A High-Efficiency Synthesis Method for Wide-Band Phased Array Antennas

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***Abstract*- In this paper, a synthetical method of wide-band phased array antenna is proposed, which the array elements arranged by the unequal space, so that the performance that the patterns in the visible range has a peak value in the radiation direction and do not have grating lobes in wide band. The design of phased array antenna for a wide-band application is discussed. The rule of arrays with unequal space for several elements is derived using this synthetical method. Sinulation results show that the array antennas can scan in a range of ±30°in wide band.**

I. INTRODUCTION

The wide-band phased array antennas can be used in systems of communication, radar, electronic warfare, and so on. But how to design the antennas is a challenge for the engineers. With the variation of the operation frequency of the array antennas, the electrical size of the space between the elements will be changed, and the coupling between the elements and the scanning scope and electrical performance of the elements will be different. In addition, the bigger the scanning angle, the smaller the space of the array, so the aperture of the elements for wide-band phased array antennas must be less than a corresponding wavelength of the maximal frequency, so that the elements with the small size are difficult to be realized.

The traditional phased array antennas have the equal space, and the size of the elements limits the minimum space between the elements, so the grating lobe can appear in the visible range when scanning to a certain angle. This paper introduces a synthetical method of wide-band phased array antennas, which adopts the special arrays with unequal space so as to realize the performance that the patterns in the visible range have a peak value in the anticipated direction and do not have grating lobe in wide band.

II. ANTENNA ARRAY DESIGN

A. Construction consideration of antenna array

The unequal space arrays are arrayed according to a certain special serials. The serial with N length meets two characteristics:

1) The number of difference of all the possible terms of the serial rule is $C(N)=N(N-1)/2$, and the difference is not repeated.

2) Among the all serials x_n meets the above characteristics, the maximal term of the needed serial is minimum.

In the linear array, the coordinate of radiating elements is L_m , that satisfies formula (1).

where d and N are scale of space between the elements and number of radiating elements, respectively, the x_N serials have been two characteristics.

$$\begin{cases} L_m = x_m d \\ x_1 = 0 \\ x_1 < x_2 < .... < x_N \end{cases} \tag{1}$$

In order to ensure that the patterns in the visible range have a peak value in the anticipated direction and do not have grating lobe, d must meet formula (2)

$$d < \frac{\lambda_{\min}}{1+\left|\sin\theta_m\right|} \tag{2}$$

where θ_m is the maximum angle that antenna array can be scanning , $\lambda_{\min}$ is the wavelength at upper frequency, formula(2) defined upper limit of frequency band.

If radiating elements with equal space were distributed on aperture L_m in length, the spacing d_e between the elements can be expressed as (3).

$$d_e = \frac{L_m}{N-1} \tag{3}$$

For the array, equivalent space d between the elements can be expressed as (4).

$$d = L_m / x_N \tag{4}$$

For unequal space special arrays are arrayed according to a certain special serials metioned above , there exists a formula (5) , so maximal filling ratio can be given as follows:.

$$\begin{cases} x_N \geq C(N) = N(N-1)/2 \\ d_e \leq \frac{2}{N} d << d \end{cases} \tag{5}$$

Define $\eta = C(N)/x_N$,if values of η varies in the range from 0.7 to 0.8, antenna pattern has relatively low sidelobe (without consideration of that space d between the elements is longer).

For unequal space arrays are arrayed according to a certain special serials, sidelobe level can be expressed as (6).

$$SL(dB)=10\log\left(\frac{2}{N}\right) \tag{6}$$

The more the number radiating elements, the lower level sidelobe is, the more longer the size of aperture array.3dB beam width antenna array with serials always narrower than beam width antenna array with equal space 3dB beam width can be calculated according to the formula (7).

$$BW_{-3dB} \approx 44°\lambda / x_N .d \qquad (7)$$

B. High-efficiency radiation element

Coventional slot vivaldi antennas employ a dielectric with high dielectric loss tagent, so that radiation efficiency of antenna is very low. In this paper antenna element constructed by vivadi, that the transmission line is excited by rectangular air coaxial line so as to realize the coupling from the open-ended line center concucotor. The main characteristics are high gain and low loss. In addition, it is characterized by easy integration, simple structure,lower cross polarization and wide bandwidth compared with the conventional tapered slot. In this design consideration, the dielectric thickness is 0.13 mm, dielectric constant is 2.2, loss tangent is 0.0009. The model of air coaxial line for simulation is shown in Fig 1, loss comparison of the two type of transmission line is given in Fig 2.

From the results of simulation, it can be seen that the loss of air coaxial line loss is considerably lower than microstrip line loss within in the whole band, so that the efficiency of the antenna can be improved a lot. In order to realize optimized radiation pattern of the antenna, Marchand balun and one-quarter wavelength impedance transformer are used to keep good match in wide band.

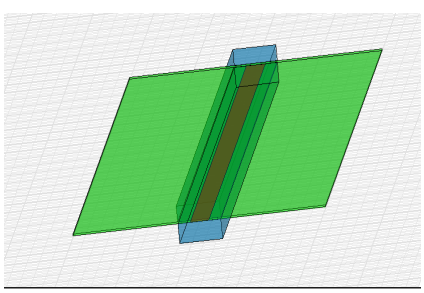

Fig.1 Model of air coaxial strip

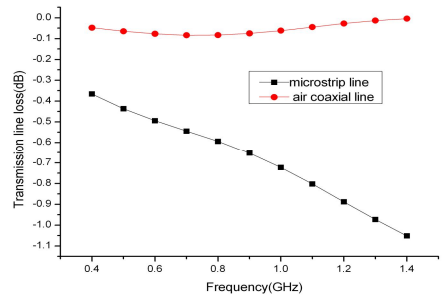

Fig.2 transmission line loss contrast

By adjusting the shape of antenna, length, width of feed line, dielectric constant and dielectric thickness, good radiation pattern with symmetrical *E* plane and *H* plane pattern can be obtained with symmetrical *E* plane and *H* plane pattern.

The equation for vivaldi antenna curve is expressed as formula (8). By optimized design, the structure of the vivaldi antenna structure as shown in Fig 3.

$$Z = -C_1 \cdot exp(r \cdot (x + X_2) + C_2 - Y_2) \qquad (8)$$

where C_1 and C_2 expressed as formula (9), (x_1,y_1), (x_2,y_2) are start and end points of curve, respectively, r is gradient factor for curve and r = 0.22.

$$\begin{cases} C_1 = \dfrac{Y_2 - Y_1}{exp(r \cdot X_2) - exp(r \cdot X_1)} \\ C_2 = \dfrac{Y_1 \cdot exp(r \cdot X_2) - Y_2 \cdot exp(r \cdot X_1)}{exp(r \cdot X_2) - exp(r \cdot X_1)} \end{cases} \qquad (9)$$

The radiation pattern of the vivaldi element at lower frequency point F_l and upper frequency point F_h are shown in Fig 4 and Fig 5, respectively, and VSWR within whole frequency band for F_h/F_l=2.5 case is as shown in Fig 6.

The vivaldi antenna element is simulated and optimized by using three-dimensional electromagnetic field simulation software HFSS. Simulation results show that vivaldi antenna element gain is up to 13.4dB at frequency F_h and up to 6.5dB at frequency F_l, in addition, in the whole frequency band, VSWR is less than 2.

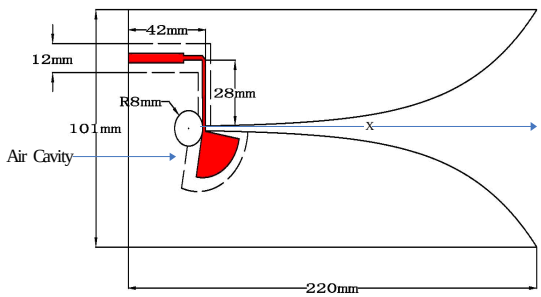

Fig. 3 vivaldi antenna element dimension size

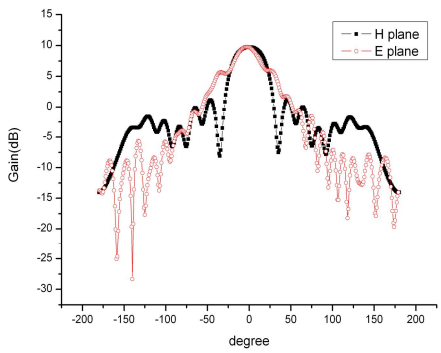

Fig 4 Radiation pattern vivaldi element at FhGHz

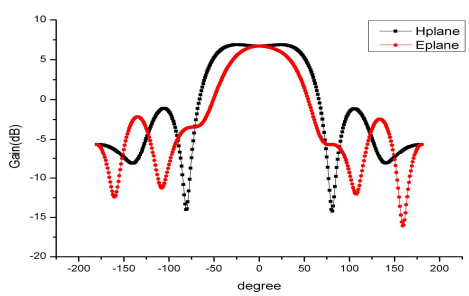

Fig. 5 Radiation pattern vivaldi element at FlGHz

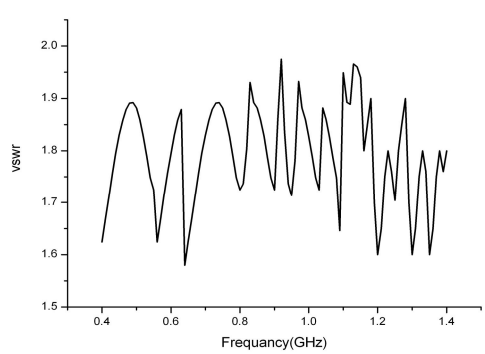

Fig. 6 Matching of vivaldi element

C. *The simulation of antenna array*

According to the serial rule, the serials with 3, 6 and 8 terms are deduced. The serial with 3 terms is 0,1,3; the serial with 6 terms is 0,1,4, 10,12,17; The serial with 8 terms is 0, 1, 4, 9, 15, 22, 32, 34.

For the array with unequal space according to serial rule, directional coefficient D is approximately expressed in formula (10) without considering the array coupling effects.

$$D \approx \frac{2dN}{\lambda + 2d(N-1)} \tag{10}$$

Therefore, for a certain x_N and θ_m, D will increase with the number N element linear increases. For antenna array with N elements, antenna array pattern $F(\theta)$ is given by (11), where d is scale of the spacings between the elements.

$$F(\theta) = 20\log\left|\frac{\sum_{n=1}^{N} f(\theta)\exp(jkd(\sin\theta - \sin\theta_m)x_n}{N}\right| \tag{11}$$

where $f(\theta)$ is the pattern of vivaldi elment.According to the derived results, the pattern of 8-element array antennas with unequal space are calculated, as shown in figure 7. The pattern with unequal space has the only one main lobe in the visible range, and all the side lobes are less than -7dB. and the pattern with equal space has several grating lobes which has the same values as the main lobe in the visible range. Along with the

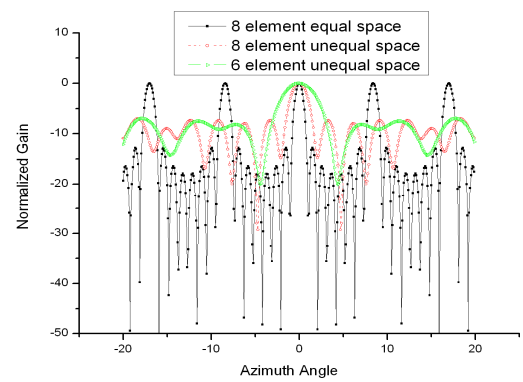

Fig 7 Radiation pattern of array antennas with unequal space

increase of number element antenna array, the side-lobe level is nearly not changed .

D. *Characteristics of wide band antenna array*

For the antenna array with equal space, patterns change with frequency, at higher frequency, beam width of pattern becomes narrower, but nonetheless, the side-lobe level within working band is almost unchanged , without grating lobe in the visible range in wide band. Taking the antenna array with 8 element as an example, antenna array works in the frequency ranging from F_l to F_h, and F_h/F_l=2.5, d=0.58λ_{max} The pattern is shown in Fig 8.

Simulation results shows that there is no grating lobe in the visible range in a wide band. Beam width of pattern becomes narrower as frequency is increased , side lobe is not changed.So according to the size of the antenna radiating elements, different scale *d* is chosen.

E. Scan capability of the antenna array with serials

Considering the actual installation size antenna,*d* is optimized by d=0.25λ_{max}.Using synthesis methods for serials methods, scanning angle is expanded to ±30 degrees. 8 element antenna array for example, antenna array works for the frequency ranging from F_l to F_h, and F_h / F_l=2.5, the pattern is shown in Fig.9.

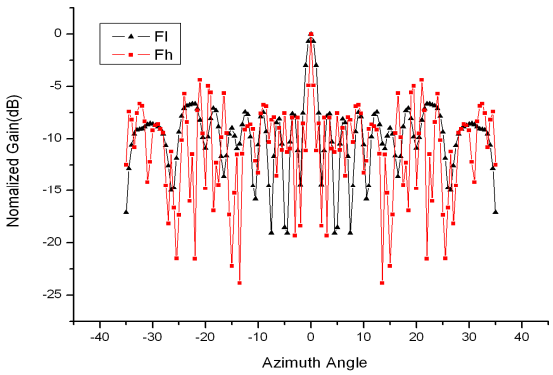

Fig. 8 Radiation pattern of array antennas with unequal space in wide band

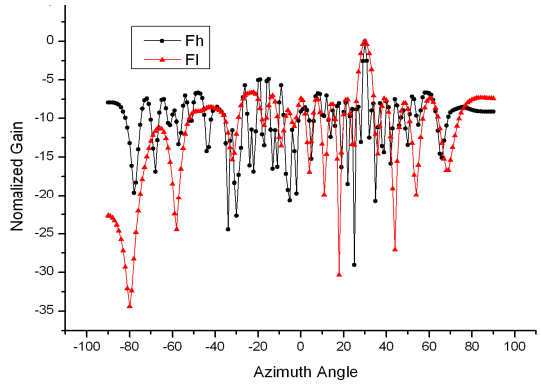

Fig. 9 scanning pattern of array antennas with unequal space in wide band

From the results of simulation, do not have grating lobe in the visible range in wide band. beam width of pattern become narrower as frequency is increased , side lobe is not changed.So according to the size of the antenna radiating elements, choose different scale *d*.

III. CONCLUSION

Regarding that the element of broadband phased array antennas require limited space, we treat this problem using this synthesis method. It can be seen that scanning range of 30°is realized. This synthesis method is more effective in small-scale phase scanning for broadband phased array antennas.

In summary, the array pattern can be written as a product of an element pattern and array factors. The pattern of an element in an array is not,however,the same as the pattern of that same element when used alone.this is because exciting one element in the array produces radiation from that elment and additional radiation from all other elements,because of current induced on them by the excited radiator, Nevertheless, the synthesis procedures are still valid if the radiating currents or aperture field has the same distribution on each element.

This synthesis method can be used for the design of general two-dimensional wide-band array. To realize the upper space scanning in a wide band.

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REFERENCES

[1] Ma,M.T, Theory and Application of Antenna Arrays, New York: Wiley Interscience,1979.

[2] Schelkunov,S.A, “A Mathematical Theory of Linear Arrarys,” Bell System Tecb.J., 1943, pp.80-107.

[3] Balanis,C.A., “Radiation Integrals and Auxiliary Potential Fucctions,” Ch.3 in Antenna Theory:Analysys and Design, New York: Harper and Row, 1997.

[4] Skolnik,M., J.W.ShermanIII, F.C.Ogg, Jr., “Statistically Designed Density- Tapered Arrays,” IEEE Trans.on Antennas and Propagation, Vol. AP-12, July 1964, pp.408-417

[5] Elliot, R.S., Antenna Theory: Analysis and Design, 2nd ed., New York: Haper and Row, 1997, pp.304-306.

[6] Balanis,C.A, “Antenna Theory:for Waveguiding Systems,” New York:Harper and Row,1997,pp.125,126.

[7] Taylor,T.T, “Design of Circular Apertures for Narrow Beamwidth and low Sidelobe,” IRE Trans.on Antennas and Propatation, Vol.AP-8, 1966, pp.358-371.

[8] Poulton,G.T., “Antenna Power Pattern Synthesis Using Method of Successive Projections with Application to Restoration from Magnitude,” J.Opt.Soc Am.A., NO.A1, 1984, pp.932-943.

[9] Janning,D .S., and B.A.Munk, “Effects of Surface Waves on the Currents of Truncated Periodic Arrays,” IEEE Trans, on Antennas and Propagation, Vol.AP-50, No.9, September 2002, pp.1254-1265.

[10] Farrell,G.F., Jr.,and D.H.Kuhn, “Mutual Coupling Effects in infinite Planar Arrays of Rectangular Waveguide Horns,” IEEE Trans. On Antennas and Propagation , Vol.AP-16, 1968, pp.405-414.