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Textile Folded Half-Mode Substrate-Integrated Cavity Antenna

Feng-Xue Liu, *Student Member IEEE,* Zhao Xu, Damith Chinthana Ranasinghe, *Member IEEE* and Christophe Fumeaux, *Senior Member IEEE*

***Abstract*—The half-mode substrate-integrated cavity antenna is a promising candidate for wearable applications because of its planar structure and high isolation from environmental effects. However, for operation at 2.45 GHz ISM band, the cavity dimensions are relatively large. To reduce the antenna size in one of the dimensions, a folded half-mode substrate-integrated cavity antenna is proposed and designed. Furthermore, as an additional significant advantage for practical applications, the folded geometry allows a planar feeding structure using a shielded stripline. A prototype of the folded cavity antenna has been fabricated using textile materials and computerized embroidery. The measured reflection coefficient and radiation patterns of the prototype compare well with the simulation results and demonstrate the feasibility of the design.**

***Index Terms*—wearable antenna, textile antenna, half-mode substrate-integrated cavity antenna, folded structure, shielded stripline.**

I. Introduction

In the last decade, technical innovations in wireless body area networks (BANs) [1] have been transformed into abundant applications in medical monitoring, sports [2], security [3] and personal communications [4]. Among the research hotspots of wireless BAN are wearable antennas. These antennas require low profile designs for integration into clothes and high efficiency considering limited battery capacities, while being lightweight, flexible and mechanically durable. Additionally, electromagnetic isolation between the wearable antenna and the human body is also necessary. Besides, the fact that a wearer could be in various postures and positions demands wide antenna coverage. In this sense, the pattern of a magnetic dipole on a ground plane is appropriate because of its wide beam angular coverage and high isolation from a wearer's body.

The half-mode substrate-integrated cavity (half-mode cavity for short) antenna is a candidate for wearable applications because of its planar geometry and good isolation from environmental effects. It has been developed from the half-mode substrate-integrated waveguide (HMSIW) [5], and is formed as half of a thin resonant cavity with the open radiating aperture offering a nearly perfect magnetic conductor boundary condition. For flexible applications, the top layer and ground plane can be copper tape, conductive ink or metalized textile [6]. The sidewalls can be practically built using pins, etched vias, rivets [7] or conductive threads [8] [9]. The shape of the thin cavity can be semicircular [9] or rectangular [8]. A rectangular cavity shape is considered in this letter.

The feeding of wearable antennas with flexible transmission lines is another important aspect of research in this area. In [8] and [9], probe feeds were realized using SMA connectors through the ground planes. Such coaxial probe feeds are convenient for modeling, manufacturing and testing, but not necessarily appropriate for practical wearable applications due to their non-planar structure. Alternatively, [10] introduced an aperture-coupling feed structure for a wearable patch antenna. This two-layer-substrate structure obviously increased the complexity of the alignment, and a second ground plane was required for the isolation between the radiating elements and the human body.

This paper introduces a novel design of a rectangular folded half-mode cavity antenna in textile technology for wearable applications. The proposed geometry takes inspiration from preliminary investigations of extreme 180° bending (folding) shown in [11] and the folded SIW cavity-backed patch antenna introduced in [12], and it presents two advantages: i) the folding reduces one dimension of the antenna allowing integration with clothing for cases where an elongated shape is preferable; and ii) it offers a convenient and practical feeding method for the half-mode cavity by a (textile) shielded stripline. The proposed concept has been realized in textile technology using computerized embroidery for a design operating at 2.45 GHz in the ISM band. The agreement of measured performance with simulations validates the concept. Furthermore, the antenna is well isolated from coupling to the human body and is shown to be resilient to bending effects because of its radiation mechanism as a magnetic dipole on a ground plane.

II. Effects of Folding for a Half-Mode Cavity

We start by considering a rectangular half-mode cavity antenna as shown in Fig. 1(a). Other cavity shapes are in principle possible, but the rectangular shape offers simple design and fabrication. Provided a shallow cavity height $h \ll \lambda$, the resonance frequency and internal E-field distribution for the fundamental $TM^z_{1,0.5,0}$ mode of this cavity can be approximated as [9]:

$$f_r = \frac{c}{2\sqrt{\epsilon_r}}\sqrt{\frac{1}{4a^2}+\frac{1}{b^2}},\ E_z \propto \cos\left(\frac{\pi y}{2a}\right)\sin\left(\frac{\pi x}{b}\right) \qquad (1)$$

where ϵ_r is the relative permittivity of the substrate, while a and b represent the cavity half-width and length, respectively.

F. X. Liu is with School of Information and Electrical Engineering, China University of Mining and Technology, Xuzhou, Jiangsu 221008, P. R. China, and was a visiting scholar with the School of Electrical and Electronic Engineering at University of Adelaide, when this work was performed. e-mail: liufengxue@gmail.com

Z. Xu is with the School of Information and Electrical Engineering, China University of Mining and Technology, Xuzhou, Jiangsu 221008, P. R. China.

D. C. Ranasinghe and C. Fumeaux are with the School of Electrical and Electronic Engineering, the University of Adelaide, Adelaide, SA 5005, Australia.

This work is supported by the Australian Research Council (ARC) under Discovery Project DP160103039 and China Scholarship Council.

Manuscript received XX XX, 201X; revised XX XX, 201X.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/LAWP.2016.2524458, IEEE Antennas and Wireless Propagation Letters

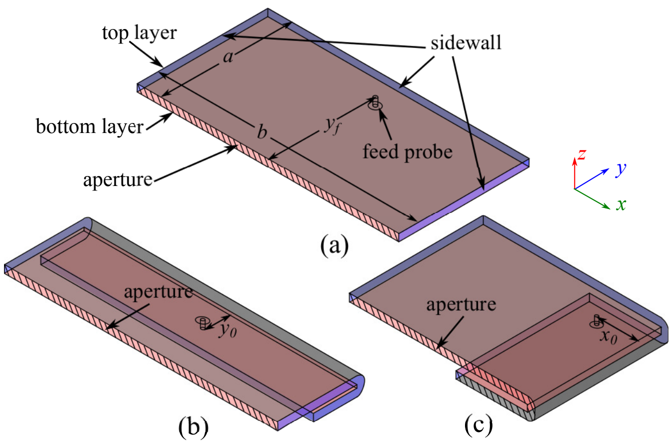

Fig. 1. Structures of ideal half-mode cavity antenna in planar condition (a) and folding with an axis in direction 1 (b) and direction 2 (c).

The common substrate materials for wearable antennas include felt, fleece, leather and foam. According to [13], a fleece substrate leads to a radiation efficiency of around 50% at 1 GHz. According to [14], the use of leather substrate for a patch antenna resulted in efficiencies below 40% over a 2.35-2.425 GHz band. The authors in [8] introduced a textile half-mode cavity antenna with Cuming Microwave foam PF-4 (ε_r = 1.06) substrate with a simulated antenna efficiency well above 90%. In this letter, the substrate is also selected to be Cuming Microwave foam PF-4 in order to obtain a high efficiency. For initial modeling in this section, the foam loss is neglected, and ideal straight vertical sidewalls made of perfectly conducting material are considered (Fig. 1). The ground plane and the top layer are set to the same size, and a half-square cavity shape is chosen, i.e., $a = b/2$. For a fundamental resonance at 2.45 GHz, the proposed ideal half-mode cavity is then 41.4 $\times$ 82.8 mm^2 with a thickness h = 1.6 mm and a feed point y_f = 35.4 mm.

Using fixed cavity dimensions and the feeding position of the planar configuration, two folding axes can be defined, namely in direction 1 for the folding with the axis parallel to the direction of the aperture and direction 2 perpendicular to it. The simulated reflection coefficient $|S_{11}|$ for various folding locations are shown in Fig. 2. The parameters x_0 and y_0 are defined as the distances between the feed point and the folding axis in x- and y-directions respectively (Fig. 1(c) & (b)).

The different curves in Fig. 2(a) have been simulated for different values of y_0. Positive value of y_0 mean that the folding axis is located between the backwall and the feeding position, while negative values represent the scenarios where the folding axis is located between the cavity aperture and the feeding position. Even when the folding axis is close to the feeding position, the simulated S_{11} curves show high similarity with that of the planar condition. The minor shift in resonance frequency can be explained by a change of the effective cavity dimension in the folding process.

The results for the second folding direction are shown in Fig. 2(b) for different positions of the folding axis x_0. In contrast to the first folding direction, folding in the direction 2 dramatically affects the matching. Since the radiating aperture can be seen as an equivalent magnetic dipole [8], a simple interpretation is that this equivalent dipole is separated into two

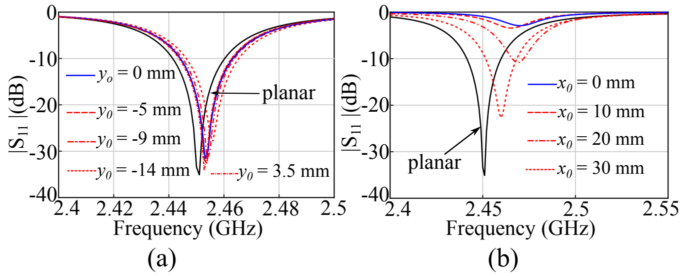

Fig. 2. Simulated reflection coefficients in (a) folding direction 1 as a function of y_0 and (b) folding direction 2 as a function of x_0.

parts with magnetic currents flowing in opposite directions. In the limit case where the folding is in the center of the antenna ($x_0 = 0$), a nearly full reflection at the feed can be observed in Fig. 2(b). Interestingly, the internal field almost remains the same in this scenario, both in terms of the distribution and the strength simulations not shown for brevity). It can be explained that the radiations of the separated halves of the magnetic dipole cancel out and thus the energy resonates in the near field without being radiated into the far field.

III. Folded Half-Mode Cavity Antenna With a Shielded Stripline Feed

As analyzed in previous sections, the folding of the cavity in direction 1 with the axis directly across the feeding position does not degrade the matching compared to the ideal planar half-mode cavity. This finding provides the opportunity to replace the impractical coaxial feeding through the ground plane by a practical planar feeding for the half-mode cavity antenna. The folded structure can be conveniently fed through the folding side using a shielded textile stripline structure. Based on this concept, a structure optimization based on more detailed simulations is carried out in this section. The design requires taking into account material imperfections and particularities of the fabrication in textile antenna technologies, including embroidery of the walls.

Thus, in the following detailed simulations, the loss of the foam substrate is considered in modeling with a loss tangent $\tan\delta$ = 0.0001 as provided by the manufacturer on the PF-4 data sheet. The top layer, middle layer and ground plane are all made of conductive fabric NCS95R-CR with a sheet resistance of 0.04 $\Omega/\square$ as empirically measured in [15]. The ground plane is set arbitrarily to be 120 $\times$ 120 mm^2 to guarantee the isolation. The vertical sidewalls are formed by linearly embroidered conductive thread Shieldit 117/17 2PLY applied in 5 passes with 1 mm stitching spacing. These sidewalls are modeled as lossy planes with an equivalent surface resistance of 1 $\Omega/\square$ as obtained through independent practical measurements and parameter studies. Because the substrate compression at the seams influences the resonance frequency and decreases the bandwidth [8], it is therefore also considered in modeling with the empirically determined shape and dimensions measured as shown in the insets of Fig. 3.

The textile shielded stripline introduced in [15] has a high flexibility and can be considered as a realization of semi-planar "coaxial" transmission line, with good transmitting performance demonstrated from DC to 8 GHz. In the current antenna geometry, the feeding with the stripline is formed

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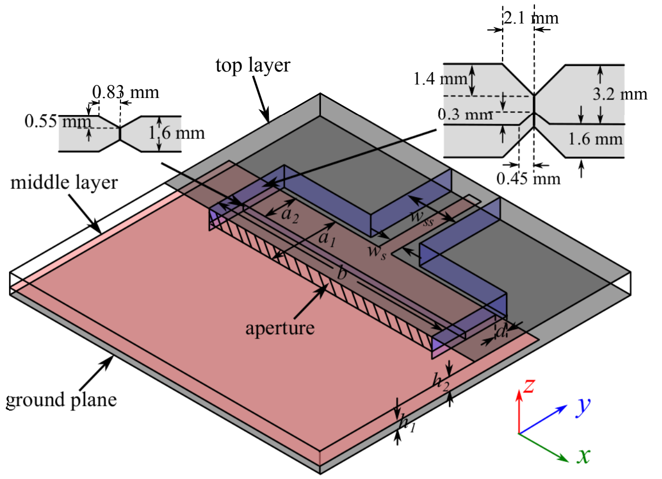

Fig. 3. Structure of the folded half-mode cavity antenna. The insets show the seam compression for two cases, namely on the left for a single layer seam, and on the right for a double layer seam.

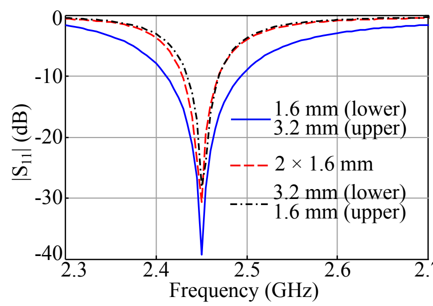

Fig. 4. Simulated S_{11} curves with different thicknesses of the lower and upper substrates.

by the same conductive fabric, as the antenna intrinsically include three conductive layers. The two sidewalls of its shield are conveniently formed by linear embroidery using the same conductive thread. The dimensions of the stripline and the shield are selected to be w_s = 4.5 mm, w_{ss} = 20 mm for a characteristic impedance of 50 Ohm. The folding edge of the antenna structure is also patterned through embroidery, thus the fabrication procedure is relatively straightforward, despite requiring three layers.

The maximum height of the prototype is 5 mm because of the mechanical limit of the embroidery machine. Considering that the first two low thicknesses of PF-4 foam are 1.6 mm and 3.2 mm, the potential combinations of 2 × 1.6 mm, 3.2 (lower substrate) + 1.6 mm (upper substrate) and 1.6 (lower) + 3.2 mm (upper) are considered in the following simulations. For each scenario, all dimension parameters are optimized to achieve impedance matching at 2.45 GHz. As shown in Fig. 4, the combination of h_1 = 1.6 mm and h_2 = 3.2 mm leads to the largest -10 dB reflection coefficient bandwidth of 3.3%, demonstrating that the height of the open aperture (i.e. of the upper substrate) mainly determines the bandwidth. Therefore, this substrate combination is selected for the final design to balance the required bandwidth and a low thickness. The dimensions parameters are set as followed: a_1 = 24.8 mm, a_2 = 16.2 mm, d = 2 mm, $b = 2(a_1 + a_2 + d)$ = 86 mm.

IV. Measurement

A prototype of this design has been fabricated as shown in Fig. 5. The rectangular cavity shape allows realizing the outer sidewalls for both layers in a single step. For connection to the measurement apparatus, a SMA connector is applied at the end of the feed stripline. For practical applications, other connection methods, e.g. the complementary overlap [16], can be applied. The reflection coefficient and radiation patterns are measured with a network analyzer in an anechoic chamber. The solid red curve in Fig. 6 represents the measured reflection coefficient of the prototype. The resonance frequency is measured to be 2.425 GHz. The slight frequency shift from desired 2.45 GHz can be explained by the limitation of fabrication accuracy. For practical applications, higher accuracies in the whole fabrication procedures, especially in the E-thread embroidery [17], might be required. The measured bandwidth of approximately 2.38-2.48 GHz provides good coverage of the ISM band. The measured bandwidth is wider than simulations due to underestimated losses in the structure and some unaccounted loss from textile glue and conductive epoxy at the contact to the SMA connector. An additional measurement of the reflection coefficient of the prototype on a human body is also provided. The resonance frequency and bandwidth are barely changed with the human body directly contacting the ground plane. This confirms its excellent electromagnetic isolation from the body of the wearer. According to additional simulations, the textile ground plane can be reduced to 60 mm in y direction without significantly degrading the antenna performance. We also note that the ground plane may be extended through weaving a loose mesh through the clothing material. Our design, in comparison to a planar structure, shrinks the 2D footprint of the antenna in one direction but at the expense of an increase in thickness.

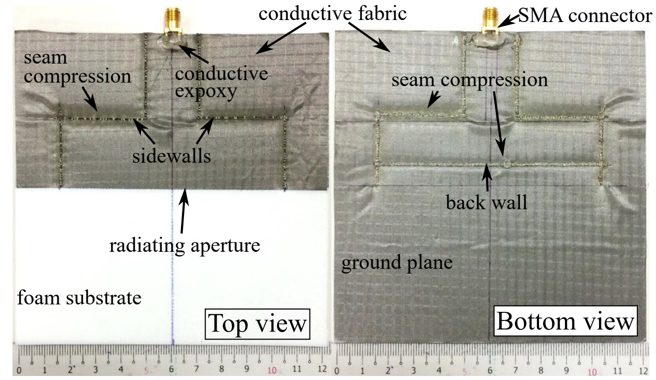

Fig. 5. Prototype fabricated with textile materials. A SMA connector is applied for antenna measurement.

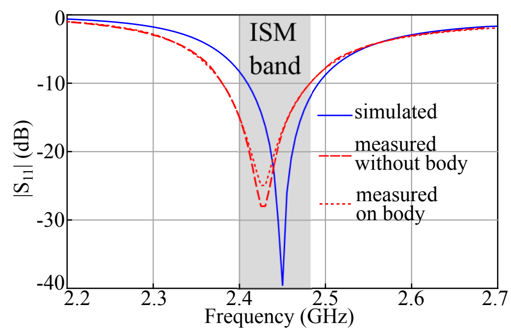

Fig. 6. Simulated and measured S_{11} curves of the folded half-mode cavity antenna with a shielded stripline feed.

For wearable applications, the resilience of the antenna

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performance to bending conditions is of importance and needs to be investigated. For the proposed folded geometry, bending tests are carried out and the measured reflection coefficients are presented in Fig. 7. In the figure, cylindrical bending conditions with two directions identically defined as in Section II are investigated. The measured reflection coefficients reveal similar properties compared to the unfolded counterpart in Fig. 7: the effect from bending in direction 1 is generally acceptable, with a frequency shift appearing for smaller bending radii. In contrast, bending in direction 2 leads to a greater impedance mismatch. To avoid a malfunction of the proposed antenna due to bending in this scenario, it is important to choose the right location and orientation of the antenna in practical applications.

To further validate the design, the measured realized gain patterns at the matched frequency of 2.425 GHz are provided in Fig. 8. The measured patterns show the expected shapes of a horizontal magnetic dipole above a finite ground and a reasonable agreement with the simulated results. The simulated and measured maximum gains are 7.6 dBi and 7.1 dBi, respectively. The simulated radiation efficiency reaches 95% and the 0.5 dB lower gain in measurement compared to simulation suggests a real-world efficiency of around 85%. The use of a cheaper felt substrate is possible, but simulations predict that the radiation efficiency for our proposed geometry would decrease to about 55%.

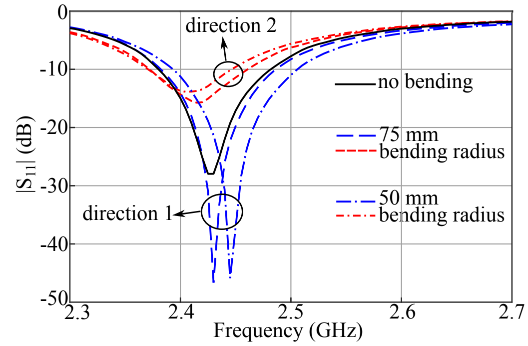

Fig. 7. Measured S_{11} curves under different bending conditions.

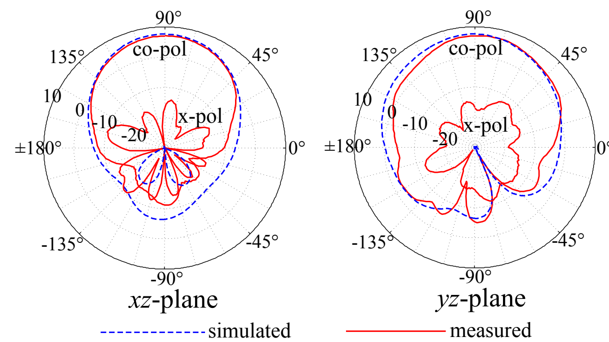

Fig. 8. Simulated and measured co- and cross-polarized gain patterns at the matched frequency of 2.425 GHz in xz-plane and yz-plane.

V. Conclusion

A folded rectangular half-mode substrate-integrated cavity antenna with a shielded stripline feed has been presented and fabricated with flexible textile materials and simple computerized embroidery. The proposed antenna not only maintains the advantages of the planar half-mode cavity antenna, but also exhibits a higher compactness because of its folded geometry. Importantly, the folding geometry allows seamless feeding with a textile stripline through the folding wall, and thus is able to better satisfy the requirements of planar designs. Besides, it can also be easily fabricated with the same method and materials as the full cavity counterpart, and thus it remains flexible. The measured results show stable coverage over the desired 2.45 GHz ISM band with negligible effects from human body. The radiation patterns show the expected characteristics of an equivalent magnetic dipole above a finite ground, as confirmed through prototype measurements. The very wide main beam in broadside direction provides a wide coverage ideal for wearable antenna designs.

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