High Gain Spherical DRA Operating on Higher-Order Mode Excited by Microstrip Patch

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Abstract: This paper proposed a high gain spherical dielectric resonator antenna (DRA) operating on higher-order mode excited by microstrip patch. A microstrip patch was used to excite $TE_{n01}$ mode on a dielectric sphere. The excited dielectric sphere operates as higher-order mode spherical DRA with high gain. Impedance matching method for conventional microstrip patch could be applied to the proposed antenna. Size minimization method for the excitation microstrip patch was also described on this paper. A prototype antenna operating on $TE_{301}$ mode at 5.8GHz was fabricated by a ceramic dielectric material, which dielectric constant is 13, and showed the peak gain of 9.03dBi.

Keywords: Dielectric resonator antennas, High gain antenna, Higher-order mode

Classification: Microwave and millimeter wave devices, circuits, and systems

References

1 Introduction

Recently, interest in massive phased array antenna technology is growing. High gain antenna is required to reduce the entire number of elements of array antenna because as antenna gain increases, the number of elements decreases exponentially. However, high gain antenna is not appropriate to array because of its large size. For these reasons, various studies have been conducted to obtain high gain property of DRA which have advantages in miniaturization and design flexibility. DRA typically operates on fundamental mode with typical gain of about 5dBi, but it can achieve high gain when it operates on higher-order mode through a suitable feed structure [1, 2].

Many studies have been suggested to raise the DRA gain up using higher-order modes. They analyzed the resonant modes occurred in various dielectric types and proposed suitable feed structures to obtain high gain antenna operating on desired mode. Petosa and Thirakoune [3] showed that a slot fed rectangular DRA operating on $TE_{613}$ mode and $TE_{615}$ mode can achieve gains of 8.2dBi and 10.2dBi, respectively. Guha at al. [4, 5] proposed a higher-order mode excitation method for cylindrical DRA using microstrip patch and showed that a cylindrical DRA operating on $HEM_{125}$ mode can achieve gain of 9.5dBi. Mrnka and Raida [6, 7] showed that a slot fed cylindrical DRA operating on the combination of two higher-order hybrid modes ($HEM_{133}$ mode and $HEM_{123}$ mode) can achieve gain of 11.6dBi. Amin at al. [8] proposed a higher-order mode excitation method for bowtie-shaped DRA to operate on $TE_{621}$ mode and $TE_{225}$ mode simultaneously using dual feed mechanism, and validated the isolation of compact MIMO DRA. As described, there are many studies on higher-order modes and excitation methods of rectangular and cylindrical DRA, but those of spherical DRA are rare. In this paper, we propose a high gain spherical DRA operating on higher-order mode.
2 Antenna design and parametric study

The resonant mode generated in dielectric sphere have been analyzed by using spherical cavity model [9]. The modes generated in dielectric sphere are classified as $TE_{nmr}$ mode and $TM_{nmr}$ mode, where $n$, $m$, $r$ denote the magnetic and electric field dependencies on $\theta$, $\phi$, $r$-direction at spherical coordinate system. The $TE_{n01}$ mode has a magnetic field distribution having a half period in the $r$-direction and $n/2$ period in the $\theta$-direction. Because of this magnetic field distribution, the energy is concentrated near the surface of the sphere as the order of the mode increases [10]. By using these characteristics, energy can be radiated intensively on higher-order $TE_{n01}$ mode.

The geometry of proposed antenna is shown in Fig. 1. A spherical ceramic, which dielectric constant is 13, was used for implementation and a microstrip patch was used to excite it. The proposed antenna was simulated by CST Microwave Studio. Magnetic field distributions in Fig. 2 shows the sequentially increasing $TE_{n01}$ modes generated in the proposed antenna structure. In this antenna, $TE_{101}$, $TE_{201}$, $TE_{301}$ and $TE_{401}$ mode are generated at 3.2GHz, 4.5GHz, 5.8GHz, and 6.8GHz, respectively.

The directivity and size comparisons of each order mode (from $TE_{101}$ mode to $TE_{401}$ mode) antennas are shown in Table I. The $TE_{101}$ mode and $TE_{201}$ mode antennas have not enough directivity to satisfy our purpose. On the other hand, the $TE_{301}$ mode antenna has enough directivity, but it is not suitable to array because of its large size. Grating lobe problem will be occurred when use this antenna. Therefore, the $TE_{301}$ mode antenna is reasonable for array antenna because of its advantages of high directivity and moderately small size.

![Fig. 1. Geometry of proposed antenna excited by microstrip patch. (a) Perspective view. (b) Side view. Parameter: $\varepsilon_r=13$, $R=13.8$mm, $L=50$mm, $t=0.76$mm. (c) Top view of excitation microstrip patch. Parameter: $D_x=14$mm, $D_y=14$mm, $D_{feed}=4$mm, $r_d=3$mm.](image-url)
Fig. 2. Magnetic field distributions of dielectric sphere when radius is 13.8mm and dielectric constant is 13. (a) $TE_{101}$ mode at 3.2GHz. (b) $TE_{201}$ mode at 4.5GHz. (c) $TE_{301}$ mode at 5.8GHz. (d) $TE_{401}$ mode at 6.8GHz.

Table I. Directivity and size comparisons of each order mode antennas

<table>
<thead>
<tr>
<th>Mode</th>
<th>$TE_{101}$</th>
<th>$TE_{201}$</th>
<th>$TE_{301}$</th>
<th>$TE_{401}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonant frequency</td>
<td>3.2GHz</td>
<td>4.5GHz</td>
<td>5.8GHz</td>
<td>6.8GHz</td>
</tr>
<tr>
<td>Directivity</td>
<td>6.1dBi</td>
<td>6.6dBi</td>
<td>10.3dBi</td>
<td>10.9dBi</td>
</tr>
<tr>
<td>Sphere size</td>
<td>$0.30\lambda_0$</td>
<td>$0.42\lambda_0$</td>
<td>$0.53\lambda_0$</td>
<td>$0.63\lambda_0$</td>
</tr>
</tbody>
</table>

The influence of some design parameters of the proposed antenna excited by microstrip patch was studied. The effect of $D_y$ is shown in Fig. 3, when $D_x=14$mm and $D_{feed}=4$mm. As $D_y$ increases, the resonant frequency decreases and the properties of directivity and input impedance deteriorate. As the resonant frequencies of excitation microstrip patch and dielectric sphere are well matched, then the directivity and input impedance show good properties. It also shows that the impedance matching methods for microstrip patch can be applied to proposed antenna, because the resonant frequency of dielectric sphere is fixed by its structure.

From these properties, we can minimize the size of excitation microstrip patch. As the length of $D_x$ decreases, the input impedance increases. This

Fig. 3. Effect of $D_y$ on proposed antenna excited by microstrip patch. (a) Reflection coefficient. (b) Directivity. (c) Input impedance.
can be compensated by placing the feeding point closer to the center of microstrip patch. Fig. 4 shows the effect of $D_{feed}$ on proposed antenna excited by minimized microstrip patch, when $D_y=14\text{mm}$ and $D_x=4\text{mm}$. The increase of the input impedance due to the decrease of $D_x$ can be compensated by shortening the length of $D_{feed}$. Thus, excitation microstrip patch could be minimized without impedance mismatch.

3 Experimental results

The dielectric sphere was fabricated by ceramic dielectric material having a dielectric constant of 13 and a loss tangent of $\tan\delta <0.002$. The minimized excitation microstrip patch was etched on a substrate RF-301 having a dielectric constant of 2.97, a thickness of 0.76mm and a size of $50\times50\text{mm}^2$.

The plastic jig which holds the dielectric sphere above the excitation microstrip patch was fabricated by PolyLactic Acid(PLA) using 3D printer. The photographs of prototype antenna and 3D structure diagram are shown in Fig. 5.

Fig. 4. Effect of $D_{feed}$ on proposed antenna excited by minimized microstrip patch. (a) Reflection coefficient. (b) Directivity. (c) Input impedance.

Fig. 5. Photographs of prototype antenna. (a) Perspective view. (b) Top view. (c) Back view. (d) Top view of minimized excitation microstrip patch. (e) 3D structure diagram.
The prototype antenna was simulated by CST Microwave Studio. The reflection coefficient of fabricated prototype antenna was measured using Agilent 8722ES network analyzer and the radiation pattern and gain were measured at anechoic chamber. Simulated and measured reflection coefficients are shown in Fig. 6(a). Simulated and measured 10-dB impedance bandwidths are about 5.77-5.85GHz and 5.75-5.84GHz, respectively. Simulated and measured radiation patterns at 5.8GHz are shown in Fig. 6(b) and Fig. 6(c). Simulated peak gain at 5.8GHz is about 9.90dBi and the 3-dB beam widths of xz-plane and yz-plane are 54° and 54°, respectively. Measured peak gain at 5.8GHz is about 9.03dBi and the 3-dB beam widths of xz-plane and yz-plane are 59° and 54°, respectively.

4 Conclusion
This paper proposed a high gain spherical DRA operating on higher-order mode excited by microstrip patch. Impedance matching method for proposed antenna and size minimization method for excitation microstrip patch were also described. A prototype antenna operating on $TE_{301}$ mode at 5.8GHz was implemented. The dielectric sphere was fabricated by ceramic having a dielectric constant of 13, and the minimized excitation microstrip patch was etched on the substrate RF-301. To hold the dielectric sphere and PCB, 3D printed plastic jig was fabricated by PLA. The 10-dB impedance bandwidth and peak gain of prototype antenna were 5.75-5.84GHz and 9.03dBi, respectively. The 3-dB beam widths of xz-plane and yz-plane were 59° and 54°, respectively. Experimental results showed reasonable agreement with simulations and validated the new concept of the high gain spherical DRA operating on higher-order mode.

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