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# Realization and Characterization of a 77 GHz Reconfigurable Liquid Crystal Reflectarray

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***Abstract*—A tunable microstrip reflectarray with beam reconfiguration capability at 77 GHz is presented. Tunablility is achieved by using anisotropic liquid crystal as RF-substrate, tunable by a biasing voltage below 15 V. The reflector has been characterized by utilizing a lens setup forming a gaussian beam. The reflector properties has been extracted in terms of its reflected phase and magnitude: While it is possible to tune about 280° of phase, the associated losses are still quite high. Nevertheless, pattern measurements of the reflectarray showed distinct beam collimation towards different angles when appropriate DC control voltages are applied.**

## I. Introduction

Reflectarrays have attracted increasing attention in the past years because of their properties: low loss due to the absence of a corporate feed, ease of fabrication, planarity, low weight. Reconfigurability is a further desirable feature of reflectarrays that would increase their versatility a lot. 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 as tunable material has also been presented in several publications [5]–[8]. In [6] we published what is to our knowledge the first LC-reflectarray with steerable beam at 35 GHz. In this contribution, the design, realization and investigation of a 16x16 elements LC-reflectarray with steerable beam in one plane operating at 77 GHz is presented.

## II. Functioning principle and unit cell investigations

The approach presented in this paper, is based on the principle of variable patch dimensions published in [9]. But instead of changing the dimensions of the metalized patch, a tunable substrate is used, which dielectric properties can be adjusted with a bias voltage below 15 V. Thus all patches will have the same geometrical size, while the effective permittivity of the substrate under each patch will differ causing different electrical dimensions of the patches. This results in different backscattered phases which can be electronically tuned independently for each unit cell. One material that provides this functionality and is used in this work is liquid crystal (LC). LCs are well-known as components of LCDs (Liquid Crystal Displays). The nematic LCs used in this work can be treated as rigid, rod-like molecules. Because of the orientational order of the molecules, a macroscopically uniaxial anisotropic permittivity is effective [10] where the dielectric anisotropy amounts to $\Delta\varepsilon_{r,eff} = \varepsilon_{r,eff,\perp} - \varepsilon_{r,eff,\parallel}$. The director $\overrightarrow{n}$, a unit vector indicating the average molecule alignment, can be oriented with different techniques:

- Surface anchoring with an orientation layer, like a mechanically rubbed polyimid film: The director of the molecules is aligned parallel to the surface along the rubbing direction.
- Application of an external electric or magnetic field: The director of the molecules is aligned parallel to the external field.

Both tuning mechanisms are used in applications to achieve an equilibrium state at a certain director orientation. The director orientation, and consequently the effective permittivity, can be tuned by varying the bias voltage. The director $\overrightarrow{n}$ is indicated in Fig. 1 by rectangles.

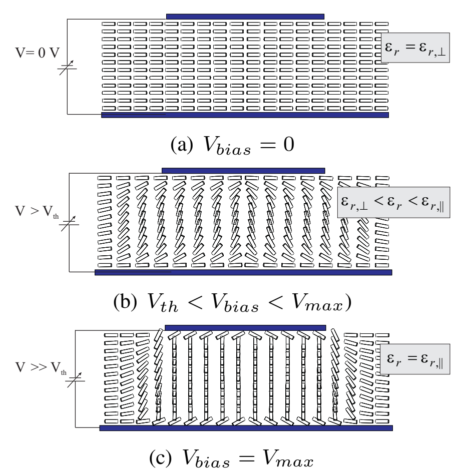


Fig. 1. Functioning principle of the LC-tunable reflectarray unit cell with single microstrip patch.

Using LCs as tunable substrate introduces several constraints in the RF-Design: As the name already suggests, LCs are fluid and hence carrier substrates are required, to support the metalization and the ground plane. Additionally the carrier substrates have to form a cavity with a well-controlled thickness in which the LC can be filled after fabrication. The cavity has to be properly sealed to avoid LC leakage. Since the surface alignment mechanism (described above)

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is only functional for thin LC-layers, the cavity thickness should not be much larger than 100 $\mu$m. This will seriously limit the bandwidth of the microstrip structure, especially for lower frequencies. Therefore, the operating frequency of the reflectarray presented in this work is situated in the W-band at 77 GHz. In Fig. 1 a schematic of the cross section of a LC-tunable reflectarray unit cell is presented. The cell consists of a patch printed on a carrier substrate, the ground plane printed on a carrier as well, and the LC cavity between patch and ground. A thin polyimide film ($<<$ 500nm) is spin coated on the ground plane and on the patches, cured and finally mechanically rubbed, in order to provide the pre-alignment of the LC-molecules.

The director of the LC-molecules is initially aligned parallel to the patch and ground, owing to the polyimide layer (Fig. 1(a)). The applied bias voltage between patch and ground generates the external electric field for rotating the director continuously. The RF-field, given by the microstrip patch fundamental mode is mainly confined in the LC-volume and is essentially perpendicular to the director. Thus, the RF-field will perceive an effective permittivity $\varepsilon_{r,eff,\perp}$. Applying an increasing bias voltage, the director will begin to rotate as soon as the voltage exceeds a certain threshold voltage $V_{th}$ of a few volts (Fig. 1(b)). When the bias voltage is increased even further, the director of the LC molecules will tend to align with the bias field lines, until the molecules are completely aligned parallel to the bias E-field. In this state, the average direction of the main axes of all molecules orients parallel to the RF-field and the experienced effective permittivity becomes $\varepsilon_{r,eff,\parallel}$ (see Fig.1(c)).

Preliminary investigations on a series of unit cells in a waveguide simulator have been carried out, in order to test the phase shifting properties of the nematic LCs with little effort. The measured results have been reported in [7] and are synthesized in Table I. From the table it can be concluded that

TABLE I
MEASUREMENTS RESULTS FOR DIFFERENT MANUFACTURED 77 GHZ UNIT CELLS MEASURED IN A WAVEGUIDE SIMULATOR.

| *LC-Type* | BL006 | Novel-Mixture | Novel-Mixture |
|---|---|---|---|
| *Printed element* | Single patch | Single Patch | Staked patches |
| *Cavity thickness* | 50 $\mu$m | 50 $\mu$m | 127 $\mu$m |
| *reflection loss* | 16 dB | 6.7 dB | 8.5 dB |
| *phase range* | 280° | 280° | 210° |

the best results in terms of tunable phase range are obtained with cavity thickness of 50 $\mu$m. Thus, this cavity thickness has been chosen for the full scale reflectarray presented in the next section.

## III. DESIGN AND CONSTRUCTION OF THE LC REFLECTARRAY BREADBOARD

The realized breadboard of a tunable LC reflectarray has been briefly presented in [11]. It consists of 16x16 unit cells with an inter-element spacing of 0.55 $\lambda_0$. This dimension was chosen due to practical reasons: it is small enough to be able to control the height of the cavity and to fill in the liquid crystal by means of capillary force, and large enough to obtain a relatively narrow beam and a reasonably high directivity. All elements in a column are connected by a 50 $\mu$m thin bias line, thus all unit cells on one row will backscatter with the same phase, reducing the number of required bias voltages to 16. As a drawback, the reflectarray will only be 1-D steerable with a linear polarized impinging field orthogonal to the bias line. Therefore, the feed antenna has to be linear polarized. Fig. 2 shows a top view photograph of the realized LC reflectarray.

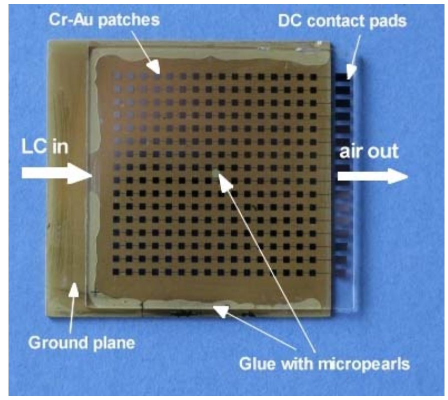


Fig. 2. Assembled 77 GHz reflectarray prior to the filling of the LC. The LC is introduced in the gap on the left and is pulled inside the cavity by capillary force.

Different carrier substrates and spacers have been investigated. Based on these investigations, fused silica has been chosen as top carrier substrate whereas a silicon wafer is used as lower substrate. Spherical spacers are mixed with epoxy glue to employ 50 $\mu$m thick cavities.

The thin polyimide film is applied on the fused silica after etching the patches and on the metalized silicon ground. The film is mechanically rubbed to achieve a grooved surface structure.

The cavity has been filled with a LC mixture developed for a maximal optical anisotropy. It also features acceptable microwave performance. Its characterization with the cavity perturbation technique at 30 GHz yielded for the dielectric anisotropy and dielectric losses the values summarized in Table II.

TABLE II
PROPERTIES OF LC-MIXTURE AT ROOM TEMPERATURE MEASURED AT 30 GHZ.

| $\varepsilon_{r,eff,\parallel}$ | $\varepsilon_{r,eff,\perp}$ | $\tan\delta_{\parallel}$ | $\tan\delta_{\perp}$ |
|---|---|---|---|
| 3.18 | 2.49 | 0.004 | 0.017 |

## IV. REFLECTOR CHARACTERIZATION

Once filled with LC, the reflector has to be characterized in order to extract the bias-phase characteristic of the reflector, which is needed to control the radiated power pattern. For this purpose, in [11] two horn antennas connected to the ports of a vector network analyzer and placed symmetrically in front of the reflectarray have been used. By measuring the

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complex transmission coefficient $S_{21}$ while applying the same control voltage to all unit cells simultaneously, the reflection characteristic of the complete reflector could be extracted. Although quite useful results were achieved, this setup suffered from spurious reflections and noise due to the low power level. For that reason a different setup is presented in this paper.

This setup consists of a quasi-optical directional coupler, terminated at one end with an absorbing material and at the other end with the reflectarray under test. Fig. 3 shows a photo of the setup with the LC reflectarray ready for measurements. The functional principle is depicted in Fig. 3 and is as follows:

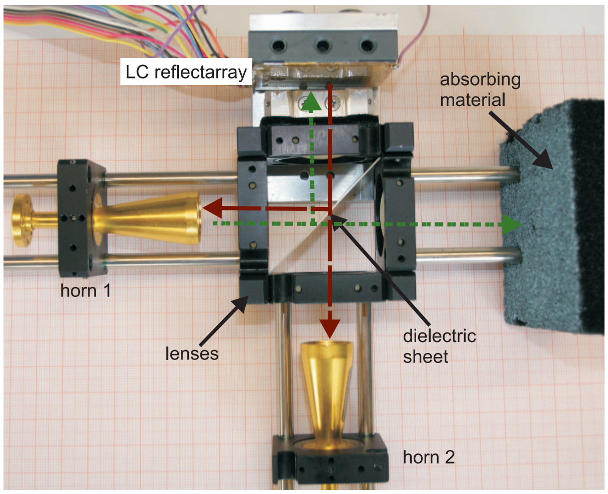
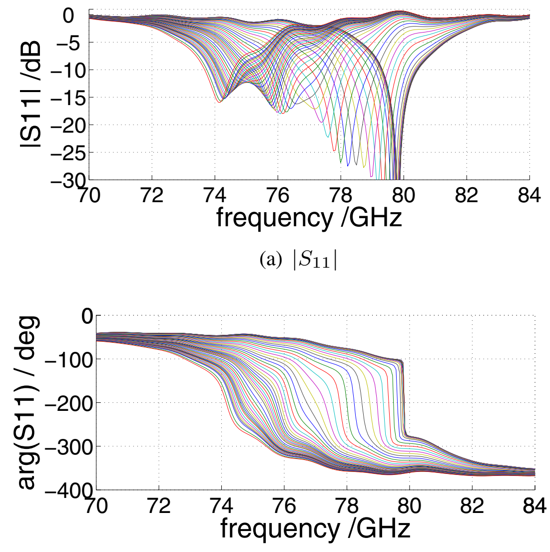



Fig. 3. Photograph of the measurement setup

the power radiated by horn antenna 1 is divided into equal parts at the dielectric sheet. Half the power is directed to the absorbing material, the other one to the reflectarray. Here, the power of the reflected wave is again divided into equal parts at the dielectric sheet. One half is directed back to horn antenna 1 and the second half is received by horn antenna 2. This measurement setup has several advantages compared to the setup presented in [11]: since the reflectarray is located in the beam waist of the Gaussian beam, only a spot in the middle of the array is illuminated, reducing the edge effects of the target. Additionally, the power level is reduced by only 6 dB due to the beam splitting in the measurement setup. Furthermore, spurious reflections and multipath effects could be reduced in comparison to the previous setup. Since the spot size illuminating the array amounts to several times the wavelengths, this setup can not resolve the characteristics of a single unit cell. But it enables the possibility to measure average characteristics of all unit cells on the reflector, if every unit cell is biased with the same control voltage simultaneously. Fig. 4 shows the measured S-parameter of the reflector for different bias voltages after being normalized to a polished silver plate and using time gating. It can be recognized that the maximum measured phase shift occurs at 77.2 GHz. Fig. 5 depicts that there is a tunable phase range of about 280 degrees. It is apparent that the losses are very high (up to -20 dB). This is due to dielectric and conductor losses.




(a) $|S_{11}|$

(b) $\arg(S_{11})$

Fig. 4. Magnitude and phase of the reflection obtained when the control voltage is swept from 0 to 25 V.

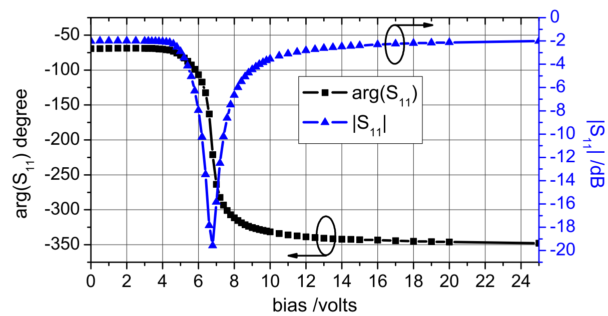



Fig. 5. Extracted magnitude and phase of the free standing LC-reflector when the DC control voltage is varied between 0-25 V.

## V. Pattern Measurements

In Fig. 6 the fully assembled reflectarray with feeding antenna is shown. To feed the array a curved open waveguide, with the aperture placed centrally in front of the reflecting surface is used. As already mentioned, owing to the setup, the array is only capable to steer and focus the beam in one plane, the E-plane. Hence there is no possibility to achieve a focussing of the beam in the non-steerable plane, the H-plane. Although the mechanical properties of the assembly have been improved in comparison to the 35 GHz reflectarray presented in [6], there are still deviations in the characteristics from cell to cell, due to variations in the cavity height and in the uniformity of the polyimide film. Therefore, the same procedure as in [6] has to be used in order to focus the beam, i.e. the reflectarray is rotated towards the desired direction and voltages are sequentially varied until maximum power is recorded.

The pattern measurements were performed in a anechoic chamber at 77.2 GHz, this being the frequency where maximum adjustable phase range was recorded. In order to illustrate

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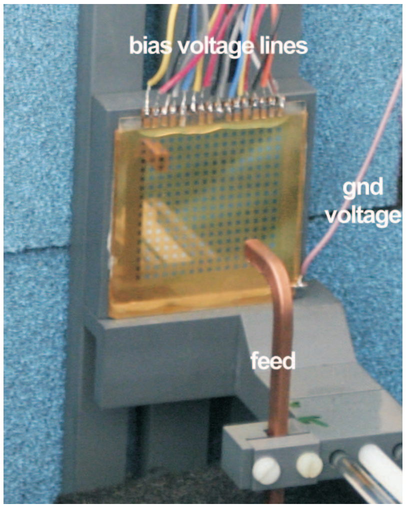


Fig. 6. Fully assembled reflectarray with feed mounted for measurements.

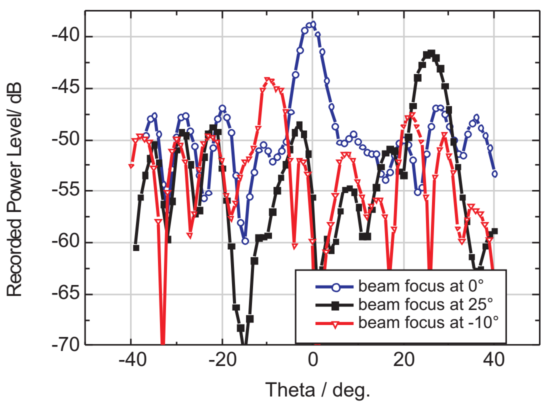


Fig. 7. Three recorded E-plane patterns for three different voltage configurations, with the main beam pointing at different angles: $-10°$, $0°$ and $+25°$ (at 77.2 GHz).

the beam steering ability of the reflectarray in the E-plane, three selected patterns are presented in Fig. 7: the main beam is in the three cases directed towards $-10°$, $0°$ and $25°$ respectively.

The side lobe level when the beam is directed at broadside is still high at -8 dB, but compared with the values in [6] it has improved. It can be observed that the pattern with the main beam pointing at $-10°$ is deteriorated in comparison to the other two. This can be caused by the beam focusing algorithm, which evaluates only a very limited number of phase/amplitude distributions, from the totality of all possible combinations. It is thus not guaranteed that the obtained pattern is the best in terms of gain or side lobe level.

## VI. Conclusion and Outlook

In this paper we presented the realization and characterization of a 77 GHz 1D-steerable reflectarray with nematic LC. The reflector properties have been characterized by two different methods: a characterization utilizing two horn antennas in the far-field of the reflector, measuring the reflection and preferable characterization using a lens setup, placing the LC-reflector in the waist of a gaussian beam. Nevertheless, the accuracy and the spacial resolution of the lens setup has to be improved, in order to allow calculation of the control voltages in advance, enabling besides beam steering also the possibility of beam forming. A tunable phase range of almost 280 degrees can be achieved with the realized reflector, which might be enough to realize a full scale reflectarray. The measured characteristics agree well with the characteristics obtained with the measurement setup presented in [11]. From the measured far-field patterns of the realized reflectarray it can be seen, that despite the high peak losses, beam focusing and beam steering is feasible. Well-behaved patterns have been achieved with side lobes around -8 dB (for the main beam steered to $0°$) which could be even further improved by a better beam forming algorithm. The losses can be reduced by using higher conductors, optimized patch width and height and by employing LCs with lower dielectric losses which have been presented in [7] at 35 GHz.

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