LETTER

Dual-mode dielectric resonator antenna and array fed by planar slot

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Abstract A dual-mode dielectric resonator antenna (DRA) and array fed by planar slot are presented. The bandwidth is expanded by merging the adjacent bands corresponding to $TE_{1\delta 1}^y$ and $TE_{1\delta 3}^y$ modes. The measured results are in good agreement with the simulated ones. The measured -10 dB bandwidth is 17.8% and the average gain is 6.5 dBi. Furthermore, a 2×2 DRA array is developed, which is improved with 45.5% impedance bandwidth and a peak gain of 12.6 dBi. The proposed dual-mode dielectric resonator antenna structure is promising for high-frequency applications due to its merits of simple feeding structure and wide band.

Keywords: dielectric resonator antenna (DRA), dual-mode, wideband, array

Classification: Microwave and millimeter-wave devices, circuits, and modules

1. Introduction

Compared with conventional microstrip antennas, dielectric resonator antennas have many attractive advantages, such as light weight, low-loss and high radiation efficiency due to the lack of surface wave. These favorable characteristics make them attractive for high-performance wireless applications from low-frequency to very high-frequency bands and from PCB to on-chip applications [1, 2, 3, 4, 5, 6].

Traditional DRAs are usually in rectangular or cylindrical shapes. However, the bandwidth of a DRA is often limited for a single-mode excitation [7, 8, 9, 10]. To overcome this limitation, a series of bandwidth expansion approaches such as the use of specially shaped dielectric resonators (DRs) [11, 12, 13, 14], special feedings [15, 16, 17] and multiple stacked dielectric resonator elements [18, 19, 20, 21] have been developed. A wider bandwidth can also be achieved by merging the bands with adjacent modes of a DR [22, 23, 24, 25]. The nonradiating modes were excited, which can increase the gain variations over the impedance bandwidth and make unstable radiation patterns [22, 23]. To avoid this problem, $TE_{1\delta 1}^y$ and $TE_{1\delta 3}^y$ modes, which have similar radiation patterns can be considered to reach a wider bandwidth [24, 25]. However, this antenna structure is limited in high-frequency applications. Specifically, as the frequency increases, the size of the DR

becomes smaller, making it difficult to attach a metal strip to the DR surface. Nevertheless, this difficulty can be well overcome by DRA fed with planar slot due to its simple structure [26, 27, 28]. It has been used in terahertz band [29, 30]. However, there is lack of dual-mode antenna design excited by planar slot structure.

This paper proposes a dual-mode DRA fed by planar slot, whose bandwidth is expandable by merging the adjacent bands corresponding to $TE_{1\delta 1}^y$ mode and $TE_{1\delta 3}^y$ mode. The measured impedance bandwidth is 17.8%. On basis of this, a feeding network is designed and the dual-mode DRA is extended to the array design, which has a 45.5% impedance bandwidth.

Fig. 1. Structure of the dual-mode DRA.

2. Design of dual-mode DRA element

2.1 Configuration and working principle of dual-mode DRA

The antenna configuration is shown in Fig. 1. It consists of a rectangular DR and a planar feeding structure. This feeding structure is created by a grounded coplanar waveguide (GCPW) and an H-slot [4]. There is also a ground plane on the bottom of the substrate. The H-slot is surrounded by a rectangular metal wall made of vias to prevent energy dissipation. For a rectangular DR mounted on this feeding structure, the $TE_{m\delta n}^y$ resonance mode can be excited by the equivalent short magnetic dipole generated along the y direction under the DR. Moreover, the resonance frequency of $TE_{m\delta n}^y$ mode can be obtained by solving the following transcendental equation [5]:

$$k_y \tan \frac{k_y b}{2} = \sqrt{(\epsilon_r - 1)k_{mn}^2 - k_y^2} \quad (1)$$

where $k_x = m \frac{\pi}{a}$, $k_z = n \frac{\pi}{2h}$, $k_x^2 + k_y^2 + k_z^2 = \epsilon_r k_{mn}^2$, $k_{mn} = \frac{2\pi f_{mn}}{c}$. ϵ_r is the permittivity of the DR. c is the speed of

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the light. And a, b, h are the dimensions of the DR in x, y, z directions, respectively. When the permittivity ϵ_r and a are chosen as 9.5 and 26 mm, the two resonance frequencies of $TE_{1\delta 1}^y$ mode and $TE_{1\delta 3}^y$ mode will be the functions of b and h , which can be derived by Eq. (1). Fig. 2 shows the ratio contour of two frequencies corresponding to the two modes. The ratio decreases as the height of the rectangular DR increases, and the frequency distance between two resonance modes will be smaller. When a suitable excitation method is chosen, the adjacent bands of the two resonance modes can be merged and a dual-mode wide-band DRA will be achieved. The dual-mode DRA can be excited by planar H-slot structure in this work.

Fig. 2. Ratio of the frequencies corresponding to $TE_{1\delta 3}^y$ and $TE_{1\delta 1}^y$ modes.

2.2 Simulation and measurement of dual-mode DRA

The antenna is fabricated on FR4 ($\epsilon_{r1} = 4.4$, $\tan \sigma = 0.02$) substrate, with the thickness of 0.6 mm. The material of the DR is 99% alumina, with the permittivity of $\epsilon_r = 9.5$. The DR has a dimension of $26 \times 26 \times 68 \text{ mm}^3$, with 2.26 GHz for $TE_{1\delta 1}^y$ mode and 2.48 GHz for $TE_{1\delta 3}^y$ mode. The optimized parameters of the dual-mode DRA are given in Table I.

Table I. Design parameters (mm) of the dual-mode DRA

l	w	w_s	w_{s1}	w_{s2}	w_{s3}	l_{s1}	l_{s2}	l_{s3}
60	60	0.5	1.4	1.6	1	20.4	11.4	25.5

The fabricated prototype is shown in Fig. 3. The simulated -10 dB impedance bandwidth of the dual-mode DRA is 18.3% (2.13–2.55 GHz), as shown in Fig. 4. There are four resonances in Fig. 4. The first two resonances are related to $TE_{1\delta 1}^y$ mode and $TE_{1\delta 3}^y$ mode, which are similar to the ones calculated by Eq. (1). The third and the fourth resonances are related to the resonances of H-slot (2.7 GHz) and $TE_{1\delta 5}^y$ mode (2.9 GHz), respectively. The measured -10 dB impedance bandwidth of the dual-mode DRA is 17.8% (2.14–2.56 GHz). The comparison between measured and simulated reflection coefficients is shown in Fig. 4, exhibiting obvious mismatches at four resonance frequencies. The three resonance frequencies of the DR resonance modes shift to lower bands, which indicates that

Fig. 3. The fabrication prototype of dual-mode DRA.

Fig. 4. Simulated and measured reflection coefficients of the dual-mode DRA.

Fig. 5. Simulated and measured gains of the dual-mode DRA.

the permittivity of the DR needs to be larger in simulation. The resonance of H-slot also has a little shift. Therefore, the permittivities of the DR and substrate should be adjusted. The permittivities of the DR and substrate are fixed to 10 and 4.2 using HFSS. The modified frequencies of the $TE_{1\delta 1}^y$, $TE_{1\delta 3}^y$ and $TE_{1\delta 5}^y$ modes are 2.22 GHz, 2.47 GHz and 2.86 GHz, which are similar to the measured ones. The modified resonance frequency of H-slot is 2.74 GHz, which agrees with the measured one. Besides, there is a slight difference between the modified reflection coefficient and the measurement, which may result from the fabrication tolerance and the alignment errors.

Fig. 5 shows the measured, simulated and modified realized gains of the dual-mode DRA. Clearly, the antenna has a stable gain within the -10 dB bandwidth, with a measured peak gain of 7.4 dBi at 2.38 GHz. The simulated

and measured radiation patterns of the dual-mode antenna at 2.22 GHz ($TE_{1\delta 1}^y$ mode) in E-plane and H-plane are displayed in Fig. 6(a). The 3-dB beamwidths of E-plane and H-plane are 67° and 69° , respectively. What's more, the simulated and measured radiation patterns at 2.47 GHz ($TE_{1\delta 3}^y$ mode) are displayed in Fig. 6(b). The 3-dB beamwidths of E-plane and H-plane are 53° and 58° , respectively. Table II presents the comparison between the proposed dual-mode DRA and earlier reported single-mode DRAs. It can be observed that the dual-mode DRA can reach a wider bandwidth.

Fig. 6. Simulated and measured radiation patterns of the dual-mode DRA. (a) 2.22 GHz. (b) 2.47 GHz.

Table II. Comparison to previously reported DRAs

Ref.	DRA mode	BW (GHz)	BW (%)	Gain (dBi)
[7]	TE_{111}	2.25~2.48	9.7	2.7
[8]	TE_{111}	3.18~3.28	3	4.7
[9]	TE_{111}	2.24~2.52	11.8	7
[10]	TE_{111}	10.37~11.15	7.2	5.5
	TE_{113}	10.16~11.08	8.7	8.2
This work	Dual mode	2.14~2.56	17.8	7.4

3. Design of DRA array

3.1 Configuration and working principle of DRA array

The dual-mode DRA structure is very suitable for the array antenna design. In dual-mode DRA, the signal is fed by GCPW. Therefore, the feeding network is designed using bridge-less GCPW transmission lines. Fig. 7 shows the details of the feeding network. The RF signal is fed to port 1. There is 180° phase shift between port 2 and port 4 and between port 3 and port 5 [31]. Fig. 8 shows the structure of the 2×2 antenna array. And the distances between the antenna elements in x and y directions are L_x

and L_y , respectively. The radiation pattern can be optimized by properly specifying the distances and feeding network.

Fig. 7. Feeding network of the array antenna.

Fig. 8. Structure of the DRA array.

3.2 Simulation and measurement of DRA array

The optimized distances in x and y directions are $L_x = 109$ mm and $L_y = 107.4$ mm, corresponding to 0.85λ , where λ is the wavelength of center frequency. Fig. 9 shows the simulated mutual couplings between the DRA elements, which are shown in Fig. 8. And S_{n1} ($n = 2, 3, 4$) represents the mutual coupling between Ant_1 and Ant_n . It is observed that at such distances the mutual couplings between elements are very small (< -20 dB) over the dual-mode operating band.

The simulated results of the bridge-less GCPW feeding network displayed in Fig. 7 are shown in Fig. 10. The return loss is better than 20 dB over the dual-mode operating band. The fabrication prototype is depicted in Fig. 11.

Fig. 9. Simulated mutual couplings between the DRA elements.

Fig. 10. Results of the feeding structure.

And the simulated and measured reflection coefficients are shown in Fig. 12, having wider impedance bandwidths including the resonances of H-slot and TE_{105}^y mode. The simulated and measured -10 dB impedance bandwidths are 37.2% (2.12–3.09 GHz) and 45.5% (1.90–3.02 GHz), respectively. The simulated result with $\epsilon_r = 10$ and $\epsilon_{r1} = 4.2$ is also given to explain the mismatch of the measured result. It can be found that the modified result agrees well with the measured one. Fig. 13 shows the measured, simulated and modified realized gains of the array. Its realized gain reaches the maximum of 12.6 dBi at 2.38 GHz. One can also easily observe the agreement between the modified result and the measured one. The simulated and measured radiation patterns of the array at 2.22 GHz in E-plane and H-plane are displayed in Fig. 14(a). The 3-dB beamwidths of E-plane and H-plane are 33° and 34° , respectively. What's more, the simulated and measured radiation patterns at 2.47 GHz are displayed in Fig. 14(b). The 3-dB beamwidths of E-plane and H-plane are 30° and 31° , respectively.

Fig. 11. The fabrication prototype of the DRA array.

4. Conclusion

A dual-mode DRA and array fed by planar slot structure are proposed. This DRA has a wider bandwidth with a stable gain by merging two bands with adjacent modes. The measured -10 dB bandwidths are improved with

Fig. 12. Simulated and measured reflection coefficients of the DRA array.

Fig. 13. Simulated and measured gains of the DRA array.

Fig. 14. Simulated and measured radiation patterns of the DRA array. (a) 2.22 GHz. (b) 2.47 GHz.

17.8% (2.14–2.56 GHz) and 45.5% (1.90–3.02 GHz) for the dual-mode antenna element and array, respectively. The proposed dual-mode antenna has the advantages of wide-band, simple structure and good integration ability, which possesses vast potentials for high-frequency applications.

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