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BANDWIDTH ENHANCEMENT AND MINIATURIZATION OF DIELECTRIC RESONATOR ANTENNA FOR 5.8 GHz WLAN

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Abstract—This paper presents the design of Dielectric Resonator Antenna (DRA) operating at 5.8 GHz, using the techniques of Two Segments DRA (TSDRA) and High-Aspect Ratio Structure. The aim of the paper is to reduce the size of the DRA while still maintaining its large impedance bandwidth. The requirements for WLAN applications are carefully taken into considerations in the design of the proposed structure. Comparison has been made between the proposed design and single layer DRA (SLDRA); and it has been found that the former has better performances than the latter.

1. INTRODUCTION

Development in wireless communication systems has grown rapidly over the last decade. As a result, there is increasing demand for effective and small sized antennas; which has posed some challenges to researchers. Traditional transmission line microstrip antenna has been widely used as a reconfigurable antenna due to its low complexity and ease in fabrication [1]. Microstrip antennas have found extensive application in modern communication systems because of their inherent properties such as small size, light weight, easy fabrication with low cost on mass production and possibility of integration with other printed circuit microwave components [2].

Even though both microstrip antennas and Dielectric Resonator Antennas (DRA) are suitable choices for wireless applications, the latter possesses some advantages over the latter. These include high radiation efficiency, low profile, wide impedance bandwidth [3],

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etc. Another attractive feature for DRA over the traditional low gain element such as microstrip antenna is that it can be used at millimeter-wave frequency bands, due to absence of surface waves and conduction losses [4] Furthermore, DRA can be fed by variety of feeding mechanisms such as probe coupling [5], microstrip coupling [6], coplanar coupling [7] and aperture coupling [8].

DRA has three basic shapes which are rectangular, cylindrical and hemispherical geometries. The hemispherical DRA is difficult to fabricate and does not provide any degree of flexibility in terms of choosing the design parameters. The cylindrical DRA is easier to fabricate and the resonant frequency can be controlled by changing the radius-to-height ratio. The rectangular DRA is the most commonly used geometry because it offers two degrees of flexibility; that is,several aspect ratios (high-to-width and length-to-width) can be chosen [9].

The resonant frequency of DRA is a function of both dielectric constant and its physical dimensions. In fact the dielectric constant does not only affect the size of the DRA but also it affects the bandwidth impedance. Increasing its dielectric constant above 20 will result in a reduced size, higher Q-factor and narrower bandwidth. On the other hand, a dielectric constant value below 20 will increase the bandwidth, although at the expense of increased size. Therefore, the major challenge in DRA designs is coming up with a tradeoff between these two useful features of the DRA [10].

There are many techniques that have been used in order to increase the bandwidth performance of a DRA, for instance, by modifying the basic shapes of the DRA [11, 12]. Another method is by integrating the DRA with other types of antenna such as patch antenna [13], or monopole antenna [14]. Last but not least, multi layers DRA, can also be used to widen the antenna's bandwidth. In the case, two or more segments can be used but the concept remains unchanged since the enhancement is done through exciting the same mode at somewhat different frequencies for each segment. Therefore, the overall bandwidth is a combination of the individual response of each segment. The Two Segment DRA (TSDRA) has been investigated when the two segments are arranged either in horizontal [15] or vertical [16] arrangement.

However, none of the afore-mentioned techniques can guarantee a compact size. Moreover, TSDRA which is designed at low frequency, which consequently leads to a bulky size due to wavelength dependence the physical size. Several methods have been proposed for meeting the small-size and performance requirements of wireless portable devices in. One approach is by increasing the dielectric constant [17], but the drawback of this method is the narrow bandwidth resulting from high

Q-factor. Another widely used method in patch antenna designs is by using fractal shapes [18]. The size of the DRA can be reduced by adding metal plate on top of the antenna which removes a part of the antenna, so as to achieve miniaturization [19]. The thin antenna, in which the surface to volume ratio is high, seems to be a good choice for reducing the DRA size [20].

TSDRA and high aspect ratio structure, otherwise known as Thin Antenna was studied in [21], where the two components are combined together to produce a new design with improved performances suitable for the existing and the next generation WLAN applications. Some of the advantages include large bandwidth, miniaturization, cost reduction and structure simplicity. Furthermore, an inexpensive FR-4 substrate is used in this design rather than the using of an expensive substrate. This will reduce the overall cost of the proposed antenna and overcome the problems associated with material availability that face many of the DRA's designers. In addition to the losses of the FR-4 used in this design, the effect of placing a DRA on top of substrate with relatively small dimensions can be quite significant. This is because many of the analysis were based on the assumption of having infinite ground plane.

The usage of the finite ground plane causes rippling in the pattern shape, a reduction in the gain and a change in the input impedance. Even though the proposed design suffers from all the previous effects, it is sufficiently compact and in addition it has a proper impedance bandwidth for use in WLAN.

2. ANTENNA DESIGN

Since the DR is mounted on top of a ground plane, the Transverse Electric (TE) modes are typically excited. Coupling through microstrip excites $TE^X_{\delta 11}$ the mode of the rectangular DRA. The initial dimensions of the radiating elements of the rectangular DRA can be calculated by using the Dielectric Waveguide Model (DWM) for a rectangular resonator in free space [22]. Therefore, the resonance frequency can be determined by using the following equations:

$$k_x \tan(k_x l/2) = \sqrt{(\varepsilon_r - 1)k_0^2 - k_x^2} \tag{1a}$$

$$k_0 = \frac{2\pi f_0}{c}; \quad k_y = \frac{\pi}{w}; \quad k_z = \frac{\pi}{2h}; \quad \text{and } k_x^2 + k_y^2 + k_z^2 = \varepsilon_r k_0^2 \tag{1b}$$

where k_0 is the free space wave number and ε_r is the dielectric constant (or, permittivity) of the material. The symbols w, l, h, represent the width, length and height of the dielectric resonator, respectively.

And the resonant frequency f_0 is given by:

$$f_0 = \frac{c}{2\pi\sqrt{\varepsilon_r}}\sqrt{k_x^2 + k_y^2 + k_z^2} \tag{2}$$

The symbols k_x, k_y and k_z represents the wave numbers in the x, y and z directions, respectively. After determining the initial dimensions of the DRA, the dielectric constant of the inserted segment and its thickness h_2 are determined by using the equations reported in the guideline of the single inserted segment [23]:

$$\varepsilon_i = \frac{\vartheta_0\sqrt{\varepsilon_r}}{z_0} \tag{3}$$

where $Z_0(\Omega)$ is the characteristic impedance of the transmission line and $\vartheta_0(\Omega)$ is the intrinsic impedance of free space.

$$h_2 = \frac{c}{4f_0\sqrt{\varepsilon_i}} \tag{4}$$

The inserted segment serves to transform the impedance of the DRA to that of the microstrip line by concentrating the fields underneath the DRA; which significantly improves the coupling performance [4]. In order to avoid radiation from the inserted segment, which might adversely affect the resonant frequency as well as input impedance [3], the resonant frequency must be greater than the desired frequency. This is achieved by testing its patterns using DWM. These parameters are substituted in the DWM. The dielectric constant ε_r and height are replaced by the effective permittivity $\varepsilon_{\mathit{eff}}$ and the effective height $(2H_{\mathit{eff}})$, respectively, so as to obtain the effect of lower segment on the desired frequency.

$$H_{\mathit{eff}} = h_1 + h_2 + t \tag{5}$$

$$\varepsilon_{\mathit{eff}} = \frac{H_{\mathit{eff}}}{\frac{h_1}{\varepsilon_r} + \frac{h_2}{\varepsilon_i} + \frac{t}{\varepsilon_s}} \tag{6}$$

Optimization is needed on the obtained dimensions if a significant shift in resonance frequency was realized. In the design, high aspect ratio in which the width is much smaller than $2(h_1 + h_2)$ has been taken into consideration $(5 : 1)$. Figure 1 shows a photograph of the fabricated antenna. The antenna configuration comprises of two segments of rectangular (RDR) fed with energy by a microstrip line. The characteristic impedance of the antenna is controlled by the width of the transmission line, the dielectric of the substrate and the height of the substrate.

The specifications of the line are: width = 1.4 mm and length = 30 mm and characteristic impedance = 50 Ω. Both DR and the

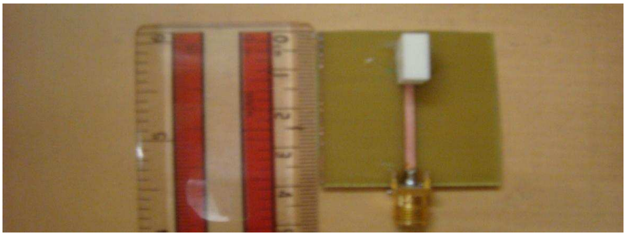
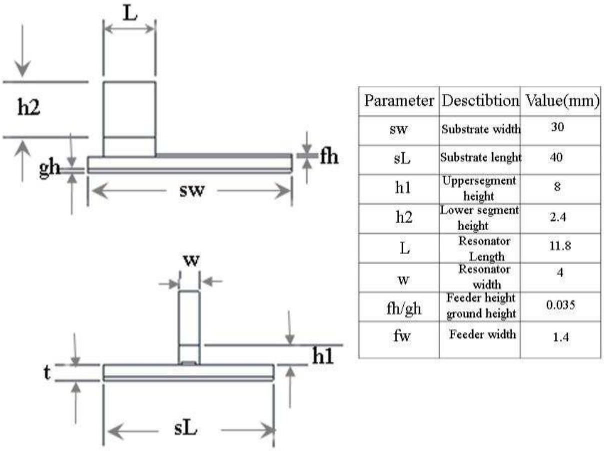


Figure 1. Photograph of the fabricated antenna.



Parameter	Desctibtion	Value(mm)
sw	Substrate width	30
sL	Substrate lenght	40
h1	Uppersegment height	8
h2	Lower segment height	2.4
L	Resonator Length	11.8
w	Resonator width	4
fh/gh	Feeder height ground height	0.035
fw	Feeder width	1.4

Figure 2. Geometry of the thin two segments dielectric resonator antenna.

microstrip line are located on top of FR-4 substrate with relative permittivity of $\varepsilon_s = 4.7$ and dimensions of $30\,\text{mm} \times 40\,\text{mm}$ (finite ground plane) and thickness of $t = 0.8\,\text{mm}$ and $\delta_e \leq 0.0019$.

A SMA connector is soldered to the microstrip line to improve the matching. The amount of coupling can be controlled by changing the position of the DR on top of the substrate. In this design, the maximum coupling is achieved when the DR is placed at a distance of $\lambda/2\,\text{mm}$ from the open end. The width, length and height of the two segments DR are represented respectively by the symbols $(w \times l \times h_1)$ for the upper segments and $(w \times l \times h_2)$ for the lower segment.

Figure 2 shows the antenna geometry, where the upper segment has a dielectric constant of $\varepsilon_r = 15$ and $\delta_e \leq 0.00015$ with dimensions of $4\,\text{mm} \times 11.8\,\text{mm} \times 8\,\text{mm}$. The lower segment has a dielectric constant of $\varepsilon_i = 30$ and dimensions of $4\,\text{mm} \times 11.8\,\text{mm} \times 2.4\,\text{mm}$ is inserted between the upper segment and the substrate.

3. RESULTS AND DISCUSSIONS

Single segment DRA and TSDRA were designed and simulated using CST software. The comparative performance evaluations of the three designs are summarized in Table 1. Parameters such as the substrate patterns, transmission patterns and dielectric constant were fixed. The table clearly shows the advantages of the proposed design over the conventional DRA and TSDRA designs without having high aspect ratio structure.

Table 1. Comparison between single DRA, TSDRA and thin TSDRA.

Structure	Impedance Bandwidth (GHz)	Impedance Bandwidth %	Boresight Gain (dBi)	Dimensions $(w \times l \times h)\lambda_0$	Volume (m^3)
SLDRA	0.39	6.7	4	$(0.17\times0.19\times0.12)\lambda_0$	$0.00387\lambda_0^3$
TSDRA	0.76	14	5.5	$(0.17\times0.22\times0.23)\lambda_0$	$0.00538\lambda_0^3$
TTSDRA	0.72	12	5.1	$(0.08\times0.23\times0.19)\lambda_0$	$0.00349\lambda_0^3$

As shown in the table, the impedance bandwidth of the proposed Single Segment is 1.48 and 1.43 greater than those of the single layer TSDRA and Thin TSDRA, respectively. It can be observed that the bandwidth impedance can be increased up to 49% and 46%, compared to using the single layer TSDRA and the Thin TSDRA (TTSDRA), respectively. Also, there is improvement in gain for both designed antennas using TSDRA and Thin TSDRA compared with that of the conventional DRA.

Evidently, the TSDRA and the Thin TSDRA are much better than the single layer DRA in terms of bandwidth impedance and gain. However, the volume is a critical issue in WLAN device applications, which must be considered. From Table 1, it can be observed that, by using the single layer DRA the volume was decreased by almost 28% compared to TSDRA. Further reduction can be achieved by using the Thin TSDRA structure rather than the TSDRA structure. For instance, up to 35% reduction in volume could be achieved for both Thin TSDRA structure and TSDRA structure.

It could therefore be argued that, using the conventional DRA will reduce the antenna size at the expense of smaller impedance bandwidth and lower gain. Conversely, TSDRA can guarantee a larger impedance bandwidth and higher gain, but the antenna's size will increase and therefore occupy more space in the wireless device. Compared to the other structures, the proposed design balances the size/gain/bandwidth trade-off by providing the smallest volume together with reasonable gain and impedance bandwidth. These features are suitable for WLAN applications operating between 5 to 6 GHz and require at least 675 MHz impedance bandwidth.

The theoretical derivations presented in Section 2 are then optimized using CST software. The software automatically computes the input impedance, return loss and radiation pattern. The antenna is also tested and these same parameters are measured by using microwave network analyzer. The comparison between the simulated and measured return losses is demonstrated in Figure 3. It can be seen that there is fairly good agreement between the two results. The return loss is less than -10 dB over bandwidth of 12.4% from the resonant frequency, whereas, the measured results show that bandwidth is 13% from the resonant frequency. Some experimental precautions were carefully observed at the fabrication stage. These include ensuring that the glue effect was avoided, and the air gap between the DR and the substrate was aligned the correct position.

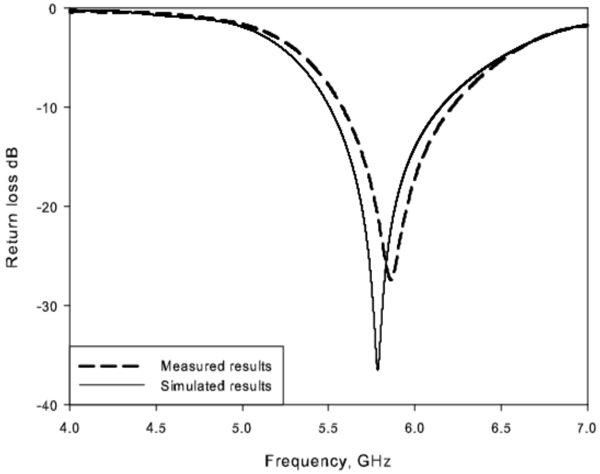


Figure 3. Simulated and measured return loss.

The radiation pattern of an antenna can be either circularly, elliptically or linearly polarized, depending on the value of the axial ratio measured in dB. For circularly polarized radiation pattern, the axial ratio must be lower than 3 dB, whereas for the elliptically polarized, the axial ratio must be larger than 3 dB and lower than 10 dB. In the case of linearly polarized, the axial ratio is more than 10 dB. It is evident from Figure 4 that the antenna is linearly polarized, since the axial ratio is 40 dB.

The normalized far field radiation patterns in E-plane and H-

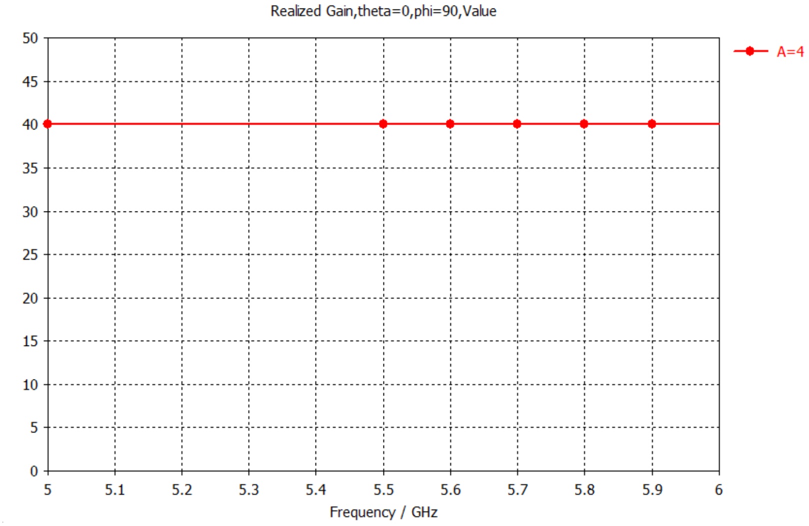


Figure 4. The axial ratio plot for proposed DRA.

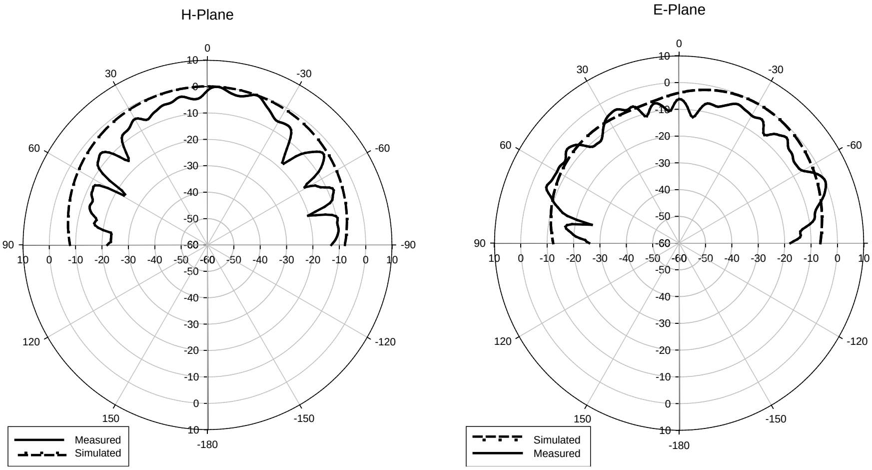


Figure 5. Simulated and measured radiation pattern for both *E*-plane and *H*-plane.

plane for both simulated and fabricated results are shown in Figure 5. It can be seen from the radiation pattern that there are some scalloping in the shape and as it was mentioned earlier; this is due to the diffraction from the edge corner of the small ground plane.

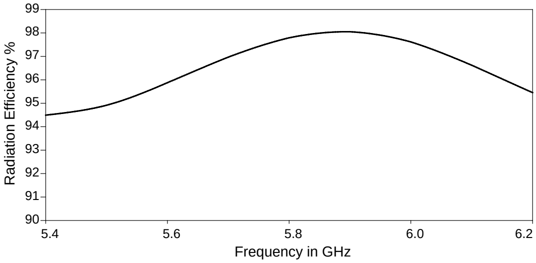


Figure 6. Radiation efficiency versus frequency.

Furthermore, any scattering from the cable and connector will affect the E-plane pattern. This is because the cable and connector lie directly along with the pattern cut of the E-Plane. Therefore, the scattering from the connector will cause ripples in the E-pattern, whereas, it does not exhibit ripples in the H-pattern.

The radiation pattern efficiency was tested over the bandwidth of the designed antenna in which the return loss is less than -10 dB. As we mentioned earlier, the bandwidth of the antenna is up to 12% from the resonant frequency. This means that, the bandwidth is less than -10 dB in the range between 5.5 GHz and 6.2 GHz. The radiation efficiency can be calculated by dividing the Gain of the antenna over its directivity. The radiation efficiency of the proposed antenna with Thin TSDRA structure shows high radiation efficiency over the entire bandwidth and it reaches the maximum up to 98% at the resonant frequency, this is shown in Figure 6.

4. CONCLUSIONS

TSDRA and High-aspect ratio structure were integrated, taking into considerations the requirements for WLAN applications. The proposed design has reduced the size, weight and cost, while still maintaining acceptable performance for the existing and next generation WLAN applications. The simulated and measured results are in close agreement. It has been found that by using the conventional DRA, a smaller size is achieved at the in expense of lower impedance bandwidth and lower gain. On the other hand, TSDRA guarantees larger impedance bandwidth and higher gain, although the price paid for these is larger size.

The proposed structure provides the smallest volume compared to the other two structures. Also the gain and impedance bandwidth are still fairly reasonable for WLAN applications, which operate between

5 to 6 GHz and require a minimum of 675 MHz impedance bandwidth. Our future submissions would focus on the possibilities of using circular polarization and increasing the impedance bandwidth.

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