Principles of Synthesis of Steerable Reflect-array Antennas

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Abstract—The synthesis of steerable reflect-array antennas, as a synthesis of any antenna, should be realized by solving two problems: external antenna problem and internal antenna problem. The first one includes the investigation of the antenna radiation pattern. The second one concerns a design of the structure providing the required amplitude-and-phase distribution along the antenna aperture. The first problem is based on the theory of antenna array. The distance between the small reflectors and geometry of the array are responsible for the directivity, the beam width, and the side lobe level of the antenna. The internal antenna problem consists of finding the phase shift required for each small reflector. Remarkable feature of a tunable reflector made as a microstrip vibrator or a patch in combination with a tunable device is that the almost 360° phase shift of the reflected wave can be provided with only one tunable device (varactor diodes or ferroelectric tunable capacitors). Commonly, simulation of the phase shift required is performed with a numerical technique. The design of reflect-array antenna can be sufficiently simplified, if the simulation by the numerical technique is amplified with a correct analytical model.

1. Introduction

Reflect-array antennas are being developed during many years [1–3]. Recently the reflect-arrays were suggested as structures with an electronically steered radiation pattern [4, 5]. Such a steerable reflect-array antenna can be used as a low cost version of a phased array antenna for a wide commercial application. The synthesis of steerable reflect-array antennas, as a synthesis of any antenna, should be realized by solving two problems: external antenna problem and internal antenna problem. The first one includes the investigation of the antenna radiation pattern. The second one concerns a design of the structure providing the required amplitude-and-phase distribution along the antenna aperture. Any reflect-array antenna consists of primary radiator or illuminator and a reflecting surface. The primary radiator provides the reasonable amplitude distribution with a minimum spillover loss. Sophisticated design technique was used to diminish a constructive space occupied by the radiator [6]. The reflected surface is covered by a large number of small reflectors in form of microstrip vibrators or patches. The vibrators or patches are connected with tunable devices (varactor diodes [4] or ferroelectric tunable capacitors [7]), which serve for controlling the phase of the wave reflected by each small reflector. The goal of this paper is to characterize the main stages of synthesis and design of a steerable reflect-array antenna.

2. External Antenna Problem

The scheme of a typical reflect-array antenna is shown in Fig. 1. The system of patches provides transformation of a spherical wave front of the primary radiator into the plane wave front in the antenna aperture. The main beam width of an antenna and the directivity of the antenna, which are required, determine the size of the antenna aperture.

In Fig. 2, radiation pattern of a circle aperture with homogeneous field distribution as a function of a generalized angle function u is shown [8]. ($u = kR\sin\theta, k = 2\pi/\lambda$, where λ is wavelength is free space, R is radius of the circle aperture). In the case of homogeneous field distribution the main beam width in degree is $\Delta\theta^\circ = 59 \cdot \lambda/2R$ and level of the first side lobe is -18 dB. The antenna directivity is $D = 4\pi(\pi R/\lambda)^2$. If the field distribution decays to edge of the aperture, the main beam width is higher and the directivity is lower, the first side lobe level being decreased.

Forming the radiation pattern is drastically influenced by the inhomogeneity of the phase distribution over the radiating aperture. In the case of the reflect-array antennas the phase inhomogeneity can be provoked by inaccuracy of realization of size and position of the elementary radiators (patches). Let us consider a statistical estimation of the inaccuracy of the array realization [9].

The array radiation pattern can be presented as follows:

$$\Phi(\theta, \varphi) = \sum_{i=1}^{m} A_{0,i}\varphi_i(\theta, \varphi) \tag{1}$$

where $A_{0,i}$ is the optimized current amplitude of i-th elementary radiator, $\varphi_i(\theta, \varphi)$ is the pattern of i-th elementary radiator taking into account the position of the center of its phase pattern, m is the number of elementary

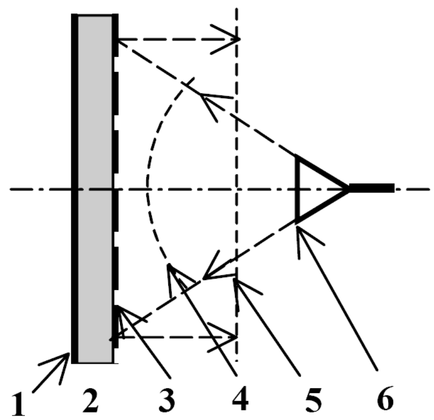

Figure 1: Scheme of a typical reflect-array antenna with: ground plane (1), dielectric layer (2), patch reflector (3), spherical wave front (4), plane wave front (5), primary radiator (6).

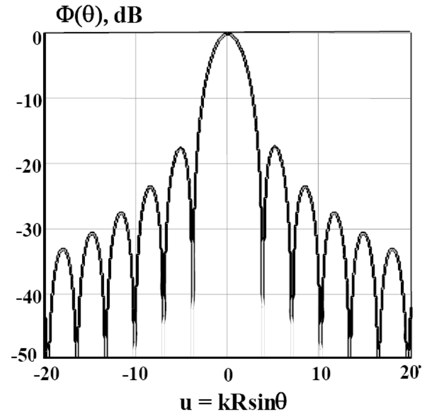

Figure 2: Radiation pattern of a circle aperture as a function of generalized angle function u.

radiator in the array.

If the real current distribution differs from the optimized one

$$A_i = A_{i,0} + \Delta_i, \tag{2}$$

the mean-square-error of amplitude/phase distribution over whole array is

$$\beta_{mse} = \left| \sum_{i=1}^{m} |\Delta_i|^2 / \sum_{i=1}^{m} |A_i, 0|^2 \right|^{1/2}. \tag{3}$$

The value β_{mse} can be used to find decay of the array directivity (by the factor g) and increase of the side lobe by ξ_{sl}:

$$g = \frac{1}{1+\beta_{mse}^2}, \qquad \xi_{sl} = \frac{3\beta_{mse}}{\sqrt{m}} \tag{4}$$

Let us suppose for example: $m = 2000$, $|A_{i,0}| = 1$ for all i, 30% of radiators are characterized by the phase error of 90°. Simple calculation gives $\beta_{mse} \cong 0.85$, $g = 0.58$ (decrease of the directivity in 2.4 dB), $\xi_{sl} = 0.06$ (increase of the side lobe level up to -12 dB).

3. Internal Antenna Problem

The primary radiator provides feed of the reflector patches with amplitude distribution required and with a minimum spillover loss. The efficiency of the primary radiator can be determined by the following equation:

$$\eta(\rho,\gamma) = \int_0^{\alpha(\rho)} [F(\theta,\gamma)]^2 \sin\theta d\theta \Big/ \int_0^{\pi/2} [F(\theta,\gamma)]^2 \sin\theta d\theta, \qquad F(\theta,\gamma) = [\cos(\theta)]^y \tag{5}$$

where $\rho = F/2R$, $\cot(\alpha(\rho)) = 2\rho$, F is the focal distance of the patch reflector, R is the radius of the aperture. $F(\theta,\gamma)$ is the radiation pattern of the primary radiator, the exponent γ determines the directivity of the primary radiator.

Table 1 illustrates the efficiency of the primary radiator expressed in dB. The data presented are followed by the conclusion that the preferable values of F and γ are $F \leq R, \gamma \geq 1$.

The phase of waves reflected by the patch mirror has to meet two principal demands: 1) Transformation of spherical wave front given by the primary radiator into a plane wave, 2) Providing phase gradient along the array, which corresponds to the beam deflection required.

The distance between the patches lies in the range $s = (0.63 - 0.67)\lambda$. If the linear size of the array (2R) is much higher than the wavelength (λ), the total phase shift change along the array can be much higher than 360°. In this case the phase distribution is corrected by reset of the phase by n times 360° where $n = 1, 2, 3, \ldots$ Such a phase correction is well known as a characteristic feature of Fresnel mirror.

The phase shift of the wave reflected by a patch depends on the patch size [1–4, 6]. That is illustrated by Fig. 3 for the operational frequency $f = 10$ GHz. Commonly, simulations of the required phase shift are performed with a numerical technique. The result of the phase shift simulation is used for designing the reflect-array antenna. In photo (Fig. 4) one can see the distribution of the patch sizes over the mirror array.

Table 1: The primary radiator efficiency $\eta(\rho, \gamma)$ in m dB.

ρ	0.2	0.3	0.4	0.5	0.6
$\gamma = 1.5$	-0.09	-0.31	-0.71	-1.21	-1.82
$\gamma = 1.0$	-0.23	-0.63	-1.20	-1.90	-2.60
$\gamma = 0.5$	-0.65	-1.22	-2.18	-3.00	-3.92

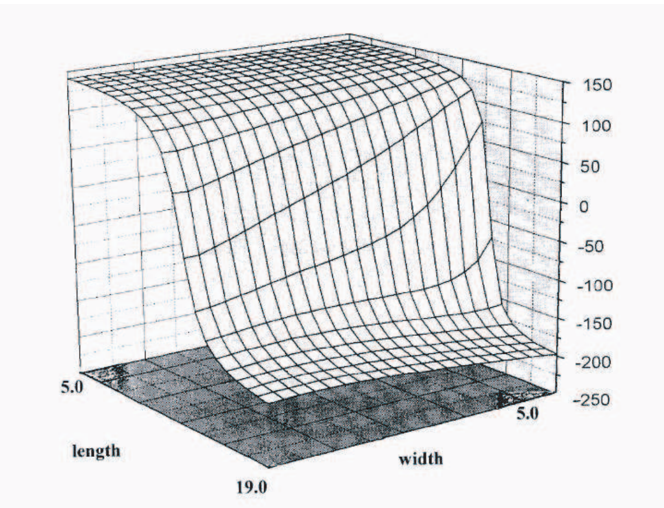

Figure 3: The phase shift of wave reflected by a patch as a function of length and width of the patch in mm for dielectric constant of the substrate $\varepsilon_{\text{sab}} = 1.06$.

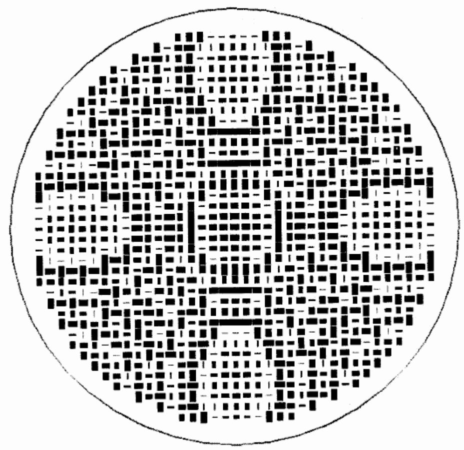

Figure 4: Distribution of the patch positions and sizes in array.

4. The Steerable Patch Array

The phase shifts (Fig. 3) and an appropriate design of the patch array (Fig. 4) correspond to a nonsteerable array with a fixed position of the main beam. In order to control the position of the main beam of radiation pattern, the phase shift of the reflection coefficient of each patch in the array should be controlled. The tunable devices (semiconductor varactor diodes [4] or ferroelectric tunable capacitors [7]) should be included in each patch. The state of the tunable device serves for controlling the phase of wave reflected by each small reflector. Remarkable feature of a tunable reflector made as a microstrip vibrator or a patch in combination with a tunable device is that the 360° phase shift of the reflected wave can be provided with only one tunable device. It should be reminded that for a realization of a digital transmission-type phase shifter one needs at least 8 tunable devices [9]. The optimum phase shift of each tunable reflector must be found as a result of a correct simulation and can be realized by applying to each tunable device the appropriate biasing voltage. The result of the phase shift simulation must be included in the driving program of the biasing voltage controller.

The problems mentioned above can be sufficiently simplified, if the simulation by the numerical technique is replaced by using a correct analytical model. The problems mentioned above can be sufficiently simplified, if the simulation by the numerical technique is replaced by using a correct analytical model. A scheme of a tunable patch is shown in Fig. 5. The sketch drawn in Fig. 5(a) presents a single patch located in a virtual waveguide confined by electrical and magnetic walls. The patch is considered as a microstrip vibrator loaded by the tunable capacitor. The microstrip is formed on a dielectric substrate with a conductive ground plane. Microwave current in the vibrator is induced by the incident wave. The current distribution along the vibrator is found on a basis of solution to telegraph equations using the method of induced electromotive forth [8]. The equivalent schematic is shown in Fig. 5(b). Two type of resonances can be observed in the circuit shown in Fig. 5(b). Firstly, fundamental resonance, which corresponds to infinite impedance of the vibrator, which

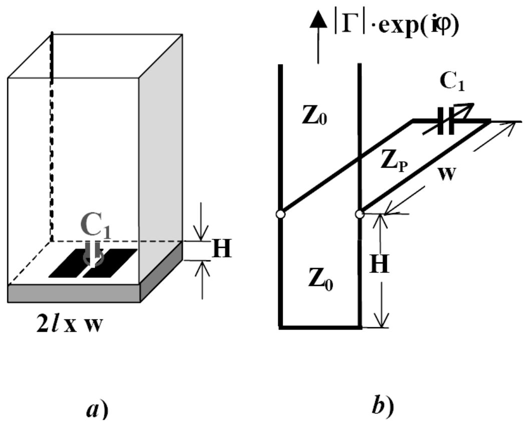

Figure 5: Scheme of a tunable patch. a) Single patch located in a virtual waveguide confined by electrical an magnetic walls and b) Equivalent schematic.

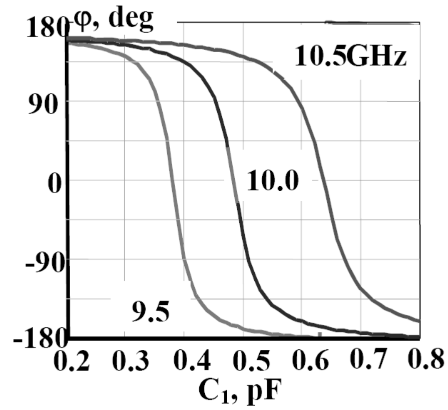

Figure 6: Simulations of the reflected wave phase shift in the framework of the schematic analytical model.

is presented by the transmission line stub with length l and characteristic impedance Z_P. In this case one observe the reflection from the ground plane through the substrate; the phase of the reflection coefficient is near to $\pm 180°$. Secondly, anti-resonance, which corresponds to parallel resonance of two transmission line stubs (l, Z_P) and (H, Z_0). In this case one observes the zero phase of reflection from the plane, in which the vibrator is located. Thus, change of capacitance of the tunable capacitor makes possible to obtain the change of the reflection phase approximately in the range $+180 \ldots 0 \ldots -180$ degrees. In Fig. 6, results of simulations in the framework of schematic analytical model are presented [10]. The following data were taken: the square virtual waveguide $20 \times 20\,\text{mm}^2$ with the substrate $H = 1\,\text{mm}$, $\varepsilon_S = 3.0$; dimensions of the patch: $w = 2\,\text{mm}$, $2l = 9\,\text{mm}$, operational frequency $f = 9.5 - 10.5\,\text{GHz}$.

Simulations based on the schematic analytical model can be used for the design of a steerable reflect-array and for developing a driving program of the biasing voltage controller. Some fitting parameters of the analytical model can be found using a comparison with the full-wave analysis simulation.

5. Conclusion

The development of simple and correct theoretical models and elaboration of material components of reflect-array antenna is an urgent problem, which solution is important for realization of a cheap steerable antenna for mass production.

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