Progress In Electromagnetics Research C, Vol. 30, 147–158, 2012

A HIGH GAIN DIELECTRIC RESONATOR LOADED PATCH ANTENNA

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Abstract—A dielectric resonator loaded patch antenna excited by a coaxial cable is proposed in this paper. The results from measurement show a wide impedance bandwidth of 57.1% from 3.75 GHz to 6.75 GHz and a peak gain of 11.5 dB at the center of frequency band with an average gain improvement of 3 dB over the frequency band in comparison with the common dielectric resonator antennas. These results are in good agreement with those obtained by the computer simulations. A simple study of the antenna shows that the aperture size increase is the cause of gain enhancement. A theoretical model based on the simulated gain results of reference antenna and its equivalent aperture is presented for the proposed antenna structure with good agreement with simulation and measurement results. The advantages of the proposed antenna are high gain with broad bandwidth, and low fabrication cost in comparison to other types of high gain DRAs having narrow bandwidths and complex structures.

1. INTRODUCTION

Dielectric Resonator Antennas (DRAs) are good candidates for many communication applications, because of their favorable characteristics, such as light weight, compact structure, wideband response, control of antenna dimensions with the value of dielectric constant, low metallic loss and prevention of surface wave propagation [1–5]. They are suitable substitutions for compact antennas, such as microstrip antennas. In modern microwave systems, needs arise for broadband antennas having appropriate gain and good radiation efficiency with compact structure, such as mobile and portable radio devices [6–8].

Received 8 May 2012, Accepted 8 June 2012, Scheduled 16 June 2012
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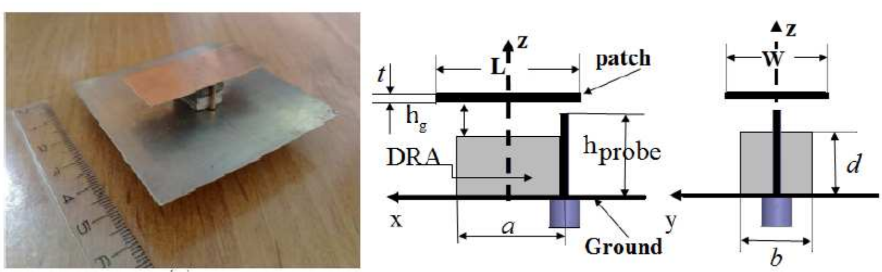
Dielectric resonator antennas with proper designs can have all of these features. Bandwidth enhancement is achieved by different approaches, such as merging two adjacent resonators [9, 10], lowering the Q-factor of the DR [11] and correcting the feed structures [12]. Monopole DRA is an example of merging two adjacent resonances that enhance the total bandwidths [13, 14].

Various methods for gain enhancement of dielectric resonator antennas have been reported. For example, the use of several DRA configuration in an array can increase the gain in the boresigth direction [15–17]. The use of electromagnetic band gap (EBG) structures to prevent surface wave propagation to increase the antenna gain [18, 19]. Other approaches include stacking two dielectric resonators with an air gap in between [20], employing short horns around DRA [21] and using DRA in its higher order modes [22]. All of these methods increase the complexity and cost of the structure. Among them, the DRA in higher order modes is less complicated. However, this structure is quite tall at microwave frequencies and is not a good candidate for compact applications. In another DRA structure, the excitation of higher order modes fed from a microstrip patch in the millimeter wave frequency band has been reported [23], where the increased electrical aperture size of the antenna eventually enhanced its gain.

In this work a new method of gain enhancement is introduced where a simple metallic patch is placed above the DRA (see Figure 1). This approach has advantages of gain improvement in a wide impedance bandwidth (52%) and low construction cost compared to other DRA gain enhancement methods. To our knowledge, it is the first time that a microstrip patch above the DRA is used for gain enhancement. It will be shown that by adding a rectangular patch



(a) (b) (c)

Figure 1. A dielectric resonator top-loaded patch antenna structure. (a) 3D view, (b) side view (XZ plane), (c) side view (YZ plane).

above the DRA the total aperture size of the antenna is increased. Moreover, a simple, general and novel theoretical equivalent aperture model is introduced that predicts the final structure gain. The simulated gain is in good agreement with the simple theoretical model.

For good excitation of the patch mode, the probe excitation is selected. In this work the probe feeding in comparison with the microstrip feed has the advantage of stronger excitation of patch mode, because the probe can be extended to the patch proximity and unlike the slot excitation has a better bandwidth. In addition, by adjusting the location of the patch on the DR, the impedance matching and gain can be improved. Also, in order to make the structure rigid and sturdy, the space between the DR and patch is filled with foam. The dielectric constant of the foam is nearly equal to that of the air.

This paper is organized as follows. In Section 2 design guidelines are presented and the gain improvement method is theoretically described. Simulation and measurement results are given in Section 3. Finally, summary and conclusions are provided in Section 4.

2. ANTENNA CONFIGURATION

Figure 1 shows the schematic configuration of the dielectric resonator loaded patch antenna. A patch with length L and width W is placed above DR having length a, width b, height d, and dielectric constant ε_r. The antenna is fed by a probe with height h_{probe} which extends from a coaxial cable. The DR is made from Rogers RT6010 with dielectric constant $\varepsilon_r = 10.2$.

It has been shown that the microstrip patch antenna radiates like two slot apertures placed $\lambda_g/2$ distant apart [24]. In Figure 1, the radiation takes place from the four sidewalls and the top surface of the patch. The two sidewalls in YZ plane radiate out of phase and cancel each other. In this work the height of the patch is comparable with its width. Hence the radiation from top surface is comparable to other radiations. Finally the total electrical aperture area is equal to those of the top surface and two sidewalls of the patch in XZ plane.

The simple theoretical model that predicts the gain of final dielectric resonator loaded patch antenna, presented in this paper, is as follows: First, the proposed DR antenna structure without the overhead patch is excited by a probe and its gain is computed by the software simulator (HFSS). Then, for the precise computation of the radiation area of the aforementioned DR the size of a square aperture antenna having approximately the same gain as the DRA is determined by the aperture antenna gain formula (Eq. (1)) and adjusting the physical area of the square aperture antenna, A_p. Figure 4(a) shows the DRA simulated gain and its best approximation by an aperture antenna with nearly the same gain. Subsequently, the total radiation surface of the DRA with the overhead patch is calculated. The ratio of the latter calculated radiation surface to that of the equivalent square aperture is actually the gain improvement. The most important aim of this simple theoretical prediction of gain is verifying the idea of gain improvement by the radiation area enhancement. However, the gain of final antenna is the sum of the DR without patch simulated ones and the calculated gain improvement.

The gain of an aperture antenna is [24]

$$G = 10 \log \left(\frac{4\pi}{\lambda^2} \varepsilon_{ap} A_p \right) \tag{1}$$

where A_p is the physical area of an aperture antenna, λ the free space wavelength, and ε_{ap} the aperture efficiency. Then as aperture area increases, the antenna gain will increase.

Another effect of placing a patch on DR is the bandwidth enhancement [25]. By a proper design of patch, its resonant frequency can be obtained in the proximity of DRA resonant frequency and then two resonant bandwidths may merge and increase the total bandwidth. By treating the patch antenna as a cavity that bounded by two electric walls at the bottom and top surfaces, and four magnetic side walls, the TM^z mode fields inside the dielectric substrate is excited [24]. An equation for the TM^z_{100} mode resonant frequency is [24]

$$f_0 = \frac{c}{2L\sqrt{\varepsilon_p}} \tag{2}$$

where f_0 is the resonant frequency, c the speed of light in vaccum, L the patch length, and ε_p the approximate dielectric constant of the space between the patch and ground plane which is approximately determined by averaging the DR and air dielectric constants, $\varepsilon_p = \frac{10.2 \times d + 1 \times h_g}{d + h_g} = 6.85$. Note that the initial values of d and h_g are chosen to be 7 mm and 4 mm, respectively.

Now, the dielectric resonator operating in TE^y_{111} mode is designed. The resonance frequency of this mode can be determined using the dielectric waveguide model. The resonant frequency of the DR is also affected by the patch position, resulting in a deviation between simulation and prediction from dielectric waveguide model. Analytical equations describing this model are given in [26]

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

$$k_x = \frac{\pi}{a}, \quad k_z = \frac{\pi}{2d}$$
$$\tan\left(\frac{k_y b}{2}\right) = \frac{\sqrt{(\varepsilon_r - 1)k_0^2 - k_y^2}}{k_y} \tag{3}$$

where c is the speed of light; ε_r is the dielectric constant of resonator; a, b, d are as shown in Figure 1. At $f_0 = 5.5\,\text{GHz}$, the dielectric resonator dimensions are $a = 13.5\,\text{mm}$, $b = 9\,\text{mm}$, and height $d = 7.62\,\text{mm}$. The half wavelength of patch (L) is determined by (2). The dielectric constant of space between the patch and ground is approximated by the average of those of vacuum and DR. Then the length $L = 10.4\,\text{mm}$ obtained. This value is selected as the initial value in the parametric study. The width of the patch shown in Figure 1(c) is approximated by the width of DR. Note that as h_g in Figure 1 decreases, the resonant frequency of DR shifts away from the isolated dielectric resonator resonance frequency. Therefore, its distance from the top face of DR is increased as far as possible. On the other hand, by increasing this parameter the gain of proposed antenna is reduced. Hence tradeoffs among the radiator characteristics, such as gain, bandwidth and the resonant frequency should be considered.

3. SIMULATION AND MEASUREMENT RESULTS

By the electromagnetic solver Ansoft HFSS, the proposed antenna is simulated and optimized in 3.5 GHz to 7 GHz band and the final values for design parameters in Figure 1 are listed in Table 1. The ground plane size is $3.53\lambda_g \times 3.53\lambda_g$ (at 5.5 GHz). The DR dielectric material, the ground plane and the patch metal are considered to be lossy.

Table 1. Optimized values of parameters in Figure 1 used for simulations.

Parameter	Value (mm)
h_{probe}	9 mm
a	13.5 mm
b	9 mm
d	7.62 mm
L	18 mm
W	42 mm
t	0.5 mm
h_g	2 mm

3.1. Reflection Coefficient

Figure 3 depicts the reflection coefficient of the proposed antenna and the results of both simulation (HFSS) and measurement. By merging the patch mode resonance and the DR resonance, the bandwidth is enhanced. It will be confirmed later that at 4.5 GHz, the resonance occur by the TM_{100}^{z} mode of the patch and at 6 GHz TE_{111}^{y} mode of the DR resonats. Note that the DR resonance is determined by the dielectric waveguide model to be at 5.5 GHz. But the resonance frequency obtained by the computer simulation is different. This discrepancy between the two results is due to the patch loading effect that disturbs the field distributions above the DR (see Figure 3). Also note that the probe resonance is placed out of the frequency band of interest. Of course, this is an interesting design because the monopole effect of the probe deteriorates the broadside radiation pattern.

3.2. Electric Field Distributions

Figure 3 illustrates the electric field distributions in the proposed antenna on two cut planes and at two sample frequencies, which are related to two minimum points on the reflection coefficient curve (see Figure 2). Since the electric fields at 4.5GHz as shown in Figures 3(a) and 3(b) are concentrated at patch edges, the corresponding field is related to the patch at TM_{100}^{z} mode. Also as shown in Figures 3(c) and (d), the concentration of fields in DR shows that the corresponding field is related to TE_{111}^{y} mode of DR. Hence, the electric field distributions verify the resonance sources of the proposed antenna.

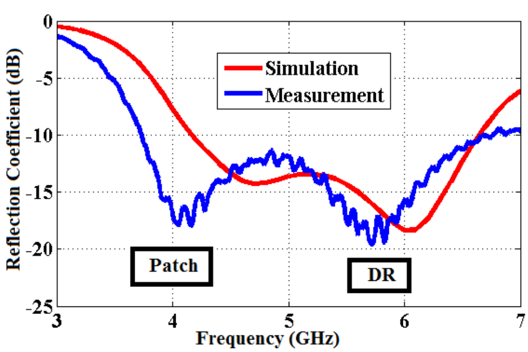


Figure 2. The reflection coefficient of proposed antenna with optimized parameter values listed in Table 1.

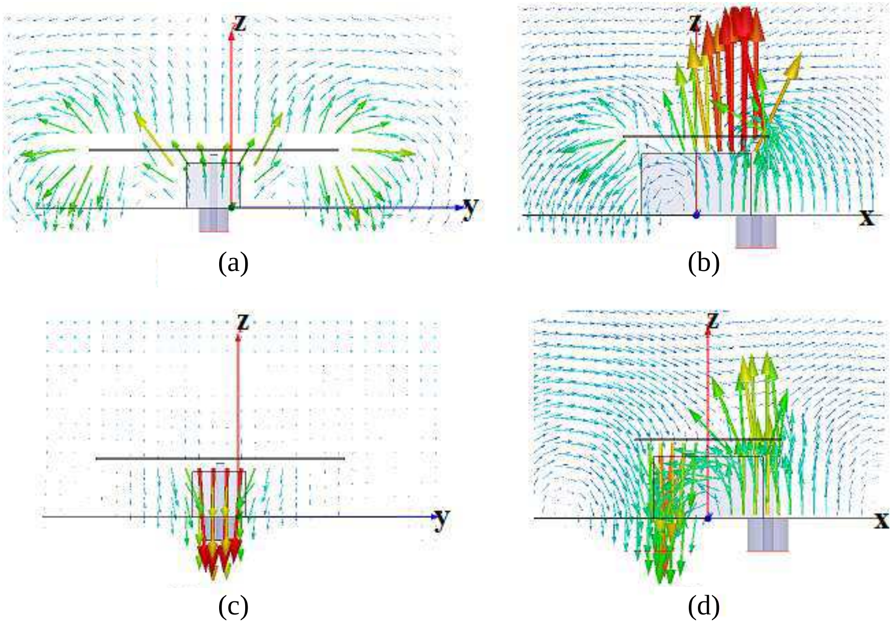


Figure 3. The simulated E-field distributions of the proposed antenna from HFSS. (a) At 4.5 GHz in YZ plane, (b) at 4.5 GHz in XZ plane, (c) at 6 GHz in YZ plane, (d) at 7 GHz in XZ plane with optimized parameter values listed in Table 1.

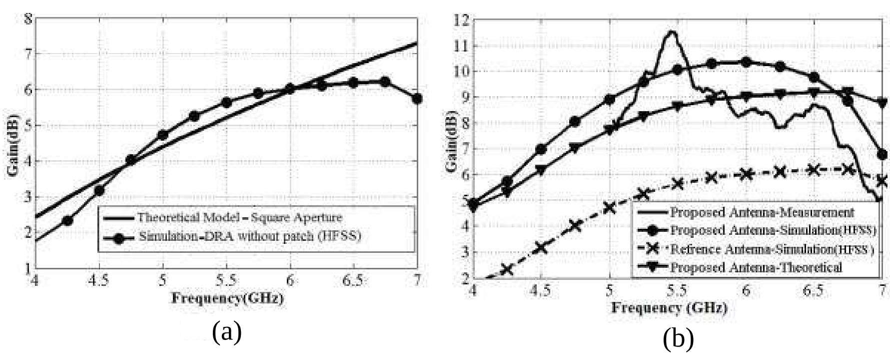


Figure 4. The gain of (a) antenna without patch (b) antenna with patch and optimized parameter values listed in Table 1.

3.3. Gain

The aim of this work is gain enhancement of DRA without degradation of bandwidth. Figure 4(b) shows that the gain of proposed antenna is considerably increased in comparison with the basic DRA. Actually, there is an increase in the gain of antenna by about 4.5 dB in the middle of bandwidth and by around an average value of 3 dB. The equivalent aperture size of a single DRA is calculated by comparison between the simulated and calculated gains by (1) for the single DRA, where the aperture efficiency is 100%, $\varepsilon_{ap} = 1$. Figure 4(a) shows the gain for a single DRA and a square aperture with dimensions of 28 mm × 28 mm. Observe that the two cases have nearly the same gain in the entire bandwidth, so the reference DRA can be modeled as this aperture antenna. Now the radiation area of the dielectric resonator loaded patch antenna will be calculated. First, the physical area of the surface is $L \times W = 756\,\mathrm{mm}^2$, then the two sidewall aperture areas (in XZ plane, because in YZ plane the radiations are out of phase and cancel each other) are $2 \times (h_g + d) \times W = 808.08\,\mathrm{mm}^2$. The sum of these two areas is $1564\,\mathrm{mm}^2$, that is $1564/784 = 2$ times the equivalent aperture size of a single DRA. Hence, the gain enhancement of 3 dB is achieved. It is obvious in Figure 4(b) that the simple theoretical model of the proposed antenna gain has nearly good agreement with that obtained by the simulation and measurement. In the simple theoretical model, the gain improvement is 3 dB, which nearly agrees with the computer simulation and measurement. Note that the slight discrepancy between two results for gain obtained by theoretical model and simulation is because of estimation in radiation area of the dielectric resonator patch loaded antenna. Also the discrepancies between the simulation and measurement results are because of fabrication and test errors. Since the standard horn antenna available in our laboratory used for gain measurement designed for frequencies above 5 GHz, the measured gain of proposed antenna depicted in Figure 4(b) is above 5 GHz.

3.4. Radiation Pattern

Figures 5(a)–(c) show the E-plane radiation patterns of the proposed antenna at three frequency samples. It is obvious that in the entire bandwidth the radiation patterns are of the broadside type. The monopole resonance of the probe is located in the proximity of the upper frequency band around 8 GHz. Therefore, because of the endfire radiation pattern of monopole and its effect on that of the proposed antenna near the upper frequency band of the bandwidth, the E-plane radiation pattern is slightly degraded from broadside type. Also, Figures 5(d)–(f) depict the H-plane radiation patterns of the proposed

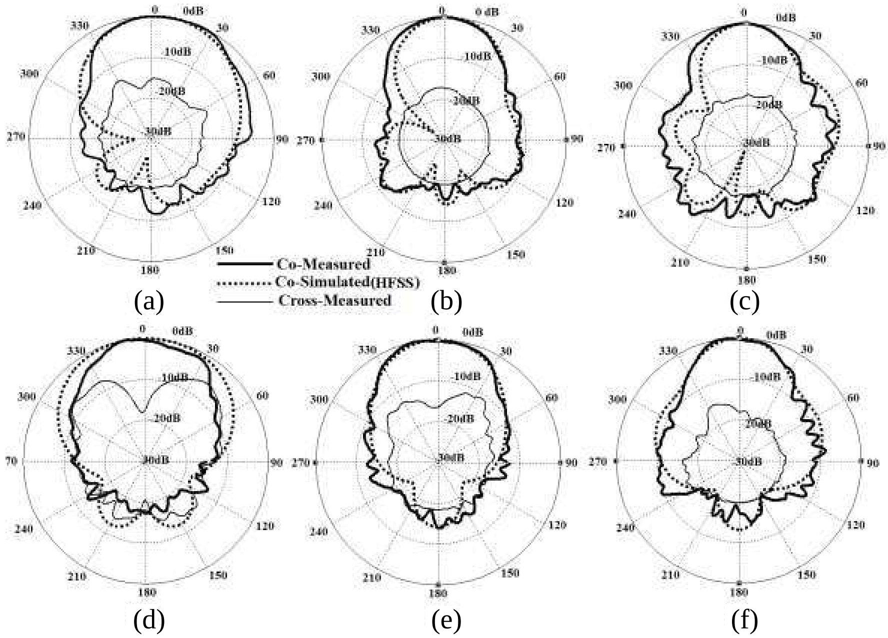


Figure 5. The measured and simulated radiation patterns of proposed antenna for parameter values are listed in Table 1 in (a) E plane (XZ plane) at 4.5 GHz, (b) E plane (XZ plane) at 5.5 GHz, (c) E plane (XZ plane) at 6.5 GHz, (d) H plane (YZ plane) at 4.5 GHz, (e) H plane (YZ plane) at 5.5 GHz, (f) H plane (YZ plane) at 6.5 GHz with optimized parameter values listed in Table 1.

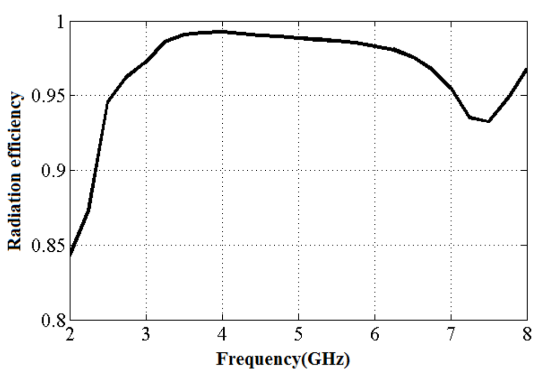


Figure 6. The radiation efficiency of DR loaded patch antenna from HFSS simulation.

antenna at those frequency samples for the E-plane radiation patterns. The symmetry in these radiation patterns is evident. It is because of the geometrical symmetry in the H (YZ)-plane. Also, these radiation patterns are broadside types. The cross-polarization levels in all samples are at least 15 dB below the main beam in the boresight direction except the first frequency sample in H-plane. Also, Figure 6 shows the radiation efficiency of the proposed antenna at frequency band from 2 to 8 GHz. Observe that in the antenna bandwidth from 3.75 to 6.75 GHz the radiation efficiency is better than 0.95.

4. CONCLUSION

We have been able to increase the DRA gain more than 3 dB over a wide impedance bandwidth by using a simple rectangular patch placed above the DR. The electrical aperture size enhancement is responsible for this gain improvement. A simple theoretical method for predicting the gain improvement is also presented. The simulated, theoretical and measured results have shown that the gain is significantly increased.

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