Int. J. Electron. Commun. (AEÜ) 70 (2016) 578–583

Contents lists available at ScienceDirect

International Journal of Electronics and Communications (AEÜ)

journal homepage: www.elsevier.com/locate/aeue

Optimum design of the array of circumferential slots on a cylindrical waveguide

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ARTICLE INFO

Article history:
Received 22 June 2015
Accepted 16 January 2016

Keywords:
Array
Slot arrays
Cylindrical waveguide slot array
Cylindrical waveguide
Circumferential slot array
Method of least squares (MLS)

ABSTRACT

In this paper the design equations for an array of circumferential slots on a cylindrical waveguide are obtained, following the procedure introduced by Elliott for slots on rectangular waveguides. The method of least squares is then developed for the synthesis of radiation patterns with specified side lobe levels (SLL) and also impedance matching of the array input. The minimization of the error function is achieved by the combination of genetic algorithm (GA) and conjugate gradient (CG) method. Several numerical examples are presented as illustrations of the proposed synthesis method. The results of array designs by the method of least squares are verified by Ansoft HFSS computer simulation software.

1. Introduction

The first study of radiation from an aperture on an infinite metallic plane was reported by Silver and Saunders in 1950, who derived a formula for the generated external field [1]. Bailin derived formulas for the radiation from axial and circumferential rectangular slots on a conducting circular cylinder in 1955 [2] and compared his results with measurement data. Golden et al. investigated some approximate techniques for the determination of mutual couplings among slots on cylindrical surfaces in 1974 [3]. Harrington presented several formulas for the far field radiation pattern from the axial and circumferential slots on cylindrical waveguides by the use of Fourier transforms in 1961 [4]. Shin and Eom derived some complex equations for the radiation pattern from several narrow circumferential slots in a thick conducting circular cylinder by the application of mode matching and Fourier transform techniques in 2005 [5]. Sorokoz et al. presented some relatively simpler relations for the far-field radiation from an array of circumferential slots on a cylindrical waveguide in 2006 [6]. Their relations are used here in this paper.

We follow the general method introduced by Elliott [7] for the evaluation of scattering from an aperture on the surface of a cylindrical waveguide, which is believed to be unprecedented for the circumferential slots in a circular cylindrical surface. Consequently, our main task is to derive two design equations which are done by assuming that the radius of the cylindrical surface is large, providing the possibility of assuming the slots to be located on a flat ground plane. This assumption may lead to some design approximations, which may then be rectified by a full-wave simulation by available computer softwares. Furthermore, the method of least squares is applied here, which has been used for the design of slots on the broad and narrow sides of rectangular waveguides where the minimization of ensuring error functions is performed by the combination of genetic algorithm (GA) and conjugate gradient method (CG) [8–10].

The TM_{01} mode is assumed in the cylindrical waveguide, where the electric field is radial in its cross-section. Consequently, the radiation from the circumferential slots on its surface is omnidirectional and independent of the azimuthal angle, which is desired for cylindrical slot arrays.

2. Development of design procedure

2.1. First design equation

The configuration of circumferential rectangular slots on a cylindrical waveguide is shown in Fig. 1, together with the related dimensions. The backward (B) and forward (C) scattered field amplitudes are given by [7, page 91]:

$$B_{mn} = \frac{\int_{slot} \bar{E}_s \times \bar{H}_{tC} \cdot \overline{ds}}{2\int_S \bar{E}_{at} \times \bar{H}_{at} \cdot \bar{u}_z ds} \tag{1}$$

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http://dx.doi.org/10.1016/j.aeue.2016.01.010
1434-8411/

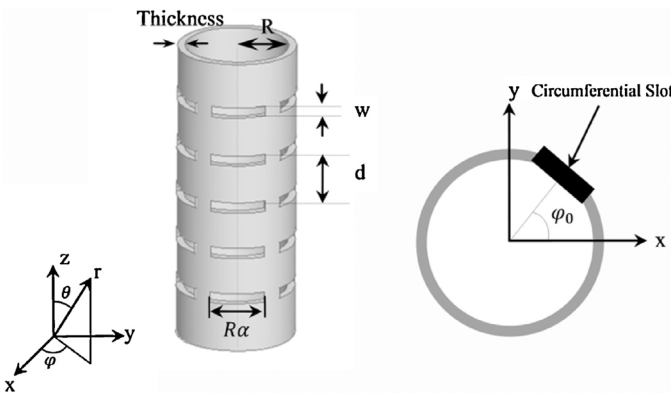

Fig. 1. An array of circumferential slots on a circular cylindrical surface.

$$C_{mn} = \frac{\int_{slot} \bar{E}_s \times \bar{H}_{tB} \cdot \overline{ds}}{2\int_S \bar{E}_{at} \times \bar{H}_{at} \cdot \bar{u}_z ds} \tag{2}$$

where subscripts B and C represent the amplitudes of backward and forward waves, t indicates the tangential field in the cross-section, S indicates the cross-section of uniform waveguide, and "slot" shows the slot surface area.

The field components of TM_{01} mode in the cylindrical waveguide are in [4].

The tangential electric field on the nth aperture is:

$$E_z = \frac{V_n}{W}\cos\left(\frac{\pi(\varphi-\varphi_0)}{\alpha_n}\right)\begin{cases} z_n - \dfrac{W}{2} < z < z_n + \dfrac{W}{2} \\ \varphi_0 - \dfrac{\alpha_n}{2} < \varphi < \phi_0 + \dfrac{\alpha_n}{2}\end{cases} \quad W \to 0 \tag{3}$$

$$\bar{E}_s = E_z \bar{u}_z, \quad E_\varphi = 0 \tag{4}$$

where α_n is the angular length of nth slot.

These field components are substituted in Eqs. (1) and (2) to obtain:

$$C_{01} = B_{01} = \frac{jV_n^s h J_1(ha)}{a\beta_{01}\pi^2}\frac{\frac{\alpha_n}{\pi}}{\left[J_1^2(ha) - J_0(ha)J_2(ha)\right]} \tag{5}$$

Observe that the forward and backward traveling wave amplitudes are equal in the vicinity of slot. Therefore the transmission line equivalent circuit such as mentioned in [7] consists of a parallel admittance.

The first design equation is then derived. The reflected power from the aperture is:

$$P_{ref} = \frac{1}{2}\mathrm{Re}\int_S \left(\bar{E}_t \times H_t^*\right)\cdot\overline{ds} = \frac{1}{2}\mathrm{Re}\int_{\rho=0}^{a}\int_{\phi=0}^{2\pi}\left(B_{01}E_{01,t} \times B_{01}^* H_{01,t}^*\right)$$
$$\cdot\, \overline{u_z}\rho' d\rho' d\phi' = \frac{\pi\beta_{01}\omega\varepsilon}{h^2}\frac{a^2}{2}\left[J_1^2(ha) - J_0(ha)J_2(ha)\right]B_{01}B_{01}^* \tag{6}$$

where

$$\bar{E}_t = \begin{cases} B_{01}\bar{E}_{at} & z < z_1 \\ C_{01}\bar{E}_{at} & z > z_2 \end{cases} \tag{7}$$

The first design equation can be derived by using of these formulas and following process of [7].

So the first design equation:

$$\frac{Y_n^a}{G_0} = -j\sqrt{\frac{4\omega\varepsilon_0 J_1^2(ha)}{G_0\beta_{01}\pi^5\left[J_1^2(ha) - J_0(ha)J_2(ha)\right]}}\frac{V_n^s}{V_n}\alpha_n \tag{8}$$

where the Bessel functions J_0, J_1 and J_2 are calculated for $ha = 2.405$ for TM_{01} mode.

2.2. Second design equation

For the derivation of the second design equation, the procedure described by Elliott [7, pp: 402–407] is followed, which for the circumferential slots on cylindrical waveguides gives:

$$\frac{Y_n^a}{G_0} = \frac{\eta^2}{2}G_0|K|^2\frac{\alpha_n^2}{Z_n^{d,a}} \tag{9}$$

where $K = -j\sqrt{\frac{4\omega\varepsilon J_1^2(ha)}{G_0\beta\pi^5\left[J_1^2(ha) - J_0(ha)J_2(ha)\right]}}$, $\eta = 120\pi$ is the intrinsic impedance of medium and G_0 is characteristics admittance of cylindrical waveguide. Eq. (9) can be written as $\frac{Y_n^a}{G_0} = K_1\frac{\alpha_n^2}{Z_n^{d,a}}$ where $K_1 = \frac{\eta^2}{2}G_0\left|K\right|^2$. $Z_n^{d,a}$ is the active admittance of equivalent dipole that is assumed in the derivation of second design equation. We have $Z_n^{d,a} = Z_{nn} + Z_n^b$ where:

Z_{nn}: Self impedance of circumferential slot, which is equal to $\frac{K_1\alpha_n^2}{Y_{nn}^s/G_0}$.

Z_n^b: Mutual impedance between circumferential slots on the cylindrical waveguide, which is equal to $\sum_{\substack{m=1 \\ m\neq n}}^{N}\frac{V_m^s}{V_n^s}Z_{nm}^d$.

Then

$$Z_n^{d,a} = Z_{nn} + Z_n^b = \frac{K_1\alpha_n^2}{Y_{nn}^s/G_0} + \sum_{\substack{m=1 \\ m\neq n}}^{N}\frac{V_m^s}{V_n^s}Z_{nm}^d$$

Z_{nm}^d is mutual impedance between two dipole which may be obtained from the mutual admittance between two slots Y_{nm}^s by the Booker's relation.

$$Z_{nm}^d = \left(\frac{\eta^2}{2}\right)Y_{nm}^s \tag{10}$$

The second design equation is then determined by these relations.

3. Design of a linear traveling wave slot array

Consider the equivalent circuit of the linear traveling wave slot array as shown in Fig. 2. The normalized admittance at the nth slot looking towards the match port is [7, pages 467–474]:

$$\frac{Y_n}{G_0} = K_1\frac{\alpha_n^2}{Z_n^{d,a}} + \frac{(Y_{n-1}/G_0)\cos\beta_{01}d_{n-1} + j\sin\beta_{01}d_{n-1}}{\cos\beta_{01}d_{n-1} + j(Y_{n-1}/G_0)\sin\beta_{01}d_{n-1}} \tag{11}$$

where the second design equation (9) is used.

The mode voltages at successive junctions are then related by:

$$V_n = V_{n-1}\cos\beta_{01}d_{n-1} + jI_{n-1}Z_0\,\sin\,\beta_{01}d_{n-1}$$
$$= V_{n-1}\left[\cos\beta_{01}d_{n-1} + j\left(\frac{Y_{n-1}}{G_0}\right)\sin\beta_{01}d_{n-1}\right] \tag{12}$$