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An Effective Method for Suppressing Second-Order Beams of 2D Edge Slot Phased Arrays

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Abstract

An effective method is proposed to suppress the second-order beams(SOBs) that result from the cross-polarized fields of 2D edge slot arrays. By rearranging the conventional sequence of stacking waveguides, the SOBs are shown to be considerably reduced and the 9 dB suppression is obtained. The optimal sequence is obtained from the genetic and exhaustive searches and its effects are verified using near-field measurements as well as theoretical estimation. Since the proposed method requires no additional polarizing structures such as baffles, it is very easy and cost-effective to implement.

Key words : Edge Slot Phased Array, Second-Order Beam(SOB), Genetic Algorithm.

Ⅰ. Introduction

For decades, slotted waveguide arrays have been widely used in the application of various radars and communication systems. Especially in the scanning arrays, edge slots cut in the narrow wall are preferred in order to avoid grating lobes. Such edge slots in a waveguide have opposite inclination angles to their adjacent slots in order to satisfy the phase conditions. This makes the cross-polarized radiated fields cancelled out in the main beam region. However, there exist certain directions where they fail to disappear and such undesirable beams are so-called second-order beams(SOBs)[1].

In order to suppress the beams, it is a basic approach to use additional filtering structures such as baffles[1],[2]. However, they may increase the volume and weight of a whole antenna. Another approach is to employ untilted slots without the inherent source of SOBs. For their implementation, specific exciting structures are required such as incorporating tilted wires[3] or strips etched on dielectric substrates[4]. Thus, the untilted slots are somewhat complicated although they do minimize the cross-polarized fields. The third approach is to adjust the depth of the trough short between two adjacent waveguides[1],[5]. This is a principal way to implement the low cross-polarization. If the half-height waveguides are used, the optimized trough short can be a very good solution[6]. Nevertheless, it has a weak point that the optimal depth depends on an empirical guideline, and it is difficult to estimate the performance in advance without numerous measurements.

In this paper, we propose a simple and effective method to reduce the undesirable SOBs. By rearranging the stacking sequence of each waveguide and breaking the periodicity of cross-polarized components only, we show that the SOBs can be dispersed along the scanning direction. This can be considered as a compromise between two conventional sequences[1]. the first one is to preserve the slot orientations in the stacking direction, and the other is to alternate them and excite every other waveguide with the additional phase shift of 180°. In both cases, one or two of the SOBs become always visible in the space as the main beam gets scanned to a specific angle.

In order to validate the proposed method, theoretical estimation and radiation pattern measurements are performed. The results show that the SOB levels are significantly reduced irrespective of scanning angles.

Ⅱ. Theoretical Modeling and Analysis

Consider a 2D edge slot array on the x-y plane composed of linear waveguides aligned along the x-direction and stacked in the y-direction. In order to estimate its SOB characteristics, we represent each inclined slot as a half-wave magnetic dipole on an infinite ground.

With the parameters shown in Fig. 1, the far-zone electric field intensity by the (m,n)-th magnetic dipole element is given by

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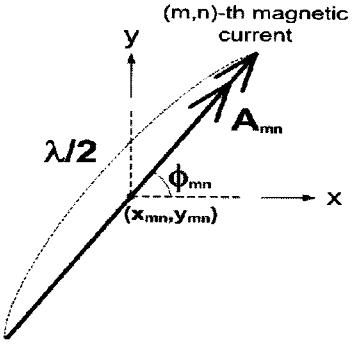


Fig. 1. A half-wave magnetic dipole model for each inclined slot and its necessary parameters for calculating the radiation patterns.

$$\vec{E}_{mn}^{el}=\frac{2jA_{mn}e^{-jk_0r}}{2\pi r}\tilde{e}_{mn}f_{mn}^{el}(\theta,\phi)$$

$$\begin{cases}\tilde{e}_{mn}=\hat{\theta}\sin(\phi-\phi_{mn})+\hat{\varphi}\cos\theta\cos(\phi-\phi_{mn})\\ f_{mn}^{el}(\theta,\phi)=\dfrac{\cos\left(\dfrac{\pi}{2}\sin\theta\cos(\phi-\phi_{mn})\right)}{1-\sin^2\theta\cos^2(\phi-\phi_{mn})}\end{cases}\tag{1}$$

where r, θ, ϕ, $\hat{\theta}$, $\hat{\varphi}$ are variables and unit vectors in the spherical coordinate and k_0 is a wave number in free space, respectively. Then, the total radiated field is easily represented as

$$\vec{E}\propto\sum_{m}^{M}\sum_{n}^{N}A_{mn}\tilde{e}_{mn}f_{mn}^{el}(\theta,\phi)e^{j\vec{k}_0\cdot\vec{r}_{mn}}\tag{2}$$

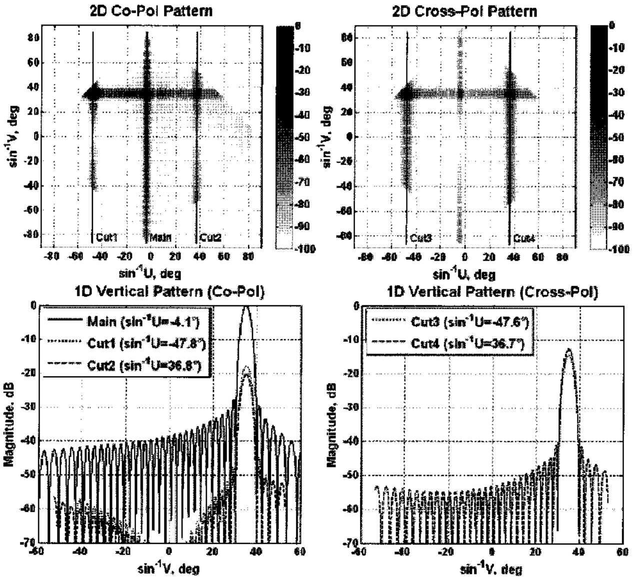
and it can be decomposed to the co- and cross-polarized components according to the Ludwig-3 definition on polarization[7].

In order to compare the SOB characteristics, the radiation patterns of two conventionally stacked arrays are calculated at the scanning angle of 35° using the array parameters given in Table 1.

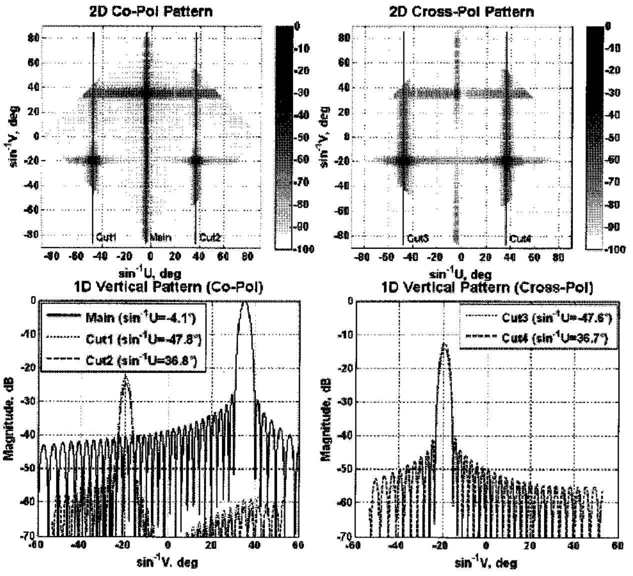
Table 1. Array design parameters.

Design parameters	Horizontal (x)	Vertical (y)
Total number of elements	54	39
Element spacing	0.7475 λ_0	0.553 λ_0
Pattern synthesis	Taylor's sum pattern SLL : −40 dB, n̄ : 5	Cos tapers on a pedestal $C+(1-C)\cos^n\{0.5\pi(n_y-n_{yc})/(n_{yc}-1)\}$ SLL : −28 dB

* C: constant, n_y: number of each element, n_{yc}: number of central element.



(a) Identically-stacked edge slot array



(b) Mirror-image edge slot array

Fig. 2. Calculated co- and cross-polarized radiation patterns of conventional arrays at the scanning angle of 35°.

As shown in Fig. 2, the patterns are plotted in the sine space, where a beam shape is invariant to its scan position[8] and the patterns in the U-V space[9] are directly mapped with their shapes preserved. Also, the unit circle in the U-V space is mapped to the rhombus ($|\sin^{-1}U|+|\sin^{-1}V|\leq 90°$) in the sine space.

In this figure, it is noteworthy that the peak SOBs are much higher than the main beam sidelobes and their locations are different for both cases according to the waveguide stacking sequences. Considering that each waveguide input phase can be so controlled with phase-shifters as to make the co-polarized components satisfy the required phase condition irrespective of the sequences, each slotted waveguide have to be stacked neither identically nor alternately in the y-direction. Therefore, rearranging the sequence makes it possible to break the y-directional periodicity of the cross-polarized components only, and consequently, the SOBs can be dispersed in the scanning direction.

Among the numerous stacking sequences, the optimal one is obtained through the typical genetic algorithm[10]. All the waveguides are divided into two groups and defined as 1 and 0 according to their slot orientations. Then, an arbitrary sequence can be represented as a simple vector. For example, the vector for a mirror-image array is written as

$$\bar{C}^0 = [\underbrace{01010101\ldots010}_{N\ elements}] \tag{3}$$

Note that this vector stands for the y-directional phase distributions of the cross-polarized components. By calculating the y-directional array factor with the above phase condition and predetermined amplitude distribution, it is possible to estimate how much the levels of the SOBs are changed as the variation of the vectors such as (3). This is because the 2D radiation patterns can be approximated to a product of the above array factor and the x-directional one which is invariant with the change of a stacking sequence. Assuming that A_n is the excitation amplitude of the n-th waveguide and d_y is the spacing between waveguides, the y-directional array factor $\boldsymbol{AF}$ becomes

$$AF(\bar{C}^k, \psi) = \sum_{n=1}^{N} A_n e^{jC_n^k \pi} e^{jnk_0 d_y (\sin\psi - \sin\psi_0)} \tag{4}$$

where C_n^k is the n-th element of the k-th chromosome vector $\bar{C}^k$. The variable ψ is an angle along the scanning direction in the sine space and ψ_0 is an arbitrary one. In order to connect eq. (4) to the genetic algorithm, the cost function is defined as

$$\textbf{Cost function} = 20\log_{10}\left(\max\left|AF(\bar{C}^0,\psi)\right| / \max\left|AF(\bar{C}^k,\psi)\right|\right) \tag{5}$$

The cost function (5) can be interpreted as a relative suppression level of the SOBs, which represents how much the SOB peak of the k-th array can be suppressed in comparison with that of a mirror-image array or an identically-stacked one.

After the genetic iterations with this cost function, the maximum relative suppression level of about 12.7 dB is finally obtained, together with the following optimized vector $\bar{C}^{OPT}$.

$$\bar{C}^{OPT} = [001\ 001\ 111\ 100\ 001\ 010\ 011\ 110\ 111\ 011\ 101\ 101\ 110] \tag{6}$$

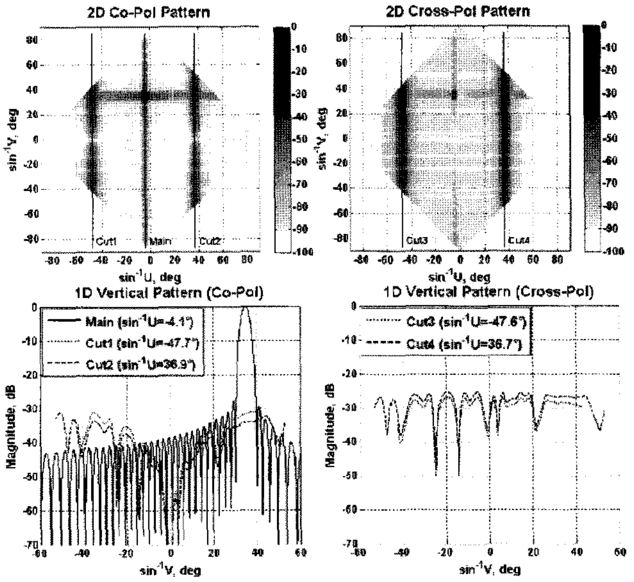


Fig. 3. Calculated co- and cross-polarized radiation patterns at 35° scan of the array stacked in the genetically-optimized order.

Fig. 3 shows the 2D radiation patterns given by $\bar{C}^{OPT}$ at the same scanning angle of 35°. As expected, the undesirable peaks in both patterns are dispersed along the scanning direction and reduced to less than −29 dB in the co-polarized pattern and −25 dB in the cross-polarized pattern, respectively. This suppression level is consistent with the value of 12.7 dB estimated by the genetic optimization of only the 1D array factor.

Ⅲ. Measured Results

The proposed method is applied to an X-band 54 by 39 edge slot phased array antenna which has been fabricated before. Since its waveguides were stacked in alternating order, two SOBs appeared in the visible space in case of scanning. However, the optimized sequence given by (6) could not be directly applied to this antenna since three waveguides had one flange in common and they constituted one module as shown in Fig. 4(a), and thus, the whole array was composed of six A- and seven B-modules in Fig. 4(b) which were alternately arranged(B-A-B-A⋯B-A-B). Therefore, a new optimal sequence should be required under this criterion. Since the number of possible cases is considerably decreased, all the sequences have been examined and the optimal one is finally obtained as follows.

$$\begin{aligned}&[\mathrm{A\ B\ B\ B\ B\ A\ A\ A\ B\ A\ A\ B\ A}]\\ &= [010\ 101\ 101\ 101\ 101\ 010\ 010\ 010\\ &\quad 101\ 010\ 010\ 101\ 010]\end{aligned} \tag{7}$$

Although the suppression level given by (7) is estimated at about 9 dB which is 3.7 dB less than the

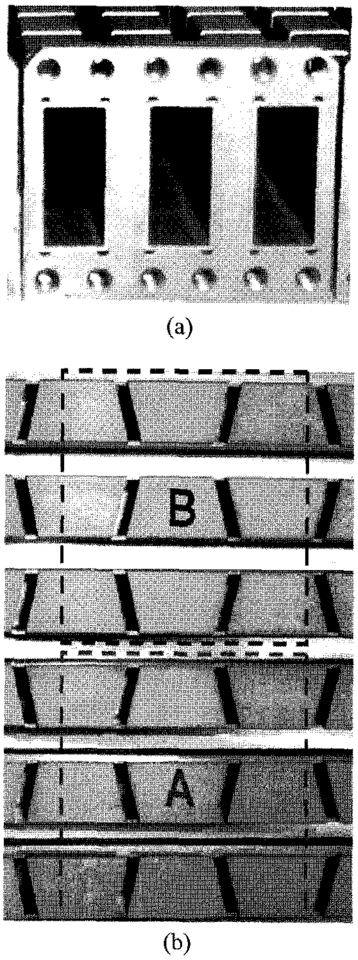


Fig. 4. (a) One module composed of three waveguides which hold one flange, (b) Two types of modules; type A and type B.

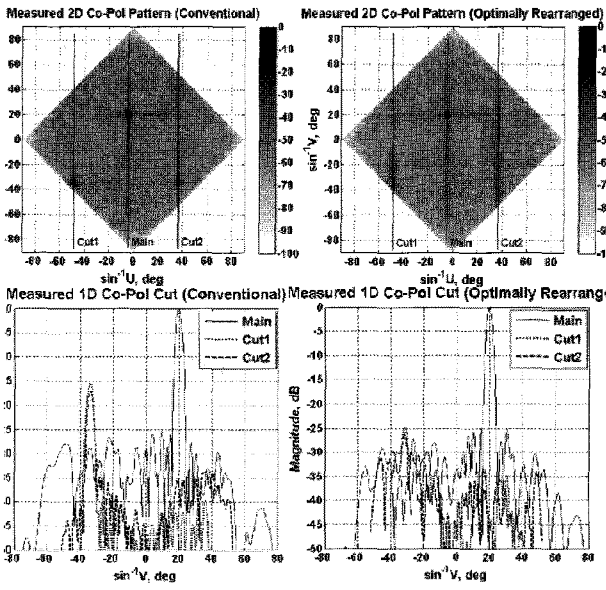
Table 2. Measured SOB levels at four scanning angles.

Scan angle	Co-polarized pattern	
	Maximum at Cut 1	Maximum at Cut 2
0°	−30.0 dB	−27.9 dB
10°	−26.4 dB	−26.8 dB
20°	−24.8 dB	−26.1 dB
35°	−25.0 dB	−26.7 dB

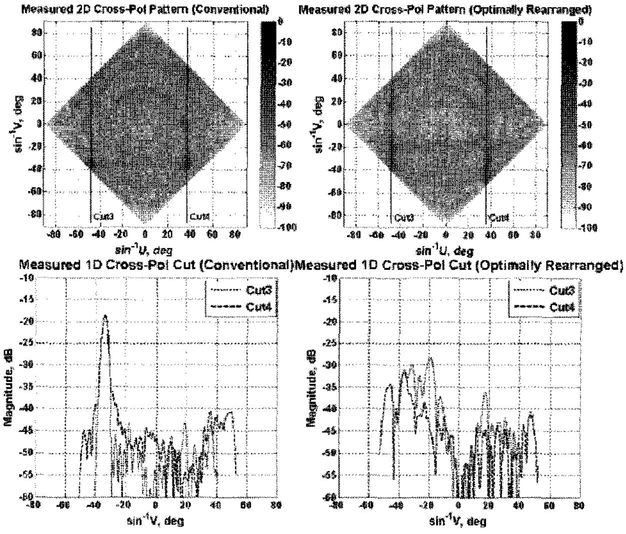
Scan angle	Cross-polarized pattern	
	Maximum at Cut 1	Maximum at Cut 2
0°	−37.6 dB	−30.1 dB
10°	−37.5 dB	−29.5 dB
20°	−28.3 dB	−30.9 dB
35°	−28.8 dB	−29.4 dB

previous value, this is enough to verify the proposed method.

In order to validate the improved performance of the rearranged antenna, its radiation patterns are obtained through the near-field measurements. In Fig. 5, the measured results are compared with those of the previous mirror-image array at the scanning angle of 20° where the measured SOBs are most conspicuous. As expected, the undesirable peaks are remarkably reduced to less than −24.8 dB and −28.3 dB in co- and cross-polarizations, respectively, with the main beam characteristics conserved. If these values are compared with the SOB levels of −15.5 dB(co) and −18.5 dB(cross) obtained from the conventional way, the suppression level is con-



(a) Co-polarized radiation patterns



(b) Cross-polarized radiation patterns

Fig. 5. Measured radiation patterns of the optimally rearranged array compared with those of the previous mirror-image array at the scanning angle of 20°.

sistent with the estimated value of 9 dB. For completeness, the peak SOB levels at four scanning angles are summarized in Table 2, which shows good results over the whole scanning range required(<35°).

Ⅳ. Conclusions

A practical and cost-effective method is proposed to suppress the undesirable SOBs of an edge slot phased array antenna. Only by rearranging waveguides in a proper manner without adding any filtering structures or optimizing the trough short, the SOBs due to slot inclination are shown to be considerably reduced. In order to validate the proposed method, it is applied to an existing edge slot phased array antenna and the 9 dB SOB suppression is obtained. Therefore, this technique is expected to be widely used in the design of an inclined slot array antenna for the single-plane scanning applications.

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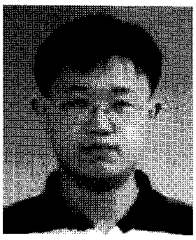

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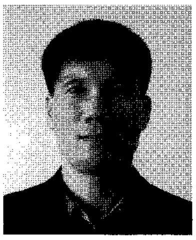

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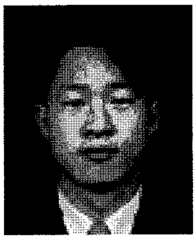

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