Additive Manufacturing of Substrate Integrated Waveguide Components

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Abstract — **This paper presents the recent advances in the implementation of substrate integrated waveguide (SIW) components and circuits by additive manufacturing (AM) techniques. The use of AM allows introducing novel features in the design of SIW structures, ranging from fully three-dimensional geometries (impossibly to obtain with standard planar circuits technologies), to the local modification of the dielectric permittivity and loss tangent of the 3D-printed material (which allows for novel classes of components and resonant cavities with modified quality factor). The implementation of a 3D-printed SIW resonant cavity is presented, with the aim to assess the technology and characterize the material. Subsequently, a 3D-printed SIW structure with four bends in the E-plane is presented and validated, as an example of a fully three-dimensional geometry. Finally, the use of 3D-printed material with different infill percentage is shown, with the aim to modify the quality factor of SIW resonant cavities and design filters with improved performance.**

Index Terms — **Additive manufacturing, 3D printing, substrate integrated waveguide (SIW), resonant cavity, filter.**

I. INTRODUCTION

The deployment of the next generation of Wireless Sensor Networks (WSN) [1] and of the Internet of Things (IoT) [2] paradigm demands for the implementation of radio-frequency (RF) and microwave components with innovative features in terms of low cost, compact size, light weight, flexibility, and environmental compliance. Moreover, the need to manufacture a very large number of wireless systems expected for IoT applications requires the identification of an efficient manufacturing technology and a suitable integration method.

Several new material and innovative manufacturing techniques have been recently proposed for the implementation of the novel wireless systems for IoT, with the aim to reduce the implementation cost and the prototyping time. Among the emerging techniques, the additive manufacturing based on 3D printing results particularly interesting, as it allows realizing complex and fully three-dimensional devices [3]-[5]. Commercially available 3D printers currently allow high resolutions and a fast and reliable prototyping. Among the different printing techniques, the fused deposition modeling (FDM) approach presents a good compromise between low cost and reasonable accuracy [5]. Different filaments can be adopted for 3D-printing by FDM, including the acrylonitrile butadiene styrene (ABS), the polylactic acid (PLA), and other flexible and/or eco-friendly materials.

Among the integration technologies, the substrate integrated waveguide (SIW) has received increasing attention in the last decade for the implementation of active and passive components and antennas, as well as for the integration of complete systems at microwave and mm-wave frequencies [6]. A variety of SIW components and antennas have been already implemented on non-standard materials for wearable and eco-friendly applications, including paper [7], textile [8], and plastic [9].

This paper summarizes the recent advances in the implementation of SIW components by adopting a 3D-printing process based on FDM. Both t-glase and ABS filaments are used. The implementation of a 3D-printed SIW resonant cavity is preliminarily presented, with the aim to assess the technology and accurately determine the dielectric characteristics of the material [10]. Subsequently, a 3D-printed SIW interconnect with four bends in the E-plane is presented and experimentally validated, as an example of a fully three-dimensional geometry [10]. Finally, the use of 3D-printed material with different infill percentage is discussed and applied to the implementation of a three-cavity filter [11]. The variation of the infill percentage of the 3D-printed material allows modifying the dielectric permittivity and reducing the dielectric loss tangent [12]: in the considered case, this strategy permits increasing the quality factor of the SIW resonant cavities and improve the performance of the SIW filter.

II. 3D-PRINTED SIW RESONANT CAVITY

The AM fabrication process has been first adopted for the implementation of an SIW resonant cavity, operating with fundamental mode at about 3 GHz [10]. The fabrication of this structure allows verifying the manufacturing process and to accurately determine the dielectric characteristics of the material.

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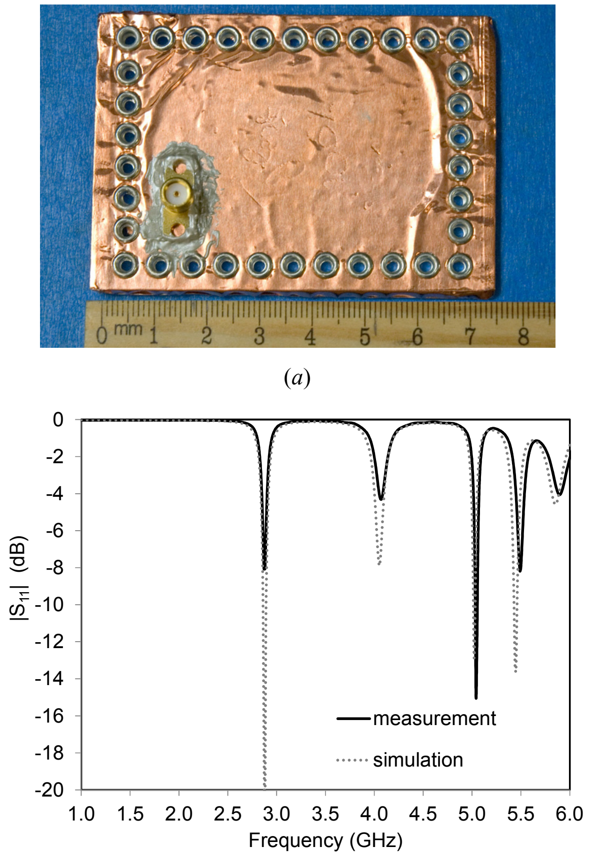


(*a*)

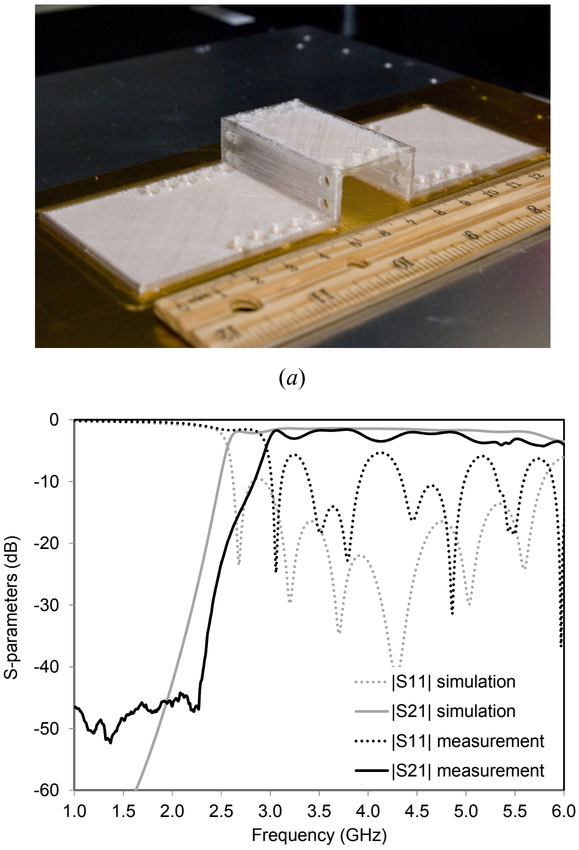
(*b*)

Fig. 1. 3D-printed substrate integrated waveguide cavity based on t-glase filament: (*a*) photograph of the prototype; (*b*) simulated and measured scattering parameters of the cavity (from [10]).

The substrate adopted for the fabrication of the SIW cavity is obtained by 3D printing of a t-glase filament with thickness of 2.0 mm, 100% infill percentage, and rectilinear printing pattern. The implementation of the top and bottom ground planes of the SIW cavity is obtained by adopting standard copper tape, pasted at both sides of the 3D-printed substrate (Fig. 1*a*). The metal vias defining the sidewalls of the SIW resonant cavity are realized by using brass rivets.

The size of the cavity is 44 mm×64 mm (from center to center of the metal vias), the diameter of the metal vias is 3.2 mm and their lateral spacing is 6.4 mm. The 50-Ω coaxial probe is placed at a distance of 12 mm and 10 mm from the sides of the cavity.

The values of dielectric permittivity ε_r=2.3 and loss tangent tan δ=0.01 were adopted in the full-wave simulation of the SIW cavity based on the commercial electromagnetic solver Ansys HFSS. Fig. 1*b* shows the comparison between simulation and measurement: there is a good agreement both for the first resonant mode at the frequency of 2.88 GHz, and for the other resonant modes (with a minor frequency shift, due to the change of the dielectric characteristics with frequency).



(*a*)

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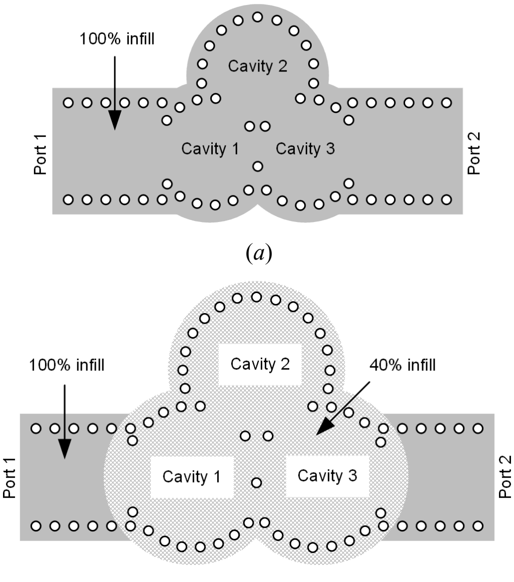
Fig. 2. 3D-printed SIW interconnect: (*a*) photograph of the prototype based on t-glase filament (before metallization); (*b*) simulated and measured scattering parameters (from [10]).

III. A FULLY THREE-DIMENSIONAL SIW STRUCTURE

A three-dimensional SIW structure was designed and manufactured by 3D printing of a t-glase filament, to fully exploit the capabilities of 3D printing fabrication process [10]. The structure consists of an SIW interconnect with four bends in the E-plane (Fig. 2a).

The SIW interconnect was designed with cutoff frequency at 2.5 GHz, to cover the ultra-wideband (UWB) frequency band, from 3.1 GHz to 4.8 GHz. The width of the SIW was selected 41.5 mm (from center to center of the metal posts), the diameter of the metal vias was 3.2 mm and their lateral spacing was 6.4 mm. The length of the vertical portion was chosen 12 mm and the length of suspended bridge was 29 mm. Also in this case, the values of dielectric permittivity ε_r=2.3 and loss tangent tan δ=0.01 were adopted in the HFSS simulations.

The fabrication of the suspended bridge section was performed without any support material: during this fabrication step, a fan behind the extruder was turned on to quickly solidify the filament. A tape of Kapton was used under the structure to enhance the adhesion to the machine bed.



(*a*)

(*b*)

Fig. 3. Geometry of the 3D-printed three-pole filters based on ABS: (*a*) filter entirely fabricated with 100% infill; (*b*) filter fabricated partly with 100% infill and partly 40% infill (from [11]).

The photograph of the 3D-printed t-glase structure is shown in Fig. 2*a*, showing the holes for the metal vias. The fabrication was completed by metalizing the top and bottom faces with copper tape, and filling the holes with brass rivets. Finally, two tapered SIW-to-microstrip line transitions and SMA connectors were added to perform the measurement.

The comparison of simulation and measurement results is reported in Fig. 2*b*. A frequency shift of approximately 170 MHz is observed in the cut-off frequency, attributed to the fabrication of the vertical sections and the suspended bridge, which may cause a variation of the material density and, therefore, of the dielectric characteristics.

IV. 3D-PRINTED SIW FILTERS WITH REDUCED INFILL

FDM allows local modification of the printed material properties, mainly by acting on the infill factor [12]. The variation of the density affects the effective dielectric permittivity of the printed material as well as its electric loss tangent. The effect of the material density on the dielectric properties of the material can be accurately estimated by adopting the Bruggeman's model [12].

To demonstrate this concept, two substrate integrated waveguide (SIW) filters with the same topology and frequency response have been designed and fabricated by 3D printing [11]. One filter is based on a dielectric substrate printed with 100% infill (Fig. 3*a*), whereas in the second filter the input/output SIW lines are fabricated with 100% infill and the resonant cavities are made with 40% infill (Fig. 3*b*). This solution allows to increase the quality factor of the filter, at the cost of a slightly increase footprint size.

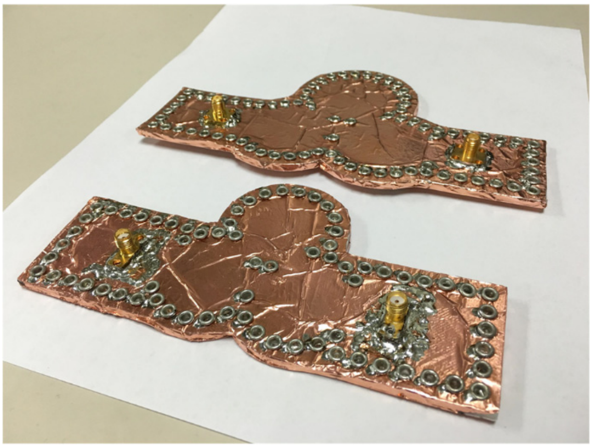


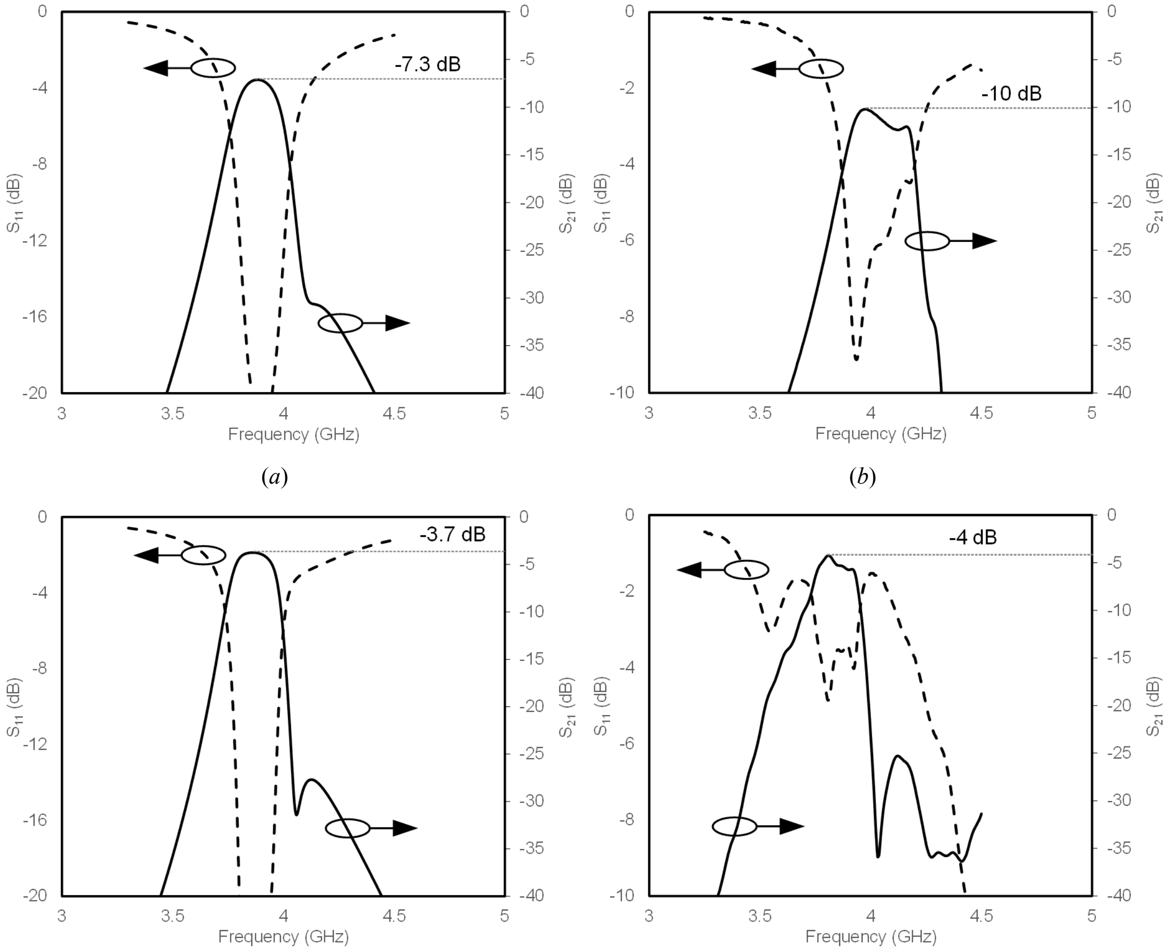
Fig. 4. Photograph of the prototypes of the first filter with 100% infill (top), and of the second filter, 40% infill in the cavities, 100% infill in the input/output lines (top) (from [11]).

The two filters have been designed to obtain the same frequency response and they were fabricated by using Hatchbox branded acrylonitrile butadiene styrene (ABS) filament printed on a Printrbot Metal Plus (Fig. 4). The first filter was designed by using a dielectric substrate with permittivity $\varepsilon_r=2.7$, corresponding to 100% infill, homogeneous in the whole structure. In the second filter, the permittivity of the cavity resonators is decreased to $\varepsilon_r=1.6$, corresponding to 40% infill, while the permittivity is kept to $\varepsilon_r=2.7$ in the input/output waveguides. Consequently, the cavities of the second filter (with lower permittivity) are larger than the cavities of the first filter (with higher permittivity), but they exhibit higher quality factor.

The simulation and measurement results are shown in Fig. 5. In particular, the simulated scattering parameters of the first filter are reported in Fig. 5*a* and show an insertion loss of approximately 7.3 dB at 3.86 GHz. Conversely, the second filter (Fig. 5*c*), exhibits an insertion of only 3.7 dB. On the other hand, the diameter of the resonant cavities is 19.2 mm in the first filter and it is increase to 24.4 mm in the second filter. The measurements confirm these results: the second filter (Fig. 5*d*) exhibits an insertion loss of 4 dB, much smaller than the first filter, which has an insertion loss of 10 dB (Fig. 5*b*).

V. CONCLUSION

This paper has presented the most recent advances in the implementation of substrate integrated waveguide components by additive manufacturing techniques based on FDM. The use of 3D printing paves the road to a completely new class of SIW components and circuits. It allows to shape fully three-dimensional structures and to locally modify the material density: this leads to the local modification of the dielectric permittivity and to the reduction of the loss tangent, thus allowing the design of innovative and fully integrated wireless circuits and systems.



(*a*) (*b*) (*c*) (*d*)

Fig. 5. Simulation and measurement results of the 3D-printed three-pole filters based on ABS: (*a*) simulation of the first filter; (*b*) measurement of the first filter; (*a*) simulation of the second filter; (*b*) measurement of the second filter (from [11]).

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