Design and Characterization of Conformal Microstrip Antennas Integrated into 3D Orthogonal Woven Fabrics

Xin Wang[1], Lan Yao[1], Fujun Xu[2], Dongchun Zhou[1], Yiping Qiu[1]

[1]College of Textiles, Donghua University, Shanghai China

[2]Key Laboratory of High-Performance Fibers and Products, Donghua University, Shanghai CHINA

Correspondence to:
Yiping Qiu email: ypqiu@dhu.edu.cn

ABSTRACT
The integration of the antenna and textile materials is very important in the army protective or data transmission clothing. In this study, a novel microstrip antenna integrated into a 3D orthogonal woven fabric was successfully designed and fabricated. This type of antenna is designed to work in wearable or conformal antenna applications. Simulation work using HFSS software was done for the determination of antenna size. Antenna performance including return loss, radiation pattern and gain were measured and the simulated results were found to have good agreement with the measured results. The measured return loss was -18.32dB with a resonant frequency of 1.75GHz. The gain under the frequency of 1.70GHz reached as high as 6.47dB. These results are considered to be very valuable, and this type of integrated antenna is expected to be useful as wearable antenna in the telecommunication or smart textile antenna field.

INTRODUCTION
Since the concept of smart textile systems was introduced in 1990s, research on electro-textile has rapidly expanded [1-8]. Nowadays, more and more attention has been given to the healthcare and protective clothing sectors [1,7]. In these circumstances, the antenna, as an electronic element, plays an important role in wireless data transmission. In order not to lose the flexibility and comfort of garments, antennas should be fully integrated into the textile materials.

Among all types of antennas, microstrip patch antennas, as flat, thin and flexible antennas, seem most suitable for integration into clothing.

A microstrip antenna in its simplest configuration consists of a radiating patch on one side of a dielectric substrate and a ground plane on the other. Microstrip antennas have several advantages compared with conventional microwave antennas.
They have low volume, low profile planar configurations and low fabrication cost. These advantages resulted in the microstrip antenna becoming the first choice in designing electro-textiles.

Up to now, many types of integratable textile microstrip antennas have been proposed [3, 6] and nearly all of them are microstrip antenna integrated textiles [9, 10]. Salonen et al. [6] introduced textile antennas in which the substrate was textile material, where both antenna and ground plane were made of copper tape. In this case, the phenomenon of peeling off will exist when the structure is subjected to a mechanical load such as impact. In the textile microstrip antennas investigated by Hertleer et al. [3], the electro-textile patches were glued onto the substrate and additionally stitched to improve fixing and to prevent an intermediate air gap. However, continuity of the conductive materials was damaged using the stitching methods, thus, probably leading to malfunction of the antenna.

In this study, we proposed a microstrip-fed microstrip antenna woven into a 3D orthogonal fabric. Different from the textile antennas mentioned above, the patch and ground plane were fully woven with the textile substrate using 3D fabric weaving methods. This method was anticipated to result in superior integrity and impact resistance. At the same time, it was felt that the peeling off phenomena could be avoided to a great extent. After fabrication, the electrical performance of the antenna was measured.

DESIGN PROCEDURES OF THE ANTENNA STRUCTURE

The fundamental design concept of the conformal antenna structure is an integral structure as shown in *Figure 1*, in which a microstrip antenna is woven into a 3D orthogonal fabric. The 3D woven fabric is constructed with three sets of yarns, namely warp, weft and Z-yarns, interlaced in three mutually orthogonal directions. Among all 3D fabric structures, 3D orthogonal woven fabric have the most ordered structures and thus can provide an adequate platform for the embedded elements [9].

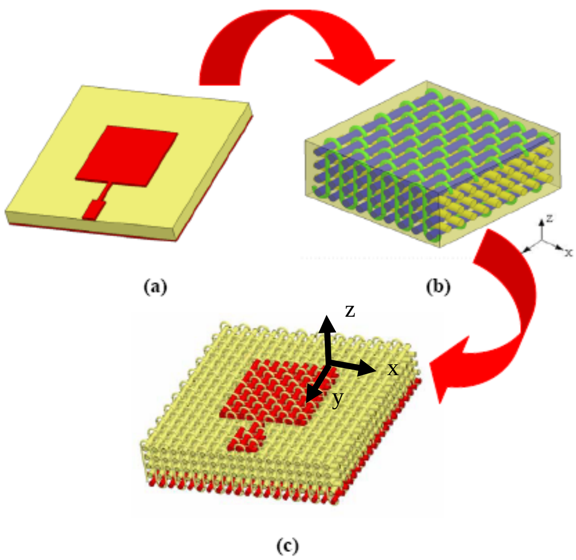

FIGURE 1. The concept of the conformal antenna structure: (a) microstrip antenna; (b) 3D orthogonal woven fabric; (c) scheme of the microstrip antenna integrated into the 3D woven fabric.

Dielectric Constant of the Fabric Substrate

The antenna was designed to work at radar L-band with a resonant frequency of 1.5GHz. The substrate of the antenna is 3D orthogonal woven glass fiber fabric with a thickness of 2.4mm. To determine the patch size of the microstrip antenna, the dielectric constant of substrate is required. The dielectric constant of the woven glass fiber fabric is 3.5, as provided by the manufacturer. However, we need to know the accurate value to design the patch size of the antenna. So we first designed a simple co-axial feeding microstrip antenna with a resonant frequency of 1.5GHz using this fabric as the substrate. The copper foils were glued onto the substrate as the patch and ground plane. Then the resonant frequency of the simple antenna was measured using the Vector Network Analyzer, and this value was 1.79GHz. The dielectric constant could be finally calculated using Eq. (1).

$$\varepsilon_r = \frac{c^2}{2W^2 f_r^2} - 1 \tag{1}$$

where c is the velocity of light, W is the width of the patch and f_r is the resonance frequency of the antenna.

Similar methods were also proposed by Hertleer et al. [3] and seemed to be very efficient. We obtained the dielectric constant of 3.3. As to the loss tangent, the value of 0.008 is usually used for this type of fabric.

Design of the Antenna

The patch size of the woven antenna was calculated according to Eq. (2) and Eq. (3). The width of the patch was calculated from

$$W = \frac{c}{2f_r}\left(\frac{\varepsilon_r + 1}{2}\right)^{-1/2} \tag{2}$$

where c is the velocity of light, f_r is the resonance frequency of the antenna, ε_r is the dielectric constant of the substrate which has been obtained using the method above. The length of the patch was then obtained from

$$L = \frac{c}{2f_r\sqrt{\varepsilon_e}} - 2\Delta\ell \tag{3}$$

where ε_e is the effective dielectric constant and Δl is the line extension. A computer aided design tool, High Frequency Structural Simulator (HFSS) provided by Ansoft Corporation, was used to simulate the performance of the antenna. The final size of the antenna, shown in *Figure 2*, was also adjusted by using HFSS.

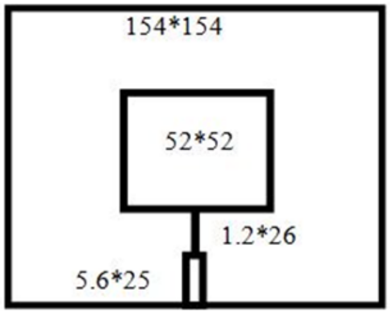

FIGURE 2. The size of the antenna (mm).

FABRICATION OF THE ANTENNA

The specification of glass and copper yarns in the 3D fabric antenna are listed in *Table I*. The conformal antenna was woven as a regular 3D orthogonal woven fabric as shown in *Figure 1(c)*. In this 3D fabric, glass fibers were used as the warp, the weft and z yarns. In weaving the antenna patch and ground plane parts, the conductive yarns in x and y directions were orthogonally woven to form the grid structure. The woven antenna was then soldered with a feeding connector. The real conformal antenna integrated into the 3D woven fabric was shown in *Figure 3*.

TABLE I. The specification of glass and copper yarns in the 3D fabric antenna.

Weaving direction	E glass yarn	Copper yarn*
Weft	600tex	7×11 ends
Warp	1102tex	1×18 ends
Z	370tex	—

* The diameter of the copper fiber in the copper yarn is 0.07mm.

ANTENNA PERFORMANCE TEST

To describe the performances of the antenna, the return loss and the radiation pattern are the two significant parameters. The reflection coefficient was measured using an 8722ES Microwave Network Analyzer under laboratory conditions, and the return loss was obtained at Port 2, with a termination at Port 1. The radiation pattern was measured in the anechoic chamber using HP 8510C Antenna Test System. The antenna was fixed with a termination of the section port, and then the signal of the vertical polarization was transmitted to the antenna. The radiation pattern was obtained from the signal received by the 360° rotating antenna. Gains were calculated by comparing field values of a reference-gain log periodic antenna.

FIGURE 3. The conformal antenna integrated into the 3D woven fabric.

RESULTS AND DISCUSSION

The return loss of the simulated and measured values of the antenna is shown in *Figure 4*. The simulated return loss is -16.33dB with the resonant frequency of 1.51GHz while the measured return loss is -18.32dB with the resonant frequency of 1.75GHz. The measured return loss shifted a little compared with the simulated one, however, it still works in the range of 1-2GHz. The measured VSWR (voltage standing wave ratio) was calculated as 1.28 from the return loss value, which needs the general requirement of VSWR below 2 in the antenna performance. In addition, the bandwidth of the measured antenna below VSWR<2 is 4.3%, resulting in an adequate bandwidth of this type of the antenna.

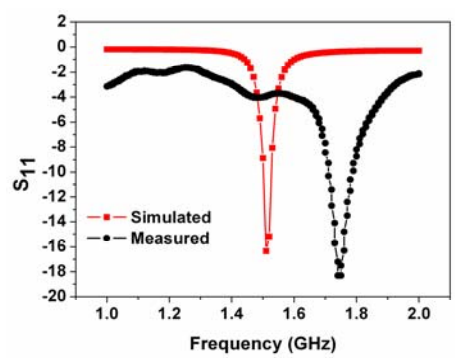

FIGURE 4. The simulated and measured return loss of the antenna.

The simulated and measured radiation patterns of the antenna are shown in *Figure 5*. It can be seen that the measured results agree well with the simulated results. The highest values can be obtained in the 0 degree direction and the front lobe has much larger level than the back lobe in both of the simulated and measured antennas. However, the beam widths of the simulated radiation patterns are narrower than the measured ones indicating more concentrated radiation direction. This is mainly due to the size control discrepancy in the weaving process. Therefore, using thinner fibers and controlling stable size of the patch are very important, which needs more attention in the future manufacturing process.

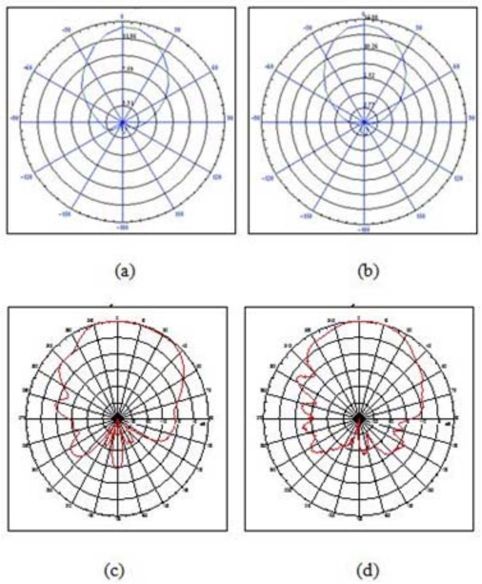

FIGURE 5. The (a) simulated E plane, (b) simulated H plane, (c) measured E plane and (d) measured H plane radiation patterns.

The measured gains of the antenna are listed in *Table II*. The gain in the frequency of 1.70GHz reaches as high as 6.47dB, which needs the general gain requirement of this type of antenna. The gain does not reach the largest value at the resonant frequency of 1.75GHz as shown in the measured return loss the antenna mainly due to the directivity accuracy for the woven antenna. In our previous paper, how the space ratios and woven structure would affect the antenna properties has been discussed [12]. In that paper, the space ratio has been determined as less than 1.7. In this paper, the space ratio the 3D fabric antenna was 0.5 which was also less than 1.7 and proved to give proper antenna properties. In the real application, this value is enough for receiving and enlarging signals.

TABLE II. The measured gain of the antenna.

Frequency (GHz)	1.70	1.72	1.74	1.75	1.76	1.78	1.80
Gain (dB)	6.47	4.98	3.81	3.46	3.15	1.75	0.43

CONCLUSIONS

A microstrip antenna integrated in the 3D orthogonal woven fabric was successfully fabricated in this study. This type of antenna is aimed to work for wearable or conformal antenna applications. The dielectric constant of the 3D fabric substrate was first calculated, which is the pre-required parameter for the design of the patch size. The simulated results of the return loss and radiation pattern showed good agreement with the measured values. The return loss, radiation pattern and gain of the antenna were in the required range of the common single-element microstrip antenna. This type of integrated antenna is expected to be a wearable antenna applied in the army telecommunication and other applications for smart textile antennas.

ACKNOWLEDGMENT

This work was supported by the National High Technology Research and Development Program of China (No. 2007AA03Z101), the State Key Program of National Natural Science of China (No.51035003), Natural Science Foundation for the Youth (No. 50803010 and 60904056), National Science Foundation for Post-doctoral Scientists of China (No.20100470664), Shanghai Post-doctoral Research Funded Project (No. 09R21410100), the Program of Introducing Talents of Discipline to Universities (No.B07024), Shanghai University Young Teacher Training Program and the Fundamental Research Funds for the Central Universities.

REFERENCES

[1] Gatzoulis L. and Iakovidis I., *IEEE Engineering in Medicine and Biology Magazine* 26(5):51(2007).

[2] Hertleer C., Rogier H., Vallozzi L., et al., *IEEE Transactions on Antennas and Propagation* 57(4):919(2009).

[3] Hertleer C., Tronquo A., Rogier H., et al., *Textile Research Journal* 78(8):651(2008).

[4] Januszkiewicz, L., Hausman, S., Kacprzak, T., et al. in *2008 Mikon Conference Proceedings, Vols 1 and 2*, 2008, pp. 377-380.

[5] Salonen, P., Keskilammi, M., and Rahmat-Samii, Y. in *2008 Ieee Antennas and Propagation Society International Symposium, Vols 1-9*, 2008, pp. 1700-1703.

[6] Salonen, P., Yang, F., Rahmat-Samii, Y., et al. in *Ieee Antennas and Propagation Society Symposium, Vols 1-4 2004, Digest*, 2004, pp. 451-454.

[7] Vallozzi, L., Rogier, H., and Hertleer, C., *Ieee Antennas and Wireless Propagation Letters* 7:440(2008).

[8] Vallozzi, L., Rogier, H., and Hertleer, C. in *2009 3rd European Conference on Antennas and Propagation, Vols 1-6*, 2009, pp. 967-970.

[9] Du, C., Zhong, S., Yao, L., et al. in *Proceedings of International Symposium on Signals, Systems and Electronics (ISSSE2010),Vol 2,* 2010*,* pp.662-663.

[10] Wang, G., Zhu, C., and Xu, C., *Advanced Materials Research* 450:175(2011).

[11] Bogdanovich, A. E., Wigent, D. E., and Whitney, T. J., *Sampe Journal* 39(4):6(2003).

[12] Yao, L., Wang, X., Xu, F., et al., *Applied composite materials (online available)* DOI: 10.1007/s10443-010-9177-4.

AUTHORS' ADDRESSES
Xin Wang
Lan Yao
Dongchun Zhou
Yiping Qiu
Donghua University
No. 2999, North Renmin Road
Songjiang District
Shanghai, 201620
CHINA