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RESEARCH ON A NEW KIND OF HIGH DIRECTIVITY END-FIRE ANTENNA ARRAY

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Abstract—In this paper, a new kind of end-fire array was built by employing high directivity plate end-fire antenna as the basic element based on electromagnetic surface wave theory. Being different from normal end-fire array, in the new array, high directivity plate end-fire antenna elements were arranged end to end along the end-fire direction, and the interelement spacing and uniform progressive phase were carefully adjusted to achieve high directivity. The simulations and measurements showed that the whole array achieved 19.2 dB directivity with four elements at 14.7 dB directivity each.

1. INTRODUCTION

End-fire array is widely adopted in many applications for its excellent characteristics such as simple structure, easy fabrication, low cost and low aerodynamic profile. Especially for airborne electronic equipment where the low aerodynamic drag is urgently required, the end-fire array is suitable to be used as the antenna, and it has already been used in some applications, such as Boeing 737 AEW&C Wedgetail Airborne Early Warning and Control Aircraft [1].

Some previous papers discussed the plate end-fire antennas and end-fire arrays which used end-fire antenna as the elements. But on the whole, the technical papers focused on this topic are far fewer than those on the broadside arrays [2–19]. In [2], plate end-fire antennas were used to make a circular array, in which the metal plate for every element was connected to be a whole circular ground plane. In [3], end-fire array was used as a surface wave radar antenna, in which the sea surface was taken as the ground plane, and the end-fire antennas

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were arranged side by side as the elements. [4] discussed the idea of building an end-fire array along end-fire direction, the preliminary experiment, and simulation results, but it did not explore the theory for the results. The work in this paper is partly based on [4], and some further discussion and simulations were presented.

It is usually difficult to adopt traditional end-fire array in the fields requiring high directivity, such as airborne AEW&C radar application. So for a long time, the end-fire antenna and end-fire array are often used as broadcasting and communication antennas where only middle directivity is needed.

To improve the directivity, people usually choose between the following two methods — using high directivity antenna as the elements and modifying the array structure, and this paper will explore both of them.

Section 2 of this paper explains the basic theory of end-fire antenna by analyzing Yagi-Uda antenna and plate end-fire antenna. Section 3 describes the design approach of a new high directivity plate end-fire antenna based on the surface wave theory. Section 4 discusses the problems of building arrays on three different directions with the high directivity plate end-fire element introduced in Section 3. The emphasis of this part is to build a new kind of end-fire array, in which elements were arranged along elements' end-fire direction. After the interelement spacing and uniform progressive phase were optimized through electromagnetic (EM) simulation, this new end-fire array achieves a high directivity, which is also proved by the measurements. The works in Section 3 and Section 4, especially the second one building the new structure end-fire array with end-fire element, are different from previous research works and might be regarded as the novelty of this paper.

2. BASIC THEORY EXPLANATION OF END-FIRE ANTENNA

Generally speaking, end-fire antenna is not a scientific and exact name of an antenna type. Only when some antennas are constituted to be an array, may they have the characteristics of broad-side radiation or end-fire radiation. But for a special kind of antenna structure made up of one driven dipole and several parasitic dipoles, such as Yagi-Uda antenna and others similar ones, their maximum radiation points to the structure's axis direction that is the 'end' direction. Even though this kind of antenna looks like an array, it only has one exciting dipole. So, it can be called an end-fire antenna in order to be distinguished from the end-fire array.

Under the definition above, Yagi-Uda antenna is treated as an end-fire antenna. As well known, this antenna is made up of one driven dipole and several parasitic dipoles. All these dipoles are arranged one by one with the same polarization and certain spacing. Among all parasitic dipoles, there is one dipole which is longer than the driven dipole and arranged at one side of the driven dipole; the other parasitic dipoles of the same length are shorter than the driven dipole and aligned on the other side of the driven dipole. According to EM coupling theory [6], the phase of the induced current on the longer parasitic dipole will lead the phase of the current on the driven dipole, and the ones of shorter dipoles' currents will be reverse. Then the currents' phase of all dipoles will lag in turn from longer dipole to the last shorter dipole. This current distribution produces the beam pointing to the structure axis direction, so the longer dipole is called a reflector and the shorter dipoles are called directors. Because the velocity of the equivalent EM wave around the Yagi-Uda antenna from the reflector to the last director is slower than the velocity of light, we call this wave 'slow wave' [5, 20]. The slow wave is indispensable for the end-fire radiation, and the detailed equations derivation can be found in [5] and [6].

If Yagi-Uda antenna is used as an airborne antenna, it should have small cross section for low aerodynamic profile and be easy to be mounted on the aeroplane's surface. To achieve these, a metal plate with smooth surface was introduced to mount Yagi-Uda antenna. Because of the mirror image effect of the metal plate, all the dipoles of Yagi-Uda antenna should be cut down to about half of the previous length and become monopoles, then this structure has smaller cross section than traditional Yagi-Uda antenna. The structure is shown in Figure 1. This structure can also result in end-fire radiation just as Yagi-Uda antenna and can be called plate end-fire antenna.

According to EM surface wave theory [7], there is surface wave

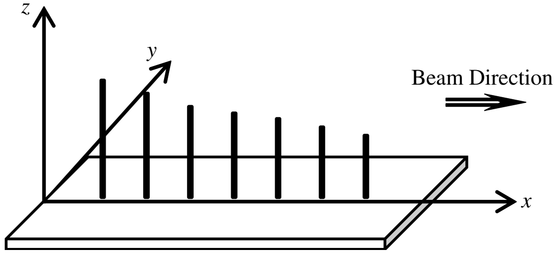

Figure 1. The structure of the plate end-fire antenna.

propagating along the metal plate's surface under this structure condition, which also has the characteristics of slow wave, just as the EM wave around the Yagi-Uda antenna. Those monopoles also act as the exciter and guide for the surface wave. So, the plate and the monopoles are radiating together.

The surface current amplitudes and phases of monopoles on the plate end-fire antenna were calculated by EM simulation software. Compared with the corresponding Yagi antenna, the amplitude of each monopole on the plate end-fire antenna was larger, but the phase distributions of two antennas were almost the same (Figure 2). Because the surface current was enhanced by the conduction of mental plate, whereas the phase relationship between dipoles was not changed, the whole end-fire radiation had been enhanced compared to the corresponding Yagi antenna.

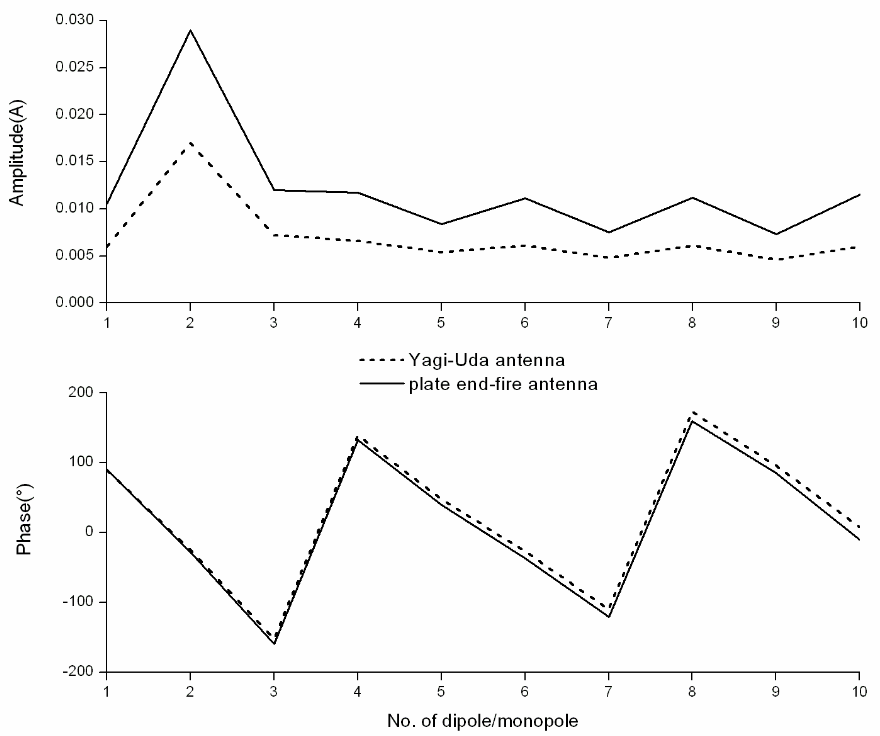

Figure 2. Amplitude and phase distribution along end-fire direction for plate end-fire antenna element shown in Figure 1.

3. HIGH DIRECTIVITY PLATE END-FIRE ANTENNA

Just as Yagi-Uda antenna, the directivity of the plate end-fire antenna is enhanced by increasing the number of directors. On the other hand, if all the directors have the same length just as the ones of Yagi-Uda, the directivity of the plate end-fire antenna will reach the limit when the directors exceed certain number. The typical number of directors for this phenomenon was observed as about 20 for plate end-fire antenna, which is also the same for its predecessor — Yagi-Uda antenna.

Based on the surface wave theory [7], for breaking through the directivity limit and increasing the antenna directivity further by increasing the directors, the antenna structure from excitation monopole to the last director can be divided into three subzones: feeding point zone, transmit zone and terminal zone (see Figure 3). The lengths of monopoles in the feeding point zone and terminal zone are step gradient to improve the efficiency of feeding point and to decrease the terminal reflect energy. Usually the number of monopoles in the feeding point zone is 30% of the total number, and the terminal zone usually includes three monopoles [8]. According to [9, 10, 12, 13] and [18], the lengths for each monopole in these three subzones can be optimized.

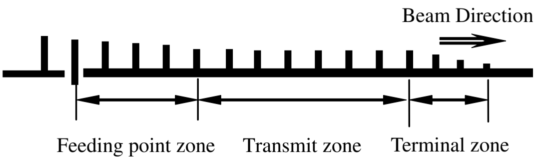

Figure 3. The structure of a high directivity plate end-fire antenna.

Three S-band plate end-fire antennas with 10, 15 and 20 monopoles respectively were designed. The interspacing between adjacent monopoles within the three antennas were all 0.2λ. Simulation results showed that the directivities of these three plate end-fire antennas were 12.31 dB, 13.74 dB and 14.91 dB, respectively. Antenna simulation models and simulation results are shown in Figure 4 to Figure 6.

There was only one driven monopole and one reflector in each of these three plate end-fire antennas. But the numbers of directors of the three antennas were different. The simulation results also showed that the slow wave's average phase velocities and optimal lengths of monopoles for three antennas were varied, which led to different directivities, and generally the directivity increased along with the

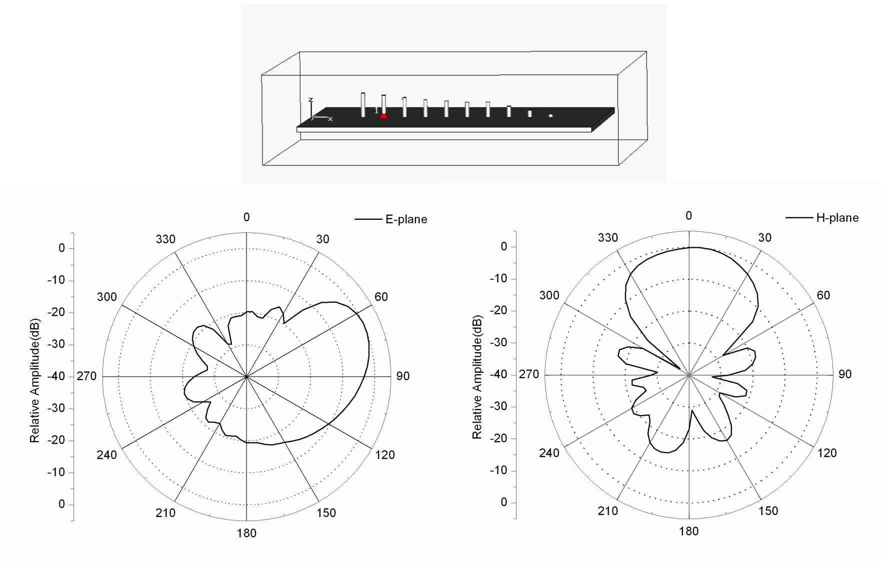

Figure 4. 10 monopoles plate end-fire antenna's simulation model and results.

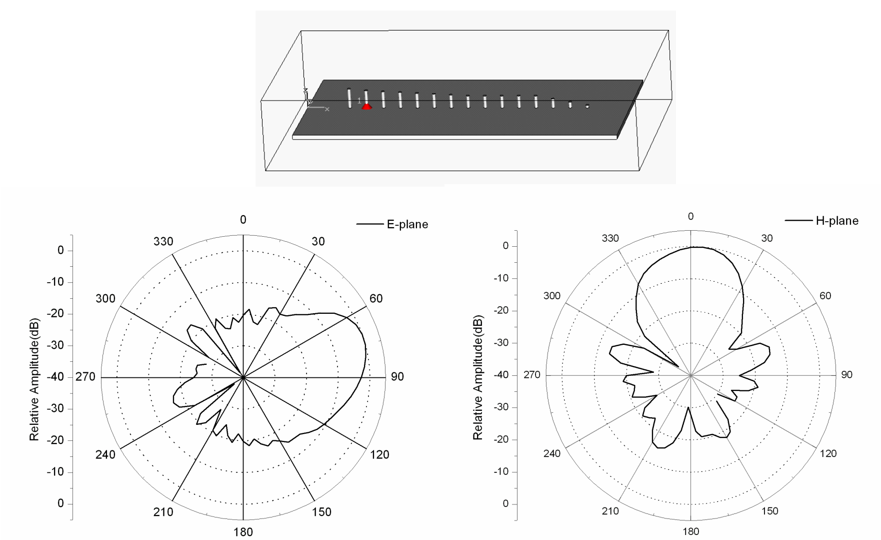

Figure 5. 15 monopoles plate end-fire antenna's simulation model and results.

director's increase.

With the same approach, a plate end-fire antenna including 120 monopoles was designed whose director number was much larger than 20, and the 22.92 dB directivity was obtained.

4. HIGH DIRECTIVITY END-FIRE ARRAY

As the main part of the paper, this section presents detailed procedures of building end-fire arrays taking high directivity plate end-fire antennas as the elements.

The name of 'end-fire array' hereafter generally means antenna arrays with the end-fire antennas as the elements.

4.1. Y-direction Array

The array axis for most traditional end-fire arrays is Y direction-elements being arranged side by side along the Y axis (Figure 7). Actually this kind of array is a broadside array, and it differs from typical broadside array only in which it utilizes the plate end-fire antenna as the element.

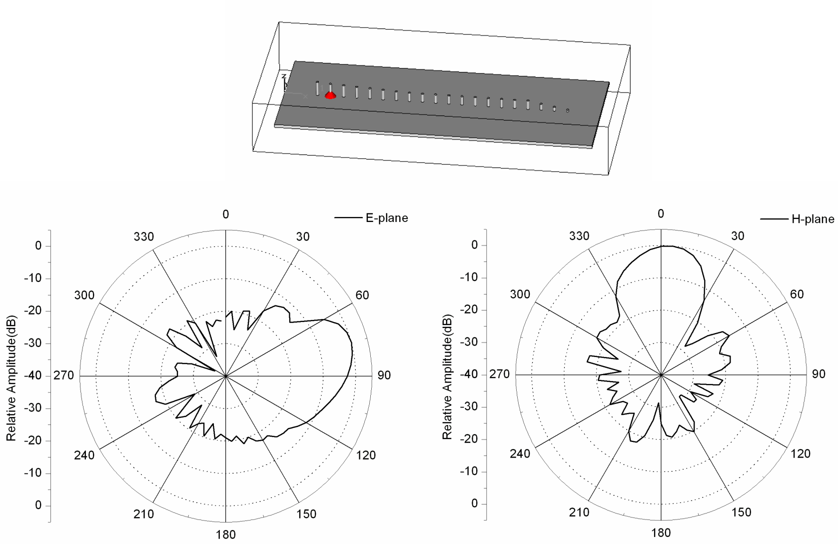

Figure 6. 20 monopoles plate end-fire antenna's simulation model and results.

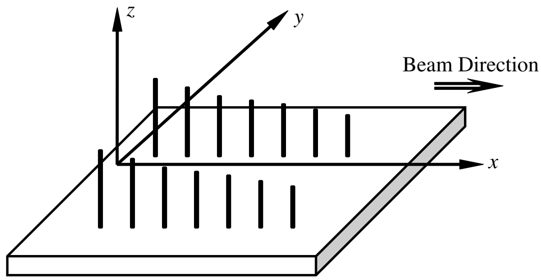

Figure 7. The Y-direction array using the plate end-fire antenna as the element.

Before constituting this kind of array, we supposed that the characteristics of this array might be the same as typical broadside array's, which means that the main beam of this array should be compressed relative to the element's beam in XY-plane and remained the same as the element's beam in XZ-plane according to classical array theory.

But our practical experiment results were absolutely inconsistent with the hypothesis above.

Taking 120 monopoles plate end-fire antenna as the element, an S-band eight elements array along Y axis with 0.6λ interelement spacing was fabricated and measured, which were shown in Figures 8 and 9.

Figure 8. Eight elements end-fire array using the 120 monopoles plate end-fire antenna as the element.

The measurement results indicate that the main beam width of array is narrower than element's in H-plane (XY-plane) as expected but is unexpectedly extended to a large scale in E-plane (XZ-plane), and the 3D far field pattern just looked like a vertical 'fan'.

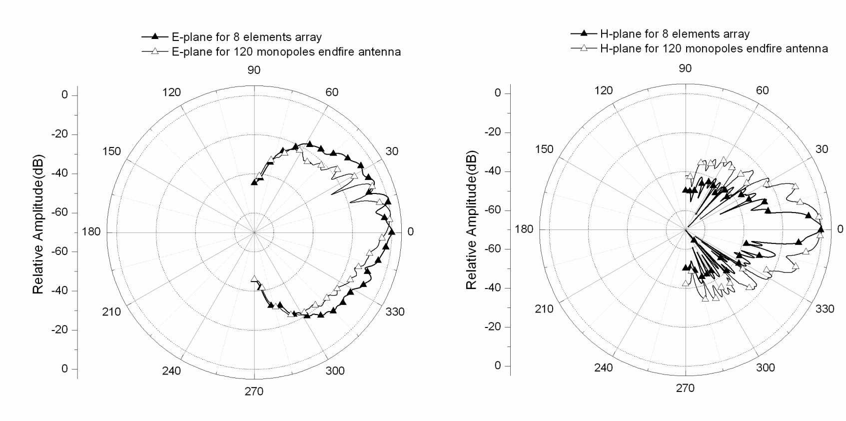

Figure 9. Measurement field patterns for the eight elements array compared with the field patterns for the element.

Investigating this phenomenon from qualitative perspective, we found that the radiation of the plate end-fire antenna elements must depend upon the surface wave propagating on the surface of the plate. If the interelement spacing is small, typically smaller than one wavelength, there will be strong mutual coupling between elements, which affects the performance of the array. Because the surface wave surrounds every element's structure, this coupling effect is much stronger than that in a broadside array. This unique feature of broadside array with this kind of end-fire elements seems worth quantitative investigation but will not be further explored here.

4.2. Z-direction Array

Correspondingly, the effort to build an end-fire array along Z axis (Figure 10) was also unsuccessful. It was also a broadside array utilizing the plate end-fire antenna as the elements actually.

Research indicated that the main lobe was narrowed in E-plane but extended in H-plane.

In conclusion, utilizing this kind of plate end-fire antenna as the elements to build a broadside array faces a series of new theoretical and technical problems which need to be solved. In this paper, only the phenomenon was introduced, but the theory interpretation and technique steps to eliminate the end-fire coupling effect were not investigated, which would be the next research focus of our group in the future.

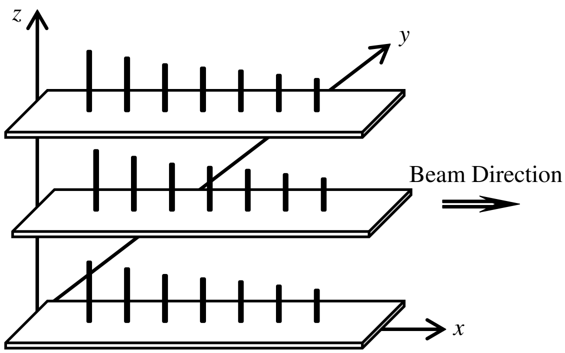

Figure 10. The Z-direction array using the plate end-fire antenna as the element.

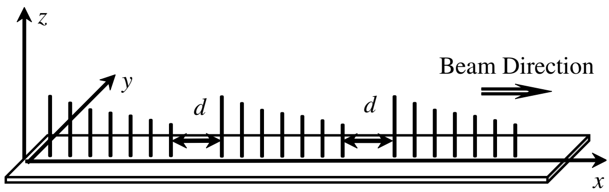

Figure 11. The X-direction array using the plate end-fire antenna as the element.

4.3. X-direction Array

Finally, a new kind of end-fire array along X axis was built. The array structure was shown in Figure 11. In this array, the elements were arranged end to end along the X axis with the constant d spacing. Here d does not denote the interelement spacing which was defined as the distance between two driven monopoles of the adjacent elements as usual, but was the distance between the last director of an element and the reflector of the next element. The array axis and end-fire beam direction were all in X-direction, and this kind of end-fire array was an end-fire array in the real sense.

On the other hand, because of using high directivity plate end-fire antenna as the element, this kind of end-fire array was different from typical end-fire array using dipole or monopole as the element. Obviously because of the length of plate end-fire element, the interelement spacing for this kind of array was far larger than a typical end-fire array.

Before constituting this array for high directivity, several questions must be answered. Firstly, which plate end-fire antenna was chosen to be the element. Secondly, what was the optimum value for d, which is a significant parameter in this kind of array's design. Thirdly, what values for every element's excitation amplitude and phase were suitable. Actually the three questions above were interrelated.

4.3.1. Simulation and Optimization for Array Taking 20 Monopoles Plate End-fire Antenna as the Element

Generally speaking, if the d spacing of every two adjacent elements was too small, the reflector of the front one would shelter off the end-fire radiation from the behind one. But the superposition of electromagnetic waves radiated from different elements would be worse when the spacing is quite large.

According to end-fire array theory, the uniform progressive phase should be chosen to make the radiating field from every element superimposed in-phase in the end-fire direction. So the uniform progressive phase should depend on the d value. That was also applicable to this kind of end-fire array. But an issue which must be taken into account was that the velocity for the slow surface wave along array axis in the new kind of end-fire array was lower than that in a typical end-fire array. Then the relationship between d and the uniform progressive phase must be different from the one in typical end-fire array.

Taking the qualitative conclusions above into account, a lot of simulations were performed to determine the optimum values for d and the uniform progressive phase.

Taking a four-elements array whose elements were 20 monopoles plate end-fire antennas as an example, the initial value for the d-spacing and the uniform progressive phase were set to 0.5 wavelength and 60°, where 60° was basically equal to the phase delay for the slow surface wave propagating from the driven monopole of an element to the driven monopole of the next element. The excitation amplitude for each element was selected to be equal.

Firstly, the simulations taking d-spacing as the variable, and the 60° for the uniform progressive phase as a constant were made to find the optimum result in directivity. The scale for d spacing was set from 0.2 to 1.0 wavelength, and the simulation results were shown in Figure 12. Secondly, the simulations taking the uniform progressive phase as the variable, and the 0.5 wavelength for d-spacing as a constant were made to find the optimum result in directivity. The scale for the uniform progressive phase was set from 0° to 360°, and the simulation results were shown in Figure 13.

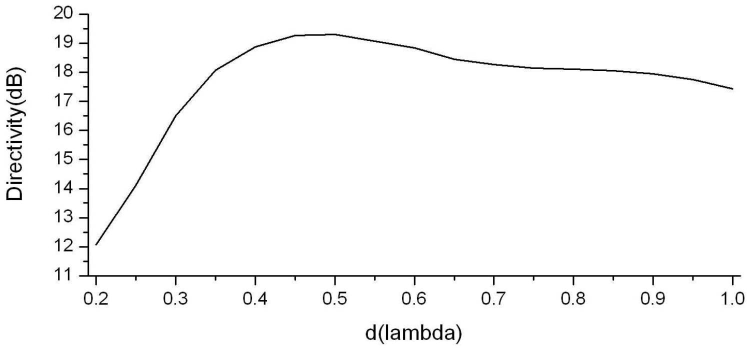

Figure 12. The simulation results for array's directivity versus the d-spacing when the uniform progressive phase was constant 60°.

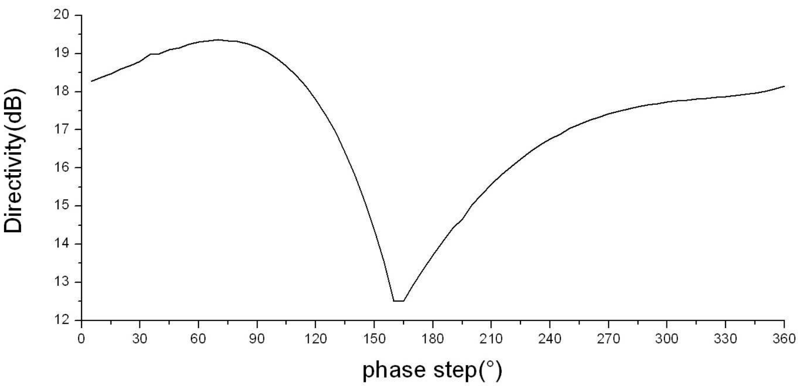

Figure 13. The simulation results for array's directivity versus the uniform progressive phase when the d-spacing was constant 0.5 wavelength.

From the above simulation results, also taking the side lobe level, back lobe level and beam width into account, 0.5 wavelength and 60° were revealed to be the optimum d-spacing and uniform progressive phase. With these two parameters, the average phase constant for surface wave along this array's axis was calculated to be $1.738\pi/\lambda$, which was obviously smaller than the phase constant of light $2\pi/\lambda$.

The simulation results of field pattern for this array were shown in Figure 14. In order to observe the benefit of building an array, the field patterns for a single element were also shown in the corresponding

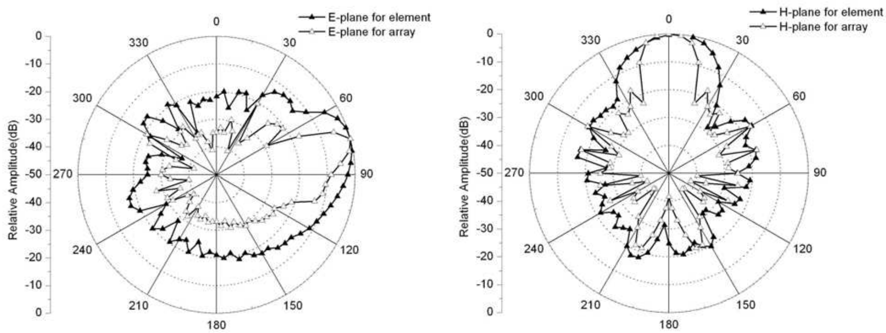

Figure 14. The simulation results of field pattern for the X axis end-fire array and a single element.

figures.

The comparisons shown in Figure 14 indicates that the beam widths of the array are narrowed in E- and H-planes simultaneously, which is obviously different from Y- and Z-direction end-fire arrays. Because the array has higher directivity and lower side lobe than the element, it could be concluded that this kind of array is efficient to enhance directivity, and it also indicates that the elements should be fed with the appropriate uniform progressive phase just equal to the slow surface wave propagation phase delay. This forced feeding combining with the in-phase addition of surface wave is the reason to obtain higher directivity for this kind of array.

4.3.2. Comparisons for Arrays with Different Elements

For the comparison of the radiation characteristics of array with different elements, 10 monopoles, 15 monopoles and 20 monopoles plate end-fire antenna were selected as the element respectively to constitute three kinds of end-fire array. The simulations were also done for the three conditions respectively.

No matter what kind of element was used, the rules for choosing the d-spacing and the uniform progressive phase were the same as mentioned above. The simulation results for the array directivity vs. the total number of monopoles within the array were shown in Figure 15.

According to Figure 15, directivity curves for different arrays had the same trend, especially when the array having 10 monopoles plate end-fire antenna as the element and the array having 15 monopoles

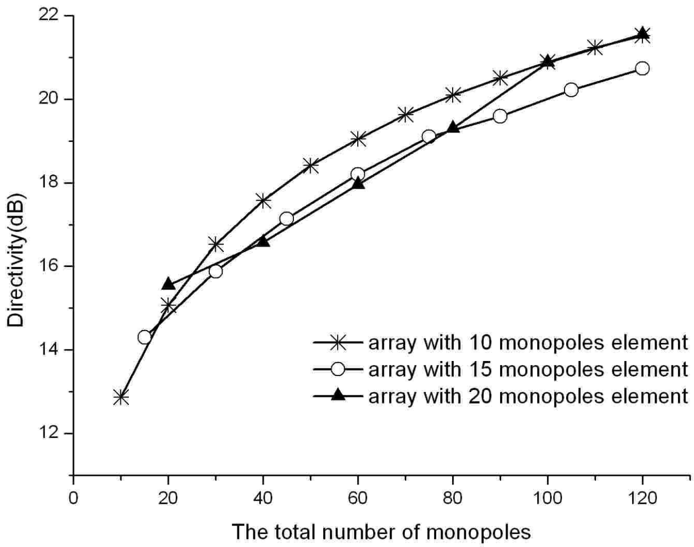

Figure 15. The simulation results of array directivity vs. the total number within the array.

plate end-fire antenna as the element.

For different arrays with the same total number of monopoles, there were different directivities. Taking the total 60 monopoles as an example, we found that the arrays using 10, 15, 20 monopoles antenna respectively as element would have 6, 4, 3 elements, and the directivity for each array was 19.1 dB, 18.2 dB and 18.0 dB respectively.

For the total number of monopoles from 30 to 90, the array with 10 monopoles element had the highest directivity. The array with 15 monopoles element had the second highest directivity, and the array with 20 monopoles had the lowest one.

But when the total number of monopoles was more than 90, the directivities of the array with 10 monopoles element and the array with 20 monopoles element were almost the same. Their directivities were both higher than the array with 15 monopoles element.

The average phase constants were calculated for slow surface wave propagating along the array axis. The results for the above three arrays with different kinds of elements were $1.656\pi/\lambda$, $1.734\pi/\lambda$ and $1.738\pi/\lambda$, respectively. Although different arrays have different phase constants, they have similar directivities when the total number of monopoles is large enough.

Figure 16. A S-band four elements end-fire array was under test.

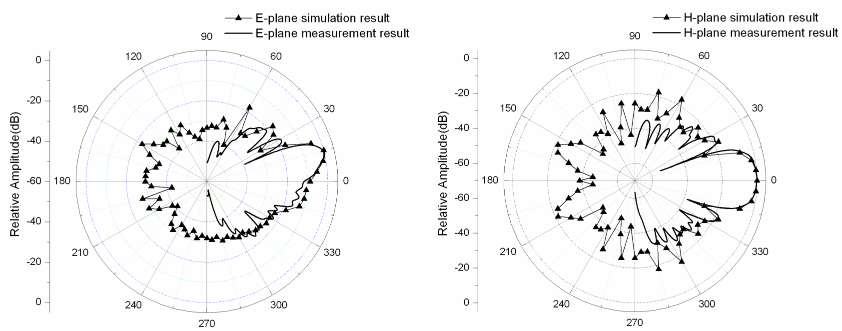

Figure 17. The measurement results for array's far field pattern.

4.3.3. Measurement for Array Taking 20 Monopoles Plate End-fire Antenna as the Element

An S-band four elements end-fire array taking 20 monopoles plate end-fire antenna as the element was chosen to be fabricated and measured for obtaining its radiation characteristics.

The whole length in X axis for this array (also the length for the integrative metal plate) was 17.7λ, and the width in Y axis was 2λ. Also the interspacing between every two monopoles was 0.2λ, and the d-spacing was 0.5λ.

Figure 16 shows that this array was under test in a near-field measurement system, and the measurement results for array's far field pattern are shown in Figure 17. These figures also give the simulation results for array's far field pattern.

The measurement results for directivity was 19.2 dB, and half power beam widths (HPBW) were 9.2° and 22.94° in E- and H-planes, respectively. The simulation and measurement results coincided very well.

The 20 monopoles plate end-fire antenna was also tested in the same measurement system. Compared with the measured directivity of this single element, 14.7 dB, the array's directivity had been enhanced by 4.5 dB, which indicated that this kind of end-fire array had the capability to obtain high directivity and then had practicability in many applications.

5. CONCLUSION

In this paper, a new kind of end-fire array was designed and built by a novel method, in which some plate end-fire antennas had been taken as the element, arranged in a line end to end along the end-fire direction and excited according to slow wave phase delay. Before this, the plate end-fire antennas were optimized to obtain high directivity based on electromagnetic surface wave theory. Simulation and measurement results showed that the directivity of this array achieved a tremendous increase.

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