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High efficient dual band stacked antennas integrated into rescue helmets for indoor communication

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Research Paper

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Abstract

A dual-band stacked antenna integrated with a rescue helmet is proposed for WLAN applications. The cross slot aperture feeding technique enables the antenna to support dual-band operation at 2.4 and 5 GHz. On the ground plane, two slots are formed, perpendicular to each other and of different lengths. Four dielectric layers of different permittivity are stacked over this cross slot to attain the desired frequency bands. Under free space condition, the radiator yields 7% (2.31–2.48 GHz), 15.87% (5.12–6 GHz) 10 dB return loss bandwidth (BW). The use of low loss dielectric layers on the slots also provides a high antenna efficiency and moderate gain at both frequency bands. The small dimension of antenna encourages its use as a wearable helmet antenna. Antenna performances are observed under wearable condition. For assessing human exposure to RF electromagnetic fields, SAR evaluations are conducted at both 2.4 and 5 GHz WLAN bands.

Introduction

Nowadays, real-time wireless communication is essential for rescuers on a mission [1]. So many future projects are aiming to make a wearable system for rescue persons deployed in battlefield or rescue operations. Rescuers on a mission need to wear helmets for personal protection and should always be connected wirelessly with the control room for continuous guidance. Both the issues of personal protection and real-time communication can be addressed by an integrated helmet antenna. There are many situations in which rescuers are bound to carry out their mission indoor. But transmission via satellite cannot support indoor communication directly. So, supportive radio communication, along with satellite communication, is required to assist rescuers in both outdoor and indoor environments. Due to its noise-resistant nature for indoor environment, WLAN standards could be a good choice for this supportive communication. The antenna must support a narrow lower band (2.4–2.484 GHz) and a broad upper band (5.15–5.85 GHz) for WLAN applications [2]. So a dual band helmet integrated antenna can cater both protection and wireless communication for rescuers. Research is undertaken to develop a protruded antenna on military helmet [3] to operate between 800 and 2300 MHz. But antennas with any protruded part may not be suitable for wearable applications. So, compact, low profile antennas have been developed on military beret [4] for indoor/outdoor positioning with ISM (915 MHz) and GPS L1 (1.575 GHz) bands. A flexible military beret, however, cannot replace the helmet of a rescuer. Rescuers can also use body worn antennas for the purpose of radio communication. Over the years, several radiator structures have been placed on flexible textile substrates to develop wearable antennas [5–7]. But wearable antennas on flexible material suffer from deviation in characteristics due to body bending and crumpling of the clothes [8]. Therefore, the performance of flexible antennas cannot be claimed reliable without conducting crumpling analysis under bending conditions. To avoid the issues of flexible antennas, research has been started to introduce a rigid antenna structure for wearable applications. A rigid antenna of such type is presented for wearable applications in [9]. With a multi input multi output (MIMO) structure, it is able to hold only the lower band of WLAN communication.

In this paper, we propose a semi rigid, lightweight, aperture fed, stacked microstrip wearable helmet antenna for supporting both WLAN lower band and upper band applications. A lightweight but semi rigid material Arlon foam clad 100 is used as the substrate for the proposed antenna to avoid the behavioral irregularities of the flexible textile antenna due to different body gestures. Aperture feeding of antenna is considered to prevent feed network radiation from interfering with the main radiation pattern. Four layers of dielectric slabs of two different permittivity are stacked on the ground plane comprising a cross slot structure to include two different WLAN bands. Initially, simulation tools are used for developing and investigating the antenna characteristics. Thereafter, a prototype structure of this antenna

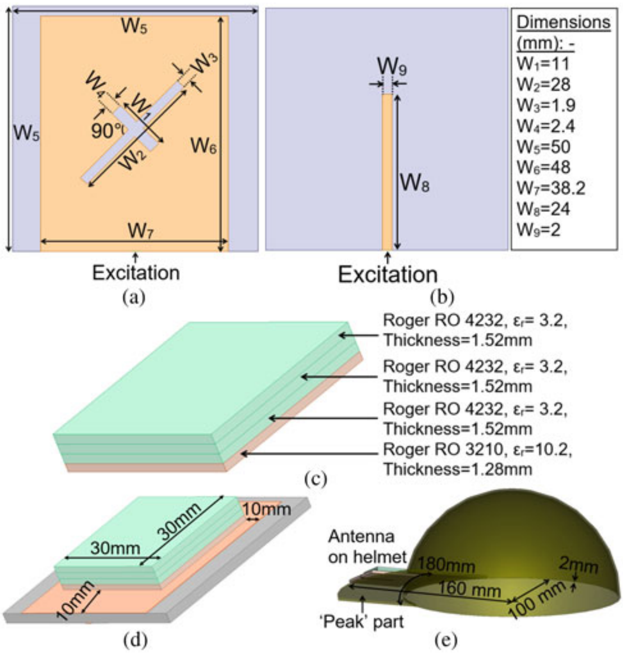

Fig. 1. Antenna geometry: (a) front view without dielectric layers, (b) back view, (c) stack organization of dielectric layers, (d) complete simulated antenna structure, and (e) integrated helmet antenna.

is fabricated for conducting measurements of scattering parameters and far field radiation pattern. Furthermore, a helmet and a human head model are included with the antenna to monitor application-specific performance of the proposed antenna. SAR assessment of the antenna is carried out to ensure RF radiation safety under wearable condition.

Antenna and helmet modeling

A double-sided copper laminated lightweight semi rigid material Arlon Foam Clad 100 ($\varepsilon_r = 1.20$, $\tan\delta = 0.004$, thickness = 2.43 mm) is considered as the substrate of the proposed antenna. Figures 1(a) and 1(b) show the antenna geometry without including dielectric slabs. A cross slot of unequal slot length on the ground plane and one microstrip line at the bottom of the substrate is created to allow the aperture feeding. The substrate structure has an overall dimension of $50 \times 50 \times 2.43\ \text{mm}^3$. The length and width of this structure are determined by the available space of its final position, while the thickness is considered depending on the material available. Figure 1(c) shows the details of stacked layers of dielectric materials to bring the desired resonating frequencies. To address both lower and upper WLAN bands, four layers of specified permittivity are required. The thickness of each dielectric layer is considered depending on material availability. The dimensions of the slots, the microstrip line, and the stacked layers are defined according to the optimization results obtained from repeated iterations. Figure 1(d) shows the complete simulated model of the proposed antenna model. The complete simulated structure, including the antenna and a rescue helmet, is displayed in Fig. 1(e). A cap shape structure is modeled for rescue helmet with simulation, and the antenna is kept on its "peak" part. Acrylonitrile-Butadiene Styrene ($\varepsilon_r = 2.8$, $\tan\delta = 0.004$) of thickness 2 mm is used as material [10, 11] for this helmet modeling.

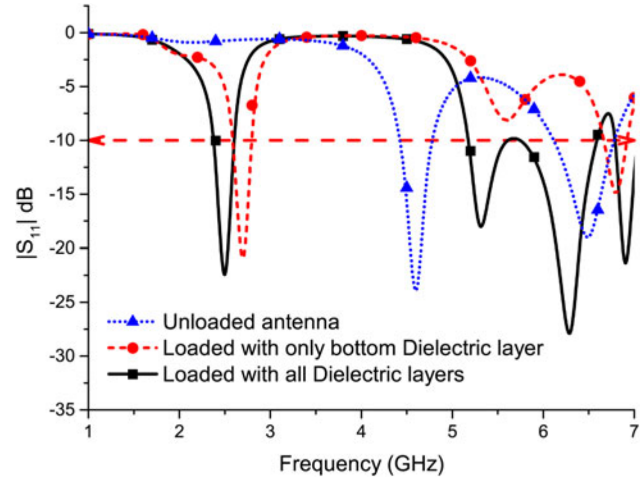

Fig. 2. Effect of stacked layers on S_{11}.

Effect of stacked layers on antenna performance

To investigate the effect of different stacked layers on the performance of proposed antenna, analysis has been carried out in three stages:

Stage 1: Cross aperture structure without dielectric layer (unloaded antenna).
Stage 2: Cross aperture structure with only bottom dielectric layer.
Stage 3: Cross aperture structure with all four dielectric layers.

Two cross slots of unequal length in the ground plane are responsible for introducing two resonant frequencies at 4.65 and 6.5 GHz. The longer slot is for lower resonant frequency, and the shorter slot is for higher resonant frequency. The bottom dielectric layer (Roger RO 3210, $\varepsilon_r = 10.2$, loss tangent $\tan\delta = 0.003$, thickness = 1.28 mm) of four layer stack causes the lower resonating frequency to shift from 4.65 to 2.4 GHz for accommodating the lower WLAN band. The challenge to incorporate the higher WLAN bands along with already obtained 2.4 GHz has been overcome by stacking three more dielectric layers of lower permittivity (Roger RO 4232, $\varepsilon_r = 3.2$, loss tangent $\tan\delta = 0.0018$, thickness = 1.52 mm) on the bottom layer. Thus non-homogeneous stacking of layers brings the two WLAN bands in operation. Figure 2 illustrates the loading effect of all dielectric layers incisively.

Parametric analysis

Figures 3(a) and 3(b) show the effect of slot length W_1 and W_2 on the WLAN frequency bands. The change in W_1 mainly affects the higher WLAN band. In the range 9–13 mm, W_1 = 11 mm stands as the best possible slot length for higher WLAN band. Similarly, in the range of 26–30 mm, desired lower WLAN band is achieved with W_2 = 28 mm only.

Measurements and result analysis

CST MWS software is used for simulation of the proposed antenna. Repetitive simulation is carried out to achieve optimization before starting the fabrication process. Simulation result along with experimental result for S_{11} are presented in Fig. 4.

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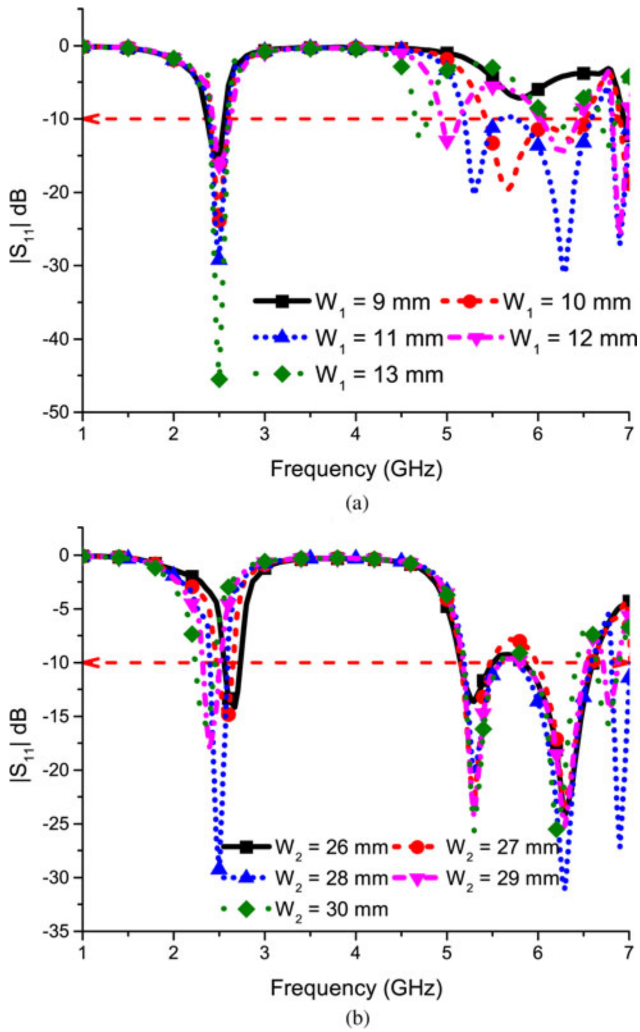

Fig. 3. Parametric analysis: (a) effect of length W_1 on S_{11} and (b) effect of length W_2 on S_{11}.

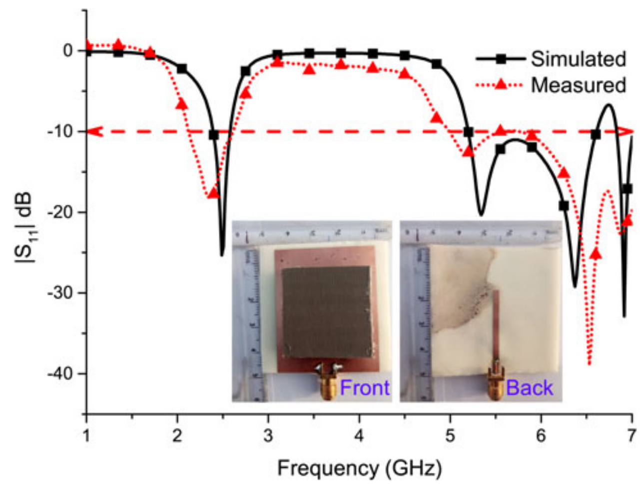

Fig. 4. Simulated and measured S_{11} in free space.

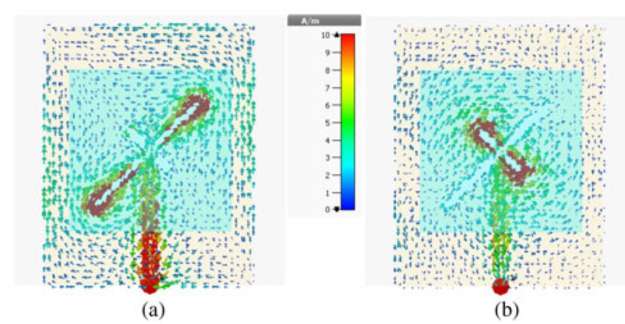

Fig. 5. Current distribution: (a) 2.4 GHz and (b) 5.2 GHz.

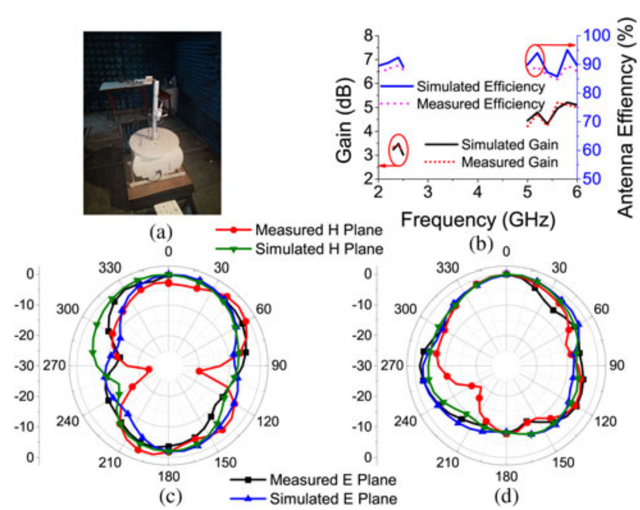

Fig. 6. Far field characteristics: (a) experimental set up, (b) antenna gain and efficiency, (c) E plane and H plane radiation pattern at 2.4 GHz, and (d) E plane and H plane radiation pattern at 5.2 GHz.

Both simulation and experimental results almost confirm 10 dB return loss bandwidth of 7% (2.31–2.48 GHz) and 15.87% (5.12–6 GHz). The current distribution confirms a path length of 28 and 11 mm for lower and upper WLAN band, respectively, as shown in Fig. 5. The far field performance of the proposed antenna in free space is measured inside an anechoic chamber with an experimental setup, as shown in Fig. 6(a). Simulated and measured gain and antenna efficiency for all the desired frequencies are included in Fig. 6(b). Significant advantages over the planar microstrip wearable antenna can be observed in terms of antenna efficiency at both WLAN bands. The normalized E plane and H plane radiation patterns at 2.4 and 5.2 GHz, as shown in Figs 6(c) and 6(d) respectively, ensure good coverage of radiation in all directions.

Comparison with other wearable antennas

The proposed antenna is compared with some other wearable antennas for identifying its significance and limitations. Table I includes a detailed discussion on antenna dimension, operating frequency, antenna bandwidth, antenna gain, and antenna efficiency for some wearable antennas. From this discussion, it could be concluded that the proposed antenna exhibits considerable gain and higher antenna efficiency than the conventional compact wearable antennas. However, thickness of proposed antenna may be an issue in some applications.

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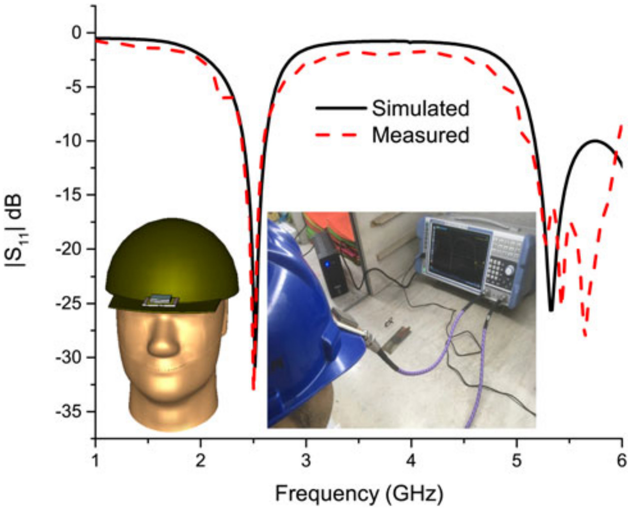

Fig. 7. S_{11} performance under wearable condition.

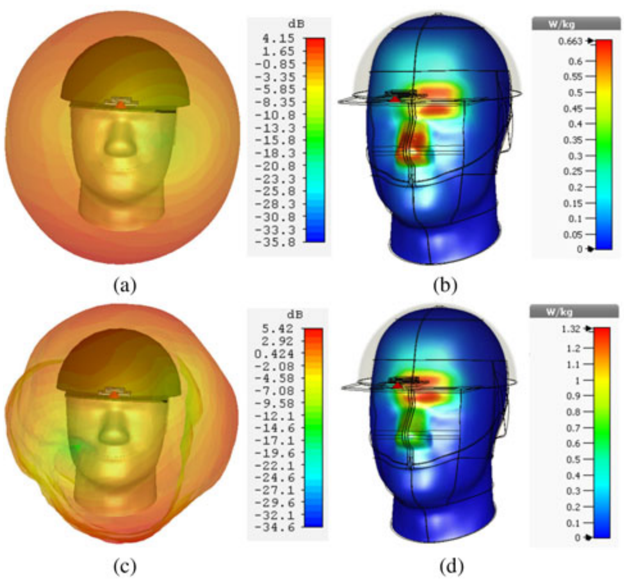

Fig. 8. Performance under wearable condition: (a) radiation pattern at 2.4 GHz, (b) SAR evaluation at 2.4 GHz, (c) radiation pattern at 5.2 GHz, and (d) SAR evaluation at 5.2 GHz.

Helmet antenna performance

In this section, the performance of the proposed antenna is observed, including a helmet and a human head model. Simulation is carried out on CST platform to observe the helmet antenna performance under wearable condition. A human head model consisting of a shell and fluid material is taken from the CST library to run the simulation. Simulated, as well as measured results for reflection coefficient under wearable condition, are presented in Fig. 7. It can be observed that the proposed antenna holds both WLAN bands under head worn condition. It also exhibits considerable enhancement in gain at both lower and higher WLAN bands, maintaining antenna efficiency still high. SAR assessment is done on both lower and upper WLAN bands to ensure the RF radiation safety norms under wearable condition. The maximum SAR amount is 0.663 W/kg at

Table 1. Performance comparison table

References	Type	Overall dimensions (mm^3)	Operating frequency (GHz)	Bandwidth (MHz)	Gain	Antenna efficiency
[2]	Low-profile dual-band stacked textile antenna	100 × 100 × 3.2	2.4, 5.1–5.9	120, 800	2.5 dB, 0–4 dB	More than 40%
[12]	UWB wearable antenna	80 × 67 × 3.4	3.68–10.1	6420	4.53 dBi	27%
[3]	UHF helmet antenna	80 × 80 × 23	0.8–2.3	1500	1.8–6.5 dBi	More than 97%
[4]	Military beret antenna	158 × 158 × 5	0.915, 1.575	26, 24	−10.96 dBi, 8.26 dBi	6.39%, 72.61%
[13]	Meta material wearable antenna	100 × 100 × 3.34	2.4	80	3.9 dB	45%
Proposed study	Compact helmet antenna	50 × 50 × 8.27	2.4, 5.12–6	170, 880	3.48 dB, 4.3–5.2 dB	89.43%, More than 85.78%

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2.4 GHz and 1.32 W/kg at 5.2 GHz, which is below the threshold of 2 W/kg for a 10 g tissue mass as per the guidelines of ICNIRP [14, 15]. Figure 8 presents the far field radiation pattern and evaluated SAR value under wearable condition for both WLAN bands on the simulation platform.

Conclusion

A dual-band stacked antenna integrated with a rescue helmet is proposed for lower and upper band WLAN applications. Its dual band operation is enabled by a cross slot created on the ground plane in aperture feeding process. Stack organization of low loss dielectric layers on the cross slot are used to achieve desired frequency bands. Under free space condition, the radiator yields 7% (2.31–2.48 GHz), 15.87% (5.12–6 GHz) 10 dB return loss bandwidth (BW). The use of low loss dielectric layers on the slots also ensures high antenna efficiency (more than 85.78%) and moderate gain (more than 3.48 dB) at both frequency bands. It is also proposed as a compact, low profile antenna implemented on a rescue helmet. The antenna performance observed under head worn conditions is found suitable for both lower and upper band WLAN communication. SAR evaluation has been carried out in both lower and upper WLAN bands for accessing human exposure to RF electromagnetic fields. The maximum amount of SAR obtained at 2.4 and 5.2 GHz is 0.663 and 1.32 W/kg, respectively, for a 10 g tissue mass.

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