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A New Strategy to Design Microstrip Antenna Array With Low Side-Lobe Level and High Gain

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ABSTRACT A new strategy for designing low side-lobe level (SLL) antenna array is presented. This strategy utilizes special arrangement of antenna elements rather than direct tapered excitation amplitude to obtain an equivalent desired amplitude distribution in the main planes and thus achieve low SLL and high gain concurrently. To illustrate the strategy, 9-element microstrip antennas are arranged in four manners. An equivalent analysis method is also proposed to predict the SLL of the arrays. Using this method, a fast analysis of the trend of a microstrip array for a low SLL can be performed and thus a proper array-element arrangement is acquired. Both numerical and experimental results demonstrate that the SLLs in E and H planes of the novel array are fairly low. Meanwhile, the main beam of the novel array is almost the same with that of a conventional high-gain array. The antenna arrangement manner and the proposed strategy are particularly suitable for applications when low SLL and high gain are both demanded.

INDEX TERMS Antenna array, low side-lobe level (SLL), gain, microstrip antenna.

I. INTRODUCTION

Antennas are the key devices in wireless communication systems [1], [2]. The radiation performance of antennas will directly affect the communication quality. Many excellent work has been done to design antennas with desired working bandwidth and radiation main beam [3]–[9]. With the improving requirement of more advanced performance, it becomes critical to reduce the side lobes of antennas. This is because high side-lobe level (SLL) will distribute the transmitted power and lead to the reception of unexpected noise from the direction away from the main beam in communication. While in detection applications, anti-interference radar usually makes its low-SLL region point in the direction of the interference source. Lots of practical applications have proved that antennas with low SLL are essential parts of many up-to-date communication and radar systems [10]–[12].

In recent years, the researchers have made great efforts to reduce the SLLs of both antenna elements and arrays. Regarding a single antenna element, the major method is changing the antenna structure. In [13], the SLL of a tapered short leaky-wave antenna is reduced more than 6 dB by adopting two rectangular slots and a shorting pin properly. In [14], a microstrip antenna working in TM_{50} mode is designed in millimeter wave range with electrically large property. The large side lobe of the TM_{50} mode antenna is effectively reduced by introducing transverse slots on the patch. Besides, the interior E-plane horn walls are coated by high impedance metasurface in [15] and a metahorn with low SLL and enhanced gain is proposed in the Ku band.

As for antenna arrays, it is well known that uniformly excited and equally spaced linear arrays usually have SLL above −14 dB, which may be not adequate for applications requiring low SLL [16]. Hence one of the important issues to improve the radiation performance of antenna arrays is to reduce SLLs. Up to now, various pattern synthesis and array optimization techniques have been proposed and proved

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very effective [17]–[21]. To summarize, these techniques can be classified into three methods. **The first method is using tapered excitations or unequal arrangements.** According to array synthesis theory, some classical excitation amplitude distributions such as binomial distribution, Dolph–Chebyshev distribution, and Taylor distribution have been widely used to control the SLL. For example, a low-SLL substrate-integrated-waveguide (SIW) antenna array is presented at 28-GHz band in [22] using a novel broadband feeding network with Taylor amplitude distribution. In [23], to reduce the SLL of the array, the power distribution of the four antenna elements is 1:3:3:1. In [24], the tapering technique of the phase constant is proposed to suppress the SLL of a short leaky-wave antenna. In [25], the fractal spatial arrangement of array elements and the fractal design of array factors are adopted to obtain low SLL. These designs provide regular and powerful measures to control the SLL of arrays.

The second method to obtain desired SLL is based on optimization algorithms. In [26], uniformly spaced wideband arrays with low SLL are designed by optimizing the tapered amplitude based on simulated annealing algorithm. In [27], the SLL of antenna array is controlled by changing the array elements' amplitudes and phases using genetic algorithm. In [11], an adaptive particle swarm optimization method is used to adjust the excitation phase and thus suppress the first SLL of large phased arrays to minimum possible level. In [28], the location of the circularly polarized antenna element is optimized in the array based on the sequential quadratic programming and low SLL is obtained for each scanning energy pattern.

The third method to reduce SLL is modifying the antenna array structure. In [29], complementary split ring resonators (CSRRs) are etched on the ground of a 10×2 microstrip antenna array, which results in 3.5-dB SLL reduction. Inspired by thinned array, the SLL of a waveguide leaky-wave antenna is reduced by changing the distances between transverse slots in [30], which can be regarded as an unequal spaced array. Regarding circularly-polarized array, low-SLL performance is obtained in [31] by using random sequential rotation technique.

All the aforementioned designs have successfully realized the reduction of SLL in antenna arrays and demonstrated the adopted methods are effective. However, the practical implementation of a low-SLL array is still very challenging. Take the tapered excitation method for example, it is required to have different weight coefficients for each antenna element. Consequently, a special unequal power divider is needed. If the working band is also considered, the design of the feed network will be very complex and even difficult when the array is large [32]. Another concern in low-SLL array design is the directivity and gain drop. It is noted that most of the reported methods always suffers from directivity and efficiency decline as well as broaden beamwidth. These additional effects are mostly undesirable.

This paper proposes a new strategy to control the SLL of antenna arrays and an equivalent method to analyze the SLL performance. Adopting the proposed strategy, the SLL of an array can be effectively reduced. Meanwhile, the well-behaved gain and beamwidth can be maintained. Besides, owing to the unique features of low profile, light weight and easy fabrication, microstrip antenna has been widely used in various radars. As an example, the proposed strategy is illustrated using microstrip antenna array. Both theoretical analysis and numerical results verify its effectiveness. Moreover, experiments are also conducted and the good agreements with simulations further prove the strategy.

II. DESIGN AND ANALYSIS STRATEGY OF LOW-SLL ANTENNA ARRAY

As is well known, N-element linear antenna arrays theoretically have no side lobes if the elements have binomial coefficients and $d \leq \lambda/2$ (d is the element space) [1], which means the amplitudes of the elements are the coefficients of $(1+Z)^{N-1}$. Uniformly excited and equally spaced antenna arrays are capable of producing preferable gains. On the other hand, the limitations of the former are the decreased gain and increased beamwidth. While for the latter, the limitation lies in the high SLL.

Inspired by the above phenomenon, we can speculate that preferable low-SLL performance is expected for an array antenna with the excited elements' amplitude distributions close to the binomial arrays. And a closer amplitude distribution with binomial array may result in a lower SLL. In another aspect, to avoid the need of a complex power divider network for direct excitations, an indirect method is proposed here to obtain EQUIVALENT tapered amplitudes using uniform planar arrays. Generally, this method can be concluded as one sentence: Obtaining EQUIVALENT amplitude distributions (EADs) close to binomial arrays in the concerned main planes rather than direct taper excitations by finding proper array arrangements. This design strategy combines the advantages of the above two kinds of classical arrays and overcomes the respective limitations as well. In specific implementations, this method can be summarized in four steps as follows:

Step 1: Assign several concrete array arrangements;

Step 2: Project all elements onto the concerned main planes and compute the EADs in the planes for each arrayč"

Step 3: Compare the EADs with binomial arrays. A closer amplitude (more 'binomial') and a smaller equivalent element distance (EED) is expected to generate a lower SLL;

Step 4 (Optional): Alter or optimize the array arrangement to obtain a satisfying low-SLL design.

Two points in the above steps are especially worthy of notice. First, an equivalent analysis method is also proposed in step 2 and step 3. This method compares the projected equivalent array with binomial array and evaluate the SLL performance, which provides a very fast way to analyze the trend of an array for a low SLL and high gain. Second, we introduce an equivalent amplitude distribution error (EADE) here to evaluate the agreement of EAD with binomial coefficient quantitatively. It is defined as the square deviation of EAD with binomial coefficient (BNC), provided

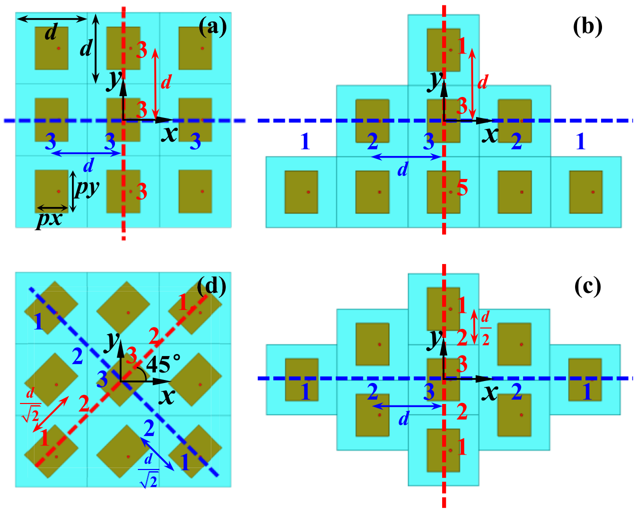

FIGURE 1. Microstrip antenna arrays with different element arrangements: (a) case A, (b) case B, (c) case C, (d) case D.

that both center antenna amplitudes are normalized. Specifically, for a N-element linear array, EADE, denoted as δ_a, can be generally expressed as

$$\delta_a = \sum_{n=1}^{N} \left(\frac{a_n}{a_{ceil(N/2)}} - \frac{b_n}{b_{ceil(N/2)}} \right)^2, \quad (1)$$

where n is the element number, a_n is the amplitude of equivalent (projected) array along observation plane, and b_n is the corresponding amplitude of an ideal binomial array. Apparently, a smaller δ_a means a closer agreement of equivalent array with binomial array and thus a lower SLL.

To illustrate the proposed design strategy, microstrip antenna, as one example, is selected as the array element. The following work is implemented by taking the above steps. As depicted in Fig. 1, 9 uniformly excited coplanar microstrip antenna elements are arranged in four ways and thus four arrays are obtained. For clarity, the arrays shown in Figs. 1(a)-(d) are denoted as case A, case B, case C, and case D, respectively. Then the elements in each array is projected onto the respective two main planes: E plane and H plane. And equivalent arrays in the main planes are obtained. Consequently, further analysis can be carried out to find a low-SLL array arrangement.

Here we mark the corresponding E plane and H plane of each array in Fig. 1 using blue and red dashed lines, respectively. Take case A for example, the equivalent array in E plane (blue dashed line) is a linear array with equal element space of d and excited amplitude distribution of (3, 3, 3), provided the excited amplitude for each practical element is 1. Therefore the SLL in E plane of case A is approximately −14 dB. Additionally, the computed δ_a in this case is 1/2 using Eq. 1. While, the equivalent linear array in E plane of case B has excited amplitude distribution of (1, 2, 3, 2, 1), suggesting that a lower SLL will be obtained when

TABLE 1. Equivalent amplitude distribution (EAD), equivalent element distance (EED) and equivalent amplitude distribution error (EADE) In E- and H planes.

Main plane & quantities		case A	case B	case C	case D
E plane	EAD	3, 3, 3	1, 2, 3, 2, 1	1, 2, 3, 2, 1	1, 2, 3, 2, 1
	EED	$d(1, 1)$	$d(1, 1, 1, 1)$	$d(1, 1, 1, 1)$	$d(\frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}})$
	EADE (δ_a)	1/2	1/18	1/18	1/18
H plane	EAD	3, 3, 3	1, 3, 5	1, 2, 3, 2, 1	1, 2, 3, 2, 1
	EED	$d(1, 1)$	$d(1, 1)$	$d(\frac{1}{2}, \frac{1}{2}, \frac{1}{2}, \frac{1}{2})$	$d(\frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}})$
	EADE (δ_a)	1/2	25/18	1/18	1/18

compared with case A since a smaller δ_a. ($\delta_a = 1/18$) is obtained. More computed results are compared in Table 1 for each case. From these results, we can speculate that low SLL in both E and H planes can be expected for case C and case D. By contrast, case B only has low SLL in E plane. While case A has the highest SLL among the four arrays.

III. NUMERICAL RESULTS AND ANALYSIS

To verify the above design and analysis strategy of low SLL, the four arrays shown in Fig. 1 are simulated numerically using HFSS. The elements in all arrays are the same except for 45-degree rotation of the radiation patches and feeding parts in case D. The element antenna size is 30 mm × 30 mm ($d \times d$) and the patch size is 13.8 mm × 18.0 mm ($px \times py$). It needs to be emphasized that each element has the same excitations including both input amplitude and phase. Fig. 2 shows the radiation performance of the single antenna element. It clearly displays that the element works at 6.0 GHz and well-behaved radiation patterns are obtained.

The radiation patterns of the arrays depicted in Fig. 1 is plotted in Fig. 3. As can be seen, the four arrays have similar gain but apparently different SLL. Regarding the E plane shown in Fig. 3(a), the SLL of case A is −13.9 dB, which is the highest of the four cases. Since the EADs of case B and case C are the same in E plane, their SLLs are very similar, i.e. approximately −24 dB. As for case D, although the EAD is the same with case C, the equivalent element distance (EED) in E plane is smaller and thus the SLL is lower. Interestingly, it is also observed that case A and case D have the similar half-power beamwidth (HPBW) and gain. While, the HPBW of case B and case C is comparatively narrower due to the equivalent larger aperture size in E plane. Detailed comparison of the four arrays is tabulated in Table 2. It is observed that these results are in good accordance with the preceding analysis, suggesting the effectiveness of the proposed strategy.

IV. EXPERIMENTS AND VERIFICATIONS

For the proof of principle, the arrays shown in Fig. 1(a) and Fig. 1(d) are fabricated and measured. As displayed in Fig. 4,

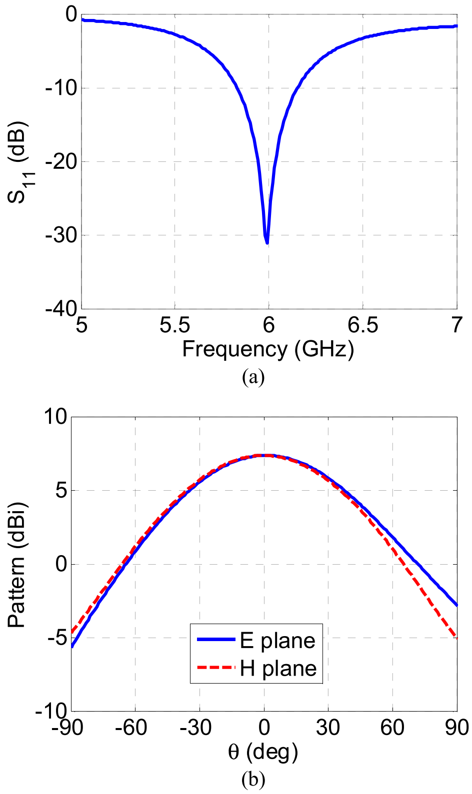

FIGURE 2. Radiation performance of microstrip antenna element in Fig. 1: (a) reflection coefficient, (b) radiation patterns at 6.0 GHz.

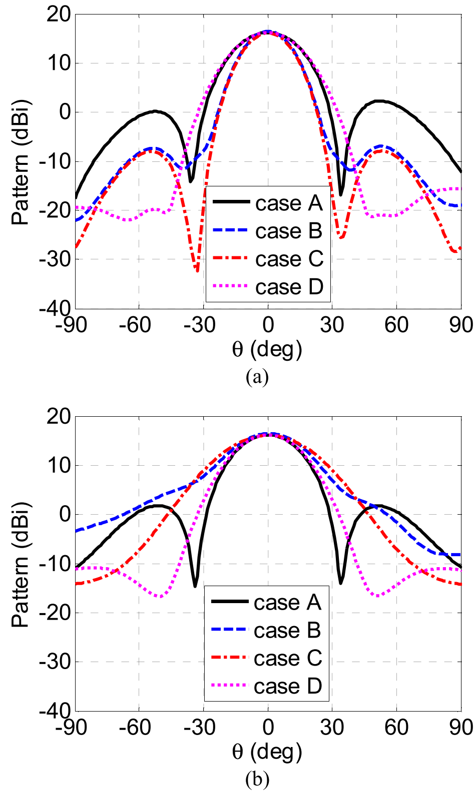

FIGURE 3. Radiation patterns of the four arrays at 6.0 GHz: (a) E plane, (b) H plane.

TABLE 2. Comparison Of side-lobe level (SLL), half-power beamwidth (HPBW), and gain.

Observation plane & quantities		case A	case B	case C	case D
E plane	SLL	–13.9 dB	–23.5 dB	–24.1 dB	–31.7 dB
	HPBW	28°	20°	20°	28°
H plane	SLL	–14.4 dB	–12.1 dB	–30.2 dB	–27.0 dB
	HPBW	28°	31°	38°	28°
Gain		16.2 dBi	16.4 dBi	16.1 dBi	16.1 dBi

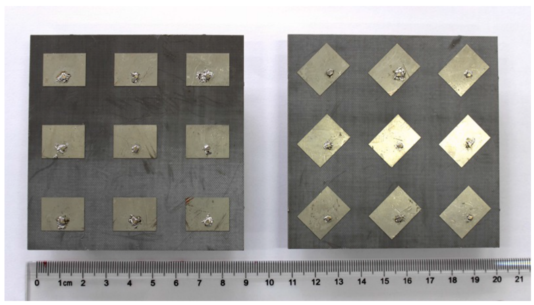

FIGURE 4. Prototypes of the fabricated antennas: case A and case D.

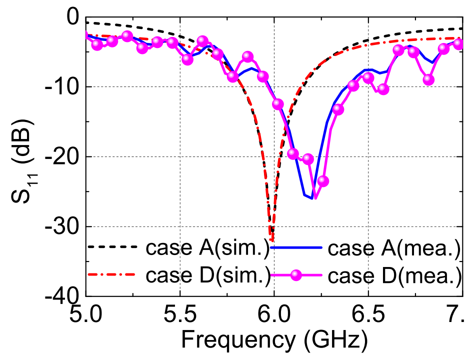

FIGURE 5. Measured and simulated reflection coefficients.

both prototypes are built using low-cost standard printed circuits board (PCB) technique. The reflection coefficients are measured using vector network analyzer Agilent N5230C. And the radiation patterns are measured in a far-field anechoic chamber.

Fig. 5 compares the measured and simulated reflection coefficients. Compared with simulations, the measured working frequency bands of both arrays shift upwards by 0.2 GHz as a whole. Further analysis indicates that these shifts arise mainly from the uncertainty of the practical substrate characteristics. Other factors, such as soldering and fabrication errors, also contribute to the shift. Nevertheless, the measured two antennas exhibit very similar S_{11}, suggesting the different arrangements of antenna elements hardly affect the port reflection performance of the array. Fig. 6 displays the realized gains at the resonant frequencies. The measured main beam is similar with

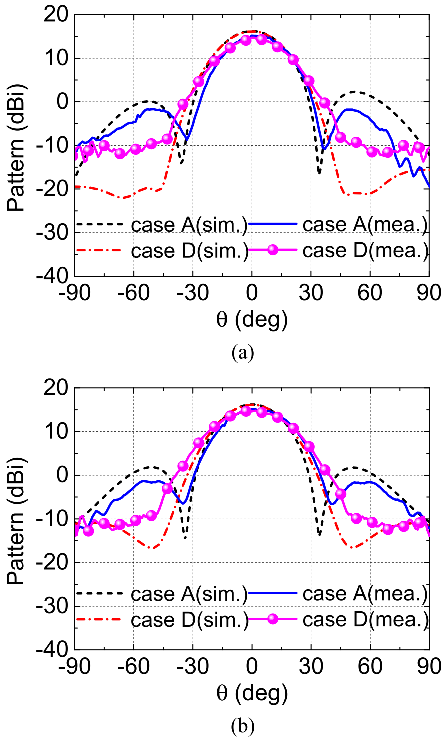

FIGURE 6. **Measured and simulated radiation patterns at resonant frequencies: (a) E plane, (b) H plane.**

TABLE 3. **Measured side-lobe level (SLL), half-power beamwidth (HPBW), and gain.**

Observation plane & quantities		case A	case D
E plane	SLL	–16.8 dB	–23.8 dB
	HPBW	28°	29°
H plane	SLL	–16.4 dB	–24.1 dB
	HPBW	32°	35°
Working band (S11<–10dB)		5.96 GHz-6.41 GHz	5.96 GHz-6.42 GHz
Gain		15.1 dBi	14.8 dBi

the simulations, expect for some gain loss resulted by the imperfect feed network. Regarding side lobe, the same change trends are observed between measurements and simulations. The measured higher SLLs for proposed antenna are imputable to the installation errors and measurement-condition limitations. For E plane, the higher measured SLL is resulted by the inaccurate cut-plane in experiments. Overall, reasonably good agreements are obtained in the figures. The proposed antenna demonstrates much lower SLL than conventional design. More detailed comparison of the two antennas can be found in Table 3. From these measured results, the proposed low-SLL array with desired gain and beamwidth as well as the analysis method are verified.

V. CONCLUSION

This paper proposes to utilize the proper arrangement of uniformly excited and equally spaced arrays to obtain equivalent desired amplitude distributions in the main planes and thus achieve low SLL and high gain performance simultaneously. This design strategy combines the advantages of conventional uniform and taper-excited arrays and overcomes the respective limitations as well. To illustrate the strategy, four microstrip antenna arrays are presented and compared. Besides, an equivalent analysis method is also proposed to facilitate the analysis and design. Using the proposed method, the four arrays are quantitatively discussed in details. Through which, a proper array arrangement is chosen and the obtained SLL of the 9-element array is below −27 dB in both E and H planes. Moreover, the gain and the half-power beamwidth of the array hardly change when compared with a conventional uniform array. The performance comparison of the arrays also infers that a lower SLL in desired plane is expected with smaller equivalent amplitude distribution error (compared with binomial array) and closer equivalent element distance as well as larger element number. Finally, the array prototypes are fabricated and measured. The experimental results agree well with the simulations, which verifies the effectiveness of the proposed design strategy and the equivalent analysis method. This strategy and the method may have potential applications especially when high gain and low SLL are both in demand.

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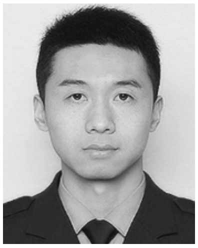

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