A Novel Additive-Manufactured Multiple-Infill Ultra-Lightweight Cavity-Backed Slot Antenna for UWB Applications

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***Abstract*—A rectangular ultra-wide band (UWB) cavity-backed slot antenna manufactured by combining 3D printing and ink-jet printing technology is introduced in this paper. The antenna substrate is made of polylactic acid (PLA) and is fabricated by using fusion deposition modeling (FDM). Two different infills are used for the slot area and for the area corresponding to the microstrip ground plane to reduce waste and dielectric loss. Thanks to 3D printing versatility, a cavity with slant sides, providing high gain, has been designed. This shape is aimed at increasing the antenna impedance bandwidth and directivity. The rectangular-like proximity-coupled feeding line of the antenna is fabricated by depositing silver nano-particle ink on a layer of SU8. The prototype has been tested and measurements confirmed the satisfactory antenna operation over the whole band of interest, from 3.1 to 10.6 GHz.**

***Index Terms*—3D printing, cavity-backed antennas, dielectric substrates, fusion deposition modeling, ink-jet printing, slot antennas, UWB antennas**

I. Introduction

With the advent of paradigms like the Internet of Things and 5G new research challenges are arising. On the one hand, the demand for low-cost broadband and ultra-wideband (UWB) RF and mm-wave components is increasing, which implicates a great effort in the direction of finding new approaches to the design of classical components. On the other hand, the need for a new generation of wireless and ubiquitous electronics, readily embeddable into common objects and thus robust, yet flexible, lightweight and conformable, has pushed in the direction of finding completely new design solutions and pioneering manufacturing technologies [1].

In this scenario, 3D printing technologies are emerging as a powerful tool to ease and speed up the fabrication process of heterogeneous and geometrically complex structures, such as lens antennas [2] and metamaterials. Materials with customized shapes and electromagnetic properties can be easily produced by using low-cost equipments while avoiding any material waste [3].

This paper is focused on the design and experimental validation of a 3D printed UWB cavity-backed slot antenna where a multiple-infill technique is employed. The use of additive manufacturing technology provides the ability to readily integrate a reflector to achieve high gain, while limiting the additional antenna weight, through material infill engineering. Sec. II focuses on a description of the adopted materials and fabrication processes. Sec. III reports a description of the antenna design, including the main antenna dimensions, while Sec. IV is devoted to the description of the antenna performance.

II. Additive Manufacturing Technologies

The proposed antenna has been prototyped by combining fusion deposition modeling (FDM) technology for the substrate, which allows us to obtain an arbitrarily-shaped low-loss dielectric material, and ink-jet printing technology for the feeding microstrip line structure, thus it relies on fully additive manufacturing techniques.

FDM is quite a mature 3D printing technology based on the extrusion of heated thermoplastic materials through nozzles. The final 3D object is fabricated by adding successive horizontal layers, which imposes a prior slicing step of the model. This procedure is performed in this work by using the CAD "Simplify3D", which permits to easily handle the simultaneous fabrication of objects with different infills by the automatic generation of the G-code needed by the printer.

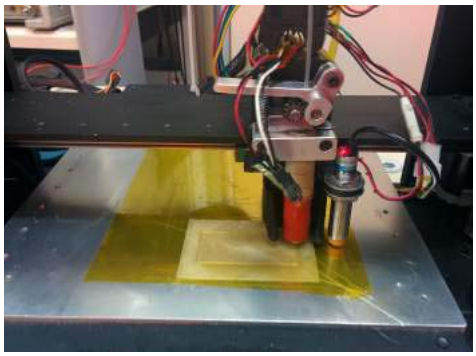


Fig. 1. 3D printing process (Printrbot Metal Plus).

A Printrbot Metal Plus with a heated bed was used to fabricate the design (see Fig. 1). The model was printed with a 200 μm nozzle with 210 μm wide traces at 210°C. The layer height of 127 um was adopted due to the minimum resolution based on the Z axis rod pitch and the full step size of the stepper motor.

Polylactic acid (PLA) is adopted for the design due to its widespread use, low cost, low dielectric loss and non-toxicity. The material properties have been determined in [8] by using Nicolson-Ross and Weir method and demonstrate low losses and a dielectric constant similar to most thermoplastic polymers. In particular, the measured permittivity for a 100% infill was 2.72 with a loss tangent of 0.008.

Fig. 2 reports the cross sectional view of the fabricated prototype with an indication of the adopted layers and the relative infill percentages.

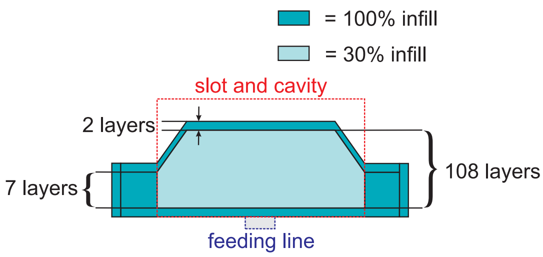


Fig. 2. Cross sectional view of the 3D printed dielectric substrate. 30% infill is used for the area corresponding to the slot aperture and the cavity, whereas 100% infill is used for the microstrip line.

Two solid layers (100% infill) on top and bottom of the substrate were utilized to maintain a solid surface for the subsequent ink-jet printing step, and a two layer perimeter is added for additional strength.

To obtain a lightweight structure and reduce the utilized material, a substrate with two different local material densities was chosen: an infill percentage equal to 100 was set for the dielectric material in correspondence of the microstrip line, whereas a 30% infill is used for the area corresponding to the slot aperture and the tapered cavity. The choice to use diverse infills allows us to reduce the use of unnecessary material in the slot area, while maintaining a higher dielectric constant for the microstrip. Both the chance to readily modify the internal structure of the material and to easily produce tapered or, more generally, arbitrary profiles are some of the major advantages of 3D printing, which have been tested here on a specific antenna structure. The ability of 3D printing to modify the dielectric constant in-situ enables gradient material designs which can be difficult to achieve with single materials in traditional manufacturing processes.

Fig. 3 shows a photo of two 3D printed substrate with different infills (100% and 30% respectively), fabricated by using a rectilinear pattern. The difference in the material density is easily identifiable. In fact, the 100% infill sample is more transparent due to the high density of the printed substrate. The sample with lower infill contains air-cavities which cause an opaque haze. The substrate thickness was set to 2.4 mm, corresponding to 19 layers of material.

An estimation of the electromagnetic properties of the 30% infill component is obtained from the 100% infill block by comparing the weight and the volume of the two samples. Regarding the first sample a weight of 6.98 g is associated to a volume of 6.1 cm^3, whereas for the second sample a weight of 3.47 g is associated to a volume of 5.64 cm^3. By removing the four solid top and bottom layers (which represent 21% of both the weight and the volume of the first sample, corresponding to 1.47 g and 1.28 cm^3), a material density of 1.14 g/cm^3 and 0.46 g/cm^3 is found respectively. As a consequence, a dielectric constant of 1.69 and a loss tangent of 0.003 are extracted by interpolation [4].

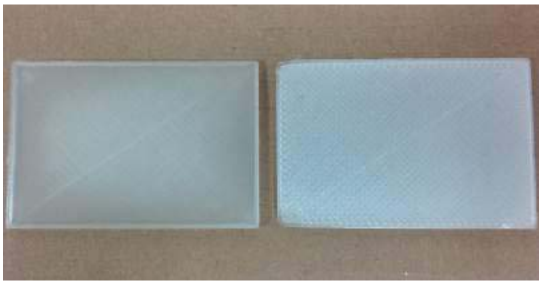


Fig. 3. 3D printed dielectric substrate with multiple infills (100% infill for the sample on the left and 30% for the sample on the right). Nominal dimensions: $6 \times 4 \times 0.24\,cm^3$.

Finally, the antenna feeding line in microstrip technology has been realized by using a Dimatix DMP-2831 ink-jet printer. The conductive traces are printed utilizing silver nanoparticle inks (SNP) over a $25\,\mu m$ thick layer of SU8, previously deposited by using ink-jet printing as well. This layer has been introduced to reduce the roughness of the surface of the 3D printed substrate and ease the adhesion of the conductive ink [7]. Although the SU8 is not included in the substrate characterization, its impact can be considered negligible, due to its small thickness (less than $30\,\mu m$). Two layers of SNP are deposited and sintered in order to achieve high conductivity. In order not to damage the 3D printed substrate the curing temperature was decreased to 100 °C for one hour.

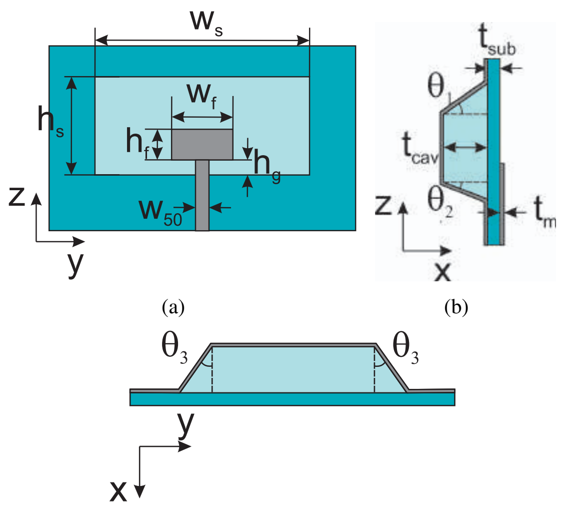
III. Antenna Design

To validate the aforementioned techniques a cavity-backed UWB slot antenna is here proposed. The choice of the slot technology is motivated by the fact that slot antennas are particularly suitable for UWB applications, thanks to their low quality factor, high integrability, compactness and low-profile (see [5], [6]), whereas the cavity, working as a reflector, is introduced to increase the antenna gain and achieve unidirectional radiation.

Fig. 4 shows the proposed antenna geometry as well as the designed antenna parameters. The circuit consists of a rectangular slot, backed by means of a cavity with slant edges, and a proximity-coupled, rectangular-like microstrip feeding structure. The specific shape of the feeding line aims to improve the bandwidth of the slot antenna, whereas the slant sides of the cavity have the function of both increase the impedance bandwidth and improve the antenna directivity.

The main antenna parameters are as follows: $w_f = 11.2\,$mm, $h_f = 10,$mm, $w_{50} = 3\,$mm, $h_g = 1.68\,$mm, $w_s = 56\,$mm, $h_s = 27.8\,$mm, $t_{sub} = 1.2\,$mm,$t_m = 0.005\,$mm,

$t_{cav} = 13\,\text{mm}$, $\theta_1 = 33\,°$, $\theta_2 = 18\,°$ and $\theta_3 = 45\,°$. The total ground plane extension is: $7.5 \times 4.8\,\text{cm}^2$.



(a) (b) (c)

Fig. 4. Geometry of the proposed UWB 3D printed antenna: front (a), and side views (b) and (c).

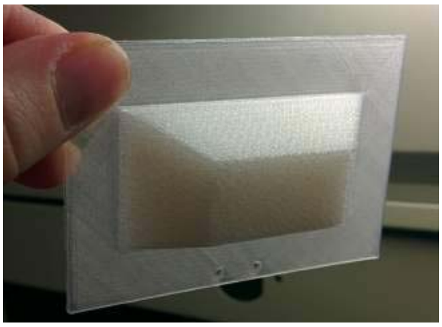


Fig. 5. 3D printed dielectric substrate with multiple infills.

A photo of the fabricated substrate is reported in Fig. 5. As already mentioned in Sec. II the area which surrounds the slot (the dark-blue area in Fig. 4) is fabricated by using 100% infill, whereas the slot and cavity area are filled by using 30% infill PLA.

In Fig. 6 the complete antenna prototype is shown. The yellow rectangle in correspondence of the feeding line is the SU8 layer. For simplicity the ground plane surrounding the rectangular slot and the cavity is fabricated by using a slab of copper tape. The weight of the whole prototype is 10.26 g.

IV. Antenna Performance

The performance of the proposed antenna is tested in laboratory and compared with the results obtained via electromagnetic simulation with the CST microwave studio solver.

Firstly, the antenna input reflection coefficient, measured with an Anritsu 37369A VNA, is illustrated in Fig. 7. A good agreement between simulation and measurement can be noticed. The antenna results to be able to operate throughout the whole UWB frequency range from 3.1 to 12 GHz,

Fig. 6. Photo of the additively manufactured cavity-backed UWB slot antenna.

corresponding to an antenna fractional bandwidth higher than 120 %. A slight mismatching is observed in the bandwidth 7-9 GHz, where ($|S_{11}| < -8\,\text{dB}$).

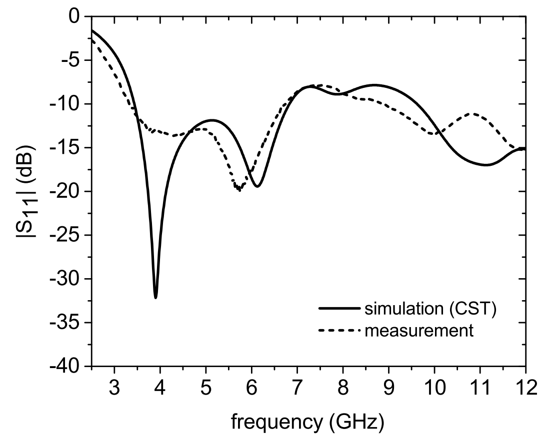
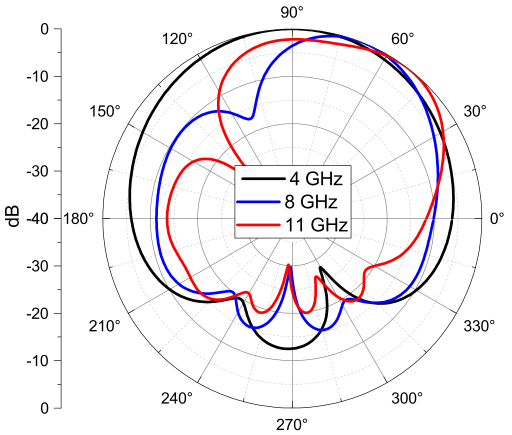


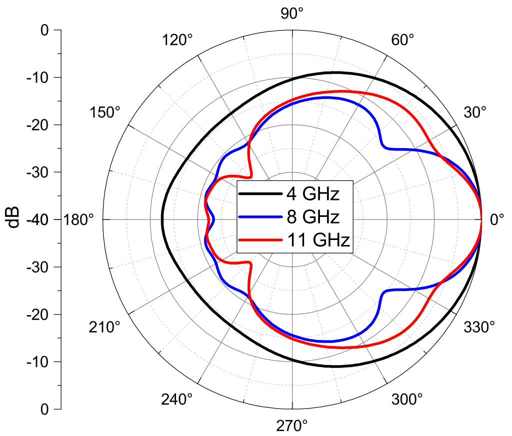
Fig. 7. Input reflection coefficient of the proposed antenna: comparison between simulation and measurement.

Fig. 8 reports the simulated antenna radiation patterns (co-polar components only), at three different frequencies: 4, 8, and 11 GHz, respectively. The antenna is linearly polarized and unidirectional, and its broadside radiation corresponds to the direction $\phi = 0°$ and $\theta = 90°$ in cylindrical coordinates. It is worth noticing that the antenna E-plane radiation pattern features a significant tilting for the higher frequencies, which is partially compensated by the asymmetrical slant sides of the slot cavity. The measured antenna gain in broadside direction varies between 4 and 8.5 dBi throughout the whole UWB band, as shown in Fig. 9.

Finally, Fig. 10 illustrates the magnitude of the whole electric field (both tangential and normal components) on the xy plane laying within the microstrip substrate (100 μm below the surface of the feed line) at f=4 GHz , f=8 GHz and f=11 GHz. The antenna is able to support field distributions at different frequencies, thus confirming its broadband operation.



(a)



(b)

Fig. 8. Simulated radiation patterns: E-plane ($\phi = 0°$) (a), and H-plane ($\theta = 90°$) (b) of the proposed antenna at f=4 GHz, f=8 GHz and f=11 GHz respectively.

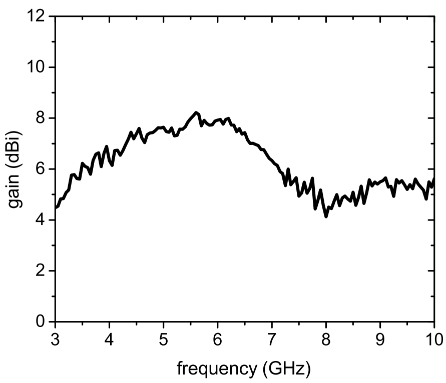
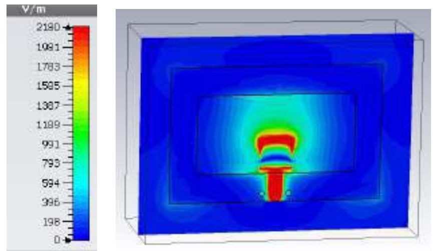
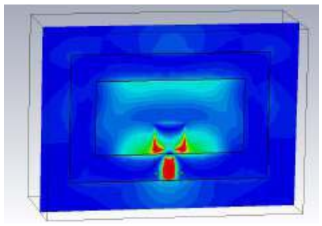


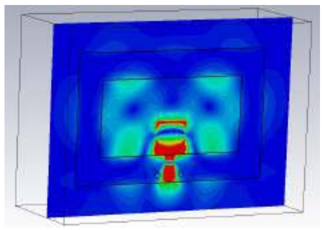
Fig. 9. Measured antenna gain in broadside direction ($\phi = 0°$ and $\theta = 90°$).



(a)



(b)



(c)

Fig. 10. Electric field distribution across the slot at f=4 GHz (a), f=8 GHz (b) and f=11 GHz (c) respectively.

V. Conclusions

A new additively-manufactured UWB backed-cavity slot antenna has been fabricated utilizing low cost, lightweight, and eco-friendly materials with varying dielectric constants due to multiple infill percentages. The high versatility of 3D printing allowed a broadband reflector-backed high-gain antenna to be introduced, that simultaneously displays a lightweight and monobloc structure. A proof-of-concept fabricated prototype has been tested demonstrating a satisfactory performance throughout the whole UWB (3.1-12 GHz) frequency band and featuring a great potential for future IoT and 5G applications.

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