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Design of a low-sidelobe-level and wideband dielectric resonator antenna array for 60 GHz millimeter wave communication①

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Abstract

A low-sidelobe-level (SLL) and wideband linear dielectric resonator antenna (DRA) array is proposed for 60 GHz millimeter wave communication. The array consists of 10 wideband DRAs which work at 60 GHz and it is fed by a Chebyshev feeding network to get a low SLL. To avoid the influence from the feeding network, a U-shaped substrate and a conformal ground are used, which can separate the DRA array and the feeding network. The parameter analysis and simulated results are presented.

Key words: dielectric resonator, antenna array, low-sidelobe-level (SLL), wideband, 60 GHz millimeter wave communication

0 Introduction

With the development of the wireless communication, demands for spectrum and data transfer rate become more and more urgent. However, the existing wireless frequency band has already been filled up with Bluetooth, WIFI, WLAN, etc. Nowadays, the 60 GHz frequency band is of particular interest because the communication systems working at 60 GHz can have a higher speed of data transmittion. According to the theoretical computations, the original data transfer rate at 60 GHz can be up to 25 000 Mbps. Moreover, the communication systems working at this frequency can have stronger anti-jamming ability and higher safe performance. All these characteristics mentioned above make the V band wireless communication systems attract special interests for high date rate and short range wireless communications, such as point-to-point system and wireless personal area network (WPAN) application.

Aiming at the bandwidth, gain, polarization and sidelobe-level (SLL), some researchers have proposed their designs of antenna arrays at 60 GHz. To overcome the conductor loss, dielectric loss, surface loss and degradation caused by transiting structure, complex structures are used in most of these designs, such as low-temperature co-fired ceramic (LTCC) substrate[1-3], FR-4 PCB/epoxy/polypropylene/epoxy composite (PEPEC) substrate[4], substrate integrated waveguide (SIW) feeding network[5], etc. However, the additional fabrication process for such especial structures increases circuit complexity and cost and may cause structural deformation[6].

Over the last decades, dielectric resonator antennas (DRAs) have become more and more popular because of their high radiation efficiency due to absence of conductor as well as surface wave loss, especially in millimeter wave frequencies. On the other hand, DRAs can be fed by various feeding techniques[7], such as the microstrip line feed, the coaxial probe feed, the coplanar waveguide feed and the aperture coupling feed. In recent years, several designs of DRA arrays working in V band have been proposed[8,9], but it is found that these designs do not have a good bandwidth and a low SLL simultaneously.

To meet the requirements in 60 GHz communication, a novel design of low-sidelobe and wideband linear DRA array have been presented in this paper. The impedance bandwidth of the proposed antenna array is of 37.9% (56.9 - 83.5 GHz), which completely covers the 57 - 66 GHz unlicensed band. The antenna gain is of 15.9 dBi at 60 GHz, and is higher than 13 dBi over the frequency band from 57 to 65.3 GHz. The SLL is of -27.3 dB at 60 GHz, and is lower than -15 dB over the frequency band from 57 to 63 GHz.

The structure and performances of the antenna array are presented and discussed in this paper.

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1 Design of the DRA array element

To design a low-sidelobe and wideband DRA array in V band, a DRA array element with good performances is needed to be designed first. Although the feeding network can enhance the impedance bandwidth of an array element in some cases[6], it is still needed to design the array element carefully to have a better impedance match because of the insertion loss of the feeding network.

The array element is shown in Fig. 1. A ceramic cube with relative permittivity $\varepsilon_r = 9.8$, length D, width W and height H is mounted above the center of a Rogers RT/duroid 5 880 (tm) substrate with relative permittivity $\varepsilon_r = 2.2$, dielectric loss tangent 0.0009 and thickness $t = 0.2$ mm, and the length and width of the substrate are both $L_s = 4.2$ mm. The DRA is excited by a rectangular feeding ring under it. The resonant frequency of the lowest-order mode $TE^x_{\delta 11}$ can be computed approximately by[10]

$$f_o = \frac{15[a_1 + a_2(W/2H) + 0.16(W/2H)^2]}{\omega\pi\sqrt{\varepsilon_{rDRA}}} \tag{1}$$

where,

$$a_1 = 2.57 - 0.8\left(\frac{D}{2H}\right) + 0.42\left(\frac{D}{2H}\right)^2 - 0.05\left(\frac{D}{2H}\right)^2 \tag{2}$$

$$a_2 = 2.71\left(\frac{D}{2H}\right)^{-0.282} \tag{3}$$

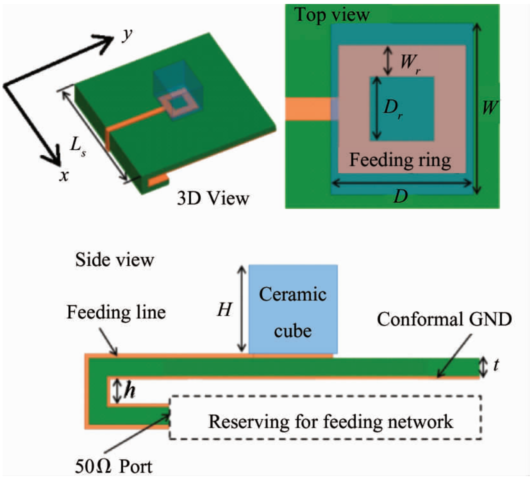
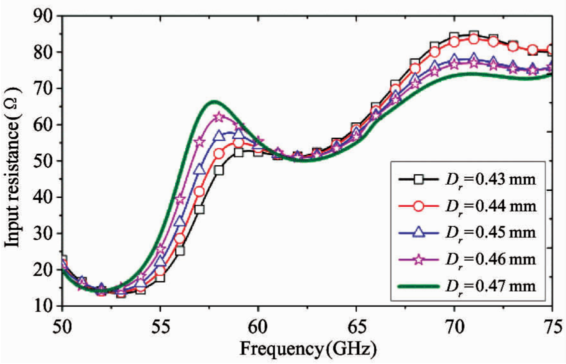


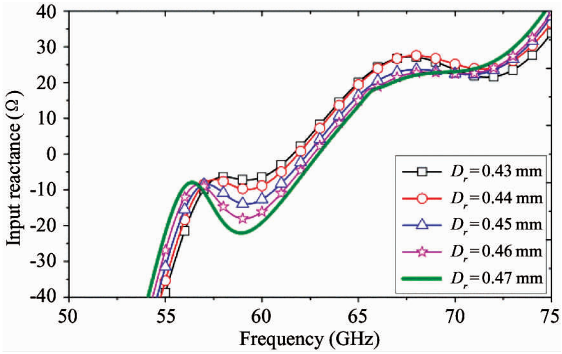
Fig. 1 The single dielectric resonator antenna

The unit of D, W and H is cm, and the unit of f_0 is GHz. In fact, for a specific resonant frequency, dimensions of ceramic cube computed by Eq. (1) are not unique. In the design, parameters D, W and H are optimized by the finite element method (FEM) based commercial software HFSS. Finally, $D = 1$ mm, $W = 1.2$ mm and $H = 1$ mm are selected in the design. To enhance the impedance bandwidth of the DRA, dimensions of the rectangular ring should be adjusted to produce a resonant frequency close to the resonant frequency of dielectric resonator. During the design process, It is found that D_r affects the DRA more than the other parameters do.

Fig. 2 shows the simulated input impedance for different values of D_r with $W_r = 0.22$ mm. For the input resistance, when D_r increases form 0.43 mm to 0.47 mm, the input resistance over the frequency band from 55 to 60 GHz will also increase, but the result above 65 GHz will decrease. For the input reactance, the result will decrease with the increase of D_r. On the whole, when the value of D_r is between 0.43 mm and 0.45 mm, a better impedance match can be obtained for the array element.



(a) Input Resistance



(b) Input reactance

Fig. 2 Effects of D_r on the input impedance of DRA

To avoid spurious radiation from the feeding network to the DRA element, a U-shaped structure should be used to separate these two, as shown in the bottom drawing of Fig. 1. The distance between upper and lower substrate is h.

Fig. 3 and Fig. 4 show the simulated reflection coefficient, gain and radiation patterns of the DRA array element. It can be seen that, S_{11} is lower than -15 dB over the frequency band from 57 to 66 GHz, and the antenna gain is higher than 6.5 dBi. The radiation pattern has no sidelobe in the upper half space, and the maximum radiation happens at $\theta = 0°$ and $\varphi = 0°$, which can ensure the design of the DRA array.

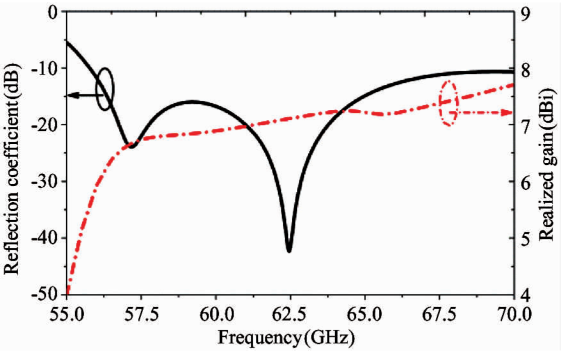
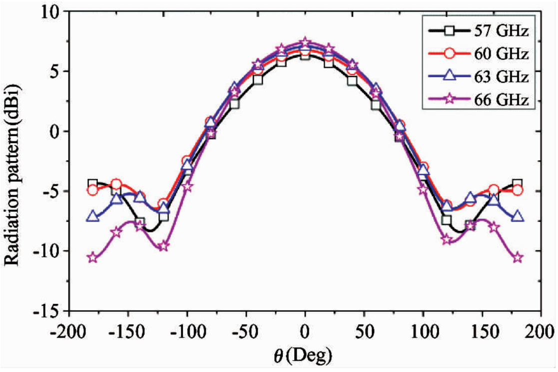
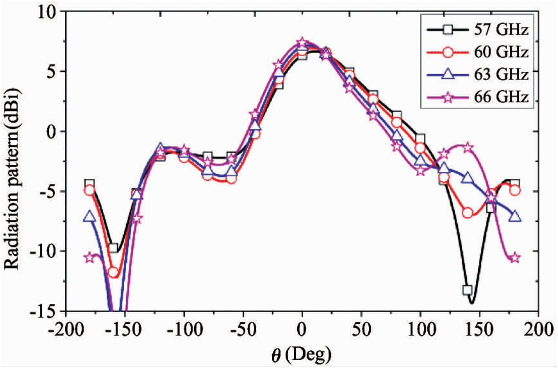


Fig. 3 Simulated S_{11} and gain of the array element



(a) *xoz* plane

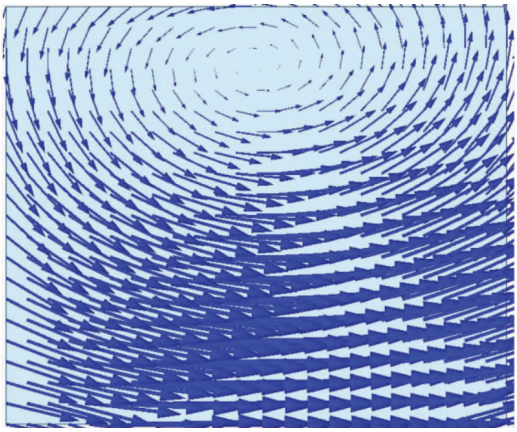


(b) *yoz* plane

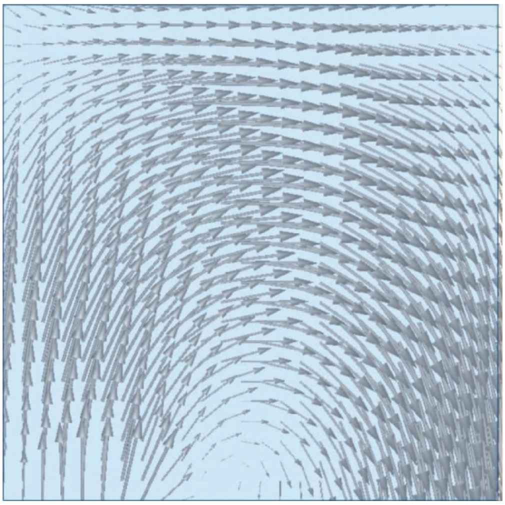
Fig. 4 Simulated radiation pattern of the array element

According to Fig. 3, there are two resonant points in the S_{11} curve of the proposed array element. To explain the working mode of the proposed U-shaped DRA, Fig. 5 and Fig. 6 show the field distribution of the array element. As shown in Fig. 5, the field distribution in the dielectric resonator at 62.5 GHz can be considered as the radiation field of a short magnetic dipole along x-axis, which means the mode of the dielectric resonator.

However, at 57 GHz, none specific mode of dielectric resonator can be found. To explain the working mode of the DRA at 57 GHz, Fig. 6 shows the current distribution on the feeding ring at different frequencies.

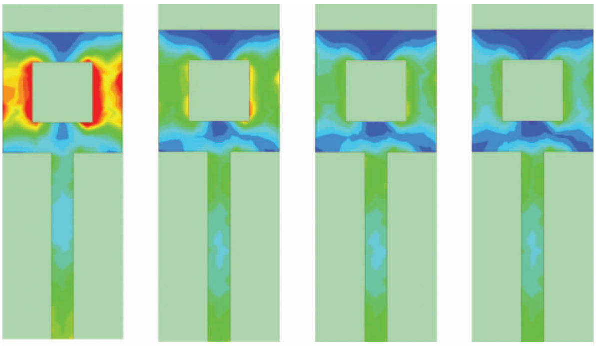


(a) *xoz* plane *E* distribution



(b) *yoz* plane *H* distribution

Fig. 5 Field distribution in the dielectric resonator



(a) 57 GHz (b) 60 GHz (c) 63 GHz (d) 66 GHz

Fig. 6 Current distribution on the feeding ring

It can be seen that, the strongest current can be found on the feeding ring at 57 GHz, which means that the resonance at 57 GHz is due to the radiation of the feeding ring. Because the dielectric resonator and the feeding structure in the proposed DRA can effectively radiate simultaneously, impedance bandwidth of the array element is effectively enhanced. In this situation, the proposed DRA can act as a hybrid-radiation DRA.

2 Design of feeding network and DRA array

Besides the impedance bandwidth, antenna gain and SLL are also important topics in the design of antenna array. According to the suggestions of IEEE 802.15 and ECMA 384 standards[11], the gain should be higher than 13dBi over the whole unlicensed frequency band. Until now, there are no standards for SLL in the design of this band. The gain of the DRA array in this paper is designed to meet the standard above, and the −30 dB SLL is hoped to achieve at 60 GHz. In the end of the paper, performances of the proposed array will be compared with the other arrays for 60 GHz applications.

To achieve the goal, a suitable feeding network should be used. Among many types of array feeding structures, two most popular ones are corporate feeding and series feeding structures. The discontinuities, bends, and other components in a corporate feeding structure will cause spurious radiation, more complex fabrication and larger size of antenna[12]. Compared with the corporate feeding structure, the series feeding structure employs shorter line, which will lead to less size, lower attenuation loss and less spurious radiation. To obtain the low SLL, a ten-element Chebyshev series feeding network is used, whose half structure is shown in Fig. 7.

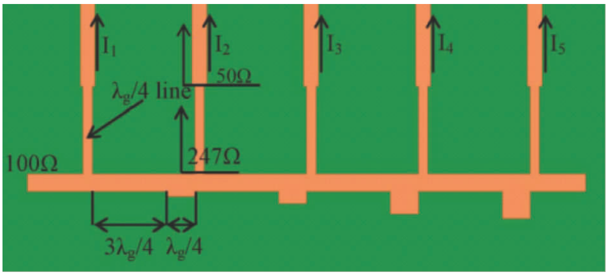


Fig. 7 Half of the series feeding network

To achieve a −30 dB SLL, the current ratios of the 10-element Chebyshev array in Fig. 7 is $I_1 : I_2 : I_3 : I_4 : I_5 = 1 : 0.878 : 0.669 : 0.430 : 0.258$. A $\lambda_g/4$ matching line is added between the single antenna and the feeding network, which can provide from 247Ω to 50Ω impedance matching. The line between every array element is composed of a $3\lambda_g/4$ line and a $\lambda_g/4$ line with different characteristic impedances, which can ensure the current ratios mentioned above and provide 100 Ω input impedance in the left port. Details of feeding network designs and analysis can be found in Ref. [13].

Fig. 8 shows the structure of the proposed DRA array. To avoid the influence of parasitic radiation from feeding network, the feeding network and antenna array are mounted on the opposite sides of the U-shaped substrate. Moreover, the optimization of air gap thickness between upper and lower substrate h is presented in Fig. 9.

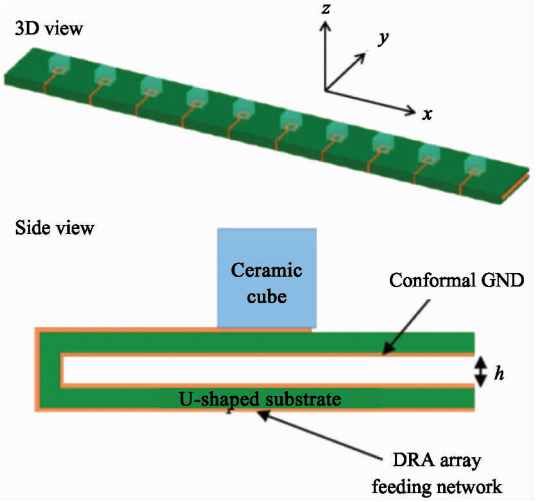


Fig. 8 Drawings of dielectric resonator antenna array

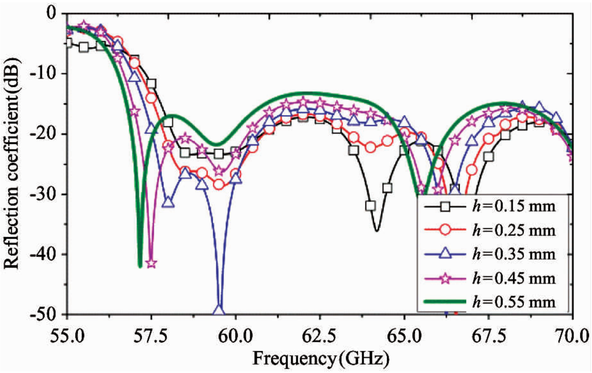


Fig. 9 The effect of parameter h

The increasing of h will make the S_{11} curve move to the lower frequency band, which can directly decide whether the bandwidth of the array can cover the unlicensed frequency band from 57 to 66 GHz. However, a larger h will cause a higher profile of array. Balancing the impedance bandwidth and the profile of the array, $h = 0.35$ mm is chosen in our design. So, the total size of the proposed antenna array is 42 mm × 4.2 mm × 1.75 mm.

Because of the limit of fabricating machinery and test instrument (mainly the difficulty in fabricating the dielectric resonator working in V-band), only simulated results are presented and analyzed in this paper. Fig. 10 and Fig. 11 show the reflection coefficient and the normalized radiation pattern of the proposed array.

The impedance bandwidth is of 37.9% (56.9 - 83.5GHz), which can completely cover the unlicensed band (57 - 66GHz). Simulated SLL at 60GHz is -27.3dB, which is very close to the design target.

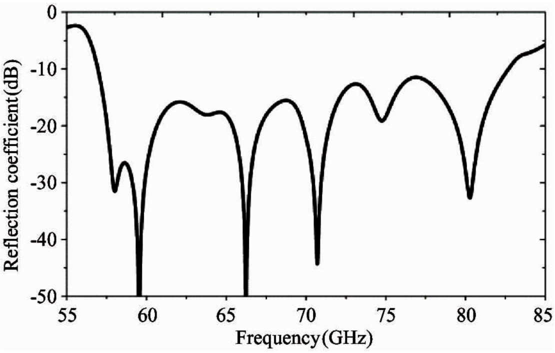


Fig. 10 Simulated S_{11} of proposed DRA array

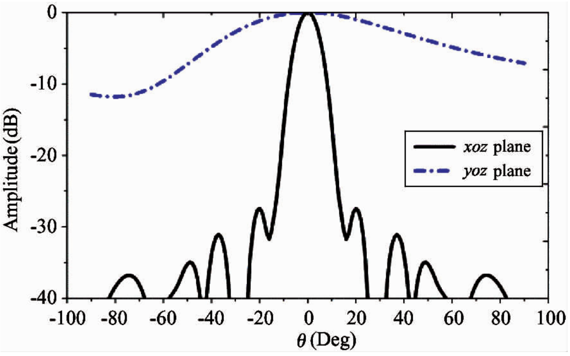


Fig. 11 Simulated normalized radiation pattern of the proposed DRA array at 60 GHz

Fig. 12 and Fig. 13 show the gain, radiation efficiency and SLL in different frequencies. The realized gain of the DRA array is no less than 13 dBi over the frequency band from 57 to 65.3 GHz, which can basically meet the requirements in the 60 GHz wireless communication systems. Radiation efficiency of the antenna array over the whole unlicensed frequency band is higher than 92%.

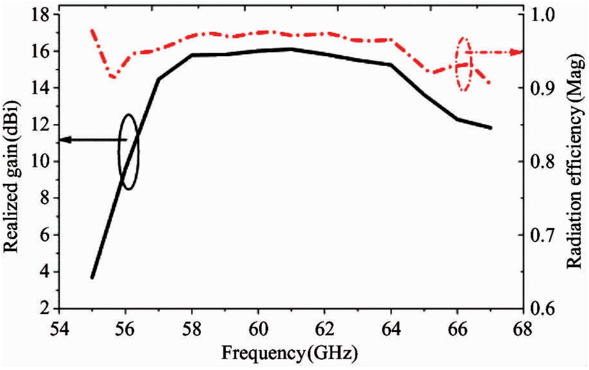


Fig. 12 Simulated gain and radiation efficiency

Fig. 13 shows the radiation pattern of the array in *XOZ* plane at 57 GHz, 59 GHz, 61 GHz and 63 GHz. The SLL is lower than -25 dB over the frequency band from 59 ~ 61 GHz, and is lower than -15dB over the frequency band from 57 to 63 GHz. Moreover, the main beams in these frequencies all radiate to $(\theta, \varphi) = (0°, 0°)$.

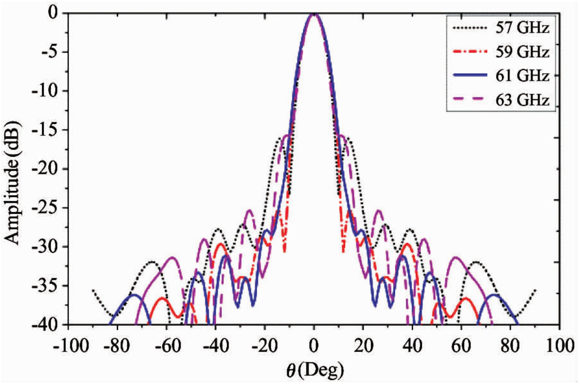


Fig. 13 Radiation pattern of the proposed DRA array

The proposed DRA array features several advantages compared to other antenna arrays for the 60 GHz applications. Table 1 gives the comparisons of the performances among these arrays.

Table 1 Comparison to other reported 60GHz antenna arrays

Reference	Guo et al.[3]	Chin et al.[1]	Xu et al.[4]	Karmer et al.[5]	This work
DRA array type	DRA array on LTCC substrate	Dual resonant slot patch structure	SIW fed cavity array	Stacked Yagi antenna array	Series fed DRA array
Element number	4 × 4	2 × 2	8 × 8	4 × 4	1 × 10
Impedance bandwidth(%)	17	23	17	10	38
Peak gain(dBi)	17.9	9	22.1	18	15.9
Aperture efficiency	0.479	0.256	0.225	0.187	0.439
SLL	-15 dB	Omni-directional	-13.5 dB	-18.5 dB	-27.3 dB
Array size	16mm × 16mm × 1mm	9.5mm × 6.5mm × 1.1mm	47mm × 30.5mm × 19mm	28mm × 24mm × 24mm	42mm × 4.2mm × 1.75mm

As shown in Table 1, the proposed DRA array provides a wider impedance bandwidth and lower SLL than the other antenna arrays reported. Moreover, no special structures are needed in this design, such as the LTCC substrate, the PEPEC substrate and the SIW feeding network, which reduces the difficulty of fabrication. Due to the differences in element number, the antenna gain of this design is lower than some other designs in Table 1. However, the gain of the proposed antenna array can meet the IEEE 802.15 and ECMA 384 standards in the 60 GHz wireless communication systems. On the other hand, good aperture efficiency can also be found in the design, which shows an effective design in the proposed DRA array.

In the end, it is meaningful to point out that, even though the 10-element series-fed linear array is proposed in our design, the proposed U-shaped array element DRA can also be used to generate a larger linear or planar array. By increasing the length of the microstrip line feeding network (MLFN), a larger linear array can be easily obtained. And by combining the series feeding and parallel feeding MLFN, a planar array can also be generated effectively. Furthermore, the scanning-phase array can also be obtained by adding phase shifters in the feeding network. In this situation, the impact of mutual coupling between the array elements will be quite important for the performance of the phased array. So, the mutual coupling between two array elements is studied in the end of this paper. When the distance between two adjacent DRAs is roughly equal to one operating wavelength at 60 GHz, the corresponding simulated port mutual coupling is shown in Fig. 14. It can be seen that the maximum mutual coupling between two array elements is lower than −20 dB over the frequency band from 50 GHz to 75 GHz, which shows a good isolation between array elements.

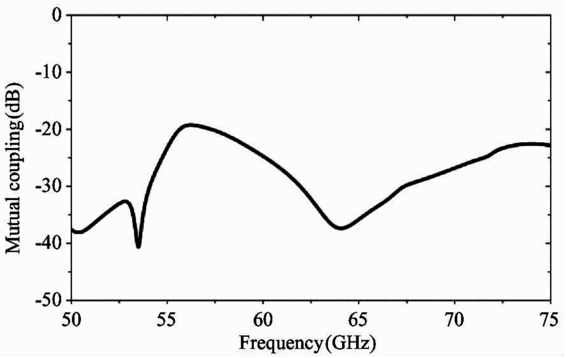


Fig. 14 Simulated mutual coupling between two adjacent array elements

3 Conclusion

A low sidelobe and wideband series-fed dielectric resonator antenna array is proposed for the 60GHz millimeter wave communications. The parasitic radiation from feeding network is segregated by a U-Shaped substrate. The impedance bandwidth of the proposed DRA array is 37.9% (56.9 − 83.5 GHz), and the gain bandwidth (>13dBi) covers the frequency band from 57 to 65.3 GHz. SLL of the antenna array is −27.3 dB at 60 GHz, and is lower than −15 dB over the unlicensed frequency band from 57 to 63 GHz. All these features make the proposed antenna array have great potential applications in the 60 GHz wireless communication systems.

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