(a), where a QD is acting as a received antenna excited by an external electromagnetic field. The QD is then connected to the load via a nanowire interconnect and the final goal of this paper is that of investigating its effect. The possibility of recasting the problem in the frame of the circuit theory provides two main advantages: (i) the use of the same key performance indicators adopted in classical antenna theory; (ii) an easy extension of the analysis to large systems.

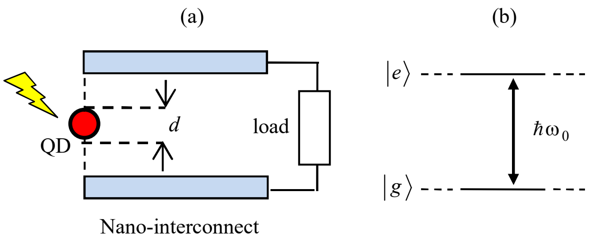

Figure 1. (a) Schematic of the problem: a QD is excited by an external field and is connected to the load by means of a nano-interconnect. (b) two-level model of the QD.

2. Equivalent circuit models

The extension of circuit theory paradigms to nanoscale and atomic scale follows the concept of equivalent circuit variables introduced for instance in [4]. If we assume the long wavelength limit (QD's diameter *d* much smaller than the signal wavelength) then the electric field is almost uniform over the spatial extent of the QD and an effective voltage can be defined. As for the current, it can be defined as an effective inflowing displacement current, derived from the electrical displacement field. Immediately, the concept of impedance may be introduced for the QD and circuit models for antennas can be derived, as done in [5] for single quantum emitter and in [6] for a coupled QD pair. Here, we refer to a single QD described as a two-level atom with a ground state $|g\rangle$ and an excited state $|e\rangle$, Fig.1(b), illuminated by a time-harmonic external field, $\mathbf{e}_0(\mathbf{r},t) = \tilde{\mathbf{z}}E_0 \,\mathrm{Re}\left\{e^{i(\omega t - kx)}\right\}$. In the weak field limit, the linear response of the QD may be provided by an equivalent Norton-type two-port element [7], and the nanowire may be modelled as a transmission line [8], hence the system in Fig.1(a) may be represented as the circuit in Fig.2. Here, the equivalent admittance of the QD is given by:

$$Y_{QD}(\omega) = \left[R_p + i\omega(L_p - C_p^{-1})\right]^{-1} + i\omega C_0, \quad (1)$$

$$R_p = \frac{2\gamma}{\omega_0}\frac{1}{G_c},\ L_p = \frac{1}{G_c\,\omega_0},\ C_p = \frac{G_c}{\omega_0}, G_c = \frac{2\mu^2}{\hbar A_e} \quad (2)$$

where ω_0, μ and γ are, respectively, the frequency, the moment and the decoherence associated the state transition in Fig.1(b), $\hbar$ is the Planck constant and A_e is the effective area of the quantum confinement. The term C_0 in (1) is the inter-electrode capacitance describing the contribution of the displacement current flowing outside the QD.

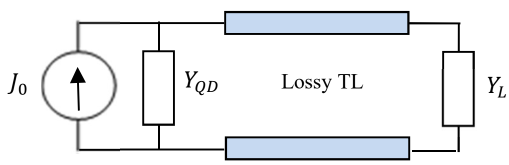

Figure 2. Equivalent circuit model for the system in Fig.1(a): Norton-type equivalent for the excited QD.

The active component is instead given by:

$$J_0(\omega) = \left[R_p + i\omega(L_p - C_p^{-1})\right]^{-1} dE_0, \qquad (3)$$

In the same assumptions as above, the nanowire can be conveniently described by a lossy RLC transmission line model, with per-unit-length parameters given by [8]:

$$L_{tl} \approx L_k + L_m,\ R_{tl} = \upsilon L_k,\ \ C_{tl} \approx C_e\ , \qquad (4)$$

where L_m and L_k are the magnetic and kinetic inductances, respectively, is the electrostatic capacitance and υ is the collision frequency. Finally, the load is modeled as an equivalent admittance, Y_L.

3. Results and discussion

Let us assume a QD of diameter d =1 nm, with the following characteristic values for the transition: f_0=100 THz, $\mu = ed$, being e the electron charge, and $\gamma = 10^{13}$ Hz. In addition, let us assume that the effective A_e is almost equal to the QD section. The equivalent admittance (1) is plotted in Fig.3, highlighting the effect of the transition.

As pointed out in [2], [7]-[8], the meaning of matching is quite different from the classical antenna theory. Therefore, we investigate here the effect on the matching of the nanowire that connects the receiving antenna to the load. Let us assume the reference case where the load is directly connected to the antenna: from the theory we know that the matching condition would be $Y_L(\omega) = Y_{QD}^*(\omega)$, being * the conjugation. Of course, in a realistic design it would be hard to synthesize such a frequency-dependent load, therefore in the following we assume a constant load, imposing the matching only at the transition frequency: $Y_L = Y_{QD}^*(\omega_0)$. Hereafter, the power delivered to this load in absence of the line is taken as the reference, say P_{ref}, and is plotted in Fig.4, normalized to its maximum.

Let us now design a nanowire in such a way to preserve the matching, by assuming an ideal wire pair, i.e. a line described by (4) with only classical parameters L_m and C_e. Let us choose a wire radius equal to d/2, an inter-wire distance equal to 3d, and a line length of 10d. The power delivered to the load in this condition is plotted in Fig.4, referred to as the case without L_k. It can be observed that this nanowire is able to provide the required matching.

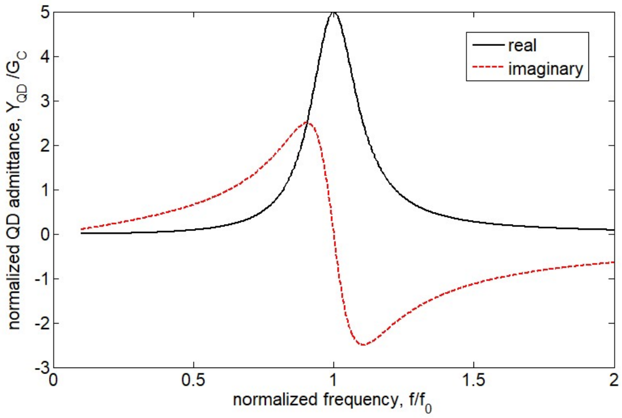

Figure 3. Equivalent admittance for the considered QD.

However, taking into account the quantum effects, the result dramatically changes. Indeed, let us assume that the nanowire is realized by two single-wall carbon nanotubes. After choosing their typical physical parameters [8], we get $L_k/L_M \approx 10^3$, hence the propagation would be dominated by the kinetic inductance. This leads to a strong reduction of the power delivered to the load (Fig.4), since the operating conditions are actually really far from matching.

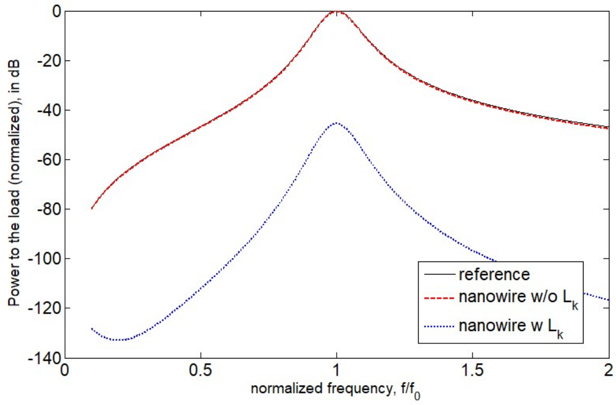

Figure 4. Power delivered to the load, without the nanowire (reference), with nanowire, with or without L_k.

4. Acknowledgements

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