Textile Folded Half-Mode Substrate-Integrated Cavity Antenna

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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 cavity by a (textile) shielded stripline. The proposed concept has been realized in textile technology using computerized embroidery using copper tape, conductive ink or metalized 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 \( TM_{1,0,5,0} \) mode of this cavity can be approximated as [9]:

\[
f_r = \frac{c}{2}\sqrt{\varepsilon_r} \left( \frac{1}{4a^2} + \frac{1}{b^2} \right) E_z \propto \cos \left( \frac{\pi y}{2a} \right) \sin \left( \frac{\pi x}{b} \right) \tag{1}\]

where \( \varepsilon_r \) is the relative permittivity of the substrate, while \( a \) and \( b \) represent the cavity half-width and length, respectively.
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 2.35-2.45 GHz band. The authors in [8] introduced a textile half-patch antenna, which resulted in efficiencies below 40% over a 2.35-2.45 GHz band. The use of leather substrate for a patch antenna leads to a radiation efficiency of around 50% depending on the material properties. According to [8], the use of foam substrate is considered in modeling with a loss tangent of 0.0001 as provided by the manufacturer on the PF-4 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 Ω as empirically measured in [15]. The ground plane is set arbitrarily to be 120 mm × 120 mm 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 Ω 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.

In this section, 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.

This analysis and the following detailed simulations, the loss of the foam substrate is considered in modeling with a loss tangent tan δ = 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 Ω as empirically measured in [15]. The ground plane is set arbitrarily to be 120 × 120 mm² 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 Ω 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 performing demonstrated from DC to 8 GHz. In the current antenna geometry, the feeding with the stripline is formed...
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, extended through weaving a loose mesh through the clothing material. Our design, in comparison to a planar structure,
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%.

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.

REFERENCES