PHASED ARRAY USING THE SEQUENTIAL ROTATION PRINCIPLE: ANALYSIS OF COUPLING EFFECTS

L. Baggen [(1)], S. Holzwarth [(2)], W. Simon [(3)], O. Litschke [(4)]

IMST GmbH
Carl-Friedrich-Gauss-Str. 2, D-47475 Kamp-Lintfort, Germany
[(1)] *Tel.: +49 2842 981-323 Fax:-399 e-mail: baggen@imst.de*
[(2)] *Tel.: +49 2842 981-326 Fax:-399 e-mail: holzwarth@imst.de*
[(3)] *Tel.: +49 2842 981-247 Fax:-299 e-mail: simon@imst.de*
[(4)] *Tel.: +49 2842 981-321 Fax:-399 e-mail: litschke@imst.de*

ABSTRACT

The growing demand for broadband multimedia services urges the aeronautical industry to provide bi-directional on-board communication services in near future. Today, the first aircrafts are already being equipped with the technology necessary to provide internet access for staff and passengers. Up to now, these solutions are developed to operate in L- and Ku-Band, due to the satellite systems available and the existence of affordable RF-components for these frequency ranges. Considering broadband multimedia applications, however, it is obvious that in the near future the technology will have to explore higher frequency regions like Ka-Band, where the required bandwidth can be provided. Several studies show that, for airborne broadband satellite communications, the terminal antenna is one of the key components in the system design. To compensate for the aircrafts movement, the terminal antenna must be steerable, to allow satellite tracking. Due to the limitations of mechanically steerable antennas, an electronically steerable array antenna using digital beamforming seems to be the most promising solution. Still, the development of such antenna arrays in Ka-Band technology faces high demands regarding performance, integration and, last but not least, component costs. In the framework of a project called SANTANA (Smart ANtenna TermiNAl), funded by the german government (BMBF) on behalf of the DLR, several antenna concepts have been investigated. One promising concept, which will be discussed in this paper, is a transmit-only array at 30 GHz that uses the sequential rotation principle to improve the circular polarisation.

1.0 INTRODUCTION

The requirements for the antenna considered here are very stringent, as it has to be able to scan down to as much as 60° from boresight, and still satisfy ETSI specifications [1] [2]. Because it is a planar array, the constraints on the axial ratio are very demanding. The design is based on circularly polarised patch elements, arranged in a sequentially rotated fashion [3]. The number of elements amounts up to more than 4000 (64x64). The beam of the array is steered and formed electronically by applying different amplitudes and phases to the antenna elements by employing Digital Beam Forming (DBF). Phase and amplitude shifts are applied on baseband level with a direct up- or down-conversion of the transmitted or received signal at each antenna element. This allows a high flexibility in the generation of the array pattern. Due to the spatial arrangement of the patch elements, the coupling effects have a large impact on the axial ratio, and are therefore of main interest for the design. This paper focuses on the analysis of these coupling effects, the models applied and possible improvements based on this analysis.

Firstly, the basic configuration of the element itself and the array are presented, along with some main specifications. Thereafter, the modelling of the array using the field solver Empire, based on the FDTD (Finite Difference Time Domain) principle, and the determination of the far field patterns of the complete array are described. Also, a glance at coupling models in general is also included. This is followed by a detailed description of the investigated coupling effects, and the coupling model used here. Finally, the results are summarised and presented in the conclusions.

2.0 BASIC ELEMENT & CONFIGURATION

The basic antenna element consists of a circularly polarised patch element, which is fed by a circular waveguide via an elliptical slot. All patches of the array have a square shape, and can each be separately steered in amplitude and phase. The schematic is displayed in figure 1.

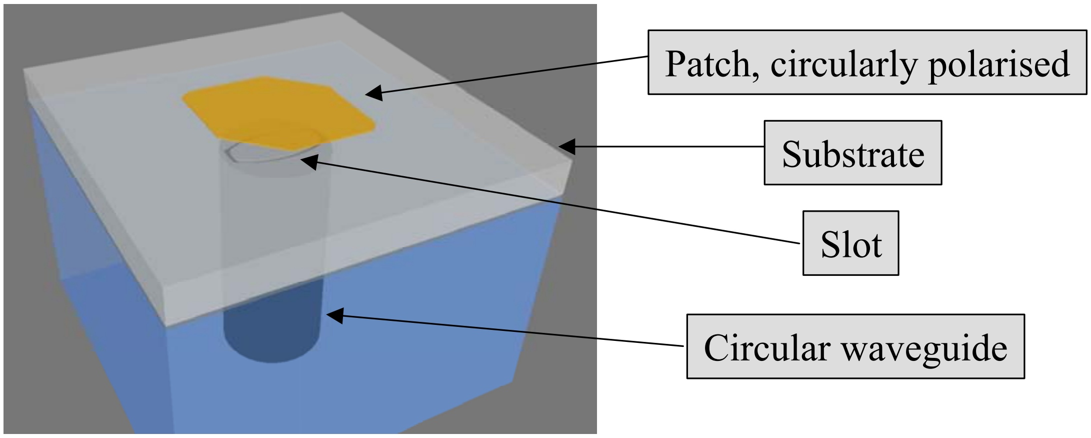


Figure 1. Overview of the basic antenna element.

As mentioned previously, these elements will be sequentially rotated as indicated in figure 2, in order to improve the axial ratio. The patches are not only rotated spatially 90° with respect to each other, but also fed with a 90° phase shift. Normally, the sequential rotation principle is used to generate circular polarisation when using linearly polarised patch elements [3]. Yet, the use of sequentially rotated circularly polarised elements enhances the polarisation behaviour of the array [4], and bring the design one step further towards fulfilling the stringent requirements. The array will be composed of approximately 4000 of such elements, arranged in subgroups of 4 rotated elements. The frequency bandwidth is 29.5-30 GHz, and the element spacing is approximately 5 mm (about half a wavelength at 29.7 GHz). The maximum scan angle is 60° with respect to boresight. Because the bandwidth is an uncritical parameter in the design, all radiation patterns given in this paper will be determined for the centre frequency of 29.7 GHz.

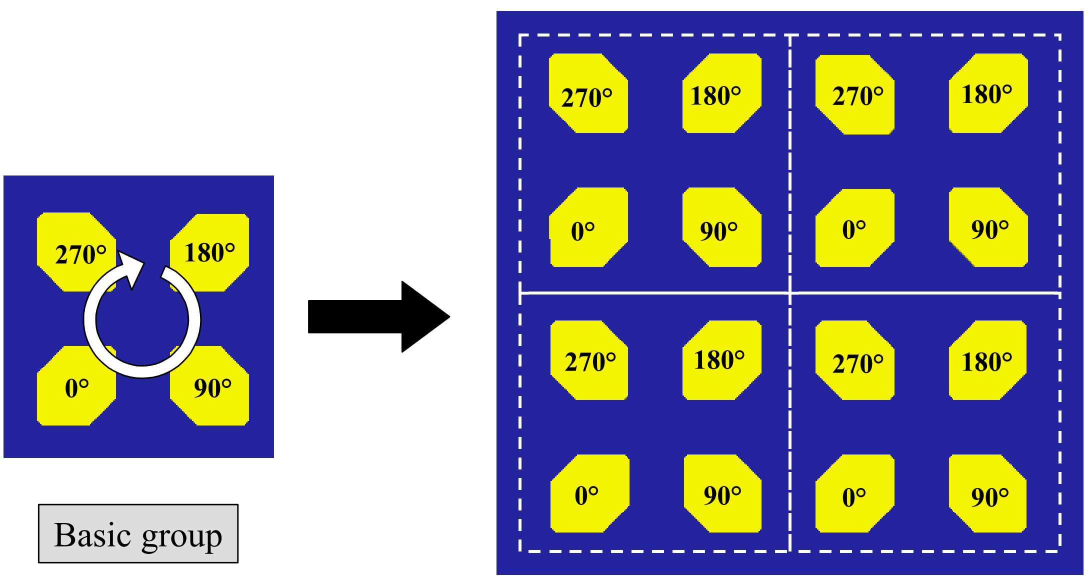


Figure 2. Patches arranged according to the sequential rotation principle.

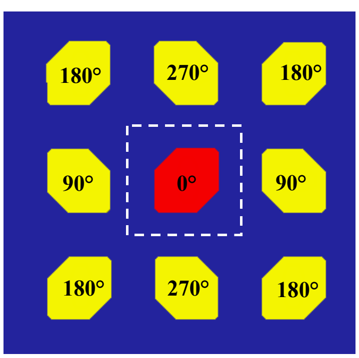
3.0 BASIC MODELLING OF THE ARRAY

The radiation patterns and the input return loss are determined with the help of the FDTD-field solver EMPIRE. It is impossible to model a large number of such complex elements due to practical restrictions as available memory and computation time, which limit the size of the array model. Moreover, beam steering, which is one of the key points of the design, is difficult to implement with FDTD-modelling. Thus, the following approach has been adopted: only a small number of elements are modelled, yet the most significant coupling effects, also called "first order" coupling effects, are included. Normally, this involves embedding the active element in the array structure, and taking only its direct neighbours into account, as displayed in figure 3a. These neighbours are considered as passive components, and are terminated with an ideal impedance (in the model, PML-walls).

The complete radiating structure (active and passive patches) is enclosed by a box that registers the near fields, as shown in figure 3a. In order to obtain the far fields, the E- and H-fields on the walls of this box are transformed, using image theory and the equivalence principle [5]. The far field pattern of this embedded element is multiplied by the appropriate array factor, in order to arrive at the far field pattern of the complete array. This is also called the C-approach [6]. By adding a phase shift for each element, the influence of coupling on the scan performance can also be easily investigated.

4.0 COUPLING EFFECTS

The sequential rotated configuration implies that the patches are arranged in groups of 4 elements, which are each situated spatially in a 90° shifted sequence (see also figure 2). First simulations have shown that this spatial orientation has a major impact on the determination of the far field patterns. Thus, modelling only one active element surrounded by passive elements does not suffice. The basic model, as presented in figure 3a, has to be extended to account for the special configuration. Therefore, the basic group adopted here consists of a total of 16 elements: a group of 4 elements sequentially arranged, surrounded by a ring of passive neighbours as depicted in figure 3b. This model is still quite good to handle with respect to required simulation time and available CPU-memory. For each of the 4 patches in the group the far field is determined, considering 1 active patch, and the remaining 15 as passive elements. Afterwards, the sequential 90° phase shift is added, and the 4 far field patterns are superimposed, with the phase centre located in the centre of the 4 patches. The far field of the phased array is calculated by multiplying the group pattern, derived from simulation, by the appropriate array factor (based on superimposing 2x2 groups of patches). This approach still offers the possibility to steer each patch with a variable amplitude and phase shift, thus enabling investigation of the scanning behaviour and tapering.



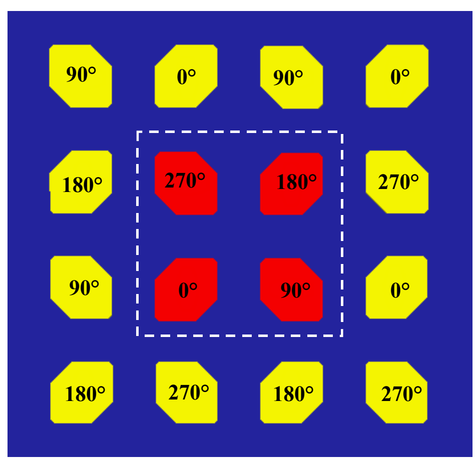


Figure 3. Coupling: general first order model (a), extended sequential rotated model (b), active patches in red.

An interesting aspect that was noticed during the investigations is that the properties of the circularly polarised patch change very quickly due to coupling. The stand alone patch (without any neighbouring patches) shows excellent properties with respect to circular polarisation. When introduced in a sequentially orientated 2x2 group, its circular performance decreases dramatically, which also applies when introduced in a 4x4 configuration. The co- and cross-polar patterns of these three configurations are displayed in figure 4 (active patch is red). This does not imply that the patch has to be redesigned right away. Indeed, the presence of the neighbouring patches influences negatively the characteristics of the active patch, yet when the radiation patterns of the 4 active patches of a single sequential rotated group are superimposed, a large part of this influence is cancelled because of the applied sequential principle.

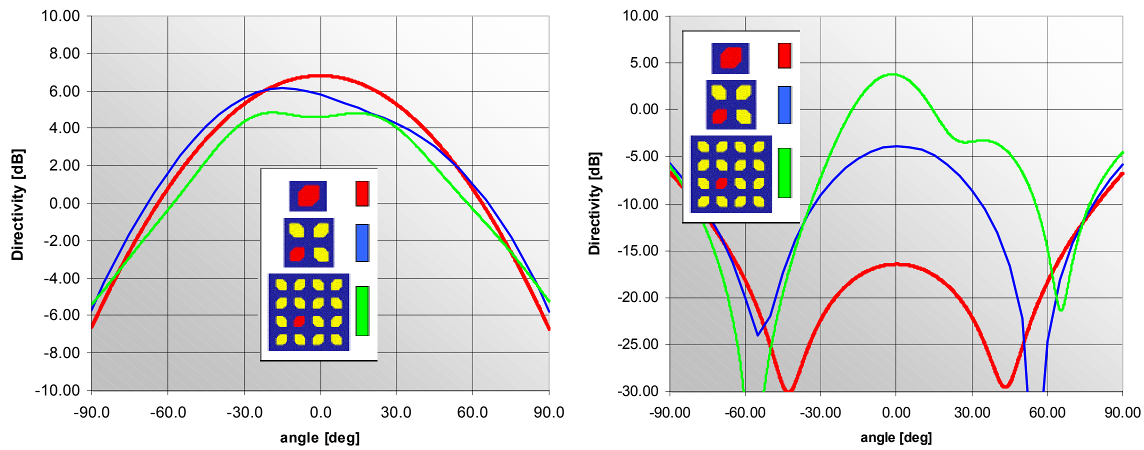


Figure 4. Co- (left) and cross-polar (right) patterns for different patch configurations, cardinal plane.

The far field patterns of an array composed of 64x64 elements for different scan angles (0° and 60°) are shown in figure 5a and 5b. One is based on the far field pattern of a stand alone patch, and the other on the 4x4 group model of patches as displayed in figure 3b. It is clearly visible that the coupling cannot be neglected, and causes severe problems, especially during scanning. The gain is reduced and a high sidelobe appears in case of scanning at 60° in the vicinity of -10°, which is due to coupling. The corresponding cross-polar components, which are not shown here, are also much higher when coupling is included. For the inter-cardinal planes, the situation is even worse, as the sidelobes increase dramatically in certain angle regions.

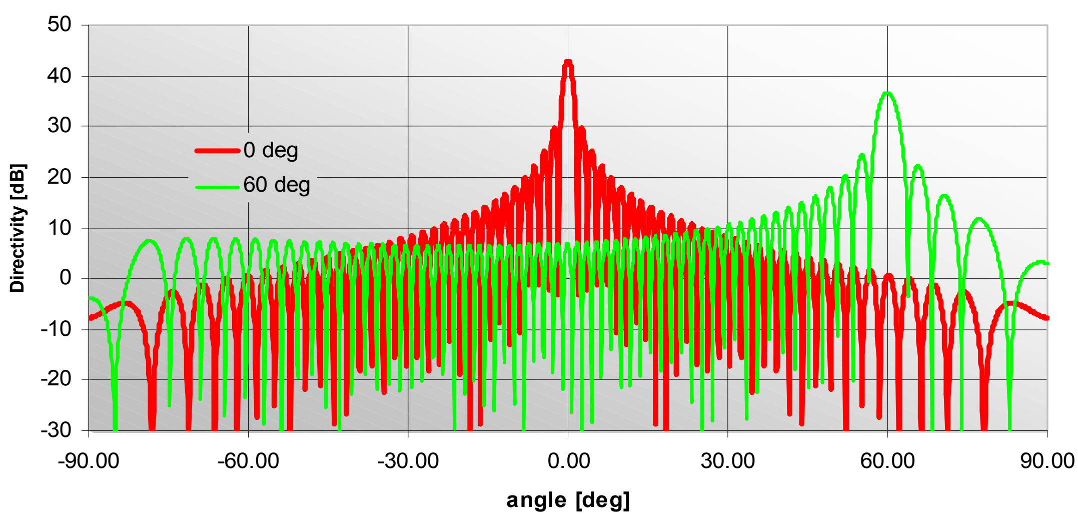


Figure 5a. Co-polar patterns of the phased array (64x64 elements), scan angles 0° and 60°, cardinal plane, without coupling.

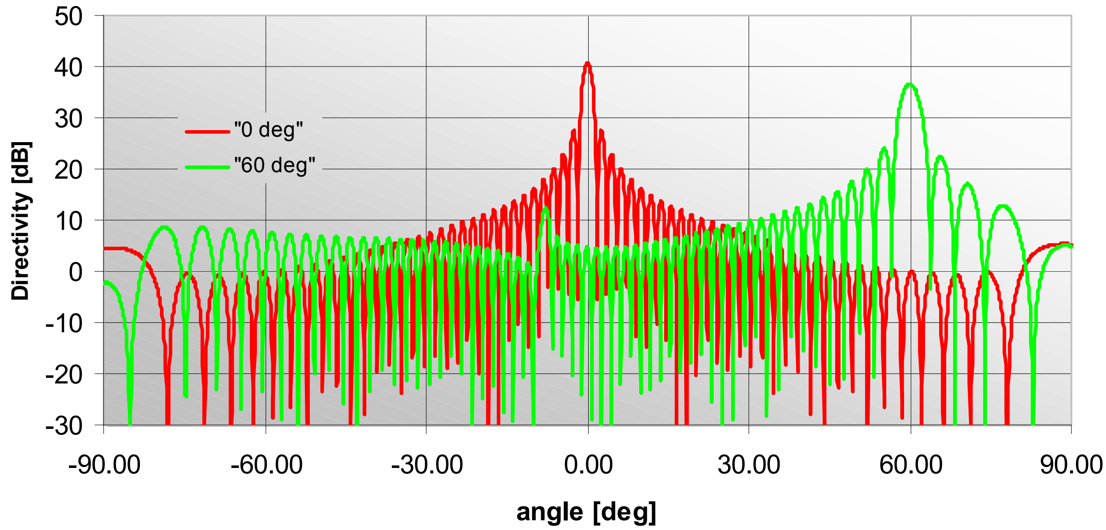


Figure 5b. Co-polar patterns of the phased array (64x64 elements), scan angles 0° and 60°, cardinal plane, with coupling.

5.0 POSSIBLE CAUSES & SOLUTIONS

In order to determine the major coupling effects, different possibilities have been investigated. Two major coupling mechanisms can be distinguished:

- Coupling via surface waves. The substrate used is rather thick (about 800 μm), and can give rise to the propagation of surface waves. In this case solutions like Photonic BandGap (PBG) structures [7], vias or similar approaches could be considered. Yet, simulations show surprisingly that only a little part of the total energy radiated is propagating via the substrate. This can be derived from the FDTD-model by applying the same box used to determine the far field (see section 3.0). To check these results, two different approaches have been considered: one model has been defined with solid metal walls between the patches, to short-circuit possible surface waves, and another model was defined with a thinner substrate. The results of these simulations are almost identical to those of the original model. This is a strong indication that surface waves can be neglected for this configuration, when considering coupling.
- Coupling via the neighbouring patches. This coupling mechanism is rather complex. It is caused by the near field generated by the active patch, which in turn excites the neighbouring patches. These adjacent patches are excited, with a certain phase lag depending on the element spacing, and start radiating. Normally, the adjacent patches act as receivers, and radiate only a small portion of the received power, which depends on the quality of the load. Yet, for this configuration where the patches are square, and sequentially rotated, only part of the power received by the neighbouring elements is of the "correct mode" and thus absorbed, the remaining part is however radiated. The transmission values from the active patch to its passive neighbours are well below -15 dB or lower. This causes an important levels of interference, which results in larger sidelobes than theoretical expected.

To sum up, it can be stated that the major coupling effects are likely to be caused by the coupling between the adjacent patches, and not by surface waves, as one would expect in first instance. This type of coupling depends on the geometrical dimensions of the patches and the distance between the elements. It is therefore hard to counteract without major changes in the layout of the array, which are not possible at this time. A possible solution would be to introduce additional, simple structures, such as linear radiators, on the surface of the substrate, to interfere with the coupling between the patches. A possible solution is depicted in figure 7, and is currently under investigation.

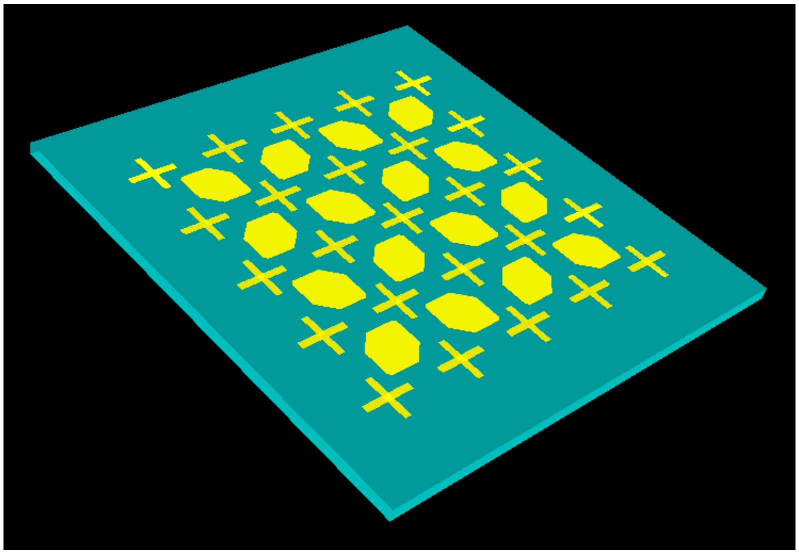


Figure 7. A possible improved layout for counteracting coupling.

6.0 CONCLUSIONS

A model for describing at least first order coupling effects for large arrays composed of sequentially rotated patch elements has been introduced. An efficient method of determining the far field patterns at different scan angles, based on the coupling model just mentioned, has also been presented. The type of coupling has been investigated in detail, and it has been shown that its main mechanism is the coupling between the patches, and depends on the geometrical configuration of the array. The effect of surface waves only plays a minor role. Investigation of possible solutions, like grid structures on the surface of the substrate is ongoing.

7.0 REFERENCES

1. Dreher, A., S. Holzwarth, C. Hunscher, A. Jacob, and N. Niklasch, " Smart antenna terminal for broadband aeronautical applications", Fifth European workshop on mobile/Personal Satcoms Proceddings (EMPS 2002), September 25-26, Baveno (Italy), 2002, pp. 263-269.
2. ETSI EN 301 459, Satellite Earth Stations and Systems (SES), section: Harmonised EN for Satellite Interactive Terminals (SIT) and Satellite User Terminals (SUT) transmitting towards satellites in the geostationary orbit in the 29.5 to 30.0 GHz frequency bands covering essential requirements under article 3.2 of the R&TTE Directive, V1.2.1,October 2000.
3. Teshirogi, et al., "Wideband circularly polarised array antenna with sequential rotations and phase shift of elements", International Symposium on Antennas & Propagation Proceedings, Japan, 1995, pp. 117-120.
4. Nauwelaers, B., G. Raguenet, and A van de Capelle, "La rotation sequentielle et la polarisation circulaire", Conference Journees Internationales de Nice sur les antennas, November 13-15, 1990, pp.459-462.
5. Harrington, R.F., Time-Harmonic Electromagnetic fields, pp. 103-111, McGraw-Hill Book company, New York, 1961.
6. Su, T. and H. Ling, "On modelling mutual coupling in antenna arrays using the coupling matrix", Microwave and Optical Technology Letters, Vol. 28, No. 4, February 2001, pp. 231-237.
7. Yang, F. and Y. Rahmat-Samii, "Mutual coupling reduction of microstrip antennas using electromagnetic band-gap structure", IEEE Antennas and Propagation Society International Symposium Vol. 2, 2001, pp.478-481.