Phase Characterization of Reconfigurable Reflectarray Antennas

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Abstract: The design and performance optimization of X-band reconfigurable reflectarray antennas have been discussed in this paper concentrating mainly on the phase characteristics. Liquid crystals based substrates and slot embedded patch elements have been proposed as two different techniques for the design of reflectarrays with frequency tunability characteristics. Reflectarray patch elements constructed on anisotropic liquid crystal substrate are proposed to be employed as a dynamic phase control strategy for terrestrial systems. A detailed analysis of dynamic phase range and frequency tunability with respect to dielectric anisotropy is presented for two different anisotropic liquid crystal substrate materials. The investigated liquid crystals substrates provided a maximum reduction of 14.1% in volume for reflectarray design at 10 GHz. Moreover rectangular slots on the patch elements are shown to offer a maximum frequency tenability of 1.7GHz. The Finite Integral Method (FIM) validated by waveguide scattering parameter measurements demonstrated a dynamic phase range of 314° and a volume reduction of up to 24.36%.

Keywords: Reconfigurable Reflectarrays, Liquid Crystals, Slot Embedded Patches, Frequency Tunability, Dynamic Phase Range.

1. Introduction

Beam steering of high gain antennas is usually required for terrestrial and space communication systems. Conventionally, parabolic reflectors and phased array antennas have been used for the antenna applications. However, in 1991 J. Huang proposed microstrip reflectarray as an alternative to the bulky parabolic reflector and expensive phased array antennas [1]. Microstrip reflectarray consists of an array of microstrip patches printed on a dielectric substrate which is backed by a ground plane [2]. Various techniques have been used in the past for the design of reconfigurable reflectarray antenna to be used in beam steering applications. Some of the commonly employed techniques include the use of liquid crystals as substrate [3] and integration of Micro Electro Mechanical Switches (MEMS) [4] and varactor diodes [5] with patch elements of reflectarray antennas.

This paper discusses a detailed analysis of reconfigurable reflectarray antennas, designed in X-band frequency range, based on two different techniques. In the first part of this work, anisotropic properties of nematic liquid crystals have been exploited for the design of electronically tunable reflectarray antenna. The second part highlights the use of slot configurations embedded in the patch elements for frequency tuning of reflectarray antennas.

2. Reconfigurable Reflectarray Antenna Design using Anisotropic Dielectric Materials.

It is possible to vary the dielectric permittivity of anisotropic liquid crystals simply by applying a dc bias voltage across the substrate, which allows the molecules of anisotropic material to be aligned parallel to the incident field and attain maximum dielectric permittivity value ($\varepsilon_\parallel$). Whereas without a DC bias voltage molecules of the materials are aligned perpendicular to the incident field and attains a minimum dielectric permittivity value ($\varepsilon_\perp$) as

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shown in Figure 1. The tenability capability in dielectric permittivity is required in order to realize dynamic phase distribution of reflectarrays. The difference between maximum and minimum values of dielectric permittivity is called dielectric anisotropy of material [6] which is given by:

$$\Delta\varepsilon = \varepsilon_{\parallel} - \varepsilon_{\perp} \tag{1}$$

Where, $\Delta\varepsilon$ = Dielectric anisotropy, $\varepsilon_{\parallel}$ = Dielectric constant with applied DC bias voltage, $\varepsilon_{\perp}$ = Dielectric constant without DC bias voltage.

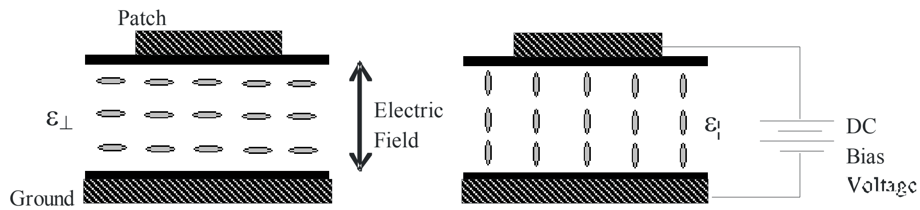


Figure 1. Alignment of molecules of anisotropic liquid crystal material without and with external DC bias voltage

In this work, two different anisotropic liquid crystal substrate materials are used to design a unit cell X-band reflectarray rectangular element, constructed on 1mm thick anisotropic substrate as shown in figure 2. Series of simulations of rectangular patch reflectarray have been performed in CST MWS computer model in order to characterize the reflectivity characteristics of reflectarray patch element based on reflection phase and frequency tunability. This section provides a detailed comparative analysis of dynamic phase range and frequency tunability performance of the proposed design with two different liquid crystal materials.

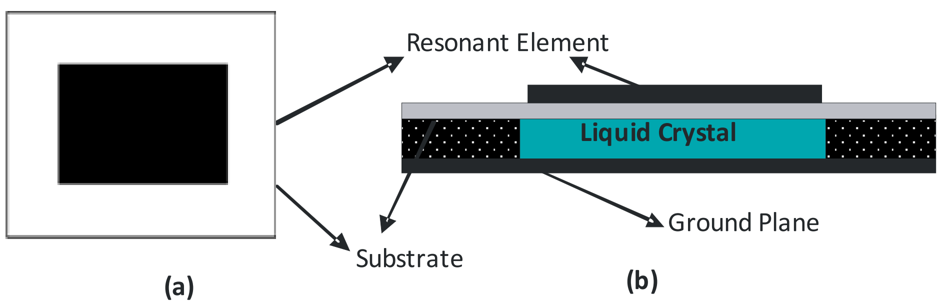


Figure 2. Built configuration of a unit cell reflectarray element (a) Top View (b) Side view

A. Dynamic Phase Range

As anisotropic materials cover a range of dielectric permittivity values, the possibility of realizing a variation in the phase distribution has been further investigated based on dynamic phase range. Therefore by changing the value of dielectric permittivity of anisotropic materials a wider phase range is achievable. Dynamic phase range in this case can be defined as:

$$\Delta\varphi = \varphi(\varepsilon_{//}) - \varphi(\varepsilon_{\perp}) \tag{2}$$

Dielectric permittivity of anisotropic materials can be changed by simply applying a DC voltage across the substrate as described in [7] and shown in Figure. 1. The dynamic phase range of materials is a measure of dielectric anisotropy. The maximum phase variations of the reflected signal occur at the resonant frequency.

Table 1. Dynamic phase range and frequency tunability of liquid crystal substrate materials

Liquid Crystals	ε⊥	ε∥	Dielectric Anisotropy (Δε)	tanδ⊥	tanδ∥	Dynamic Phase Range (°)	Frequency tunability (MHz)
K15 Nematic	2.1	2.27	0.17	0.072	0.06	90	372
LC-B1	2.6	3.05	0.45	0.022	0.007	160	784

The dynamic phase range values for anisotropic liquid crystal materials used for reflectarray design at 10 GHz resonant frequency with 1mm substrate thickness are shown in Figure 3. The results in Figure 3 shows that LC-B1 has a wider dynamic phase range of 160° with a dielectric anisotropy of 0.45 compared to K-15 Nematic which attains a narrower dynamic phase range of 90° with a dielectric anisotropy of 0.17. Table 1 summarizes the results of dynamic phase range with dielectric anisotropy for anisotropic liquid crystal materials that are used as reflectarray substrate. As shown in Table 1, it can be observed that dynamic phase range increases from 90° to 160° with an increase in dielectric anisotropy from 0.17 to 0.45. This is because of the fact that, higher tunable range of dielectric permittivity of anisotropic materials increases the tunable range of reflection phase which results in a higher dynamic phase range performance.

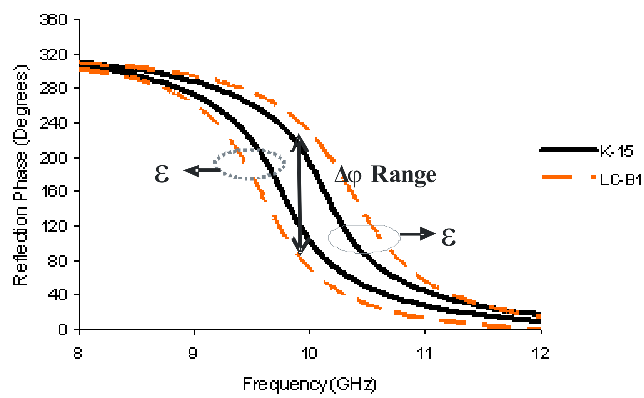


Figure 3. Dynamic phase ranges of anisotropic liquid crystal materials

B. Frequency Tunability

A change in the dielectric permittivity of dielectric anisotropic materials can also cause a significant change in resonant frequency that is known as frequency tunability. The summary of the frequency tunability performance of liquid crystal materials employed for reflectarray antenna design is shown in Table 1. It can be observed from Table 1 that LC-B1 has a wider frequency tunability of 784 MHz with a dielectric anisotropy of 0.9, whereas K-15 Nematic has a narrower frequency tunability of 372 MHz with a dielectric anisotropy of 0.17.

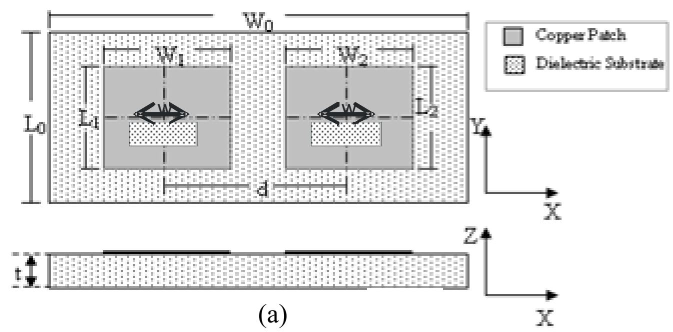
It has also been observed that a change in dielectric anisotropy of materials can significantly affect the dynamic phase range and frequency tunability performance of reflectarray antenna. Based on the resultsshown in Figure 3, it can be concluded that the dielectric anisotropy is directly proportional to the dynamic phase range and frequency tunability of reflectarray antenna.

3. Reconfigurable Reflectarray Design using Slots Embedded patch elements

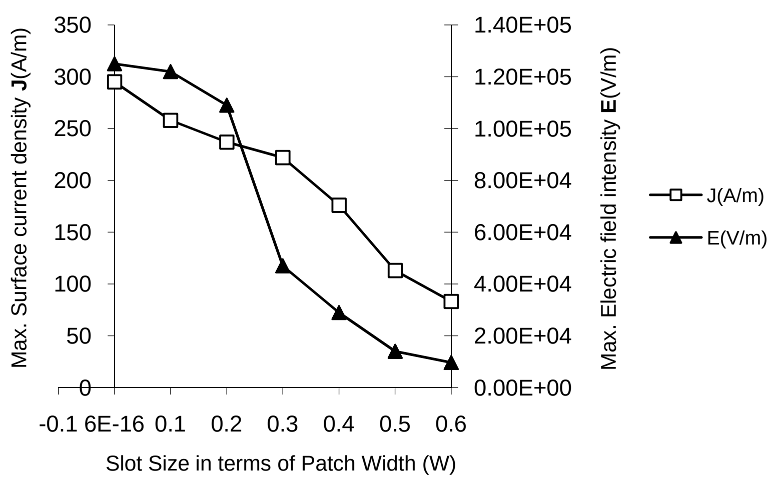
Commercially available computer model of CST Microwave Studio has been used to design a unit cell patch element with proper boundary conditions in order to represent an infinite reflectarray and scattering parameters of modeled resonant elements have been analyzed. Initially a reflectarray with rectangular patch element was designed to resonate at 10GHz using Rogers RT/d 5880 (ε_r=2.2 and tanδ=0.0010) as a substrate. Then rectangular slots of variable width were introduced in the patch element and the effect on the performance of the reflectarray was observed. The geometry of the designed 2-patch element unit cell reflectarray with rectangular slots in the centre of each patch is shown in Figure 4 (a). In Figure 4 (a), the two patch elements are identical with dimensions L_1 xW_1 and L_2 x W_2 and an interelement spacing (d) while the embedded slots has a variable width (w).

A. Effects of Slots on Electric Field Intensity and Surface Currents

The effect of variable width slots in the patch element on the maximum surface current density (J) and maximum electric field intensity (E) analyzed by Finite Integral Method (FIM) is shown in Figure 4. As depicted in Figure 4 (b), both surface current density and electric field intensity decrease from 255A/m to 113A/m and 121KV/m to 14KV/m respectively by an increase in the width of the slot configuration from 0.1W to 0.5W ($W=W_1=W_2$is the width of patch elements at 10 GHz). The decrease in the electrical field intensity has the effect of increasing the dielectric constant. Consequently the resonant frequency of the patch element decreases and reflection loss increases [8]. Moreover the change in resonant frequency also varies the phase response of the element at a particular frequency which provides the feasibility of designing a tunable reflectarray antenna using this configuration.



(a)



(b)

Figure 4(a). Geometry of the designed 2-patch element unit cell reflectarray with rectangular slots in the centre of each patch. (b). Maximum surface current and electric field intensity for different patch widths at resonant frequency

B. Scattering Parameter Measurements

In order to validate the simulated results, scattering parameters measurements of the designed samples have been carried out using Agilent 8722ET vector network analyzer as given in [9]. An X-band waveguide was designed for the measurement of scattering parameters which has been connected to the vector network analyzer using an Agilent coax to waveguide APC-7 connector (Amphenol Precision Connector-7 mm). The variation in the reflection phase of the reflectarrays with different width of slots in the patch element is shown in Figure 5. It can be observed from Figure 5 that both the measured and simulated reflection phase curves are in good agreement. A small difference that can be observed in the measured and simulated reflection phases is due to the discrepancy caused by the connectors and the waveguide simulator used for scattering parameter measurements. Moreover it can be observed from Figure 5 that the slope of the reflection phase curve increases from 0.28°/MHZ to 0.61°/MHZ as the width of the slot is increased from 0.3W to 0.5W causing a reduction in the bandwidth performance. This effect can be attributed to the increased reflection loss with increasing slot width.

As a figure of merit, Dynamic Phase Range (DPR) has been defined as the difference in the reflection phase variation curves without slot and with a particular slot at the mean frequency of two curves. The summary of the measured and simulated dynamic phase ranges for different lengths of slot configurations is shown in Table 2. It can be observed from Table 2 that a measured dynamic phase range of 120° to 314° is achievable with a variation of slot width from 0.3W to 0.5W which shows the feasibility of using slot configurations to achieve a dynamic phase tuning control of a reflectarray antenna.

Furthermore the possibility of reducing the volume of a unit cell patch element in a reflectarray designed at 10GHzhas also been demonstrated in Table 2. The volume reduction has been determined based on the comparison of the proposed designs with the conventionally used rectangular patch element reflectarray design at 10 GHz. It can be observed from Table 2 that a maximum reduction of 24.36% in the volume of the unit cell is shown for slot of 0.5W x 0.125L. Therefore a larger number of patch elements embedded with slots can be used to design a reflectarray without varying its overall aperture dimensions. On the other hand anisotropic LC-B1 shows a 14.1% reduction while anisotropic K-15 shows an increase of 7.11% in unit cell reflectarray volume.

Table 2. Dynamic phase range (DPR) and volume reduction for reflectarray designed with slot embedded patch elements and liquid crystals at 10GHz

<table>
<tr><th colspan="2">Design Configuration</th><th colspan="2">Dynamic Phase Range (°)</th><th>Volume Reduction (%)</th></tr>
<tr><td rowspan="2">Anisotropic Liquid Crystals</td><td>K-15 Nematic</td><td colspan="2">90</td><td>-7.11</td></tr>
<tr><td>LC-B1</td><td colspan="2">160</td><td>14.1</td></tr>
<tr><td rowspan="6">Slot Embedded Patch Elements with Rogers RT/d 5880</td><td rowspan="2">0.30W x 0.125L</td><td>Measured</td><td>Simulated</td><td rowspan="2">5.85</td></tr>
<tr><td>120</td><td>122</td></tr>
<tr><td>0.35W x 0.125L</td><td>210</td><td>207</td><td>8.08</td></tr>
<tr><td>0.40W x 0.125L</td><td>235</td><td>233</td><td>14.89</td></tr>
<tr><td>0.45W x 0.125L</td><td>295</td><td>291</td><td>19.60</td></tr>
<tr><td>0.50W x 0.125L</td><td>314</td><td>319</td><td>24.36</td></tr>
</table>

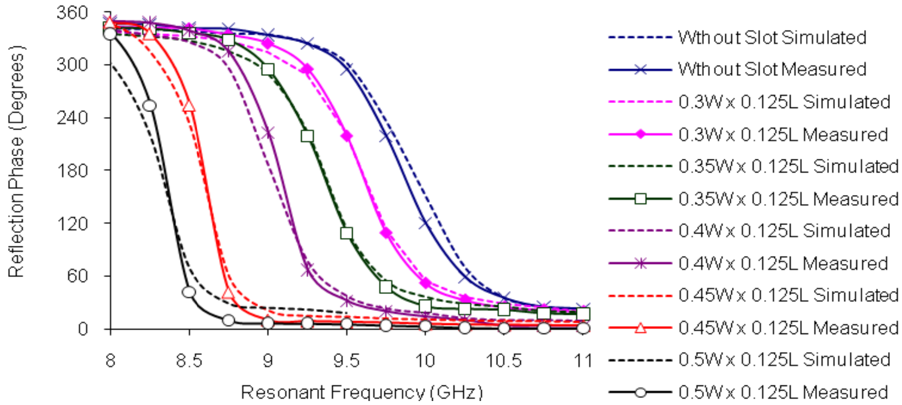


Figure 5. Simulated and measured reflection phase for different widths of rectangular slots

4. Conclusion

A detailed analysis based on Finite Integral Method, presented in this work demonstrates that a suitably selected material can increase the phase range performance of reflectarray which is required to realize a progressive phase distribution. Dielectric anisotropic materials are shown to offer a rapid dynamic phase change behavior for designing an electronically tunable reflectarray antenna. It has been shown that the dielectric anisotropy of anisotropic materials can affect the tunability performance of reflectarray resonant elements. Furthermore materials having high dielectric anisotropy values also offer wider dynamic phase ranges with higher frequency tunability. Moreover the measurements and simulations of slotted patch elements used in reflectarray design demonstrated a great potential to be used in reconfigurable reflectarray design. The slot embedded patch elements of reflectarray provided anenhanced dynamic phase range and reduces the volume of the reflectarray antenna.

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6. References

[1] J. Huang, "Microstripreflectarray," *IEEE AP-S/URSI Symposium, London Canada, pp.612–615, 1991.*

[2] D.M. Pozar, D. Targoski, and H.D. Syrigos, "Design of Millimeter Wave Microstrip Reflect Arrays,"*IEEE Transactions on Antennas and Propagation*,Vol. 45, No. 2, pp. 287–296, 1997.

[3] M.Y. Ismail, W. Hu, R. Cahill, V.F. Fusco, H.S. Gamble, D. Linton, R. Dickie, S.P. Rea and N. Grant, "Phase Agile Reflectarray Cells Based on Liquid Crystals," *IET Microwave Antennas Propagation*, Vol. 1, No. 4, pp. 809–814, 2007.

[4] S. V. Hum, G. M. Feetors, and M. Okoniewski, "Integrated MEMS ReflectarrayElements," *Eur. Conf. Antennas and Propagation (EuCAP 2006)*, Nov. 2006, ESA SP 626.

[5] S. V. Hum and M. Okoniewski, "An Electronically Tunable Reflectarray using Varactor Diode-Tuned Elements," *2004 IEEE Int. Symp. Antennas Propagation*, Vol. 2, Jun. 2004, pp. 1827–1830.

[6] S. M. Kelly and M. O'Neill, "Liquid Crystals for Electro-Optic Applications," *Handbook of Advanced Electronic and Photonic Materials and Devices, Edited by H.S. Nalwa, California: Academic Press, pp. 1–66, 2000.*

[7] M. Y. Ismail and R. Cahill, "Beam Steering Reflectarrays Using Liquid Crystal Substrate," *Tenth IEEE High Frequency Postgraduate Student Colloquium, University of Leeds, England*, 2005, pp. 62-65.

[8] M. Y. Ismail and M. Inam, "Performance Improvement of Reflectarrays Based on Embedded Slots Configurations". *Progress In Electromagnetics Research C*, Vol. 14, pp. 67-78, 2010.

[9] M. Inam and M. Y. Ismail, "Reflection Loss and Bandwidth Performance of X-Band Infinite Reflectarrays: Simulations and Measurements". *Microwave and Optical Technology letters*, Vol. 53, No. 1, pp. 77-80, 2011.

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