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Customizing 3D-Printing for Electromagnetics to Design Enhanced RFID Antennas

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Abstract— **This document discusses some of the advances in additive manufacturing 3D-printing for electromagnetic applications that have been investigated in the literature in the last few years. Starting from the research activity of the authors on this topic, this work summarizes and showcases the effectiveness of the 3D-printing technology in electromagnetics, with reference to UHF RFID technology. Specifically, the first part of the work deals with Fused Deposition Modeling (FDM) printing technique and faces the problem of the characterization of 3D-printable materials using a made-in-lab instrument based on the T-Resonator theory, which has been purposely designed to be 3D-printed. Once verified the dielectric properties of substrates realized with common 3D-printable materials, two techniques to improve their electrical permittivity are explained. Moreover, the possibility to realize fully 3D-printed RFID devices based on the use of novel 3D-printable materials with noteworthy conductive properties is discussed. Then, two new 3D-printed antennas are presented and discussed highlighting some of the advantages of 3D-printing in electromagnetics. Finally, the application in RFID of another promising 3D-printing technology called Digital Light Processing (DLP) and based on the photopolymerization of liquid resins is discussed as well.**

Keywords—3D printing, enhanced filaments, T-Resonator, conductive filament, fully 3D printed antennas, UHF, RFID

I. INTRODUCTION

3D printing by additive manufacturing is a disruptive technology that is proving to be an increasingly promising method to create high-detailed models in a fraction of the time and at a fraction of the cost required by traditional techniques. Moreover, the advent of affordable new 3D printers has considerably stimulated the community to explore the possible electromagnetic applications of this technology. Indeed, 3D printing paves the way to novel and appealing approaches to realize microwave components and antennas by taking advantage of versatility, cost-effectiveness, and ease of use.

In the earliest works on the matter, the Fused Deposition Modeling (FDM) printing technique has been mainly used with commercial materials like ABS (acrylonitrile butadiene styrene) or PLA (polylactic acid) to realize substrates for antennas or microwave components [1]-[9]. Further, many others 3D-printable materials and techniques have been explored, mainly focusing on the realization of flexible devices [10]-[14]. On the other hand, the possibility to realize 3D-printed structure with conductive properties remains a significant problem to be faced, even if some possible solutions have been investigated in [15]-[19]. Some of these solutions can be used to realize the first attempts of 3D-printing metamaterials or related metastructures like, for example, plasmonic metamaterials or metasurfaces [21]-[23]. Nevertheless, the manufacturing techniques needed to realize these structures are still "hybrid", and the role of 3D-printing is still limited. Moreover, the use of 3D-printed metamaterial in RFID is still a research challenge.

As an extension of [24], this work summarizes and showcases the effectiveness of the 3D-printing technology in electromagnetics by focusing the attention mainly on the advantages of the 3D-printing for UHF RFID antenna applications. The goal is to the provide the reader with knowledge, techniques, examples, data, and experiences useful to design increasingly complex electromagnetic RFID structures. The research activity is discussed basing on some authors' works on various aspects of 3D-printing in electromagnetics [3], [5], [9], [12], [19].

As a first step, a research activity has been carried out with the aim of characterizing the dielectric properties of the 3D-printable materials at different working frequencies. For this reason, a resonant structure, like the well-known T-resonator, has been used to design a device capable of characterizing 3D-printed substrates. The device has been designed, simulated and then realized in PLA by using the 3D-printing technology itself. Specifically, the main steps of the realization of a T-Resonator device are briefly recalled, highlighting the aspects useful for UHF RFID designs.

As a second step, two possible solutions to increase the permittivity of 3D structures are explained. In the former, Barium Titanate ($BaTiO_3$) is combined with a silicone matrix to obtain hi-permittivity flexible substrates useful to design compact and robust electromagnetic structures through 3D-printed molds. A bracelet-shape UHF RFID tag has been designed and realized with the enhanced material to assess the advantages of the technique. Instead, in the latter, common PLA has been used as matrix and doped with $BaTiO_3$ as well, thus allowing the realization of permittivity-enhanced filaments useful to directly 3D-print advanced RFID antennas.

Purposely, the third part of the work is devoted to novel fully 3D-printed devices. The electromagnetic characteristics of a new 3D-printable filament with conductive properties, called Electrifi, are used for designing and realizing a fully 3D-printed UHF RFID tags with PLA-made substrate and Electrifi-made meandered radiating structure.

The last part of the work is dedicated to two examples of complex 3D-printed antennas that smartly exploit the degree of freedom offered by the "third dimension" of the 3D printing technology with the aim of realizing efficient, miniaturized, and reconfigurable RF devices. The former is a novel microstrip antenna with the patch meandered along the direction orthogonal to the plane hosting the patch element. Other being meandered, the novel 3D antenna is also miniaturized through a proper use of ceramic-doped materials. The latter design is a tunable-band UHF RFID planar inverted-F antenna (PIFA). Leveraging on two doped-PLA 3D-printed elements opportunely combined to realize a sliding structure, the antenna resonance frequency can be mechanically switched between two RFID bands. With the same principle, the mutual position of the sliding elements could be modified to adjust the matching in case of variations of the background material rather than modification of the used RFID chip.

Finally, another affordable 3D-printing by additive manufacturing technology, the Digital Light Processing (DLP), which exploits the photopolymerization of a liquid polymer material, is briefly described and a first dielectric

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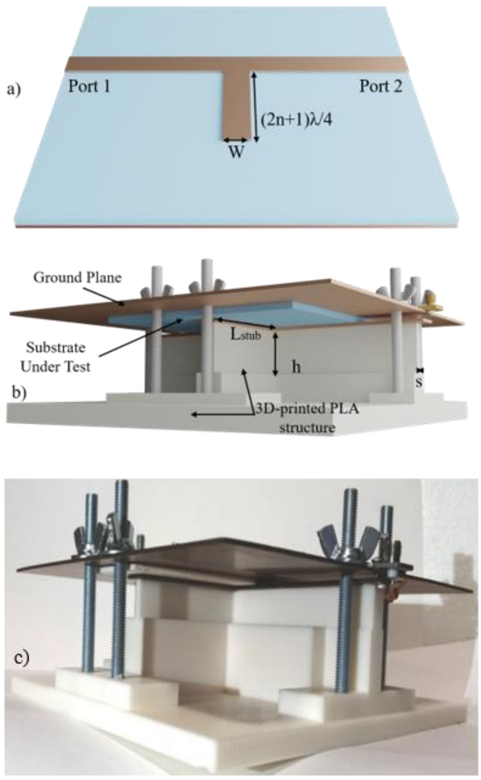


Fig. 1 3D-printed dielectric characterization. (a) Classic T-resonator structure – (b) Model of a printable version – (c) Picture of the realized system.

characterization of one of the just mentioned resins in the UHF RFID band is also proposed.

II. T-RESONATOR

In this section, the T-Resonator-based system detailed in [5] is described and used to characterize 3D-printed materials. It can measure the dielectric constant and the loss tangent of a planar printed substrate, exploiting the well-known T-Resonator theory [25]-[26]. Briefly, it consists in a two-port microwave circuit composed of a microstrip line with an open-end stub that resonates at odd-integer multiples of its quarter-wavelength frequency. As for the mathematical model of the T-resonator, both ε_r and tanδ can be determined once the scattering parameter S_{21} is known.

On such a basis, a structure capable to place a certain pressure all over the "T" —which must perfectly adhere to the substrate under test— without considerably impacting on the microstrip functioning has been designed. A 3D-printed structure has been developed both to sustain and lock the substrate under test between the two copper elements. In Fig. 1b a simplified model is reported. The T-resonator structure is placed upside down and the T-shaped line rests on a dielectric structure sufficiently rigid but thin enough not to interfere with the E-field lines of force. Screw regulators are foreseen to assure the contact between the substrate under test and metallic parts and to form a sandwich structure whose height can be adjusted to adhere to substrates of different thickness.

L_{stub} (5.72 cm) and W (1.38 cm) have been calculated in order to have characteristic impedance Z_0=50 Ω and first resonance at around 900 MHz with a typical plastic substrate of thickness 2 mm and permittivity ε_r = 2.7. Moreover, a first prototype reproducing the simple scheme of Fig. 1a has been simulated with CST Microwave Studio, realized and tested on PLA substrates of various densities. Obtained results have been compared with outcomes from many simulations of the whole structure when varying *s* and *h* parameters of Fig. 1b. In order to safeguard both robustness and footprint, the largest *s* and the smallest *h* guaranteeing comparable results, i.e. *s* = 3 mm and *h* = 25 mm, have been selected.

Using this simple and powerful instrument, it is possible to characterize the dielectric properties of the most common 3D-printable commercial materials, as well as to demonstrate how the proper tuning of the infill parameter led to dielectric constant customizability. Indeed, the infill parameter determines how much the printer fills the 3D model inside. A low value of infill means that the printed object has a greater air percentage, whilst a 100% infill value, means that the object has no empty space inside. As stated, a proper setting of this parameter can vary with continuity the dielectric constant of the final printed element. A characterization example of how the PLA electromagnetic properties change by varying the infill percentage has been studied in [3] and reported in Tab. I for convenience. In particular, it can be observed how both the dielectric constant and the loss tangent of the material vary with a predictable behavior ranging the infill from 20% to 100%. As expected, the lower is the infill percentage, the lower are the values of dielectric constant and loss tangent of the substrate under test.

The materials characterization using the T-Resonator has also highlighted that, probably, the most problematic drawback of the commercial filaments is their relatively low value of dielectric constant. Specifically, it varies approximately between 2 and 3, which could not be high enough in some applications where, for instance, antenna miniaturization is needed. For this reason, the next step of the research aims at developing new materials and techniques to overcome this limit, keeping on exploiting the 3D-printing advantages.

TABLE I
DIELECTRIC PLA PARAMETERS

Infill %	ε_r	tanδ
20	1.503	0.0031
30	1.578	0.0034
40	1.646	0.0035
50	1.8	0.0043
60	1.942	0.0048
70	2.13	0.0051
80	2.25	0.0054
90	2.371	0.0062
100	2.541	0.0071

III. ENHANCED MATERIALS

As stated, the main goal of this research is to overcome the limits of common 3D-printable materials mainly by enhancing the dielectric constant while preserving the low losses. At this regard, two possible solutions have been investigated. The former, rather useful when flexible devices are designed, consists in the realization of a silicone compound to be shaped through 3D-printed molds and electromagnetically enhanced by adding highly dielectric powders. The latter consists in the realization of a 3D-printable filament with an enhanced dielectric constant. The material is realized by extruding a specific ceramic-doped PLA-based mixture. Both materials and techniques are described below:

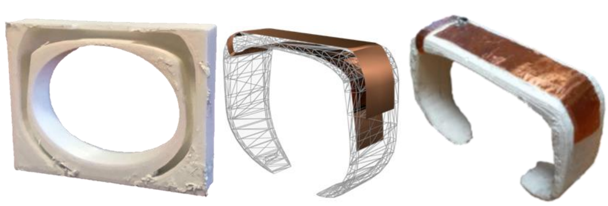
A. Silicone compound and the mold technique.

Briefly, the first proposed approach consists in realizing 3D-printed molds by using common filaments. Then, these molds are filled with the desired silicone-based material with enhanced dielectric properties so to realize, after drying, the desired free-from-factor antenna substrate. The accurate choice of both silicone matrix and doping material is crucial for the final compound electromagnetic properties. Indeed, the compound other than guaranteeing high dielectric constant, must be homogeneous as well as easy to cast into the molds. Accordingly, the silicone emerged as the most adequate candidate as a matrix. It is a well-known, flexible, inert and non-toxic material; moreover, a large literature has been produced exploring the possibility to dope silicones with ceramic powders, like for example [27]-[28]. In our experience, both Alumina (AlO_3) and $BaTiO_3$ have been tested as doping agents. They are both ceramic powders used to increase the dielectric constant of the compound. In Tab. II dielectric constant and loss tangent for different percentages of doping elements, obtained through the T-resonator of Fig. 1c, are reported at around 1 GHz (in order to be exploitable in UHF-RFID design). It can be observed that $BaTiO_3$ produces a much higher impact on the final product even with lower concentration of filler in the mixture. It is worth noting that, once the permittivity of the two mixing elements is known, the complex permittivity of the compound can be efficiently forecast using the Lichtenecker's equation, already used in [29] and recalled in (1) for the sake of clarity.

$$\log \hat{\varepsilon}_{compound} = \log \hat{\varepsilon}_{silicone} + \varphi \log\left(\hat{\varepsilon}_{filler} / \hat{\varepsilon}_{silicone}\right) \qquad (1)$$

where φ is the volume fraction of the filler in the whole composite, while $\hat{\varepsilon}$ is the complex permittivity.

Using the described mold technique, an RFID on-body application has been developed, consisting in a bracelet realized with a Silicone/$BaTiO_3$ compound with a dielectric constant equal to 4.8, then used as substrate for an RFID tag antenna shown in Fig. 2. In particular, Fig. 2a represents the 3D-printed mold, Fig. 2b a render of the bracelet tag where the PIFA-inspired antenna can be observed. Finally, Fig. 2c represents the realized tag where the metallic part has been shaped on a thin adhesive copper tape through a cutting plotter [30]. The tag has been fully characterized demonstrating an adequate working range of almost 2.5 m when dressed. It is worth highlighting that higher values of dielectric constant can be achieved increasing the doping agent percentage. Obviously, this could reduce the flexibility and ease of use of the compound.



(a) (b) (c)

Fig. 2 (a) PLA printed mold to shape the bracelet – (b) Render of the designed bracelet highlighting the antenna shape – (c) final prototype of an UHF RFID tag for on-body application realized with the mold technique.

TABLE II
DOPED SILICONE SUBSTRATES PROPERTIES

Filler [%]	AlO_3		$BaTiO_3$	
	ε_r	tanδ	ε_r	tanδ
5	3.455	0.020	4.199	0.020
10	3.630	0.023	4.954	0.020
15	3.825	0.019	6.240	0.017
17.5	4.007	0.016	-	-
20	4.040	0.016	-	-

B. 3D-printable filament with enhanced dielectric constant

The goal of the research activity described below is to realize filaments with a high dielectric constant value, which could be easily printable with a common and affordable 3D printer. As reported in [31]-[32] the main idea consists again in increasing the electromagnetic properties of a base material by adding highly dielectric powders. The PLA has been chosen, instead of ABS adopted in [31]-[32], as a polymer base material, due to its higher printability and lower toxicity, whilst the $BaTiO_3$ has been confirmed as doping filler.

The mixing operation, in this case, has required a more complex approach, due to the thermoplastic behavior of the PLA, which is initially solid at room temperature. First of all, the PLA, in a pellet form, has been milled (after freezing) to reduce its granulometry, allowing for a more efficient dry blending with $BaTtiO_3$ powder. Then, the two materials have been mixed by means of a twin-screw extruder, equipped with a 2 mm circular rod die. The result is a printable PLA-based filament which is shown in Fig. 3. The dielectric constant, as expected, is dependant on the doping percentage in the final product. Equation (1) remains a valid formula to forecast the final permittivity value of the compound which achieved $\varepsilon_r \simeq 4.6$ and $\tan\delta \simeq 0.015$ for a doping percentage of 17.5% of the total volume.

It is worth highlighting how the result strongly depends on the starting permittivity of the polymer which, in this case, is characterized by a dielectric constant of about 2.5 (see Tab. I). A higher value can still be achieved increasing the powder percentage in the mixing. However, increasing too much the filler percentage could cause the filament to become brittle

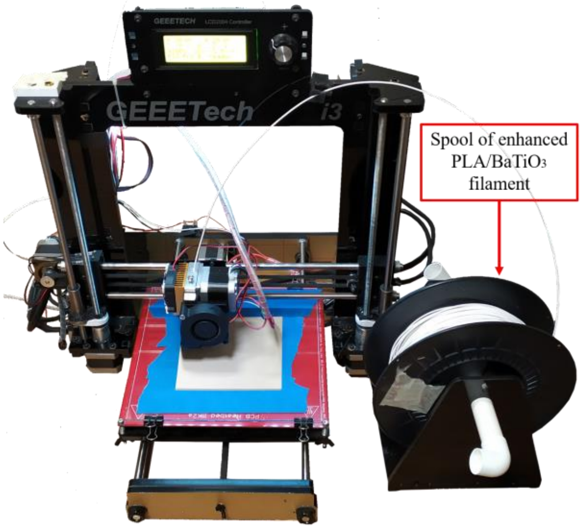


Fig. 3 17.5 % $BaTiO_3$ PLA-based filament in printing.

and difficult to print, due to an increased viscosity during extrusion.

IV. Conductive Filaments and Fully 3D Printable UHF RFID Devices

In this section the possibility of realizing a fully 3D-printed electromagnetic device, without the need of other techniques to produce the antenna or its conductive parts. This possibility has been investigated thanks to the availability of conductive filaments for 3D printing on the market. Specifically, in the first part of the research, two different conductive filaments, respectively based on graphene and copper inclusions, have been tested. As expected from the conductivity values declared by the producers, the filament based on copper inclusions, which is called Electrifi and produced by Multi3D [33], revealed to be the most promising one, with the conductivity at least two orders of magnitude higher compared with the other. Specifically, the declared Electrifi surface conductivity is about $1.6 \cdot 10^4$ S/m measured at zero Hertz.

With the aim to test this new material in some real applications, an UHF RFID tag has been realized exploiting 3D printing as a comprehensive manufacturing technique.

This prototype consists in a trapezoidal dipole tag antenna designed to resonate at 866 MHz. The antenna shape is based on a work presented by some of the authors in [19] where different prototyping techniques (not including 3D printing) are compared. The tag structure discussed in the present work has been properly optimized and resized in order to consider the electromagnetic properties of both Electrifi and PLA.

It is worth noting how, in the manufacturing process, no other prototyping techniques but 3D printing have been involved. Indeed, the final tag, shown in Fig. 4, has been built during a single printing process. Specifically, in the order:

- The PLA has been printed as a substrate and a slot has been created to allow for the upside-down positioning of the RFID chip.
- The chip has been properly located onto the top surface of the substrate using the slot as a guide.
- The antenna radiating element has been printed with the Electrifi filament, connecting the chip in the meantime.

The realized tag has been eventually tested with the systems proposed in [34] in order to evaluate its characteristics. In accordance with the normalized radiation patterns shown in Fig. 5, a good dipolar behavior has been obtained. However, as expected, a degradation of the performance is registered in comparison with the same tag produced with other techniques, due to the dissipative nature of the polymeric matrix of the Electrifi. In particular, the final tag guarantees a maximum reading distance of about 2 m. It is a very remarkable working distance for one of the first examples of RFID tag prototype completely realized with 3D printing. Nevertheless, if compared with the companion version realized with copper, which reaches a working distance of around 8 m, the effects of the lower conductivity of the Electrifi filament is apparent. In some cases, as will be shown in the next sections, the shape of the substrate (used only as thin and regular support in this case) can contribute to compensate the effects the radiation efficiency reduction due to the Electrifi adoption.

V. Examples of Enhanced 3D-Printed Antennas

In this Section various aspects of the 3D printing technology have been exploited to realize complex 3D-electromagnetic devices. The goal is to definitely demonstrate the usefulness of the 3D-printing technology for realizing complex structures, substrates, and radiating elements by using simple and cost-effective 3D printers. In particular, the possibility of realizing unconventional non-planar structures leveraging on the "third dimension'' enabled by the 3D printing technology is studied. Just to give an idea, an example of electromagnetic structure based on 3D-printed dielectric lens for a log-periodic dipole array is proposed in [20].

The next subsections discuss about the design of miniaturized and reconfigurable antennas making use of advanced 3D-printed materials, methods, and novel design techniques.

A. Miniaturazing antenna using 3D-printing

The starting point is a common 2.4 GHz patch antenna, designed and simulated in CST (Fig. 6a), considering a simple PLA substrate (εr = 2.55 and $\tan\delta = 0.007$) with copper annealed conductive parts. Consequently, a miniaturization process has been started, exploring two possible ways to achieve the goal. These are: increasing the εr of the substrate, using one of the BaTiO3 PLA-based filament already introduced in Section III B, or exploiting the third-dimension degree of freedom introduced by the manufacturing process. In the former case, the PLA of the substrate has been substituted with a doped one realized with a 17.5% of BaTiO3, bringing to an increase of the dielectric constant from 2.55 to 4.6. The result has been a decrement of the antenna size of about a 40% in terms of surface ratio of the radiating element (Fig. 6b). On the contrary, in the latter case the substrate material remained the PLA, but the radiating element has been "meandered" (Fig. 6c), thus reducing the planar projection size of the antenna. Even in this case a reduction of about 40%

Fig. 4 Fully 3D printed UHF RFID tag made of PLA (substrate) and Electrifi (antenna).

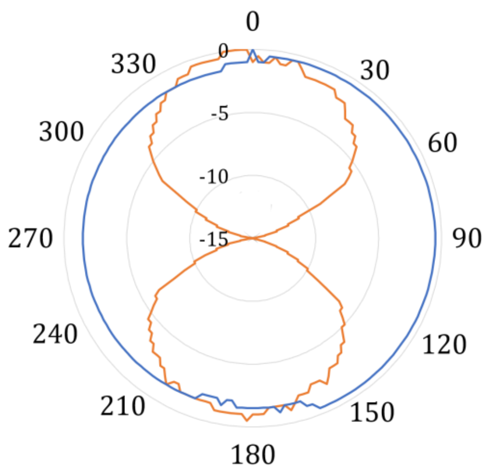


Fig. 5 Normalized radiation patterns of the fully 3D-printed dipole UHF RFID tag antenna.

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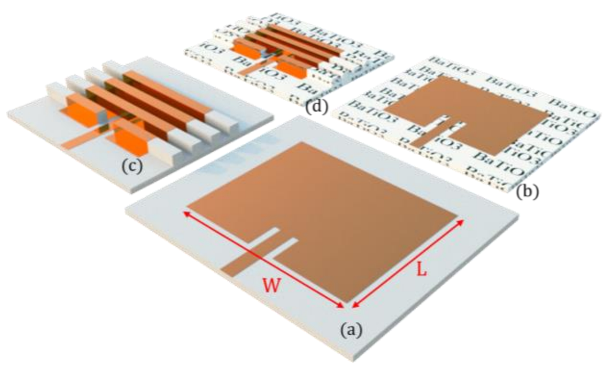

Fig. 6 3D models of the 4 simulated patch with L and W as reference parameters. (a) Normal patch antenna – (b) Normal patch antenna with size reduction due to the higher dielectric constant of the substrate – (c) Meandered patch antenna with size reduction due to the meandering – (d) Final version of the patch antenna with size strongly redued due to both meandering technique and doped substrate.

is achieved, only exploiting the third dimension in a way as simple as possible

Finally, a last patch has been designed and simulated with both the $BaTiO_3$ substrate and the antenna meandering technique to combine their advantages. This results in a patch antenna which can exhibits a planar size reduction of about 60% compared with the normal one, as can be seen in Fig. 6d. The W and L parameter values of the four antennas are reported in Tab. III, as well as the radiating element area and the simulated radiation efficiency. It is worth noting how both the antenna types (b) and (c) have almost the same dimensions in terms of "L" and "W". This means that the size reduction obtained by increasing the dielectric constant of the substrate, can be completely achieved even with simple meandering technique. Moreover, it is clear how the radiation efficiency of the meandered versions of both the standard antennas, improves sensibly. For instance, when comparing the results

TABLE III
PATCH SIZES ON XY PLANE AND RAD. EFFICIENCY

Antenna type	L projected on XY plane [mm]	W [mm]	Radiating Element Surface [mm^2]	Simulated Radiation Efficiency [dB]
(a)	36.6	47	1720.2	-1.51
(b)	28.5	35	997.5	-2.75
(c)	28	35	980	-1
(d)	22	31	682	-2.27

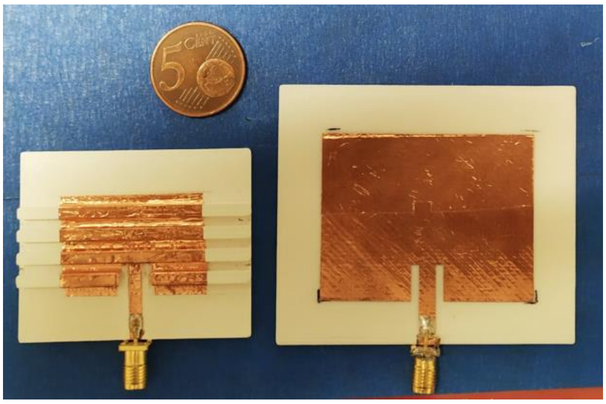

Fig. 7 Normal patch (right) and size-reduced patch (left).

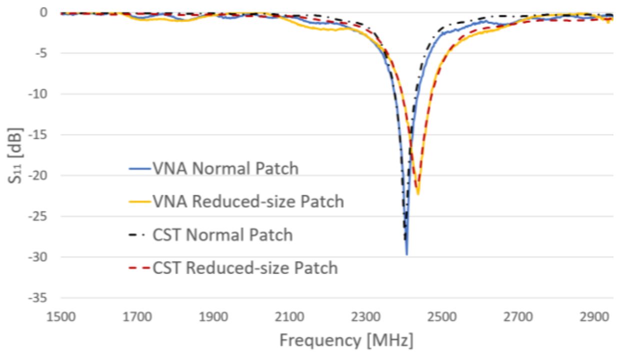

Fig. 8 Measured (continous lines) and simulated (dotted lines) S_{11} parameters of the two prototype antennas.

related to antenna of Fig. 6c with those of Fig. 6a, the effects of the unconventional shape of the substrate are clear both in terms of size reduction and radiation efficiency increment of the meandered version. Such a radiation efficiency increment is straightforwardly exploitable to partially balance the degradation effect due to the conductivity of the Electrifi filaments in the fully 3D-printed device realization, as anticipated in the previous Section.

Finally, comparing the efficiencies of the antennas made with simple PLA with the ones realized with the $BaTiO_3$-enhanced PLA, a slight degradation is observed. This is due to the higher losses of the latter which, however, are comparable with those of a standard FR4 substrate.

In order to practically evaluate these results, two of the four simulated prototypes, have been realized. Specifically, the standard one as well as the one with the highest size reduction. Both the substrates of the prototypes have been printed with the same printer setting: temperature 205 °C; speed 2600 mm/min; nozzle diameter of 0.5 mm and a layer height of 0.2 mm. The radiating elements have been produced shaping the antenna profiles with a cutting plotter, onto a copper adhesive tape, whilst SMA connectors have been soldered on the antennas in order to perform the scattering parameter measurements.

A picture of the two final prototypes is shown in Fig. 7 while in Fig. 8 a graph highlighting the good agreement between measured and simulated S_{11} results is presented. In particular, it can be observed that the behavior of the miniaturized antenna is perfectly predictable from the simulation, demonstrating the doped filament is well characterized.

B. *Tunable double-band UHF RFID planar inverted-F antenna design*

Interesting scenarios are expected by combining the clever use of the third dimension in 3D-printing structures with the availability of printable materials characterized by an enhanced permittivity. This could pave the way to the possibility of realizing, for example, some complex dielectric structures with modular parts, capable of interacting with each other in different ways depending on different operative conditions. Some appealing ideas at this regard are, for example, the possibility to realize antennas with parameters like gain, return loss and directivity which can be tuned by mechanically moving some antenna elements; the possibility to realize antennas physically reconfigurable and so capable to better suit stringent constraints, only when it is really needed; the capability to tune the performance of IoT devices, like RFID tags or BLE nodes, depending on the characteristics of the surface on which they are applied to; the possibility to change the working frequency of RF circuits; and these just to name a few.

In particular, without loss of generality and with a purely explicative purpose in this paragraph a novel 3D-printed RFID tag, based on the design of a tunable 3D-ptinted PIFA antenna with an unconventional shape, is described. The proposed antenna layout is reported in Fig. 9. The device is composed of two main 3D-printed dielectric parts:

a) the body, hosting antenna radiating element, feeding line, and ground plane:

b) the base, hosting a rectangular ring wrapped around the body (see Fig. 9).

As for the antenna body, the radiating element, the feeding line and the ground plane are realized by properly shaping, through a cutting plotter, a 50 µm adhesive copper tape according to the antenna parameters reported in Tab. IV.

As for the antenna base, the ring is internally covered with a thin strip of 50 µm adhesive copper tape placed on three of the four sides of the ring. The copper inside the ring provides electrical contact between the antenna radiating element and the ground plane, according to the PIFA requirements. Thanks to the proposed 3D-printed structure the body is free to move inside the ring, where the copper acts as sliding shorting wall for the PIFA.

This movement allows to vary the distance between the shorting wall and the feeding line of the antenna, thus enabling a tuning procedure that can mechanically adapt the antenna parameters to the ones that better suits the needs of the specific application.

In order to reduce the size of the whole antenna, the prototype has also been simulated considering the same doped PLA, realized with a 17.5% of $BaTiO_3$, previously described in section III. During the simulations, the main antenna parameters have been tuned in order to match the impedance of an Impinj Monza 6 IC, characterized by a very low power activation threshold of -20 dBm.

The simulations have been performed calculating the S_{11} curve for 2 different configurations of the antenna, corresponding to different positions of the wrapping ring (respectively for the parameter *s* in Fig. 9 equal to 1.2 mm and 3.2 mm). As can be seen in Figure 11, this results in two diverse operative conditions of the PIFA. The former is more suitable for working in the European band (865-867 MHz), whilst the latter is more appropriate for applications in the American band (902-927 MHz). This simple result has to be intended as a prove of concept for the tuning of other important antenna parameters. Indeed, many other characteristics like, for example, the quality of the conjugate matching between chip and antenna when varying the background material (or the chip itself) could definitely get benefit from a reconfigurable antenna geometry.

VI. Other 3D-printing promising techniques

Some last considerations need to be done regarding other types of techniques for additive manufacturing 3D-printing. Indeed, Fused Deposition Modelling (FDM), is only one of the different techniques that allow to print objects in 3D. This is the most used one and the most adopted in literature, due to both its ease of use and its cost-effectiveness. However, especially in the last few years, the resin-based (also known as vat polymerization) 3D-printing technology is spreading out

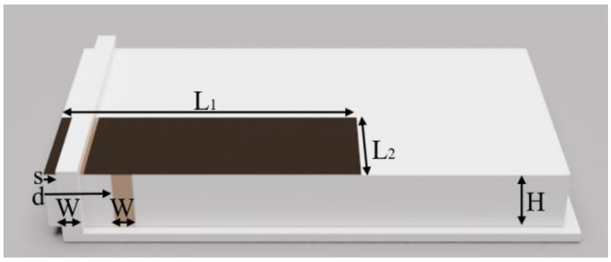

Fig. 9 Render of the proposed PIFA design.

TABLE IV
PIFA design parameters [mm]

L_1	30.5
L_2	10.5
W	2
S	1.2/3.2
D	6.5
H	6

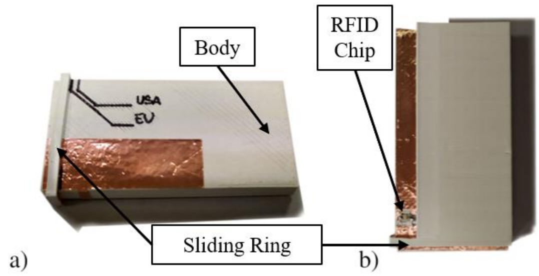

Fig. 10 Top (a) and bottom (b) view of the realized prototype.

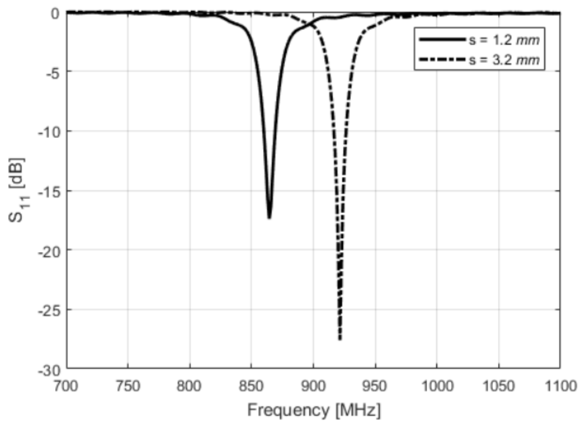

Fig. 11 Simulated S_{11} curves for both the working configurations.

also in the consumer market. Specifically, the advent of the Digital Lightening Polymerization (DLP) technology has made the cost of this type of printer more and more affordable. Briefly, it works using a high-resolution screen emitting UV light (typically at 405 nm), to photopolymerize a sensible resin. This allows to print objects with a resolution even 10 times higher if compared with the standard for the FDM. Moreover, more complex geometries can be easily realized, due to the unnecessary presence of printing supports.

In order to explore the possibilities enabled by this kind of technology, a preliminary study has been made to characterize the dielectric properties of one common commercial resin. A cheap Anycubic Photon-S DLP 3D printer has been used to produce a simple 40x80x1.6 mm^3 substrate, with the Anycubic 405 nm resin provided by the manufacturer.

Subsequently, a copper adhesive tape has been shaped into a properly dimensioned T through a cutting plotter, so to obtain a T-Resonator as shown in Figure 12.

The 52 mm length of the stub allows to measure the dielectric properties of the polymer at a frequency around 800 MHz, near the working band of UHF RFID technology. Specifically, values of $\varepsilon_r = 3.11$ and $\tan\delta = 0.033$ have been found. From this preliminary investigation, it is clear how the resin exhibits higher value for dielectric constant, but also for loss tangent if compared with common materials printable with FDM technology. Despite the higher losses of this specific resin, the printing technology is appealing since it allows to realize geometries which are unprintable otherwise. Moreover, further studies could show the possibility to combine a resin matrix with some kinds of doping agents to enhance the dielectric properties as has been already done for the PLA with $BaTiO_3$.

VII. 3D-Printing in electromagnetics: possible applications, limits and further development

As explained before, 3D-printing in electromagnetics involves different but connected topics. The proposed techniques can be effectively applied to many interesting frameworks dealing with both experimental research and real applications. On the one hand, the mold technique described in sections III.A, could be proficiently used in medical or wearable applications or whenever the capability to realize flexible structures with a conformable shape is needed. On the other hand, the capability of easily using 3D printable filament to realize devices with customizable shapes and enhanced dielectric properties (described in III.B) can be very useful in applications where reduced antenna size is mandatory. Finally, the capability to realize fully 3D printed devices would shorten the prototyping times while reducing manufacturing costs, thus speeding up the R&D activities.

Summarizing, additive manufacturing by 3D printing can naturally adapt to different application constraints, thanks to its degrees of freedom in designing complex structures. This feature, combined with cost-effectiveness and ease of use makes 3D printing technology in electromagnetics potentially suitable for several application frameworks. For instance, a 3D-printed slotted waveguide array antenna with 12 radiating elements has been proposed in [35] for automotive applications. Another example is described in [36], where DLP 3D-printing has been used to realize a low-cost mm-vawe antenna for various RF sensing applications like food-safe and health.

Fig. 12 Resin-made T-Resonator printed with a DLP 3D printer.

However, despite 3D-Printing can guarantee interesting perspectives in electromagnetics, some limits need to be discussed. The first one is related to the working frequency of the targeted device. If, for instance, Electrifi filaments want to be used, it must be considered that the minimum printing thickness is limited by the technology (FDM) constraint. Moreover, also the accuracy of the printed "conductive" tracks other than its rugosity, are not adequate for working frequencies higher than some GHz. To give an idea, when printing tracks of a nominal width of 0.3 mm, an effective width variable between 0.32 and 0.35 mm is generally obtained. This uncertainty can compromise the predicted behavior of the designed device depending on the wavelength. Then, preliminary tests have shown that conductivity of the conductive filament depends on different factors, such as the printing pattern and the thickness of the tracks.

In this regard, a new activity is in progress to evaluate the conductivity of printed Electrifi tracks in a wide range of frequencies when varying the thickness, so to provide the RF designer with accurate values to define the material in the electromagnetic simulation environment. Moreover, the properties of hybrid polymer/conductor materials and their use in the fast prototyping of RF devices by 3D-printing will be deeply explored in future works. Finally, a more effective use of the DLP 3D printing technology, especially in the framework of the UHF RFID applications, will be also explored trying to exploit the higher precision of this technique with respect to the traditional FDM one.

VIII. Conclusions

In this work, many different aspects of the 3D printing in electromagnetics have been discussed. This should introduce the reader to the fundamentals of the matter, making him understand, in the meantime, the complexity and the promising prospects of this research branch. It is authors' opinion that the realization of fully 3D-printed innovative devices, exploiting in the meanwhile the advantages introduced by the third-dimension degree of freedom, is definitely possible other than desirable.

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Riccardo Colella received the M.Sc. degree (with honors) in Telecommunication Engineering from the University of Salento (Italy) in 2010, and the Ph.D. degree from the same University in 2015. Currently, he is Researcher at the Institute of Clinical Physiology of the National Research Council (IFC-CNR), Italy. His research activity is mainly focused on the design of innovative RFID antennas and systems, wirelessly-powered sensing systems for the Internet of Things, wearable antennas for healthcare applications and novel RF devices in the framework of 3D-printing and flexible electronics. He authored about 110 papers appeared in international journals and in national and international conferences, two chapter books with international diffusion and a patent.

Francesco Paolo Chietera received the M.Sc. degree in Communication Engineering at the University of Salento (Italy) in 2018, with a thesis named "Enhanced UHF RFID Antennas exploiting additive manufacturing 3D printing". His main field of interest is about 3D-printing in Electromagnetics, with a particular focus on RFID technologies for sensing and traceability as well as for IoT applications in general. He coauthored more than 10 papers on these topics. He is currently collaborating with the Dept. of Innovation Engineering of the University of Salento, with the "Electromagnetic Solution for Hi-Tech" group.

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Catarinucci authored more than 150 scientific works of which 65 international journals, 4 chapters of books with international diffusion and more than 80 proceedings of international conferences. Moreover, he holds 2 National Patents about RFID technology.