Novel Inkjet-Printed Substrate Integrated Waveguide (SIW) Structures on Low-Cost Materials for Wearable Applications

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Abstract—**The implementation of Substrate Integrated Waveguide (SIW) structures in paper-based inkjet-printed technology is presented in this paper for the first time. SIW interconnects and components have been fabricated and tested on a multilayer paper substrate, which permits to implement low-cost and eco-friendly structures. A broadband and compact ridge substrate integrated slab waveguide covering the entire UWB frequency range is proposed and preliminarily verified. SIW structures appear particularly suitable for implementation on paper, due to the possibility to easily realize multilayered topologies and conformal geometries.**

Keywords—**Substrate integrates waveguide, paper-based inkjet-printed technology, eco-friendly materials.**

I. INTRODUCTION

The implementation of microwave components (in microstrip or coplanar technology) is typically based on the chemical etching of plastic or ceramic substrates, metalized on both faces. This fabrication process determines a significant environmental impact, both during the fabrication of the components, and at the end of its operational life. The major reasons for this impact are the use of acids and heavy metals (especially copper) during the fabrication phase, and the substrate material to be dumped at the end of the operational life of the components. For this reason, since a long time there is an open discussion about the possible techniques for reducing the environmental impact of electronic circuits fabrication [1]. Among the proposed solutions, the use of paper looks like an optimal candidate. In fact, paper is a widely available and extremely cheap material, and it is completely environmentally friendly, both during its production and at the time of its dumping.

The implementation of paper-based electronic components can be obtained by ink-jet printing [2-7], with no need of chemical etching and use of acids. The procedure is straightforward: the printer jets the single ink droplets from the nozzle to the desired position (usually silver is adopted, due to its high conductivity [7]). A metal thickness of 12 μm can be achieved with 12 ink layers [4]. The fabrication process ends with the sintering, which is needed in order to make the ink droplets continuous and to increase the conductivity [3]. This procedure can yield a resolution of about 20 μm [2], compatible with most of the microwave circuits.

The paper used for this application is commercially available and must have a hydrophobic coating. The thickness of a single paper layer is around 250 μm and multilayer configurations can be achieved by heat bonding [3]. The electromagnetic characteristics of paper have been measured in the frequency range 0.5-2.5 GHz, providing a relative dielectric permittivity of 3.2-3.3 and a loss tangent of 0.07 [3]. It is possible to realize metalized holes in the paper substrate [4]: the procedure requires making the holes by a micro-drill, filling them with silver epoxy, and finally sintering the conductor ink. Moreover, active elements can be integrated on the paper substrate, by means of conductor tape, with proper heating and pressure [4]. Antennas, RFID, and sensors have been implemented with this technique, in the frequency range up to 2.5 GHz [6,8].

In this paper, the implementation of substrate integrated waveguide (SIW) components on paper substrates is presented for the first time. SIW structures are similar to traditional rectangular waveguides, and are implemented in dielectric substrates by using two rows of metalized holes that connect the two ground planes of the substrate [9]. SIW technology represents an emerging approach for the development of microwave and millimeter wave components in planar form [10]. It allows integrating all components on the same substrate including passive structures, active components, and antennas, according to the system-on-substrate (SoS) approach [11]. SIW technology combines the advantages of classical microstrip circuits (low cost, easy fabrication, compact size, low weight) and metallic waveguides (low losses, complete shielding, high power handling capability).

Paper-based fabrication appears very suitable for the realization of SIW components, as it allows for arbitrary geometry, conformal shape, and multilayered configuration. The use of paper substrate increases the advantages of SIW components: flexible and environmental friendly dielectric substrates are investigated with interest for a variety of wireless systems and wearable applications. Moreover, the possibility of manufacturing multilayered configurations permits to reduce appreciably the size of components and to increase the flexibility in the design of SIW structures.

II. PAPER-BASED INK-JET PRINTED TECHNOLOGY

Ink-jet printing technology is utilized to fabricate SIW structures on paper substrate. The ink-jet printing has a couple of advantages compared to conventional fabrication methods. It does not produce any byproducts because it drops conductive ink on the desired position while conventional etching technique subtracts metals from on the substrate surface using strong acids. Therefore, the ink-jet printing is cost effective and environmentally friendly [6]. The paper substrate is also environmentally friendly and renewable organic material. In addition it is one of the cheapest materials in the world and easy to process.

A paper substrate for high frequency application such as SIW has lots of advantages. Mass production is feasible when it is combined with roll-to-roll ink-jet printing technology which is enabling to reduce fabrication cost. The properties of the paper substrate were studied and characterized using the microstrip ring resonators method in previous work [3]. The dielectric constant (ε_r) of a 0.23 mm thick paper substrate is 3.0 around 5 GHz, and the loss tangent (tan δ) is 0.06 throughout the frequency band of interest.

For the fabrication, the DMP2800 inkjet printer with the Dimatix 10pL cartridge (DMC-11610) was used. The cartridge height from the paper substrate was kept at a distance of 500 µm. The nozzle of the cartridge was adjusted to achieve a print resolution of 1270 dpi. Cabot conductive ink CCI-300 [12] was jetted at a temperature of 36 °C, while the paper substrate was maintained at 50 °C. The printed pattern was sintered in a thermal oven for 8 hours at 120°C. After sintering, the pattern has consistent DC conductivity in the range 9×10^6 S/m ~ 1.5×10^7 S/m with roughness of 1µm [13]. The via holes were perforated by laser cutter and were filled by thin wires and sealed by conductive epoxy in order to prevent possible leakage of the wave.

III. PRELIMINARY IMPLEMENTATION OF PAPER-BASED SIW COMPONENTS

A variety of SIW interconnects and components have been designed and fabricated, to verify the applicability of ink-jet printing technology to this type of circuit topology.

A. SIW interconnects

As a first step, straight SIW interconnects on paper have been implemented. The SIW lines have been designed for operation frequency of 5 GHz, and for this reason the cutoff frequency of the fundamental mode was set to f_0=3.65 GHz. This performance is achieved by selecting the geometrical parameters of the SIW structure (Fig. 1): the width of the SIW is w=24 mm, the diameter of metal vias is d=0.8 mm and their longitudinal spacing is s=1.6 mm.

The substrate thickness is 0.69 mm, which is obtained by stacking 3 layers of paper (each of them with a thickness of 0.23 mm). As conductor loss can be minimized by increasing the substrate thickness [10], this thickness has been chosen to reduce the loss due to the relative low ink conductivity.

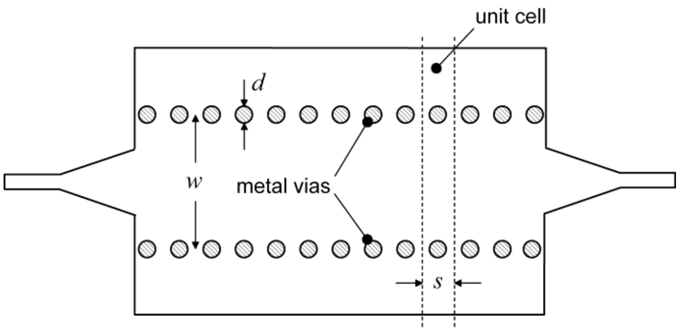


Figure 1. Geometry of SIW interconnect on paper.

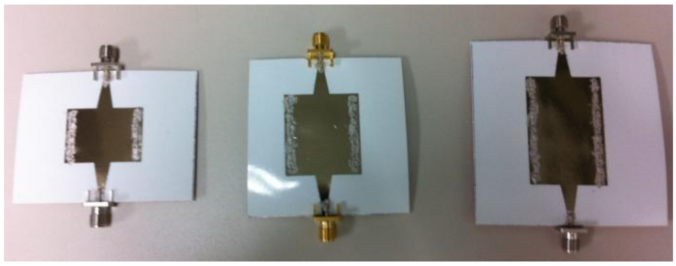


Figure 2. Photograph of the SIW interconnects with different length.

The design of SIW structures has been performed by using the full-wave electromagnetic simulator Ansys HFSS. The design of the SIW interconnects includes the transitions from 50-Ω microstrip line to SIW to allow the experimental characterization. The structures have been designed, considering the relative dielectric permittivity ε_r=3, the loss tangent tanδ=0.06, and the ink conductivity σ=1.5×10^7 S/m.

Three transmission lines with different length (13, 20, and 27 unit cells, respectively) have been fabricated, with the aim to determine the dispersion curve of the SIW interconnect and to extract the electrical parameters of paper substrate. The photographs of the prototypes are shown in Fig. 2.

The scattering parameters of the three SIW structures have been experimentally determined. The comparison between simulations and measurements is reported in Fig. 3, in the case of the shortest interconnect. Moreover, the dispersion curve of the SIW fundamental mode has been derived by comparing the measured scattering parameters of two SIW interconnects with different length, according to the method described in [14]. The simulated and measured propagation constant versus frequency is shown in Fig. 4. The small discrepancies between theory and measured data are attributed to repeatability issues in the fabrication of the different SIW interconnects.

The dispersion curve also permits to derive the permittivity of the dielectric substrate, which results close to the nominal value of ε_r=3 over the entire frequency band of interest. In addition, the attenuation was estimated: the insertion loss of the SIW is 0.85 dB/cm at 5 GHz, while each microstrip-to-SIW transition and connector introduces an additional attenuation of approximately 0.2 dB.

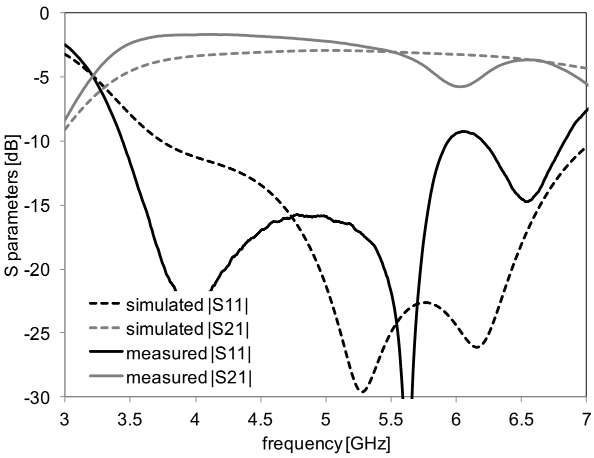


Figure 3. Simulated and measured scattering parameters of the SIW transmission line on paper.

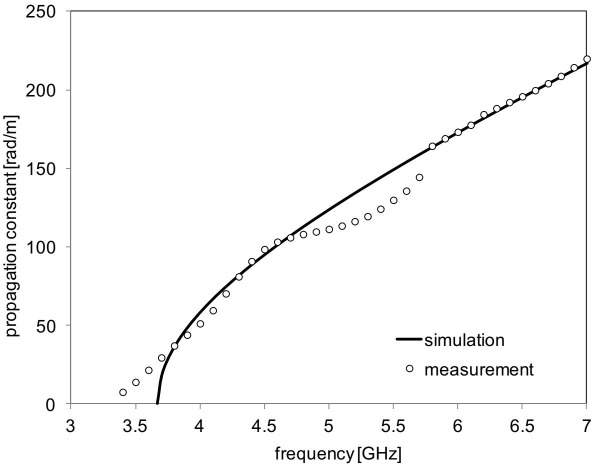


Figure 4. Simulated and measured propagation constant of the SIW transmission line on paper

B. *SIW cavity filter*

An SIW two-pole filter has been designed, fabricated and measured, to investigate the feasibility of SIW components on paper substrate. The filter includes two cavities, connected by an iris coupling aperture, and the dimensions are optimized for band-pass operation around 5 GHz.

The layout of proposed filter is illustrated in Fig. 5, whereas a photograph of the prototype is shown in Fig. 6. The simulated and measured frequency response of the component is reported in Fig. 7, with a measured insertion loss of approximately 5 dB at 5 GHz.

These results demonstrate how the performance of the filter is affected by the significant losses of the material. For this reason, the most suitable filter topology needs to be carefully selected, possibly based on pre-distorted filter configurations [15].

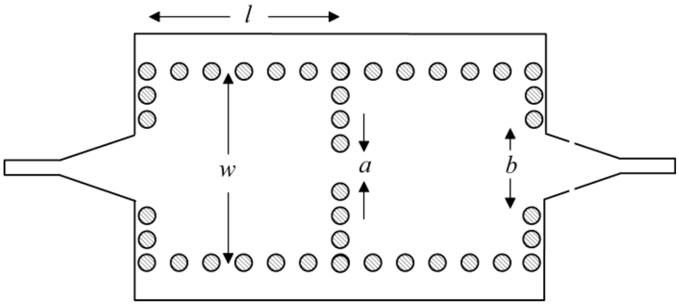


Figure 5. Geometry of the SIW filter on paper (w=24 mm, a=14.27 mm, b=15.89 mm, l=19.17 mm).

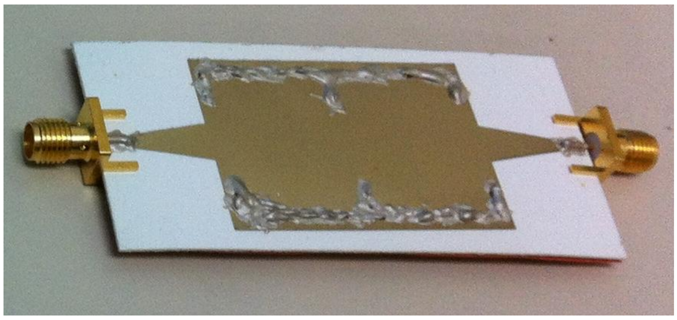


Figure 6. Photograph of the SIW filter on paper.

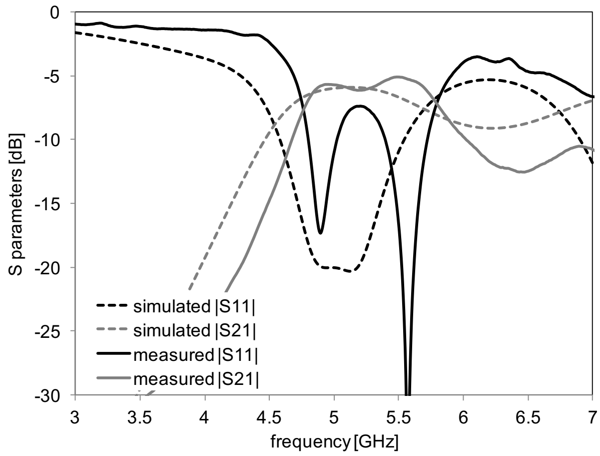


Figure 7. Simulated and measured scattering parameters of the SIW filter on paper.

C. *Ridge Substrate Integrated Slab Waveguide*

A ridge substrate integrated slab waveguide (SISW) was designed and fabricated on multilayered paper (Fig. 8). This compact and broadband SIW structure, originally introduced in [16], allows for covering a mono-modal bandwidth much broader than classical waveguides and SIW structures, due to the presence of the ridges (which allow lowering the cutoff frequency of the fundamental mode) and the air holes (which increase the cutoff frequency of the second mode). The ridge SISW was designed for covering the entire ultra-wide band

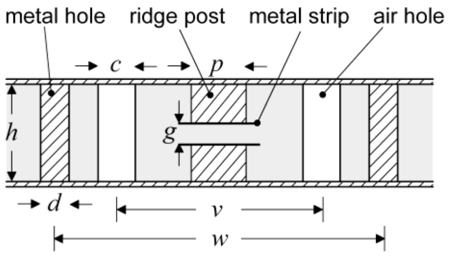
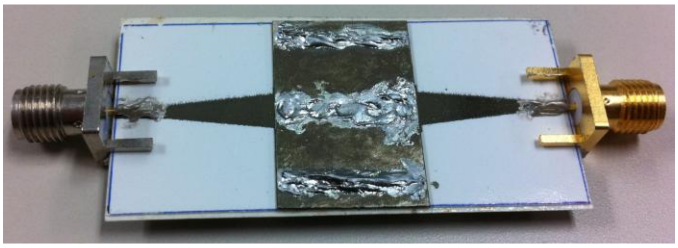
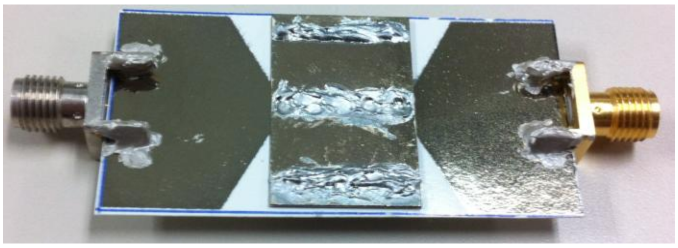


Figure 8. Geometry of the ridge substrate integrated slab waveguide (w=18.4 mm, v=9.7 mm, d=0.8 mm, c=p=2.4 mm, h=1.15 mm, g=0.23 mm).



(*a*)



(*b*)

Figure 9. Photograph of the ridge substrate integrated slab waveguide: (*a*) top view; (*b*) bottom view.

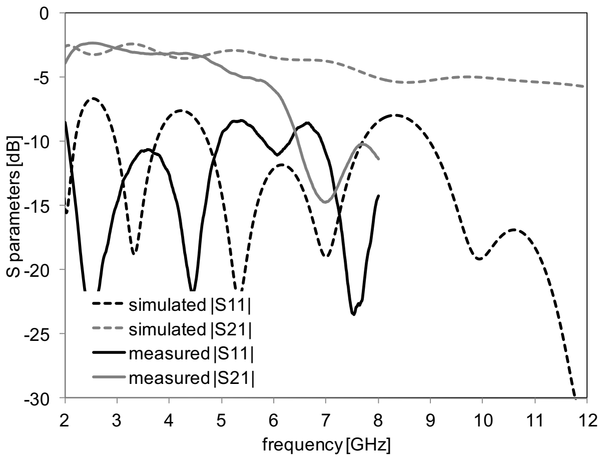


Figure 10. Simulated and measured scattering parameters of the ridge substrate integrated slab waveguide.

(UWB), with frequency ranging from 3.1 GHz to 10.6 GHz. For this reason, the cutoff frequency of the fundamental mode is 2.5 GHz and the cutoff frequency of the second mode is 12.4 GHz. A preliminary prototype of ridge SISW on paper, based on a five-layer configuration, is shown in Fig. 9.

The simulated and measured scattering parameters are shown in Fig. 10. The significant discrepancy above 5 GHz is attributed to technological problems in the implementation of the multilayered topology.

IV. Conclusion

SIW interconnects and components have been implemented by ink-jet printing on paper substrate for the first time. Straight interconnects, a filter, and a broadband ridge substrate integrated slab waveguide have been fabricated and tested, demonstrating the applicability of paper-based technology to SIW structures.

While the achievable performance of paper-based SIW components is still inferior to components based on commonly used dielectric material, the implementation of SIW structures on paper substrate represents a significant step: it is the groundwork for future wireless systems and wearable devices, as it combines the advantages of low cost, flexible and environmental friendly material with the integration potential of SIW technology.

V. References

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