Wearable Dual-Band Stripline-Fed Half-Mode Substrate-Integrated Cavity Antenna

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A low-profile dual-band half-mode substrate-integrated cavity antenna with a fully shielded textile feeding mechanism is presented for wearable applications. The antenna operates at the lower and upper microwave industrial, scientific and medical (ISM) bands. The cavity geometry is accurately defined with conducting thread through computerized embroidery. Design guidelines are developed for a practical realization. Good agreement between simulated and measured results validates the proposed structure.

Introduction: Wearable electronics have garnered significant attention within the research community for their potential applications in healthcare, personal and military communications. An integral component of the proposed wearable electronics systems are the antennas which need to be flexible, low profile, mechanically robust whilst being unaffected by the presence of the human body.

In the context of medical applications it is often desirable to have a dual-band antenna to cover distinct communication bands for various requirements such as on-body and off-body propagation [1]. A dual-band fully textile wearable antenna structure was developed in [2] by combining a coplanar patch antenna with an EBG (electromagnetic bandgap) structure in a multilayer fabrication process. To obtain size reduction and simpler fabrication a metamaterial inspired structure exploiting composite right-hand left-hand transmission line (CLRH-TL) was explored in [3], albeit at the cost of reduced gain. With the aim of achieving both high radiation efficiency and isolation from the body a dual band magneto-electric dipole was proposed in [4], however in this case the feeding structure is non-trivial.

An alternative approach to meeting the multiband requirements whilst preserving a simple fabrication procedure is through the use of computerized embroidery to realize conductive paths as done in [5, 6, 7]. These solutions often lack a ground plane making them not suitable for operation in close proximity to the human body, as dielectric loading leads to severe de-tuning of the antenna. In this sense, cavity resonators offer the advantage of intrinsically including a shielding ground plane.

A textile half-mode substrate-integrated cavity antenna was demonstrated in [8]. Based on a similar concept, a textile dual-band half-mode substrate-integrated cavity antenna was introduced in [9]. Both these realizations were fed by a coaxial probe through the ground plane. This letter presents a highly flexible dual-band substrate-integrated cavity antenna with a fully textile feedline [12] capable of operating at the lower and upper microwave ISM bands.

Specifications: The antenna must be low profile, flexible and unobtrusive to the wearer to minimize discomfort. In addition the antenna must also cover the lower and upper microwave ISM bands (2.45 GHz and 5.8 GHz bands respectively) with a required fractional bandwidth of 4.1% and 2.6%. The antenna was manufactured using PF-4 foam which is a highly flexible low-loss substrate with a relative permittivity ϵ_r = 1.06 and a dielectric loss tanget of tan δ = 0.0001. The conductive layers are formed through Marktek NCS95R-CR metallized fabric with an empirically determined DC sheet resistance of 0.04 Ω/□. The conductive yarns used to form the cavity walls are ShieldEx 117/17 2ply. The total thickness of the structure was selected as 4.8 mm to meet the bandwidth requirements.

Proposed topology: The proposed antenna geometry is shown in Figure 1. To meet the aforementioned requirements a half-mode substrate-integrated cavity, adapted from [11], is used with an additional slot cut on the top layer to generate another band of operation. The excitation of cavity and slot resonances is achieved through a shielded stripline. The cavity operates at the lower microwave ISM band whilst the slot operates at the upper microwave ISM band.

Design: The initial dimensions of the resonant half-mode substrate-integrated cavity can be determined through the standard design guidelines provided in [8]. The width of the stripline (F_W) is determined for 50 Ω characteristic impedance whilst the parameters C_B, W_T and

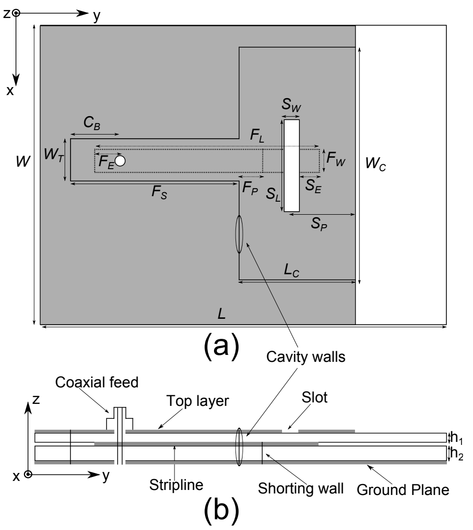

Fig. 1: Geometry of proposed antenna (a) Top View, (b) Side View. The optimized parameters are C_B = 4 mm, F_E = 2 mm, W_T = 12 mm, F_S = 20 mm, W_C = 81.5 mm, L_C = 35.5 mm, F_P = 9 mm, F_L = 40 mm, F_W = 6 mm, S_L = 18 mm, S_W = 1 mm, S_E = 5.2 mm, S_P = 18 mm, h_1 = 1.6 mm, h_2 = 3.2 mm, W = 100 mm, L = 95 mm

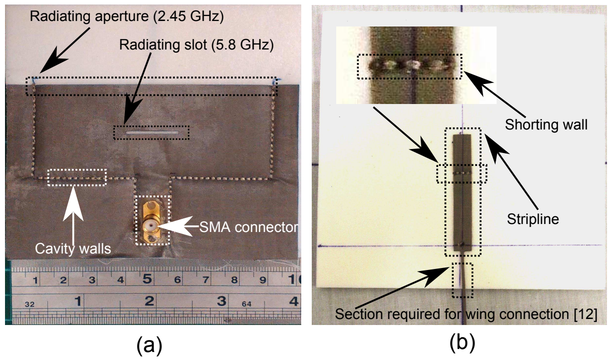

Fig. 2: Proposed Structure, (a) Top view, (b) Middle layer view with a zoom on shorting wall on the central stripline shown in inset.

F_E are chosen to provide a matched transition to the coaxial connector. However, exciting the half-mode substrate-integrated cavity through a stripline requires a transition from a stripline TEM mode to a waveguide mode. Viewing a stripline as a flattened coaxial line, the well-known method of connecting the inner pin of the coaxial line (in this case the central strip) to the ground plane [10] can be used. In this realization connecting the inner pin to the ground plane can be achieved by adding an embroidery wall from the stripline to the ground plane as shown in the inset in Figure 2(b). The shorting position (F_P) within the cavity needs to be optimized for a 50 Ω match to the cavity mode.

The design of the slot radiator starts by cutting a slot of dimension $\lambda_g/2$ on the top layer (S_L) whilst the slot width (S_W) can be tuned for enhanced bandwidth. The slot dimensions will need to be re-optimized as the cavity is larger than necessary at the higher frequency. Matching of the slot can be achieved by extending the stripline a few millimeters beyond the slot (S_E).

Addition of the slot and excitation of the slot will affect the matching of the half-mode substrate-integrated cavity, consequently re-optimization of the shorting wall position for excitation of the half-mode substrate-integrated cavity is required. The effect of seam compression must also be considered as this will induce a frequency shift whilst simultaneously reducing the ohmic losses in the cavity [11].

Fabrication: The embroidery was done with a stitch spacing of 2 mm repeated five times to create a dense wall. The empirically determined effective DC sheet resistance for the selected density is 2.7 Ω/□ and 10 Ω/□ for 3.2 mm and 4.8 mm respectively. The DC sheet resistance values can be used to calculate an effective frequency dependent sheet resistance [12]. The fabricated prototype is shown in Figure 2. To

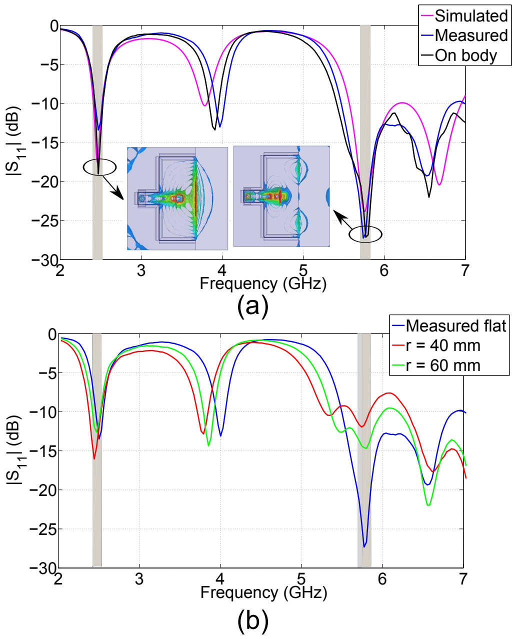

Fig. 3: Simulated and measured reflection coefficient for free space and on-body scenarios, (a) Simulated and measure free-space reflection coefficient in planar configuration, with comarision to on-body measurements. The inset shows the instantaneous electric field magnitude at the two resonant bands. (b) Measured reflection coefficient for antenna in flat scenario and bent around cylinders of radius of 40 mm and 60 mm respectively.

guarantee a reliable connection, the wing connection strategy from [13] is adopted for connecting the SMA connector to the textile stripline.

Results: Figure 3 shows the simulated and measured reflection coefficient. The simulated results in Figure 3 shows the two notches at the desired frequencies of operation, with an additional dip at approximately 3.7 GHz. This additional resonance is due to a $\lambda/4$ transmission line mode on the stripline section within the cavity which is coupled into the cavity through the shorting wall. The measured results show a clear notch at the fundamental cavity mode (2.45 GHz) with a slight frequency drift which is attributed to fabrication tolerances. An excellent match is achieved at the upper microwave ISM band. Figure 3(b) shows the measured reflection coefficient with the antenna in a flat condition and when bent (along the zx plane) around cylinders of radii 40 mm and 60 mm respectively. The reflection coefficient remains largely unchanged during bending and thus indicating the antenna is robust for wearable applications.

The gain patterns are shown in Figure 4. The patterns observed in the E and H planes are typical of radiation from a magnetic dipole. The slight distortion of the gain pattern observed at the higher frequency band is attributed to the interference effects from the magnetic dipole from the half-mode substrate-integrated cavity aperture. Note that in the zy plane the simulated cross-polarization is below -40 dB and is not observable on the scale. Generally, good agreement is observed between the simulated and measured results. The slightly higher than simulated cross-polarization in all cases is attributed to cable and connector effects. The peak measured gain is 5.30 dBi at 2.47 GHz and 4.09 dBi at 5.74 GHz (occurring off normal incidence). A slight discrepancy to simulated values in both cases is attributed to connector effects. The simulated efficiency at 2.47 GHz is 86% with a slightly smaller measured efficiency of 84%. At the higher band the simulated and measured efficiencies are 82% and 80% respectively.

Conclusion: A fully textile dual-band antenna based on the half-mode substrate integrated-cavity has been developed. A simple manufacturing process and a fully shielded textile feed allowing for simple integration with electronic circuitry are the main advantages of the proposed structure. Design guidelines have been developed to allow for a practical realization. A good agreement between simulated and measured results validates the proposed structure.

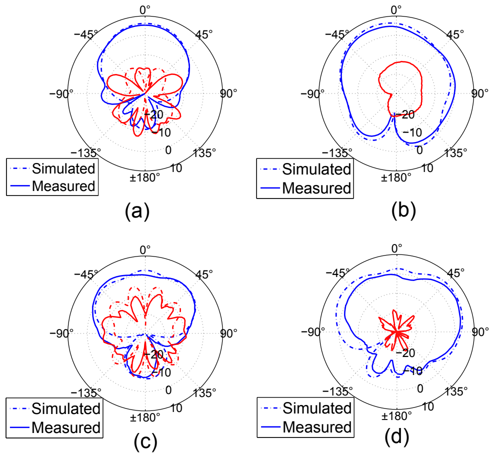

Fig. 4: Simulated and measured gains at 2.47 GHz and 5.74 GHz. (a) ZX plane - 2.47 GHz, (b) ZY plane - 2.47 GHz, (c) ZX plane - 5.74 GHz, (d) ZY plane - 5.74 GHz.

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