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Wireless energy transfer between anisotropic metamaterials shells

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HIGHLIGHTS

- Anisotropic metamaterial shells exhibit high quality factors and sub-wavelength size.
- Exchange of electromagnetic energy between shells with high efficiency is analyzed.
- Strong coupling is supported with high wireless transfer efficiency.
- End-to-end energy transfer efficiencies higher than 83% can be predicted.

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ABSTRACT

The behavior of strongly coupled Radial Photonic Crystals shells is investigated as a potential alternative to transfer electromagnetic energy wirelessly. These sub-wavelength resonant microstructures, which are based on anisotropic metamaterials, can produce efficient coupling phenomena due to their high quality factor. A configuration of selected constitutive parameters (permittivity and permeability) is analyzed in terms of its resonant characteristics. The coupling to loss ratio between two coupled resonators is calculated as a function of distance, the maximum (in excess of 300) is obtained when the shells are separated by three times their radius. Under practical conditions an 83% of maximum power transfer has been also estimated.

1. Introduction

Wireless energy transfer has received in the last few years a renewed interest partly linked to the tremendous development of mobile and wireless devices. Transmitting energy without the need of a

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connecting physical infrastructure was already a matter of study at the times of Nicola Tesla [1], or even Heinrich Hertz. Nevertheless, the advent of the electrical wired grid has hidden that interest for a long time. More recently, the evident advantages of this type of technology have made it especially attractive in certain environments or circumstances. For example, mobile devices of all sorts (telephones, robots, sensors, cars...) or devices working in harsh environments with access limitations (satellites or emergency systems) would sensibly benefit from the possibility of using wireless power to recharge their batteries or allow their un-interrupted operation without severely compromising mobility. Different types of technological schemes have been proposed to perform a wireless energy transfer without the need of a physical connection [2–4]. In this sense, radiative and non-radiative energy transfers have been investigated for metamaterial structures [5]. The radiative energy transfer has been limited by its low performance and thus the radiative regime has traditionally been employed to transmit 'information signals' rather than 'energy'. Focusing now on resonant coupling between relatively close resonant elements, this phenomenon has been widely studied from different points of view [6,7]. It takes advantage of a strong electromagnetic coupling between resonant elements that fundamentally have a sub-wavelength size. At the same time, resonators with high quality factors (Q) are required so that absorptive and radiative losses may not preclude an effective transfer of energy from the source element to a load element. In reaching high efficiencies, examples of coil-based systems have been widely investigated, but they have the drawback of being bulky, especially when working at low frequencies [8,9].

In this letter we propose the use of Radial Photonic Crystals (RPCs) shells as resonant elements enabling electromagnetic energy transfer wirelessly between them. The proposed shells consist of a layered anisotropic metamaterial whose constitutive parameters (namely electric permittivity ε and magnetic permeability μ) are radially dependent. They have a cylindrical shape with a central void cavity. Among other purposes, valid also for their acoustic counterparts [10,11], RPC shells have been employed as high Q-factor resonant elements, position and frequency sensors or structures for beam-shaping [12,13]. These functionalities are a consequence of the anisotropy of the constitutive parameters. RPCs shells can be considered 'very ordered' systems and this fact is also linked to a high degree of flexibility in implementing their resonant characteristics, both in terms of resonant mode selection as well as in the operation frequency range (due to scalability). Other advantages are pointed out in the following.

We start by introducing a design of a metamaterial shell with the target of having a high-Q resonance at low (microwave) frequencies. The design is based on a 4-layer cylindrical microstructure of sub-wavelength size at the operation frequency. A particular operation mode is selected so that the analysis of a system formed by two coupled shells allows the evaluation of the energy transfer between them. A strong coupling regime is established when one of the two identical shells acts as a source and the other acts as the load of the system [14]. The shells are analyzed in terms of their quality Q and coupling κ factors, which are compared with other possible solution implemented with homogeneous materials. This comparison is performed through a figure of merit (FOM) relating loss and coupling. Finally, the performance of the energy transfer is evaluated by means of an efficiency figure and discussed in view of possible implementation of this proposal.

2. Theoretical background

The designed anisotropic metamaterial shell consists of alternating layers of type a and of type b whose constitutive parameters are as follows:

$$\mu_{ra}(r) = \frac{40d}{r}; \qquad \mu_{rb}(r) = \frac{60d}{r} \tag{1}$$

$$\mu_{\theta a}(r) = \frac{35r}{d}; \qquad \mu_{\theta b}(r) = \frac{20r}{d}, \tag{2}$$

$$\varepsilon_{za}(r) = \frac{40d}{r}; \qquad \varepsilon_{zb}(r) = \frac{60d}{r}. \tag{3}$$