STUDY OF A FINITE LINEAR WAVEGUIDE ANTENNA ARRAY WITH DIELECTRIC PLUGS

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A finite waveguide antenna array of open ends of the waveguides, which are surrounded by a metal screen, is under consideration. The influence of the permittivity and the height of dielectric plugs on the modulus of the reflection coefficient in waveguides of the finite antenna array is studied. Dielectric plugs with different values of permittivity are considered. It is shown that dielectric plugs effectively match the impedance of the antenna array for the case of a slight deviation of the beam from the normal to the array.

Keywords: antenna array, dielectric plugs, reflection coefficient, permittivity, overlapping regions.

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1. Introduction

When designing an antenna array, it is very important to match the impedance of the antenna array over the entire sector of scanning angles [1, 2]. The active impedance of each element in a phased array changes substantially with scan angle due to mutual coupling [3]. Therefore, a key challenge in the design of wide-angle scanning phased array is to achieve wide-angle impedance matching. Various devices can be used as matching elements, depending on the design of the antenna array. These may be design features of the supply probe-fed system [4] or special radomes that are closely spaced to the radiating aperture of a phased array [5]. One of the matching options can be dielectric plugs or artificial dielectric layers with low losses [6]. It should be noted that to avoid losses, the value of the permittivity should be small.

Real-time location (RTLS) allows a spatial and time related tracking of objects in their environment [7]. An increasing number of technologies and providers are available nowadays. Besides applications in e.g., healthcare and general logistics, RTLS bear also interesting potentials in context of factories [7]. In RTLS technology, a linear antenna array of waveguides can be used as radiators.

Indoor localization has recently witnessed an increase in interest, due to the potential wide range of services it can provide by leveraging Internet of Things, and ubiquitous connectivity. Different techniques, wireless technologies and mechanisms have been proposed in the literature to provide indoor localization services to improve the services provided to the users [8]. In this technology, a linear waveguide antenna array can be used.

For the organization of wireless communication generation 5 G uses antenna arrays of various designs. The most widespread are two-dimensional antenna arrays made based on microstrip technology. It is known that terrestrial application of radio access technologies 5 G can be combined with a system of low-orbit satellites [9]. In this case, antenna arrays based on waveguides have an advantage. A common problem with antenna arrays, as mentioned above, is the change in input impedance depending on the scan angle. Such a change in impedance is quite difficult to compensate with the help of matching circuits. Therefore, this problem requires detailed precise consideration.

2. Formulation of the problem

Let us consider the cross section of a finite antenna array of plane-parallel waveguides for the case of scanning in the E-plane (the electric field strength vector is directed along the Oy axis), Fig. 1.

We conditionally divide electromagnetic field definition domain into two overlapping regions: regions *A(j)*, which includes *j* endless waveguides $(j-1)p \le y \le w+(j-1)p,\ j=1,2...;\ -\infty \le z \le \infty$; region *C* is the half-space above the metal screen $-\infty \le y \le \infty,\ 0 \le z \le \infty$.

Let us consider an electrodynamic problem based on the method of overlapping regions [10]. We use the second Green's formula for the component of the magnetic field strength vector H_x, which does not depend on the x coordinate, and the continuity condition for this component at the boundaries of the selected regions.

Then we obtain a system of integral representations for the total fields of the regions *A* and *C*:

$$H_x^A(y,z)=\sum_{j=1}^{J}H_x^{A(j)}(y,z)=\sum_{j=1}^{J}\{-\int_0^{\infty}[G^{A(j)}(y,z;y'=(j-1)p,z')\left.\frac{\partial H_x^C(y',z')}{\partial y'}\right|_{y'=(j-1)p}-$$

$$-G^{A(j)}(y,z;y'=w+(j-1)p,z')\left.\frac{\partial H_x^C(y',z')}{\partial y'}\right|_{y'=w+(j-1)p}]dz'+H_{x\,exc}(y,z)\}; \qquad (1)$$

$$H_x^C(y,z)=\sum_{l=1}^{J}\{-\int_{(l-1)p}^{w+(l-1)p}G^C(y,z;y',z'=0)\left.\frac{\partial H_x^{A(l)}(y',z')}{\partial z'}\right|_{z'=0}dy\}$$

Here $G^{A(j)}$ $(j=1,2...J)$ are the Green's functions of the regions; G^C is the Green's function of the region *C*; $H_{x\,exc}^{A(j)}$ is the field strength of TEM waves in waveguides.

Function $G^{A(j)}$ $(j=1,2...J)$ has the form:

$$G^{A(j)}(y,z;y',z')=\sum_{g=0}^{\infty}\varphi_g^{(j)}(y)\varphi_g^{(j)}(y')\frac{1}{2\gamma_g}e^{-\gamma_g|z-z'|},$$

here γ_g are propagation constants in waveguides; $\varphi_g^{(j)}$ is an orthonormal system of transverse eigenfunctions of the *j*-th waveguide, which can be represented in the following form:

$$\varphi_g^{(j)}=\sqrt{\frac{2-\delta_{0g}}{W}\cos\left[\frac{g\pi}{W}\left(y-(j-1)p\right)\right]}$$

where δ_{0g} is the Kronecker delta and *W* is a waveguide width.

The Green's function of region *C* has the form [11]:

$$G^C(y,z;y',z')=-\frac{i}{4}\left\{H_0^{(2)}(k\sqrt{(y-y')^2+(z-z')^2})+H_0^{(2)}(k\sqrt{(y-y')^2+(z+z')^2})\right\},$$

here $H_0^{(2)}$ is the Hankel function of the second kind of order zero.

Let us exclude the equation for the region *C* from the set of integral representations. Using the projection method, we obtain a set of algebraic equations.

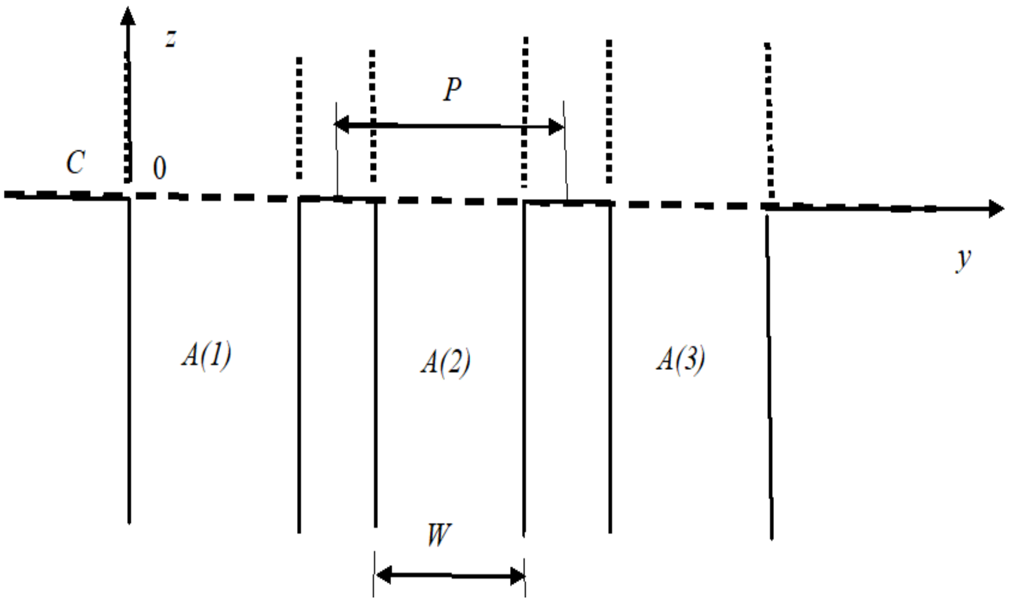

Fig. 1. A finite antenna array of plane-parallel waveguides.

Dielectric plugs in waveguides are used to match the antenna array and free space. They are placed from the aperture surface (z = 0) to the position $z = -h_d$. Thus, the height of the dielectric plugs is h_d. To consider the effect of dielectric plugs with permittivity ε, it is necessary to make some changes in the first equation of set (1).

3. Results and discussion

A finite linear antenna array consisting of five elements is considered. A study of the influence of the height of the dielectric plugs on the value of the modulus of the reflection coefficient at a fixed value of the permittivity was carried out. The results of this study for the value of dielectric constant $\varepsilon = 2.08$ are shown in Fig. 2. From Fig. 2, the modulus of the reflection coefficient takes two minima. The first minimum can be approximately observed at the value of the height of the dielectric plug $h_d = 0.43\Lambda_d$, and the second one – at the value of $h_d = 0.94\Lambda_d$. Here Λ_d is the wavelength in a dielectric-filled waveguide. That is, it can be assumed that the distance between these minima is $\Delta h_d = 0.51\Lambda_d$. It is obvious that an increase in the value of h_d. leads to an increase in the loss of electromagnetic energy in the dielectric, while the matching properties of the dielectric plugs do not improve. Therefore, for the value of the permittivity $\varepsilon = 2.08$, the optimal height of the dielectric plug can be the value of $h_d = 0.43\Lambda_d$. And only for the case when there is a need to strengthen the mechanical properties of the radiator design, the height of the dielectric plug can be $h_d = 0.94\Lambda_d$.

Studying a finite antenna array with dielectric plugs that have a permittivity of $\varepsilon = 3$ gives the results shown in Fig. 3. From Fig. 3, the modulus of the reflection coefficient takes two minima. The first minimum is observed at the value of the height of the dielectric plug $h_d = 0.45\Lambda_d$, and the second one – at the value of $h_d = 0.95\Lambda_d$. The difference between the two minima is $\Delta h_d = 0.5\Lambda_d$.

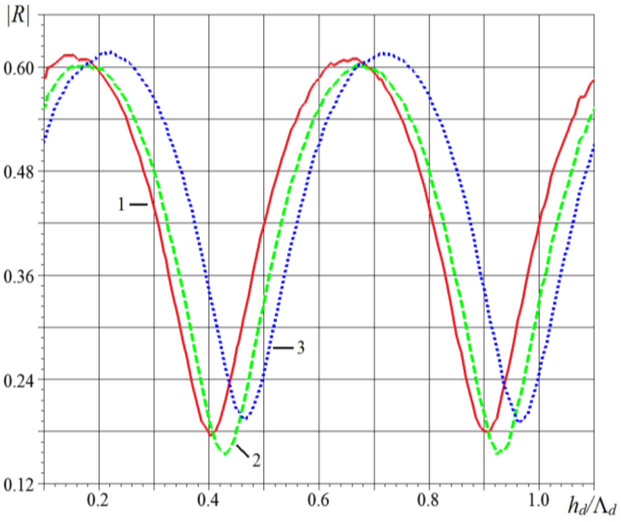

Fig. 2. Dependence of the module of the reflection coefficient on the height of the dielectric plugs h_d at different phase shifts between the waveguides: 1 - $\psi = 0°$; 2 - $\psi = 45°$; 3 - $\psi = 90°$.

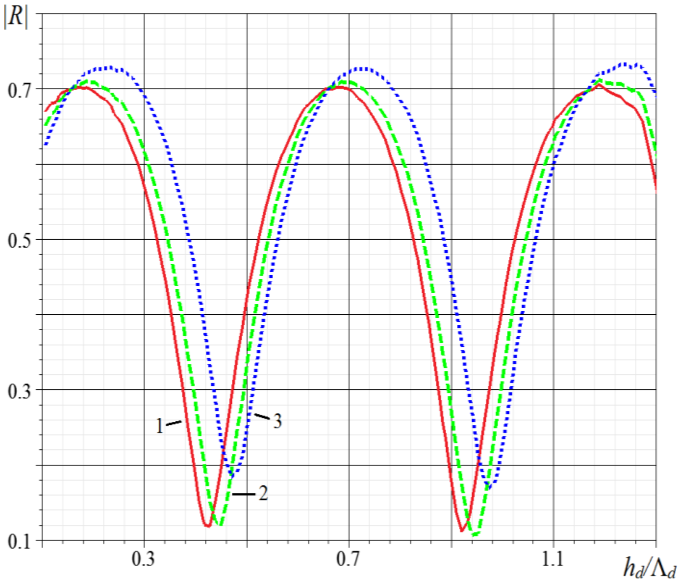

Fig. 3. Dependence of the module of the reflection coefficient on the height of the dielectric liners h_d at different excitation phases: 1 - $\psi = 0°$; 2 - $\psi = 45°$; 3 - $\psi = 90°$.

The dependence of the reflection coefficient modulus in the central element of the antenna array on the scanning angle for an array that scans in the *E*-plane was considered with different values of the dielectric plug permittivity. The results of this study are shown in Fig. 4. From Fig. 4, in the range of phase shifts from 0° to 90°, the antenna array with dielectric plugs with permittivity $\varepsilon = 2.08$ has lower values of the reflection coefficient modulus than the array without dielectric plugs. But in the range of phase shifts from 90° to 180° it is better to use an antenna array without dielectric plugs.

Also, in the range of phase shifts from 0° to about 100°, an antenna array with dielectric plugs with permittivity $\varepsilon = 3$ has significantly lower values of the reflection coefficient modulus than an antenna array without dielectric plugs. But when scanning in the range of phase shifts from 100º to 180º, it is better to use an antenna array without dielectric plugs.

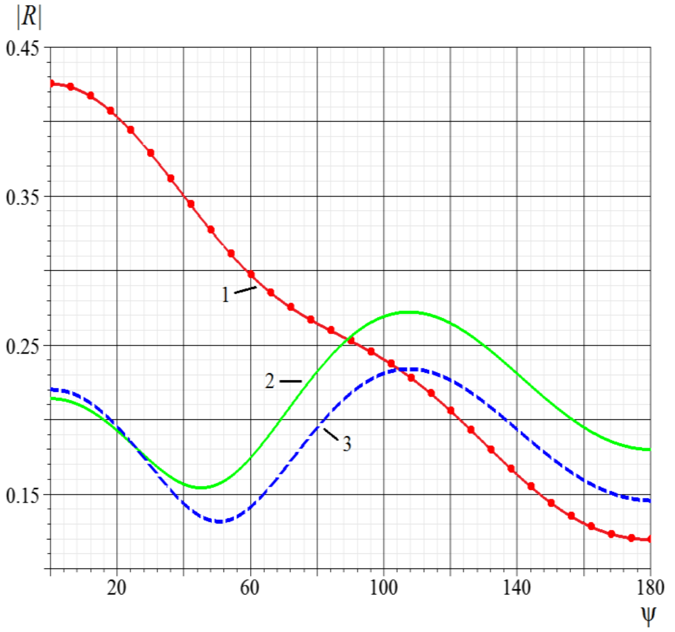

Fig. 4. Dependence of the reflection coefficient modulus on the phase shift:
1 - ε = 1; 2 - ε = 2.08; 3 - ε = 3.

4. Conclusions

It can be concluded that, in general, dielectric plugs in a finite antenna array provide additional coupling between the antenna array and free space compared to a finite antenna array without dielectric plugs. However, this conclusion is valid for an insignificant deviation of the beam from the normal to the plane of the antenna array. For cases of significant beam deviation, an antenna array without dielectric plugs is preferable.

References

1. **Hansen, R. C.** Standing waves in scan impedance *E*-plane finite array / R. C. Hansen, D. Gammon // Microwave Optical Technology Letters. – 1996. – Vol. 11. – P. 26 – 32.

2. **Tyagi, Y.** Broadband impedance matching of narrowband slotted waveguide array antenna / Y. Tyagi, P. Mevada, S. Chakrabraty, M. Mahajan // Proceedings of IEEE Indian Conference on Antennas and Propagation. – 2018. – P. 1 – 5.

3. **Xia, R.** Wide-angle scanning phased array using an efficient decoupling network / R. Xia, S. Qu, P. Li, D. Yang, S. Yang, Z. Nie // IEEE Transactions on Antennas and Propagation. – 2015. – Vol. 63, No. 11. – P. 5161 – 5165.

4. **Arand, B. A.** Design of a phased array in triangular grid with an efficient matching network and reduced mutual coupling for wide-angle scanning / B. A. Arand, A. Bazrkar, A. Zahedi // IEEE Transactions on Antennas and Propagation. – 2017. – Vol. 65, No. 6. – P. 2983 – 2991.

5. **Bianchi, D.** Element-independent design of wide-angle impedance matching radomes by using the generalized scattering matrix approach / D. Bianchi, S. Genovesi, M. Borgese, F. Costa, A. Monorchio // IEEE Transactions on Antennas and Propagation. – 2018. – Vol. 66, No. 9. – P. 4708 – 4718.

6. **Syed, W.H.** Wideband wide-scan planar array of connected slots loaded with artificial dielectric superstrates / W.H. Syed, D. Cavallo, H.T. Shivamurthy, A. Neto // IEEE Transactions on Antennas and Propagation. – 2016. – Vol. 64, No. 2. – P. 543 – 553.

7. **Thiede, S.** Real-time locating systems (RTLS) in future factories: technology review, morphology and application potentials / S. Thiede, B. Sullivan, R. Damgrave, E. Lutters // Procedia CIRP. – 2021. – Vol. 104. – P. 671 – 676.

8. **Zafari, F.** A survey of indoor localization systems and technologies / F. Zafari, A. Gkelias, K.K. Leung // IEEE Communications Surveys & Tutorials. – 2019. – Vol. 21, No. 3. – P. 2568 – 2599.

9. **You, L.** Massive MIMO transmission for LEO satellite communications / L. You, K.-X. Li, J. Wang, X. Gao, X.-G. Xia, B. Ottersten // IEEE Journal on Selected Areas in Communications. – 2020. – Vol. 38, No. 8. – P. 1851 – 1865.

10. **Gnilenko, A.B.** Method of overlapping regions for solving electromagnetic problems / A.B. Gnilenko, V.I. Magro // Proceeding of XXIInd International seminar/workshop on direct and inverse problems of electromagnetic and acoustic wave theory. – 2017. – P. 36 – 41.

11. **Tai, C.T.** Dyadic Green’s functions in electromagnetic theory / C.T. Tai. – New York: IEEE Press.– 1994. – 343 p.