Compact Cavity-Backed Antenna on Textile in Substrate Integrated Waveguide (SIW) Technology

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***Abstract*— In this paper a folded cavity-backed patch antenna implemented in substrate integrated waveguide (SIW) technology is presented. The antenna has been designed to operate at 2.45 GHz, in the industrial, scientific and medical (ISM) frequency band, and a textile substrate has been adopted for the realization of the component. This topology of textile antenna could be useful for the monitoring of the activities of rescue workers in emergency situations such as the localization of fire-fighters, and the communication in critical operations.**

The proposed antenna has been experimentally verified: the response of the antenna exhibits a small frequency shift, caused by a discrepancy between the nominal and the real value of electrical permittivity of the textile substrate. The measured radiation characteristics of the antenna show a good agreement with simulations, and a measured radiation efficiency of approximately 70%.

***Keywords*—Substrate integrated waveguide; textile material; new and emerging technologies and materials; cavity-backed antennas; wearable antennas.**

I. Introduction

In the last years, textile on-body radio systems have received an increasing interest and, nowadays, they represent an important field of research. In particular, different antenna typologies fabricated on textile materials were proposed in order to achieve not only good electromagnetic performance, but also robust and comfortable systems [1]. Applications such as the tracking of the position of rescue workers and the communication with fire-fighters in critical conditions motivate the research towards novel efficient radio systems.

A key point in rescue operations is the monitoring of body functions of the fire-fighters together with the characteristics of the external environment. All the data collected by the sensors integrated in the suit of rescue worker should be transmitted in order to evaluate in real time the risk of the rescue operation. For this reason the system of communication requires an antenna which should assure sufficiently large bandwidth and high radiation efficiency. Moreover, the antenna should be integrated into jackets of fire-fighters but it should not disturb their movements. The use of textile materials as substrate enables the fabrication of light and flexible components which are, at the same time, robust and reliable, and which can be easily integrated into garments [2].

A variety of patch antennas on textile, operating in the ISM band (2.4–2.4835 GHz), have been proposed [1,3]. Recently an SIW cavity-backed slot antenna was presented, demonstrating the feasibility of combining the fabrication of textile components with substrate integrated waveguide technology (Fig. 1) [4]. The SIW technology permits to integrate into a single substrate different components such as passive and active devices, as well as antennas. Therefore, in an entire system, the number of transitions between elements is limited and a reduction of losses is guaranteed [5]. Furthermore, by adopting SIW technology, we increase the efficiency and minimize the physical dimensions of the complete system. The choice of the substrate integrated waveguide technology for the implementation of the proposed antenna is motivated by the simple and low cost fabrication process and by its potential to easily realize multilayer structures. Moreover, the characteristics of SIW structures appear suitable for implementation of components on textile material because the flexibility of the substrate is preserved and conformal structure can be fabricated.

In this paper a folded cavity-backed patch antenna realized in substrate integrated waveguide technology is presented. The integration of a patch antenna in an SIW cavity allows to reduce the surface wave effects and, consequently, to increase the radiation efficiency. In addition, thanks to the structure of the cavity, the designed antenna exhibits a high front-to-back ratio, which is an essential property for limiting the radiation towards the fire-fighter body. The proposed folded SIW cavity-backed patch antenna was fabricated: it results

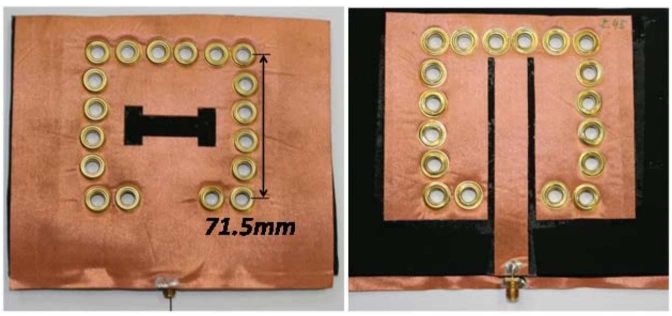


Fig. 1. Photograph of the SIW cavity-backed slot antenna (from [4]).

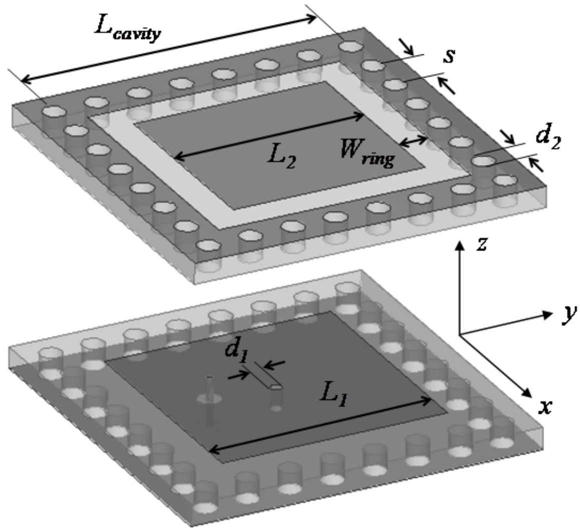


Fig. 2. Geometry of the folded SIW cavity-backed patch antenna.

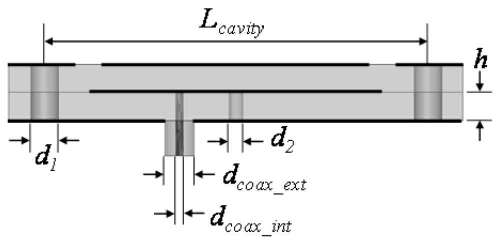


Fig. 3. Side view of the folded SIW cavity-backed patch antenna.

in a compact and light-weight antenna. The electromagnetic performance was tested by measuring the input matching and the radiation patterns of the antenna in an anechoic chamber.

II. Antenna Design

One of the advantages of the folded SIW cavity-backed patch antenna with respect to other textile antennas, and in particular, to the SIW cavity-backed slot antenna presented in [4], is the dimension of this structure. In fact, the small size of the antenna not only enables an easier integration into suits but also makes the component more comfortable to wear. For this reason the design aims to reduce the dimension of the structure by realizing a multilayer antenna.

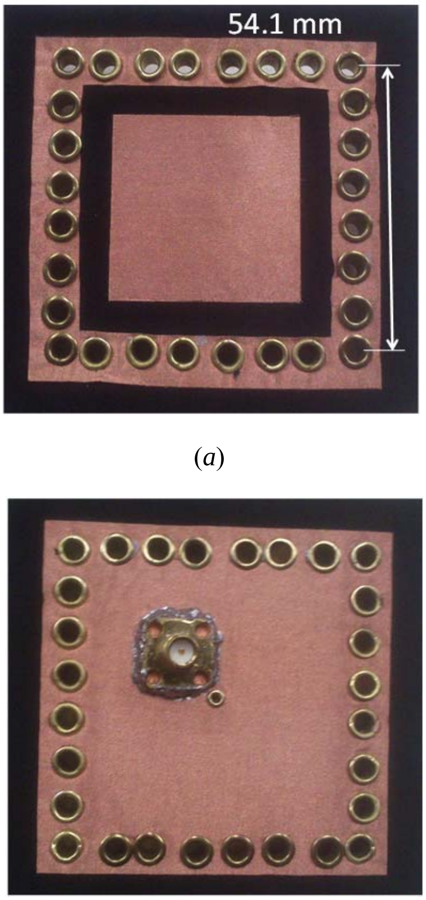
The substrate adopted for the realization of the structure is a cell expanded foam, commonly used in protective clothing such as the fire-fighters suits. The textile material with a thickness of 3.94 mm was experimentally characterized in [4] at the frequency of 2.45 GHz through the measurement of the frequency response of interconnects with different length, according to the method described in [6]. From this analysis, a dielectric permittivity $\varepsilon_r = 1.575$ and a loss tangent $\tan\delta = 0.0238$ are obtained. These values were confirmed by the design of the cavity-backed slot antenna presented in [4], exhibiting a good agreement between simulated results and measured data. For the conductive patches and ground of the antenna, the commercially available electro textile Flectron® was used. This conductive material was characterized in [6] and exhibits a surface resistivity R_s=0.18 Ω/sq at 2.45 GHz.

The topology proposed in this paper consists of a folded cavity with a square ring aperture cut out in the top metal layer thus forming the radiating patch with side L_2 (Fig. 2). In order to obtain the folded cavity, two substrate layers with the same thickness h are stacked and a second metalized patch with side L_1 is glued between them. A metalized via hole is placed at the centre of the cavity to connect the bottom ground plane and the lower metal patch (Fig. 3). As a starting point, the length L_1 of the side of the lower patch has been initially set to 75% of the side L_{cavity} of the cavity. This size permits to minimize the dimension of the cavity and, at the same time, it prevents a strong increase of losses due to the large value of the electric field in the small gap between the metal patch and the sides of the SIW cavity. Furthermore, in the final configuration the dimension of the lower patch was optimized to obtain the first resonant mode of the cavity at the desired frequency of 2.45 GHz, in order to improve the performance of the antenna. The dimensions of the square ring slot cut out in the top metal sheet were selected to maximize the radiation efficiency and to increase the operating bandwidth of the component. In fact, due to the parasitic patch, an improvement of 15% of the bandwidth was achieved. The final design of the antenna aims to combine the small dimensions of the structure with good radiation performance. The antenna is fed from the back side by a coaxial excitation as shown in Fig. 3. The inner conductor of coaxial line is attached to the lower metal patch whereas the outer conductor is connected to the bottom ground plane. The position of the feeding pin was chosen for optimal coupling with the fundamental mode of the patch. A good input matching can be obtained with the feeding point located on the diagonal of the patch, 11.31 mm away from the centre of the cavity. The position of the feed is selected in order to obtain broadside radiation with the electric field linearly polarized along the diagonal of the cavity.

The antenna was designed and simulated by using the FEM-based full-wave electromagnetic solver Ansys HFSS. The dimensions of the final design of the folded SIW cavity-backed patch antenna are reported in Table I.

Table I. Dimensions of Folded SIW Cavity-Backed Patch Antenna

Parameter	Dimension [mm]	Parameter	Dimension [mm]
L_{cavity}	54.1	d_1	2
L_2	35	d_2	4
W_{ring}	5.5	s	8
L_1	41.2	$d_{\text{coax\_ext}}$	2.1
h	3.94	$d_{\text{coax\_int}}$	0.6



(*a*)

(*b*)

Fig. 4. Photograph of the folded SIW cavity-backed patch antenna: (*a*) radiating side; (*b*) feed side.

From the optimization of the folded antenna it results that the side of the cavity is about 54 mm, compared to the cavity size of 72 mm of the SIW slot antenna presented in [4]. Therefore, the proposed antenna offers a size reduction of 43% over the area of the previous SIW cavity-backed antenna (shown in Fig. 1).

III. Fabrication Process

Given the materials used for the fabrication of the antenna, all the metalized vias, including the holes that define the lateral walls of the square SIW cavity, are easily implemented by fixing rivets into the substrate. In fact the use of eyelets provides a good ohmic contact between the two ground planes and permits to preserve the flexibility of the structure. In order to avoid radiation leakage from the side walls of the cavity, the diameter and the longitudinal spacing were set to 4 mm and 8 mm respectively. Moreover, to implement the lateral walls of the cavity, 10 mm high rivets were chosen avoid compression of the substrate due to the heads of eyelets. In addition the diameter and the height of the post in the center of the cavity are 2 mm and 6 mm, respectively.

The fabrication of the prototype was done manually. The conductive layers were cut from the Flectron® material and attached to the substrate foam by means of thermal glue. An eyelet press was used to fix the brass eyelets at the correct location in the substrate to realize the vias. The result is displayed in Fig. 4.

IV. Experimental Results and Discussion

After the fabrication of the prototype, the antenna was experimentally characterized in terms of input matching and radiation pattern.

The measured input matching of the folded SIW cavity-backed patch antenna is shown in Fig. 5. The return loss is larger than 10 dB over a bandwidth of 155 MHz, but the frequency response exhibits a shift of approximately 3%, with a minimum value of $|S_{11}|$ at 2.53 GHz. The possible explanation of this shift was investigated by simulating the potential inaccuracies of the fabrication process. In particular, misalignment between the patches, rotation of the square ring, and incorrect positioning of the feed were simulated, without identifying a good match between the measured and simulated return loss.

Therefore, the frequency shift was attributed to a discrepancy between the actual dielectric permittivity of the textile substrate and the value used for the design of the antenna. Since the textile material adopted in this work is not a substrate commonly used for microwave applications, its electrical characteristics can change moderately among different parts of the material. In order to characterize the correct dielectric permittivity of the substrate used for the folded SIW antenna, a sensitivity analysis was performed. The value of ε_r that permits to achieve a good agreement of measured and simulated return loss is $\varepsilon_r = 1.47$, as shown from the plot in Fig. 5.

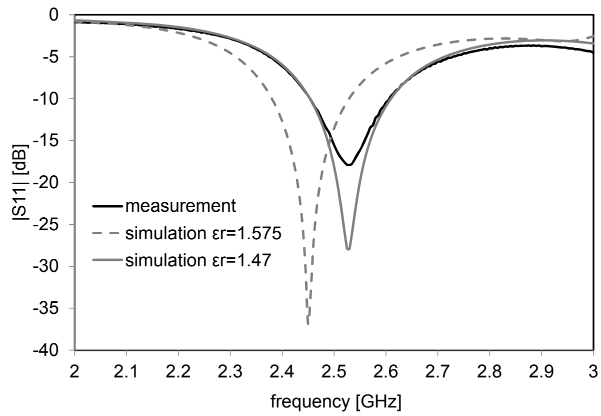
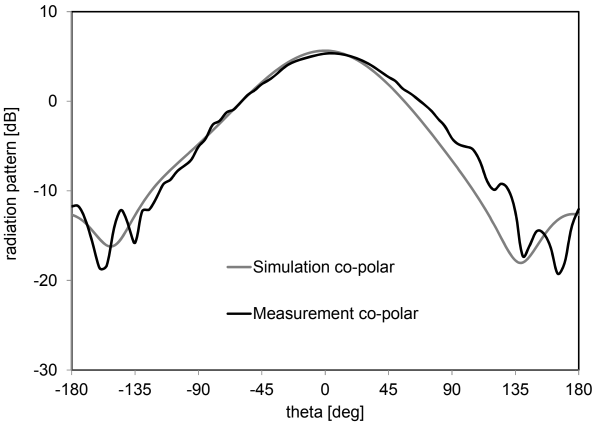


Fig. 5. Simulated and measured input reflection coefficient of the folded SIW cavity-backed patch antenna.



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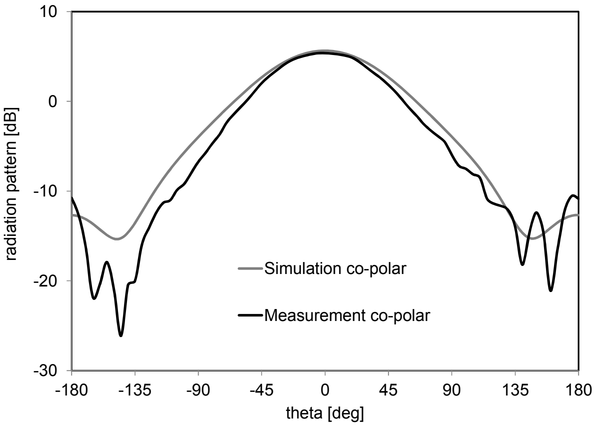

(*b*)

Fig. 6. Simulated and measured radiation pattern of the folded SIW cavity-backed patch antenna: (*a*) in the plane ϕ=45°; (*b*) in the plane ϕ=135°.

Subsequently, the radiation pattern of the antenna was measured in anechoic chamber in stand-alone condition: the radiation pattern of the antenna, in both planes ϕ=45° and ϕ=135°, was measured at the frequency of 2.53 GHz. Fig. 6 shows the comparison between simulation and measurement, which exhibits a very good agreement. The antenna provides an efficiency of 70%, with a maximum gain of 5.3 dBi at boresight direction, which is consistent with the simulated value (5.63 dBi). The front-to-back ratio of the antenna is approximately 17 dB.

V. Future Works and Conclusion

The design of a folded SIW cavity-backed antenna, realized entirely in textile materials, has been presented in this paper. The light-weight, flexibility and very compact size make this antenna suitable for a complete integration in the suits of rescue workers.

The antenna was fabricated and experimentally verified and the measured return loss exhibits an upward frequency shift due to an inaccuracy in the estimation of dielectric permittivity. When using the correct value of ε_r, the results of the simulation of the folded cavity-backed patch antenna are in very good agreement with the measurements in terms of both input matching and radiation patterns.

The future developments of this research activity will include the design of a compact SIW cavity-backed antenna, operating in circular polarization. Antennas with circular polarization are very useful for the localization and tracking of fire-fighters in rescue operation. The circular polarization can be achieved by properly locating the feed point and using a quasi-square cavity, with no need to substantially modify the overall antenna topology.

Another important step will be the integration of the cavity-based antenna with active devices, with the aim to achieve compact integrated antenna oscillators [7]. The integration of active components on top of the antenna will permit the implementation of complete radio systems in textile material.

Acknoledgments

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