Reconfigurable LC-Reflectarray Setup and Characterisation

A. Moessinger[1], S. Dieter[2], R. Jakoby[1], W. Menzel[2], S. Mueller[1]

[1]Universität Darmstadt, Merckstrasse 25, Darmstadt, Germany
[2]Universität Ulm, Albert-Einstein-Allee 41, Ulm, Germany

***Abstract*— This paper presents the realisation and characterisation of an electronically reconfigurable reflectarray based on liquid crystals at 35 GHz, which is able to electronically steer the main beam continuously in between ±35°. To extract the characteristics of each single tunable unit cell directly on the reflectarray, a specific near field measurement setup is used to enable spatial resolution of the reflected magnitudes and phases.**

I. INTRODUCTION

A reflectarray antenna combines, as its name already suggests, some of the best features of reflector and array antennas. A cost-effective type of reflectarray is the microstrip reflectarray. It consists in its basic form of a planar, thin substrate with microstrip antenna elements, i.e. patches or dipoles, which are arranged in an equidistant grid on the substrate. The array is illuminated by a feed antenna. The elements of the array, in the following called "unit cells", are designed to scatter the incident wave with an appropriate phase to form a planar phase surface in front of the aperture as depicted in Fig. 1. Reflectarrays have attracted increasing attention in the past years because of their properties: low loss due to the absence of a corporate feeding network, ease of fabrication, planarity, low weight. Reconfigurability is another desirable feature of reflectarrays that would increase their versatility.

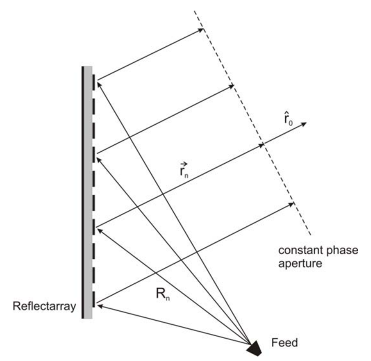

Fig. 1 Principle functioning of a microstrip reflectarray.

II. RECONFIGURABLE REFLECTARRAY PRINCIPLES

There have been various attempts to achieve electronic reconfigurability of reflectarrays: some of them made use of varactor diodes [1] in order to change the reflection phase, others used tunable materials such as Barium Strontium Titanate (BST) [2]. With the advances in the field of MEM-switches, these have become preferred to varactor diodes due to their superior RF properties [3], [4].

The idea of using liquid crystal (LC) as tunable material for reconfigurable reflectarrays has been presented in few publications [5], [6]. The phase shift required at each reflectarray element in order to generate a focussed beam in a desired direction is achieved by using the dielectric anisotropy $\Delta\varepsilon_r = \varepsilon_{r,\|} - \varepsilon_{r,\perp}$ of a thin liquid-crystal film, introduced between the patches of the reflectarray and the ground plane. The rigid, rod-like LC molecules are pre-oriented by a polyimide film to be aligned parallel to the ground and patch surfaces, i.e. perpendicular to the RF electric field. We denote the LC permittivity of this state as $\varepsilon_{r,\perp}$. By applying a bias voltage between patch and ground, the LC molecules rotate, changing their permittivity from $\varepsilon_{r,\perp}$ to $\varepsilon_{r,\|}$ as depicted in Fig. 2.

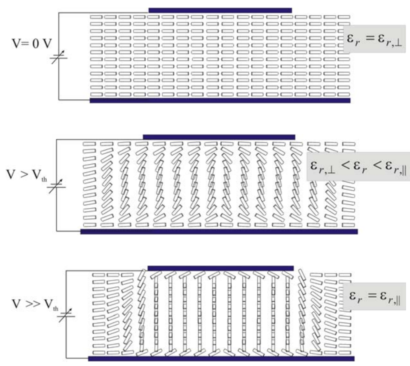

Fig. 2 Functioning principle of the tunable LC- reflectarray unit cell with a single microstrip patch.

As a first step towards a full-scale reconfigurable LC-reflectarray, several types of unit cells filled with different LC-mixtures have been realised and characterised [7].

The patches are printed on a 0.5 mm thick Rogers TMM3 carrier substrate, chosen for its rigidity due to the ceramic powder content. The cavity is realised by introducing spacers made of 0.127 mm thick RT-Duroid 5880. The LC is filled in the cavity by capillary force. The realised unit cells are measured in a waveguide simulator, an instrument commonly used to characterize reflectarray unit cells. It consists of a WR 28 waveguide terminated at one end with a pair of identical unit cells. At the other end, a network analyser is connected to measure the S_{11} parameter. The TE_{10} mode propagating in the waveguide can be described as a superposition of two plane waves impinging at a certain angle of incidence on the unit cells, depending on the dimensions of the waveguide and the frequency. This represents a good approximation of the simulation environment, consisting of a plane wave impinging at normal incidence on an infinite array of identical unit cells.

The set of curves depicted in Fig. 3 shows the measured S_{11}-parameter for different bias voltages of a single patch unit cell filled with *MDA-03-2844*. This is a R&D LC-mixture from Merck KGaA, especially developed for mm-wave applications, which features a high dielectric anisotropy and relatively low losses. Its dielectric properties, extracted with the cavity perturbation method at room temperature are summarised in Table 1 [8]. From the plot one can observe that the resonant frequency of the patch and the corresponding phase characteristic can be swept over more than 4 GHz, owing to the change in the effective permittivity of the LC-layer under the patch. The operating frequency of the tunable LC unit cell is defined as the frequency for which the phase difference for the two bias voltage extremes (lowest and highest bias voltage) is maximum, which occurs in this case at 35 GHz.

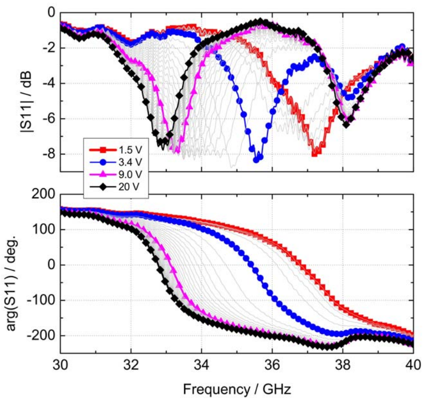

Fig. 3 Measured magnitude and phase of the reflection coefficient of a unit cell with single patch filled with MDA-03-2844.

A vertical cut through the plot in Fig. 3 at the operating frequency of 35GHz is given in Fig. 4. It shows the amplitude and phase characteristics of the unit cell versus bias voltage at a fixed operating frequency.

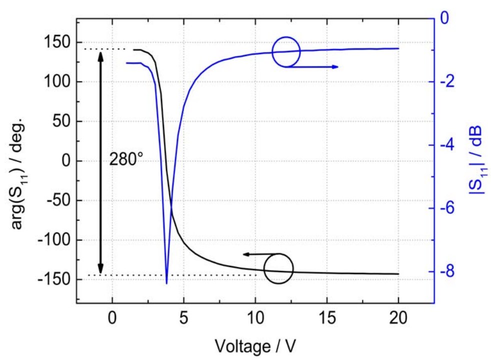

Fig. 4 Phase and magnitude of the complex reflection coefficient S_{11} over the control voltage at 35 GHz.

From this plot it can be observed that the reflected phase of the unit cell can be continuously tuned from approx. -140° to +140°, resulting in a tunable phase shift of 280°. The reflected amplitude varies in between -8 dB and -1 dB, depending on the tuning state.

Table 1: Dielectric properties of the employed LCs at room temperature.

LC	$\varepsilon_{r,\perp}$	$\varepsilon_{r,\parallel}$	tan $\delta_{\perp}$	tan $\delta_{\parallel}$	freq / GHz
MDA-03-2844	2.4	3.4	0.02	0.007	9
MDA-05-894	2.3	2.65	0.025	0.01	35

III. LC REFLECTARRAY

In [9] we presented the first LC reflectarray with electronically steerable beam at 35 GHz. In order to simplify the bias circuitry including multiplexing of the tuning voltages and the steering algorithm for this reflectarray, only steering in one plane was implemented, e.g. in azimuth.

This paper presents the realisation and near field characterisation of a successor reflectarray, with two design improvements: (1.) hardware implementation of 2D steering (possibility to steer the main beam in azimuth and elevation) and (2.) the use of SU8-epoxy resin for structuring the LC cavity [10].

The concept of two-dimensional steering is realised by etching a fine grid (gap g = 100 µm) on the ground plane, thus providing each patch with its own ground. A via connects the potential of each separate ground to the backside while each row of patches is connected by a thin line perpendicular to the E-field polarisation to apply the bias voltage between patch and ground. The cross-section of three unit cells illustrates the implementation of the 2D control in Fig. 5.

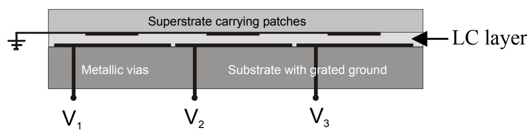

Fig. 5 Schematic diagram of the voltage control using vias.

Additionally, to achieve better control of the LC cavities height, which is a sensitive design parameter, some support points (spacers) structured with SU8-epoxy resin are used over the whole reflectarray. Fig. 6 shows the realised ground plane with the etched grid and the highlighted positions of the SU-8 spacers. With this setup it was possible to realise LC-cavity whose overall thickness averages to 115,8 µm (±14,6 µm). The cavity is filled with LC *MDA-05-894* from Merck KGaA with dielectric properties summarised in Tab. 1.

To simplify the bias circuitry in a first approach only 1D-beam steering has been applied although the array features 2D-reconfiguration possibility.

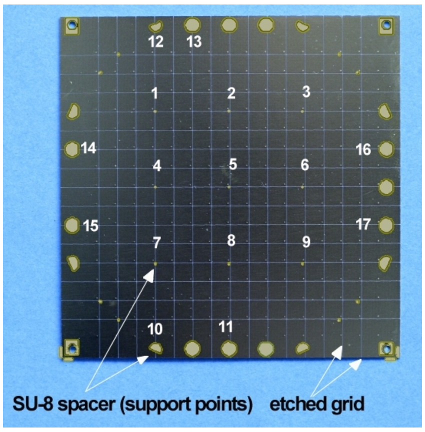

Fig. 6 Substrate carrying ground with etched grid and positions of the SU8 spacers.

To achieve a narrow beam in the non-steerable plane as well, a slotted waveguide is used as feed antenna which excites a cylindrical phase front on the surface of the reflectarray. The realised reflectarray with slotted waveguide feed is depicted in Fig. 7

To focus the beam in a desired direction, the algorithm described in [9] is applied in a first approach. It optimises the received power by testing different voltage distributions. Fig. 8 shows, that it is possible to focus the beam by applying suitable bias voltages. The reflectarray is able to scan the main beam continuously in between ±35°. Fig. 9 shows two exemplarily selected power patterns to demonstrate the beam steering functionality of the reflectarray.

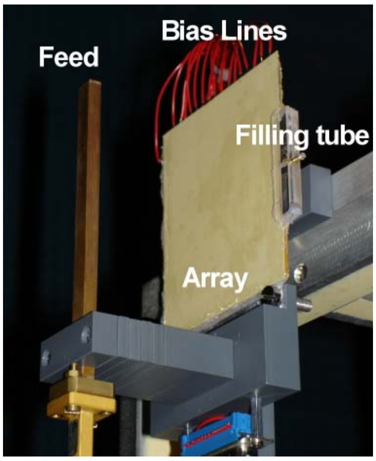

Fig. 7 Realised 35 GHz LC-reflectarray with feed.

One can observe the distinct focusing of the beam, but a side lobe level (SLL) of only 4.2 dB could be achieved. For the steered cases the SLL improves to about 6 dB. The relatively poor SLL is due to phase and amplitude errors, since only about 280° could be tuned with the employed LC and the losses show large variations with the tuning voltage.

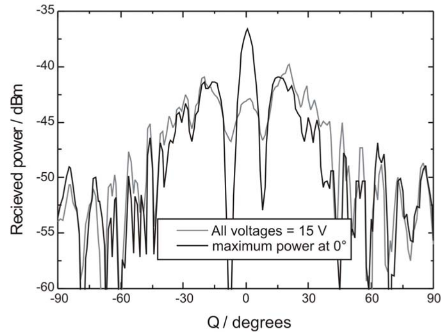

Fig. 8 Measured power pattern at 34.8 GHz with all voltages at 15 V and beam focused towards broadside.

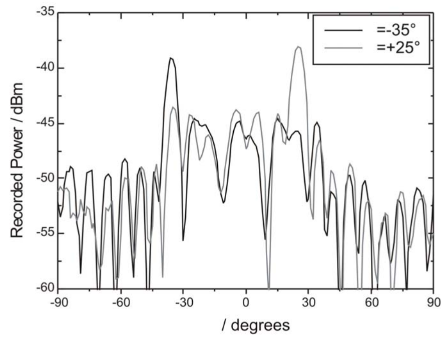

Fig. 9 Measured power pattern with main beams steered to -35° and +25°, respectively.

Another factor contributing to the high side lobes is the optimisation algorithm: the voltage configuration yielding maximum power in one direction does not necessarily yield a low SLL, due to the losses in the tunable elements. Additionally, only one point of the entire far field is taken into account by the optimisation algorithm, and thus only beam scanning but neither beam forming nor sidelobe level control is possible.

A gain of about 20.3 dBi was measured for this reflectarray, with the beam pointing at 0°. From the two 360°-cuts, one in the E-plane and one in the H-plane with the main beam pointing towards 0°, an approximate directivity of about 24 dBi is calculated. This yields an antenna efficiency of 42,6%. Thus, the overall loss on the reflectarray is about 4 dB.

To enable the possibility of beam forming instead of simple beam steering it is necessary to have a precise knowledge of the reflection characteristics of each single tunable unit cell on the reflectarray, connected with the applied bias voltages. Thus, in the next section a first approach to extract these characteristics directly on the reflector will be presented.

IV. REFLECTARRAY CHARACTERISATION

Up to now the tuning voltages used to steer the reflectarray are calculated by an optimisation algorithm, since the characteristics of single unit cells could not be measured [9]. Phase and amplitude over control voltage of two LC prototype unit cells have been investigated using a waveguide simulator, as used in [7]. Another possibility for characterisation is the usage of a farfield measurement method, where all patches of an antenna are set to the same control voltage and therefore, an average characteristic of the reflection behaviour over all patches can be measured [5].

A new approach in order to analyse the reflection behaviour of a tunable LC-patch array is a near field measurement of each unit cell separately, a few millimetres a the antenna surface. The principle of the measurement setup is shown in Fig. 10. An open waveguide is used to illuminate the patches of the reflectarray antenna (DUT). The reflected field is detected with the near field probe. Instead of using a hollow waveguide for detection, for this setup, a dielectric filled waveguide has been employed. The probe is a waveguide filled with acrylic glass, a simulation model of the structure is also shown in Fig. 10.

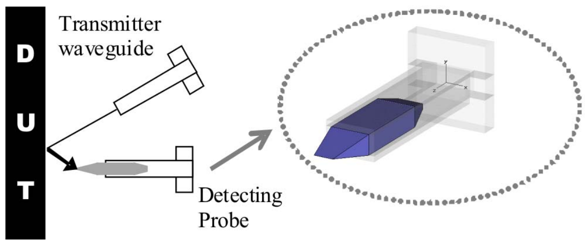

Fig. 10 Near field measurement principle and probe structure.

The tip of the acrylic structure has been designed to improve the field concentration in front of the probe, resulting in a higher spatial resolution compared to an open waveguide probe without dielectric filling. The tapered transition from waveguide to dielectric filled waveguide provides a better matching at the operating frequency around 35 GHz, see Fig. 11.

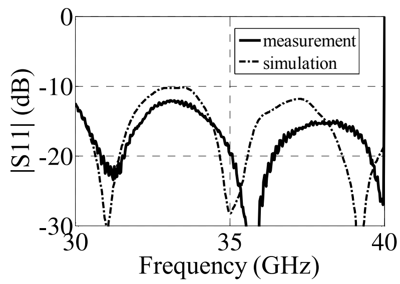

Fig. 11 Return loss optimisation of the probe for 35 GHz.

Within the desired frequency band around 35 GHz the matching is fair, below -20 dB.

Fig. 12 shows the measured amplitude result of a near field scan carried out with the waveguide probe over one section of the liquid crystal reflectarray antenna, which has been presented in the previous section. The grid indicates the sampling points. From the plot one can observe that with this measurement setup spatial resolution of the reflected magnitude is possible. The positions of single patches in resonance are visible.

During the measurements it was noticed that a section of the LC reflectarray was damaged and some part of the LC leaked. This defect in the LC layer is also detectable by the measurement setup: it is the region where the reflected magnitude remains constant over a certain area, marked in Fig. 12 as “defective region”.

So with this method, it is also possible to detect defective regions of the antenna automatically, enabling to control if there have been spurious air bubbles introduced during the filling process. Nevertheless, the spatial resolution of this near field probe is not sufficient. For this reason, the extracted characteristics of the unit cell are not usable to control the array yet.

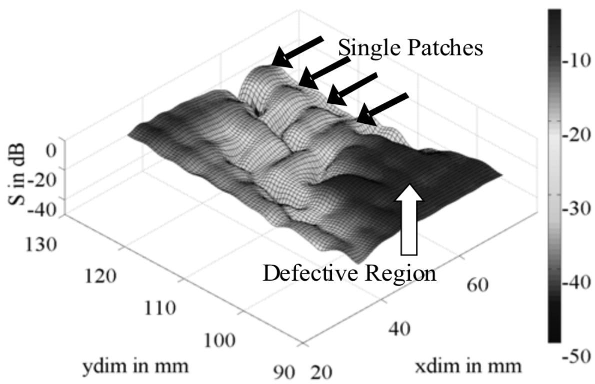

Fig. 12 Measured amplitude near field scan of LC reflectarray.

V. CONCLUSIONS

In this paper the fabrication and characterisation of an electronically reconfigurable LC reflectarray with 2D voltage control capability and SU8 structured spacers have been presented. Although a LC with relatively poor microwave properties has been used, the reconfiguration capability of the reflectarray could be demonstrated by focusing the beam in the desired direction between ±35°.

In the second part of the paper, a novel characterisation method has been introduced for aiming to extract the characteristics of each single unit cell directly on the reflector by near field measurements.

With this characterisation method, measurements with spatial resolution are possible. This is the main benefit in comparison to measurement methods with average results of all patches or unit cell prototypes.

So in principle, assignment of measurement results to single patches is possible and hence, characterisation of phase and amplitude over the control voltage. Since the spatial resolution for the near field probe presented in this paper is not high enough, further designs of near field probes with higher spatial resolution are currently under development.

ACKNOWLEDGMENT

Thanks are due to CST GmbH for providing the CST Microwave Studio solver and Merck KGaA for providing the employed LCs. This work has been supported by the DFG-Project "Rekonfigurierbare Millimeterwellen-Antennen mit steuerbaren hoch-anisotropen Flüssigkristallen".

REFERENCES

[1] Hum, S.V.; Okoniewski, M. and Davies, R.J.: "Realizing an electronically tunable reflectarray using varactor diode-tuned elements", *IEEE Microwave and Wireless Components Letters*, vol. 15, June 2005.

[2] R.R. Romanofsky, J.T. Bernhard, F.W. van Keuls, F.A. Miranda, G. Washington, and C. Canedy.: "K-band phased array antennas based on $Ba_{0.60}Sr_{0.40}TiO_3$ thin-film phase shifters", *IEEE Transactions on Microwave Theory and Techniques*, pages 2504 - 2510, Dec. 2000.

[3] Legay, H.; Caille, G.; Girard, E.; Pons, P.; Calmon, P.; Perret, E.; Aubert, H.; Polizzi. J.P.; Laisné, A.; Gillard, R; Van der Vorst, M.: "MEMS controlled phase-shift elements for a linear polarized reflectarray", *28th ESA Antenna Workshop*, 31 May - 3 June 2005, Noordwijk, Netherlands.

[4] R. Sorrentino, R. V. Gatti, L. Marcaccioli, B. Mencagli: "Electronic Steerable MEMS Antennas", EUCAP 2006 *Proceedings of the 1st European Conference on Antennas and Propagation*, Nice, France, 6-10 Nov. 2006

[5] R. Marin, A. Moessinger, F. Goelden, S. Mueller, R. Jakoby, „77 GHz Reconfigurable Reflectarray With Nematic Liquid Crystal", *the 2nd European Conference on Antennas and Propagation (EUCAP)*, Edinburgh UK, November 2007.

[6] Ismail, M.Y.; Cahill, R., "Application of liquid crystal technology for electronically scanned reflectarrays" in *Asia-Pacific Conference on Applied Electromagnetics*, 20-21 Dec. 2005, Page(s): 4 pp

[7] R. Marin, A. Moessinger, J. Freese and R. Jakoby, "Characterisation of 35 GHz Tunable Reflectarray Unit Cells Using Highly Anisotropic Liquid Crystal," in GeMiC 2006 *German Microwave Conference*, Karlsruhe, Germany, 28.-30. March 2006.

[8] A. Penirschke, S. Muller, P. Scheele, C. Weil, M. Wittek, C. Hock, and R. Jakoby, "Cavity perturbation method for characterization of liquid crystals up to 35 GHz" *European Microwave Conference, 2004,* pp 545-548, 2004

[9] A. Moessinger, R. Marin, S. Mueller, J. Freese and R. Jakoby: "Electronically reconfigurable reflectarrays with nematic liquid crystals," *IEE Electronics Letters*, vol. 42, pp. 899-900, Aug. 2006.

[10] A. Moessinger, R. Marin, D. Eicher, H. Schlaak, and R. Jakoby, "Liquid crystal reflectarray with electronic 2D-reconfiguration capability," *29th ESA Antenna Workshop on Multiple Beam and Reconfigurable Antennas*, Apr 2007.