Dual Band-Notched Microstrip-Fed UWB Antenna for Wearable Medical Applications

F. Bahmanzadeh* and F. Mohajeri†(C.A.)

Abstract: In this article, a very small flexible antenna with dual-band rejection specifications is proposed for operating in both wearable and ultra-wideband (UWB) applications. The overall size of this antenna is about 18×18×0.508 mm³ and by etching out two rectangular slot type single split-ring resonators (SRRs) of different dimensions from the radiating patch, dual band-notched specifications are obtained in WiMAX (3.3 GHz to 3.7 GHz) and WLAN (5.15 GHz to 5.825 GHz) wireless communication bands. The designed antenna operates over a wide impedance bandwidth (|S₁₁| < −10 dB) from 2.1 GHz to 12 GHz which can cover the whole UWB band from 3.1 GHz to 10.6 GHz and reject the two mentioned bands. An asymmetrical partial ground plane and a beveled radiating patch are utilized to achieve 140% fractional bandwidth. Also, due to the good wearable radiation characteristics, this antenna can operate in industrial scientific medical (ISM) band from 2.4 GHz to 2.5 GHz. Meanwhile, the specific absorption ratio (SAR) value of the proposed antenna is less than the standard limit of 1.6 W/kg.

Keywords: Dual Band-Notched Specifications, ISM Band, UWB Antennas, Wearable Characteristics.

1 Introduction

Since the Federal Communication Commission (FCC) assigned unlicensed frequency range from 3.1 GHz to 10.6 GHz, UWB technology and different subsets of it such as Wireless Body Area Network (WBAN) and Wireless Personal Area Network (WPAN) has drawn lots of attention [1] hence a large number of researchers have been allocated in designing UWB and wearable antennas due to their special characteristics [2, 3]. One permanent challenge in the confrontation of designing UWB antennas is the interferences between UWB spectrum from 3.1 GHz to 10.6 GHz and some existing narrowband wireless communication systems such as Worldwide Interoperability for Microwave Access (WiMAX) from 3.3 GHz to 3.7 GHz [4], IEEE INSAT/Super-Extended C-band from 6.7 GHz to 7.1 GHz and Wireless Local Area Network (WLAN) from 5.15 GHz to 5.825 GHz [5, 6]. Therefore UWB microstrip antennas with band-notched specifications have come as a feasible solution to reduce the interferences of the mentioned systems. In addition, various methods have been used to obtain UWB antennas with single or several band-notched specifications. Etching different shapes of slots on the feed-line [7], on the radiating element [8-10] or the ground plane [11], embedding elliptical [12], circular [13] and rectangular [14] SRRs on the radiating patch, placing different shapes of strips near the feed-line [15, 16] ground plane [17] and radiating element [18] are some of these methods. Also using parasitic elements such as bended dual L-shaped branches [19] and U-shaped strips [20] is another method to achieve band-notched specifications. Microstrip UWB antennas due to their special features such as compact size, low profile, lightweight and small size, have become a noteworthy candidate in wearable applications. For instance, in [21] a wearable CPW-fed square slot antenna with an overall size of 23.5×22×1
mm$^3$ and impedance bandwidth of 134%, and in [22] a full ground UWB arc-shaped microstrip antenna with an overall size of 80x67x3 mm$^3$ and impedance bandwidth of 94% are proposed. Moreover, a medical wearable antenna for ISM band with Koch fractal geometry is reported in [23] with an overall size of 39x9x0.508 mm$^3$. Although a large number of researches have been allocated on designing UWB wearable antennas and UWB band-notched antennas separately, just a few researches have been applied on designing UWB wearable antennas with band-notch specifications, which can be claimed with certainty that is a promising subject for wearable applications. For instance, a dual band-notch CPW-fed denim based wearable antenna with the total size of 43x40x2 mm$^3$ and impedance bandwidth of 138%, and a hexagonal-shaped patch with the total size of 26x18x0.5 mm$^3$ and impedance bandwidth of 109% are reported respectively in [24, 25]. The designed and simulated approach is based on a simple wearable antenna with dual band-notch specifications with a very small size of 18x18x0.508 mm$^3$. The proposed antenna comprises a beveled radiator fed by a 50 Ω microstrip line and a partial ground plane printed on the bottom side of the substrate which provides a wide impedance bandwidth from 2.1 GHz to 12 GHz. Moreover, the designed antenna operates in both wearable on-body WBAN and ultra-wideband (UWB) applications, using a flexible substrate polymer-based PTFE material, commercially known as Rogers 5880 with the thickness of $h = 0.508$ mm, the dielectric constant of 2.2, and a loss tangent of about 9x10$^{-4}$. The technique of etching two rectangular half-wavelength slot type SRRs of various dimensions out of the patch is applied to achieve two notched bands around 3.3 GHz to 3.7 GHz for WiMAX and 5.15 GHz to 5.825 GHz for WLAN wireless communication bands. The presented antenna also resonates at 2.45 GHz, the central frequency of the ISM band for operating in medical applications. Compared to the design presented in [24], the proposed antenna has a much smaller size for operating in UWB spectrum and wider impedance bandwidth. It is good to mention that the SAR value of this antenna is less than the standard limit set by the FCC, without any special design for reducing it, such as EBG based antennas, AMC based antennas [26-28], or metamaterial wearable structures [29]. High radiation efficiency above 97%, low value of SAR, and nearly omnidirectional radiation pattern are some other good characteristics of the designed antenna.

2 Antenna Design Methodology

2.1 The Structure of the Split-Ring Resonators

The geometry of the final optimized design and position of the single rectangular slot type SRRs on it, are depicted in Fig. 1. The total length and width of the two rectangular slots directly affect the notched central frequency and notched bandwidth respectively. The longer length means lower central frequency and the wider width means wider band-notched bandwidth. The proper length of the SRRs to filter the WiMAX and WLAN bands, can be obtained from the following design equations and the width of both slots are chosen as $a = 0.2$ mm:

$$S_n = 2 \times (W_{sn} + L_{sn}) - (g_n) \approx \frac{\lambda_c}{2} = \frac{c}{2f_{notch}\sqrt{\varepsilon_{eff}}}$$ (1)

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left(1 + \frac{12h}{w_f}\right)^{-\frac{1}{2}}$$ (2)

where $S_n$ represents the total length of each single rectangular SRR. For $n = 1$ the structure filters WiMAX frequency band and for $n = 2$ the WLAN band rejection is obtained. $L_{sn}$ and $W_{sn}$ are the length and width of the rectangular resonators respectively, and $g_n$ is the gaps which shown clearly in Fig. 1 (b), $c$ is the speed of light, $f_{notch}$ is the notched center frequency and $\varepsilon_{eff}$ is the effective dielectric constant of the substrate which is equal to 2.2 in this case.

2.2 Design Procedure of the Proposed Antenna

The presented antenna, designed in four different steps as shown in Fig. 2. The initial design is a monopole UWB antenna without any slot on it, depicted in Fig. 2(a). The radiating patch comprises a rectangular part having the size of $W_p \times L_p$ and a trapezoid shape part which printed on the top side of the Rogers 5880 flexible substrate with the size of $W \times L$, the thickness of $h = 0.508$ mm, the dielectric constant of $\varepsilon_r = 2.2$, and a loss tangent of $\tan \delta = 9 \times 10^{-4}$. Furthermore, a rectangular part with the size of $W \times L_1$ etching out of the ground plane to improve impedance bandwidth of the antenna. To achieve 50 Ω characteristic impedance, the length and width of the microstrip feed line are chosen as $W_p \times L_F$. Antennas with single band-notch specifications are also shown in Figs. 2(b) and (c). By etching out a single rectangular slot type SRR of suitable dimensions, which
obtained from (1), symmetrically from the radiating patch, two notches at WiMAX and WLAN bands were obtained respectively having the following parameter values: $L_{\text{i}}= 4.45 \, \text{mm}$, $W_{\text{i}} = 11.2 \, \text{mm}$, $g_1 = 2.2 \, \text{mm}$, $L_{\text{g}} = 3.5 \, \text{mm}$, $W_{\text{g}} = 8.4 \, \text{mm}$, $g_2 = 1.25 \, \text{mm}$. Final design is a dual band-notched UWB wearable antenna having two slots on the radiator and operates in the wide impedance bandwidth that shown in Fig. 2(d). The radiating patch and ground plane optimum dimensions are mentioned as: $W = 18 \, \text{mm}$, $L = 18 \, \text{mm}$, $W_f = 11.5 \, \text{mm}$, $L_f = 4.7 \, \text{mm}$, $W_1 = 14.8 \, \text{mm}$, $L_1 = 8.25 \, \text{mm}$, $W_j = 1.5 \, \text{mm}$, $L_j = 4.85 \, \text{mm}$, $P = 1.9 \, \text{mm}$, $s_1 = 0.65 \, \text{mm}$.

### 3 Full-Wave Simulation Results

A simulator Ansoft HFSS has been utilized to calculate frequency domain parameters such as return loss, VSWR, far-field radiation patterns, gain, radiation efficiency, and surface current distribution to understand the ultra-wideband behavior of this design. The return loss of the proposed antenna in free space and in the vicinity of a simple human tissue model is shown in Fig. 3(a), which it is clear that the designed antenna operates in the frequency range from 2.1 GHz to 12 GHz ($|S_{11}|$ less than -10 dB) except the two notched bands. Also, the antenna resonates at 2.45 GHz for ISM medical frequency band with $|S_{11}|$ less than -40 dB and -20 dB in free space and on the tissue model respectively. Furthermore, for SAR evaluation, a cubic human tissue model is simulated and shown in Fig. 3(b).

The tissue model has an overall size of $150 \times 150 \times 70 \, \text{mm}^3$ consist of three different layers of skin, fat, and muscle with the thickness of 3 mm, 7 mm, and 60 mm respectively, and antenna’s radiation performance examined in planar configuration at a distance of 3 mm from the mentioned human tissue model. Simulated SAR value at 2.45 GHz is obtained about 1.2 W/kg which is below the standard limit. Furthermore, the variation of VSWR versus frequency for different stages of this design is depicted in Fig. 4. As it is shown in this figure, the initial antenna (yellow curve), operates in the impedance bandwidth of about 140% from 2.1 GHz to 12 GHz (VSWR<2) without incorporating any notched bands, which is noticeable due to its small dimensions.

A single rectangular SRR is etched out of the radiating element in antenna 1 to decrease the interferences of WiMAX equipment from 3 GHz to 5.1 GHz covering 2100 MHz as demonstrates in Fig 4 (red curve). Similarly, another SRR is engraved into the patch for the second frequency notched band aiming to filter the WLAN frequency range from 4.6 GHz to 5.7 GHz covering about 1100 MHz (green curve). Eventually, the value of VSWR for the presented dual band-notchted antenna is plotted in the black curve which is less than 2 in the frequency range from 2.1 GHz to 12 GHz except at the two notched bands from 3 GHz to 4.6 GHz and peak VSWR=113 at 3.7 GHz for WiMax and 5 GHz to 5.9 GHz, peak VSWR=25 at 5.5 GHz for WLAN and the passband is from 4.6 GHz to 5 GHz as illustrated in Fig. 4. For further description, Table 1 represents different frequency ranges of the bandwidth and rejection bands of the antenna in each step.

Simulated surface current distribution on the radiating patch and ground plane of the presented antenna, are depicted in Fig. 5 at the center frequencies of two
Table 1 Bandwidth and rejection bands of the designed antenna in each step.

<table>
<thead>
<tr>
<th>Step</th>
<th>Initial antenna</th>
<th>Antenna 1</th>
<th>Antenna 2</th>
<th>Proposed antenna</th>
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<tr>
<td></td>
<td>2.1 GHz – 12 GHz</td>
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<td>3 GHz – 5.1 GHz</td>
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<td>3 GHz – 4.6 GHz</td>
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<td>–</td>
<td>4.6 GHz – 5.7 GHz</td>
<td>5 GHz – 5.9 GHz</td>
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Fig. 5 Distribution of surface current on the conductors of designed antenna at center resonant frequencies: a) 3.7 GHz and b) 5.5 GHz.

Fig. 6 Effect of varying dimension of single rectangular SRRs: a) Major length of outer SRR, \( W_s1 \), and b) Major length of inner SRR, \( W_s2 \).

notched bands. Fig. 5(a) depicts the distribution of surface current at 3.7 GHz for the first notched frequency. As it is clear, the flows of current are more concentrated around the outer rectangular SRR rather than the ground plane. Also, Fig. 5(b) depicts the distribution of surface current at 5.5 GHz for the second notched frequency, and similarly, it is more dominant around the smaller rectangular SRR rather than elsewhere. Generally, it can be construed that a large amount of electromagnetic energy concentration is in the vicinity of the two slots so the antenna has no radiation in the mentioned rejection bands.

To understand the effects of geometrical dimensions of the rectangular SRRs on the notched performance and impedance bandwidth, different values of \( W_s1 \) and \( W_s2 \) are investigated as shown in Fig. 6. \( W_s1 = 11.2 \) mm and \( W_s2 = 8.4 \) mm are the optimum variations that provide perfect notched bands and cover the whole WiMAX and WLAN spectrum. By increasing the length of \( W_s1 \) from 9.7 mm to 11.2 mm, both upper and lower frequencies of the first notched band affected and shifted in the amount of about 600 MHz to the right which interfere WLAN frequency band. Similarly, by increasing \( W_s2 \) from 7.9 mm to 3.4 GHz, second notched band shifted in the amount of about 600 MHz to the right.

2-D radiation patterns of the proposed antenna for elevation and azimuth planes were obtained and shown in Fig. 7 at four different frequencies of 2.45 GHz, 4.8 GHz, 7 GHz, and 10.6 GHz within the bandwidth. This antenna provides a nearly omnidirectional radiation pattern in E-plane (xoz-plane) and bidirectional radiation pattern in H-plane (yoz-plane) in each frequency and also over the entire UWB spectrum. Moreover, the magnitude of cross-polarized pattern is acceptable over the impedance bandwidth in both planes.

Furthermore, Fig. 8 depicts the variation of peak gain versus frequency of the designed antenna. The very sharp notched performance of the antenna at the center frequencies of the rejection bands can be seen in this plot. Also, the peak gain is about 5.2 dBi which is significant due to the very small dimension of the antenna and the radiation efficiency of the antenna is over 97% even though the substrate is quite lossy that makes this design reasonably good compared to other previous works.
This article represents a very small dual band antennas for wearable 2.45 GHz ISM medical band and UWB applications. The total volume of the proposed antenna is $18 \times 18 \times 0.508$ mm$^3$ covering 9.9 GHz impedance bandwidth from 2.1 GHz to 12 GHz. Other than UWB application, this antenna can also resonate in 2.45 GHz for medical frequency band and has an acceptable SAR value. Two single rectangular SRRs are applied on the radiator aiming to reject the interferences of WiMAX and WLAN bands from 3 GHz to 4.6 GHz and 5 GHz to 5.9 GHz respectively. Designed antenna shows a good behavior in far-zone and radiation patterns are quite stable considering the frequency domain results. Peak gain is about 5.2 dBi and radiation efficiency is over 97% in free space. SAR parameter evaluated over a human tissue model at 2.45 GHz with the amount of 1.2 W/kg. Consequently the proposed antenna demonstrates a good behavior for UWB systems.

**Intellectual Property**

The authors confirm that they have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property.

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**Declaration of Competing Interest**

The authors hereby confirm that the submitted manuscript is an original work and has not been published so far, is not under consideration for publication by any other journal and will not be submitted to any other journal until the decision will be made by this journal. All authors have approved the manuscript and agree with its submission to “Iranian Journal of Electrical and Electronic Engineering”.

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**Fig. 7** 2-D radiation patterns of the designed antenna in E-plane (left) and H-plane (right) at various frequencies: a) 2.45 GHz, b) 4.8 GHz, c) 7 GHz, and d) 10.6 GHz.

**Fig. 8** Peak gain of the reference antenna and antenna with dual band-notched specifications.

**4 Conclusion**

This article represents a very small dual band-notched antenna for wearable 2.45 GHz ISM medical band and UWB applications. The total volume of the proposed antenna is $18 \times 18 \times 0.508$ mm$^3$ covering 9.9 GHz impedance bandwidth from 2.1 GHz to 12 GHz. Other than UWB application, this antenna can also resonate in 2.45 GHz for medical frequency band and has an acceptable SAR value. Two single rectangular SRRs are applied on the radiator aiming to reject the interferences of WiMAX and WLAN bands from 3 GHz to 4.6 GHz and 5 GHz to 5.9 GHz respectively. Designed antenna shows a good behavior in far-zone and radiation patterns are quite stable considering the frequency domain results. Peak gain is about 5.2 dBi and radiation efficiency is over 97% in free space. SAR parameter evaluated over a human tissue model at 2.45 GHz with the amount of 1.2 W/kg. Consequently the proposed antenna demonstrates a good behavior for UWB systems.

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The authors hereby confirm that the submitted manuscript is an original work and has not been published so far, is not under consideration for publication by any other journal and will not be submitted to any other journal until the decision will be made by this journal. All authors have approved the manuscript and agree with its submission to “Iranian Journal of Electrical and Electronic Engineering”.
References


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