Novel Hollow Substrate Integrated Waveguide for 5G and Robotic Applications

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***Abstract*—This paper presents, a novel design of a Hollow Substrate Integrated Waveguide (HSIW), that is built by using both Subtractive and Additive Manufacturing technologies. Specifically, it utilizes Polymer jetting method to print an Acrylonitrile butadiene styrene (ABS) dielectric substrate and a water laser cutter system to produce smooth copper sheets as the top and bottom enclosures of the HSIW. Also, the fabrication process is utilizing mechanical through hole plating of commercially available prefabricated vias, eliminating the cost and complexity of performing vias fabrication and metallization process as in other SIW designs. The proposed waveguide covers 5G new radiofrequency bands, specifically from 21 GHz to 31 GHz. It has a simulated and a measured attenuation constant of 0.636 Np/m and 1.56 Np/m respectively, for the whole operating frequency range and is among the lowest reported values to date. The proposed HSIW of this paper, can be compared with other state- of-the-art designs in terms of compactness, manufacturing cost and performance. The designed HSIW can be integrated with other planar circuits and can be used to build functional devices such as antennas or filters for 5G, robotics and IoT applications.**

***Index Terms*—component, formatting, style, styling, insert**

I. Introduction

Substrate Integrated Waveguides have become very popular in recent years. There are being used as microstrip line alternatives since they offer many benefits like high power handling and high Q-factor. They have replaced the bulky rectangular waveguides and they are easy to integrate with other planar circuits. SIW components are a good compromise between an air-filled rectangular waveguide and a microstrip line, especially in the higher mm-wave range [1]–[6]. They are outperforming other planar transmission lines, because of the low propagation loss, limited Electromagnetic (EM) leakage and do not suffer dispersion at higher frequencies [6]–[8]. During the last few years, some basic types of SIW were reported: (a) the dielectric filled SIW and (b) Hollow or air-filled SIW. Both types were developed basedon PCB, LTCC or other similar fabrication techniques. The air-filled or hollow SIWs have the benefit of lower losses since the dielectric has been removed from the structure [9].This is the reason that the author in [10], has developed anovel Hollow SIW based on LTCC fabrication method andhas achieved an attenuation constant of 1 Np/m. In overall, the designed HSIW offers very low losses compared to otherstate-of-the-art designs and it has a great potential to realizehighly integrated millimeter-wave modules. On the other hand,the LTCC fabrication method requires a lot of processing stepsand it is a very expensive fabrication technology. AnotherAir-filled SIW is reported in [11], that is fabricated using astandard multi-layer PCB process, with a lossy FR-4 substratethat achieved a measured propagation constant of 0.51 Np/m.Although the attenuation constant is kept at low level, theoverall cost is high, and the fabrication process is complex. Recently, 3D printing methods or as otherwise called Additive Manufacturing, is being widely used, to fabricate millimeterwave and RF devices [12]–[16]. They have been proved to bevery useful for low-cost rapid-prototyping of high-frequency components up to sub-THz frequency range [17]–[19]. Specifically, FDM, SLA or DLP methods are using resin-basedphotopolymer to pattern a 3D structure. The author in [15], has used stereolithography (SLA) method to fabricate passive microwave devices, operating in the X,W and Ka frequencybands. The accuracy of the 3D printing process providedexcellent responses which are comparable to the traditional metallic waveguides. Subtractive manufacturing has been used also in RF and microwave devices. In paper [20], the lid of a WR-10 rectangular waveguide has been fabricated based onphoto-laser subtractive manufacturing. This has offered thebenefit of precise, smooth, and rapid developed metallic layer.This paper presents a novel methodology to fabricate a Hollow Substrate Integrated Waveguide (HSIW) based on additive manufacturing poly-jet method, subtractive manufacturing water laser cutter and assembly with through hole mechanical plating method.

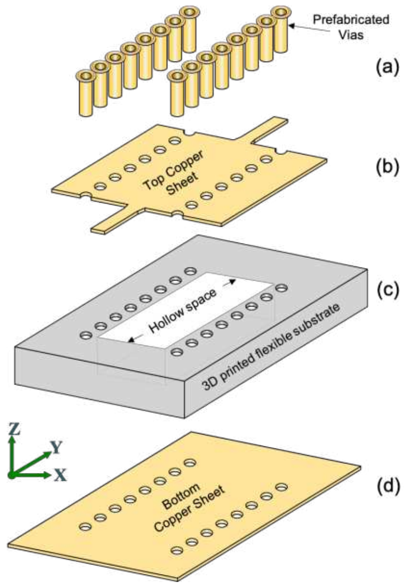


Fig. 1. Geometry of the proposed HSIW, (a) prefabricated copper rivets, (b) top copper sheet, (c) dielectric ABS substrate, (d) bottom copper sheet

II. HSIW DEVELOPMENT

A. Design and Analysis

Based on fundamental design considerations as given in paper [21], [22] and using a similar approach as the paper in [10], the author of this paper has developed a novel low cost Hollow SIW, as analyzed in this section. The geometry of the novel HSIW is shown in Fig.1. It consists of : (a) prefabricated copper rivets, (b) top copper sheet, (c) 3D printed ABS substrate and (d) bottom copper sheet. The top and bottom copper sheets with thickness 0.15mm, shown in Fig. 1 (b) and Fig. 1(d) respectively, are the top and bottom enclosures of the waveguide. The top copper sheet is transitioned to 50 Ohm microstrip line [23], [24], that can be connected to an RF coaxial connector. The ABS material in Fig. 1 (c) has a dielectric constant of 2.75, a loss tangent of 0.025 and a thickness of 0.5 mm.

The commercially prefabricated copper rivets in Fig. 1 (a) act as the vertical wall of the waveguide and are attaching all the layers together using a Through Hole Mechanical Press machine, all supplied by Fortex [25]. The spacing between adjacent vias (S_{via}), is kept at minimum, that is just equal to the head width of the copper rivet (H_{via}) accordingto the condition set by equation (1),

$$S_{via} \geq H_{via} \tag{1}$$

Therefore, with this condition, the electromagnetic wave is kept well confined into a cavity, eliminating energy leakages and losses. The HSIW structure is simulated in CST Studio Suite [26] and it is optimized to work in the operating frequency range of 21-31 GHz. The hollow waveguide is not purely empty space, but includes some dielectric loading from the substrate, therefore the proposed HSIW has an effective dielectric constant because of this loading. This is described in detail in [10], where the author has defined a loading ratio, that represents the amount of the dielectric filling in respectto the total width of the waveguide. The equation proved by the author in [10] is shown in (2):

$$q = \frac{2a_1\sqrt{\varepsilon_r}}{W_{HSIW}} \tag{2}$$

It is possible, to use the calculated loading ratio (q),to calculate the cutoff frequency(f_c) for the proposed HSIW, as shown by equation (3) [10]:

$$W_{HSIW} = \frac{c_0}{2f_c\left[0.999+4.946\times10^{-4}\times e^{(9.406q)}\right]} \tag{3}$$

The proposed HSIW has been designed with the least possible loading ratio, therefore the dielectric losses are kept at minimum level.

B. Fabrication and Assembly

The final fabricated HSIW parts are shown in Fig. 2. Three different lengths 46.8 mm, 52.0 mm and 91.0 mm, of HSIW are developed, in order to use the multiline calibration method to extract the propagation losses of the proposed structure. As it can be seen from figure Fig. 2, the copper sheets supplied by Goodfellow [27], were cut precisely by using water laser cut machine (Synova Laser-Microjet Cutter) [28]. The laser beam is transmitted through a water stream, providing total internal reflection and therefore, energy is transferred efficiently to the copper sheet during the cutting phase. The dielectric substrate is printed by using an ABS material with the Stratasys Objet 1000 3D printer [29]. This printer is based on polymer jetting (PJ) 3D printing method, that offers the best printing accuracy and resolution and it is also cost-effective, compared to other 3D printing methods that are used to develop RF and millimeter wave devices; these are the reasons, that it was chosen to fabricate the ABS substrate of this work. The ABS substrate is built layer upon layer with the 3D printing technique. As soon as all the three layers of the proposed HSIW are ready, the HSIW structure is assembled. Top copper sheet, ABS dielectric and bottom copper sheets are perfectly aligned, and the copper rivets are inserted through the vias holes. By using the Fortex mechanical through hole plating machine, the copper rivets are pressed until fully compressed, to attach all the layers together. It is important to avoid over pressing the machine since it will possibly damage the HSIW structure layers. The fabrication process as described here, could be further improved by automating process like layers alignment and vias rivets compressing. The final assembled parts are shown in Fig. 3(a), where all the three parts having their connectors attached on both ends.

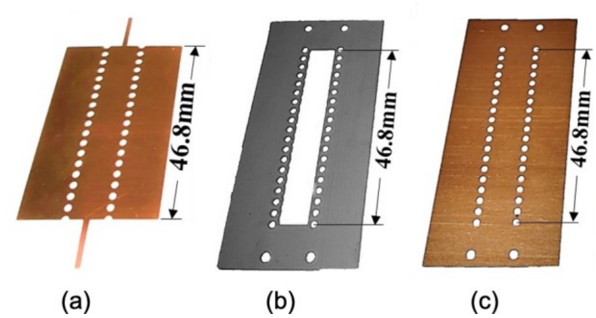
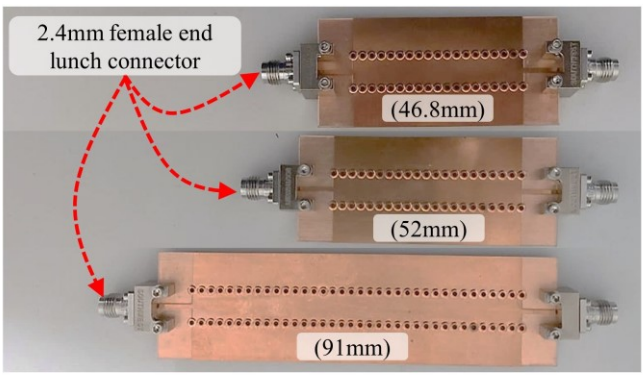
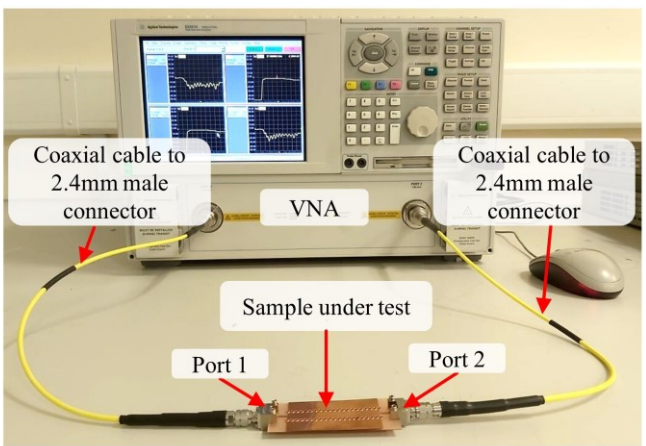


Fig. 2. Fabricated HSIW with a length of 46.8 mm, (a) top copper sheet, (b) dielectric ABS substrate, (c) bottom copper sheet



(a)



(b)

Fig. 3. Assembled HSIW (a) all HSIW lengths with attached 2.4mm connectors, (b) measurement with VNA.

C. Measurements

Relaunch-able 2.4 mm coaxial SOUTHWEST connectors are attached and mounted on both sides of the microstrip feed lines. The assembled HSIW relates to 2.4 mm wires on a E8361A PNA Microwave Network Analyzer as shown in Fig. 3(b). The PNA is calibrated bringing the *S*-parameters reference plane to the ends of the coaxial cables used. The measurement is done in the frequency range of 15 GHz - 40 GHz with 3,201 frequency points used. Fig. 4, shows the simulated and measured S-parameters of the proposed structure. The measured return loss is lower than -10 dB and the transmission loss is higher than -3.56 dB for the entire working frequency range. Utilizing the multi-line calibration technique is possible to extract the propagation constant for the HSIW frequency operating range. The multi-line calculation is done by using the shortest (46.8mm) and the longest (91mm) HSIW structures. The plot can be seen in Fig. 5 and it can be observed that the assembled HSIW gives an average attenuation constant of 1.56 Np/m, that is among the lowest values reported to date.

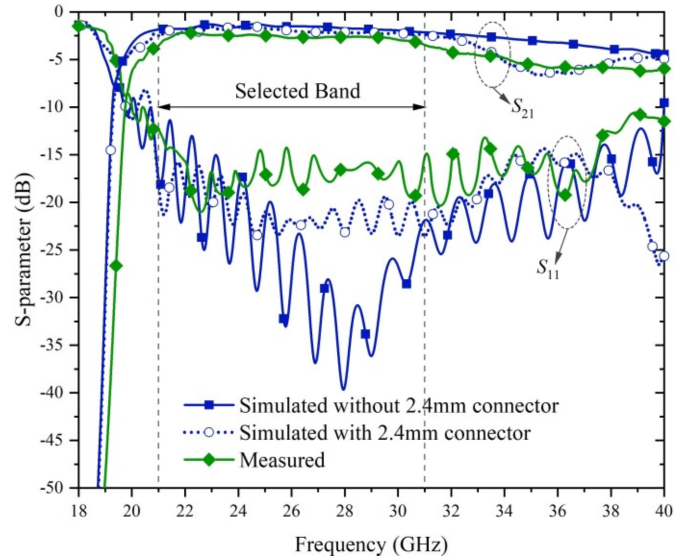


Fig. 4. Simulation and measurement of s-parameters from 18 GHz to 40 GHz

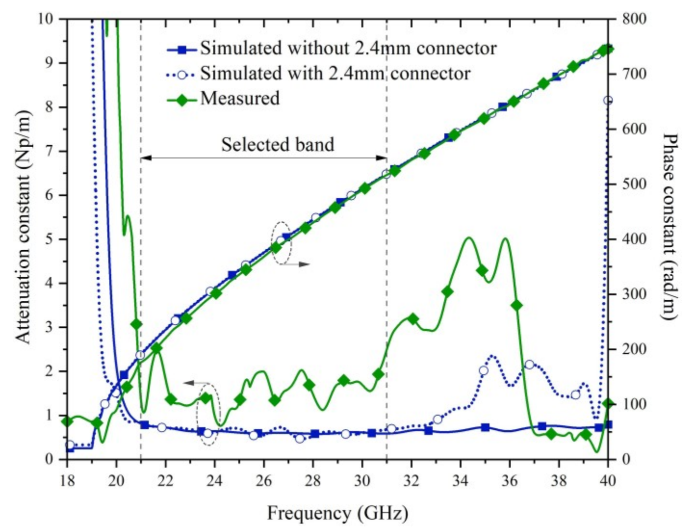


Fig. 5. Simulation and measurement of propagation constant from 18 GHz to 40 GHz

III. CONCLUSION

This paper presented a novel HSIW structure for millimeter wave devices based on new fabrication method, that uses 3D printing, laser cutting and prefabricated metallic copper rivets. The combination of 3D printing technology and using commercial prefabricated through-substrate vias eliminates the issues arising from traditional fabrication methods, like the complexity and the total expenses required, therefore opening opportunities to develop low-cost and low-complexity wirelessdevices for IoT and Robotic applications. The fabricated HSIW has a measured attenuation constant of 1.56 Np/m for the frequency of operation, having a fractional bandwidth of 38.46%. The device can be easily integrated with other planar circuits, for example on a PCB circuit board and it is thereforeproved in this paper, that it can operate in 5G frequency bands and it could be the basis to design other passive and active devices, like a filter, antenna or combiner. By comparing the HSIW with traditional SIW that use fabrication methods like LTCC or PCB, the HSIW of this work has a very low manufacturing cost but a slightly worse performance. Thiswork has proved the concept of a new HSIW, but more improvements could be done to optimize the design and the fabrication process.

ACKNOWLEDGMENT

This work was supported in part by the Thailand Science Research and Innovation Fund, and King Mongkut's University of Technology North Bangkok with contract no. KMUTNB-FF-65-42, and in part by the Engineering and Physical Science Research Council under Grant EP/S016813/1 and Grant EP/N010523/1.

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