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T-shaped dielectric resonator antenna with a high antenna gain

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This Letter proposes a T-shaped dielectric resonator (DR) antenna (DRA) to achieve a high antenna gain. The proposed antenna comprises a cylindrical DR top-loaded by a cylindrical DR disk, forming a T-shaped DRA that can be fabricated in one go. It is excited in the higher-order HEM_{115} mode. The DRA was designed in Ku band and fabricated to validate the idea. Its measured peak gain is 16.13 dBi at 13.34 GHz, with a 10-dB impedance bandwidth of 9.36%. As compared with a conventional DRA, our design has a large gain enhancement of ~9 dB.

Introduction: Although it had been shown as early as 1939 [1] that a dielectric resonator (DR) can radiate electromagnetic waves, the first DR antenna (DRA) was not designed until 1983 [2]. Various DRAs have been investigated, including wideband, dual-frequency, circularly polarized (CP), frequency-tuning, and dual-function designs [3, 4]. Since the DRA has no conductor loss, its radiation efficiency can be higher than 90%, making it a promising candidate for wireless communication systems. Typically, a DRA excited in its fundamental broadside mode has an antenna gain of ~6 dBi. This gain value, however, may not be sufficient for point-to-point communications where high-gain antennas are needed. Arraying DRA elements together is the most straightforward way to increase the antenna gain, but it substantially increases the antenna size and the complexity of the feed network [5].

Recently, some new techniques have been developed to enhance the gain of a DRA. In the first approach, additional structures are used to increase the antenna gain, such as deploying a surface-mounted short horn to increase the gain of a cross DRA up to 9 dBi [6]. Similarly, a plastic-based conical horn has been used to improve the antenna gain of a cylindrical DRA to 11.3 dBi [7]. A mushroom-like circular periodic EBG substrate offers a gain enhancement of 3 dB for a cylindrical DRA [8]. In [9], a spherical lens and a metal reflector have been used to increase the gain of a hollow cylindrical DRA to 16 dBi. Its cost is to substantially increase the antenna complexity and the antenna profile from $0.44\lambda_0$ (without the top-loading part) to $1.1\lambda_0$ (including the top-loading part), where λ_0 is the operating wavelength in air.

The second approach is to excite higher-order modes of a DRA. For instance, a cylindrical DRA excited in the higher-order HEM_{121} mode has an antenna gain of ~10 dBi [10]. This high gain level has also been obtained by exciting the higher-order TE_{115} mode of a rectangular DRA [11]. The gain of the rectangular DRA can be further increased to 13.7 dBi by exciting the next higher-order TE_{117} mode [11], but it increases the DRA height from $1.06\lambda_0$ (TE_{115} mode) to $3.3\lambda_0$.

This Letter proposes a high-gain T-shaped DRA excited in a higher-order mode. As compared with the lens-loaded DRA in [9], which has a non-planar ground plane, the proposed DRA has a much simpler structure with a lower profile of $0.68\lambda_0$ ($1.1\lambda_0$ in [9]). Our design has both the measured and simulated antenna gains and front-to-back ratios of higher than 16 dBi and 20 dB, respectively. These values are the same as given by [9], although the design in [9] has a wider impedance bandwidth because of using a hollow DR. Unlike the lens-loaded DRA which requires two different dielectric constants, our design has one dielectric constant only and can therefore be easily fabricated in one go.

Antenna design: The proposed T-shaped DRA is designed in Ku band to demonstrate the idea. Figure 1 shows the configuration. The DRA consists of a lower cylindrical DR loaded by an upper DR disk, placed on the top of an aluminium square ground plane. It is excited in its higher-order HEM_{115} mode by attaching a probe of diameter ϕ_p and height h_p to the sidewall of the lower DR.

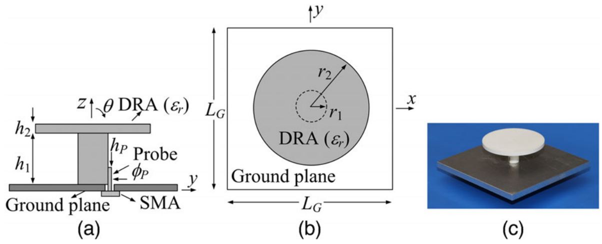

Fig. 1 *Configuration of T-shaped DRA: the parameters are $L_G = 70$ mm, $r_1 = 3.5$ mm, $r_2 = 20$ mm, $h_1 = 12.5$ mm, $h_2 = 2.5$ mm, $h_P = 3.7$ mm, $\phi_P = 0.25$ mm, and $\varepsilon_r = 7$. (a) Front view, (b) top view, (c) perspective view of the fabricated prototype. DRA, dielectric resonator antenna.*

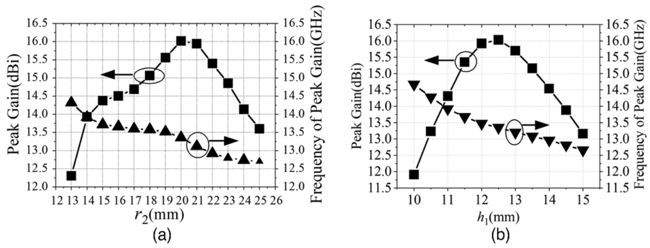

Fig. 2 *Simulated peak gain and its corresponding frequency as functions of r_2 and h_1. Other parameters are the same as in Figure 1. (a) r_2, (b) h_1*

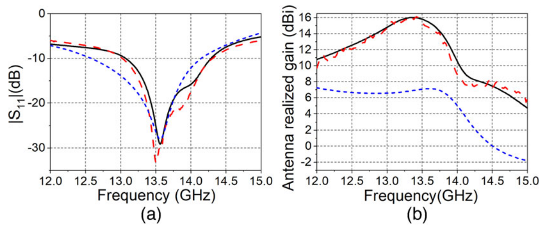

Fig. 3 *Measured and simulated results of T-shaped DRA along with the simulated results of reference DRA. The parameters are given in Figure 1.——— Proposed DRA (Sim.)– – – – Proposed DRA (Meas.)………… Reference DRA. (a) Reflection coefficient, (b) Antenna gain*

It is of interest to know the effects of the upper-disk radius r_2 and lower-cylinder height h_1 on the antenna gain. Figure 2a shows the simulated peak gain and the corresponding frequency as a function of r_2. With reference to the figure, the gain first increases and then decreases, with the peak value found at $r_2 = 20$ mm. In contrast, the peak-gain frequency decreases monotonically, which is expected because increasing the disk radius will increase the antenna size. Figure 2b shows the peak gain and the corresponding frequency as a function of the lower-cylinder height h_1. As seen from the figure, there exists an optimum h_1 (12.5 mm) that gives the maximum antenna gain. The peak-gain frequency also decreases monotonically as h_1 increases, which is, again, expected because the antenna size increases with an increase in h_1. In this Letter, the optimum values of $r_2 = 20$ mm and h_1 12.5 mm are used in our design.

Results: Figure 1c shows the DRA prototype that was fabricated in one go from a dielectric block, with machining errors of ±0.1 mm. Figure 3a shows the measured and simulated reflection coefficients of the DRA. With reference to the figure, the measured and simulated resonant frequencies of the T-shaped DRA are 13.50 and 13.56 GHz, respectively, which are in good agreement. The discrepancy is caused by experimental tolerances, including the cable reflections. As can be found from the figure, the measured and simulated 10-dB impedance bandwidths are 9.36% (13.03–14.31 GHz) and 8.85% (13.07–14.28 GHz), respectively. To know the effects of the upper loading disk on the antenna performance, a conventional HEM_{115}-mode cylindrical DRA resonating at the same frequency (13.56 GHz) was designed as a reference antenna.

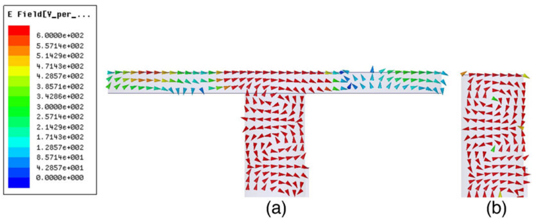

Fig. 4 *Simulated resonant E-fields inside the DRAs using HFSS. (a) T-shaped DRA. (b) Reference DRA. The parameters are given in Figure 1. (a) Proposed DRA, (b) reference DRA*

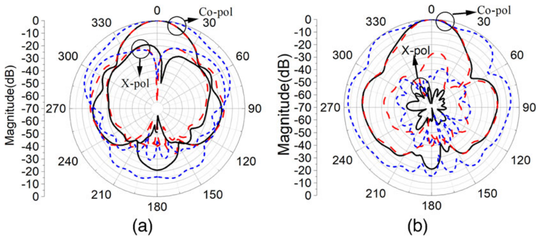

Fig. 5 *Measured and simulated radiation patterns of T-shaped DRA at 13.34 GHz and simulated result of reference DRA at 13.6 GHz. (a) H-plane. (b) E-plane. The parameters are given in Figure 1.——Proposed DRA (Sim.)– – – – Proposed DRA (Meas.)………… Reference DRA (Sim.). (a) H-plane, (b) E-plane*

It has a radius of $r_3 = 3.8$ mm, a height of $h_3 = h_1 + h_2 = 15$ mm, and a dielectric constant of $\varepsilon_{r3} = \varepsilon_r = 7$, that is, it has the same height and dielectric constant as used in our T-shaped DRA. For the ease of comparison, its simulated reflection coefficient is shown in the same figure. With reference to the figure, the impedance bandwidth of the reference DRA (11.68%) is wider than that of the T-shaped DRA (8.85%). This is expected because some energy is trapped between the loading disk and ground plane, leading to a higher Q-factor and thus, a smaller bandwidth.

Figure 3b shows the measured and simulated antenna gains of the T-shaped DRA in the boresight direction ($\theta = 0$), and reasonable agreement between them is observed. With reference to the figure, the measured and simulated peak gains are 16.13 dBi and 16.03 dBi at 13.34 GHz and 13.36 GHz, respectively. The simulated gain of the reference antenna is also shown in the same figure. As seen from the figure, the reference DRA has a much lower peak gain of 7.13 dBi at 13.6 GHz, meaning that upper loading disk of our T-shaped DRA has provided a gain enhancement of 8.89 dB. The gain enhancement can be understood by comparing the internal fields between the two antennas. Figure 4 shows the internal fields inside the two antennas at 13.36 GHz. With reference to the figure, the T-shaped DRA has more horizontal *E*-fields parallel to the ground plane due to the loading disk. It significantly increases the radiation aperture size and thus, the antenna gain.

Figure 5 shows the measured and simulated radiation patterns of the T-shaped DRA at 13.34 GHz, along with the simulated result of the reference DRA at 13.6 GHz. With reference to the figure, the T-shaped DRA has broadside radiation patterns, which is expected when the DRA is excited in the TE_{115} mode. In both the E- and H-planes, the measured and simulated co-polarized fields are stronger than their cross-polarized counterparts by more than 20 dB in the boresight direction, which is sufficient for many applications. Both the measured and simulated front-to-back ratios are desirably higher than 20 dB. It is noted that the reference DRA has a much wider beamwidth, which is reasonable for a much lower antenna gain of 7.13 dBi.

Conclusion: This Letter presents a simple high-gain T-shaped DRA, excited in the HEM_{115} mode. A prototype was fabricated and measured to validate the simulations. It has a measured peak gain of 16.13 dBi over an impedance passband ($|S_{11}| < -10$ dB) from 13.03 to 14.31 GHz. The T-shaped DRA has been compared with a conventional cylindrical DRA excited in the same resonant mode with the same frequency. It has been shown that our T-shaped DRA can provide a gain enhancement of ~9 dB. The internal fields of the T-shaped DRA and conventional DRA have been compared with each other. It has been observed that the upper DR disk of our design has more horizontal E-fields, increasing the radiation aperture and, thus, the antenna gain.

Author contributions: Li Ying Feng: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Writing – original draft. Kwok Wa Leung: Conceptualization; Funding acquisition; Methodology; Project administration; Supervision; Validation; Writing – review & editing.

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Conflict of interest: The authors declare no conflict of interest.

Data availability statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

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