Additive manufacturing of 3D substrate integrated waveguide components

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The implementation of fully three-dimensional (3D) substrate integrated waveguide (SIW) components by using an additive manufacturing technique is demonstrated for the first time. In particular, a 3D printing process based on the t-glase filament has been adopted. 3D printing allows for the manufacturing of very complex shapes in a few hours, thus leading to a one-day prototyping time for microwave components. To characterise the electromagnetic properties of the 3D printed material, a microstrip lines technique has been adopted. To fully demonstrate the potential of the proposed fabrication process, a SIW cavity resonator and a 3D SIW interconnect with four E-plane bends have been fabricated and tested.

Introduction: The development of the next generation of wireless sensor networks towards the Internet of things (IoT) paradigm [1] demands RF and microwave components with special features in terms of flexibility, light weight and environmental compliance. The deployment of the large number of wireless systems expected for IoT applications requires a suitable manufacturing process and an efficient integration technology.

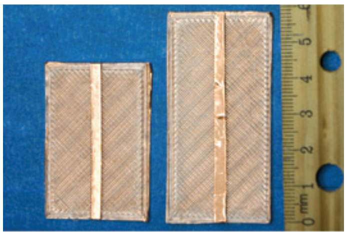
Several innovative manufacturing techniques are currently being developed with the aim of reducing the implementation cost and the prototyping time. Among the emerging techniques, additive manufacturing based on three-dimensional (3D) printing is particularly suited to realise complex and fully 3D devices [2]. Commercially available 3D printers allow high resolutions together with a fast and reliable printing process. Commonly available printing materials can be dropped off by the fused deposition modelling (FDM) approach [3], and comprise acrylonitrile butadiene styrene, polylactic acid, and other flexible and/or eco-friendly materials. On the contrary, bulky metals can only be printed with the laser sintering process that is definitely more expensive and adopted only in very specific fields.

Among the integration technologies, the substrate integrated waveguide (SIW) has been widely adopted 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 [4]. A variety of SIW components and antennas have been already implemented on non-standard materials for wearable and eco-friendly applications, including paper [5], textiles [6], and plastic [7].

This Letter presents the implementation of SIW components by using a 3D printing manufacturing process, based on a recently proposed material called t-glase. After the description of the 3D printing process, the electromagnetic characterisation of the material is presented. The fabrication of SIW components and the implementation of a 3D interconnect with four E-plane 90° bends are reported to demonstrate the potential of the 3D printing fabrication process.

Electrical characterisation of t-glase: The material adopted in this reported work is named t-glase: it was introduced in the market by Taulman3D, and initially developed for optical applications. This material, based on the highest quality polyethylene terephthalate, is printed by using the Metal Plus by Printrbot, a commercial available FDM printer. As we are dealing with an innovative material and fabrication process, the preliminary characterisation of the electrical properties of the 3D printed material based on the t-glase filament is mandatory. In fact, the electrical properties of the printed material are critically dependent on the printer settings (e.g. extrusion speed and temperature, infill density and printing pattern). A characterisation method based on the transmission line technique has been adopted for the experimental evaluation of the electrical properties of the 3D printed material.

The transmission line technique requires the realisation of two microstrip lines of different lengths and allows broadband characterisation of the material [6]. The comparison of the measured scattering parameters of the two lines permits extracting the relative dielectric permittivity ε_r and the loss tangent tan δ. Namely, the phase difference of the S_{21} parameters is related to ε_r, whereas the amplitude difference is proportional to the losses and therefore it permits calculating tan δ. For implementation of the microstrip lines, two substrates have been printed, with a thickness of 1.2 mm, 100% infill percentage, and a rectilinear printing pattern (Fig. 1*a*). The ground planes and the metal strips (width 3 mm) have been realised by pasting a copper tape. For a good estimate of the electrical properties of the substrate, the length difference of the two microstrip lines has been set to 25 mm. Fig. 1*b* shows the dielectric permittivity and the loss tangent, extracted from measurements, in the frequency band from 1 to 6 GHz. The value of the dielectric permittivity ranges from 2.2 to 2.35 over the entire frequency band. The measurement of the loss tangent is more critical, and the extracted values exhibit some variation. The values $\varepsilon_r = 2.3$ and tan $\delta = 0.01$ were obtained at the frequency of 3 GHz.



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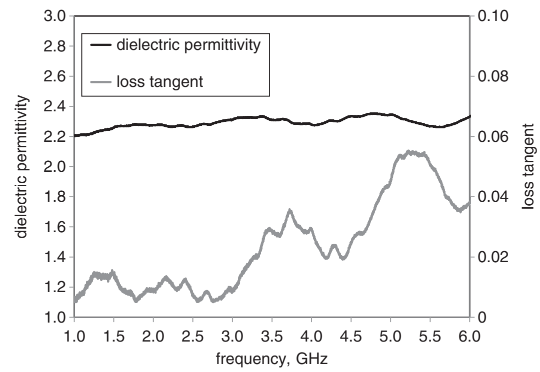

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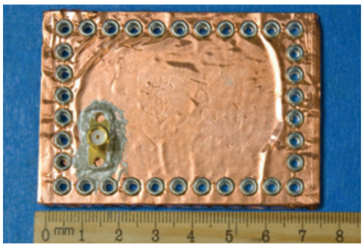
Fig. 1 *Transmission line technique for material characterisation*

a Photograph of microstrip lines based on t-glase
b Dielectric permittivity and loss tangent against frequency, extracted from measurements.



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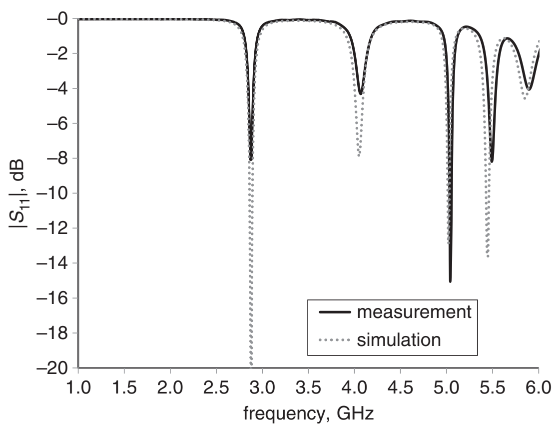

b

Fig. 2 *3D-printed SIW cavity*

a Photograph of prototype
b Measured and simulated scattering parameters

SIW resonant cavity implementation and validation: A SIW resonant cavity has been fabricated to verity the manufacturing process of the SIW structures and to cross-check the electrical properties retrieved from the microstrip lines. The substrate adopted for the implementation of the SIW cavity has been manufactured by adopting a 3D printed t-glase, with a thickness of 2.0 mm, 100% infill percentage, and a rectilinear printing pattern. The top and bottom ground planes are realised by pasting standard copper tape, and the metal vias are realised using brass rivets (Fig. 2*a*). The cavity dimensions are 44 × 64 mm (measured from the centre of the metal posts), the diameter of the posts is 3.2 mm and their spacing is 6.4 mm. The coaxial probe is located at 12 mm and 10 mm from the corner of the cavity.

The values of ε_r and tan δ obtained using the microstrip lines technique at the frequency of 3 GHz were used in the full-wave analysis of the SIW cavity over the entire frequency band. Comparison between the simulation and measurement results is shown in Fig. 2*b*; while there is an excellent agreement for the first resonant mode at the frequency of 2.88 GHz, a minor shift is observed for the other resonant modes, with a maximum variation of 0.9% at 5.5 GHz, in accordance with the variation of the dielectric permittivity shown in Fig. 1*b*.

SIW interconnect implementation and validation: To fully exploit the 3D printing capabilities, a 3D SIW interconnect has been designed and realised by the manufacturing process described in the previous Section. The structure consists of five sections of the SIW connected by four E-plane bends (Fig. 3*a*). The SIW interconnect has been designed to cover the lower part of the ultra-wideband frequency range, from 3.1 to 4.8 GHz. Consequently, the cutoff frequency of the SIW is set to $f_C = 2.5$ GHz, so that the useful band starts at $1.25 \cdot f_C = 3.1$ GHz according to the usual definition. The dimensions of the SIW have been selected accordingly: the width of the SIW is 41.5 mm (measured from the centre of the metal posts), the diameter of the posts is 3.2 mm and their spacing is 6.4 mm. The length of the vertical portion is 12 mm and the length of the suspended bridge is 29 mm.

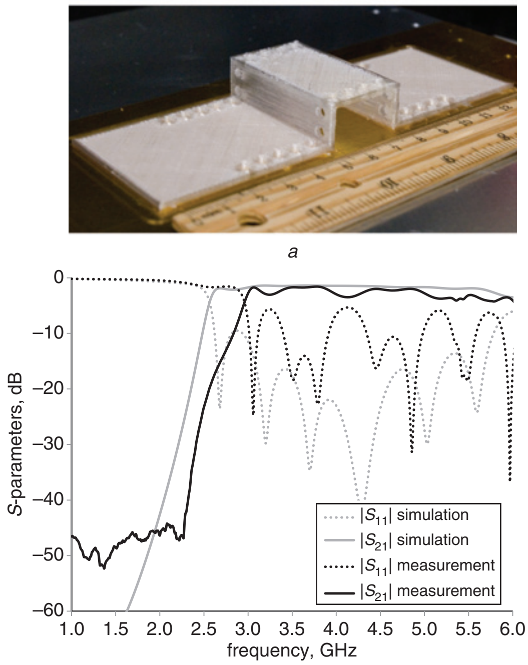

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Fig. 3 *3D printed SIW interconnect*
a Photograph of prototype (only dielectric substrate, before metallisation)
b Measured and simulated scattering parameters

In the fabrication process, the most difficult part was the suspended bridge section, as the support material was not available and, therefore, the plastic material had to be printed through an air gap. During this step, the fan behind the extruder was turned on to solidify as fast as possible the filament. A tape of Kapton was used under the structure to enhance adhesion to the machine bed. The photograph of the printed t-glase structure (before metallisation) is shown in Fig. 3*a*. The fabrication was completed by metalising the top and bottom faces with standard copper tape, and the holes with brass rivets. Finally, two tapered SIW-to-microstrip line transitions and SMA connectors were added for measurement purposes.

Measurement and simulation results are shown in Fig. 3*b*. A discrepancy of roughly 170 MHz in the cutoff frequency is observed: it is mainly attributed to the fabrication of the vertical sections and the suspended bridge, which may cause a variation of the material density and, consequently, of the dielectric characteristics. On the other hand, the measured insertion loss is very close to the simulated value.

Conclusion: A 3D printing additive manufacturing technique has been demonstrated for the first time for the implementation of SIW components. The adopted material, based on the t-glase filament, has been characterised using the transmission line technique. A resonant SIW cavity and a fully 3D SIW interconnect have been manufactured and tested. The realisation of fully 3D SIW components can hardly be achieved by commonly used manufacturing technologies, and it will be useful in the development of densely integrated microwave circuits and systems.

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One or more of the Figures in this Letter are available in colour online.

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