Miniature Dual Band Button Antenna Using Cylindrical Dielectric Resonator Antenna for On/Off Body Communication Devices

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Abstract **─** This paper presents miniature dual-band cylindrical dielectric resonator antenna (CDRA) based on button antenna for wireless body area network (WBAN) applications. A button antenna is designed by stacking two CDRAs (low and high permittivity) fed by coaxial probe through the ground plane and penetrates the bottom CDRA. The prime contributions of using DRAs are to enhance the performance and to provide a compact size of antenna. However, the coaxial probe realizes two radiation patterns, monopole and broadside patterns. A comprehensive validation using CST microwave studio is carried out to determine the characteristics of the proposed button antenna. In addition, to ensure that the results are acceptable to the practitioner in this field, a prototype was fabricated and tested. The superiority of the proposed antenna is confirmed by possessing 39% more compact size compared to previously reported studies, efficiency of more than 63% and bandwidth of 4.9% and 6.6% for lower and upper band, respectively. This proposed design is a promising candidate to benefit on/off body communication devices operating at 2.4 and 5.6 GHz.

Index Terms **─** Button antenna, dual-band dielectric resonator antenna, on/off body communications, wearable antenna, wireless body area network (WBAN).

I. INTRODUCTION

In the latest years, it is remarkable that the wireless technologies have been grown-up rapidly and making an extensive change in electronic devices that are able to be inserted in pockets or worn such as smart glasses, wearable sensor systems, wireless medical systems [1], and smart watches. Practically and during the last decade, wearable devices have been awarded a wide consideration in a lot of operating bands such as ultra-wideband (UWB), wireless local area network (WLAN) and wireless body area network (WBAN) [2]. With the rapid and ongoing development of wearable devices, the need to design a wearable antenna with low cost, lightweight, maintenance-free and installation capability for on/off body communication is required for all modern wearable applications.

WBAN is classified into: in-body mode, on-body mode, and off-body mode [3]. In-body mode is the mode where the antennas are inserted inside the body. It needs to take into account the effects of the human body tissue. In on-body mode, the antenna is able to share data with other antennas placed on other locations on the body surface. Thus, this mode needs omnidirectional radiation pattern alongside the surface of the body [4]. However, off-body mode indicates that the antenna can communicate with stations far away from the body. Thus, it requires broadside radiation pattern [5]. In many researches of same area, wearable antennas were developed to be either flexible using textile material [2, 6-8], or robust material [9-12]. Typically for both types, the radiation element is made up of conductive material such as copper.

A number of studies concentrate on the shapes of antenna and how to obtain miniature size antenna. Authors in [13, 14] achieved a compact size for on/off body communication devices, but the antenna's performance suffered from high conductive losses which negatively influenced the efficiency. However, authors in [2, 15] studied the stability and characteristics of the materials and their effects on the performance of antenna. Both of these studies had achieved a good antenna performance suitable for body centric applications. In contrast, achieving acceptable antenna's performance while keeping the size compact is a major challenge faced nowadays.

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Button antennas have clearly several advantages over entirely textile antennas such as being easily attached on clothes or being embedded into a system [16]. In fact, button antennas are rigid in many cases and might significantly and directly impact the antenna's performance stability [17, 18].

From the above discussion, a miniature dual-band circular dielectric resonator antenna (CDRA) based on button antenna that is expected to benefit on/off body communication devices is proposed in this paper. Despite the numerous works carried out on the same subject, no previous work has thoroughly investigated using DRA as a radiation element in the same area. DRA is chosen due to the practical advantages such as a high radiation efficiency, low dielectric loss, and bandwidth [19] which can easily be controlled by using different design techniques[20, 21]. Since there is an experimental validation, this work will pave the way to integrate this work in real life application such as healthcare monitoring system.

The proposed button antenna is designed for frequencies 2.4 GHz for on body communication and 5.6 GHz for off body communication. The frequency 5.6 GHz is confirmed by the UNII (Unlicensed National Information Infrastructure) band. The UNII worldwide is used for both indoor and outdoor and it is exposed to dynamic frequency selection. The 5.6 GHz band has higher bandwidth and power and mostly used by wireless distribution systems [22]. The characteristics of the proposed button antenna are simulated and optimized using CST microwave studio. Section II introduces the geometry, elaborates the method and provides optimization of the proposed button antenna. Section III discusses the simulation and the measurement results including the comparison to previously reported works. Finally, conclusion and suggestions are provided in Section IV.

II. ANTENNA DESIGN

This section elaborates the geometry of the proposed dual-band CDRA based on button antenna for on/off-body communications. The strategy of achieving dual-band on and off radiation pattern of the proposed antenna is obtained by **a** proper modification of CDRA's size. Moreover, the resonance frequency can be adjusted by optimizing the position and length of the probe. The enhancement of this work is also demonstrated in order to improve the performances of antenna.

A. Antenna geometry

The initial structure of the proposed CDRA based on button antenna is illustrated in Fig. 1. The radiation element is a button-shaped that is made of dielectric material (ceramic) as shown in perspective view in Fig. 1 (a). The proposed antenna is fed from the bottom side by a coaxial probe, where the probe penetrates the CDRA with a height of h_p = 3 mm and is located at X = 7.8 mm from the center of the CDRA as it is shown in Fig. 1 (b). The CDRA has a radius of r = 12 mm, height of h = 9 mm, dielectric loss tangent of tanδ = 0.009 and relative permittivity $\boldsymbol{\varepsilon_d}$ = 30. The CDRA is placed on top of a Rogers RT5880 substrate that has the same radius as CDRA with relative permittivity of $\boldsymbol{\varepsilon_s}$= 2.2, dielectric loss tangent of tanδ = 0.0009, and substrate thickness of h_s = 0.254 mm.

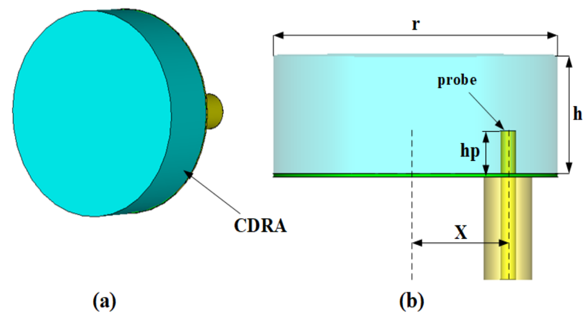


Fig. 1. Geometry of the proposed button antenna: (a) front perspective view and (b) side view.

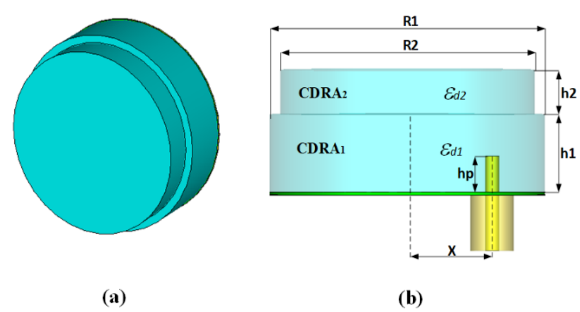


Fig. 2. Geometry of the optimized button antenna: (a) front perspective view and (b) side view.

B. Design methodology

The design has two main objectives. The first one is to obtain a very compact size dual-band CDRA based on button antenna operates in the 2.4 GHz and 5.6 GHz bands for on and off body communications respectively. The second objective is to achieve better performance of the antenna in order to maintain the specifications of on/off body communication devices.

One of the interesting features of CDRA is the size of the CDRA that is inversely proportional to the relative permittivity ($\boldsymbol{\varepsilon_d}$). Therefore, a high dielectric constant can be chosen in order to reduce the size of the DRA [23]. The theoretical resonant frequency (f_r) of the CDRA can be found from the equation (1) [24]:

$$f_r = \frac{c}{2\pi r}\left(\frac{1.6+0.513x+1.392x^2-0.575x^3+0.088x^4}{\varepsilon_d^{0.42}}\right), \quad (1)$$

where $x = R/2h$, c is the free space speed of light, r, $\boldsymbol{\varepsilon_d}$, and h are the radius, relative permittivity, and height of the CDRA, respectively.

The resonance frequency of the CDRA can be modified by adjusting the position and length of the probe. Moreover, a dual-band omnidirectional and broadside radiation patterns can be achieved by proper modification of CDRA's size. The main advantage related to penetrating the CDRA by a probe is that, a high coupling is delivered to the DR resulting in high radiation efficiency [23]. In contrast, the main drawback associated high dielectric constant of DRA is that the bandwidth is reduced as relative permittivity is increased. In this case optimization should take place.

One of the common techniques used to enhance the bandwidth is stacked DRA. The idea of stacked DRA is to place a DRA of low permittivity on a DRA of high permittivity [25, 26] as depicted in Fig. 2. The dimensions of $CDRA_1$ are $R_1 \times h_1 = 13 \times 7$ mm^2 with permittivity of $\boldsymbol{\varepsilon_{d1}}$ = 30, where the dimensions of $CDRA_2$ are $R_2 \times h_2 = 12 \times 4$ mm^2 with permittivity of $\boldsymbol{\varepsilon_{d2}}$ = 10. The height and the position (from the center of CDRA) of the probe are h_p= 3.246 mm and X = 8 mm, respectively.

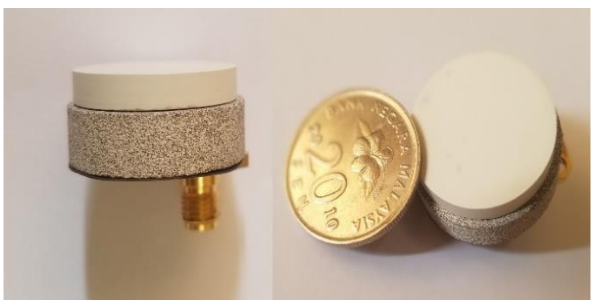


Fig. 3. Shows the fabricated prototype of button antenna, front side view (left) and side view(right).

III. RESULTS

A prototype was fabricated as illustrated in Fig. 3 to verify the proposed button antenna. For this wok, E5071C series network analyzer (NA) is used to test the reflection coefficients while anechoic chamber room used to measure the radiation pattern of the proposed button antenna.

A. Reflection coefficient and bandwidth

The characteristics of the antenna depend on the return loss which describes the matching impedance of the antenna and the amount of power coupled to the antenna around the resonance frequencies. Figure 4 shows the simulated reflection coefficient before and after optimization. Both of the designs achieve dual-band around the resonance frequencies 2.4 GHz and 5.6 GHz. Before optimization, the bandwidth for lower and upper band was 2.1% and 3.7%, respectively. After optimization, bandwidth is increased to 2.7% and 5.2% for lower and upper band, respectively.

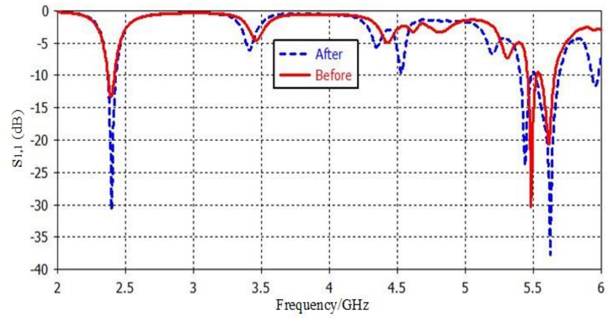


Fig. 4. Simulated reflection coefficient of the proposed button antenna before and after optimization.

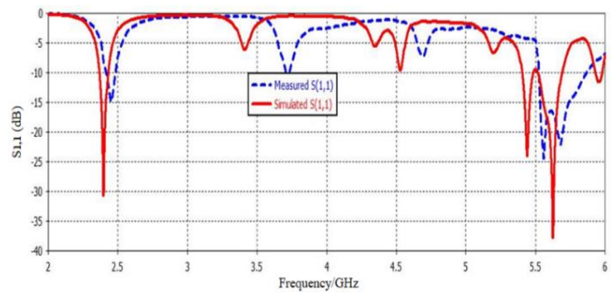


Fig. 5. Measured and simulated S-parameter of the proposed button antenna.

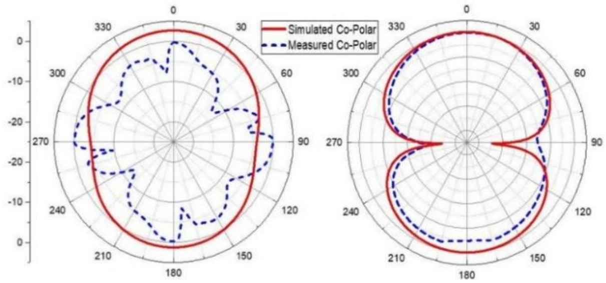
Figure 5 illustrates the measured and simulated return loss of the proposed button antenna. The result ensures that the proposed antenna functions in the dual-band at 2.4 GHz and 5.6 GHz. The result less than -10dB shows that the measured results agree with the simulated ones with wider bandwidth of 4.9% (2.38-2.5GHz) and 6.6% (5.52-5.9GHz) for the lower and upper band, respectively. There is a slightly deviation of the resonance frequency at lower band due to inaccuracy fabrication of CDRA.

B. E-field distributions

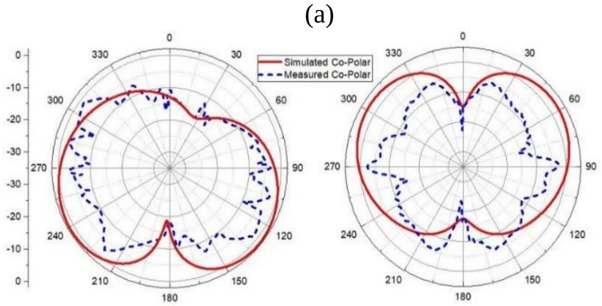
To understand the behavior of the proposed antenna, the simulated E-field distributions of operation mode at the resonance frequencies 2.4, 5.6 GHz are shown in Fig. 7. A 50Ω coaxial probe is used to excite CDRA. It has been obtained that the coaxial probe excites fundamental $HEM_{11\delta}$ (Hybrid electromagnetic) mode in the CDRA at both resonance frequencies.

C. Radiation pattern

Figure 6 illustrates the measured and simulated normalized co-polar radiation patterns in E-plane and H-plane of the proposed button antenna at 2.4GHz and 5.6GHz. It can be noticed that, the measured result verifies that the proposed button antenna has omnidirectional radiation pattern at 2.4GHz, which is expected to serve on body communications.



(a)



(b)

Fig. 6. Simulated and measured radiation patterns in E-plane (left) and H-plane (right) of the proposed button antenna at (a) 2.4 GHz and (b) 5.6 GHz.

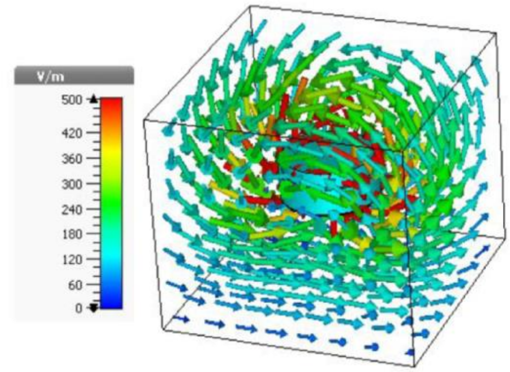
Moreover, broadside radiation pattern is obtained at 5.6GHz, which is well-suited for off body communications. Table 1 elaborates the summary of the proposed button antenna performance. The simulated peak gains are a 1.8 and 2.78 dBi at the lower and upper bands, respectively. This is due to the small ground plane. A very good simulated efficiency of 81.5% is obtained at the lower band while due to the high relative permittivity an efficiency of 64% is obtained at the upper band, which is more acceptable than the conventional dual-band antenna compares to [15]. The equivalent figures are not provided here for conciseness.

D. Comparison with previous work

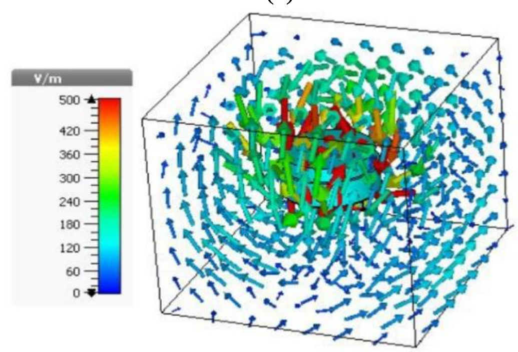
Table 2 shows the comparison between this work and the previous works. It can be remarked that the proposed button antenna has realized the smallest size more than 39% reduction compared to references. Moreover, this work has materialized both omni/broadside radiation patterns applicable for both on/off body communication applications with better performance.

Table 1: Summary of the proposed button antenna performance

Parameters	Lower Band	Upper Band
Frequency	2.4	5.6
BW Sim. (GHz)	2.7	5.2
BW Meas. (GHz)	4.9	6.6
Gain Sim. (dBi)	1.8	2.78
Eff. Sim. (%)	81.5	64



(a)



(b)

Fig. 7. Simulated E-field distributions at (a) 2.4 GHz and (b) 5.6 GHz.

Table 2: Comparison between the proposed button antenna and previously reported designs

Ref.	Freq. (GHz)	Pattern	Efficiency (%)	Volume (mm^3)
[2]	2.45 5.5	Monopole Patch	90 84	12568
[15]	2.45 5.8	Monopole Patch	46.3 69.3	9965
[27]	2.45 5.8	Monopole Patch	NA	18775
[28]	2.4 5	Monopole Monopole	NA	38520
This work	2.4 5.6	Monopole Patch	81.4 64	5840

IV. CONCLUSION

Based on the findings of this work, it can be concluded that, a new compact dual band CDRA based on button antenna for WBAN 2.4 GHz and 5.6 GHz applications has been proposed, simulated, fabricated and tested. The optimization and feeding technique of the proposed antenna is clarified and elaborated to achieve the objectives of this work. Besides that, the proposed work has notable several features, namely a very compact size of more than 39% reduction compared to references, bandwidth and efficiency improvement and achieve omni/broadside radiation patterns appropriate to be used for on/off body communication devices.

This work is based on stacked CDRA antenna in which two CDRAs placed on each other with different permittivity. It is suggested to use materials of higher dielectric constants for this kind of applications where the performance of the antenna will be improved, and the size will be smaller. Moreover, the cost of diversity verified by DRAs is the increased complication related to fabricating DRAs, compared to conventional technology. However, as more researches are carried out on DRAs and new fabrication methods are implemented, most of the fabrication issues will be solved.

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