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Mutual coupling reduction through choke structures in a Slotted Waveguide Antenna Array

Shandipsing Robee

Thales LAS
Elancourt, France

shandipsing.robee@thalesgroup.com

Anne-Charlotte Amiaud

R&D departement

Thales LAS
Elancourt, France

anne-
charlotte.amiaud@thalesgroup.com

J. P. Coupez

Lab-STICC, IMT Atlantique
Brest, France,

jp.coupez@imt-atlantique.fr

Thomas Merlet

R&D departement

Thales LAS
Elancourt, France

thomas.merlet@thalesgroup.com

Christian Person

Lab-STICC, IMT Atlantique
Brest, France,

christian.person@imt-atlantique.fr

Abstract— This article presents a comprehensive study on reducing mutual coupling in a slotted waveguide antenna array (SWAA), operating in the X band. The objective is to limit such parasitic coupling effects on radiation pattern performances. Optimised choke structures are inserted between adjacent slots sub-arrays in order to control surface currents distribution. Simulation results exhibit a remarkable reduction on isolation between adjacent waveguides. This induces an overall performance improvement in terms of main beam and side lobes control. Furthermore, using field calculator on HFSS™, the e-field levels of each slot are extracted. The plus points and drawbacks of the choke structure on the radiation pattern are then explained.

Keywords—Direct Metal Laser Sintering (DMLS), Mutual coupling reduction, Slotted Waveguide Antenna Array (SWAA), Choke, 3D printing

I. INTRODUCTION

In modern adaptive radar applications, mechanical beam steering antenna arrays have been replaced by Active Electronically Scan Array (AESA), offering improved performances (compactness, beam-scanning...) [1]. In AESA structures, slotted waveguide antenna [2] arrays have been widely used instead of planar arrays as they offer low-loss structures and can handle high power levels [3].

SWAA were initially fabricated through conventional metal machining process, with drawbacks (cost, limited geometrical complexity...) [4]. Additive manufacturing techniques like 3D printing and Direct Metal Laser Sintering (DMLS) have made accessible low-cost prototyping with enhanced complexity [5].

Beamforming capabilities in AESA generate compactness constraints, regarding the number of radiating elements to be used to create beam diversity. This inevitably increases interferences between adjacent slotted waveguides structures due to proximity effects and mutual coupling affecting performances in terms of radiation characteristics [6].

This work proposes an optimised choke structure in order to reduce mutual coupling and to increase isolation levels between adjacent slotted waveguides. The objective of this paper is to underline the success of the proposed choke structure on mutual coupling reduction while also highlighting

its impact on radiation pattern properties. This is done by displaying the electric field on each slot while simulating the structure on HFSS™. An analysis of the radiation pattern and electric field level is then done, with and without the choke structure.

II. THEORETICAL BACKGROUND

A quarter wavelength groove called choke, as shown in figure 1, is often used as a decoupling option [7], [8], providing a practical and efficient solution to mitigate mutual coupling effects.

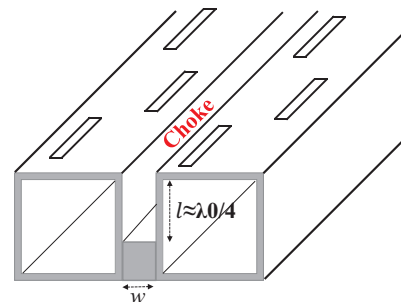


Figure 1: Choke between two adjacent slotted waveguides

The choke structure is equivalent to a short-circuited quarter wavelength stub, between a load and a source, used in transmission lines theory in order to reduce an impedance mismatch [9].

It means that, when a groove of length $\lambda_0/4$ is applied between two adjacent slotted waveguides, its upper region will be an open circuit with an infinite impedance. In reality, the impedance will be very high but not infinite. Having a very high impedance on the choke upper part will prevent the flow of surface currents, hence reducing mutual coupling between adjacent waveguides.

III. VERTICAL SLOTTED WAVEGUIDE DESIGN AS A GROOVE

Usually, the quarter wavelength groove is carved directly in a piece of metal using traditional metal machining process. Those processes have some limits. For example, when using a drill to carve the choke, its bottom is not a perfect rectangle but rounded. This can modify the short-circuit property of the choke structure and make it less efficient. Moreover, in our

case, the choke has reduced dimensions, typically a width (w) of 1 mm large and a depth (l) of 7.5 mm. Drilling such a small groove with precision can be quite complex and costly. The groove can also present some manufacturing irregularities along its length.

To overcome those hurdles, we have investigated an alternative approach to integrate such choke structures exploiting DMLS printing technology. The overall structure, including the choke and the adjacent waveguides can be printed at once. By this means, a high-quality complex structure of the slotted antenna array can be designed under low cost processing considerations. The design of the slotted waveguide array antenna is composed of 3 waveguides, each containing 4 radiating slots as shown in the figure 2.

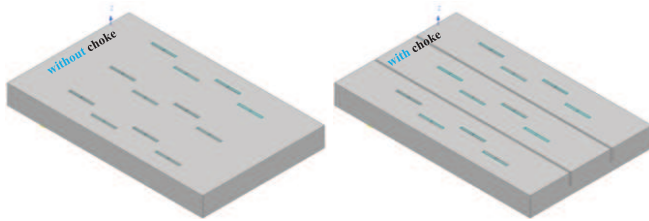


Figure 2: Slotted waveguide antenna array, with and without choke

IV. MUTUAL COUPLING REDUCTION

The slotted waveguide antenna array and the choke structure are optimised for an X-band antenna array. With the use of the choke structure, the isolation between adjacent waveguides is improved, leading to an enhancement in the overall performance of the antenna array.

To evaluate the efficiency of the proposed choke configuration and its influence on the radiation pattern, simulations using HFSSTM software were conducted. The effect of the choke structure on the mutual coupling are often monitored by observing the Scattering parameters [10].

In the following section, the central waveguide of the three parallel sub-linear-array (each containing 4 radiating slots) is fed and the mutual coupling on the other two waveguides is observed in figure 3.

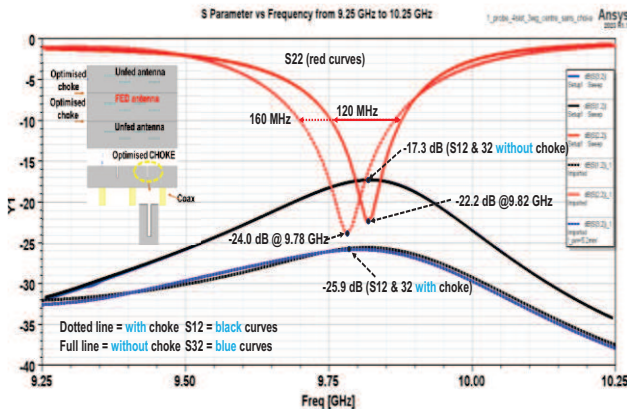


Figure 3: S parameters of a 3*4 SWAA centre fed

Without the choke, the reflection coefficient (S_{22}) has a value of -22.2 dB (@ 9.82 GHz) and the isolation coefficients are at -17.3 dB (@ 9.82 GHz).

Adding the choke cause the reflection coefficient to decrease to -24.0 dB (@ 9.78 GHz) and the isolation

coefficients to reach a value of -25.9 dB (@ 9.78 GHz). It means that only a small part of the mutual coupling occurs after adding the quarter wavelength groove. The low frequency shift of 40 MHz (from 9.82 GHz to 9.78 GHz) can be easily overcome by adjusting the antenna dimensions.

The antenna bandwidths are defined as the frequency ranges in which the reflection coefficients are lower or equal to -10 dB. It can also be noted that the introduction of the choke induces an increase of the bandwidth, from 120 MHz to 160 MHz (@ S_{22} value -10 dB). This can be explained by the fact that the central fed waveguide is disturbed by the mutual coupling from the two unfed waveguides. One of the consequences is that its input impedance is altered, which in results diminishes its bandwidth. When the chokes are added, they reduce the surface current between adjacent waveguides. Thus, the input impedance of central waveguide is less affected leading to an increase in bandwidth and an increase in the isolation.

The mutual coupling can be observed qualitatively by observing the surface current distribution on the antenna array (Figure 4). On figure 4-a, (no choke), high current leakage can be spotted on the unfed waveguides. Adding the optimised choke structure decreases drastically those leakages (fig 4-b).

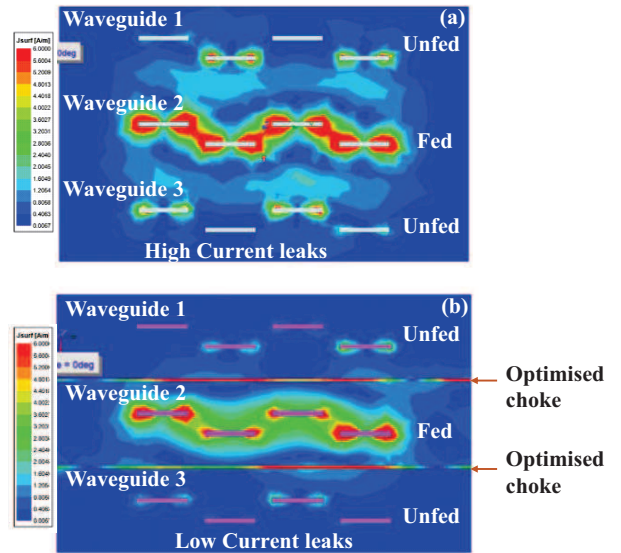


Figure 4: Centre fed SWAA: Surface current leak on the upper metallic plane

V. CHOKE EFFECT ON THE RADIATION PATTERN

Most publications in the literature shows only the positive mutual coupling reduction impact of the choke. The decoupling ability of the choke is only shown globally in terms of S parameters. With such information, it is almost impossible to analyse properly the effects of the choke. The only way possible to have a good visualisation is to display what is happening locally on each slot, before and after adding the choke. In this section, the positive influence of the choke will be underline, as well as its drawbacks, on the radiation pattern and the waveguide slots antenna's weightings.

In order to facilitate the explications, the radiation pattern is divided into 4 zones: a, b, c and d on figure 5. The E planes curves are blue and the H plane curves are red. The dotted lines represent the SWAA without choke and the full lines with choke.

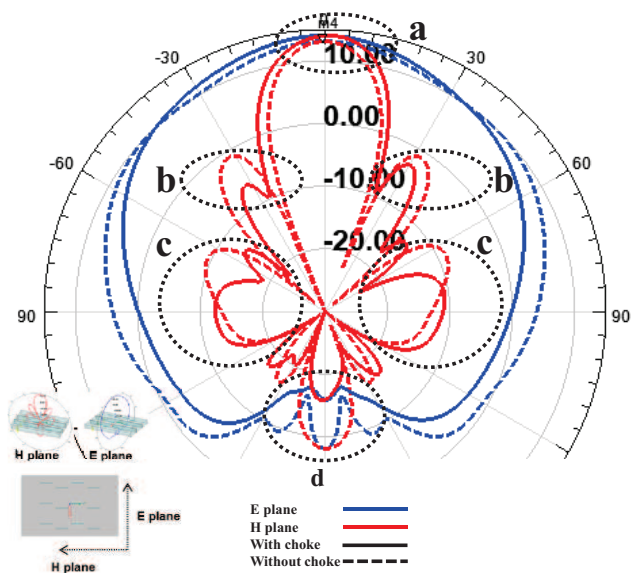


Figure 5: Radiation pattern improvements

In zone “a”, the E plane is more directive along the axis with the choke. The choke makes the radiation more effective in the desired radiation plane, that is, perpendicular to the SWAA plane.

Similarly, in zone “d”, the E plane back lobe decreases from -8 dBi to -16 dBi. The choke prevents most of the surface current overflow towards the back of the SWAA. This is mainly due to a reduction of undesired currents in the external parts of the slots reference ground plane (i.e. the upper face or the metallized aligned waveguide), with therefore a reduced contribution of the different discontinuities (corners of the waveguides) in the backward radiation.

The positive influences of the choke on the H plane are:

- In zone “a”, the gain increases from 13 dBi to 14 dBi
- In zone “b”, first side lobes are decreased by 5 dB on the left and by 3 dB on the right
- In zone “c”, second side lobes are decreased by 2 dB on the left and by 1 dB on the right
- In zone “d”, the back lobe is decreased by 8 dB.

At a quick glance, we can rapidly conclude that the overall radiation pattern has been improved by the addition of the choke. But, if we look closely at the curves some issues can be identified, mainly in the H plane (red curves).

The negative consequences of the choke on the H plane (red full line curves) are:

- In zone “a”, the H plane becomes less directive. That is the main lobe is larger with the choke than without.
- In zone “b”, we can observe some dissymmetry. The left and right side of the first side lobe are not equal. It can be explained that the weightings on each slot in the fed waveguide are no more equal.
- A dissymmetry is also noticed in zone “c” after the choke was added.

Normally, it was not expected that the choke will have such a significant influence on the H plane. We can suppose that the weights and the phases of the field distribution on each slot of the central waveguide are change in the presence of the choke. This alteration does not allow correct summation required to have a symmetric radiation pattern.

The above phenomenon can also qualitatively be observed when looking at the surface currents on the top of SWAA while varying the phase of the field distribution of the slots in the central fed waveguide from 0° to 360° (figure 6).

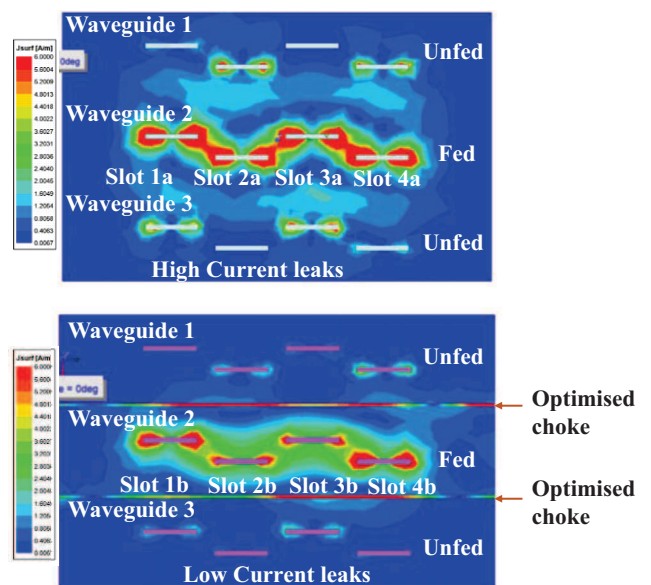


Figure 6: Centre fed SWAA: Surface current leak on the upper metallic plane at a particular phase (0°).

Without the choke, when the phase of the slots field distribution on the central fed waveguide is varied from 0° to 360°, all 4 slots (slot1a, slot2a, slot3a and slot 4a) lights up and turn off at the same time. It means they are in phase and the weights for the 4 antennas are equal.

With the choke, when the phase of the E-field is varied from 0° to 360°, we can observe that Slot 1b and Slot 4b, resonate together but not at the same time as Slot 2b and Slot 3b. Slot 2b and 3b, light and turn off at the same time. To summarise, Slots 1b/4b and Slot 2b/3b are out of phase in the presence of the choke.

This phenomenon was not expected. Normally, no changes were expected on the fed waveguide as with and without the choke the feeding, position of the slots and general configurations stayed the same.

Till now, the observation was made only qualitatively. In order to better understand the phenomenon, we need to know the impact of the choke on amplitudes and phases distributions in each slot.

VI. ON SLOT LOCAL DISPLAY OF THE ELECTRIC FIELD

The local E-field display is done by adding a “polyline” together with the use of field calculator. The polyline acts as a probe during simulations on HFSS™ when placed on each slot antenna centre phase as shown Figure 7. The electric field

value is then calculated using the field calculator with the appropriate equations on HFSS™.

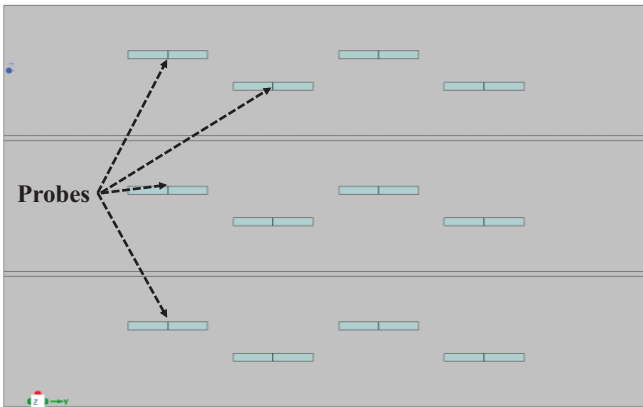


Figure 7: Probes on the centre phase of each slot antenna

The n° 8 picture depicts the SWAA without the choke.

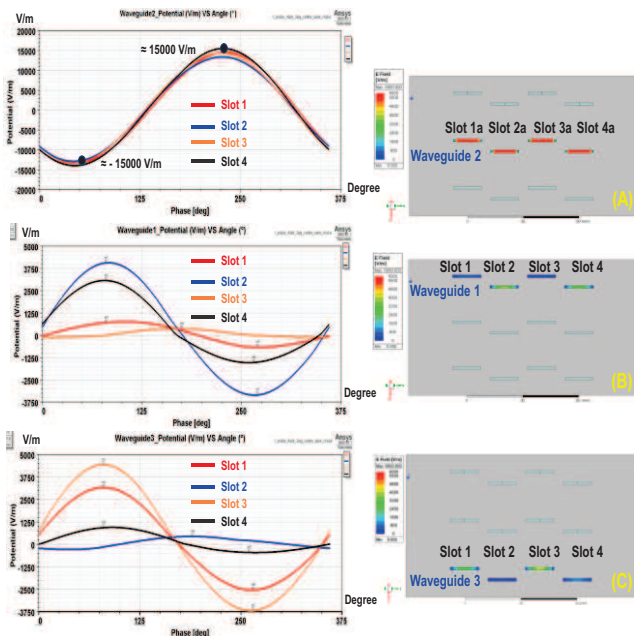


Figure 8: E-field phase and amplitude on each slot without choke

The graphs show the variation of the electric field with the phase of the slots on the SWAA without the choke.

Figure 8-A shows the centre fed waveguide (waveguide 2). It can be observed that all four slots present on this waveguide are in phase and have equal field amplitude of 15,000 V/m. It means that the weighting on those slots are equal. To obtain a radiation pattern, the weights of the four central waveguides are added. The result is the red dotted H plane radiation pattern present in figure 5. As all weights are equal and have the same phase, the resultant radiation pattern is symmetric.

Figures 8-B (waveguide 1) and 8-C (waveguide 3) show the unpowered couple waveguides. The maximum field amplitude on each slot of those two waveguides is around 5000 V/m. Here we have the evidence of mutual coupling between adjacent waveguides in SWAA as only the centre waveguide is fed here.

In figure 8-B, slot 2 and slot 4 have the highest E-field levels as they are closer to the central fed waveguide. Slot 2 level is higher than slot 4 as it is surrounded by slot 1 and 3. While slot 4 is at the end of waveguide 1. It only one slot close to it.

A similar observation is made in figure 8-C. Slot 1 and Slot 3, have the highest levels as they are closer to the central fed waveguide. Slot 3 E-field level is higher than slot 1. This is because slot 1 is at the start of waveguide 1 and has only one slot close to it.

Figure 9 illustrate the SWAA in the presence of chokes.

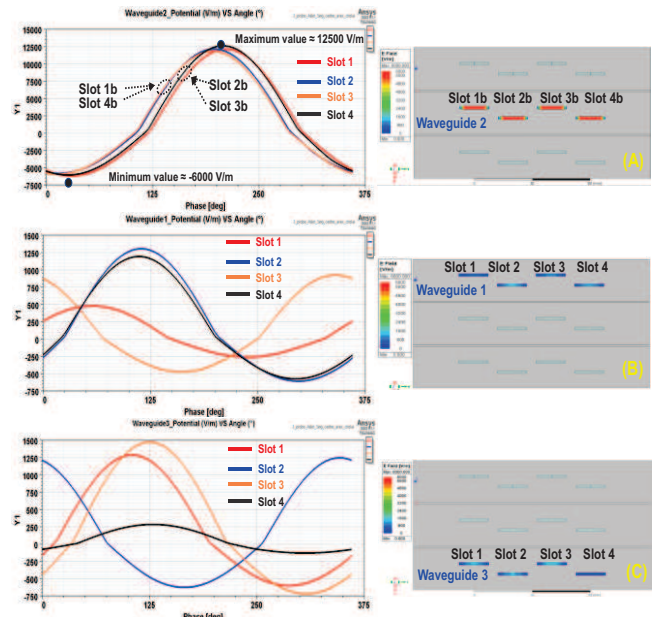


Figure 9: E-field phase and amplitude on each slot with choke

The graphs show the variation of the electric field with the phase of the field distribution in each slot.

Figure 9-A show the centre fed waveguide. We can already observe that the electric field amplitudes on the powered waveguide have been altered by the presence of the quarter wavelength groove. Going from 15000 V/m to 12500 V/m on the top and from -15000 V/m to -6000 V/m. This means that the weight attribution to each of the individual antenna is no more perfect. Additionally, we can observe an offset on the graphs. Investigation is still going on to know why the addition of the choke causes this offset.

Furthermore, we can remark that Slots 1b/4b and Slot 2b/3b are out of phase by 10° in the presence of the choke. The fact that all the slots are no more in phase was qualitatively observed in Part 5. This leads to an inefficient recombination of the individual slot weightings causing a dissymmetry in the radiation pattern. We suppose that this snag can be overcome by slightly readjusting the positions of slot 2b and slot 3b in terms of alignment and distance between phase centres. Research is still going on to confirm this supposition.

Now considering Figures 9-B and 9-C, we can notice that the electric field coupled on the unpowered waveguide has drastically decrease. The level falling from a 5000 V/m in the upper part to 1500 V/m and from 5000 V/m in the lower part to 500 V/m. The average coupled electric field have been

divided by 5. We can now say that the presence of the choke reduces the mutual coupling by 5.

Here the same curves offsets are observed. An inquiry is still going in order to better understand those observations.

VII. OUTLOOK AND CONCLUSION

This paper makes a complete investigation on the effects of adding a choke structure on a SWAA. It also explains how the choke is used to reduce unwanted parasitic coupling in a SWAA design. Then with the help of a new methodology of e-field calculation with the help of probes on HFSS™ show the plus points and drawback of the choke structure.

The knowledge of the in detailed functioning of choke structure helped us to readjust and optimise our design further. Once the chokes added, the slots position can be modified to put the right weighting on each of them. Our final structure will be composed of a double choke structure decreasing the mutual coupling by 1 or 2 more dB.

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