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Dielectric resonator antennas using high permittivity ceramics

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Abstract

The dielectric resonator (DR) antennas with probe-feed in both cylindrical and rectangular shape using high permittivity ceramics were investigated. The bismuth-based low-firing ceramics with the dielectric constants of 97, 71 and 37 were adopted as dielectric materials, respectively. The result of theoretical calculation and experimental measurement are presented and analyzed.

Keywords: Dielectric resonator antenna; High permittivity; Bismuth-based ceramic

1. Introduction

Dielectric resonators (DRs) have been widely used in shielded microwave circuits, such as cavity resonator, filters and oscillators. In recent years, application of these components as antennas in microwave and millimeter band has been extensively studied [1–4], as they had the advantages such as light weight, low cost, small size, low profile, high radiation efficiency, large bandwidth and ease of integration with other active or passive microwave integrated circuit (MIC) components. It has been reported that DRs in cylindrical [5], hemispherical [6], rectangular [7] and other geometries [8,9]. The feed mechanism varies from probes [10], slot [11], microstrip [12] and CPW feed [13]. Low-firing bismuth-based ceramic is a kind of typical high frequency dielectrics with high permittivity and low dielectric loss and attracts more and more attentions with the advances in microelectronic technologies and microwave communication [14–16]. In this paper, the cylindrical and rectangular dielectric resonator antennas using bismuth-based low-firing ceramics with the permittivity in 97, 71 and 37 were designed and fabricated.

2. Experimental

2.1. Dielectric ceramics

The ceramics used in this paper are bismuth-based low-firing ceramics $Bi_{3x}Zn_{2-3x-y}A_y(Zn_xNb_{2-x-z}B_z)O_7$ ($A = Ca^{2+}$, $B = Sb^{5+}$, Ti^{4+}, $x = 0.5$–0.67, $y = 0.2$–0.3, $z = 0.2$–1.4) with the dielectric constants of 97, 71 and 37, respectively [17]. These ceramics with permittiviy in series were synthesized by the conventional solid-state reaction method. The permittivity was measured using the Hakki–Coleman method as modified by Kobayashi and Katoh [18] with a network analyzer (HP-8720ES) in the frequency range of 2–5 GHz. The real measured permittivity of the three kinds of ceramics is 33.3, 71 and 96.7, respectively.

2.2. Antenna configuration

The configurations of the cylindrical and rectangular DRAs are shown in Fig. 1. The DRA is placed above a conducting ground plane (in this paper, the ground plane size is 30 cm × 30 cm), and excited by a coaxial probe. The coaxial probe goes through the ground plane and is connected to a SMA connector. In Fig. 1a, the cylindrical DRA has a radius a, height h, and dielectric constant ε_r. The probe is located on the x-axis at $x = a$ and $\phi = 0$.

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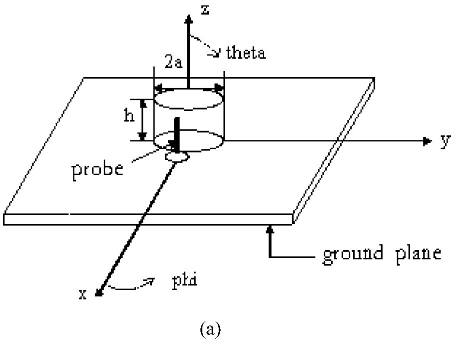


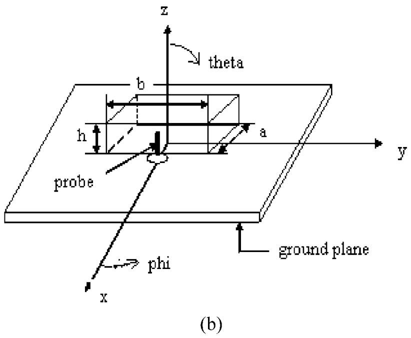


Fig. 1. Antenna configuration of cylindrical DRA (a) and rectangular DRA (b).

In Fig. 1b, the rectangular DRA has a length a, width b, height h and dielectric constant ε_r. The probe is located on the x-axis at $x = a/2$ and $\phi = 0$.

2.3. Resonator frequency

The cylindrical DRA is worked at $HE_{11\delta}$ mode and the rectangular DRA at TE^y_{111} mode. Two methods are used to calculate the resonator frequency of the DRAs: the theoretical formula of conventional dielectric wave-guide mode (CDWM) [19] and numerical simulation result obtained by Ansoft high frequency structure simulator (HFSS), a soft package based on the finite element method (FEM).

In the CDWM model, the dielectric-air boundaries are considered as perfect magnetic walls, the resonator frequency of the $HE_{11\delta}$ mode of the cylindrical DRA can be written as [20]:

$$f_0 = \frac{3\times 10^8}{2\pi\sqrt{\varepsilon_r}}\sqrt{\left(\frac{1.841}{a}\right)^2 + \left(\frac{\pi}{2h}\right)^2} \quad (1)$$

For the rectangular DRA working at TE^y_{111} mode, the resonator frequency is given by [21]:

$$k_x^2 + k_y^2 + k_z^2 = k_0^2\varepsilon_r \quad (2)$$

where $f_0 = k_0 c/2\pi$ and k_x, k_y, k_z are determined by

$$k_x = \frac{\pi}{a}, \qquad k_z = \frac{\pi}{2h},$$
$$k_y \tan\left(\frac{k_y b}{2}\right) = \sqrt{k_x^2 + k_z^2 - k_0^2} \quad (3)$$

3. Results

The return loss was measured using a HP 8720ES network analyzer.

As a typical case, the measured and HFSS simulated return loss of a cylindrical DRA versus frequency is shown in Fig. 2. The parameters of the cylindrical DRA are $a = 5.01$ mm, $h = 9.12$ mm, $\varepsilon_r = 71$. The simulated resonant frequency is 2.74 GHz and the measured is 2.91 GHz. The simulated and measured results are agreed well. Fig. 2

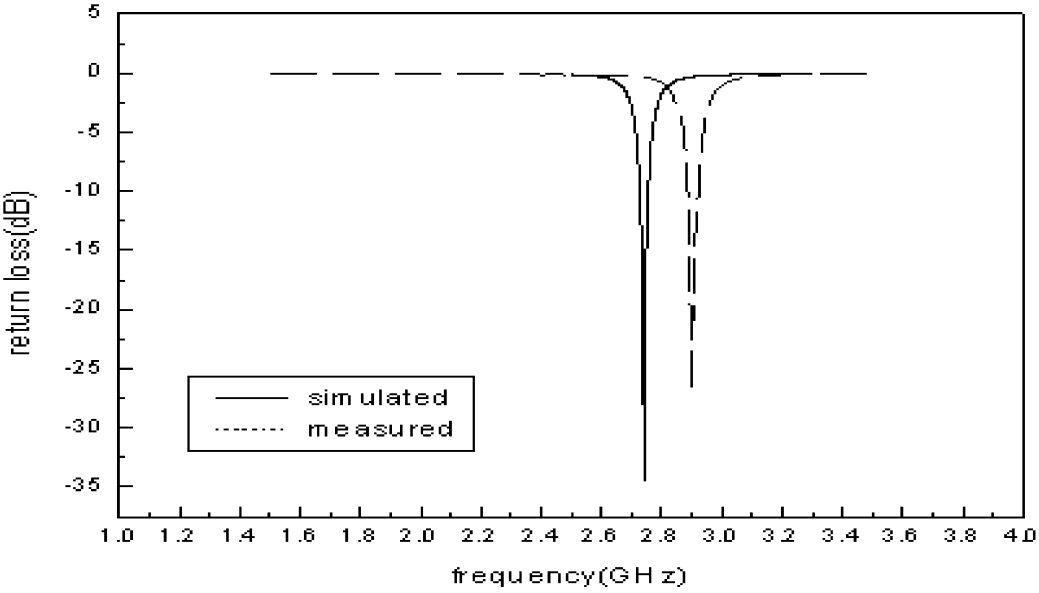
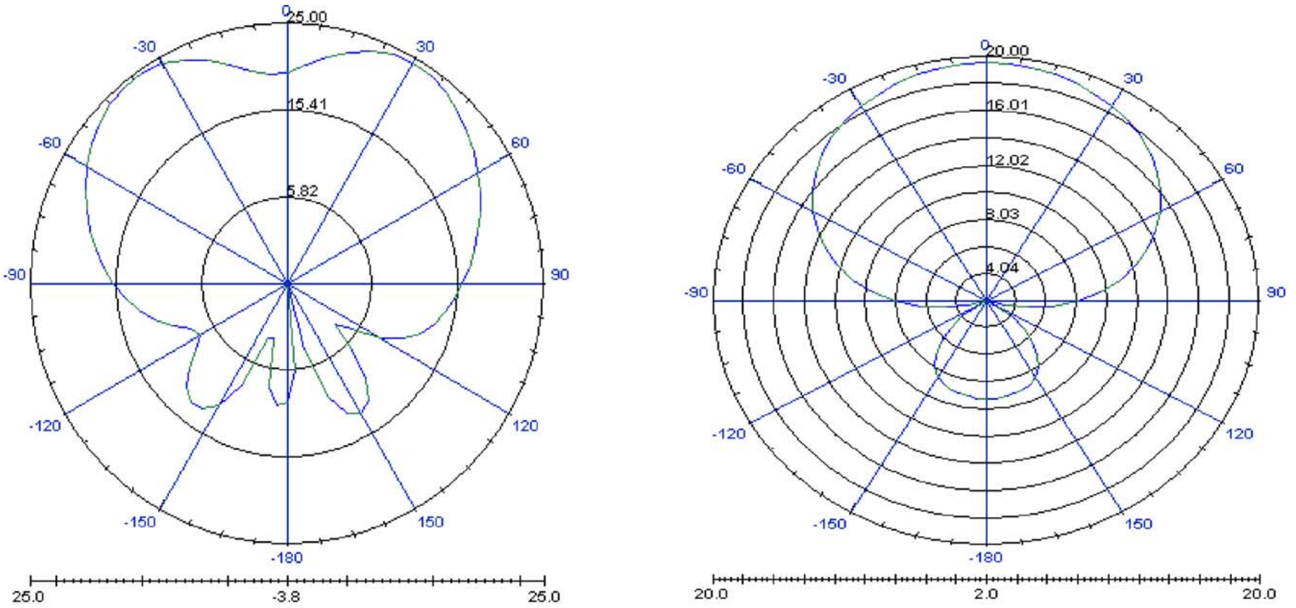


Fig. 2. The simulated and measured return loss vs. frequency for cylindrical DRA: $a = 5.01$ mm, $h = 9.12$ mm, $\varepsilon_r = 71$.



(a) (b)

Fig. 3. Simulated radiation pattern of *E* plane (*x*–*z* plane) (a) and *H* plane (*y*–*z* plane) (b).

revealed that the return loss of the antenna is less than −10 dB over the frequency bandwidth of 1.37%. The computed radiation patterns of *E* plane and *H* plane at resonant frequency are list in Fig. 3.

The theoretical and experimental frequencies of all the cylindrical and rectangular DRAs are listed in Tables 1 and 2. The computed results have been found to be in reasonably good agreement with experimental results. In addition, the results calculated with CWDM model accord with the results gained by HFSS simulation, but there are about 10–20% difference between them and the measured results. This maybe attributes to the difference of perimittivity, manufacturing tolerance, and the frequency excursion caused by the air-gap between the probe, resonator and the ground plane [22,23].

According to the results listed in Tables 1 and 2, the resonator frequency of the antenna decreases as the permittivity increasing and increases as the size of the antenna decreasing. The expected resonator frequency can be obtained by choosing the permittivity and size of the antenna. Therefore, the option of the DRA is much more than that of the microstrip antenna. The resonator frequency can be decreased to 2 GHz by choosing the materials with high permittivity and suitable size. This means such kinds of DRAs can be suitable candidates for the applications in the field of mobile communication.

The 10 dB bandwidth of return loss is also listed in the tables. We can see that the bandwidth of the DRA is much wider than that of the microstrip antenna (0.19%) [24]. The bandwidth of the antenna decreases (from 3 to 1.5%) as the permittivity increasing. Moreover, the bandwidth of the antenna is mainly influenced by the permittivity of the material. The antenna fabricated with the same material has almost the same bandwidth. If the permittivity of the material is 33.3, the bandwidth is 100–200 MHz (3%). Because a very

Table 1
Theoretical and experimental resonant frequencies and 10 dB bandwidth of cylindrical DRA

ε_r	*a* (mm)	*h* (mm)	Estimated frequency CDWM (GHz)	Estimated frequency HFSS (GHz)	Measured frequency (GHz)	Error CDWM (%)	Error HFSS (%)	Meas. BW (MHz)
96.7	5.20	9.12	2.187	2.298	2.595	15.7	11.4	40 (1.5)
96.7	6.36	7.84	2.000	2.016	2.200	10.0	8.3	29 (1.3)
71.0	4.23	6.72	3.155	3.277	3.767	16.2	13.0	56 (1.5)
71.0	4.23	8.74	2.977	3.204	3.530	15.6	9.2	56 (1.6)
71.0	5.01	7.66	2.750	2.829	3.070	10.4	7.0	40 (1.3)
71.0	5.01	9.12	2.605	2.741	2.910	10.5	5.8	40 (1.4)
33.3	4.27	3.90	5.654	5.532	6.270	9.0	11.7	27 (3.6)
33.3	4.27	5.44	4.953	4.994	5.370	7.7	7.3	178 (3.3)
33.3	5.13	3.90	5.128	4.994	5.340	3.9	6.5	151 (2.8)
33.3	5.12	6.60	4.100	4.103	4.360	6.4	6.4	132 (3.0)
33.3	5.10	8.12	3.853	3.943	4.110	6.2	4.1	131 (3.1)

Values shown in the parentheses are in percentage.

Table 2
Theoretical and experimental resonant frequencies and 10 dB bandwidth of rectangular DRA

ε_r	A (mm)	B (mm)	H (mm)	Estimated frequency CDWM (GHz)	Estimated frequency HFSS (GHz)	Measured frequency (GHz)	Error CDWM (%)	Error HFSS (%)	Measured BW (MHz)
96.7	9.64	19.80	2.90	3.140	3.178	4.058	22.6	21.6	80 (1.9)
96.7	9.60	18.55	4.10	2.538	2.613	3.305	23.2	20.9	64 (2.0)
71.0	10.10	19.14	2.10	4.606	4.700	5.807	20.7	19.0	108 (1.9)
71.0	9.90	19.18	3.74	3.309	3.146	3.865	20.7	18.6	69 (1.9)
71.0	9.80	19.08	5.30	2.551	2.659	3.217	20.7	17.3	54 (1.7)
33.3	10.10	19.52	3.84	4.414	4.366	5.160	14.4	15.3	239 (4.7)
33.3	9.92	19.24	4.40	4.120	4.113	4.653	11.5	11.6	178 (3.9)

Values shown in the parentheses are in percentage.

high permittivity has been used, the bandwidth is smaller than the typical value of 8–13% of conventional DR antennas using lower permittivity materials (ε_r). Nevertheless, the obtained bandwidth in this case is still adequate for many practical applications.

4. Conclusion

Some probe-feed cylindrical and rectangular dielectric resonator antennas made of three kinds of bismuth-based ceramic materials with high permittivities (33.3, 71 and 96.7) have been fabricated, measured and analyzed. The computed and experimental are presented and in good agreement. The obtained results of resonate frequency have been shown as a function of material and structural parameters of the resonators. The bandwidth of the antenna decreases as the perimittivity increasing.

Acknowledgements

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