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Wireless energy transfer: Dielectric lens antennas for beam shaping in wireless power-transfer applications

Transfert d'énergie sans fil : antennes diélectriques pour la mise en forme des faisceaux dans les applications de transfert d'énergie sans fil

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ABSTRACT

In the current contest of wireless systems, the last frontier remains the cut of the power cord. In that sense, the interest over wireless energy transfer technologies in the past years has grown exponentially. However, there are still many challenges to be overcome in order to enable wireless energy transfer full potential. One of the focus in the development of such systems is the design of very-high-gain, highly efficient, antennas that can compensate for the propagation loss of radio signals over the air.
In this paper, we explore the design and manufacturing process of dielectric lenses, fabricated using a professional-grade desktop 3D printer. Lens antennas are used in order to increase beam efficiency and therefore maximize the efficiency of a wireless power-transfer system operating at microwave frequencies in the K_u band. Measurements of two fabricated prototypes showcase a large directivity, as predicted with simulations.

RÉSUMÉ

Dans la compétition actuelle entre les systèmes sans fil, la dernière frontière reste la coupure du cordon électrique. Dans ce sens, l'intérêt des technologies de transfert d'énergie sans fil a crû exponentiellement au cours des dernières années. Cependant, de nombreux défis à surmonter demeurent pour qu'on puisse déployer à son plein potentiel le transfert d'énergie sans fil. L'un des objectifs poursuivis dans le cadre du développement de tels systèmes est la conception d'antennes à très haut gain, très efficaces, qui permettraient de compenser les pertes liées à la propagation des signaux radio dans l'air. Dans cet article, nous explorons la conception et la fabrication de lentilles diélectriques, réalisées à l'aide d'une imprimante 3D de bureau de qualité professionnelle. Les antennes à lentilles sont utilisées en vue d'accroître l'efficacité du réseau et donc de maximiser celle d'un système de transfert d'énergie actif aux fréquences des micro-ondes dans la bande K_u. Les mesures

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réalisées sur deux prototypes mettent en évidence une grande directivité, ainsi que les simulations le prédisaient.

1. Introduction

Wireless power transfer (WPT) is a technology that has been idealized by Nikolas Tesla more than a century ago. However, only recently the advances in technology have allowed it to become a reality. After the boom in the wireless communications in the past decades, only the power cord is left to cut in order to create truly wireless systems.

The first approach to wireless power transfer was based in inductive coupling, also referred as near-field power transfer, appearing in the toothbrushes charging systems and more recently in the form of charging pads for cell phones. This is a well-established technology; however, near-field power transfer only allows the transmission of energy in very close distances of communication. The transfer of energy over larger distances is yet a field of high interest and one that has motivated a lot of research in the past few years.

Far-field WPT is a current research topic of high interest. It is being thought of for applications to Wireless Sensor Networks (WSNs), in Radio Frequency Identification (RFID), and is a key feature for enabling the implementation of the concept of the Internet of Things [1]. More than that, WPT solutions are being considered for a wide variety of applications such as electric vehicle charging [2,3], to power up exploration probes in space [4], and for space-to-earth power transmission [5,6].

The major drawback in these systems is their efficiency in energy transfer. The wavefronts of electromagnetic waves spread in space, dissipating the energy in all directions. From this realization comes the well-known Friis transmission equation that allows the calculation of the ratio of power transmitted to power received by two antennas separated by a distance $R > 2D^2/\lambda$, being D the biggest dimensions of the antennas, which imposes that those antennas be in the far-field region of each other. The Friis transmission equation states that

$$P_\mathrm{r} = P_\mathrm{t}(1 - |\Gamma_t|^2)(1 - |\Gamma_r|^2)\left(\frac{\lambda}{4\pi R}\right)^2 G_\mathrm{t}(\theta_t, \phi_t) G_\mathrm{r}(\theta_r, \phi_r) |\hat{\rho}_\mathrm{t} \cdot \hat{\rho}_\mathrm{r}|^2 \quad (1)$$

being P_r the received power, P_t the transmitted power, Γ the reflection coefficient of the antenna, G the gain of the antenna, and $|\hat{\rho}_\mathrm{t} \cdot \hat{\rho}_\mathrm{r}|^2$ the polarization ratio.

From this relation, it is easy to realize that in order to maximize the power received, one should provide antennas that have the best matching possible, and are perfectly aligned in the direction of maximum gain to each other, as well as polarization. The hardest part is overcoming the losses due to wave-front spreading $\left(\frac{\lambda}{4\pi R}\right)^2$. To compensate this loss, very high gain antennas are needed, such as antenna arrays of several elements, parabolic antennas, or lens antennas.

Parabolic antennas have dimensions and weights that make them very difficult to integrate in many systems, even in space applications, where the size of satellites is being constantly decreased. Antenna arrays are very interesting, however, when the number of elements in the array increases, the feeding networks increase as well and the insertion losses can become quite considerable, hindering the overall gain of the antenna.

In this paper, we present the development of a dielectric lens antenna for transmission and harvesting of energy in the $\mathrm{K_u}$ band for space applications; more specifically, to be used as a transmitting source to power up passive sensors in space.

The dielectric lens is developed using 3D printing techniques, which allows the reduction of the cost, but specially to perform quick prototyping and optimization of the structures. The interest and availability of household 3D printers have increased in the past few years. Due to that, the prices of these equipments have decreased considerably. Most low-cost household 3D printers work based on the superposition of layers of a polymer material, known as thermoplastics, such as ABS (acrylonitrile butadiene styrene) or PLA (polylactic acid). These polymeric-type materials are non-magnetic dielectric and therefore can be useful for microwave applications. That has launched a new interest on this kind of technology and has incited the development of quick prototyping in many fields of science, namely electronics and including microwave circuits and antennas [7–9].

In this paper, we show the development of a 3D-printed convex paraboloid dielectric lens with a microstrip patch feed for the $\mathrm{K_u}$ band. This antenna is especially useful for WPT applications when compared to the use of antenna arrays. Arrays usually comprise a feeding network that will inevitably introduce power losses. With a lens antenna, we can, with a single-feed radiating element, achieve very high directivities, comparable to those obtained with a 16- to 20-element antenna array, without the inherent feeding network losses. The paper is organized as follows. In the following section, the dielectric lens as well as the feeding patch characteristics are described. In section 3, the simulation and measurement results are discussed. Section 4 draws the main conclusions about this work.

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