A New Design Procedure For Slot Arrays Fed By Single-Ridge Waveguide

Yang Bing, XuHaitao, GaoZhiguo, Chen Zhen
Institute No.25 of the Second Academy China Aerospace Science & Industry Corp. Beijing, 100854

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Abstract

Design procedure for longitudinal slot arrays fed by air-filled rectangular waveguide including mutual coupling has been discussed and studied in many papers, and widely applied. Due tocomplexity of internal field, it is difficult toemploy the same method on slot arrays fed by ridge waveguide. In this paper, a newdesign procedureis introduced for slot arrays fed by single-ridge waveguide, which simplified the procedure of the previous one.A1×6 array wasconstructed and tested, and the result validates the theory.

1 Introduction

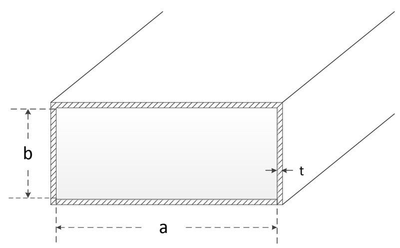
Slot arrays fed by waveguide have been widely applied in radar and communication system,owing toa great number of merits, as high power capacity, low loss, simple feeding, easy manufacture, precise control of aperture distribution, and etc.Slots can be cut in the broad or narrow wall of the waveguide[2].In this paper, longitudinal slots cut in broad wall are discussed. In 1948, Stevenson founded the basis theory ofslotted waveguide in paper[1], and Oliner[2] has derived approximate expression of the admittance concerned to length and offset for the slot.Yee[3] has extendedOliner'svariational solution,proposed the slot resonant length, accounting for the offset of the slot from the center of the waveguide.The design procedure for slot arrays fed by rectangular waveguide has been deeply and numerously studied including mutual coupling,since 70's by Elliott[6-8], which has been widely employedin waveguide slot array design fieldnowadays.Dolph-chebyscheff or Taylorpolynomials[9] are usually applied to synthesizecurrent distribution of slot array, for the sake of high gain and low side-lobe.

However, the bandwidth of slotted array fed by rectangular waveguide is an obvious defect[10]. An effective method to broaden the bandwidth is to separate anarray into several sub-arrays and feed them with a power divider[11]. Another option is to choose ridge waveguide instead of rectangular waveguide[12][13]. One design procedurefor slot arrays fed by single-ridge waveguide[14],deduced from ones by the rectangular waveguides,in which eigenvalue of ridge waveguide is required. A new procedure is presented in this paper, which avoids complex computation.

2 New Design Procedure for slot arrays fed by rectangular waveguide

In [6][8],Elliott has demonstrated the design procedure of slot array fed by rectangular waveguide, which includes self-admittance simulation of single waveguide slot[1][2], reciprocity theorem, and mutual coupling between two slots, which has been approximatedas two dipoles in space[7].

2.1 Traditional design procedure for slot array fed by rectangular waveguide



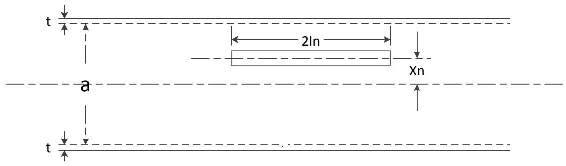


Figure 1. Rectangular waveguide (Up), longitudinal slot in the broad wall of a rectangular waveguide (Down)

Elliott deduced 2 equations (1) and (2) to calculate thelengthsand offsetsof each slotonce the desired radiation pattern and input admittance were determined.

$$\frac{Y_n^a}{G_0} = K_1 f_n \sin kl_n \frac{V_n^s}{V_n} \quad (1)$$

$$\frac{Y_n^a}{G_0} = \frac{K_2 f_n^2}{Z_n^a} \quad (2)$$

In which

$$K_1 = -j\left[\frac{8}{\pi^2 \eta G_0}\frac{(a/b)}{(\beta/k)}\right]^{\frac{1}{2}} \quad (3)$$

$$f_n = \frac{\cos\beta l_n - \cos kl_n}{\sin kl_n}\sin\frac{\pi x_n}{a} \quad (4)$$

$$K_2 = \frac{292(a/b)}{0.61\pi(\beta/k)} \quad (5)$$

Here, G_0 is characteristic admittance of the waveguide, η is impedance of free space and $\eta = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 377\Omega$, k and β are free-space wave number and propagation constant respectively.$V_n^s$is the mode voltage across the center of the slot, and V_n is the equivalent voltage as figure 2.

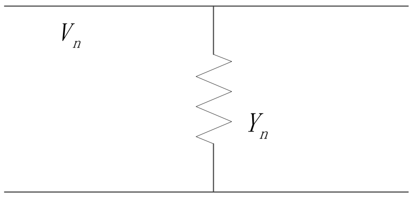


Figure 2. Definition of equivalent voltage

$Z_n^a$is active impedance of nth slot, and

$$Z_n^a = Z_{nn} + Z_n^b \quad (6)$$

In which

$$Z_n^b = \sum_{m=1}^{N}{}' \frac{V_m^s \sin kl_m}{V_n^s \sin kl_n} Z_{mn} \quad (7)$$

$Z_{nn}$is self- impedance of nth slot. Z_{mn} is mutual impedance between the mth and nth slots, which is assimilated as half wavelength dipole and discussed in [7]. V_m^sandV_n^s are mode voltages across shunt elements, respectively.

The design procedure could be summarized as: first of all, current distribution can be synthesized according to desired radiation pattern and side-lobe, thusinitialadmittances of each slot Y_{nn} with its offsets and lengths of each slot are acquired. Afterwards, equation (1) and (2) should be employed to compute active admittance Y_n^a of each slot. Once active admittance of the nth slot$Y_n^a$is achieved, Y_{nn} should be adjusted to compensate the effect brought by mutual coupling, and offsets and lengths of each slot should be adjusted subsequently.Iterates the design procedure several times, final offsets and lengths of each slot of slot array are achieved.

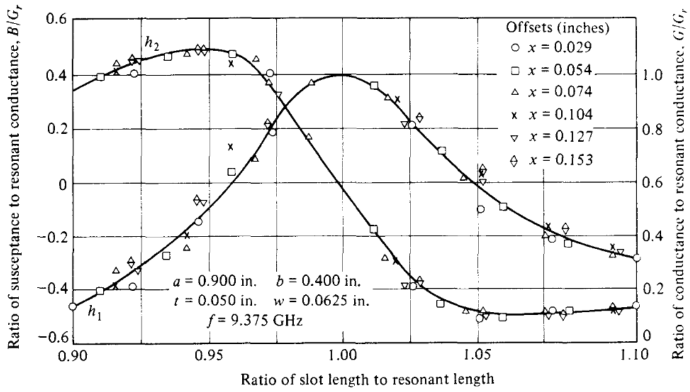


Figure 3.Normalized Self-Admittance Components for a Longitudinal Shunt Slot (by Stegen[4])

Usually after adjusted, self-admittances of slots won't be resonant anymore, due to effort of mutual coupling. Instead,active admittances are purely real and accord with the desired current distribution.

2.2 New method with assistance ofelectromagnetic calculating software

There are 2 equations (1) and (2) proposed to design slot array fed by rectangular waveguide by Elliott. But usually only (2) is used, (1) barely employed in design procedure. In [6], formula (1) is defined at resonant point, and Y_n^a is purely real. For single slot, $Y_n^a$is Y_{nn}, which can be calculated by electromagnetic software, in this paper, HFSS is employed. And the computational model isas figure 4.

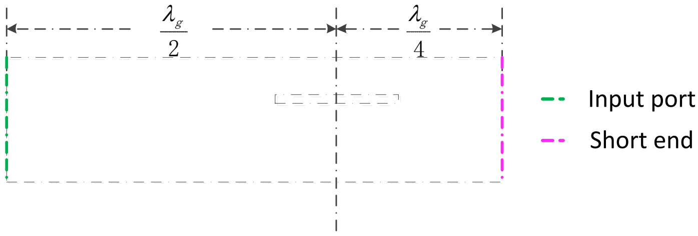


Figure 4. One-port model (short end) of slot fed by rectangular waveguide

As definition, $V_n^s$and V_n, also can be computed through electromagnetic software. The model is shown in figure 5.

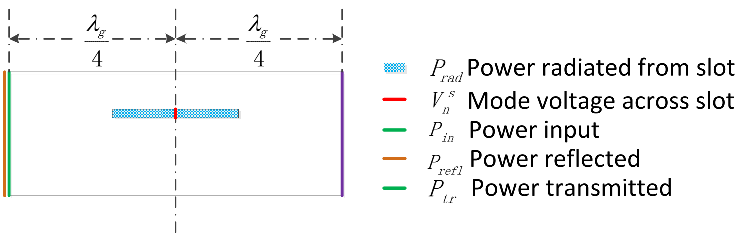


Figure 5. Two-port model (matched loaded) of slot fed by rectangular waveguide

Slot can be considered as a lumped circuit as figure 2. V_n^s can be read directly by HFSS. Relation of power radiated P_{rad} from slot gets from software and Y_{nn} is calculated from the model of figure 4. Therefore, equivalent voltage V_n of nth slot is obtained

$$V_n = \sqrt{\frac{2P_{rad}}{Y_{nn}}} \quad (9)$$

Thus, Y_{nn}, V_n^s and V_n are all computed through computational electromagnetic software directly or indirectly. Put all these values in (1), K_1 isachieved.

For example, arectangular waveguide works at $f_0 = 17.6\text{GHz}$, of whichwidth and height are $a = 10.73\text{mm}$ and $b = 3.5\text{mm}$ respectively. Calculated directly from(3), the result turns $K_1^{dir} = 1.6428$.

From formula (1) and electromagnetic software, K_1 also can be calculated as aforementioned, written as K_1^{indir}, and the results are illustrated in table 1.

No.	Slot length(mm)	Slot Offset(mm)	K_1^{indir}
1	8.3931	1	1.6783
2	7.9	1	1.6524
3	8.6	1	1.6184
4	8.3931	1.3	1.6692
5	8.3931	1.5	1.6455

Table 1.K_1^{indir} computed in aid of software for slot fed by rectangular waveguide

Relative error is defined as (10):

$$\varepsilon_{K_1} = \left\| \frac{K_1^{dir} - K_1^{indir}}{K_1^{dir}} \right\| \quad (10)$$

And all results are less than 2%.

3 New Design Procedure for slot arrays fed by single-ridge waveguide

Compared to rectangular waveguide, ridge waveguide has smaller size and wider bandwidth. In [14], Kim and Elliottapplied the same design procedure of last section on single-ridge waveguide, in which

$$K_1 = \frac{2k_T}{k_0} \sqrt{\frac{k_T^2}{\omega \mu_0 \beta_{10} G_0}} \quad (11)$$

k_T isthe eigenvalue of the single-ridge waveguide for the dominant modeTE_{10}.Computation of k_T is described in [5], which is complicated and obscured.

The new method for calculate K_1 discussed above will be appliedin later section to simplify the computation.

3.1 New design procedure applied to compute K_1 of slot array fed by single-ridge waveguide

As previous, Y_{nn}, V_n^s and V_n could be computed, and with equation(1), K_1 could be calculated.

For example, a single-ridge waveguide, illustrated as figure 6,

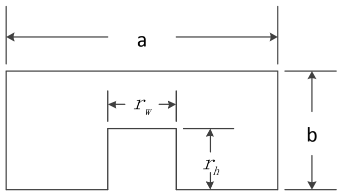


Figure 6.Geometry of single-ridge waveguide

which works at $f_0 = 17.6\text{GHz}$, and $a = 8.29\text{mm}$, $b = 3.5\text{mm}$, $r_w = 3\text{mm}$, $r_h = 1.5\text{mm}$.

No.	Slot length(mm)	Slot Offset(mm)	K_1^{indir}
1	9.018	1.5	1.5263
2	8.9	1.5	1.5200
3	8.8	1.5	1.4868
4	9.2	1.5	1.4737
5	8.8251	1.2	1.5567
6	9	1.2	1.5071
7	8.7	1.2	1.5505
8	8.6	1.2	1.5211

Table 2.K_1^{indir} for slot fed by single-ridge waveguide above

Relative error is defined as

$$\varepsilon_{K_1} = \left\| \frac{avr(K_1^{indir}) - K_1^{indir}}{avr(K_1^{indir})} \right\| \quad (12)$$

In which $avr(K_1^{indir})$ is average of K_1^{indir}, and calculated as, $K_1^{indir} = 1.5178$.

Error results are all less than 3% .Therefore, K_1 of single-ridge waveguide can be approximated as a constant through the method aforementioned,instead of complex formula (11).

3.2 Example of slot array fed by single-ridge waveguide designed with new method

One such case which can be instructive involves the design of a six-slot lineararray, shown as figure 7.

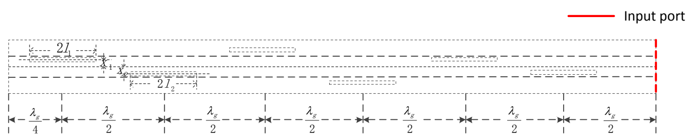


Figure 7.A1×6array of longitudinal shunt slots in the broad wall of a single-ridge waveguide

The slot current distribution accords Taylor synthesis and the side lobe is designed at -25dB. Normalized current distribution is computed as:

0.1010 0.1701 0.2289 0.2289 0.1701 0.1010

Array works at $f_0 = 17.6\text{GHz}$, and the waveguide wavelength is $\lambda_g = 22\text{mm}$.Parameters of the ridge waveguide are

$a = 10\text{mm}$, $b = 3.5\text{mm}$, $r_w = 4\text{mm}$, $r_h = 1.7\text{mm}$.

The slots' solution is:

$x_1 = 0.5868\text{mm}$ $2l_1 = 8.2710\text{mm}$ $g(x_1) = 0.0557$

$x_2 = -0.9764\text{mm}$ $2l_2 = 8.4463\text{mm}$ $g(x_2) = 0.1581$

$x_3 = 1.3436\text{mm}$ $2l_3 = 8.6033\text{mm}$ $g(x_3) = 0.2862$

$x_4 = -1.3436\text{mm}$ $2l_4 = 8.6033\text{mm}$ $g(x_4) = 0.2862$

$x_5 = 0.9764\text{mm}$ $2l_5 = 8.4463\text{mm}$ $g(x_5) = 0.1581$

$x_6 = -0.5868\text{mm} \quad 2l_6 = 8.2710\text{mm} \quad g(x_6) = 0.0557$

The radiation pattern is as figure 8:

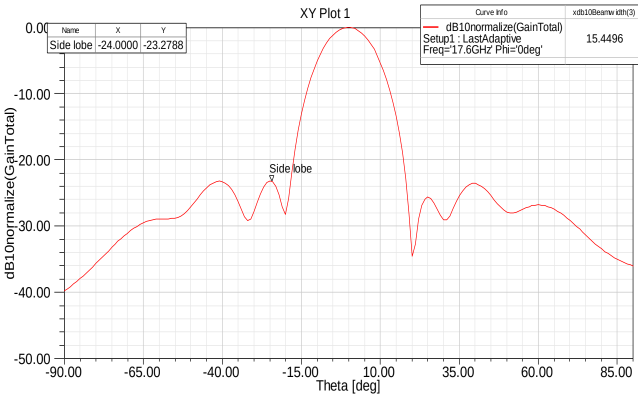


Figure 8.Pattern of the 1×6slot array example

We get from the figure that the side lobe is at -23.2788dB, nearly up to the request. At meanwhile, the desired normalized input admittance is equal to 1, butread from computational software, $\text{VSWR} = 1.3866$.

With the method aforementioned, we get new solution:

$x_1 = 0.7220\text{mm} \quad 2l_1 = 8.2342\text{mm} \quad g(x_1) = 0.0754 + j0.0192$

$x_2 = -1.1810\text{mm} \quad 2l_2 = 8.4295\text{mm} \quad g(x_2) = 0.2118 + j0.0469$

$x_3 = 1.5530\text{mm} \quad 2l_3 = 8.6098\text{mm} \quad g(x_3) = 0.3554 + j0.0622$

$x_4 = -1.5530\text{mm} \quad 2l_4 = 8.6098\text{mm} \quad g(x_4) = 0.3554 + j0.0622$

$x_5 = 1.1810\text{mm} \quad 2l_5 = 8.4295\text{mm} \quad g(x_5) = 0.2118 + j0.0469$

$x_6 = -0.7220\text{mm} \quad 2l_6 = 8.2342\text{mm} \quad g(x_6) = 0.0754 + j0.0192$

The VSWR result reduces to 1.1499, which approaches the expectation.Nevertheless, effect of thickness of waveguide, precision of the computation and other factors which impact the accuracy should be taken into account.

4 Conclusion

In this paper, a new design procedure for longitudinal broadwall slots fed by a single-ridge waveguide is presented, which is less complex in contrast to the traditional one. The new design procedure derives from slot array fed by rectangular waveguide, and extends to arrays fed by single-ridge waveguide. The new method simplifies the mathematic computation of K_1 with the aid of electromagnetic computational software. Two examples are illustrated later. The first one proves K_1 is nearly a constant also for shunt slots of single-ridge waveguide. The latter one, that is a 1×6 slot array, attains better VSWR after decoupling by the method. In conclusion, this new means assists us with in designing slot array fed by single-ridge waveguide.

REFERENCES

[1]. A. F. Stevenson, "Theory of slots in rectangular waveguides," *J. Appl. Phys.*, vol. 19, pp. 24-38, Jan. 1948.

[2]. A. A. Oliner, "The impedance properties of narrow radiating slotsin the broad face of rectangular waveguide, Part I-Theory, Part II-Measurements,"*IRE Trans. Antennas Propagat.*, vol. AP-5, pp. 4-20,Jan. 1957.

[3]. H. Y. Yee, "Impedance of a narrow longitudinal shunt silno ta slottedwaveguide array," *IEEE Trans. Antennas Propagat*, vol. AP-22, pp. 589-592, July 1974.

[4]. R. J. Stegen,"Longitudinal Shunt Slot Characteristics,"*Hughes Technical Memorandum* No. 261,Nov. 1951.

[5].J. P. Montgomery, "On the complete eigenvalue solution of ridge waveguide," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, pp. 547-555, June 1971.

[6].Robert S. Elliott ,L. A. Kurtz, "The Design of Small Slot Arrays,"*IEEE Trans. Antennas Propagat*, vol. AP-26, Mar. 1978.

[7].Robert S. Elliott, William R. O'Loughlin, "The Design of Slot Arrays Including Internal Mutual Coupling,"*IEEE Trans. Antennas Propagat*,vol. AP-34, No. 9, Sep. 1986.

[8].Robert S. Elliott, "An Improved Design Procedure for Small Arrays of Shunt Slots,"*IEEE Trans. Antennas Propagat*,vol. AP-31, No. 1, Jan. 1983.

[9].R. S. Elliott, "Design of Line-Source Antennas for Narrow Beamwidth and AsymmetricLow Sidelobes," *IEEE Trans. Antennas Propagat*, vol. AP-23, No. 1, pp. 100–107, Jan. 1975.

[10].MazenHamadallah"Frequency Limitations on Broad-Band Performance of Shunt Slot Arrays,"*IEEE Trans. Antennas Propagat*, vol. 31, No 7. Jul. 1989.

[11].J. C. Coetzee, J. Joubert, and W. L. Tan, "Frequency performance enhancementof resonant slotted waveguide arrays through the use ofwideband radiators or subarraying," *Microwave Opt. Technol. Lett.*,vol. 22, no. 1, pp. 35–39, Jul. 1999.

[12].J. R. Pyle. "The Cutoff Wavelength of the TE,, Mode in RidgedRectangular Waveguide of Anv Aspect Ratio,"*IEEE Trans. Microwave Theory Tech*. vol.14, No. 4. Apr. 1966.

[13].S. Hopfer, "The Design of Ridged Waveguides", *IRE Trans. Antennas Propagat*.vol. MTT-14, No. 4,Oct. 1955.

[14]. David Y. Kim, Robert S. Elliott, A Design Procedure for Slot Arrays Fed by Single-Ridge Waveguide, *IEEE Trans. Antennas Propagat*, vol. 36, No. 11, Nov. 1988.