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Study of Grating Efficiency of Planar Arrays

Abbas Vosoogh[1], Per-Simon Kildal[1]
[1] Department of Signals and Systems, Chalmers University of Technology, Gothenburg, Sweden
abbas.vosoogh@chalmers.se, per-simon.kildal@chalmers.se

***Abstract*—This paper studies the aperture efficiency reduction due to grating lobes of a uniformly excited planar array. The grating lobes will not cause major interference problems in the millimeter wave region, because of the attenuation in the atmosphere, but they cause a reduction of the directivity and thereby aperture efficiency of the antenna. Therefore, we present a simple formula for calculating the aperture efficiency in the presence of grating lobes, from knowledge of the element pattern. The accuracy of the formula is verified by comparing with simulated results for a full array with slot elements.**

***Index Terms*—array antenna, grating lobe, aperture efficiency**

I. Introduction

The use of millimeter waves is growing in many applications such as automotive, radar and communication system terminals. Communication at millimeter waves is advantageous because of the high attenuation in the atmosphere, and large absorption in urban scattering obstacles. This enables frequency reuse over small distances. For this purpose, highly-directive antennas with high aperture efficiency are needed. The planar array antennas are good candidate for millimeter wave applications because of their low volume and weight. In the design of a broadside-radiating antenna array, the element spacing is required to be within one wavelength to avoid high grating lobes. However, the element spacing may become larger than one wavelength in order to accommodate a fully branched also called corporate distribution network, and in particular to accommodate a low loss waveguide distribution network that requires more space than other alternatives. Therefore, it is important to know the grating lobe behavior and its effect on the aperture efficiency. The present paper makes such a study and validates a simple formula for the efficiency reduction due to grating lobes.

The gap waveguide technology presents some benefits when it is used for high frequency antenna applications [1]. It has a planar profile and it can be used as low loss distribution network for antenna array. The width of the gap waveguide ridges or lines can be increased to reduce the conductive losses, and there is no problem with excitation of surface waves, which severely affect common microstrip distribution networks at high frequency [2]. In [3] a planar dual mode horn array antenna fed by an inverted microstrip gap waveguide is presented. A slot-coupled dual mode horn element is designed to decrease the power loss due to the grating lobes, but it should be further reduced.

Large array antennas can be designed as an array of subarrays, i.e. with subarray approach. In [4] a cavity-backed 2x2 slot subarray is used as a directive array element, designed for suppressing grating lobes due to the large two lambda element spacing required to accommodate the distribution network. Grating lobes will also appear due to amplitude and phase differences between the elements within the subarrays. Reference [5] categorized and demonstrated specific subarray pattern distortions that can cause grating lobes to appear in uniform arrays .The paper [6] shows how dielectric superlayers can be used to reduce the grating lobe level in thinned phased arrays.

The aperture efficiency reduction due to the grating lobes can be accounted for by a separate grating efficiency, for which there exist a simple formula, see Chapter 10 in [7]. We will validate this by using a simple broadside radiating example, i.e. a 32×32-element array of slots in an infinite ground plane. The dimensions of the unit cell in the E- and H-planes are normally selected to try to get the maximum gain from the array, in which case we need to have full control of the grating lobes in the different planes. In this paper we verify the grating efficiency formula for a uniformly excited array, but the formula is also valid for tapered arrays. We compute the radiation patterns and directivities of the array for different element spacing, using two commercial softwares (CST Microwave Studio and HFSS). The aperture efficiency is found from the directivity, and this is compared with the results of the simple grating efficiency formula. The latter is evaluated by using the relative grating lobe levels obtained from the CST and HFSS results, and in addition by assuming that the relative grating lobe levels are given by a simple analytic form of the isolated element pattern.

II. Grating Efficiency

Traditionally the antenna aperture efficiency is defined as:

$$e_{ap} = D / D_{\max} \quad (1)$$

where D is the directivity of the antenna and $D_{\max}$ is the maximum available directivity from the aperture of the antenna obtained by using:

$$D_{\max} = \frac{4\pi A}{\lambda^2} \quad (2)$$

where A is the area of antenna aperture evaluated as the number of elements times the area of the unit cell.

In [7, Sec.10.3.5] there is presented a simple formula called "grating efficiency" that is the reduction in directivity (and aperture efficiency) due to the power lost in the grating lobes. It is given by the following formula:

$$e_{grt} = \frac{|G(\theta_0,\varphi_0)|^2}{\sum_{pq} |G(\theta_{pq},\varphi_{pq})|^2 \frac{\cos\theta_0}{\cos\theta_{pq}}} \qquad (3)$$

The sum is taken over all visible grating and main lobes. In (3) $G(\theta,\varphi)$ is the far-field function and $|G(\theta,\varphi)|^2$ is the directive gain function of the single embedded array element, (θ_0,φ_0) is the direction of main beam and $(\theta_{pq},\varphi_{pq})$ is the direction of the grating lobes. The relative level $|G(\theta_{pq},\varphi_{pq})|^2 / |G(\theta_0,\varphi_0)|^2$ will also be the same as the level of the grating lobe relative to the main lobe of the array, so that it is also possible to read this from a computed or measured radiation pattern of the full array.

Therefore, using this simple formula (3), we can calculate the aperture efficiency and thereby directivity of big array antennas analytically even in the presence of grating lobes. For this purpose we need either the far-field function of the element (i.e. the unit cell), or the radiation pattern of the full array.

Fig. 1 shows the slot unit cell geometry used as a radiating element of the 32×32-element slot array antenna. The slot has a length of 3 mm and width of 0.4 mm ($<< \lambda$). The far-field function of the isolated slot antenna can be modeled by the far-field of a magnetic current source. Therefore, the E-plane pattern (φ=90°) of the slot element is omni-directional and we used this far-field function to calculate the grating efficiency analytically from (3) when there are two grating lobe in E-plane.

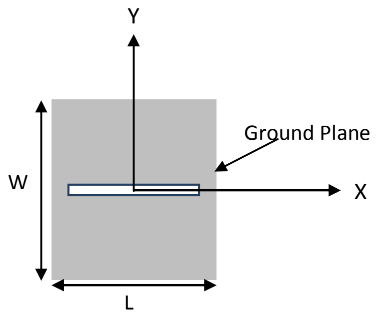


Fig. 1. Slot unit cell geometry

III. Simulation and analytical results

The simulations were done by modeling the slot of each element as an open waveguide of a finite length. The simulation in HFSS was done by the infinite array approach using the Master/Slave boundary condition. Using this approach, the effects of the surrounding elements in the array are automatically included. The HFSS simulations provide both the far-field function of the element and of the full 32×32-element slot array antenna.

We simulated the full array by the CST time domain solver with simultaneous excitation of all slots, and compared the results of the HFSS infinite array approach with the CST full array simulation. By using each of these two simulation approaches we obtained 2 curves: one aperture efficiency curve by using the directivity of array and the D/D_{max} formula, and the other grating efficiency curve by substituting the level of the main beam and grating lobes from the simulated radiation patterns into the grating efficiency formula. Furthermore we calculated the grating efficiency by using the approximate analytical expression for the isolated element pattern.

The appearances of grating lobes are determined by the element spacing in E-plane and H-plane. When the element spacing is slightly smaller than one wavelength, the grating lobe starts to appear in the visual region. In this paper we consider only element spacing for which there are zero or two grating lobes in E plane, one on each side of the broadside main beam.

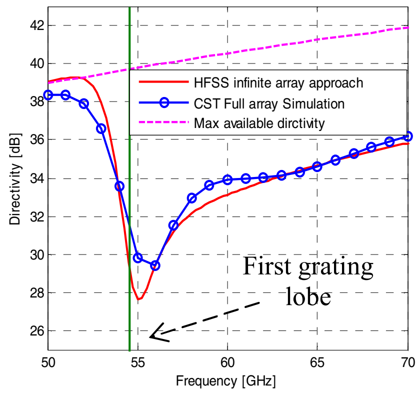
The dimension of the unit cell in E-plane (W=5.5 mm) passes from being smaller than to greater than one wavelength over the analyzed frequency band, while the unit cell dimension in H-plane (L=4 mm) is smaller than one wavelength to avoid grating lobe in this plane. In Fig. 2 the frequency at which the first grating lobe starts to appear in E-plane is marked. Fig. 2a compares the directivity of the 32×32-element slot array acquired by HFSS (infinite array approach) and CST (full array simulation). We see that the results of the two different computer codes and approaches agree well with each other, but it should be noted that the infinite array approach (i.e. the HFSS result) take much shorter computation time.

The curve for the maximum available directivity is also shown in Fig. 2a. We see how the simulated directivities start to reduce from the maximum available value even before the frequency reaches the frequency at which the first grating lobe appears. This is happening when the beam width of the gratings lobe starts appearing in visible space. This beam width is actually much wider than the width of the broadside main beam, when it appears along the ground plane of the array (the endfire direction).

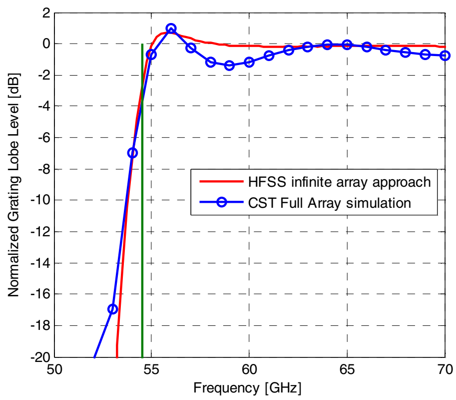
Fig. 2b shows the normalized grating lobe level obtained by HFSS (infinite array approach) and CST (full array simulation). As expected, the grating lobes have approximately the same level as the main beam because the pattern of the slot element is omni-directional in E-plane.

The aperture efficiencies corresponding to the simulated directivities in Fig. 2 are shown in Fig. 3. In Fig. 3 the aperture efficiencies are calculated by subtracting the maximum available directivity from the simulated directivity (in dB), i.e. the common definition of aperture efficiency. The corresponding grating efficiency is calculated by using (3). The curves of the aperture efficiency and grating efficiency obtained by each simulation tool (CST or HFSS) agree with each other after the entire grating lobes have appeared in the visual region while there are differences between the results during the transition of the grating lobe from imaginary to visible space.

In addition, we show grating efficiencies calculated by using (3) and the analytic formula for the element pattern. For this case we use an omni-directional far-field function of the slot unit cell in E-plane. The simulation and analytical results are in good agreement, detecting the change of the aperture efficiency when the grating lobe starts to appear close to 55 GHz, even though the details of the curves around 55 GHz are different. The reason is the grating efficiency formula is derived under the assumption of all grating lobes being in the visible region, and the array being large [7].



a)



b)

Fig. 2. a) Directivity b) Grating lobe level of 32×32-element slot array with unit cell dimentsion of W=5.5 mm and L=4 mm.

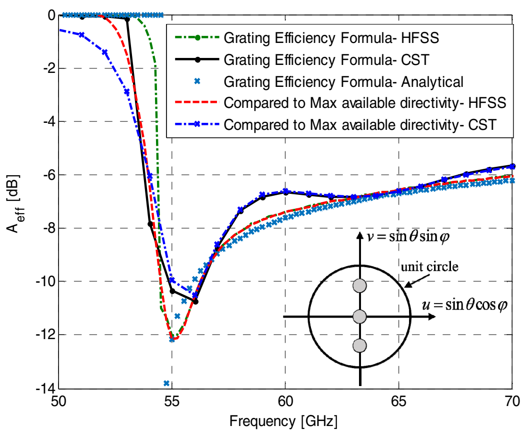


Fig. 3. Aperture efficiency of 32×32-element slot array with 2 grating lobes in E-plane

IV. Conclusion

We have verified a simple formula referred to as a grating efficiency for calculating the aperture efficiency of an array with grating lobes. We validated this by simulations in HFSS and CST. We have shown we can calculate the aperture efficiency of the array analytically even in the presence of grating lobes, provided we know the isolated element pattern, but the accuracy is not very good at the frequencies for which the element spacing is close to 1 wavelength, i.e. when the grating lobes starts to enter from imaginary to visible space alongside the array. We have also shown that the grating efficiency formula is valid if we know the radiation pattern and use the relative grating lobe levels from these in the same analytical formula.

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References

[1] P.-S. Kildal, A. Uz Zaman, E. Rajo-Iglesias, E. Alfonso, A. Valero-Nogueira, "Design and experimental verification of ridge gap waveguides in bed of nails for parallel plate mode suppression", *IET Microwaves, Antennas & Propagation*, vol. 5, no 3, pp. 262-270, March 2011.

[2] H. Raza, J. Yang, P.-S. Kildal, E. Alfonso, "Microstrip-ridge gap waveguide – study of losses, bends and transition to WR-15", *IEEE Transactions on Microwave Theory and Techniques*, Vol. 62, Issue. 9, pp. 1943 - 1952, 2014.

[3] E. Pucci, E. Rajo-Iglesias, J.-L. Vazquez-Roy and P.-S. Kildal, "Planar dual-mode horn array with corporate-feed network in inverted microstrip gap waveguide", IEEE Transactions on Antennas and Propagation, Vol. 62, Issue 7, pp- 3534 - 3542, 2014.

[4] S. A. Razavi, P.-S. Kildal, L. Xiang and E. Alfonso, "2×2-slot element for 60GHz planar array antenna realized on two doubled-sided PCBs using SIW cavity and EBG-type soft surface fed by microstrip-ridge gap waveguide", *IEEE Transactions on Antennas and Propagation*, Vol. 62, Issue. 9, pp. 4564 - 4573, 2014.

[5] T. J. Brockett and Y. Rahmat-Samii, "Subarray design diagnostics for the suppression of undesirable grating lobes", *IEEE Trans. Antennas Propag.*, 2012.

[6] D. Blanco, N. Llombart, E. Rajo-Iglesias, "On the use of leaky wave phased arrays for the reduction of the grating lobe level", *IEEE Trans. Antennas Propag.*, 2014.

[7] P. S. Kildal, Foundations of Antennas: A Unified Approach for Line-of-Sight And Multipath, book manuscript to be published by Artech House in 2015.