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Improved Fabrication Methodology for Foldable All-Textile Cavity-Backed Slot Antennas

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Abstract

In this work, a new fabrication methodology for the production of textile cavity-backed substrate integrated waveguide slot antennas is proposed. This methodology involves laser cutting the entire electrotextile part in one single patch, which is then folded around a dielectric textile substrate. Since this procedure realizes the vertical cavity walls by slabs protruding from the electrotextile patch, heavy metal eyelet vias can be omitted, leading to a drastic reduction in antenna weight and improving wearability. Furthermore, this method is more suitable for automated mass production compared to existing design procedures: it requires fewer manipulations, diminishes alignment errors and suffers less from textile cutting inconveniences such as inaccuracies and textile fraying. This leads to a higher yield, and thus lower production costs. As a proof of concept, a broadband multi-moded cavity backed slot antenna is realized in this novel fabrication methodology. Measurements show a broadside gain of 6.5 dBi, a radiation efficiency of 70% and a fractional impedance bandwidth of 16%.

1 Introduction

The emergence of the Internet of Things and Wireless Body Area Networks has caused a great increase in applications that would benefit significantly from the use of Smart Fabrics and Interactive Textiles (SFIT). Examples of application scenarios include military or first aid responders communication and localization devices [1, 2], built-in personal locator beacons [3, 4], infant monitoring equipment, applications in healthcare, medical monitoring [5, 6], etc. Yet, full access to the consumer market can only be achieved when these devices are comfortable to wear and are manufacturable in an easy, cheap and reliable way.

Several wireless textile nodes have been proposed addressing the issues arising with the textilization of these components. In [7], metal, long sail eyelets and a conductive coated fabric were used to create the first full-textile Substrate Integrated Waveguide (SIW) antenna. In [8], the size of the antenna has been drastically reduced through miniaturization techniques. Furthermore, this antenna exhibits two modes and operates in the 5.8 GHz ISM band, thereby demonstrating the suitability of textile antenna operation at higher frequencies. Moreover, techniques such as embroidery of conducting wires have been investigated [9, 10]. Concerns about the compression of the substrate have been addressed by using metal eyelets in [11]. Here, two resonant modes are excited to achieve a larger bandwidth. Still, both textile manufacturing and electronic components industries remain reluctant about a large scale industrial deployment of these systems, as textile antenna manufacturing methods so far still suffer from issues such as unhandy alignment procedures, imprecise cutting, wire snapping and reduced sheet conductivity as a result of embroidery. Furthermore, the use of metal eyelets results in a heavier structure, which is an impeding factor considering wearability. Summarizing, previous manufacturing methods suffer from a lack of reliability and manufacturing ease.

In this paper, a novel manufacturing method for the production of SIW cavity backed antennas is proposed. The procedure offers better alignment compared to earlier described production methodologies, requires fewer manipulations, and suffers less from cutting inconveniences such as inaccuracies and fraying of the electrotextile. Furthermore, since no metal eyelets are used, the manufacturing procedure offers a significant reduction in both size and weight of the antenna. As a proof of concept, an SIW cavity backed slot antenna is fabricated based on this manufacturing method. Cavity backed antennas are highly suitable as body-worn antennas because of their large gain and their high front-to-back ratio (FTBR). As such, antenna radiation is directed away from the human body, which decreases the specific absorption rate (SAR) in the wearer's body tissues. In contrast, orientation of the radiating aperture towards the human body offers opportunities for communication with medical implants. In this, the system suffers less interference from outside radiation sources in comparison to antennas with a lower FTBR. In conjunction with other SFIT advancements, such as nondestructive material characterization and on-textile electronics design [12], this fabrication procedure can prove to be a valuable asset in bringing wearable electronics closer to traditional manufacturing industry.

This paper is structured as follows. In Section 2, the novel manufacturing procedure is demonstrated by the design of a cavity backed slot antenna operating in the [5.15-5.85] GHz band. Together with the manufacturing procedure, both the antenna principle and the choice of materials are discussed.

Section 3 elaborates on the simulation and measurement results of the prototype fabricated according to the proposed manufacturing procedure. The reflection coefficient and the radiation pattern of the antenna have been measured, both in free space and when deployed on the human body. Conclusions are drawn in Section 4.

2 Antenna design and manufacturing

In this section, an SIW cavity backed slot antenna prototype is designed to demonstrate the novel fabrication procedure. In Section 2.1, the prototype antenna's working principle, the influence of the design parameters and the used materials are discussed. Section 2.2 elaborates on the manufacturing procedure itself.

2.1 Antenna Design and Principle

To demonstrate the feasibility of the proposed manufacturing process, a cavity backed slot antenna has been realized using this manufacturing procedure. This antenna topology uses the bandwidth enhancement technique proposed in [13]. As thoroughly discussed in [14], the antenna is constructed from two SIW half-mode cavities which both exhibit their own resonance frequency. By tuning the dimensions of the cavity halves and the slot, the coupling between both cavities can be controlled. Since this coupling triggers the mode bifurcation effect [15] which causes the natural resonances of both half-mode cavities to shift, the antenna resonance frequencies can be judiciously tuned using the aforementioned parameters, allowing for a high-bandwidth antenna topology. Furthermore, as the electromagnetic field is confined inside the cavity, cavity backed antennas exhibit no surface waves, which would cause unwanted back and side radiation. This is a clear advantage over for example patch antennas when considering on-body deployment.

The antenna has been simulated and optimized using the electromagnetic simulator "CST Microwave Studio". The resulting dimensions of the patch to be cut are displayed in Figure 1. As noted before, the location of the resonance frequencies can be controlled by tuning W_a and W_b, being the widths of the cavity on either side of the slot. As the dimensions of the slot, W_{es} and W_s influence the degree to which the mode bifurcation effect takes place. Furthermore, W_{es} is an important parameter for impedance matching. Other important parameters for impedance matching are the cavity length L and the location of the feed D_f. The height H of the substrate influences the possible bandwidth that can be used. This is often a given constant that is dependent on the textile used in the garment. S_1 and S_2 are chosen sufficiently large compared to $D_{sl,1}$ and $D_{sl,2}$ for the cavity to confine the field, but are kept small enough so the textile of the vertical walls doesn't experience crumpling when bent.

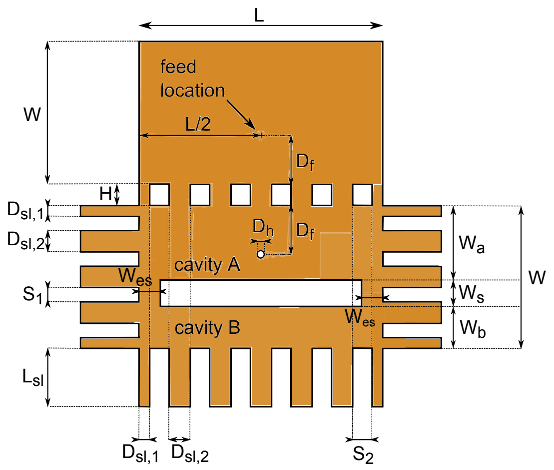
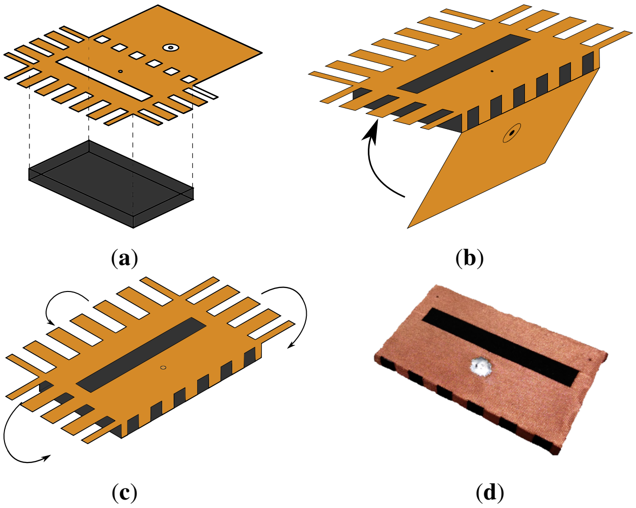


Figure 1. $H = 4mm$, $W = 26.84mm$, $L = 45.94mm$, $W_a = 16.49mm$, $W_b = 10.35mm$, $W_{es} = 4mm$, $W_s = 5mm$, $D_f = 9.22mm$, $D_h = 0.65mm$, $D_{aux} = 5mm$, $H_{aux} = 2.85mm$, $W_{aux} = 1.94mm$, $D_g = 0.9mm$, $L_{sl} = 11mm$, $D_{sl,1} = 2mm$, $D_{sl,2} = 4mm$, $S_1 = 2.71mm$, $S_2 = 4mm$.

As a substrate, a closed-cell expanded rubber is chosen, which is a material commonly used in firefighter jackets [16]. This material is mechanically flexible and recovers easily from folding and compression. Furthermore, the substrate is fire-resistant, water-repellent and it has a low moisture regain. The material exhibits a loss tangent of 0.016 and has a relative permittivity of 1.495, which, together with the thickness of 4 mm, allows to achieve sufficient bandwidth when applied in a cavity backed antenna topology. The chosen electrotextile material is the copper-plated Pure Copper Taffeta as used in [11, 14], with a sheet resistivity of $0.05\ \Omega/\square$ [17]. As such, conductor losses in the antenna are very limited, which is beneficial for antenna efficiency.

2.2 Manufacturing procedure

Previous fabrication procedures for textile antennas often suffer from cutting and eyelet punching inaccuracies, textile fraying and alignment errors. The methodology proposed in this paper remedies these issues. In a first step, the electrotextile is glued together with a thermally activated sheet adhesive. Next, both the electrotextile attached to the sheet adhesive and the substrate are laser cut into the shapes shown in Figure 2a. Moreover, the connector footprint is implemented in the future bottom plane of the cavity. This is done to ensure its correct position and to make sure that the center conductor does not make direct contact with the bottom plane. In the top plane, an aperture is cut out to form the radiating slot. Also, several electrotextile straps are realized. Those will be folded around the substrate to realize the vertical cavity walls. The substitution of metal eyelets by textile straps greatly reduces the weight of the antenna and increases the mechanical flexibility of the device. Laser cutting the materials greatly reduces the inaccuracies involved with cutting. An additional advantage of lasering is that it avoids any fraying of the cut textile. As the electrotextile is cut out in one piece, the alignment of the substrate and the electrotextile is significantly more straightforward, as seen in Figure 2a. In this way, alignment errors are way more visible and, hence, less likely to happen. When the electrotextile-adhesive patch makes contact with a heated surface, the adhesive activates and attaches to the top side of the substrate. Then, the electrotextile can simply be folded around the substrate while again pressing it against a heated surface, as displayed in Figure 2b. Next, the cavity can be finalized by folding the electrotextile slabs around the substrate (Figure 2c), while heating and thus gluing them as well, resulting in the antenna cavity displayed in Figure 2d. This procedure can be much more easily automated than the manual manufacturing techniques described in earlier publications.


(**a**) (**b**)

(**c**) (**d**)

Figure 2. Antenna fabrication procedure. (**a**) Alignment and attachment of top (antenna slot) plane to substrate; (**b**) Folding around substrate; (**c**) Folding of electrotextile slabs; (**d**) Realized antenna prototype.

Due to a lower radiation leakage towards the human body, a probe feed is chosen over other feeding methods that could be used to excite the antenna cavity. Therefore, a brass-gold pin with a diameter of 1 mm is soldered at the bottom to the center conductor of a Hirose U.FL connector and at the top to the antenna, as shown in Figure 3.

3 Simulation and Measurements

To validate the manufacturing process, both the reflection coefficient and the radiation pattern of the antenna have been measured. Measurements were performed in free space as well as in two on-body deployment scenarios where the antenna was mounted either on the torso or the arm of an average person, thereby pointing away from the body. This is a realistic deployment scenario for off-body communication. The presence of both separate resonances due to mode bifurcation is clearly visible, as there are obviously two dips in the reflection coefficient displayed in Figure 4. Here it is clear that the impact of the presence of the human body on antenna performance is very limited. Figure 5 shows the radiation pattern of the antenna prototype. This, along with the antenna's FTBR of approximately 8.4 dB visible in Table 1, confirms that the antenna prototype is suitable for on-body deployment, since the radiation pattern experiences little influence of presence of the human body and antenna radiation is directed away from the wearer. Note that both simulations and measurements agree that the antenna has a good antenna efficiency, which is especially desirable in wearable applications, as they are often battery-powered. Also, the antenna gain retains a stable value around 6.4 dBi over the desired band.

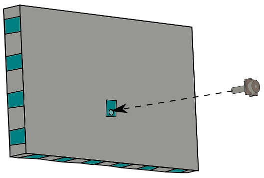


Figure 3. Punching of connector with mounted pin into antenna cavity.

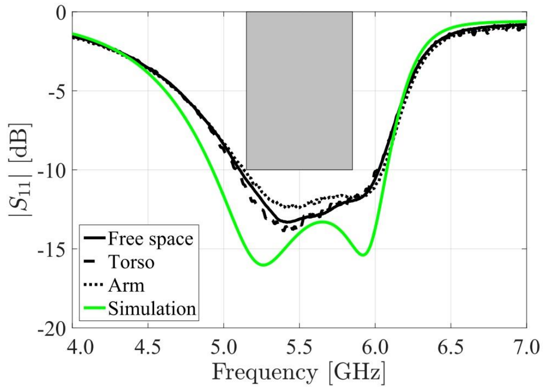


Figure 4. Reflection coefficient of the prototype in different deployment scenarios.

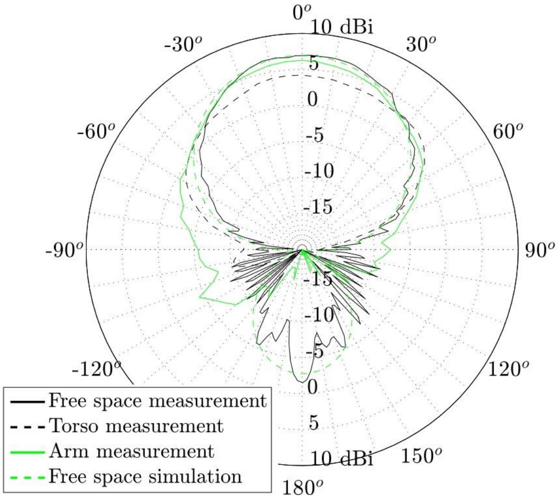


Figure 5. Radiation pattern of the prototype in different deployment scenarios.

Table 1. Radiation efficiency, broadside gain and front-to-back ratio (FTBR) of the measured antennas.

Frequency [GHz]	**5.15**	**5.50**	**5.85**
Simulated total radiation efficiency [%]	91	89	82
Measured total radiation efficiency [%]	94	90	74
Simulated maximum gain [dBi]	6.72	6.83	6.62
Measured maximum gain [dBi]	6.73	6.64	5.81
Simulated FTBR [dB]	10.47	11.99	14.38
Measured FTBR [dB]	8.39	8.50	7.85

4 Conclusion

In this contribution, a novel design procedure for the manufacturing of cavity backed textile antennas was proposed. The design procedure is more accurate, more reliable and much easier to automate than currently existing design procedures. As a proof of concept, a lightweight and mechanically flexible SIW cavity backed slot antenna has been simulated and realized. The antenna has been measured in free space, when deployed on the torso, and when deployed on the arm of an average human. In all scenarios, the prototype covers the [5.15-5.85] GHz band. Furthermore, the antenna exhibits a stable gain of around 6.4 dBi and a FTBR of approximately 8.4 dB. This makes the realized antenna most suitable for use in a body-worn communication system.

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