Low Sidelobe Coupled Broadband Microstrip Array Antenna With Non-Uniform Spacing and Variable Groove Length

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ABSTRACT To reduce the sidelobe level (SLL) and widen the bandwidth, this article uses the differential evolution algorithm to optimize the array element spacing and excitation amplitude, and designs an 8-element coupled microstrip array antenna with non-uniform spacing and variable groove length. Based on the power equally divided feed network, the non-uniform length of the groove to achieve a quantitative change in the excitation amplitude. This method does not need to adjust the width of the microstrip line of the feed network one by one, nor is it limited to an array of equal spacing, which simplifies the complex design process. And to establish a mathematical relationship of all feeder segments to ensure that all array elements are in phase excitation under unequal spacing conditions. At the same time, the H-groove coupling feed form reduces the antenna Q value and increases the bandwidth. The measurement results show a gain of 16 dBi and an SLL of $-19.5$ dB within the operating bandwidth. And the antenna has a voltage standing wave ratio of less than 1.5 in the range of 13.84 to 15.62 GHz, which meets the bandwidth requirement of SatCom on-the-move.

INDEX TERMS Coupled feed, differential evolution algorithm, low sidelobe, microstrip antenna arrays, non-uniform spacing.

I. INTRODUCTION

Modern communication pursues stability and large capacity, and puts forward higher requirements on the antenna sidelobe level and bandwidth. To reduce the antenna sidelobe level, there are mainly two types of antenna pattern synthesis methods. One type is the analytical method, including Chebyshev synthesis method [1], Taylor synthesis method [2]. This type of method is suitable for equidistant array antennas. By changing the feeder width of the feeder network to weight the excitation amplitude of the array elements, the purpose of reducing the sidelobe level is achieved [3], [4]. However, the antenna pattern is a complex exponential function of excitation amplitude, phase, and array element position, which is nonlinear and non-convex. The analytical method is not the optimal solution. With the improvement of computer performance, it has become a trend to use modern intelligent algorithms to reduce the antenna sidelobe level, including genetic algorithm [5] and differential evolution algorithm (DEA) [6], etc. This kind of algorithm takes the factors that affect the antenna sidelobe level as optimization variables, and it does not depend on the prior information, nor is it limited to the equal spacing array, and increases the freedom of design.

Slot-coupled feeding [7]–[9] is a commonly used method to increase the antenna bandwidth (BW). Groove feeding usually uses multilayer substrates, which increases the thickness of the equivalent dielectric plate and reduces the equivalent dielectric constant. At the same time, this feeding method is a capacitive coupling method, which avoids the inductive component caused by the probe, and therefore reduces the antenna Q value. The length of the slot affects the energy that the bottom feeder couples to the upper patch. Therefore, the change of the slot length can be used to control the excitation amplitude of the array element, thereby reducing the sidelobe level. Reference [10] qualitatively analyzed that the longer the slot length, the more coupling energy, but there is no method that can quantitatively analyze the relationship between the slot length and coupling energy, so the power distribution of the array element cannot be accurately achieved.

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And there is no integrated method of using antenna patterns, which is not conducive to reducing the sidelobe level of large array antennas.

In this article, a low-sidelobe broadband array antenna is designed using differential evolution algorithm. Starting from the two aspects of array element pitch and excitation amplitude, the unequal spacing feed network is designed to achieve non-uniform placement of array elements, and the slot length is gradually changed to achieve quantitative changes in excitation amplitude. And use the H-shaped slot coupling to increase the bandwidth.

II. ANTENNA ELEMENT DESIGN
The radiation characteristics of the antenna element directly affect the performance of the array antenna, which is the basis of the array antenna design. Many design details need to be clarified, such as substrate material, numbers of layers, patch size, and groove shape.

The antenna uses a three-layer design, as shown in Fig. 1. The bottom layer uses a Rogers RT5800 substrate of thickness $h_1 = 0.254 \text{ mm}$, dielectric constant $\varepsilon_r = 2.2$, and the loss tangent 0.0009. The bottom surface of the bottom substrate is a microstrip feeder, and the top surface is a ground plate with an H-shaped groove. Compared with the rectangular slot, the H-shaped groove can obtain greater coupling at the same size. The middle layer is an air layer with a thickness of $h_2$. The top layer uses a Rogers RT5800 substrate of thickness $h_3 = 0.787 \text{ mm}$, and a rectangular patch unit is placed on the bottom surface so that the top substrate can also act as an antenna cover to protect the antenna. The center of the H-shaped slot corresponds to the center of the patch, and the feeder is perpendicular to the slot. The parameter $l_l$ is the length of the microstrip feed line passing through the center of the H-shaped slot, which is mainly used to adjust the impedance matching.

To reduce excessive variable parameters and improve optimization efficiency, this antenna uses a square patch instead of a rectangular patch. The length of the square patch is still determined by the calculation formula of the rectangular patch.

Antenna element voltage standing wave ratio (VSWR) and pattern are shown in Fig. 2.

III. ARRAY ANTENNA DESIGN
A. ANTENNA PATTERN SYNTHESIS
For 2N array elements, non-uniformly spaced array antennas are shown in Fig. 3. $\Delta x_n$ represents the distance between the n-th array element and its previous array element.

For a linear array, when the unit antenna is omnidirectional, the array antenna pattern function can be approximately determined by the array factor (AF) function, as shown in (1)

$$AF(u) = \sum_{n=-N}^{N} I_n e^{j k x_n u} = 2 \sum_{n=1}^{N} I_n \cos(k x_n u) \quad (1)$$

where $x_n$ is the position of the n-th element and $I_n$ is the normalized excitation amplitude of the n-th element. $k = 2\pi/\lambda$ is the wavenumber and $\lambda$ is the spatial wavelength. $u = \sin \theta$, $\theta$ is the azimuth, as shown in Fig. 3.

The calculation formula of Peak Side Lobe Level (PSLL) is

$$PSLL = f(x, I) = \max_{u_s \in \text{Sidelobe}} \left\{ \frac{|AF(u_s)|}{AF_{\text{max}}} \right\} \quad (2)$$
where \( d_{\text{min}} \) is the range of the side lobe except the peak of the main lobe, \( AF(u) \) is the level of any side lobe, \( AF_{\text{max}} \) is the level of the main lobe, \( x = [x_1, x_2, \cdots, x_n] \) is the position of the array element, and \( I = [I_1, I_2, \cdots, I_n] \) is the excitation amplitude of the array element.

Considering the constraints of antenna size, array element position, and minimum spacing, the final objective function is

\[
\begin{align*}
\min \{ f(x_1, x_2, \cdots, x_n, I_1, I_2, \cdots, I_n) \} \\
0 < I_n < 1 \\
x_1 = 0 \\
s.t. x_i - x_j \geq d_{\text{min}} \geq 0 \\
d_{\text{max}} \leq 1 \\
i, j \in \mathbb{Z}, 1 \leq j \leq i \leq N
\end{align*}
\]

(3)

where \( d_{\text{min}} \) is the normalized minimum spacing of the array elements and \( d_{\text{max}} \) is the normalized maximum spacing of the array elements.

Generally speaking, in antenna design, the minimum distance between antennas is greater than half a wavelength, the minimum excitation amplitude should not be too small, and the difference in excitation amplitude between adjacent array elements should not be too large. The performance comparison between the improved algorithm and the original algorithm in terms of operation efficiency, sidelobe level and half-power beamwidth (HPBW) is shown in Tab. 1.

**TABLE 1. Algorithm performance comparison.**

| Spacing | \( d_{\text{min}} \geq 0.5, d_{\text{max}} \leq 1 \) |
|---------|-----------------|
| Number  | 8               |
| Element | [11]            |
| Amplitude | \( I_n = 1 \) | \( I_n \geq 0.5 \) | \( I_n \geq 0.3 \) | \( I_n \leq 1 \) | \( I_n = 1 \) | \( I_n \geq 0.5 \) | \( I_n \geq 0.3 \) | \( I_n \leq 1 \) |
| 50 times running time (s) | 195.4 | 196.5 | 200.6 | 240.2 | 240.8 | 240.6 |
| PSLL (dB) | -17.2 | -26.5 | -34.5 | -20.6 | -25.4 | -35.4 |
| HPBW (°) | 5.69 | 6.40 | 7.29 | 3.56 | 3.67 | 3.92 |

It can be seen from Table 1 that when the range of array element spacing and the number of array elements are the same, the running time of the improved algorithm is not much different from that of the original algorithm, and the running efficiency of the algorithm has not decreased due to the increase of variables. The sidelobe level has been effectively reduced, and as the excitation amplitude adjustment range increases, the sidelobe is reduced more significantly. When the minimum spacing is set smaller, the antenna can obtain a lower side lobe, and the antenna aperture becomes smaller, which is beneficial to the miniaturization of the antenna, but the HPBW becomes larger. When the minimum spacing is the guided wavelength, the antenna aperture is larger than Chebyshev antennas, the HPBW becomes smaller, but the control power of the sidelobe level decreases accordingly. The changing trend of HPBW is opposite to that of sidelobe level. The lower the sidelobe level, the wider the HPBW. This is because when the sidelobe level is reduced, the main lobe energy is more concentrated, resulting in a wider beam.

When the number of array elements is different, the larger the number of array elements, the more adjustable parameters of the antenna, the stronger the control of the directional pattern, and the lower the sidelobe level within the same excitation amplitude range.

### B. FEED NETWORK DESIGN

The antenna adopts a left-right symmetric structure, and the feeding network is formed by connecting multiple T-shaped power dividers.

For traditional parallel antennas, the excitation amplitude of the array element is changed by the power ratio of the T-shaped power splitter, which requires complex microstrip line width adjustment for each T-shaped power splitter. This antenna does not rely on changing the width of the feeder to change the excitation amplitude, but by changing the length of the slot to achieve quantitative distribution. Therefore, it is only necessary to maintain the same feeder width at the output of each T-type power splitter, which greatly reduces the design difficulty.

The phase of the antenna unit is determined by the length of the feed line from the feed port to the antenna unit. To ensure consistent phases, the feeder length of each branch must be equal. Based on the position of the antenna unit, each section of the branch feeder is set as a variable to determine the mathematical relationship of each section. Since the feed network is a symmetrical structure, only the feeder relationship on one side of the antenna is constructed, as shown in Fig. 4.

**FIGURE 4.** Structure relationship of the parallel feed network branch.

The mathematical relationship of each feeder segment is shown in (4)

\[
\begin{align*}
I502 &= (q_1 - w50)/2 - 170 \\
I505 &= (q_3 - w50)/2 - 170 \\
I504 &= (q_2 + q_3 - w50)/2 - 170 \\
I506 &= (q_1 + q_2 - w50)/2 - 170 \\
I508 &= (q_1 + q_2 + q_3 + q_4 - w50)/2 - 170
\end{align*}
\]
$i501, i503, i507,$ and $i509$ are 50Ω impedance connecting lines. The length does not affect the phase difference of each array element and can be flexibly configured according to the antenna size.

Combined with the characteristics of coupled feed, an identical microstrip line is added to each output port. By adjusting its size, the impedance matching of the antenna can be quickly achieved without affecting the power distribution.

The power distribution and phase value of each port are shown in Fig 5.

![Fig 5. Power distribution and phase value of the feed network port. (a) Power distribution; (b) Phase.](image)

The power values of the output ports are all around $-9$ dB, the range does not exceed 0.4 dB. At the same time, the phase curves are coincident, indicating that the feeder network achieves equal amplitude in-phase excitation in a wide frequency range.

C. ANTENNA SIMULATION AND MEASUREMENT

To reduce the antenna mutual coupling effect, the antenna sets the minimum spacing to $0.7\lambda$ and the normalized minimum excitation amplitude to 0.4. The antenna element spacing and excitation amplitude are shown in Tab. 2. Under the conditions of the above spacing and excitation amplitude, the theoretical value of the sidelobe level is $-25.46$ dB.

![Fig 6. Poynting vector. (a) Patch; (b) H-shaped groove.](image)

The Poynting vector is used to explore the amount of energy obtained by the patch. The relationship between energy $W$ and the Poynting vector $S$ is

$$ W = -\oint_A S \cdot dA $$

where $A$ is a closed surface.

The Poynting vector of the patch and H-shaped groove is shown in Fig. 6. The Poynting vector on the surface of the patch points from the center of the patch to the sides along the length of the patch and the vector direction is parallel to the plane of the patch. To calculate the energy obtained by the patch, in theory, it is necessary to construct countless slices perpendicular to the Poynting vector, and then calculate the Poynting vector integral on the slice. But the design model is too complicated and difficult to operate. The Poynting vector of the H-shaped groove points from the center to both sides and the direction of the vector is approximately perpendicular to the groove surface, which helps calculate the energy passing through the groove surface. Since the energy obtained by the patch is radiated out of the microstrip feeder through the H-shaped slot, this article uses the energy flowing through the H-shaped slot to replace the energy obtained by the patch.

In HFSS, the Fields Calculator can calculate the energy flowing through the H-shaped groove. The operation flow is: Quantity: Poynting $\rightarrow$ Complex: Real $\rightarrow$ Geometry, Surface: H-shaped groove $\rightarrow$ Normal $\rightarrow$ Integration $\rightarrow$ Eval. The simulation results show that the ratio of the energy passing through the groove surface is not completely equal to the ratio of the groove length, and the energy and the groove length are nonlinear. Therefore, the excitation amplitude ratio cannot be simply replaced by the slot length ratio. Continuously adjust the slot length until the energy received by the patch meets the proportional relationship of the excitation amplitude. When the input power is 1 W, the length and power of the H-shaped slot corresponding to the patch are shown in Tab. 3.

![Fig 6. Poynting vector. (a) Patch; (b) H-shaped groove.](image)

| Par | Spacing (A) | Excitation amplitude $l_1 : l_2 : l_3 : l_4$ |
|-----|-------------|---------------------------------------------|
| Value | 0.7, 0.72, 0.75, 0.77 | 1:0.89:0.64:0.4 |

The simulation and measurement results of the antenna VSWR and photograph of the prototype are shown in Fig. 7. The measured results show that the impedance bandwidth of VSWR $\leq 1.5$ is 1.79 GHz, which satisfies the bandwidth requirement of Satcom on-the-move.

To observe the sidelobe level of the antenna within the operating bandwidth, three frequency points of 14 GHz,
14.25 GHz, and 14.5 GHz are selected as the measurement frequency points. The antenna pattern is shown in Fig. 8, and the performance comparison of Gain, PSLL, and half-power beamwidth (HPBW) is shown in Tab. 5.

As the frequency increases, the gain of the antenna decreases slightly. And the higher the gain, the narrower the HPBW. The PSLL of the three frequency points are all lower than −19.5 dB.

Compared with other antennas, this antenna effectively reduces the sidelobe level and enhances the anti-interference performance of the communication while meeting the bandwidth requirements. Under the condition of the same number of array elements, high gain, low sidelobe, and wide bandwidth are contradictory. In actual design, we should focus on the most needed antenna characteristics. And set the performance indicators reasonably according to the requirements of the antenna type and application environment.

The measured results are different from the theoretical calculation result. The reasons are as follows: 1) The theoretical calculation does not consider the mutual coupling effect.

A comparison with a similar array, provided in Tab. 6, confirms the effectiveness of the antenna.

### TABLE 4. Antenna parameter.

| Par | Value(mm) | Par | Value(mm) | Par | Value(mm) |
|-----|-----------|-----|-----------|-----|-----------|
| \(L_p\) | 6.4 | \(l_1\) | 1.05 | \(q_1\) | 14.31 |
| \(w_{f_1}\) | 0.4 | \(w_{50}\) | 0.745 | \(q_2\) | 13.89 |
| \(w_{f_2}\) | 0.2 | \(l_f\) | 2 | \(q_3\) | 13.28 |
| \(w_{f_3}\) | 1 | \(l_f\) | 4 | \(q_4\) | 12.95 |
| \(\lambda_{01}\) | 1 | \(\lambda_{02}\) | 2.86 | \(w_{70}\) | 0.41 |
| \(\lambda_{03}\) | 2 | \(\lambda_{04}\) | 9.29 | \(w_{10}\) | 3.92 |
| \(\lambda_{05}\) | 2.35 | \(\lambda_{06}\) | 9.81 | \(w_{501}\) | 0.745 |
| \(\lambda_{07}\) | 2 | \(\lambda_{08}\) | 22.92 | \(\lambda_{09}\) | 5 |
| \(h_1\) | 0.254 | \(h_2\) | 2.4 | \(h_3\) | 0.787 |

### FIGURE 8. Antenna VSWR and photograph of prototype. (a) VSWR; (b) Photograph of the prototype.

### TABLE 5. Performance comparison at different frequencies.

| Freq. (GHz) | Gain(dBi) | PSLL(dB) | 1/2HPBW(°) |
|-------------|-----------|----------|------------|
| Sim. | Mea. | Sim. | Mea. | Sim. | Mea. |
| 14 | 14.25 | 1.3 | 5.5 | 4 |
| 14.25 | 14.5 | 16.1 | 16 | 13 | 16 |
| 14.5 | 16.7 | 16.1 | -0.91 | -20.3 | 11.0 | 11.06 |

### TABLE 6. Comparison of antennas in this article with related array structures in other literature.

| Item | This Work | [12] | [13] | [14] |
|------|-----------|------|------|------|
| Freq.(GHz) | 14.25 | 1.3 | 5.5 | 4 |
| Element | 8 | 12 | 4 | 16 |
| Gain(dBi) | 16.1 | 16 | 13 | 10.2 |
| PSLL(dB) | -20.3 | -20 | -10 | -18 |
| BW(GHz) | 1.79 | 0.75 | 4.1 | 1.3 |
between the antenna units, and the antenna unit is considered to be an omnidirectional antenna; 2) The microstrip line has a discontinuity. When the electromagnetic wave propagates in the microstrip line, there is energy leakage, and it is impossible to guarantee that the power distributed to each antenna unit is the same; 3) The microstrip transmission line radiates energy outwards, which affects the antenna pattern. In addition, the antenna adopts a coupled feeding method, which sacrifices the sidelobe and gain performance in exchange for bandwidth; 4) There are errors in the antenna manufacturing, and the measurement equipment is not accurate enough.

IV. CONCLUSION

A low sidelobe antenna was constructed using DEA. This method optimizes the array element spacing and excitation amplitude, and is not limited to uniformly spaced arrays, which increases the design freedom. The gradual change of the slot length can change the excitation amplitude, thereby reducing the difficulty of the feed network design. And the energy distribution is verified by the Poynting vector integral of the groove surface. The measured results show that this type of antenna achieves low sidelobes and wide bandwidth.

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