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Research Article

Enhanced gain and miniaturisation method of stacked dielectric resonator antenna using metallic cap

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Abstract: The authors introduce a miniature and gain enhancement method of dielectric resonator antenna (DRA) using a metallic cap. The structure of the proposed antenna consists of a stacked cylindrical dielectric resonator, a metallic cap that is located on the resonator, and a ground plane. By adjusting the size of the metallic cap while retaining the size of the antenna, the proposed antenna operates in the lower frequency band and shows improved realised gain. As the radius of metallic cap increases, wavelength at *z*-axis increases and the resonance frequency gets lower. In addition, tangential field at side wall surface increases, which leads to the enhancement of realised gain at resonance frequency. The authors have fabricated a prototype of the antenna for the experimental verification. The simulation results are in a close agreement with the experimental finding.

1 Introduction

Dielectric resonator antennas (DRAs) are good candidates for various wireless communication because DRAs have several advantages, such as high radiation efficiency, compactness, ease of excitation, light weight, loose tolerance, ease of coupling, and low cost [1]. Despite such advantages, there are technical limitations to reducing size and gaining enhancement of the DRA at the same time.

Some research on reducing the size of the DRA have been done by researchers. Using a high dielectric constant material, DRA reduction method is proposed in [2]. As the dielectric constant increases, the bandwidth and radiation efficiency decrease. In addition, the performance of DRA is greatly influenced by the material properties and geometrical parameters. In [3], a comparatively lower resonance frequency is obtained by using metallic post array inside DRA, when compared with the fundamental mode of DRA. Although this method can increase the bandwidth, size reduction of antenna was not achieved. The half and quarter size reduction method of the DRA using the electric conductor and magnetic conductor is presented and demonstrated in [4, 5]. However, this method cannot derive exact resonance frequency when compared with the full size structure. In [6], the size reduction structure, whose top surface of the rectangular DRA is metallised, is proposed. The resonance frequency is assumed to be independent of y-direction dimension because the wavenumber in y-direction is reduced to zero when the top of the rectangular DRA is metallised. In addition, through the adjustment of the thickness of the metallic caps, the size reduction is achieved as mentioned in [7]. Unfortunately, it is difficult to define the size reduction mechanism depending on the size of the metallic cap since the reduction of the wavenumber in y-direction to zero is equivocal to explain. Here, we clearly analyse and verify the phenomenon of the size reduction using metallic cap.

To enhance the gain of the DRA, many researches have been studied in [8–10]. Although they achieved gain enhancement of the DRA, the size of the DRA becomes very bulky, compared to the conventional DRA. Some research team studied the high gain antenna by stacking two different dielectric sheets as in [11, 12]. The antenna has high gain, even with the same size of conventional DRA, by enhancing the radiation intensity from the side wall of the DRA. Although they obtained high gain, the size of the DRA is the same with conventional DRA. The study that can be miniaturised while maintaining high gain by increasing the intensity of the side wall of DRA was strongly demanded. Therefore, we focused on the antenna of the cylindrical structure with various size of the metallic cap to devise the miniaturised and gain-enhanced antennas.

Here, we propose a novel method to achieve the gain enhancement and size reduction of the cylindrical stacked DRA (SDRA) simultaneously. The mechanism of SDRA with various size of the metallic cap is analysed and demonstrated. Using the metallic cap which plays a role in increasing the wavelength along z-axis of the resonator, the lower resonance frequency can be obtained. In addition, due to the metallic cap, the radiation intensity from side wall becomes stronger than that of top wall. Therefore, boresight gain of SCDRA is increased. Considering that even SDRA without metallic cap was also gain enhancement structure [12], the proposed method achieved much progress for the improvement of DRA. The novelty of this method is that the gain of DRA is improved along with the considerably minimised antenna size, compared with conventional CDRA.

2 Antenna configuration

The geometry of the proposed antenna is illustrated in Fig. 1. The antenna consists of a stacked dielectric resonator (DR), a ground plane, and a metallic cap. The DR is placed on a conducting ground plane, which is made of aluminium with a diameter of D ($= 75$ mm) and a thickness of T ($= 3$ mm), and is excited by a vertical probe source. The probe source consists of a coaxial probe and a curved metallic strip with a width of W_f and height H_f. By adjusting the W_f and H_f, the impedance between the antenna and feeding structure can be matched. The metallic cap is located on the centre of the top surface of the CDRA. The thickness(T_m) of metallic cap is 0.1 mm and radius of r_c is variable value. The stacked structure which is in contact with coaxial probe consists of two materials, a d_1 thick dielectric sheet with ε_1 and a d_2 thick dielectric sheet with ε_2. The structure satisfies an equivalent homogenised permittivity tensor given by [13]

$$[\varepsilon] = \begin{bmatrix} \varepsilon_{\perp} & 0 & 0 \\ 0 & \varepsilon_{\perp} & 0 \\ 0 & 0 & \varepsilon_z \end{bmatrix} \quad (1)$$

where

$$\varepsilon_{\perp} = \frac{\varepsilon_1 d1 + \varepsilon_2 d2}{d1 + d2}, \quad \varepsilon_z = \frac{\varepsilon_1 \varepsilon_2 (d1 + d2)}{\varepsilon_1 d1 + \varepsilon_2 d2}$$

where $\varepsilon_{\perp}$ and ε_z are perpendicular and parallel permittivity, respectively. The radius (r_d) and height of dielectric sheets (d_1 and d_2) are 6.5 and 0.5 mm, respectively. Stacking six pairs of dielectric sheets with 2.2(ε_1) and 23(ε_2), homogenous uniaxial DR with $\varepsilon_{\perp} = 12.6$ and $\varepsilon_z = 4.016$ is produced. The parameters of proposed antenna which guarantee the best performance are listed in Table 1. To verify the proposed antenna performance, isotropic antenna (conventional CDRA) model is simulated and compared with proposed antenna. Isotropic antenna (case A) has radius to height ratio (r_d/L) = 1.05 that is equal to that of proposed antenna. For the equal resonance frequency between the isotropic antenna and SDRA with metallic cap at same size, the dielectric constants (ε_r) = 7 of case A is used.

3 Simulation analysis

In order to understand the antenna mechanism, the proposed SDRA with metallic cap is verified using CST microwave simulator, which is based on the finite integration method. Depending on the radius r_c of the metallic cap, the simulation results of the reflection coefficients are shown in Fig. 2. The simulated result of SDRA without metallic cap (r_c = 0 mm), which was introduced in [12], is 7.35 GHz. It is observed that the resonant frequency of the $HE_{11\delta}$ mode shifts to a lower frequency as the size of the radius of the metallic cap increases. The resonance frequency at r_c = 6 mm is 5.87 GHz and is shifted to the lower about 1.48 GHz, compared with the resonance frequency at r_c = 0 mm.

To verify the size reduction and gain enhancement mechanism of the proposed antenna, the field distributions at resonance frequency with and without metallic cap are analysed. The simulated results of the E-field distributions with various r_c range from 0 mm to 6 mm are shown in Fig. 3. As expected, through the field distribution of the cutting plane of the antenna, the antenna excites the $HE_{11\delta}$ mode. In the SDRA without metallic cap case, the quarter wavelength along z-direction is almost identical to the height (L) of the antenna as shown in Fig. 3(a). The E_x-field component is dominant in surrounding the top surface. When metallic cap is located on the top surface of the DR, the boundary condition between the metallic cap and the SDRA are as follows:

$$E_{\rho}^{1}\big|_{z=L} = E_{\phi}^{1}\big|_{z=L} = 0, \text{ at } 0 < \rho < r_d \qquad (2)$$

The above equation shows that the tangential E-field vanishes while the normal E-field exists at metallic cap boundary. Therefore, the E_z–field component inside the SDRA increases significantly as the tangential E-field component vanishes at the boundary of the metallic cap. As shown in Fig. 3(b), when the metallic cap covered the SDRA(r_c = 6 mm), the tangential fields are almost vanished and E_z–fields are generated. The wavenumber along z-axis of the antenna without metallic cap is shown in third column of Table 2. In no metallic cap case, the quarter wavelength at z-direction is almost equal to the height (L) of the antenna, which is already identified in Fig. 3(a). At r_c = 6, the quarter wavelength at z-direction increases by about 1.8 times. When the r_c increases, the quarter wavelength at z-axis increases and the resonance frequency gets lower while retaining the size of the SDRA.

In [6], it is assumed that resonance frequency of the rectangular DRA with metalised top surface is reduced because wavenumber along the y-direction is reduced to zero and y-direction dimension is independent of the resonance frequency. However, this assumption does not explain the variation of the resonance frequency with the change of the size of the metallic cap. Therefore, the reason for the lowered resonance frequency by the metallic cap is due to the decrease of wavenumber of z-axis not of y-axis.

When the permittivity of the dielectric is high enough, the surface of DR is modelled as magnetic wall. In this case, the equation about equivalent current sources from [14] is $\overline{M_s} = \bar{E} \times \hat{n}$, where $\hat{n}$ is a unit normal pointing outward from the dielectric. The equation establishes that the more electric fields whose direction is the same as that of the resonator surface exist, the more equivalent current source is generated. In other words, we can assume that the directivity of the antenna increases as the tangential electric fields to the surface of resonator increase. [11, 12, 15] substantiate that the directivity of the radiation pattern of the antenna increases by increasing the ratio $|E_z(\pm r_d, 0, 0)|/|E_x(0, 0, L)|$. In the purposed antenna case, the $|E_x(0, 0, L)|$ is almost zero due to the boundary condition (2) of metallic cap. The magnitude of E-fields at the side wall (E(- r_d, 0, 0)) is analysed as shown in Fig. 4(a). As expected, the E_z components that are tangential fields of side wall increase as r_c increases. However, there is no significant variation in other fields. The change of total field magnitude is affected by the variation of E_z component, dominantly. By increasing the

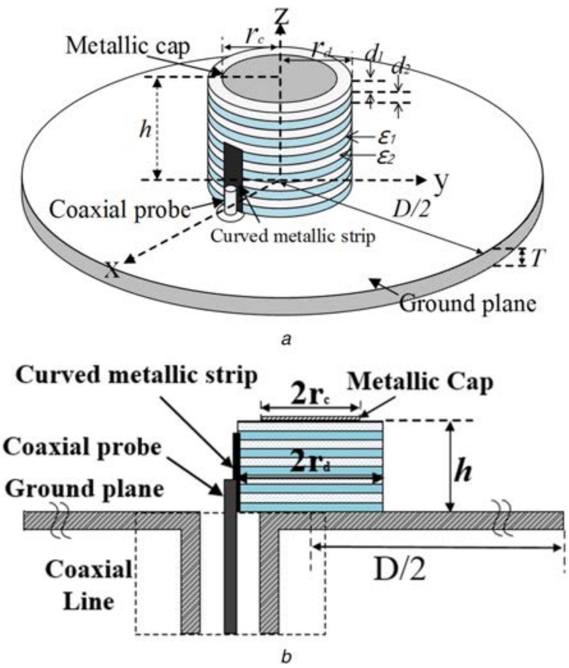

Fig. 1 *Geometry of proposed antenna structure*
(a) 3D view, ***(b)*** side view

Table 1 Optimised parameters of dielectric resonator antennas

Case	Material Properties	f_r (GHz)	$r_d \times L$ (mm)	$W_f \times H_f$ (mm)	r_c (mm)
a (isotropic)	$\varepsilon_r = 7$	5.88	7.4 × 8	1.2 × 5.7	0
b (proposed)	$\varepsilon_{\perp} = 12.6$, $\varepsilon_z = 4.016$	5.87	6.5 × 6	1.2 × 4.1	6

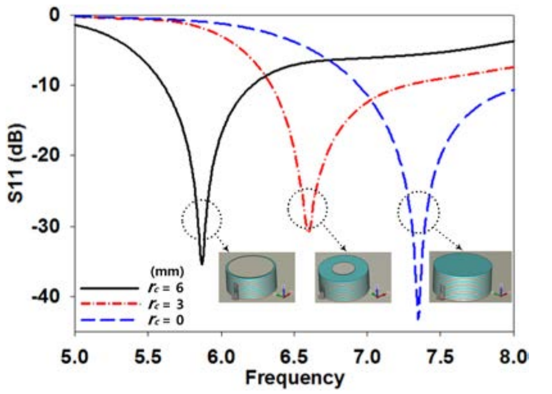

Fig. 2 *Simulation results of reflection coefficient versus the radius of the metallic cap*

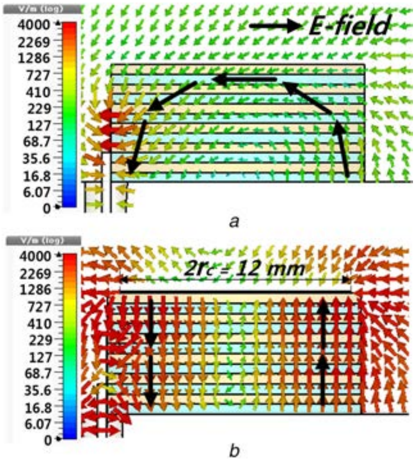

Fig. 3 *Simulated E-field distribution versus metallic cap size*
(a) without metallic cap($r_c = 0$ mm), ***(b)*** with metallic cap($r_c = 6$ mm)

Table 2 Summary of simulated results depending on radius of metallic cap

r_c (mm)	Simulated $HE_{11\delta}$ (GHz)	Quarter wavelength of z-axis (($\lambda/4$(mm))	Gain (dB)
0	7.35	5.89 (0.98*L*)	7.37
3	6.61	7.8 (1.3*L*)	7.75
6	5.87	10.8 (1.8*L*)	8.68

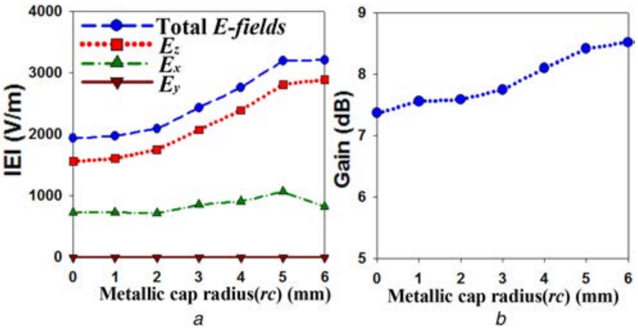

Fig. 4 *Simulation results depending on radius of metallic cap*
(a) Magnitude of electric fields, ***(b)*** Gain

tangential fields at side wall surface depending on the r_c, the realised gain at resonance frequency increases as shown in Fig. 4(b). In Table 2, the gain with metallic cap is 8.68 dB and increases by 1.15 dB, compared to the gain without metallic cap. Considering that the stacked DRA without metallic cap [12] is a gain enhancement structure, our proposed antenna has even more enhanced gain because tangential electric fields of side wall increases due to metallic cap.

By comparing the isotropic antenna (case A), miniaturisation and gain enhancement rate of the proposed antenna (case B) are achieved as shown in Fig. 5. The volume of the proposed antenna is 57% smaller than the volume of case A. In addition, the maximum gain of case A is 6.8 dB. The proposed antenna has 1.88 dB of enhanced gain and a small size when compared to conventional CDRA.

4 Result and discuss

The prototype of the proposed antenna was fabricated. Fig. 6 shows the photographs of the fabricated antenna. The input reflection coefficients of prototype antennas are measured using a vector network analyser (Agilent 8722ES) as shown in Fig. 7. The prototype antenna retains an acceptable impedance matching (VSWR < 2) even if the metallic cap size changes.

The resonance frequency without metallic cap is 7.35 GHz while that with metallic cap is 5.85 GHz. As expected, as the radius of the metallic cap increases, the lower resonance frequency is

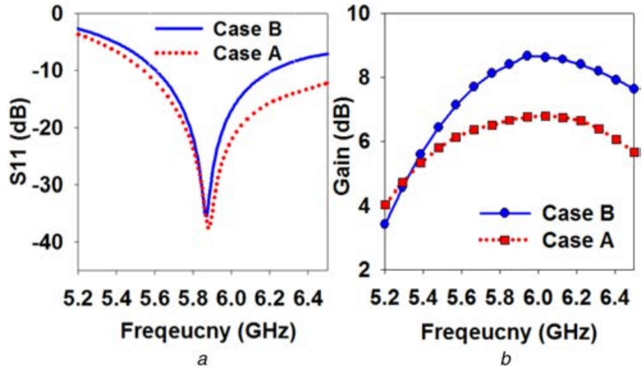

Fig. 5 *Simulation results of anisotropic and isotropic case*
(a) reflection coefficients, ***(b)*** Gain

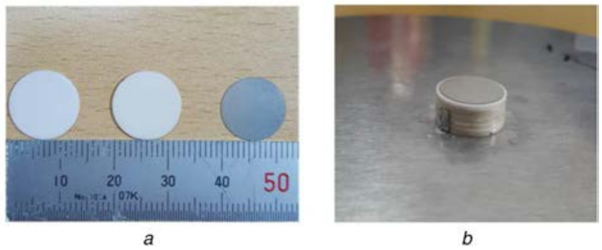

Fig. 6 *Photograph of the fabricated antenna*
(a) dielectric sheets and metallic cap, ***(b)*** proposed antenna with $r_c = 6$ mm

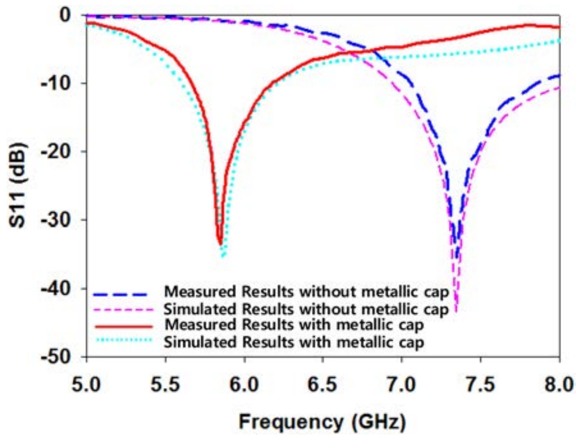

Fig. 7 *Measured and simulated reflection coefficient of the antenna with and without metallic cap*

obtained. There is a close correspondence between the simulated and measured results. A slight discrepancy between the measured and simulated results arises from the fabrication tolerance, such as the air gap between the resonator and feeding probe.

Fig. 8 shows the simulated and measured radiation patterns when r_c is 0 and 6 mm. There is an agreement with the simulated and measured results of both *xz* plane and *yz* plane. The cross-polarisation level is <−15 dB at boresight (+*z*-axis), which indicates the linearly polarised radiation. In addition, both planes, broadside radiation patterns, are observed. The measured and simulated realised gain with and without metallic cap is shown in Fig. 9. The maximum gain of SDRA without metallic cap is 7.2 dB at 7.45 GHz. The maximum gain of proposed antenna using metallic cap is 8.54 dB at 5.9 GHz and. Although the two prototype antennas have a same size, the proposed antenna obtained higher gain at a lower frequency than the antenna without metallic cap.

As a result, it is verified that the miniaturisation is obtained because the metallic cap plays an important role in increasing the wavelength of *z*-axis of the resonator. In addition, the gain enhancement is achieved by increasing the field intensity of the side wall due to the boundary condition of metallic cap.

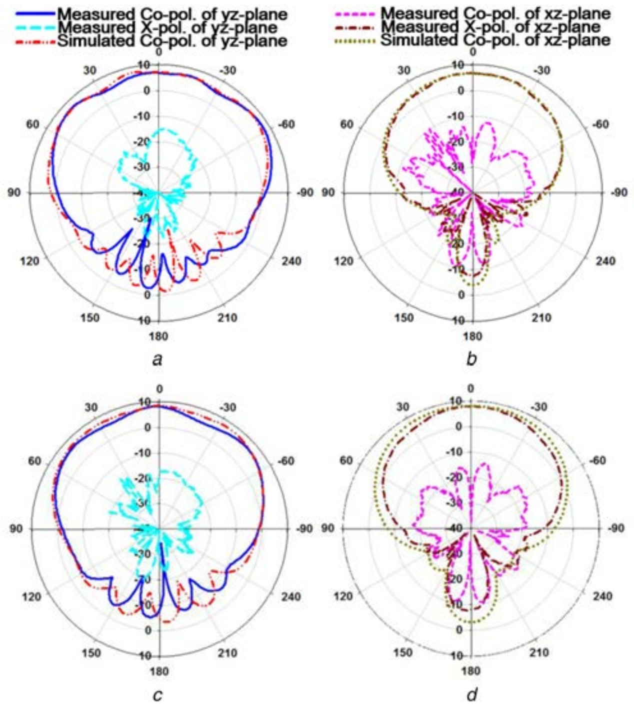

Fig. 8 *Simulated and measured radiation patterns*
(a) yz- plane at $r_C = 0$ mm, ***(b)*** xz-plane at $r_C = 0$ mm, ***(c)*** yz- plane at $r_C = 6$ mm, ***(d)*** xz-plane at $r_C = 6$ mm

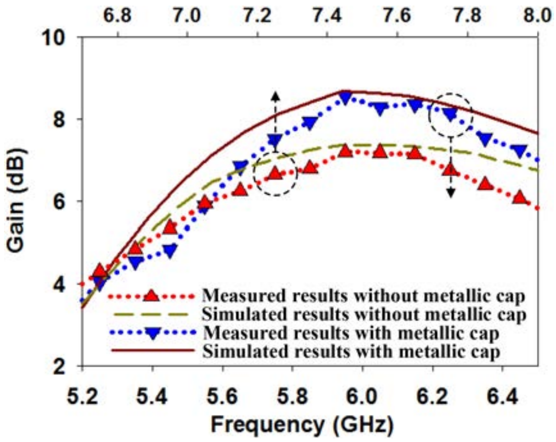

Fig. 9 *Measured and simulated gain of the prototype antennas*

5 Conclusion

The new concept to reduce the size and to enhance the gain of the SDRA using the metallic cap is presented and discussed here. When the size of the metallic cap increases, the resonance frequency decreases. In addition, the directivity is improved because the field density at sidewall increases. The two kinds of prototype antenna with and without metallic cap, respectively, are fabricated and the size reduction and gain enhancement phenomenon are verified. The resonance frequency of the proposed antenna with metallic cap is 5.85 GHz and has 1.5 GHz of lower frequency compared to the antenna without metallic cap. Moreover, the proposed antenna offers an acceptable radiation performance with improved realised gain in the entire range of frequencies. The maximum realised gain of the proposed antenna is 8.54 dB. The concept is verified by comparing the simulation and measured results.

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