Hexagonal CORPS-BFN to feed OLAF SAR Instrument

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***Abstract*— The concept of Coherently Radiating Periodic Structures-based Beam Forming Networks is applied to feed OLAF (OverLapped SubArray Fed) antenna for SAR Instrument at L-Band. The proper feeding of this system requires the multiple beams to be highly overlapped, and that is generated by a CORPS-BFN using a new 4-port Gysel power combiner/divider implemented in a suspended stripline technology. The network provides high isolation between inputs/outputs, low insertion loss, great return loss and the desired ovelapping of the different beams.**

***Index Terms*— CORPS, Beam-Forming Network, multibeam arrays, SAR.**

I. INTRODUCTION

The SAR (Synthetic Aperture Radar) instruments were often implemented by planar Direct Radiating Arrays (DRA) scanning the beam electronically, which involves most of the elements of the DRA to scan the beam properly. In these systems the maximum achievable gain is defined directly by the size of the total DRA, limiting the resolution capabilities [1]. Recently, the possibility to include a reflector fed by an smaller array has been introduced [2].

The OLAF antenna is an L-Band SAR instrument based on a reflector antenna fed by overlapped subarrays. Antenna arrays based on overlapped subarrays permit generating highly directive beams, enabling low spillover losses with the possibility of creating contiguous beams with a low required cross-over level. In this scenario, each single element of the array takes part in several contiguous beams. Although this purpose could be done completely with a Digital Beamformer (DBF) using an array of elementary of small antennas, the combined use of this DBF with fixed overlapped subarrays, referred as equivalent feeds (EF's) could be helpful to reduce the number of controls.

In particular, in the OLAF SAR instrument, a reflector of 15m diameter would be in an offset configuration with a focal length of 13.5m, and the feeding array would be approximately 9x1m. The Swath width is 400 km and the range and azimuthal resolutions is 5 m. The NESZ (Noise Equivalent Sigma Zero), a parameter that measures the sensitivity of these SAR systems, should be below -28dB.

In order to illuminate the reflector properly, trying to minimize spillover losses, the EF should have a directivity of approximately 15 dB. On the other hand, in order to achieve the desired resolution, the separation between neighbouring equivalent feeds should be smaller than one wavelength. However, in a lattice of planar apertures with a diameter of a wavelength, the maximum directivity achievable by one element is limited to 11 dB (assuming uniform illumination). To overcome this limitation, at least three elements of the lattice should be grouped for each beam. Furthermore, each element should be shared by contiguous beams in order to reduce the distance between their phase centres, hence increasing the resolution of the system.

In this work, the overlap between the different equivalent feeds is implemented with a single layer of a hexagonal CORPS-BFN using Gysel power dividers of 4-ports (1 input and 3 output ports)[3]. By using this configuration, the combination of three equally excited, small radiators (whose diameter is limited to the minimum separation between beams in order to reach the desired resolution), could provide the desired 15 dB directivity.

II. CORPS-BFN CONCEPT

The COherently Radiating Periodic Structures – Beam Forming Networks (CORPS-BFN) were proposed in the last decade [4], [5] and present interesting properties for feeding antenna arrays. A CORPS-BFN consists of N layers of split (S) and recombination (R) nodes. Previous work employed 3-port Gysel cells, where both S- and R- nodes consist on the same unit cell: a 3dB power divider/combiner. Depending on the S or R function of each node, one port of the cell act as the input port whereas the other two act as output ports (S-node) or two input ports and one output port (R-node). This concept could be generalized using M-port power combiners (where $M \geq 3$ theoretically could be any number). At S-nodes, the input power at Port 1 is distributed among the M-1 output ports, while in R-nodes the power available at the M-1 input ports is recombined at the output port. Given that every node consists of the same basic element, coherent coupling is ensured between the different ports at the same time the power spread is controlled on each layer.

The configuration proposed in this work is a single layer of a hexagonal CORPS-BFN, defining sub-arrays (EF's) of three small radiators equally illuminated from the common input. Since the whole BFN is shared by the whole array, each small radiator receives contributions from one up to six neighbouring inputs, hence overlapping the effective radiating areas of the EF's.

In Fig. 1, the overlap between the different Equivalent Feeds is represented. In our case, OLAF SAR experiment will work with two orthogonal polarizations, so we could choose the more favourable planes. The idea is to use one BFN for each polarization sharing a single antenna array. In the figure, the circumferences represent the antenna apertures with diameter D. Here, only a single EF for each polarization (red and blue triangles) are drawn for clarity. We can arbitrarily refer to Pol. V as red colour and Pol. H as the blue colour for a clearer understanding of the figure. The small red and blue circles represent the phase centres for the rest of the EF's of the array. By sharing some but not every radiating element, the phase centres of one polarization fill the "gaps" between the phase centres of its counterpart. Some geometries are indicated on the top right corner of the figure. The distance between co-polar phase centres is "D" in the three symmetry axes of the hexagonal lattice. The distance between co-polar phase centres arranged in contiguous rows decomposes into a horizontal D/2 and vertical √3D/2, both distances below one wavelength.

In order to provide these two polarizations, two identical, decoupled (independent) and interleaved single layer hexagonal CORPS-BFN should be used and their outputs combined in the antennas directly. It is possible to conclude that every single small radiating element could be shared by a maximum of six EF's, three per polarization. The design of the antenna and the dual polarization feeding system is out of the scope of this communication. Nevertheless, hexagonal apertures of diameter D=250 mm have been considered as potential candidates. In simulation, by joint operation of three equally illuminated apertures, the desired directivity of 15 dB was obtained (see Fig. 2 to 4), with azimuthal symmetry to be able to work properly, and equally, in both polarizations. Please note that the antenna is still under development and here we only focus on the aperture field distribution achievable to analyse the whole antenna system. Coupling between the two polarizations at the aperture plane that remains below -35 dB in simulation. The design of the final horn, combining both polarizations at the throat and developing the hexagonal aperture, remains a challenging task and special attention shall be paid to the polarization discrimination.

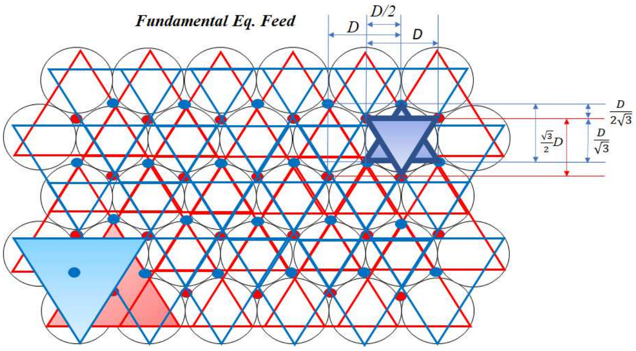


Fig. 1. Hexagonal lattice of small radiators (here represented by circles), the small red circles would be representing the phase center of the EF defined by three small radiating elements (red triangle) and the small blue circles the phase centers for the orthogonal polarization EF (blue triangle).

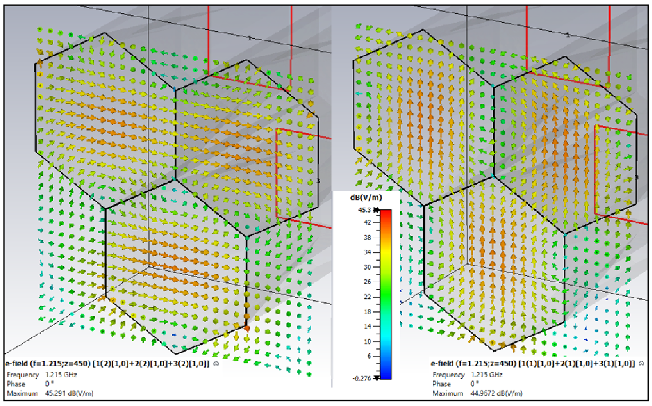
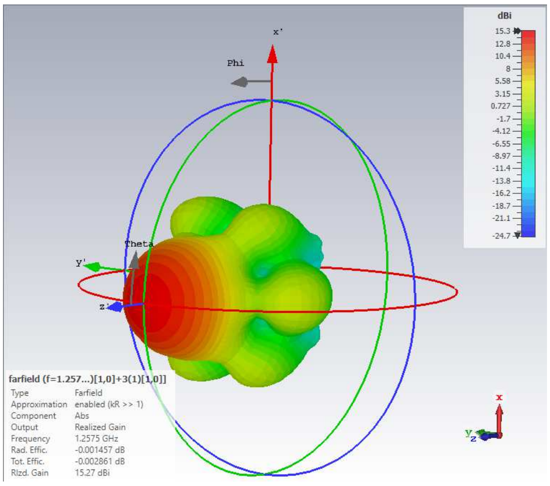


Fig. 2. E-Field distribution in a Equivalent Feed composed by three small hexagonal horns for vertical (left) and horizontal (right) polarizations.

In traditional arrays, the physical size of the radiating elements limits the minimum distance between contiguous beams, thus limiting the maximum achievable resolution. On the other hand, the CORPS-BFN stands out as an interesting candidate to feed multibeam systems due to their ability to share elements among several beams ensuring isolation between them.



farfield (f=1.257...)[1,0]+3(1)[1,0]]

Type	Farfield
Approximation	enabled (kR >> 1)
Component	Abs
Output	Realized Gain
Frequency	1.2575 GHz
Rad. Effic.	-0.001457 dB
Tot. Effic.	-0.002861 dB
Rlzd. Gain	15.27 dBi

Fig. 3. 3D plot of Far-field radiation pattern of one EF composed by three small hexagonal horns. The values given for the efficiency shall not be paid attention, since only the hexagonal apertures and not realisable horn antennas are being considered.

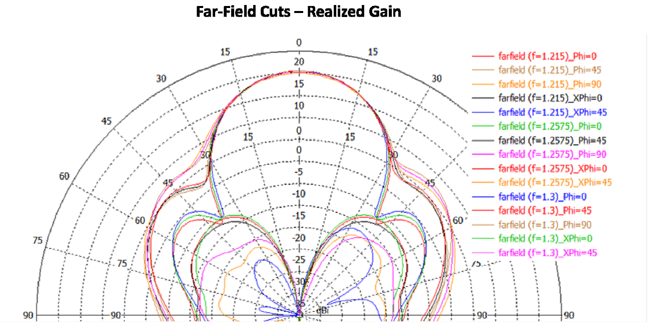


Fig. 4. Main cuts of the far-field (Realized Gain) of one EF composed by three hexagonal apertures. Extracted from CST.

III. NEW 4-PORT GYSEL POWER DIVIDER

To feed the elements of the array in a hexagonal lattice, a power divider with its output ports arranged with a 120º span was required. Furthermore, the array elements are placed on top of the BFN, imposing the need for output ports that are perpendicular to the plane in which the BFN lays. Moreover, the system requires an isolation between ports higher than 30 dB and return loss below 20 dB. For this reason, a Gysel Power Divider topology was chosen. This power combiner features the required return loss and isolation and provides a higher power-handling capabilities than the Wilkinson combiner [3]. As seen in Fig. 5, the proposed 4-port Gysel cell consists of fifteen quarter-wavelength lines with three different impedances: $Z_1=\sqrt{3}\cdot Z_0$, $Z_2=Z_0$ and $Z_3=Z_0/\sqrt{3}$. In this case, a nominal value of 50Ω was chosen as Z_0. Moreover, it was obtained by means of circuital simulation (Keysight ADS) that the optimal value for the resistor loads lays around $R_L=2\cdot Z_0/3$ (no significant difference in performance was observed between 33 and 35Ω). Fig. 6 presents the S-Parameters of the proposed Gysel combiner/divider simulated in ADS designed to operate at a centre frequency of 1.2575 GHz with ideal transmission line elements. For clarity purposes, only one transmission parameter "S12", isolation parameter "S23" and two matching parameters "S11" and "S22" have been plotted. The required operational bandwidth in our case ranges from 1.215-1.3 GHz.

In order to validate the proposed cell, a prototype was designed on a suspended stripline technology. A 254-um-thick Rogers 5880 was chosen as the supporting substrate, although a dielectric-free suspended solution will be considered for the final design. The substrate is then encapsulated and suspended in between two metallic enclosures that include an air-filled channel, forming the suspended stripline. The stripline consist of a 16um-thick strip of copper, commercially available. The impedance of each line section is controlled by both the width of the metallic strip and the height of the channel, as in a common stripline technology. The width of the channel was kept constant to simplify manufacturing process. Table 1 summarizes the dimensions of each line section.

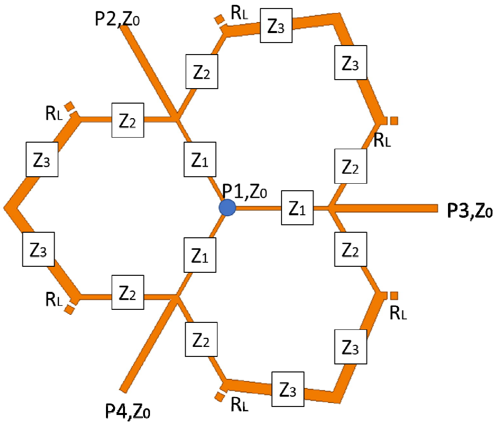


Fig. 5. Sketch of the proposed 4-port Gysel power combiner/divider, highlighting each section's impedance (quarter-wavelength tranformers).

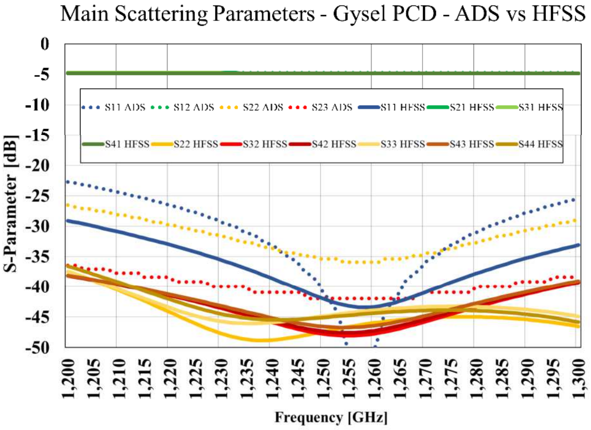


Fig. 6. S-Parameters of a 4-port Gysel cell simulated in ADS (dotted lines) and HFSS (solid lines).

TABLE I. DIMENSIONS OF EACH LINE SECTION

Impedance	Strip width	Strip length	Channel height	Channel width
Z1 (86.6 Ohm)	1.7 mm	58.8 mm	3mm	10mm
Z2 (50 Ohm)	2.4 mm	58.7mm	2mm	10mm
Z3 (28.8 Ohm)	5.4 mm	61.3 mm	2mm	10mm

The reason why the height has been reduced for the lower impedances is that very wide line sections were required if the height was kept constant for the low impedances. The length of each section was optimized to compensate the intersections of lines with different width. Very short lines were also included to bond surface-mount resistor loads. The outputs of the cell were defined as suspended-stripline wave-ports, while the central, input port consist of a 50Ω coaxial port. The inner conductor of the coaxial port is extended until electrical contact with the stripline is ensured. This contact takes place at the junction between the three sections of impedance Z1 (inset in Fig. 7).

The power combiner was simulated in HFSS and its S-Parameters are shown in Fig. 6 as solid lines. It can be observed that both isolation and return loss requirements are fulfilled, while very low insertion loss is achieved (ideal S21 value is around -4.77dB, corresponding with an amplitude of $1/\sqrt{3}$, and the simulated value lays around -4.9dB).

IV. PROPOSED APPLICATION

Once the base cell has been presented, the design of the beam-forming network will consist of connecting as many cells as the number of inputs/outputs required by the specific application. In our case, a BFN to work both in transmission and reception scenarios is required. Since the network is fully passive, its reciprocal behaviour allows us to operate in both modes. As a result, while in transmission mode, one input port reaches M=3 radiating elements, in reception mode, the signal entering from one radiating element reaches M ports (and the same M elements will deliver power to the original input port).

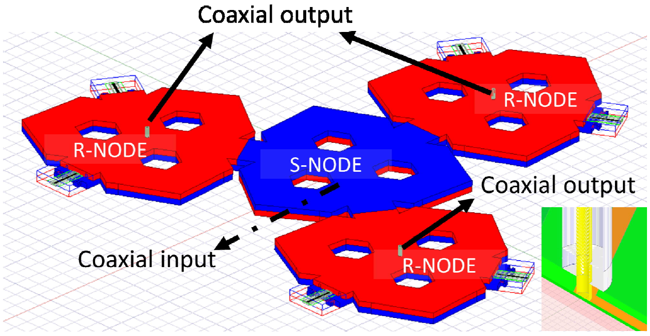


Fig. 7. Simulated network. Blue and red colours have been chosen to differentiate between both halves of the split-block encapsulation. It can be seen that the bottom half on the S-nodes is used as the top cover on the R-nodes and viceversa. Inset: Zoom into coax-stripline transition.

The proposed SAR application consists of a high-power pulse being delivered to each input port at an S-node. This node divides the power equally among its neighbouring cells, which are R-nodes. Each R-node combines the power incoming at each input port. Since every path is electrically equal and the combiners are identical, a coherent recombination takes place and no loss is introduced (except for those R-nodes on the edges of the network, which do not have three S-nodes around them).

Since every node of the BFN consist of the Gysel cell and the outputs are isolated, only a few cells are enough to characterise the network. Considering a transmission scenario, the Split Nodes will be the inputs (with the coaxial port pointing downwards in the Z-axis), while the Recombination nodes will be considered the outputs (coaxial port pointing upwards in the Z-axis). Thus, the same cell is used for S-and-R-nodes by flipping them 180º along the XY plane. In this case, we simulated four Gysel cells, resembling one input port (one beam) and three output ports (three radiating elements conforming one single Equivalent Feeder or sub-array), as shown in Fig. 7. With this simplified scenario, we can determine the isolation between the radiating elements. Since the network is reciprocal, that isolation corresponds to the isolation between input ports as well. The interconnection between cells is possible thank to the selected split block technology. The bottom part of the split block is enlarged with respect to the top part at the junctions. Because the neighbouring cell is flipped top-down, the same bottom half acts as the top half in the neighbour cell and ensures the enclosure.

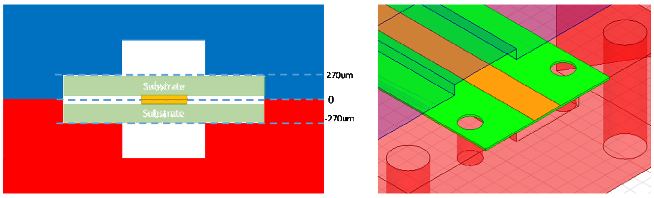


Fig. 8. Detailed cross-section of the junction between two Gysel cells (left). Zoom into the junction area at one individual cell (right). Blue and red colours are used to differentiate between top and bottom covers. Green: Rogers. Orange: copper.

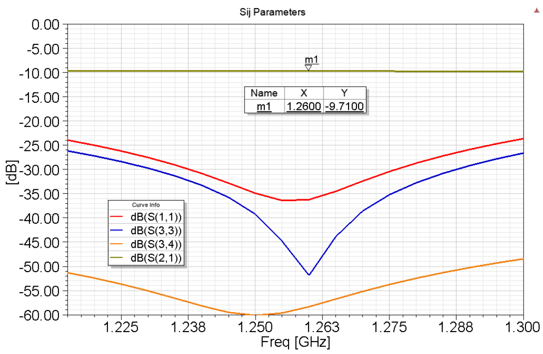


Fig. 9. Simulated parameters of the 4-cell sample CORPS-BFN. Port 1 is the coaxial port at center cell. Ports 2-4 are the coaxial ports at external cells.

The electrical connection is achieved by pressing both substrates between each other, ensuring that the striplines touch. A detailed sketch of the junction between two cells is presented in Fig. 8. The simulated S-parameters are shown in Fig. 9. The requirements in terms of isolation and return loss are widely satisfied, maintaining a low insertion loss (-9.7dB vs ideal -9.55dB) under perfect electric conductor (PEC) assumption.

V. OPERATION

In transmission mode, every input port introduces the same signal pulse into the network with same amplitude (let us normalize it to unity). The network's coherent properties enable the distribution of this signal to every output port, with each input reaching only the three surrounding R-Nodes, with very low loss. These nodes recombine the incoming signals at its three strip-line ports and deliver it to the coaxial output port located at the centre of the node. Since the surrounding S-nodes would be providing the same signal and all the paths are electrically identical, coherent signal combination allows to recover at each output port the same signal amplitude introduced at each input port. The only possibility that this could not occur would be at the edges of the network, were an R-Node might not have three S-Node neighbours and therefore will only recover one or two thirds of the original amplitude. This means, R-nodes surrounded by three S-Nodes are able to recover the unity in both power and amplitude while ones located at the edges of the array combining two inputs would have a -3.52dB power loss and the ones with one third of amplitude a -9.55dB loss with respect to the power at one input port.

In reception mode, a reciprocal behaviour is expected, where R- and S- nodes exchange functionalities. Whereas in transmission a single input port fed three output ports (defining an EF with three elements for that input port), in reception mode we assume that the three elements conforming the EF to be illuminated by the same amplitude. Each R-node then splits the power among its three neighbour cells. Because the network is reciprocal, one third of the amplitude from each input signal reaches the common output port of the central S-node and the coherent combination allows recovering the unity in amplitude in the central port of the S-node. In the same way as in transmission, no losses are expected from the network, except for the EF located at the edges of the array.

VI. CONCLUSIONS AND FUTURE WORK

In this work, the CORPS-BFN concept has been proposed to feed an antenna array for a SAR application. For this purpose, a new Gysel power combiner/divider has been designed on a suspended stripline technology and hereby presented. The network enables the definition of equivalent feeders (EFs) composed of three radiating elements with a diameter aperture of a wavelength. The shared used of the radiating elements between several EFs allow to reduce the distance between their phase centres, hence increasing the resolution of the system and making it possible to achieved the required spec in range and azimuth. Promising simulation results show high isolation and return loss for every port. Furthermore, very low loss is introduced in the operating frequency band. Future work will involve the manufacturing (which is already in process) and measuring of the proposed structure. Other aspects, such as the study of multipactor behaviour of the structure are left as next steps.

ACKNOWLEDGMENT

This work was supported by an ESA ITT AO/1-9524/19/NL/AF with Airbus Defense and Space, S.A.U., Spain, to develop the "Overlapped subarray fed reflector antennas for SAR instrument", as well as the FPU Program from the Spanish Ministry of Science, Innovation and Universities (FPU18/00013).

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