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EFFICIENT ANTENNA DESIGN USING 3D EM AND CIRCUIT CO-SIMULATION

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ABSTRACT

This paper presents the design process for a feeding network of a multiple spot beam satellite antenna with overlapping beams in Ka-band. We describe an efficient EM-field/circuit co-optimisation technique, which uses the advantages of both, EM-field solvers and circuit simulators. With this approach a fast and accurate design of a complex beam forming network, comprised of a high number of waveguide components, as part of a multibeam satellite antenna is possible. The feed array structure was manufactured using conventional techniques. The measurement results are in a very good agreement with the simulation results.

Index Terms— satellite antennas, offset reflector antennas, multibeam antennas, antenna array feeds, reflector antenna feeds

1. INTRODUCTION

There is an increasing need for multi spot beam antennas in Ka-band. They illuminate a coverage area by a lattice of small overlapping high gain spot beams in order to provide two-way broadband services using small user terminals. There are two basic principles for multi spot beam antennas with overlapping spots, single aperture designs with a complex beamforming network and multiple aperture designs [1]. In this paper we investigate the design of a feed system for a single aperture design. The proposed approach is used for the design of a demonstrator model for a multiple spot beam antenna within the DLR granted project “Medusa”.

2. DESCRIPTION OF THE ANTENNA

Multiple spot beam antennas are usually single offset designs with an unshaped parabolic reflector. Between 20 and 100 beams with typical diameters between 0.5° and 1.0° are realised. The most conservative antenna configuration has a single feed horn allocated to each beam. In this case the antenna is fed by a “Single Feed per Beam” (SFB) array. However, adjacent horns in the focal plane of the reflector generate an angular beam spacing being about twice as high as required. The horn apertures would have to overlap in order to generate beams with the required narrow spacing. Therefore for the generation of the most commonly used four colour scheme using the SFB concept, four reflectors, one for each colour, are required. The need for four reflectors leads to a high mass, high costs and a difficult accommodation of the antennas on the space craft.

To overcome this problem a “Multiple Feeds per Beam” (MFB) array could to be used [2]. In most cases one beam is formed by seven horns. Adjacent beams share horns and so a physical overlapping of the feed aperture is realised (Fig. 1). Thanks to the physical overlapping of the feed apertures, the generation of a four colour scheme with overlapping spots using only one reflector becomes possible.

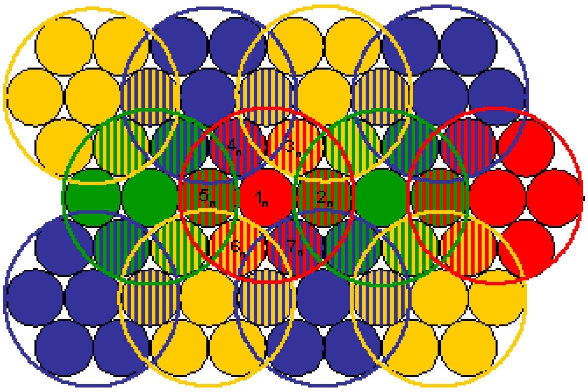

Fig. 1. MFB concept: shared horn elements between adjacent beams

The total number of horns is between 80 and 400 for typical multi spot beam MFB antennas. Each horn is connected to a septum polariser in order to produce circularly polarised signals. The input ports of the septum polarisers are fed by a complex beam forming network (BFN). The BFN is realised as a multi layer waveguide network and consists of a few hundreds of branchline couplers and phase shifters to provide the required excitation coefficients of the array elements as well as waveguide loads in order to terminate unused ports.

Numerous waveguide via interconnections are needed to connect the different network layers.

The size and shape of each beam can be influenced by magnitude and phase of the excitation coefficients. Therefore it is possible to adapt the beam to geographical or political borders or other requirements of the target polygon. This additional degree of freedom also makes high demands on the design of the beam forming network.

3. DESIGN PROCESS

Physical optics is usually used to calculate the secondary pattern of large reflector antennas. Mode matching (MM) and Method of Moments (MoM) are often used for the primary pattern of the feed. However, for multi feed antennas both, mutual coupling and the influence of the BFN must be considered, when the primary pattern is calculated. We use an in-house tool [3] to calculate the horn pattern considering mutual coupling of the horns. The tool can handle several hundreds of horns.

Designing RF systems it is generally accepted that optimisation within reasonable CPU time limits should be based on conventional circuit-oriented simulators if possible. Circuit simulators use the description of a system in terms of lumped elements and transmission lines to account for distributed effects. They also rely on a S-parameter description of the different parts of the feed structure. This approach in general relies on a divide-and-conquer technique in which the feed system is subdivided into separate parts, for which models exist or can be calculated. There are two advantages: the circuit simulator approach is fast and, therefore, easily to combine with advanced optimisation techniques.

However, partitioning and circuit description do not always account properly for the actual field effects that occur in the waveguide structure. To design microwave components properly, it is necessary to take into account physical effects of the actual physical layout. Powerful electromagnetic (EM) field solvers have emerged to predict these effects, which are often described as parasitic effects. When considering the class of antenna feed components it becomes even less evident to make a distinction between circuit description and EM behaviour, as physical effects here are often an integrated part of the desired system behaviour.

From the above reasoning, it seems to be logical to rely even more on EM solvers for feed system design and optimisation purposes. However, the feed array system, including BFN, of the considered multibeam MFB antenna is of a high complexity. Although in the recent decade much progress has been made in the development of efficient field solvers, accompanied by a strong increase in computer speed and memory, field solvers ultimately remain slowly (depending on the model dimensions) with respect to circuit simulators. This lack of speed is especially detrimental for optimisation, which requires a large number of simulation runs.

From this point of view, there is a need for an approach, which uses the advantages of both, the accuracy of the field solver and the speed of the circuit simulation, combined together within one design process. The EM/circuit co-analysis and optimisation problem can be considered as shown in Fig. 2. EM field solvers offer very accurate results for parts and/or single components of the feed chain system, but the costs of this accuracy are long computation time and high memory requirements. On the other hand, conventional circuit simulators are somewhere in the lower right corner of this figure. They are fast and highly flexible, but do not account for all parasitic effects, and accuracy strongly depends on the available models and is not always guaranteed. One way to combine field and circuit analysis properly is the use of spatially extended microwave modules based on a library of basic transmission line elements [4].

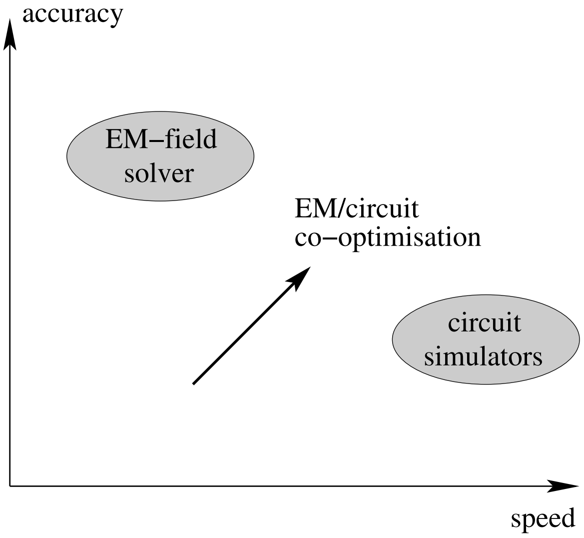

Fig. 2. Global perspective of the EM field/circuit co-optimisation problem

Our approach is to divide the antenna feed structure into their basic components in order to keep the complexity of the 3D EM models as low as possible. Within a circuit simulation tool the components can be imported as blocks, described by their S-parameter characteristics. In this way the antenna feed system can be built up by the composition of the components for a fast and accurate analysis of the entire feed chain structure. This technique was successfully used to design a complex dual circularly polarised high performance feed chain in Ku-band [5]. With a correct modelling, the performance of a entire and complex structure is calculated accurately considering mutual influence of the components because of finite reflection coefficients and including even effects caused by multiple reflections between discontinuities of two or more different components.

4. THE BEAM FORMING NETWORK

The beam forming network is a key element of MFB antennas. It provides the required amplitude and phase values of the excitation coefficients for the horns. In order to satisfy very conservative requirements for space applications, it was decided to use for the project Medusa only well established materials and processes. The network is made of space qualified Aluminium and consists of multiple layers. Fig. 3 shows the front-side of the BFN with its 74 output ports. Each layer of the network contains milled waveguide runs, branchline-couplers, phase shifters and waveguide via interconnections. A single layer of the network is shown in Fig. 4. In total the network has about 100 different branch-line couplers, 150 different phase shifters, numerous waveguide via interconnections and waveguide bends. It is clear that the whole network structure with several hundreds of components can not be simulated and optimised as a single complex 3D model. The components were optimised using field solvers. We used the program Mician Microwave Wizard [6], which is based on mode matching, for the branch-line couplers and CST MWS [7] for the phase shifters. CST MWS is using finite integration technique. Side conditions like minimum gap size or wall thickness have to be considered during the optimisation. All components have to be manufactured by milling, so milling radii were included in the design. The network analysis was performed using CST Design Studio (CST DS). CST DS can read CST MWS and Mician models. Components which are used several times in the network but always with an identical geometry, for example the waveguide via interconnections, need to be calculate only once. Models for empty waveguides, based on analytical formulas, are available as well as an import of Touchstone files. CST DS allows a direct and bi-directional access to 3D field solvers, so the field solvers can be controlled via CST DS. This allows not just to analyse but also to optimise or tune characteristics of the whole network with a minimum effort in field computation. Of course a correct modelling, for example a sufficient number of modes at the interfaces, must be assured by the design engineer.

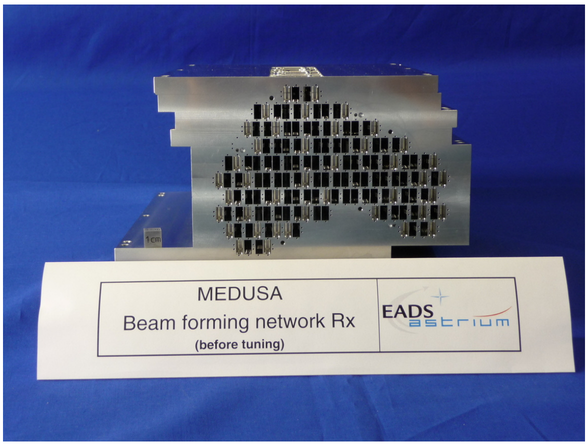

Fig. 3. Front-side of the BFN of the Medusa engineering model

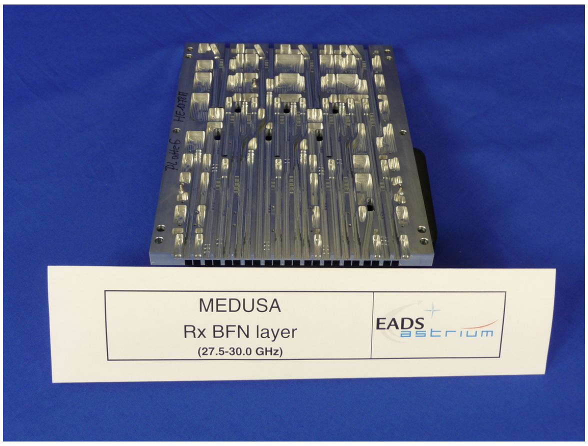

Fig. 4. One layer of the beam forming network for the engineering model of the Medusa antenna

5. RESULTS

In order to verify the electrical performance of the beam forming network, amplitude and phase of all excitation coefficients need to be measured. The measurement of the BFN is a very complex task. The network has 20 input ports and 74 output ports. Each input port is connected to 3-10 output ports. A large number of output ports are connect to two different input ports. During the measurement of the excitation coefficient of an output port, all output ports belonging to the same beam must be terminated by a waveguide load. Special measurement equipment was developed to achieve this. In total 131 sets of S-parameter had to be measured. Fig. 5 shows the set-up for the S-parameter measurement.

The S-parameters were measured using a network analyser. The measurement was performed in an air-conditioned room. It is very important to keep the temperature constant during the measurement. Temperature changes lead to expansion or shrinkage of the device under test and the set-up, which can cause significant measurement errors for the excitation phase values. Fig. 6 shows a comparison between the measured and calculated amplitude values of the excitation coefficients for one of the beams. For the calculation a surfaces roughness of 0.8 μm was considered. An ex-

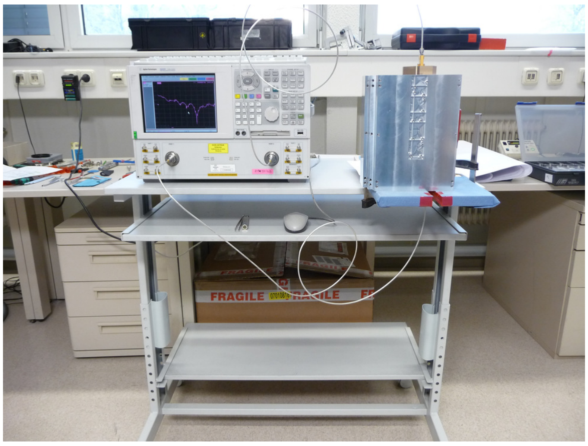

Fig. 5. Set-up for the measurement of the excitation coefficients

cellent agreement between the predicted and measured amplitude values was achieved. Fig. 7 compares the measured and calculated phase values of the excitation coefficients for one of the beams. Each path has an electrical length of approximately 420 mm. This includes the lengths of the waveguides as well as the contributions of the phase shifters, couplers and waveguide via interconnections between the different layers. The measured deviations for the phase values are less than 10°. This is equivalent to an absolute deviation of the electrical length of the waveguide run of 0.36 mm or a relative deviation of less than 0.09 %. For a network with such a high complexity this is a brilliant result. A further improvement will be achieved by tuning of the phase shifters.

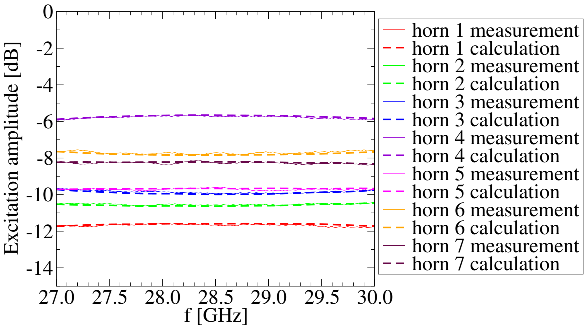

Fig. 6. Comparison of measured and calculated amplitude values of the excitation coefficients

6. CONCLUSIONS

A complex beamforming network for the feed system of a MFB multiple spot beam antenna was designed and optimised using a co-simulation of electromagnetic field solvers and circuit simulators. The complex network is divided into smaller parts that can be calculated by 3D field solvers. The performance of the network is calculated using a circuit simulator. In this way a mutual influence of the components or multiple reflections between discontinuities of different components are considered very accurately. An excellent agreement between the predicted performance and the measured performance was achieved.

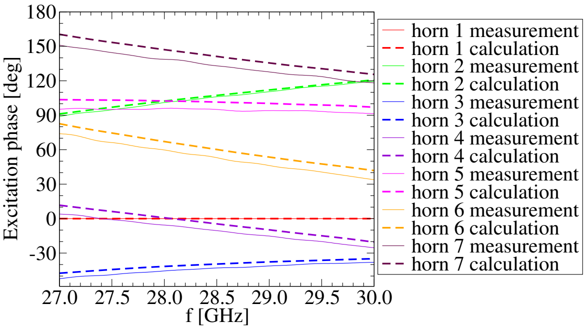

Fig. 7. Comparison of measured and calculated phase values of the excitation coefficients

It has been demonstrated that a multi layer waveguide beam forming network with an excellent performance can be designed and manufactured accurately and efficiently. Both, the design process and the manufacturing process are validated and can be used for commercial or scientific space applications.

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