Design of Density Tapered Array for Arbitrary Density Distribution

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***Abstract*— Density tapered array has a feature of having uniform excitations in all array elements. Then, a feeding network becomes very simple and array antenna will be applied for multi frequency operations. In this paper, a MATLAB program of achieving arbitrary density tapered distributions is developed. For example, the density distribution of cosine on a pedestal is designed. Moreover, radiation patterns in the wide range of frequencies are investigated. For the frequency change from 900 MHz to 2500 MHz, low side lobe levels are kept unchanged.**

Keywords—Density tapered array; multi frequency; grating lobe; antenna gain.

I. INTRODUCTION

Currently, next generation mobile communication system (5G) is being developed [1],[2]. For mobile base station antennas, multi beam and wideband characteristics are requesting in addition to low side-lobe characteristics of present base station antennas. In a present mobile base station antenna, an equally spaced linear array configuration is employed. Low side-lobe characteristics are achieved by giving adequate excitation coefficients (amplitude and phase) to array elements [3]. Although excellent low side-lobe characteristics are obtained, grating lobe appearances in higher frequencies are shown as problems. For suppressing grating lobes, unequally spaced arrays are considered [4]. The concept of the unequally spaces array was summarized in a textbook [5]. A method of determining unequally array spacing was shown. However, more promising characteristics of wide band capabilities were not discussed. The authors studied preliminary wide frequency characteristics in a linearly density tapered array configuration [6]. In the case of a linear tapered array, there were problems in low side-lobe designing.

In this paper, a MATLAB program achieve arbitrary density taper is developed. As an example, cosine on a pedestal density distribution is studied. Low side-lobe design is successfully achieved. Moreover wideband radiation patterns are studied.

II. DESIGN METHOD OF ARBITRARY DENSITY TAPERING

Concept of a density tapered array is shown in Fig.1. *f(x)* indicates density tapered function. *f(x)* has a symmetrical distribution around the array center element. Small circles indicate array elements. d_i indicate array element spacing. *Si* indicates areas of the tapered function.

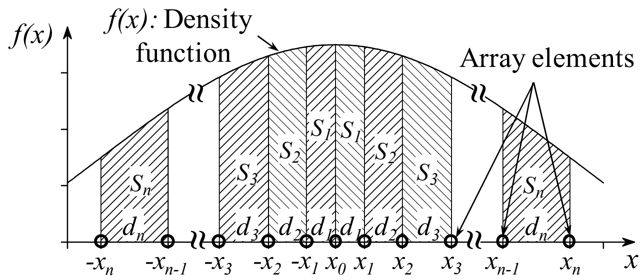


Fig. 1. Relation between array element position and density tapered function

In the reference [5], a method of achieving arbitrary density taper is explained. The important concept is equal-area approximation expressed by the next equation.

$$S_1 = S_2 = \ldots = S_n = S \tag{1}$$

Total segment number (N_s) is given by the next expression. Here, N is the array element number. And n indicates the number of spacing in half an array.

$$N_S = N - 1 = 2n \tag{2}$$

Total area (S_{all}) is expressed by the next equation.

$$S_{all} = \int_{-L/2}^{L/2} f(x)dx \tag{3}$$

Then, (S) is given by the next expression.

$$S = \frac{S_{all}}{N-1} \tag{4}$$

The array element positions (x_j) are determined by the next equation.

$$\int_{-L/2}^{-x_j} f(x)\,dx = (n-j)S \tag{5}$$

Here, $j = n\text{-}1,\ n\text{-}2\ \ldots 0$.

Then, the element spacing (d_i) is given by next expression.

$$d_i = |x_i - x_{i-1}| \quad (6)$$

Here, $i = n, n\text{-}1 \ldots 1$.

III. Design Example

A. Density tapered function

As for density tapered function, the next cosine on a pedestal distribution is used. Here, ΔA indicates pedestal value. The sketch of $f(x)$ is shown in Fig. 2.

$$f(x) = \cos\left(\frac{\pi x}{L}\right) + \Delta A \quad |x| \le \frac{L}{2} \quad (7)$$

The total array element number is set N=31. Total array length (L) is expressed by the next relation.

$$L = 2\sum_{i=1}^{15} d_i \quad = 0.7(N-1)\lambda_1 \quad (8)$$

And, the total area S_{all} is expressed as follows.

$$S_{all} = \int_{-L/2}^{L/2} \left\{\cos\left(\frac{\pi x}{L}\right) + \Delta A\right\} dx = 2L\left(\frac{1}{\pi} + \frac{\Delta A}{2}\right) \quad (9)$$

Then, S is calculated as follows.

$$S = \frac{S_{all}}{N-1} = 1.4\lambda_1\left(\frac{1}{\pi} + \frac{\Delta A}{2}\right) \quad (10)$$

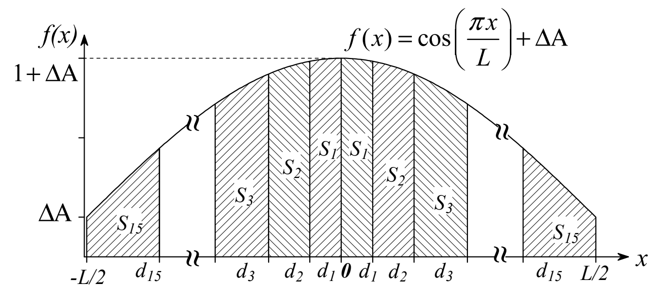


Fig. 2. Density tapered distribution

Study frequencies are shown in Table 1. In designing, 900 MHz is utilized.

TABLE I. Calculation Frequency

Frequency [MHz]	f_1	f_2	f_3	f_4
	900	1500	2000	2500
Wave Length [mm]	λ_1	λ_2	λ_3	λ_4
	333	200	150	120

B. Method of determining element spacing

By using equations (5) and equation (10), element positions (x_j) are determined by the next expression.

$$(n-j)\left(\frac{1}{\pi} + \frac{\Delta A}{2}\right)1.4\lambda = \int_{-L/2}^{-x_j} f(x)\,dx \quad (11)$$

Here, $j = n\text{-}1, n\text{-}2 \ldots 0$.

By using equations (7), the integral equation become as follows.

$$\int_{-L/2}^{-x_j} f(x)\,dx = \int_{x_j}^{L/2} f(x)\,dx = \frac{L}{\pi}\left(1 - \sin\left(\frac{\pi x_j}{L}\right)\right) + \Delta A\left(\frac{L}{2} - x_j\right) \quad (12)$$

Finally, (x_j) is determined by the next equation.

$$(n-j)\left(\frac{1}{\pi} + \frac{\Delta A}{2}\right)1.4\lambda = \frac{L}{\pi}\left(1 - \sin\left(\frac{\pi x_j}{L}\right)\right) + \Delta A\left(\frac{L}{2} - x_j\right) \quad (13)$$

In order to obtain (x_j), a MATLAB program is developed. The flaw chart of a MATLAB program is show in Fig.3. From (x_j) values, (d_i) is obtained by equations (6).

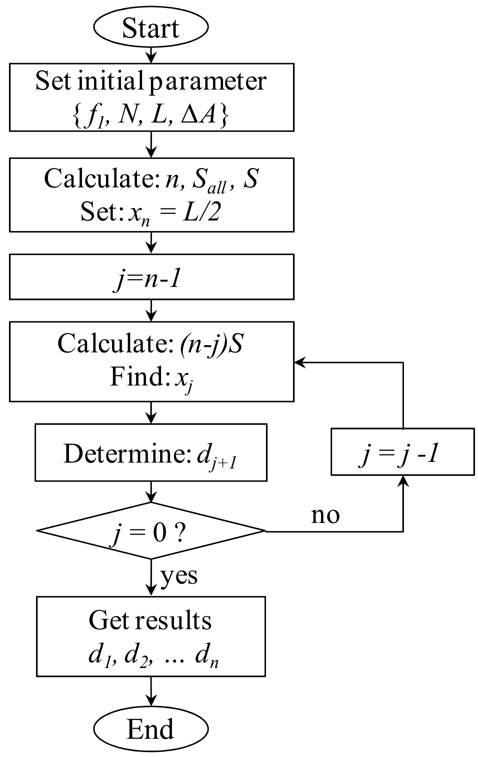


Fig. 3. Flow chart of MATLAB program.

Each d_i values in different ΔA values are summarized in Table 2.

TABLE II. ARRAY ELEMENT SPACING

Label	DTA1	DTA2	DTA3	DTA4	DTA5
ΔA / d	0.5	0.4	0.3	0.2	0.1
d_1	177	173	168	163	156
d_2	178	174	169	164	157
d_3	179	175	170	165	158
d_4	181	177	173	167	161
d_5	185	180	176	170	164
d_6	189	185	180	175	168
d_7	195	191	186	180	173
d_8	202	198	193	188	181
d_9	211	207	203	197	190
d_{10}	223	220	215	210	202
d_{11}	239	236	232	227	219
d_{12}	261	259	256	251	244
d_{13}	292	294	293	290	283
d_{14}	343	351	358	362	360
d_{15}	442	477	524	589	682

IV. RADIATION CHARACTERISTIC

Radiation patterns are calculated by using an electric point source model in FEKO. As a reference, an equally spaced array of $0.7\lambda_1$ element spacing is calculated as shown in Fig.5. Calculation is made at $f_1 = 900$ MHz. In this case, power density of an array becomes uniform. So, the first side-lobe level becomes -13.2dB

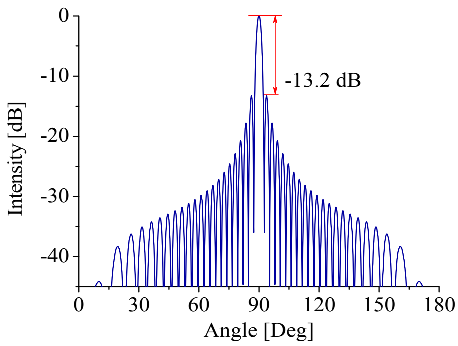
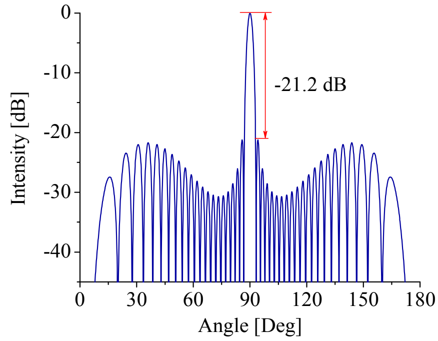
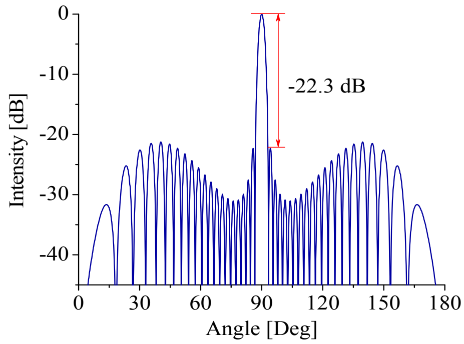


Fig. 4. Equally Spaced Array (ESA)

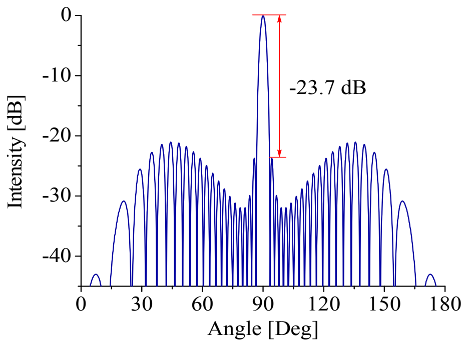
Radiation patterns of density tapered arrays (DTAi) are shown in Fig.6 (a)~(e). In Fig.6, the density tapering is sharpest in the case of DTA5. The first side-lobe levels decrease in accordance with sharpness of tapering. However, high side-lobe regions are approaching to the main lobe.



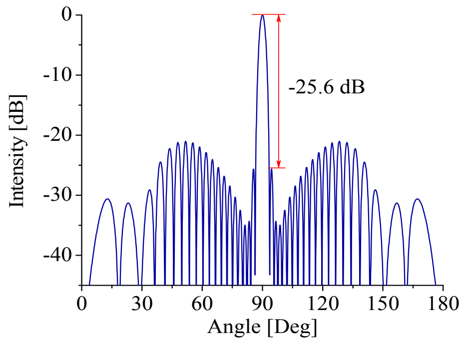
(a) DTA1 (ΔA = 0.5)



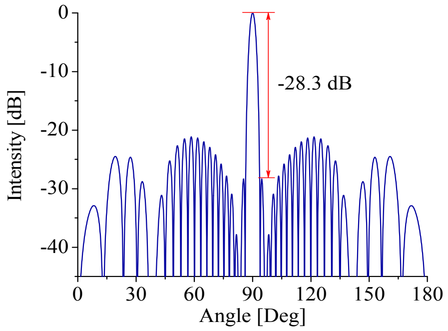
(b) DTA2 (ΔA = 0.4)



(c) DTA3 (ΔA = 0.3)



(d) DTA4 (ΔA = 0.2)



(e) DTA5 (ΔA = 0.1)

Fig. 5. Radiation patterns of density tapered arrays

The first side-lobe level dependences density tapering are summarized in Fig. 7. Side-lobe levels are decreased well by using sharp density tapering.

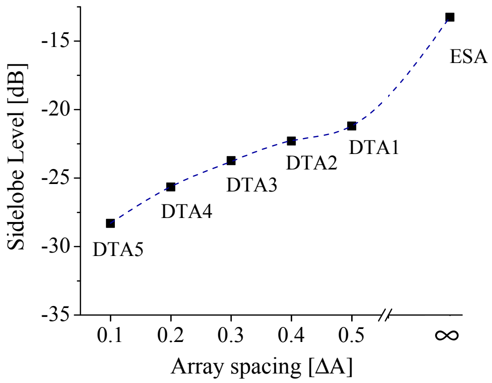
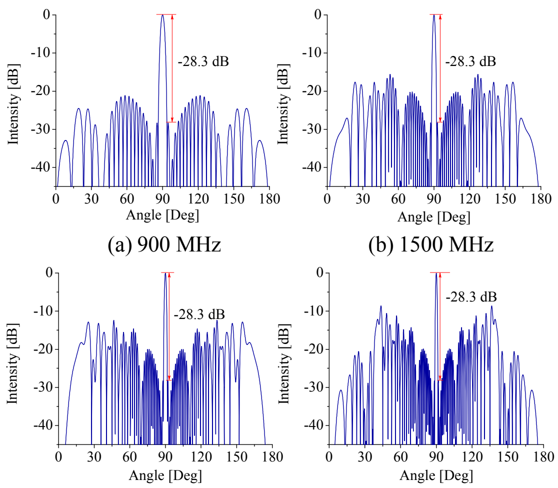


Fig. 6. Side lobe versus array spacing

V. Frequency Characteristic

Radiation characteristics of the array in the frequency range are calculated by an electric point source model in FEKO. Radiation patterns changes from f_1 = 900 MHz to f_4 = 2500 MHz are show in Fig. 8 (a)~(d).



(a) 900 MHz (b) 1500 MHz

(c) 2000 MHz (d) 2500 MHz

Fig. 7. Frequency characteristics (DTA5)

As a remarkable point, the first side-lobe levels are maintained unchanged over all the frequency bands. Other higher side-lobes are approaching to the main lobe at higher frequencies.

Frequency dependent characteristic of the first side-lobe levels are summarized in Fig. 9. No frequency dependence are ensured. The relation between antenna gain and frequency is shown in Fig. 10. As can be seen, the antenna gains are not increased when the frequency is high. This is because large side-lobe levels spread in wide angular region at high frequencies

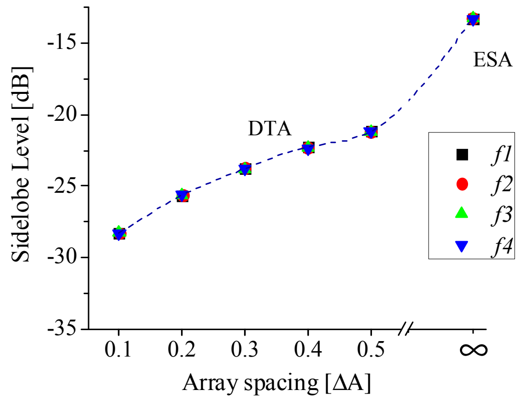


Fig. 8. Side lobe versus array spacing

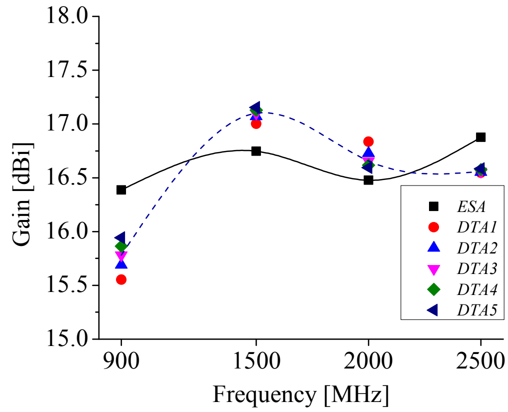


Fig. 9. Array gain versus frequency

VI. Conclusion

Density tapered array having cosine on a pedestal density distribution is designed. The first side-lobe reduction by sharp tapering distribution is ensured. Moreover, the first side-lobe levels do not change in the frequency range from 900 MHz to 2.500 MHz. Also, antenna gains become almost unchanged over the frequency range.

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