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Development of Substrate Integrated Waveguides with Textile Materials by Manual Manufacturing Techniques

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Abstract: Substrate integrated waveguide (SIW) technology enables the fabrication of millimeter and microwave components and subsystems with the advantages of conventional metal waveguides, but being lighter and easier to integrate along with planar components and circuits. Some attempts have been made to integrate the SIW technology in flexible materials, allowing further integration of the SIW components into garments. There, the metallized cavities have been made with rigid brass eyelets. This reports on the implementation of SIW in flexible substrates by means of conductive yarns, fabrics and knitted strings. Manual manufacturing techniques are applied to produce SIW that fully preserve the flexibility of the substrate. The developed prototypes, being transmission lines and antennas, were validated by S_{11} and S_{21} measurements. The obtained results prove that the use of conductive threads through embroidering enables the implementation of more flexible SIW components with efficiencies equal to those fabricated with rigid eyelets. Embroidering is thus a promising technique for manufacturing wearable SIW components.

Keywords: Substrate Integrated Waveguides; SIW; Textiles; Embroidering; Textile Antennas.

1. Introduction

Currently, the development of smart textiles for intelligent clothing is increasingly attracting interest in different application domains, such as healthcare, protection, military [1–3] and even conceptual ideas for fashion [4]. When developing smart textile systems for wearable applications it is necessary to construct structures that are conformable to the body shape, and comfortably and unobtrusively integrated [1]. In this context of wearables, the substrate integrated waveguide (SIW) technology is suitable for implementation into clothing and wearable textile systems, as this topology improves the isolation of the electromagnetic fields from its environment, being mainly from the human body [1–3,5]. Moreover, SIW components are easy to fabricate in conformal structures that preserve the flexibility of the substrate [1–3,5].

In general, the SIW technology implements two metallized rows of conducting cylinders or slots embedded into the dielectric. These vias connect two metal parallel plates [6–8]. Currently, the SIW technology has been implemented in flexible materials, using foam as a dielectric substrate and conductive fabrics laminated to this substrate to create the parallel plates [1–3,5]. In these works, the cavities were constructed using metallic eyelets with a diameter of 4 mm.

SIW is thus a cost-effective solution for millimeter and microwave components, enabling the fabrication of passive components, active circuits and antennas for wireless systems embedded into flexible materials, including textiles. Therefore, this technology serves as a platform for wearable applications, enabling the integration of different components in the same substrate, paving the way to a system-on-textile, similar to the concept of system-on-substrate [6–8].

2. Experimental Study

We have experimentally studied the fabrication of new SIWs that fully preserve the flexibility of the substrate. These new SIWs serve as an alternative to SIWs made of brass eyelets [1–3,5,6]. Therefore, textile materials such as conductive yarns, fabrics and knitted strings were applied through embroidering, sewing and gluing techniques to produce SIW components in a flexible substrate.

These structures exhibit higher conformability to the body shape than those based on rigid eyelets. This enhances the wearability of the SIW components, improving their performance when deployed on-body and in case of compression and deformability.

The work was performed in two main phases: First, to simplify the tests, Microstrip Transmission Lines (MTLs) were developed and tested with one shorting via in their centre, realized in different materials and using techniques. Second, the antenna presented in [2] was implemented in different textile SIW technologies, relying on the materials and techniques that yielded the best results in the first phase.

2.1. Materials

In all developed MTL prototypes, a protective closed-cell expanded-rubber foam¹ was applied as dielectric substrate. In the textile antennas the substrate was a spacer fabric². The conductive layers

¹ <http://www.javaux.com>

² <http://www.eschler.com/english/home/home.html>

were made of pure copper polyester conductive fabric³ were used in both the transmission lines and the antennas, which was glued to the substrate with a thermal adhesive interlining sheet. Table 1 presents the conductive textile materials that were used to fabricate the shorting vias. The presented characteristics were provided by their suppliers^{4, 5, 6}.

Table 1. Conductive textile materials used to fabricate the shorting vias in the prototypes.

Conductive Materials	Characteristics	Electrical Resistance	Application in Prototypes:
YARN 1	Highly conductive silver plated nylon, 275 dtex (Ref.: PW018A) ⁴	<300 Ω /m	Sample 2 and 5: Embroidered circle with and without cavity. All three prototypes of antennas.
YARN 2	Conductive silver plated nylon, 293 dtex (Ref.PW018) ⁴	<2 k Ω /m,	Sample 3: Embroidered circle with a cavity.
YARN 3	Stainless steel conductive yarn (Ref.ADA-641) ⁵	10 Ω /m,	Sample 7: Embroidered circle with a cavity.
KNITTED STRING	Tubular jersey ⁶ with 11 columns, made of Yarn 1 together with polyester yarn	—————	Sample 6: Introduced in the circular cavity and sewn to the conductive elements.
FABRIC	Highly conductive fabric tape, 0,5 mm thick, made with Nickel, Copper and Cobalt coated nylon ripstop fabric with adhesive ³	<0.1 Ω /sq	Sample 4: Glued inside the circular cavity and over the conductive elements.

2.2. Tested Prototypes

2.2.1. Microstrip Transmission Lines (MTL)

Table 2 presents an overview of the several prototypes of MTL with a shorting via, which were fabricated with the materials presented in Table 1. Sample 1 was considered as a reference, as it is based on the already validated technique to produce the SIWs with metallic eyelets [1–3,5]. For testing the MTLs, two connectors were soldered at both extremities of the transmission line.

2.2.2. Antenna Implemented in the New SIW Technology

Based in the experience obtained in developing the MTLs, we relied on Yarn 1 and embroidering as adopted material and technology, respectively, to produce the antennas in SIW technology. As antenna topology, we opted for the half-diamond antenna operating in the 2.45 GHz Industrial, Scientific and Medical band, following the design presented in [2]. A bottom and top view of this antenna is shown in Figure 1. Yarn 1 was easier and faster to manipulate by hand than the other tested yarns. This is particularly important in this antenna design, which requires multiple SIW cavities. Therefore, three antenna prototypes were fabricated with different types of embroidered SIWs, being circular vias with

³ <http://www.lessemf.com/>

⁴ <http://www.pluginwear.com/default.asp?mod=home>

⁵ <http://www.inmotion.pt/store/e-textiles>

⁶ <http://www.logik.pt/site/index.php/pt/loja>

cavity, circular vias without cavity and square vias without cavity. All cavities have size 4 mm, either as diameter or side. This is similar to the diameter of the metallic eyelets of the antenna presented in [2], which was considered as a reference.

Table 2. Prototypes of Microstrip Transmission Lines and detail of the shorting via.

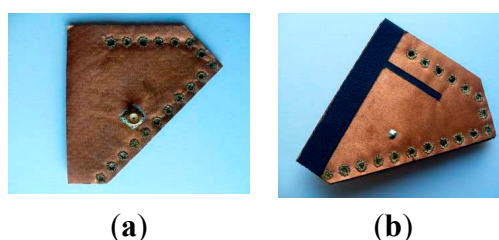
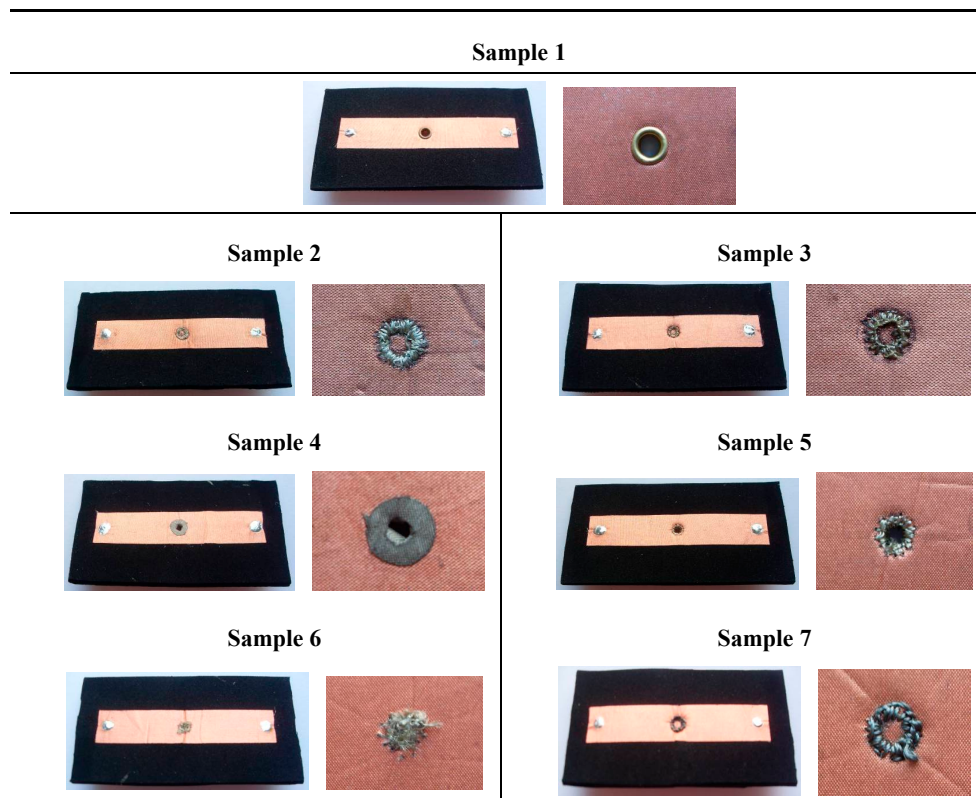


Figure 1. Half Diamond textile antenna with embroidered SIWs (circular with cavity), bottom (a), top (b) view.

3. Results and Discussion

3.1. Microstrip Transmission Lines (MTL) with Shorting Via

Among all tested MTLs, Sample 2 (made with Yarn 1 through embroidering) showed the best performance, yielding a result comparable to that of reference sample 1, as shown in Figure 2. Despite that Samples 3 and 6 also exhibit good performance in terms of S_{11} and S_{21} parameters, the Yarn 3 applied in Sample 3 has a lower conductivity and the conductive string used in Sample 6 is difficult to manipulate by hand. Therefore, these samples were discarded.

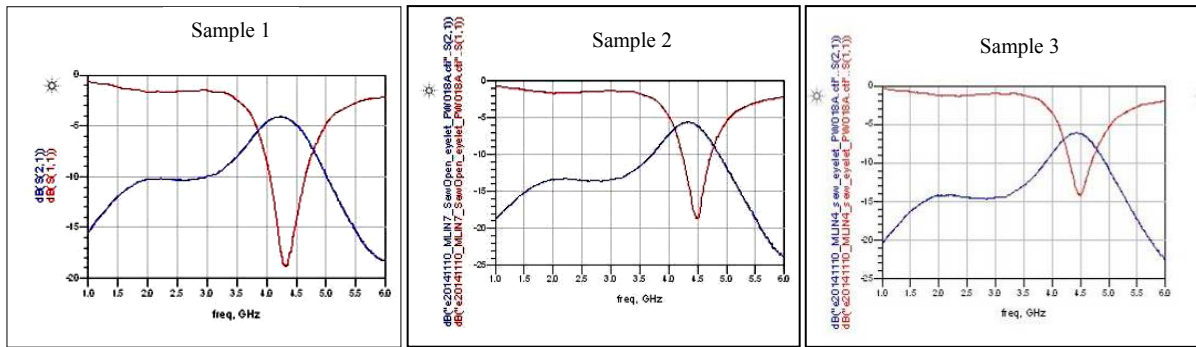


Figure 2. S_{11} (red line) and S_{21} (blue line) parameters measured for the MTL samples 1, 2 and 3.

3.2. Half-Diamond Textile Antennas with Embroidered SIW

Figure 3 shows the S_{11} parameter, in the frequency range of 1 GHz up to 4 GHz, for the half-diamond textile antennas implemented in SIW technology through embroidering. The resonance peak of the antenna around 2.40 GHz is clearly visible for all samples. These results are very close to the simulation presented in [2] for the antenna with an SIW cavity made of brass eyelets. Clearly, the SIW antenna fabricated using circular vias with cavities (type 1) yields the best matching. The SIW antenna with vias of type 2 (without cavities), only reaches -10 dB, and the SIW antenna with vias of type 3 (square shape, no cavities), only reaches -15 dB. Yet, these results are also promising, as such types of vias do not require that the substrate is perforated, and hence, they may be easily produced by an industrial embroidering machine.

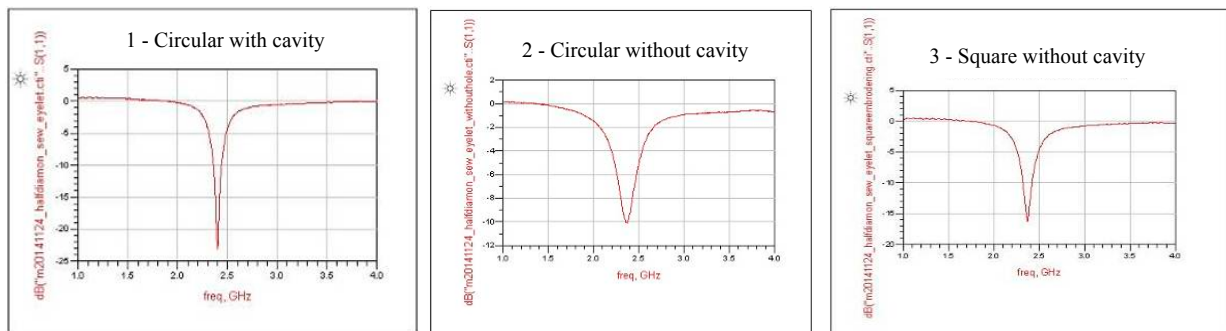


Figure 3. S_{11} parameters for the textile antennas with embroidered SIWs of types 1, 2 and 3.

4. Conclusions

We have shown that MTLs and antennas with embroidered cavities yield similar results to MTLs and antennas with SIW cavities implemented using metallic eyelets. The embroidering technique is thus a promising technique to fabricate SIW components. It can be used to improve flexibility and reduce weight of several components, mainly when their design requires a large quantity of SIWs. Moreover, it can be used to produce SIW without perforating the substrate. Therefore, embroidered SIWs may enhance the development of systems-on-textile for wearable applications. Finally, there exist industrial embroidering technologies that may bring progress in the mass production of such wearable systems.

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Author Contributions

CL, CLO, SA and HR designed the experimental plan. CL and CLO performed the experimental work. CL and CLO assembled the data. CL, CLO and RS wrote the manuscript. RS, PP, SA and HR revised the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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