3D Printed Lens Antenna for Wireless Power Transfer at Ku-Band

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Abstract— **In this paper we present the design of an antenna, operating in the Ku-band, conceived for wireless power transfer systems. It comprises an hemispherical dielectric lens, fabricated using 3D printing technology, fed by a microstrip patch antenna array. The conjugation of the dielectric lens with the microstrip patch array allows the development of a compact high gain antenna. The antenna presents a matched bandwidth between 12.7 and 13.15 GHz and a maximum gain of 18.1 dBi at each element.**

Index Terms— **lens antenna, microstrip patch, 3d printing, wireless power transfer**

I. Introduction

Wireless power transfer (WPT), specially in far-field, as is the case of focus of this paper content, is an highly interest and current research topic. It is being thought and applied 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].

In each of these scenarios, custom WPT solutions are being developed in order to maximize the efficiency of the power transfer systems. One of the scenarios of application of the WPT systems is in space applications. Either to power remote stations/probes, or to power up sensors inside satellites/spaceships or even to transfer solar collected energy down to earth [2], [3]. There's a lot of potential on the development of this technology for space applications.

It is important to note tough, that when developing space technologies several things have to be considered: the environment is rough so rugged equipment is mandatory; the frequencies of operation are usually higher; and due to the large ranges of operation needed, higher gains/efficiencies in higher power regimes are necessary. Due to these reasons the development of technology for space applications is rather challenging.

In this paper we present the development of a microstrip patch fed dielectric lens antenna for transmission and harvesting of energy in the Ku-band.

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. 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 [4]. Most low-cost household 3D printers work based on the superposition of layers of a polymer like material, known as thermoplastics, such as ABS (Acrylonitrile Butadiene Styrene) or PLA (Polylactic Acid). This polymeric type materials are dielectric and therefore can be useful for microwave applications.

The use of a dielectric lens has allowed to obtain a compact high gain antenna, that can be used for wireless energy transfering applications.

The paper is organized as follows. In the following section the design of the proposed antenna is presented and discussed, including the properties of all the materials used. The third section discusses a possible implementation of the proposed antenna for wireless power reception and conversion. Finally the main conclusions are drawn in section IV.

II. Lens antenna design

Lenses are used to shape wavefronts and are usually classified as dielectric lenses or constrained lenses [5]. Dielectric lens are easier to fabricate and can be less expensive, specially when we consider the fabrication with 3D printers.

The lens size are bound to the radiation properties one pretends to achieve. For very high gain lens antennas, the size and weight associated to the transmission loss in the lens itself can prohibit its use. Nevertheless, dielectric lens are a very attractive solution to achieve high gain and to easily manipulate radiation characteristics of antennas, specially when working on high frequencies above X-band.

The lens can have flat surfaces, in either the focal plane or the wavefront, spherical surfaces on both planes, but can also take arbitrary shapes, in order to achieve a very particular radiation shape [6].

A. Material properties

The size of the lens depends on the shape and dielectric properties of the material. The dielectric lens was manufactured with a BEEtheFirst 3D printer from BEEVeryCreative. In order to be able to design a proper lens, the permittivity and loss of the PLA material must be determined. For that purpose, we used a differential-phase length method with microstrip lines [7]. We built two rectangular slabs of white PLA with 1.5mm thickness and applied copper tape on both sides to make the microstrip lines as shown in Fig. 1.

The length difference of the lines imposes the maximum frequency to which this method provides a reasonable estimation for the permittivity. Given the 20 mm difference in length between the two lines and considering the estimated

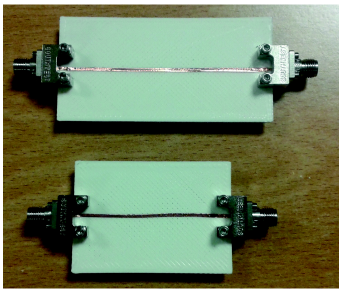

Fig. 1. Photograph of two microstrip lines built on white 3D printed dielectric substrate.

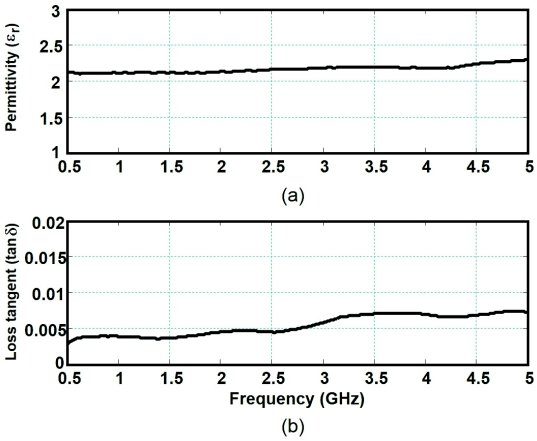

Fig. 2. Estimated (a) permittivity and (b) loss tangent of the 3D printed white PLA material for a 1.5 mm thick slab, between 0.5 and 5 GHz.

permittivity, the maximum measurable frequency is of 5 GHz, which falls short considering we're designing the lens to 13 GHz. Besides the length difference, the lines manufacturing process comprises some considerable errors in the width of the lines and height of the substrate, which would increase the errors further for higher frequencies. In order to characterize up to 13 or 26 GHz frequencies, the length difference between the lines should be at most 7.29 mm and 3.64 mm respectively. Moreover, the the width of the line and the height of the substrate must be measured down to, at least, the tenths of micrometers scale. For the lens simulation, the permittivity value assumed was 2.3 which is the value obtained at 5GHz. The estimated permittivity and loss tangent of the white PLA is depicted in Fig. 2.

B. Feeding antenna

There are several ways to feed a lens antenna. In this paper we used a slot fed microstrip patch. This is a good approach due to it's simplicity and compact characteristics.

The patch is etched on a Rogers RT5880 substrate with 0.787 mm of thickness and the microstrip feeding line is etched on a Rogers RO4003 with 0.508 mm of thickness.

The standalone feeding antenna is operating at 13 GHz with a matched bandwidth of 560 MHz between 12.67 and 13.23 GHz. Presenting a directive radiation pattern with a maximum directivity of 7.3 dBi and an efficiency of 91.2%.

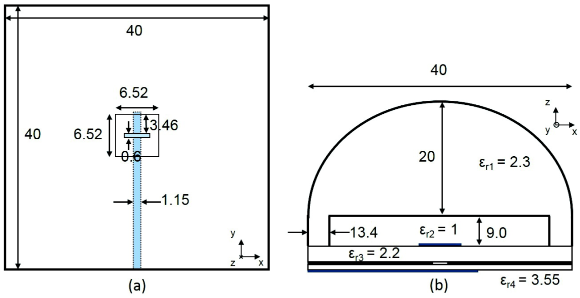

Fig. 3. Schematic of the proposed feeding patch antenna (a) top view of the patch antenna and (b) profile view of the antenna layers. All dimensions are in mm.

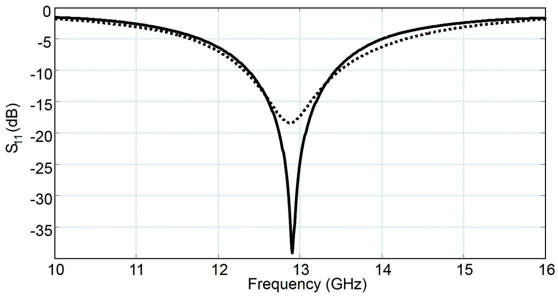

Fig. 4. Simulated reflection coefficient without (solid line) and with lens (dashed line).

The simulated reflection coefficient results are shown in Fig. 4.

C. Lens antenna

The previously presented patch antenna is used to feed an hemispherical lens antenna as shown in Fig. 3 (b). Although simple, the few parameters of the hemispherical antenna can be used in order to improve the gain of the antenna while keeping the side lobe level to a minimum. Besides changing the radiated fields the placement of a dielectric on top of the patch antenna can influence the input impedance. Still, it can be seen from Fig. 4, that the antenna retains the same working frequency. Nevertheless, the matching can be returned by adjusting the slot dimensions.

The use of the dielectric lens reshapes the radiation pattern of the antenna and can highly increase the gain of the microstrip patch. Further improvements to the gain can be made by scaling the antenna. However, in this particular case, we tried to find a compromise between the size of the antenna and the obtainable gain. Therefore, we reached a respectable gain of 14.3 dBi with a lens antenna that has 20 mm radius and 34 mm height.

A comparison between the radiation pattern of the lens and the standalone patch is made in Fig. 5.

III. Lens Antenna for Energy Harvesting

The proposed designed of the lens antenna can be expanded to a patch array with multiple receivers. In order to account for the change in the radiation pattern of the antenna array and to further increase the gain of the antenna the lens has to be re-sized. For a 2x2 patch array we have reached the dimensions shown in Fig. 6.

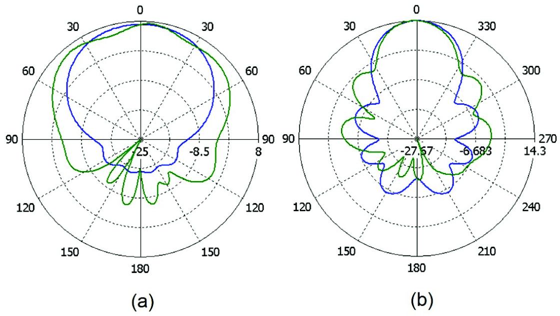

Fig. 5. Simulated radiation pattern of the (a) standalone microstrip patch antenna and (b) complete lens antenna, in the XZ-plane (blue line) and the YZ-plane (green line).

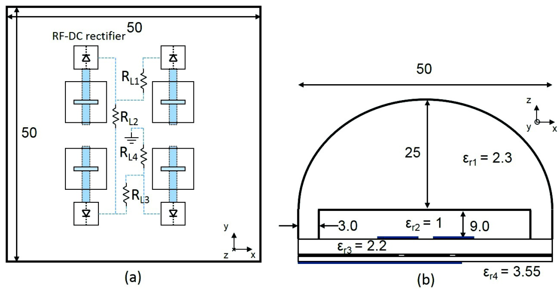

Fig. 6. Schematic of the proposed rectifier array with lens antenna (a) top view of the array and circuit and (b) profile view of the antenna layers. All dimensions are in mm.

The overall gain of an array is dependent on the feeding of a given amplitude and phase of each element of the array. Therefore, if we pick a microstrip patch array, as depicted earlier, and apply an RF-to-DC converter in each element, the patches work as standing alone. The power at the input of each converter circuit is the power received by each patch, subject to the gain of each of the elements by itself and not the gain of the overall antenna array. Each microstrip patch element by itself has typically around 7 dBi gain, with the application of the lens the gain of each element is increased to 16 dBi, thereby boosting significantly the received power and therefore the efficiency of the WPT system. This is clear with the comparison between the radiation patterns of the patch elements, with and without the lens, which is shown in Fig. 7.

The individual microstrip patches in a standalone version have a directivity of 8.1 dBi with estimated efficiencies around 94.4% each. When coupled with the dielectric lens, each array element present a directivity of 16.1 dBi with estimated efficiencies around 91.2%. This is the great advantage of this approach, since it means an increased input power of 8 dB for each of the rectifier elements. Moreover, this system can be scaled up to any physically feasible/economically viable number of elements.

There is a tilt in the main lobe direction, but it can be corrected with a proper manipulation of the lens.

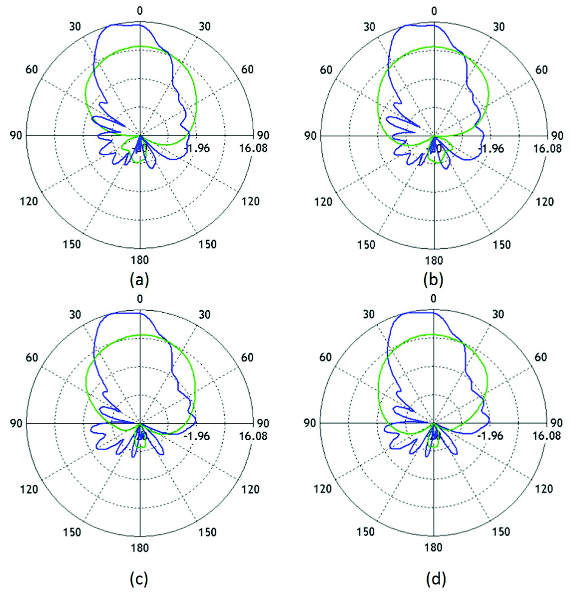

Fig. 7. Comparison of the simulated radiation patterns of each patch element with a lens (blue line) and without the lens (green line).

IV. Conclusion

In this paper we presented the design of a 3D printed dielectric lens that can be coupled with slot fed microstrip patches in order to enhance the radiation gain and therefore increase efficiency on wireless power transfer systems designed for the Ku-band. A possible implementation for wireless power receiver based on a lens antenna focusing on a patch array is also presented. The use of the lens in the reception element can effectively provide a boost in the input power of the rectifying elements, therefore significantly increasing the efficiency of the system. The lens designed in this approach take a simple hemispherical design, but further optimizations can be made to the lens in order to better match the focusing of the wavefronts from the patches.

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