Cavity Backed Capacitively Coupled Stacked Patch Element for Electrically Small P-Band Array

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***Abstract*—The Microwaves and Radar Institute at the German Aerospace Center operate an airborne multi-frequency, polarimetric, imaging SAR system. The F-SAR sensor is equipped with a variety of different antennas, based on patch technology. A new antenna element is developed for the P-Band frequency range from 400 to 470 MHz. Due to the requirements of the aircraft the size of the antenna array, and therefore of each single element, is reduced to a minimum. A cavity backed, capacitive coupled stacked patch element is designed and presented in this paper.**

***Index Terms*—patch antenna, SAR sensor, cavity backed, p-band, small array.**

I. Introduction

Imaging radar systems are widely used in earth observation purposes, either operated on spaceborne or airborne platforms. For high resolution products synthetic aperture radar (SAR) sensors are most suitable. The resolution in azimuth direction, corresponding to the direction of motion, is limited by the physical length of the antenna. A short antenna is preferred for high resolution imaging. The range resolution is, like in a conventional radar system, given by the pulse length and the bandwidth.

Fig. 1. One of the P-band antenna, mounted under the fuselage of a Dornier Do 228-212, in front of the main gear [4].

The Microwaves and Radar Institute at German Aerospace Center in Oberpfaffenhofen operates an airborne SAR system called F-SAR. It is equipped with five different frequency bands. The lowest frequency band is P-band - 300 MHz up to 470 MHz - , receiving data of the earth's surface also through dense vegetation.

At lower frequencies, bandwidth requirements could be challenging by the means of relative bandwidth. Not only the antenna but components inside the radar-frontend, like circulators, are limited in bandwidth. The P-band range is therefore divided into subsystems, PI 300 – 400 MHz and PII 400 – 470 MHz. For the upper band the new antenna design is presented here. The airborne platform, a Dornier Do 228 and the mounting area, underneath the fuselage, limits the physical dimensions of the PII-band antenna, see Fig 1. The envelope is about 1.4 m x 1.4 m x 0.4 m with a maximum weight of 100 kg.

The SAR geometry bases on a side looking radar antenna. Physically small antennas could be mounted at the side of the fuselage, in a manner that their main beam is directed to 40 degree view angle to the ground. With an antenna the size of P-band the only available mounting position is underneath the fuselage. The main beam has to be tilted electrically to 40 degree side looking condition. In this configuration strong echoes can occur from nadir and opposite swath direction. A proper beam shaping is required. For opposite swath suppression and minimum signal at nadir a number of at least five antenna elements in elevation direction will be necessary. The given requirements for SAR operations leads to another five elements in azimuth direction, resulting in 30 degree half power beam width. The entire array consists than of 25 elements in a square aperture. With about 70 cm wavelength at center frequency the antenna is only two by two wavelengths with 25 radiating elements inside.

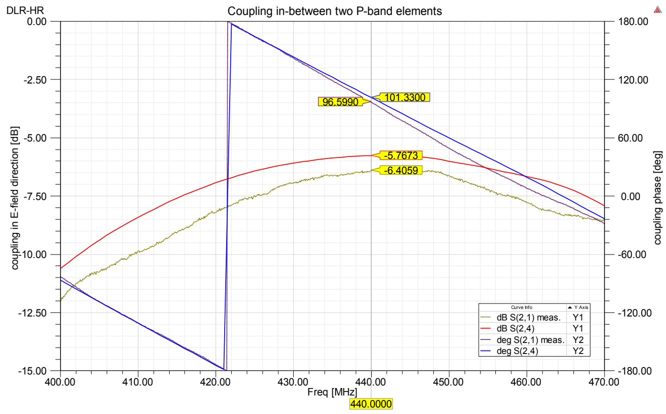

Fig. 2. Coupling vector for two adjacent patch elements in E-plane direction. Simulation and measured data in amplitude and phase.

A single, slot coupled, patch element design was already presented, together with the network of power dividers [1]. Setting up the antenna array, strong mutual coupling effects inbetween this type of radiating elements makes their usage in an electrically small array unfeasible see Fig. 2. The coupling vector is at -6 dB and overlays the desired amplitude and phase tapering. Broadside radiation shows sufficient performance but the side looking configuration is distorted by the overlay of amplitude and phase taper to the mutual coupling vectors. Strong variations over frequency in beam shape and pointing occurs beneath low radiation efficiency.

To overcome the coupling effects an antenna element is designed with metallic walls to the neighboring elements. Consequently a resonator is generated with metallic walls and ground plane. Inserting patches and a feeding structure a wideband antenna can be formed [2], [3]. Various layouts were tested to meet the requirements of the SAR system with dual polarizations and wideband operation in a resonator of reduced size. The dimensions of the resonator are therefore the most critical aspects in the design.

II. SPECIFICATION

The F-SAR system is a modular, experimental airborne SAR sensor designed for flexible operations. It can be adjusted to new radar modes and frequency ranges, acting like a test bed for new algorithms and future SAR systems in orbit.

The new frequency range for spaceborne earth observation at 435 MHz is not yet covered by the F-SAR system. The current P-band design starts at 300 MHz and ends at 400 MHz, where the new range will initiate. A new antenna in conjunction with an additional radar front end shall enhance the F-SAR capabilities to the higher frequencies. The new PII-band specification covers the range from 400 to 470 MHz.

The antenna operates in two modes, a nadir looking sounder configuration and the standard side looking SAR configuration with an electrical shift of the main beam to 40 degree off-nadir direction. In side looking mode the antenna main beam covers the area on ground from 25 degree up to 60 degree off-nadir angle. At least five elements are required in the case of the PII-band antenna. The desired number of elements in a 5x5 configuration leads to resonators with reduces size in an electrically small array.

The maximum pulse power for the antenna array is 1 kW with 10% duty cycle. The first stage of the power dividing network is most affected by the pulse power. At a flight altitude of 3000 m up to 6000 m the components must be designed to withstand the thermal dissipation due to the electrical losses as well as the high voltage of the peak power and voltage standing wave ratio.

The mechanical structure of the antenna array has to meet all airworthiness aspects like lightning protection, static weight, dynamic weight (50 feet gust) or forces of airflow. A wind shield, to prevent the structure from direct wind impact, exists already and one mechanical interface of it will be located around the aperture of the antenna array.

III. ANTENNA ELEMENT DESIGN

The standard patch element design, stacked and or slot coupled, is used for most of the F-SAR antennas. Due to the small array size at PII-band and the beam pointing over more than 16% bandwidth, this type of radiating elements is unfeasible. The radiating areas of the patch elements, the magnetic walls, are very close to each other, thus the electromagnetic coupling is strong, in the range of -6 dB, see Fig. 2. The diagram shows simulated and measured data for the mutual coupling in-between adjacent elements. The difference between simulated and measured amplitude is due to the fact, the measurement is done in the complete array. It could be shown that also the termination of the second neighboring element, not only the immediate neighbor, has a strong influence of the coupling vector.

With this high amount of coupling it is not possible, pointing the main beam to a dedicated position and shape the diagram for all frequencies. In addition the efficiency of the antenna array is below 60%. To overcome the strong coupling effects the radiating elements can be moved away from each other. In consequence the array will grow in size or elements have to be neglected. Both possibilities are out of the specification.

To weaken the electromagnetic coupling the direct path between adjacent elements has to be suppressed. With conducting structures the electrical field vector, at least the tangent component of it, can be controlled. A metal wall is included between the radiating edges of the patch elements, it shortcuts the electric field vector and minimizes the coupling effects. The result is a resonator backed patch element, see Fig 3.

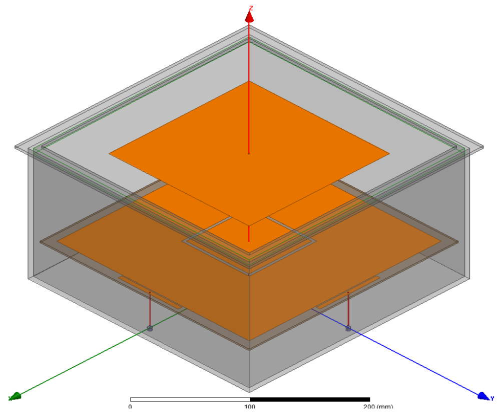

Fig. 3. Antenna model from HFSS simulation. Two resonant patches are located inside a metalic resonator. For sual polarized operations two feeding pads are visible.

A number of band width enhancement methods are published for this type of radiating structure. They are based on regular resonator dimensions and show more than 25% bandwidth for dual polarized elements.

The design goal is to reduce the resonator size and simultaneously obtain the bandwidth performance. These requirements are antipodal and additional components have to be inserted in the common design.

IV. OPTIMIZATION AND SIMULATION RESULTS

The specified frequency range of the PII-band subsystem is 70 MHz of bandwidth at a center frequency of 435 MHz, the wavelength in air is 690 mm. A resonator at TEM_{10} mode will have an optimum length of 345mm according to $\lambda/2$ of free space wavelength. The available space is smaller than 280 mm and it has to include mechanical structures as well. To cover the required 16% of bandwidth the design is enhanced with an additional patch layer. The lower patch is excited by two capacitive coupled feeding probes, one for each polarization. The capacitive coupling is necessary due to the distance between the ground plane and the first patch layer inside the resonator. The antenna is feed by coaxial lines, in which the inner conductor is soldered to a pad. A major inductive part is added to the input impedance due to the very long inner conductor. To compensate the inductance the capacitive coupling is used. Pad length, width and distance to the edge of the patch are degrees of freedom to match the antenna element. With a second passive patch underneath the radome layer a square slot inside the feed patch is necessary, adjusting the real part of the input impedance.

In Fig. 3 the HFSS model is shown, consisting of the aluminium box with a frame on top. Inside the metallic box made of 1.2 mm aluminium the patches are located. On a Rogers RO 3006™ board of 1.28 mm the lower, driven patch is placed, together with the feeding pads. The patch dimensions are 230 mm whereas the board dimensions are 250mm and slightly smaller than the resonator length. Two pads at a distance of 1.4 mm, size 72 x 4.5 mm, are used to feed the patch. The inner conductor of a coaxial line is soldered to the center of each pad. The outer conductor ends at the resonators bottom plate.

The center pin diameter and its length, 41 mm, are responsible for the inductance part of the input impedance. It has to be compensated by the capacitive coupling between the pad and the patch. With the square slot inside the patch the real part of input impedance is controlled it is 3 mm wide. A second patch is located underneath the radome layer, made of 6 mm FR4 material. This patch is of dimensions 168 mm. All dimensions, including the size of the RO 3006™ material are optimized to enhance the band width of the antenna element.

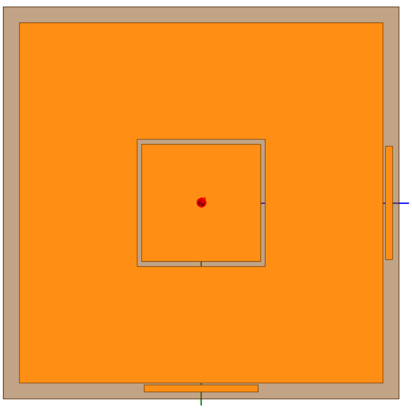

Fig. 4. RO3006™ board with patch and feeding pads.

To protect the antenna element from environmental influences the FR4 radome layer is essential. At the position of the antenna, underneath the front part of the airplanes fuselage, stone-chipping from the front wheel is likely. The FR4 layer is able to withstand most of the impacts without any damage. The free space area inside the antenna resonator is complete with Rohacell HF31©.

The single antenna element is optimized with the help of Ansys HFSS simulations. Several designs were tested and build up to compare simulation results with real measurements and testing the mechanical structure in terms of tolerances and to solve production problems.

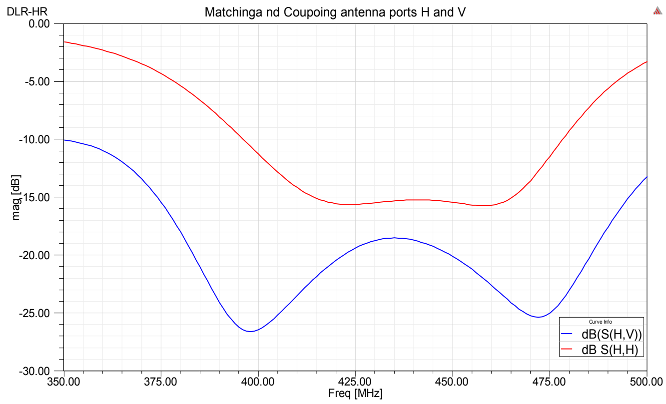

Fig. 5. Reflection coeficient of one port of a single element, including coupling coeficient inbetween the h- and v- ports.

The 70 MHz bandwidth requirement, according to about 16% relative bandwidth, is defined at -10 dB return loss at the antenna feeding connector. In general a wider and deeper resonator gives better performance, but both sizes are clipped by the physical dimensions the antenna has to keep, under the airplane's fuselage. To comply with the specified bandwidth the -10 dB return loss is best what could be achieved. In a single element the cross pol level is only at -18 dB, caused by the unbalance of the feeding structure. The cross-pol level will be enhanced in the array configuration due to alternating elements [5].

Symmetric feeding structures were tested but with minor success. The bandwidth and cross pol level could be dramatically improved. The drawback is that two matched ports in one polarization give an optimum transmission coefficient. A major part of the input energy passes through the resonator to the second port and the radiating efficiency is reduced, whereas the active reflection coefficient is reduced to some dB.

V. Single Element and Array Design

A prototype is manufactured to compare the simulated results with real measurements. It is also an indication for manufacturing tolerances and material parameter variation. The important factor of overall weight of the antenna is combined with the single element design. In the case of the P-band antenna the resonator box is part of mechanical structure of the antenna, guaranties at the same time electrical performance and structural stiffness. The necessary components are included into the RF-design and simulations. Due to structural requirements the resonator is again reduced, housing additional elements to support the radome layer and the input connectors.

Based on standard materials with airworthiness certificates an array of 25 elements is constructed. All mechanical interfaces and rived connections are considered. One row of the constructed antenna array is simulated in HFSS, testing the amplitude and phase tapering for the pointing and shaping of the antenna diagram.

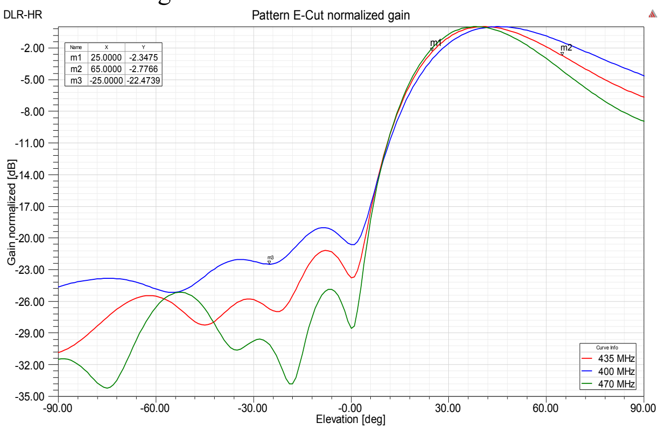

Fig. 6. Normalized one-way E-plane pattern in V-polarization at 400, 435 and 470 MHz.

In Fig. 6 the simulated pattern is shown, with nadir and opposite swath suppression better than 20 dB is possible. The pattern is normalized for all frequencies, demonstrating the pointing and shaping of the antenna pattern at different frequencies. The next figure shows measured results from the previous 25 element array of patch elements, with identical array parameters like in the simulated of the new resonator elements.

The new design shows promising results in reduced coupling vectors and at the same time better performance under beam steering conditions.

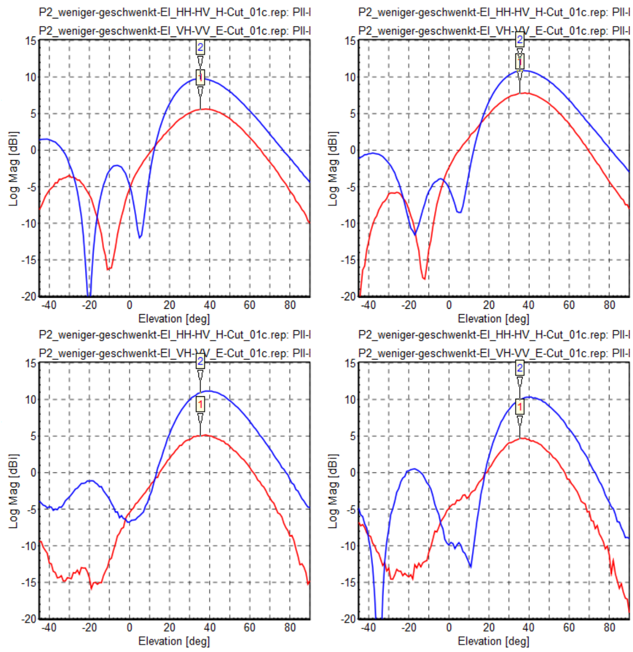

Fig. 7. Measured antenna pattern of a 25 elements patch array. The effect of the strong inter-element coupling is visible in the bad beam shaping , pointing and variation over frquency.

VI. Conclusion

A new antenna type was tested and included into the F-SAR system. The low coupling effects of the resonator backed patch element makes it extremely useful in electrically small arrays. It shows good frequency band width performance and has advantages in airborne use. The design with dedicated resonator boxes will be refined and adopted to other frequency ranges in the F-SAR. In L-band an antenna array with variable main beam directions is used. It offers a test bed for a resonator design. Bases on the methods of substrate integrated waveguides a resonator element could be formed at higher frequencies.

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