Printed Antenna Arrays with High Side Lobe Suppression: the Challenge of Design

Marija Milijić[1], Aleksandar Nešić[2], Bratislav Milovanović[1]

Abstract – **The design of printed antenna arrays with high side lobe suppression has been analysed in this article. The parallel, perpendicular and corner reflectors have been investigated. The arrays are with symmetrical pentagonal dipoles as radiating elements operating at a second resonance. The symmetrical tapered feed network, which consists of impedance transformers, with Dolph-Chebyshev distribution of second order enables in theory side lobe suppression better than 44 dB at the frequency of 12 GHz in E-plane. Due to tolerances during fabrication of antenna array, the side lobe suppression of realized antenna will be less a few dB.**

Keywords – **Printed antenna arrays, side lobe suppression, tapered feed network.**

I. Introduction

The most telecommunication systems, such as indoor and outdoor wireless LANs, point-to-point and point-to-multipoint, and also radar microwave and millimetre-wave systems need antennas with low cost, low weight, smaller price of production, great reproducibility and the possibility of integration with other microwave circuits. The printed antennas have all these advantages unlike conventional antenna systems. Their main disadvantage is design printed antenna array with high side lobe suppression (SLS). SLS is defined for telecommunication systems (usually for microwave links) by international standards and recommendations [1]. Furthermore, this characteristic is crucial for evaluation radar class. This is expected because unsatisfying side lobe suppression can cause that reflected signal is got by lobe out of radar direction resulting in errors with disastrous consequences. Depending on the antenna class, the desired SLS in telecommunication systems is approximately 20 to 40 dB; in radar systems the required suppression is even higher.

There are several problems in realization of printed antenna arrays with relatively high SLS. The main of them are: tolerances in fabrication, mutual coupling between radiating elements, limitations in feasibility of feeding network realization, surface wave effect as well as parasitic radiation from a feeding network [2]. A relatively small number of publications dealing with this issue are available [2-6]. The mentioned limitations in realization of printed antenna arrays with relatively high SLS can be overcome using antenna arrays with printed dipoles, usually in a pentagonal shape (one half of them on one side and another half on the opposite side of the substrate) [7-10]. These dipoles operate on the second resonance and are fed by a symmetrical (balanced) microstrip line. The dipole's impedance varies with frequency very slow which is of crucial importance for arrays with high SLS [8]. Also, due to the fact that feed network is symmetrical and consists of symmetrical balanced microstrip lines, parasitic radiation from it is practically eliminated. The dipoles are axially placed decreasing their mutual impedance.

The paper introduces the printed antenna array with parallel, perpendicular and corner reflectors. In previous research [7-10], the antenna arrays with corner and cylindrical reflector were investigated. The presented antenna is designed for frequencies around 12 GHz. The antenna radiating elements are fed by tapered distribution enabling relatively high SLS. The feeding network with impedance transformers is specially investigated. The tapered distribution in feeding network is enabled by required pedestal (I_{max}/I_{min}). The transformers with greatest and the least impedance have the least and the biggest width. The impedance transformers with the least width are mechanically unreliable; they can easily be broken. Also, the impedance transformers with biggest width can have high modes. Besides the tolerance in fabrication, these limitations are the main problem of modelling feeding networks for printed antenna arrays with high SLS.

II. Dolph-Chebyshev 's Distribution

In order to decrease the side lobe levels, various tapered distributions are used in antenna arrays: cosine, cosine-squared, Gaussian, Taylor, Dolph-Chebyshev, etc. These distributions are chosen depending on the required side lobe attenuation, possible pedestal in distribution (Imax/Imin ratio), desired position of the radiating elements, distance between radiating elements, number of radiating elements and expected tolerances in fabrication.

Uniformly spaced linear arrays with nouniform excitation of the elements can use Chebyshev polynomials. A Chebyshev polynomial $T_m(x)$ of m-th order and an independent variable x is an orthogonal polynomial. In region $-1 \le x \le 1$, it contains equal ripples with amplitudes between +1 and −1. $T_m(x)$ outside the region (−1, +1) rises exponentially. $T_m(x)$ is actually expressed as [11]:

$$\mathrm{T}_m(x) = \left\{ \begin{array}{ll} \cos[m\cos^{-1}(x)], & |x| \le 1 \\ \left(\dfrac{x}{|x|}\right)^m \cosh(m\cosh^{-1}|x|), & |x| > 1 \end{array} \right\} \quad (1)$$

For zero and first order as well as for the recursion relation, there are:

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$$T_0(x) = 1 \tag{2}$$

$$T_1(x) = x \tag{3}$$

$$T_m(x) = 2xT_{m-1}(x) - T_{m-2}(x), \qquad m = 2,3,.... \tag{4}$$

These equations are used to create the Chebyshev polynomials of any order.

Dolph has found that maximum directivity for a given sidelobe level can be obtained using Chebyshev polynomials. Their equal ripples describe the sidelobes, and the exponential increase beyond $|x|=1$ gives the main lobe. The excitation distribution is symmetrical in the centre of the array.

The independent variable of the Chebyshev polynomial is:

$$x = x_0 \cos(\psi/2) \tag{5}$$

At $x=x_0$, the Chebyshev polynomial takes its maximum value R:

$$T_m(x_0) = R \tag{6}$$

$$x_0 = \cosh\left(\frac{1}{m}\right)\cosh^{-1} R \tag{7}$$

Nulls of $T_m(x)$ are located at:

$$x_k = \pm\cos\frac{(2k-1)\pi}{2m}, \tag{8}$$

where $k=1,2,\ldots,m$

$$\psi_k = \pm 2\cos\left(\frac{x_k}{x_0}\right), \tag{9}$$

By using the expression $z_k = e^{j\psi_k}$, you can find u_k, the excitation of the k-th element of the array from the following polynomial expression:

$$AF(\theta) = C\prod_{n=1}^{m}(z - z_n) = C\sum_{k=0}^{m} u_k z^k \tag{10}$$

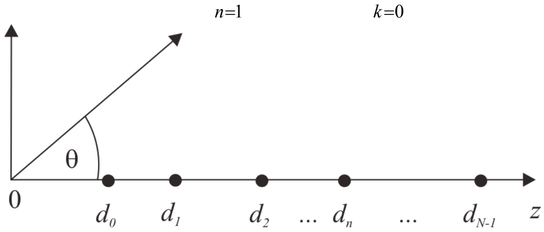

Fig. 1. Linear antenna array with N radiating elements

where C is constant. The array factor $AF(\theta)$ of the linear array shown in Fig. 1 depends only on the angle θ and is written as:

$$AF(\theta) = \sum_{n=0}^{N-1} u_n e^{j\beta d_n \cos\theta} \tag{11}$$

If the elements are equally spaced in terms of distance d, then Eq. 11 yields to:

$$AF(\theta) = \sum_{n=0}^{N-1} u_n e^{j\beta n d\cos\theta} = \sum_{n=0}^{N-1} u_n z^n \tag{12}$$

$$z = e^{j\beta d\cos\theta} \tag{13}$$

The order of the polynomial should be one less than the total number of elements of the array.

The distribution coefficients are calculated using LINPLAN program package [12] enabling Dolph-Chebyshev distribution of the second order with pedestal (I_{max}/I_{min}) of 19 dB. Under these conditions, the distribution coefficients shown in Table I have been obtained, which enable the highest side lobe level of -44.5dB.

III. Feeding Network

Binary symphysis feeding network has three stages. After the coaxial connector there is a BAL-UN for transition from conventional microstrip to symmetrical microstrip structure. In the first stage of the feeding network there is one T-junction, in the second stage – two T-junctions and in the third stage there are four T junctions. Between the first and the second as well as the second and the third stage, there is a linear tapering in order to transform characteristic impedance from 100Ω to 50Ω. Layout of the antenna array is presented in Fig. 2.

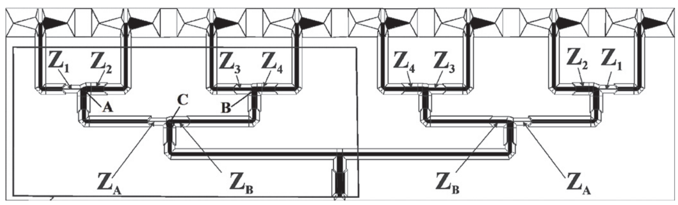

Fig. 2. Layout of printed antenna array with feeding network

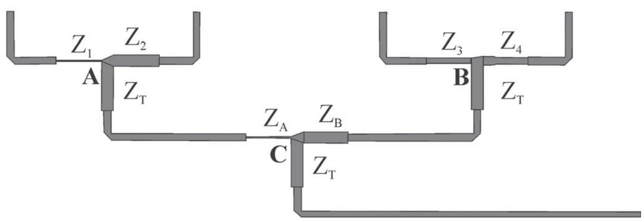

Fig. 3. The half of feeding network enabling Dolph-Chebyshev distribution of the second order with pedestal of 19 dB

TABLE I

THE DISTRIBUTION COEFFICIENTS FOR DOLPH-CHEBYSHEV DISTRIBUTION OF SECOND ORDER WITH PEDESTAL OF 19 dB

Calculated Dolph-Chebyshev distribution coefficients enabling the highest side lobe level of -44.5 dB								
Dipole No.	u_1	u_2	u_3	u_4	u_5	u_6	u_7	u_8
u	0.121	0.387	0.742	1	1	0.742	0.387	0.121
u (dB)	-18.34	-8.24	-2.59	0	0	-2.59	-8.24	-18.34
u – excitation intensity								

The feeding network was designed using a symmetrical (balanced) microstrip technique with $\lambda_0/4$ impedance transformers, assuming Z_d impedances at its ends. The corresponding layout is shown in Fig. 3. Characteristics and dimensions of the $\lambda_0/4$ impedance transformers with symmetrical microstrip lines have been calculated using TEM analysis. It can calculate relative power of radiating elements P_i, i=1,2,3,4:

$$P_1=(u_1)^2 \tag{14}$$

$$P_2=(u_2)^2 \tag{15}$$

$$P_3=(u_3)^2 \tag{16}$$

$$P_4=(u_4)^2 \tag{17}$$

The values u_1, u_2, u_3 and u_4 are taken from Table I. The ratio between relative feeding power of dipole D2 and relative feeding power of dipole D1 is:

$$P_2/P_1=(u_2/u_1)^2=k_{21} \tag{18}$$

Similarly, the ratio between relative feeding power of dipole D4 and relative feeding power of dipole D3 is:

$$P_4/P_3=(u_4/u_3)^2=k_{43} \tag{19}$$

Consequently, the ratio of input impedances of transformers Z_1 and Z_2 corresponding to dipole D1 and dipole D2 respectively is:

$$Z_1/Z_2=P_2/P_1=k_{21} \tag{20}$$

likewise, the ratio of input impedances of transformers Z_3 and Z_4 corresponding to dipole D3 and dipole D4 respectively is:

$$Z_3/Z_4=P_4/P_3=k_{43} \tag{21}$$

The point A is node where feeding lines for D1 and D2 dipoles separate. If the impedance at point A is the node impedance Z_S, then:

$$Z_S=\frac{Z_1 Z_2}{(Z_1+Z_2)} \tag{22}$$

respectively:

$$Z_S=\frac{k_{21}Z_2Z_2}{(k_{21}Z_2+Z_2)}=\frac{k_{21}Z_2}{k_{21}+1} \tag{23}$$

$$Z_1=k_{21}Z_2 \tag{24}$$

Therefore:

$$Z_2=\frac{Z_S(k_{21}+1)}{k_{21}} \tag{25}$$

$$Z_1=Z_S(k_{21}+1) \tag{26}$$

Similarly, the transformers for dipole D3 and for dipole D4, respectively impedance Z_3 and Z_4 can be calculated:

$$Z_4=\frac{Z_S(k_{43}+1)}{k_{43}} \tag{27}$$

$$Z_3=Z_S(k_{43}+1) \tag{28}$$

The separation between node A and node B occurs at point C using impedance transformers Z_A and Z_B. The feeding power for transformer Z_A is:

$$P_A=P_1+P_2 \tag{29}$$

while for transformer Z_B is:

$$P_B=P_3+P_4 \tag{30}$$

Subsequently:

$$\frac{P_B}{P_A}=\frac{P_3+P_4}{P_1+P_2}=k_{BA} \tag{31}$$

Corresponding to Eq. 25 and Eq. 26:

$$Z_B=\frac{Z_S(k_{BA}+1)}{k_{BA}} \tag{32}$$

$$Z_A=Z_S(k_{BA}+1) \tag{33}$$

The output of all impedance transformers are loaded with impedance of Z_d in ideal case. Their characteristic impedances, namely the impedances of symmetrical microstrip lines of $\lambda_0/4$ length, Z_i, i=1,2,3,4,A,B are equal:

$$Z_{ci}=\sqrt{Z_i Z_d} \tag{34}$$

Using Eq. 14-34, values u_1, u_2, u_3 and u_4 from Table I and with Z_s=100 Ω and Z_d=100 Ω, for dielectric substrate of 0.508 mm thickness, 2.1 relative dielectric permittivity, 41 MS/m conductivity of metal, 0 loss tangent and 0 mm conductor thickness, the parameters of impedance transformers have been obtained (Table II).

TABLE II

THE PARAMETERS OF IMPEDANCE TRANSFORMERS OF THE FEEDING NETWORK

Transformers of impedance	Width [mm]	Characteristic impedance [Ω]
Z_1	0.152	236.95
Z_2	1.232	74.08
Z_3	0.615	118.66
Z_4	0.97	88
Z_A	0.147	228.37
Z_B	1.245	74.36

The feeding network has been realized in programme package WIPL-D Microwave Pro [13]. Table III presents the values of excitation in the ends of feeding networks. It can be concluded that feeding network enables necessary excitations for antenna array dipoles. Also, phase differences are insignificant.

TABLE III

THE EXCITATIONS AND PHASE IN THE ENDS OF SIMULATION MODELS OF FEEDING NETWORK REALIZED IN WIPL-D MICROWAVE PRO

Dipole No.	$u_{1,8}$	$u_{2,7}$	$u_{3,6}$	$u_{4,5}$
excitation	0.08702	0.2782	0.532	0.715
phase (°)	-6.55	-5.847	-6.2	-5.78

IV. Concept of Printed Antenna Array with High Side Lobe Suppression

The antenna array consists of four parts: (1) the axial array of eight radiating elements, (2) feeding network and (3) bal-un – part (1), (2) and (3) are printed on the same dielectric substrate and (4) reflector (parallel, perpendicular or corner).

Radiating elements of the antenna array are pentagonal dipoles which are printed on a dielectric substrate of 0.508 mm thickness end ε_r=2.1. One half of each dipole is placed on one side and another half on the opposite side of the dielectric substrate. Symmetrical (balanced) microstrip line is used as a feeding structure, because dipoles are electrically symmetrical elements. Differently from conventional dipoles that operate on the first resonance, these dipoles operate on the second resonance.

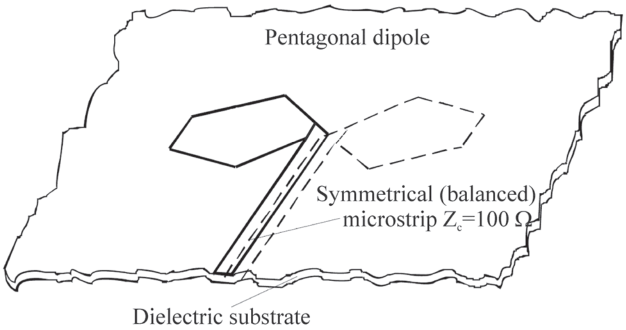

Fig. 4. Pentagonal dipole

Modification of pentagonal dipole's dimensions enables us to change impedance on the second resonance in a relatively wide range (Fig. 4). In our case, we have adjusted dimensions of pentagonal dipoles in order to obtain dipole impedance of Z_d=100Ω at the centre frequency (12 GHz) taking into consideration the reflector influence and symmetrical microstrip feeding line of impedance Z_c=Z_d.

Along axis there is an array of 8 axially placed pentagonal dipoles. Distance between the dipoles is $0.77\lambda_0$=19.25 mm (at the centre frequency) in order to obtain maximum side lobe suppression [12]. Also, with such distance between axial dipoles, mutual coupling is not oversize making the design and optimization of the antenna array easier.

There are three steps in design antenna array with high side lobe suppression:

a) antenna array dipoles are fed by generators in their centres – there is not influence of feeding lines;
b) antenna array dipoles are fed by generators in the end of feeding lines - there are both influence of feeding lines and influence of reflector;
c) antenna array dipoles are fed by feeding network with transformers of impedance.

A. Antenna Array with Parallel Reflector

The antenna array with parallel reflector is presented in Fig. 5. The reflector is on distance $\lambda_0/4$ from antenna array. Its dimensions are 304mmx52.25mm.

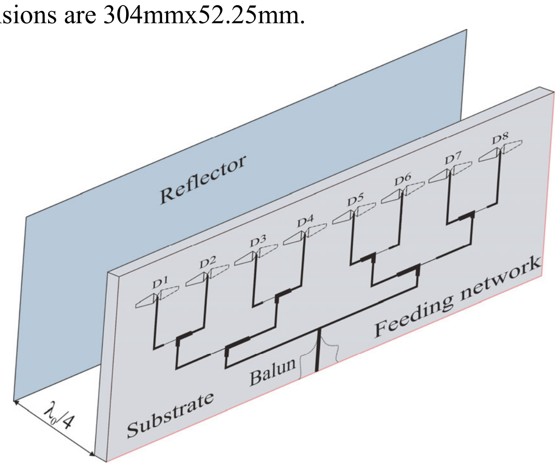

Fig. 5. Printed antenna array with parallel reflector

The radiation pattern of simulation model of antenna array with parallel reflector is presented in Fig. 6 [13]. The gain is about 14 dB. The side lobe suppression varies in different steps of design. When the antenna array dipoles are fed by generators in their centres or by generators in the end of feeding lines, the side lobe suppression is about 43 dB. When the antenna array and feeding network are connected, SLS significantly decreases and it is about 20 dB.

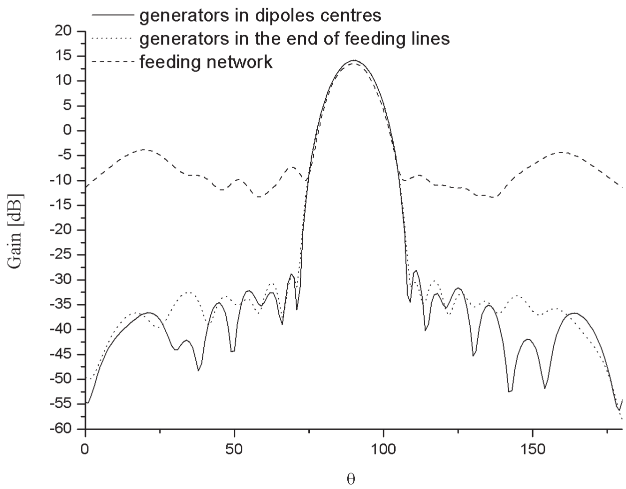

Fig.6. The radiation pattern of simulation model of antenna array with parallel reflector

B. Antenna Array with Perpendicular Reflector

The Fig.7 shows antenna array with perpendicular reflector. The reflector is on distance $\lambda_0/4$ from axis where antenna array dipoles are suited. Its dimensions are 286mmx40mm.

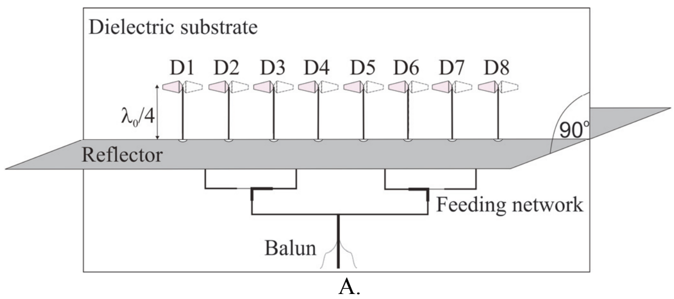

Fig.7. Printed antenna array with perpendicular reflector

Its radiation pattern of simulation model is shown in Fig. 8 [13]. Similarly as previous antenna array with parallel reflector, the side lobe suppression of antenna array with perpendicular reflector change in different steps of design. In case when dipoles are fed by generators in their centres or by generators in the end of feeding lines, the side lobe suppression is very close to ideal theoretical value, about 43 dB. But, when dipoles are fed by feeding network, side lobe suppression is about 30 dB. The gain is constant and independent on design step; it is about 13.5 dB.

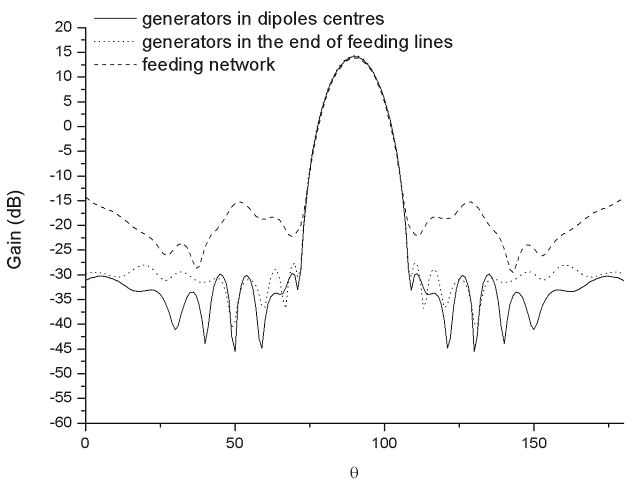

Fig. 8. The radiation pattern of simulation model of antenna array with perpendicular reflector

C. *Antenna Array with Corner Reflector*

The antenna array with corner reflector is shown in Fig.9. The reflector is on distance $\lambda_0/2$ from antenna array dipoles. The reflector plates form angle of α=90°. The reflector has length of 290 mm while its width is 70.71 mm.

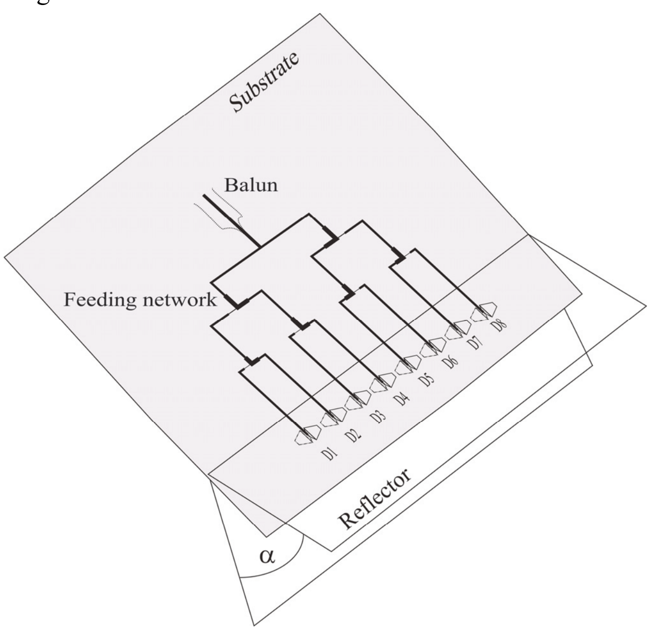

Fig. 9. Printed antenna array with corner reflector

The radiation pattern of simulation model of antenna array with corner reflector is shown in Fig. 10 [13]. The gain of antenna array with corner reflector is biggest; it is about 19 dB. Also, the radiation pattern when dipoles are fed by feeding network is the closest to the radiation pattern when dipoles are fed by generators in their centres or by generators in the end of feeding lines (41 dB). The simulated values of side lobe suppression of antenna array with dipoles fed by feeding networks is about 35 dB for lobes closest to main lobe; distant lobe have less suppression (about 27 dB) although it can be consequence of parasite coupling of radiations elements and feeding network.

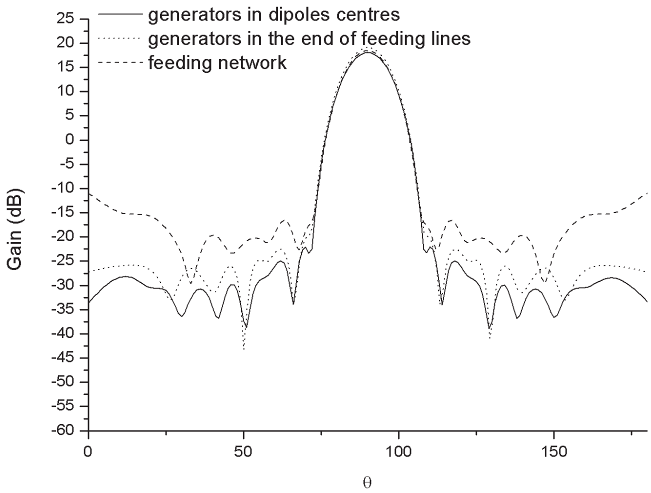

Fig. 10. The radiation pattern of simulation model of antenna array with corner reflector

V. Conclusion

The paper investigates side lobe suppression of printed antenna arrays with parallel, perpendicular and corner reflectors. SLS, satisfactory for most microwave telecommunication and especially radar systems, is hardly achievable with conventional microstrip antenna arrays with patches due to their narrow bandwidth, quick variation of impedance with dimensions change, parasitic radiation from the feed network, and surface wave effect. Antenna structure with printed pentagonal dipoles forming the array is proposed. The dipoles operate on the second resonance.

The distribution coefficient are determined to enable Dolph-Chebyshev distribution of the second order with pedestal I_{max}/I_{min}=19dB. In ideal case, obtained SLS value is bigger than 44 dB. Three steps in design of antenna array with high side lobe suppression are analysed: dipoles fed by generators placed in their centres, dipoles fed by generators placed in the end of feeding lines and dipoles fed by feeding network. Simulated SLS value is in range from 41 dB to 43 dB when dipoles are fed by generators in their centres or by generators in the end of feeding lines. When the antenna array dipoles are fed by feeding network with transformers of impedances, SLS significantly decreases.

It can conclude that reason for significant decrease of side lobe suppression of antenna array fed by feeding network is parasite coupling of radiations elements and feeding network. This parasite coupling is the biggest for parallel reflector: there are not any obstacles between antenna array and feeding network – they are in the same plane. The parasite coupling is less for perpendicular reflector because it separates antenna array from feeding network. Further, the parasite coupling is the least for corner reflector since it significantly close the antenna array decreasing the influence of feeding network.

Also, the considered parasite coupling for antenna arrays with similar dipoles fed by feeding network enabling uniform distribution does not influence significantly radiation pattern [14]. But, for antenna arrays with tapered distribution, especially for antenna array with great pedestal, the electromagnetic insulation of feeding network must be considered. It can assume that the use of corner reflector with small angle between reflector plates or cylindrical-parabolic reflector will totally suppress the parasite coupling between antenna array and feeding network [15]. Further, possible solution for antenna array with perpendicular reflector is to isolate feeding network using sheet metal that eliminates the parasite coupling.

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