Characterization of 35 GHz Tunable Reflectarray Unit-Cells Using Highly Anisotropic Liquid Crystal

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Abstract— **This paper presents the study, relization, and measurement of diferent tunable unit-cells for reconfigurable reflectarrays at 35 GHz. The emphasis of the work lies in the use of nematic Liquid Crystal, a material with electrically tunable dielectric properties. Unit cells have been optimized with respect to the trade-off between maximum attainable phase range and losses. The realised structures have been tested in a waveguide simulator and phase ranges up to 290° could be demonstrated.**

I. Introduction

Microstrip reflectarray antennas have benefitted from increased attention from the part of the antenna community in the recent past [1]–[3], since they combine some of the advantages of reflectors and of array antennas. The main advantage of reflectarrays is the reflectorlike spatial power distribution by means of a feed antenna, thus replacing the lossy power distribution network. The phase of the reflected wave can be adjusted element-wise, thus enabling the possibility of beam-scanning. Low profile, low weight and easy fabrication are additional features which make microstrip reflectarrays appealing.

There have been various attempts to make reflectarrays with steerable beam, using different approaches to control the unit cells. In [4], [5] the use of varactor diodes is proposed. An approach making use of MEMS is presented in [6]. In [7], we proposed an alternative approach, based on the dielectric properties of Liquid Crystal (LC), a material that changes permittivity when DC voltage is properly applied. In this paper, the design and measurement of different cell topologies with improved characteristics is presented.

The next section of the paper presents the two concepts proposed for the LC-unit cell, section III describes the realization of the different unit-cells and of the measurement set-up, and the measured results are finally presented in section IV.

II. Concept of Tunable Unit-Cell based on Nematic LCs

Properties of nematic LCs as phase shifting material at microwave frequencies have been studied lately [8]. Under an applied DC-voltage the molecular arrangement of LC changes, causing a change in LC permittivity. We make use of this property, in order to obtain the necessary phase shift at each unit cell of the reflectarray.

In this section we propose two concepts for tunable unit-cells for reflectarrays, based on nematic LCs. The first concept is based on modifying the resonance frequency of a microstrip patch by changing the permittivity of the LC. In order to achieve this, a cavity has to be formed under the patch and filled with LC, as shown in Fig. 1. A single patch as well as stacked patches could be used, with no additional layer, since they can be printed on both sides of the substrate.

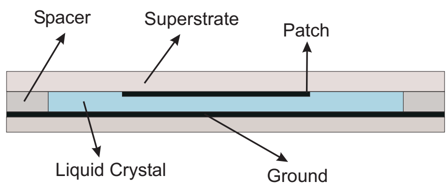


Fig. 1: Configuration of the LC-loaded unit-cell employing microstrip patch element.

The second concept consists of a delay line coupled to the microstrip patch by means of an apperture in the ground plane. The phase of the reflected wave can be controlled by filling LC under the line, as in Fig. 2. By varying the permittivity of the LC, the electric legth of the line changes, and thus the phase of the reflected wave can be adjusted, since it holds:

$$\Delta\varphi = \Delta\left(\beta \cdot \ell\right) = \frac{2\,\pi \cdot \ell}{\lambda} \cdot \Delta\left(\sqrt{\varepsilon_r}\right) \qquad (1)$$

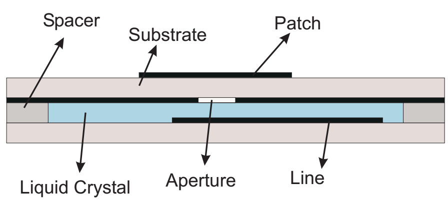


Fig. 2: Configuration of the LC-loaded unit-cell with aperture coupled line.

Both concepts have advantages as well as drawbacks. The first concept, employing a single patch (or stacked patches) is simpler and thus easier to realise, whereas the dimensions of the components at 35 GHz make it harder to etch the line and the aperture accurately and to align them to the desired position. On the other hand, with a single/stacked patch cell, theoretically a maximal phase range of 360° can be achieved (practically even less), while with an aperture coupled line a theoretically unlimited phase range can be reached, in accordance with Eq.1. It is obvious from Eq. 1 that the physical length of the microstrip line can be increased, thus increasing the tunable phase range. In reality, one will nevertheless eventually come across physical limitations due to the finite space available for the line belonging to one unit cell.

In both cases, the LC-cavity must be very thin ($\leq 150\mu\mathrm{m}$), in order to allow the prearrangement of the LC-molecules parallel to the ground and microstrip patch (or microstrip line respectively), with the aid of a polyimid film (A reduced thickness of the LC layer also helps improving the otherwise low response times of the LC). The prealignment of the LC molecules parallel to the surface due to the polyimid film causes a $\varepsilon_{eff\perp}$. A DC-voltage applied between the lower microstrip patch (microstrip line) and the ground plane will cause the molecules to rearrange, until reaching a saturation voltage, when they are completely aligned with the static electric field. In this state the LC molecules are almost parallel to the RF-field and the permitivity is denoted as $\varepsilon_{eff\|}$.

In order to test the both concepts, simulations were made with values of ε_r between $\varepsilon_{eff\perp}$=2.6 and $\varepsilon_{eff\|}$=3.4, which are situated in the attainable measured range reported in [9]. These values refer to a LC provided by Merck.

The simulations were aimed at improving the ratio between attainable phase range and return loss, since there is a trade-off between the two. A steeper slope of the phase curve means wider tunable range, but also more losses, because of the sharper resonance. The most promising results, two cells with stacked patches, one cell with a single patch and one cell using aperture coupled line were manufactured and measured in a waveguide simulator.

III. Realization of the Unit Cells and of the Measurement Setup

As known from the theory, in the waveguide simulator it is possible to emulate the plane wave impinging on a infinite array, but not at normal incidence. The field distribution propagating in the waveguide in the main TE_{10}-mode is similar to the field distribution of two plane waves who make an angle of $\theta_i = \arcsin(\lambda_0/\lambda_c)$ with the plane containing the unit cells (λ_0: free-space wavelength, λ_c: cut-off wavelength). For the particular structure that we investigated this angle amounts to about 37°, and since the phase response of the unit cell is dependent of the incidence angle, we expect slight differences between simulation and measurement results. However it has been shown ([10]) that this differences are not very severe, and thus the setup can be seen as adequate for the purpose of testing the functionality of a LC-unit-cell.

As mentioned in the previous section, we decided to manufacture and test different structures, who showed promising results in the simulations. One of the structure had a simple patch etched on one side of the substrate (**Structure 1**), two of them employed stacked patches (**Structure 2** and **Structure 3**), finally, **Structure 4** designates the cell using the aperture coupled line as phase shifter.

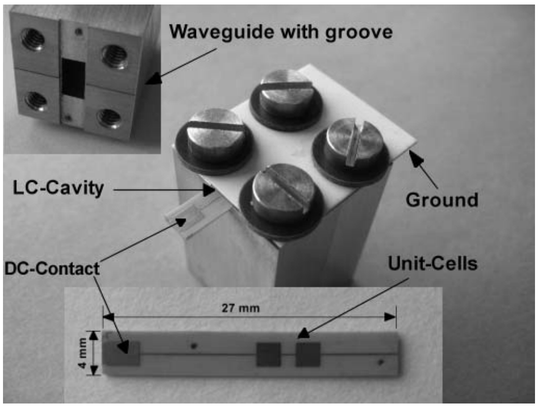


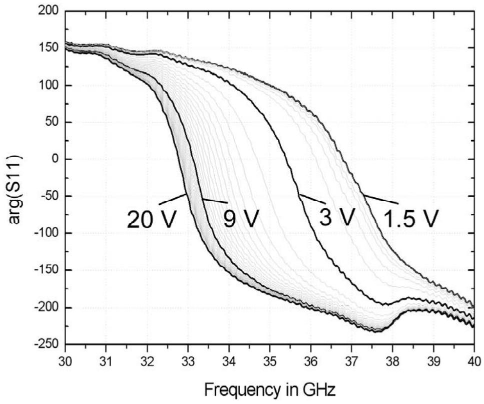
Fig. 3: Setup for mesuring the unit cells in a waveguide simulator.

For the structures 1 to 3 TMM3 with a thickness of 0.5 mm was used as substrate. The two patches on the LC-side are connected through a thin line, which is then prolonged over the edge of the metal-block in order to ensure a proper soldering point for the DC-Voltage lead. This line has very little influence on the measurement, since, due to the polarization of the E-field, it is placed in a quasi zero-field point. The same technique is used to connect the two aperture couled lines to the DC-Voltage, as can be seen in Fig 3 and Fig 6.

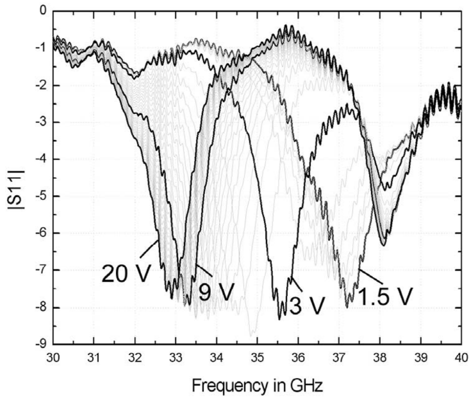
For structure 4 we employed RTDuroid 5880 with 0.5 mm thickness as substrate: on one side were printed the patches, on the other side the apertures in the ground plane. The lines were printed on TMM3, 0.5 mm thick. RTDuroid 5880, 0.127 mm thick was used as spacer for all structures. On both sides of the LC-cavity a 300 nm thick polyimide film was spinned, having the role to prealign the LC molecules.

IV. Measurement results

The applied control voltage was swept during the measurements between 0 V and 20 V. The measured frequency dependent phase and magnitude of the reflection coefficient are shown exemplarily for Structure 1 (simple patch) in Fig. 4. In Fig. 5, the phase and magnitude of the reflection coefficient are shown in dependence of the control voltage at a chosen frequency (we chose in each case the frequency where the maximum phase range was obtined). **Structure 1** (single patch) showed a phase range of about 270° between 34 GHz and 36 GHz, while return loss had values between -0.5 dB and -8 dB depending on the frequency and on the control volage. With **Structure 2** (stacked patches) the phase could be controlled in a range of roughly 250°, with somewhat higher return loss, between -4 dB and -11 dB. **Structure 3** (stacked patches) exhibited phase range of 270° to 290° between 31 GHz to 32.5 GHz, while the return loss was again between 0.5 dB and -8 to -9 dB. **Structure 4** (aperture coupled line) showed the poorest performance of all, with around 240°

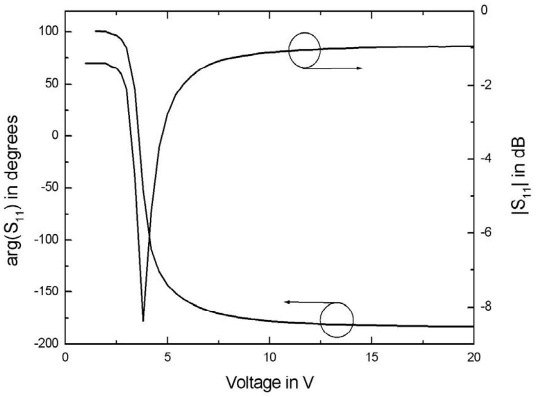


(a) Phase - $\arg(S_{11})$

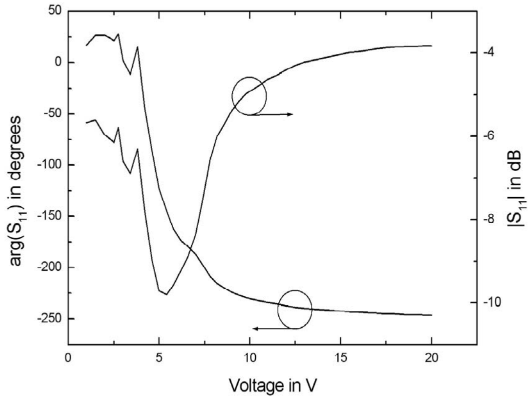


(b) Magnitude - $|S_{11}|$

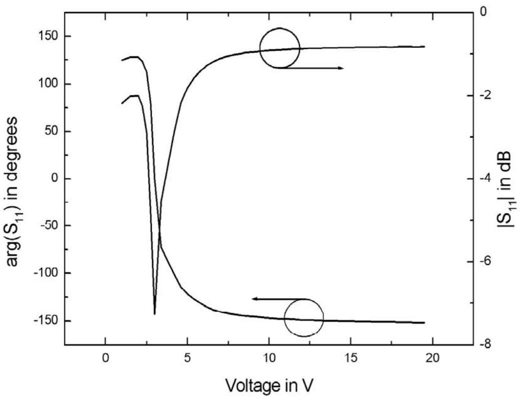
Fig. 4: Frequency dependent variation of the reflection coefficient, shown exemplarily for **Structure 1**



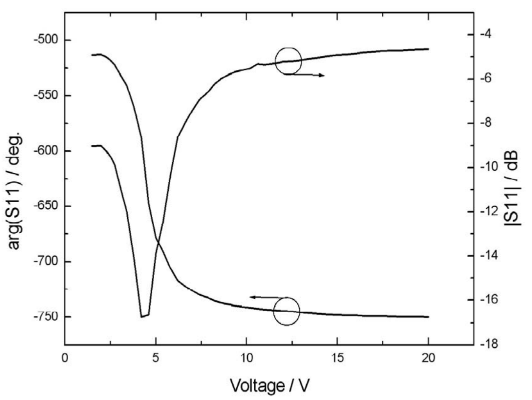
(a) **Structure 1** - at 35 GHz



(b) **Structure 2** - at 33 GHz



(c) **Structure 3** - at 31 GHz



(d) **Structure 4** - at 36 GHz

Fig. 5: Phase and magnitude of the reflection coefficient for the four mesured unit-cell structures in dependence of the control voltage - at the frequency of maximum phase range.

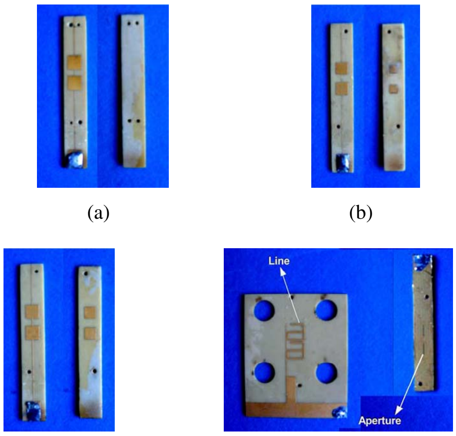


Fig. 6: (a) Structure 1 - patch, (b) Structure 2 and (c) Structure 3 - stacked patches, (d) Structure 4-aperture coupled line.

phase range and return loss between -5 dB and -15 dB.
Structures 1 and **3** showed almost similar performance, so one can assume those two structures to be most suitable candidates for the realisation of an electronically reconfigurable reflectarray. Even though the peak losses are high (around -8 dB), in a reflectarray they would be between -1 dB and -8 dB, depending on the phase distribution on the aperture. The measured results of **Structure 4** exhibit much higher loss than expected and a somewhat narrower phase range, which can be due to manufacturing and alignment tollerances. **Structure 2** , though having a somewhat reduced phase range, of only 250° and higher losses, compared to the structures 1 and 3, exhibits a rather broad frequency range where it can be used (31.5 GHz to 34 GHz) without noticeable performance degradement. This fact encourages the assumption that not only narrow-band unit-cells are possible, as expected from a highly resonant structure.

V. Conclusion and Outlook

Several structures to be used as tunable unit-cells in a LC-based electronically reconfigurable reflectarray have been proposed, realised and measured in a waveguide simulator. The results show a usable phase range of up to 290°, with control voltage between 0 V and 20 V. However, additional structures which may exhibit lower losses are curently under investigation.
Simulations based on the measured unit cell results (phase range and losses) resulted in usable patterns. As shown in Fig. 7, the simulated pattern of a 15x15 reflectarray using structure 3 as unit cell, has a 4 dB lower gain than the pattern of a fixed beam reflectarray using microstrip patches of variable sizes on RTDuroid. The gain difference is expected, since the 4 dB represent the averaged losses of the structure. The realisation of a small reconfigurable LC-reflectarray demonstrator is currenly in progress.

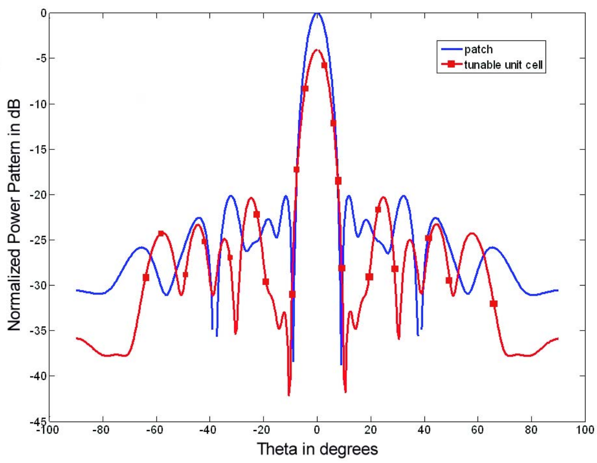


Fig. 7: Simulated patterns of the reflectarrays using microstrip patches and Structure 3 as unit cell respectively (patterns normalized with respect to the array with microstrip patches).

Acknowledgement

Thanks are due to Merck KGaA for provinding the Liquid Crystal mixture and to CST GmbH for providing the *CST Microwave Studio* package for simulations.

References

[1] David M. Pozar, Stephen E. Targonski and H. D. Syrigos: *Design of Milimeter Wave Microstrip Reflectarrays*. IEEE Transactions on Antennas and Propagation, vol. 45, Feb. 1997.
[2] John Huang and Ronald J. Pogorzelski: *A Ka-Band Microstrip Reflectarray with Elements Having Variable Rotation Angles*. IEEE Transactions on Antennas and Propagation, Vol. 46, No. 5, May 1998
[3] Jose A. Encinar: *Design of Two-Layer Printed Reflectarrays Using Patches of Variable Size*. IEEE Transactions on Antennas and Propagation, Vol. 49 , No. 10 , Oct. 2001 .
[4] 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.
[5] Boccia, L., Venneri, F., Amendola, G. and Di Massa, G.: *Experimental investigation of a varactor loaded reflectarray antenna*. IEEE Microwave Symposium Digest,2002 IEEE MTT-S International Vol. 1, 2-7 June 2002.
[6] Legay, H., Pinte, B., Charrier, M., Ziaei, A., Girard, E. and Gillard, R.: *A steerable reflectarray antenna with MEMS controls*. IEEE International Symposium on Phased Array Systems and Technology, 14-17 Oct. 2003 Page(s):494 - 499.
[7] Marin, R., Mössinger, A., Freese, J., Müller, S. and Jakoby, R.: *Basic Investigations of 35 GHz Reflectarrays and Tunable Unit-Cells for Beamsteering Applications*. Proceedings of the 8th European Microwave Week, Page(s): 291 - 294, Paris, Oct. 2005.
[8] Stefan Müller, Patrick Scheele, Carsten Weil, Michael Wittek, Christian Hock and Rolf Jakoby: *Tunable Passive Phase Shifter for Microwave Applications Using Highly Anisotropic Liquid Crystals*. Microwave Symposium Digest, 2004 IEEE MTT-S International , Vol. 2 , June 6-11, 2004.
[9] Andreas Penirschke, Stefan Müller, Patrick Scheele, Carsten Weil, Michael Wittek, Christian Hock, and Rolf Jakoby:*Cavity Perturbation Method for Characterization of Liquid Crystals up to 35 GHz*. Proceedings of the 34th European Microwave Conference, Page(s): 545 - 548, Amsterdam, Oct. 2004
[10] Targonski, S.D. and Pozar, D.M.: *Analysis and Design of a Microstrip Reflectarray Using Patches Of Variable Size*. Antennas and Propagation Symposium Digest, Vol. 3, Page(s):1820 - 1823, 20-24 June 1994