Inkjet-Printed Substrate Integrated Waveguides (SIW) with "Drill-less" Vias on Paper Substrates

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***Abstract*—In this paper, an inkjet-printed substrate integrated waveguide (SIW) on commercially available cellulose paper is implemented for the first time. Unlike traditional inkjet-printed SIW's, it does not require any etching process to form the conductive side walls and utilizes the porosity of the paper to get through-substrate conduction. The frequency response of the waveguide along with its performance under bending is discussed in this paper, verifying that such a structure would be particularly suitable for Quality of Life and Internet of Things applications**

***Keywords*—Substrate integrated waveguide, inkjet-printing on paper, Internet of things, multi-layer structures, additive manufacturing, viaholes**

I. Introduction

Inkjet-printing technology has attracted a lot of attention during the last decade for fabricating microwave and radio frequency (RF) components because it is low cost, environmentally friendly, repeatable and scaling to industrial scale is much easier than traditional wafer-to-wafer production [1]. It allows the direct printing of a wide variety of materials ranging from conductors, dielectrics, polymers to active materials like carbon nanotubes onto different substrates, such as paper, plastic, glass and silicon wafers [2], [3], [4], [5], [6], [7], [8]. This makes inkjet-printing technology ideal for rapid prototype fabrication of a broad range of electronics, microwave and RF structures for numerous applications, such as Quality of Life and Internet of Things (IoT) applications.

Nevertheless, one of the key challenges for the realization of higher-complexity integrated sensors and communication systems for IoT applications is the reliable implementation of low-cost flexible multilayer electronics. The overall cost of the system can be significantly reduced by using inkjet-printing on organic substrates such as paper - which one of the cheapest and most environmentally friendly substrates available. However, the typical conductive traces and interconnects are relatively inflexible and thus limit system's performance under bending or folding.

A number of solutions have been reported in the last years to address the aforementioned problems [3], [9], [10] using inkjet-printing technology on hydrophobic substrates like photo-paper [11] and [12]. Even though these substrates require fewer layers of silver nano-particle (SNP) ink to achieve the desired conductivity values and can feature a better line resolution, the realization of viaholes requires drilling holes in the substrate and then filling them with conductive epoxy [11] or directly printing via sidewalls by using SNP ink [12] for an electrical contact with other substrates in multilayer structures. While it is easier to fill conductive epoxy than printing the via as the ink has a bad step coverage and requires laser etching to form a two-sided stepped conical via [3], conductive epoxy is not flexible and commonly cracks during bending or folding thus limiting flexibility.

In this paper, a novel inkjet-printed substrate integrated waveguide (SIW) on commercial cellulose paper substrates is presented for the first time, which does not require physically etched vias and still maintains a very good electrical conductivity and RF performance. Since the cellulose paper is porous, it absorbs much of the ink and both sides of the paper can be potentially electrically shorted by printing an optimal number of SNP ink layers on both sides. This also allows the formation of much more flexible conductive traces as the cellulose paper does not have any coating on its surface, which typically solidifies during heating process. However, the high dielectric loss tangent ($\sim$ 0.07) [2] limits its applicability in high-frequency applications. Moreover, the hydrophilic nature of the paper does not allow very high resolution conductive traces but it can be neglected for low-frequency applications. The problem of higher substrate and conductor losses can be typically resolved by introducing an intermediate layer of perforated paper substrate, which effectively reduces dielectric and conductor losses [13], as proposed in this paper.

II. Inkjet printing on cellulose paper

The most important characteristics of paper for inkjet-printing purposes include its dielectric constant, loss tangent, porosity, surface roughness etc. Previously, photo-paper has been one of the most commonly used substrates for inkjet-printed microwave and RF structures [11], [12]. However, the lamination on the photo-paper surface solidifies during sintering process, which is a key step used in printing SNP ink traces. Therefore, the printed conductive lines commonly crack upon bending [14]. The cracking can be reduced by either folding the paper before the sintering process or by making micro-laser perforations at the bends, but these approaches do not resolve it completely.

In contrast, the commercially available cellulose paper with thickness of 110μm has fibers of width and length around 10-30um and 1-2mm [14], respectively. The SNP ink - which mainly consists of an ethanol based solvent carrying the silver nano particles (30-40nm in diameter) easily pass through these fibers via capillary effect. The cross-section of inkjet-printed conductive lines along with their surface roughness

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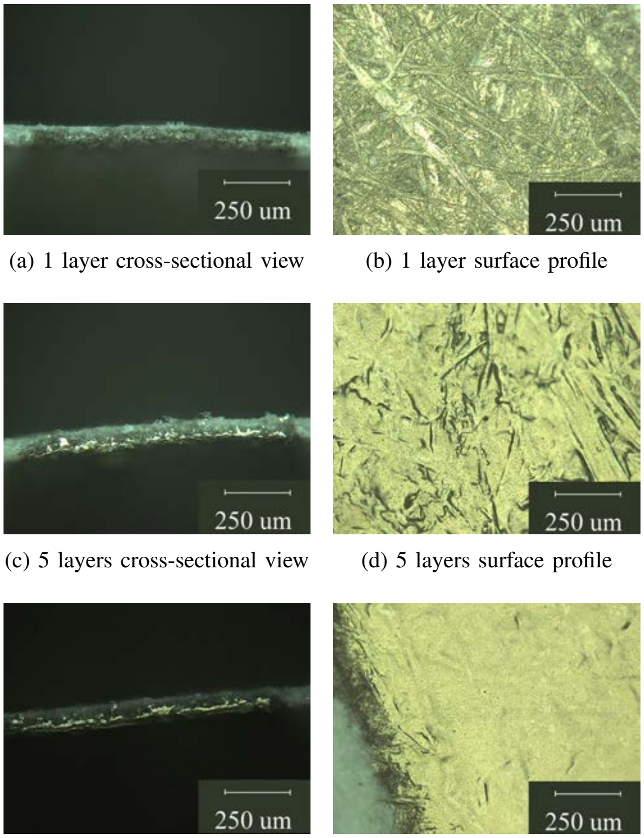

(a) 1 layer cross-sectional view (b) 1 layer surface profile

(c) 5 layers cross-sectional view (d) 5 layers surface profile

(e) 10 layers cross-sectional view (f) 10 layers surface profile

Fig. 1: Cross-sectional view and surface profile of 1 mm wide inkjet-printed lines with SNP ink on cellulose paper for different number of layers

for different numbers of layers after curing at 150^0C for about 2.5 hours is shown in Fig.1. The nano particles congregate during the curing process and form a continuous conductive trace within the paper. This is fundamentally very different from printing on hydrophobic substrates, where most of the ink remains on their surface leading to potential cracks when bent [14].

In case of the cellulose paper, the fibers containing the conductive SNP act as randomly oriented conductive wires (given that enough layers have been printed), thus enhancing the flexibility of the overall conductive traces. Therefore, some part of the trace is always connected to other fibers even though few may break along potential sharp bends. Preliminary experiments have demonstrated that at least ten layers are required to get a resistivity of at least 0.0175 Ω per square. Table 1 shows how the resistance per square of an inkjet-printed line with SNP ink on cellulose paper changes with the number of layers. Since the fiber size and orientation is random throughout the paper bulk, it features larger voids throughout its cross-section. Therefore, the resistance for fewer number of layers is quite high since there are not enough SNP available to fill up these voids. Moreover, the particles are more scattered along the cross-section and thus not all of them bind together during the curing process. However, by increasing the number of layers, the surface becomes much smoother and more SNP join together to form solid conductive traces. Thereby, the enhanced conductivity for larger number of layers is verified in Fig. 1 and Table 1.

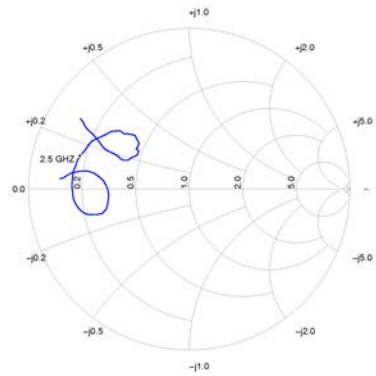

Fig. 2: Via impedance using TRL de-embedding technique from 0.1-4GHz range

The fact that the ink is absorbed into the paper can be exploited to realize through-substrate electrical contacts without physically etching the substrate. It was found that the two sides the 110 μm thick cellulose paper can be electrically shorted when both sides are printed with eight or more layers with a droplet size of 10pL. Furthermore, alignment is relatively easy in the case of a cellulose paper since the contour of conductive traces is visible from the non-printed side. To characterize the through-substrate printing behavior, a single square "drill-less" via of $1mm \times 1mm$ size, fabricated by printing 10 SNP layers on both paper sides, was characterized by using the de-embedding Through-Reflect-Line (TRL) method with impedance values for 0.1-4GHz range is shown in Fig. 2.

TABLE I: Sheet resistivity for different SNP layers on cellulose paper

Number of layers	reistance (Ω / square)
2	1.3
3	0.225
4	0.105
5	0.0625
6	0.05
7	0.0375
8	0.03
9	0.025
10	0.0175

III. Inkjet-Printed SIW on Cellulose paper

A conventional substrate integrated waveguide (SIW) requires etching an array of regularly spaced vias at the edge of SIW and a microstrip-to-SIW transition for coaxial excitation. The main purpose of the via array is to electrically short the SIW side walls with the ground sheet and thus minimize radiation leakage [15]. In order to do so, via diameter must be typically five times less than the wavelength of the cutoff frequency and pitch should be smaller than two times the via diameter (ideally close to zero i.e. approximating the

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performance of an ideal/solid sidewall)[15]. Nevertheless, the solid sidewalls can be easily fabricated on a porous cellulose paper by just inkjet-printing ten layers of SNP ink over a continuous line on both sides of the paper (something that is impossible in hydrophobic substrates).

A multi-layer inkjet-printed substrate integrated waveguide (SIW) prototype using a (110μm thick) cellulose paper, for a cutoff frequency of 4 GHz is shown in Fig. 3. The structure was designed and simulated using a full-wave electromagnetic solver, Ansoft HFSS. The sidewall width was chosen to be 1mm wide to minimize fabrication error [15]. The length of the SIW (and sidewall) was 20mm while the width was 21mm.

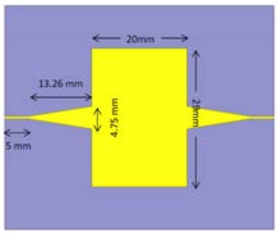
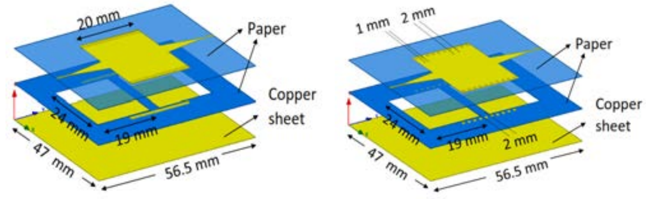


Fig. 3: Top view of inkjet-printed SIW

The SIW was fabricated by first printing the pattern shown in Fig.3 on one side of the paper using ten (10) layers of SNP ink to obtain better conductivity values. The printed structure was then cured in the hot oven for 2.5 hours at 150^{o}C. Afterwards, two rectangular sidewalls (with width=1mm, length=20mm and 21mm spaced apart) were printed on the back side of the printed SIW structure with ten layers of SNP ink to effectively realize “drill-less” fully printed solid sidewalls as shown in Fig. 4a. The substrate was put into the hot oven with the same sintering conditions after printing. Next, to realize a proof-of-concept SIW prototype, an intermediate layer of perforated cellulose paper was inserted between the top printed layer and the bottom conductor implemented for simplicity with a (100μm thick) copper sheet, although it could be easily implemented through inkjet-printing as well. While the perforations reduce the high dielectric losses, the conductor losses are also reduced by increasing the overall thickness of the waveguide [15]. The perforations are made large enough to remove most of the part underneath the SIW to minimize dielectric losses and maximize the bandwidth. However, this does not produce any discontinuities in the SIW dominant mode as the waveguide would only see a microstrip feed exciting it. However, the impedance of the microstrip feed would change due to increased substrate height with an impedance the change of which due to the different substrate thickness can be easily accounted in the design process. The void between the top layer and ground plane helps in reducing the effective dielectric losses between them, therefore, a beam-like structure is added to make sure that they do not touch each other. Since the width of the beam-like-structure is very small compared to the wavelength, its losses can be ignored. Two ”sidewall” rectangular-shaped traces (with width=1mm, length=20mm and 21mm spaced apart), were also inkjet-printed on both sides of the intermediate paper layer using ten layers of SNP ink as shown in Fig. 4a. Hence the intermediate paper would be electrically shorted along the length of each trace. Finally, the whole structure is combined by first carefully



(a) (b)

Fig. 4: Exploded view of inkjet-printed SIW with (a) via-array (b) rectangular solid sidewall

aligning the printed sidewalls on the top and the intermediate layer and then bonding them together with spray glue. The bottom conductor is then attached to the resulting structure after ensuring the solid sidewalls on the top and intermediate layers are electrically shorted using an ohmmeter. The resultant structure is shown in Fig. 5. For comparison purposes, a similar inkjet-printed SIW with fully inkjet printed “drill-less” viaholes was also fabricated using same fabrication process with dimensions shown in Fig. 4b.

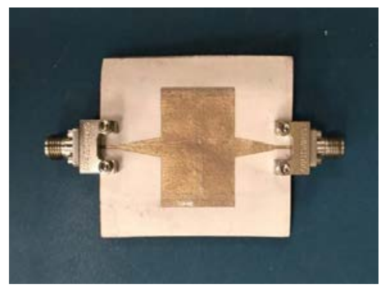


Fig. 5: Prototype of inkjet printed SIW with inkjet-printed solid side walls on cellulose paper

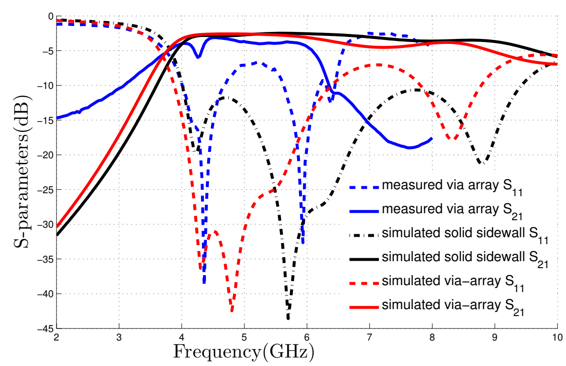


Fig. 6: S-parameters of inkjet-printed “drill-less” via-array sidewall SIW prototype vs simulated values for via-array and solid-sidewall SIW

The measured and the simulated S-parameter values for the inkjet-printed SIW with “drill-less” viahole-array sidewall show a very good agreement as shown in Fig. 6 with the measured bandwidth slightly reduced due to the fact that the printed via resistance increases in higher frequencies. The simulated S-parameter values for the solid sidewall SIW also shown in Fig. 6 for comparison. The measured results of the inkjet-printed side-wall SIW in Fig. 7 show that the structure is relatively flexible and does not feature large variations for moderate bending radii.

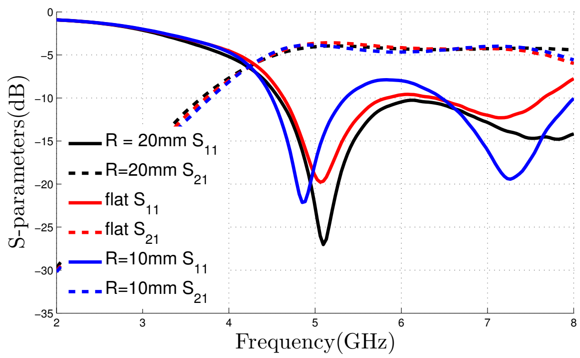


Fig. 7: Variation in measured S-parameters of the inkjet-printed SIW prototype with solid-sidewalls for different radii of curvature

IV. Conclusion

An inkjet-printed multi-layer substrate integrated waveguide along with the capability of inkjet-printed "drill-less" via-hole on commercially available cellulose paper is presented for the first time. The design does not require any etching process to realize the side walls and features a high flexibility. The high dielectric and conductive losses are reduced by inserting an intermediate perforated paper layer between the top and bottom conductor allowing for a very good RF performance for frequencies at least up to 6 GHz.

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