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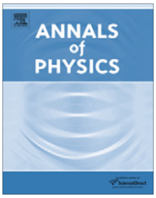

Wireless adiabatic power transfer

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ABSTRACT

We propose a technique for efficient mid-range wireless power transfer between two coils, by adapting the process of adiabatic passage for a coherently driven two-state quantum system to the realm of wireless energy transfer. The proposed technique is shown to be robust to noise, resonant constraints, and other interferences that exist in the neighborhood of the coils.

1. Introduction

The search for wireless power transfer techniques is as old as the invention of electricity. From Tesla, through the vast technological development during the 20th century till recent days, many proposals have been made and implemented in this research field. Established techniques for wireless energy transfer are known both in the near- and far-field coupling regimes. Examples for the former can be found in resonant inductive electric transformers [1], optical waveguides [2] and cavity couplers [3]. In the far field, one can find the mechanism of transferring electromagnetic power by beaming a light source to a receiver which is converted to usable electrical energy [4]. Although these techniques enable sufficiently efficient energy transfer, they suffer either from the short-range interaction in the near-field, or from the requirement of line of sight in the far-field approaches. Recently, it was shown that weakly radiative wireless energy transfer between two identical classical resonant coils is possible with sufficiently high efficiency [5–7]. This breakthrough was made possible by the application of the coupled-mode theory into the realm of power transfer. In this experiment, Kurs et al. [5] showed that energy can be transferred wirelessly at distances of about 2 m (mid-range) with efficiency of about 40%.

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Currently, most efficient wireless energy transfer devices rely upon the constraint of exact resonance between the frequencies of the emitter (the source) and the receiver (the device, or the drain) coils [5–7]. When the frequency of the source is shifted from the frequency of the device, due to lack of similarity between the coils or by random noise (introduced, for example, by external objects placed close to either coils), a significant reduction of the transfer efficiency would occur. In such case, one may implement a feedback circuit, as suggested in Ref. [5], in order to correct the reduction of the transfer efficiency.

In this paper, we suggest a different approach to resolve the issues of the resonant energy transfer process. Here, we present a novel technique for robust and efficient mid-range wireless power transfer between two coils, by adapting the process of adiabatic passage (AP) for a coherently driven two-state quantum system [8,9], as will be explained in the following sections. The adiabatic technique promises to be both efficient and robust for variations of the parameters driving the process, such as the resonant frequencies of the coils and the coupling coefficient between them.

2. Overview of the coupled-mode theory

We follow the description of the coupled-mode theory in the context of wireless energy transfer as described in detail by Kurs et al. [5]. The interaction between two coils, in the strong-coupling regime, is described by the coupled-mode theory, through the following set of two differential equations [3,5]:

$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} a_S(t) \\ a_D(t) \end{bmatrix} = \begin{bmatrix} \omega_S(t) - i\Gamma_S & \kappa(t) \\ \kappa(t) & \omega_D(t) - i\Gamma_D - i\Gamma_W \end{bmatrix}\begin{bmatrix} a_S(t) \\ a_D(t) \end{bmatrix}. \tag{1}$$

Here, $a_S(t)$ and $a_D(t)$ are defined so that the energies contained in the source and the drain are, respectively, $|a_S(t)|^2$ and $|a_D(t)|^2$. Γ_S and Γ_D are the intrinsic loss rates (due to absorption and radiation) of the source and the drain coils, respectively, and the extraction of work from the device is described by the term Γ_W. The intrinsic frequencies of the source and drain coils are $\omega_S(t)$ and $\omega_D(t)$; these are given explicitly as

$$\omega_m(t) = 1/\sqrt{L_m(t)C_m(t)} \quad (m = S, D), \tag{2}$$

where $L_{S,D}(t)$ and $C_{S,D}(t)$ are the inductance and the capacitance, respectively, of the source and the drain coils. The coupling coefficient between the two coils reads

$$\kappa(t) = M(t)\sqrt{\frac{\omega_S(t)\omega_D(t)}{L_S(t)L_D(t)}}, \tag{3}$$

where $M(t)$ is the mutual inductance of the two coils. The source coil is a part of the driving circuit and is periodically recharged, while the energy is transferred wirelessly to the device coil. The dynamics of such process in the case of static (time independent) resonance frequencies, as describe in Ref. [5] is illustrated in Fig. 1 (top).

The evolution of Eq. (1) is connected to the dynamics of the Schrödinger equation for a two-state atom written in the rotating-wave approximation [8,9]. The variables $a_S(t)$ and $a_D(t)$ can be identified as the probability amplitudes for the ground state (corresponding to the source) and the excited state (corresponding to the drain), respectively. The coupling between the coils are analogous to the coupling coefficient of the two-state atom (also known as the Rabi frequency), which is proportional to the atomic transition dipole moment $\mathbf{d}_{12}$ and the laser electric field amplitude $\mathcal{E}(t)$ as follow $\Omega(t) = -\mathbf{d}_{12} \cdot \mathcal{E}(t)/\hbar$ [8,9]. The difference between the resonant frequencies of the two coils corresponds to the detuning $\Delta(t)$ in the two-state atom: $\Delta(t) = \omega_D(t) - \omega_S(t)$.

The power transfer method was demonstrated for the resonant case of $\omega_S = \omega_D = \text{const}$, which is the case of $\Delta = 0$ in atomic physics. However, the power transmitted between the coils drops sharply as the system is detuned from resonance, i.e. for the case of $\omega_S \neq \omega_D$. Also, any time dependent dynamics or change of coupling strengths between the coils can results in lower energy transfer between the coils.