International Journal of Electrical, Electronic and Communication Sciences
ISSN: 2517-9438
Vol:10, No:1, 2016

Liquid Crystal Based Reconfigurable Reflectarray Antenna Design

M. Y. Ismail, M. Inam

***Abstract*—**This paper presents the design and analysis of Liquid Crystal (LC) based tunable reflectarray antenna with slot embedded patch element configurations within X-band frequency range. The slots are shown to modify the surface current distribution on the patch element of reflectarray which causes the resonant patch element to provide different resonant frequencies depending on the slot dimensions. The simulated results are supported and verified by waveguide scattering parameter measurements of different reflectarray unit cells. Different rectangular slots on patch element have been fabricated and a change in resonant frequency from 10.46GHz to 8.78GHz has been demonstrated as the width of the rectangular slot is varied from 0.2W to 0.6W. The rectangular slot in the center of the patch element has also been utilized for the frequency tunable reflectarray antenna design based on K-15 Nematic LC. For the active reflectarray antenna design, a frequency tunability of 1.2% from 10GHz to 9.88GHz has been demonstrated with a dynamic phase range of 103° provided by the measured scattering parameter results. Time consumed by liquid crystals for reconfiguration, which is one of the drawback of LC based design, has also been disused in this paper.

***Keywords*—**Liquid crystal, tunable reflectarray, frequency tunability, dynamic phase range.

I. 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 [1]. However, in 1991 J. Huang proposed microstrip reflectarray as an alternative to the bulky parabolic reflector and expensive phased array antennas [2]. Microstrip reflectarray consists of an array of microstrip patches printed on a dielectric substrate which is backed by a ground plane [3]. Reflectarray can achieve a wide-angle electronic beam scanning. Direct Broadcast Satellites (DBS) and Multi Beam Antennas (MBA) are also considered as potential applications of reflectarrays. Moreover, they can also act as amplifying arrays by including an amplifier in each reflectarray element [4]. However, the main concerns of a reflectarray antenna are its limited bandwidth and high loss performance as compared to the parabolic reflector antennas [5]-[7]. Different configurations have been proposed by researchers in the past few years for the bandwidth and loss performance improvement of reflectarray antennas [8]-[10] but considerable efforts are still required to improve the bandwidth performance of reflectarrays.

M.Y. Ismail and M. Inam are with the Wireless and Radio Science Center, Universiti Tun Hussein Onn Malaysia, BatuPahat, 86400, Johor, Malaysia (e-mail: yusofi@uthm.edu.my, muhammad_inamabbasi@yahoo.com).

In order to steer the main beam of an active reflectarray, the reflected phase from each of the resonant element can be controlled. Hence the reflected beam can be directed in the desired direction which makes a reflectarray capable of achieving a wide-angle electronic beam scanning. Such beam forming approach can have many advantages over traditional tunable antenna array architectures, including a major reduction in hardware required per element and increased efficiency [11]. There have been a considerable research in beam steering antennas such as the use of non-linear dielectric materials [12]-[14], the integration of Radio Frequency Micro Electro Mechanical Systems (RF MEMS) as switches [15], [16], loading varactor diodes with the patch elements and varying the varactor capacitance by using various biasing [17], [18] and using aperture coupled elements where the tuning circuit can be located on the non-resonating surface of the element in order to control the contributed phase from each element [19].

In this work, the use of slot embedded patch element configurations has been proposed for Liquid Crystal (LC) based unit cell reflectarray designs. Two patch unit cells with different type of slots embedded into the patch elements have been designed using Rogers RT/Duroid 5880 dielectric substrate and K-15 nematic Liquid Crystal. Detailed investigations have been carried out for rectangular slots in the center of the patch element used for reflectarray designs. The 3D EM computer simulation software results have been verified using waveguide scattering parameter measurements.

II. Reflectarray Passive Unit Cell Design

A. Design Procedure

Commercially available computer model of CST Microwave Studio and Ansoft HFSS were used to design unit cells patch elements with proper boundary conditions in order to analyze the scattering parameters of an infinite reflectarray. Initially a reflectarray with rectangular patch element was designed to resonate at 10 GHz using Rogers RT/Duroid 5880 (ε_r=2.2 and tanδ=0.0010) as a substrate with thickness of 0.3818mm. Then different types of slot configurations are introduced in the patch element and the effect on the performance of the reflectarray was observed.

The direction of port excitation and surface currents on a patch without slot is shown in Fig. 1. It can be observed from Figs. 1 (a) and (b) that the maximum currents on the surface of the patch occur in the center of the length of patch when the electric field is excited in the Y-direction. Figs. 1 (c) and (d) show a clear modification of surface current distribution when a rectangular or a circular slot is embedded in the center of patch element. This phenomenon of surface currents modification is exploited in this work to tune the reflection phase of the proposed reflectarray element. The proposed slot configurations can be used for active and reconfigurable reflectarray antenna design. Rectangular slots and circular slots are observed to have a similar kind of effect on the performance of reflectarray unit cells. Therefore, the detailed investigation provided in this work only comprises on the design with rectangular slot embedded in the center of the patch element.

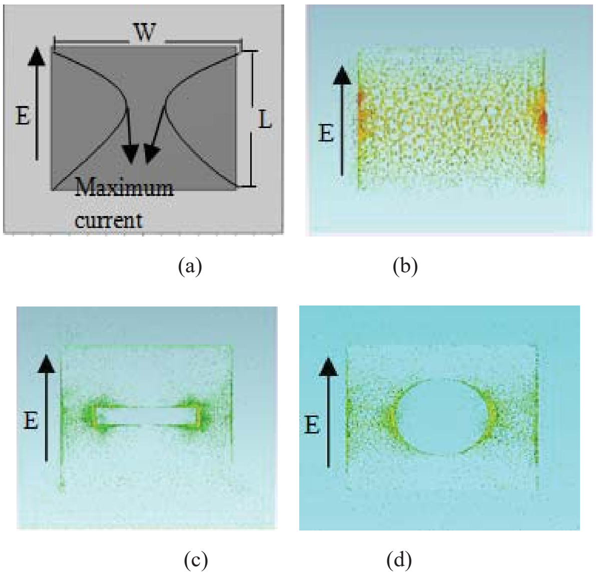


Fig. 1 Proposed reflectarray design (a) A unit cell showing E-field and maximum surface currents (b) Surface currents on patch without slot (c) Surface currents with rectangular slot, and (d) Surface currents on a patch with circular slot

In order to validate the detailed analysis carried out for different slot embedded patch element configurations, a number of unit cells were designed and fabricated for operation in X-band frequency range. Two patch element unit cells were used for the waveguide scattering parameter measurements [20]. The main objective of this work was to practically verify the proposed configurations and to characterize the resonant elements based on their performance. Fig. 2 shows the basic geometry of the unit cell patch element and the measurements set-up that was used in this work. The unit cell patch element was inserted inside the aperture of the waveguide which is attached with the network analyzer through a coaxial cable and an X-band coax-waveguide adapter.

Reflection loss and reflection phase curves for different resonant elements were obtained in order to demonstrate the feasibility of practical implementation of the proposed designs. In order to obtain appropriate scattering parameter measurements of unit cell patch elements, apart from standard network analyzer calibration, manual calibrations using different ground planes was also done. The scattering parameters of different ground planes of each sample were carried out. Ideally the ground plane should exhibit a straight line at zero when its reflection loss is measured. However due to losses generated by the connections and the equipment, the reflection loss for different samples of ground is observed to have some ripples throughout the measured frequency range. Moreover, it was observed that all the samples provide almost constant curves which show that the loss is caused by the measurement set-up. Therefore, these curves can be used as a reference for the manual calibration in order to reduce the discrepancy in the measured and simulated results.

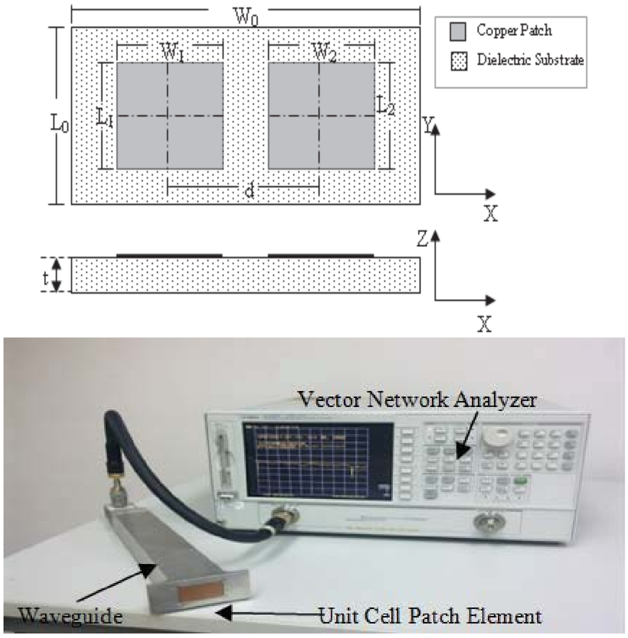
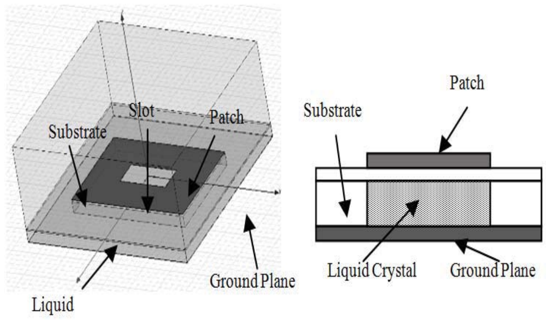


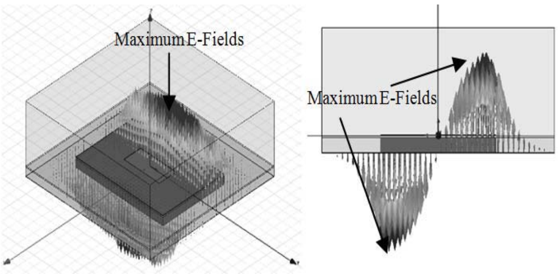
Fig. 2 Geometry of the unit cell patch element and complete measurement set-up

B. Fabrication and Measurements

The basic design topology of unit cell reflectarray has been utilized where periodic boundary conditions have been used in Ansoft HFSS to represent a single patch element as an infinite array as shown in Fig. 3.



(a) (b)



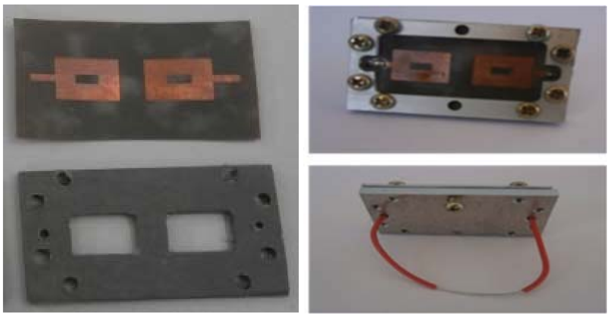
(c) (d)

Fig. 3 Active reflectarray unit cell design (a) perspective view of rectangular slot embedded patch element unit cell (b) Illustrative side view (c) E-fields in perspective view (d) E-fields in side view

The resonant patches, as shown in Figs. 3 (a) and (b), have been fabricated on a thin supporting layer of Rogers RT/Duroid 5880 with substrate thickness of 0.127mm. K-15 nematic LC has been deposited within a cavity made in dielectric substrate of Rogers RT/Duroid 5880 with substrate thickness of 0.787mm backed by a ground plane. The dimensions of resonant patch element are kept 8.4mm x 11.8mm (L x W) for resonance within X-band frequency range. It can be observed from Figs. 3 (c) and (d) that the E-fields are sinusoidaly distributed with maxima at the corners of the resonant patch element. Therefore, the surface currents will be maximum in the center of the patch element along the direction of field excitation (X-axis).

In order to design a frequency tunable reflectarray unit cell, the properties of K-15 nematic LC have been exploited. For this type of LC, a voltage variation from 0V-20V can be applied to change the orientation of K-15 nematic LC molecules from perpendicular (ε_r=2.7 and tanδ=0.04) to parallel (ε_r=2.9 and tanδ=0.03).

Different rectangular slots embedded unit cell patch elements have been fabricated for X-band frequency range operations as shown in Fig. 4 (a). Encapsulations made of aluminum shown in Fig. 4 (b) have been used to keep intact different parts of unit cells and a connecting wire has been used to electrically short the two patches in order to apply the desired voltage.



(a) (b)

Fig. 4 Fabricated Samples (a) Unit cell patch element and LC cavity (b) Rectangular slot embedded path and back side of complete unit cell assembly in encapsulator

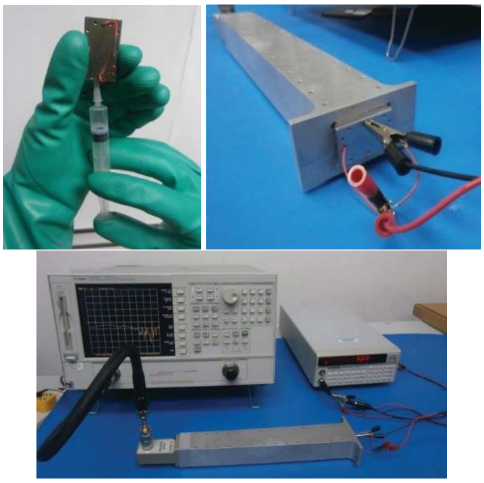


Fig. 5 LC filling in cavity, unit cell inserted in waveguide simulator and complete measurement set-up for scattering parameter measurements

Fig. 5 shows the measurement procedure and LC filling inside the cavity constructed under the resonant patch element. The complete assembly of unit cell patch elements filled with LC has been inserted in the aperture of waveguide and scattering parameter measurements have been carried out using waveguide simulator with vector network analyzer while the voltage from to 0V to 20V has been supplied by a function generator to the resonant patch elements.

III. Results and Discussion

The scattering parameter measurements of the LC based rectangular slot embedded patch elements unit cells have been carried out and a comparison between simulated and measured results has been presented in Fig. 6. The simulated and measured results provided a close agreement with a variation in measured resonant frequency from 10GHz to 9.88GHz with an increase in voltage from 0V to 20V. Moreover, a dynamic phase range of 103° measured from reflection phase curve has been demonstrated by the proposed design of reconfigurable LC based unit cell.

In order to further investigate the proposed design, different voltage levels have been applied to K-15 Nematic LC and the effect on reflection loss and resonant frequency has been observed as shown in Fig. 7. It can be observed that each increment in voltage level contributes to a small frequency tunability which reaches to 180 MHz at 20V level. It can also be observed from Fig. 7 that the reflection loss also decreases from 8.5dB at 10GHz to 6.2dB at 9.88GHz with an increase in voltage from 0 to 20V.

The decrease in reflection loss is because of decrease in loss tangent value of K-15 Nematic LC material from 0.04 to 0.03 with an increase in voltage from 0 to 20V.

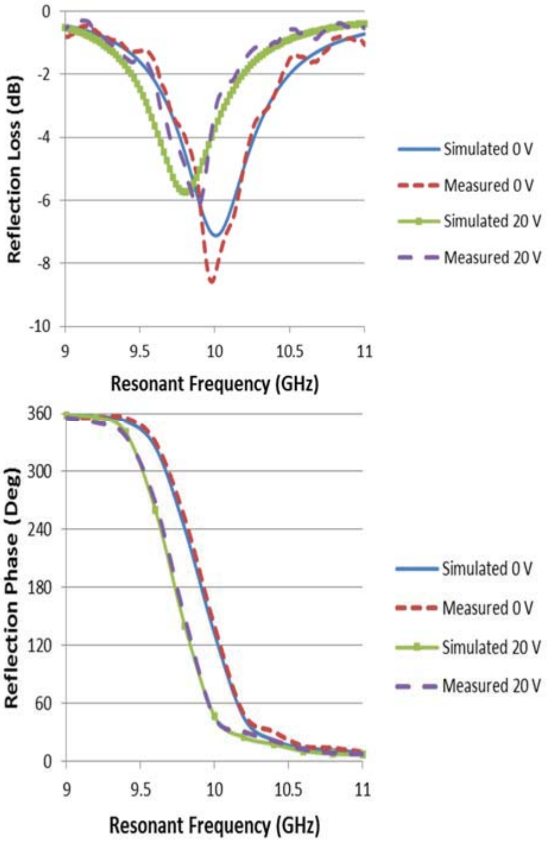


Fig. 6 Comparison of measured and simulated results for rectangular slot embedded patch element unit cell reflectarray

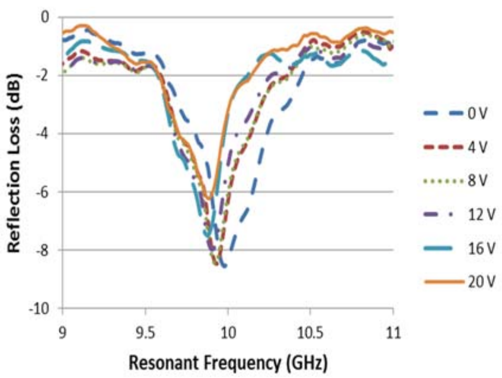
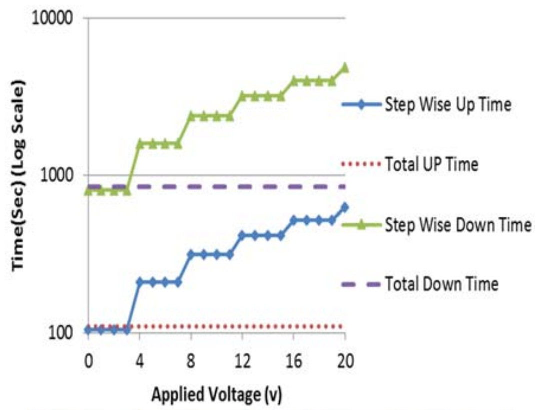


Fig. 7 Measured reflection loss curves for different voltage levels applied to LC of unit cells designs

One of the main issue with liquid crystal is the time consumed by its molecules to change its orientation. The time taken by the liquid crystal based unit cell planar reflector with for demonstrating frequency tunability was also investigated. Fig. 8 depicts step wise and total time consumed for setting of liquid crystal for different increasing and decreasing voltage levels. It can be observed from Fig. 8 that the time taken for each variation with increasing voltage (up time) is between 102s to 110s while the time taken for decreasing voltage (down time) is even longer with variation between 801s and 840s. This huge time takes for frequency tunability can restrict the use of liquid crystal based planar reflectors in a number of applications.



Voltage (V)	Up Time (Sec)	Voltage (V)	Down Time (Sec)
0-4	105	20-16	813
4-8	105	16-12	813
8-12	102	12-8	801
12-16	102	8-4	801
16-20	102	4-0	801
0-20	**110**	**20-0**	**840**

Fig. 8 Step wise and total time consumed for setting of liquid crystal for different increasing and decreasing voltage levels

IV. Conclusion

Slot embedded patch element configurations have been identified as a potential configuration for the improved design of passive and reconfigurable reflectarray antennas. The slot embedded patch elements also provide an extra parameter which is the dimensions of the slot for the control of resonant frequency and reflection phase of reflectarray unit cells. The dependence of liquid crystals on the applied voltage has been exploited in order to design reflectarray antennas with a control over a wide range of frequencies. Further investigations are required to improve the frequency tunability and reflection loss performance of reconfigurable reflectarray antennas by investigating the material properties of liquid crystals.

Acknowledgment

Research funding for this work is fully provided by the Ministry of Higher Education, Malaysia, under Best Project of Fundamental Research Grant Scheme (FRGS, VOT 0983), Prototype Research Grant Scheme (PRGS, VOT 0904) and Research Acculturation Collaborative Effort (RACE, VOT 1119). The authors would like to thank the staff of Wireless and Radio Science Centre (WARAS) of Universiti Tun Hussein Onn Malaysia (UTHM) for the technical support.

REFERENCES

[1] Berry, G. D. G., Malech, R. G. and Kennedy, W. A., "The reflect array antenna", IEEE Trans. Antennas Propag., Vol. AP-11, pp. 645-651, 1963.
[2] Huang, J. and Encinar, J. A., Reflectarray Antennas, Wiley Interscience, 2007.
[3] 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.
[4] Bialkowski, M. E., Robinson A. W., and Song, H. J., "Design, Development and Testing of X-band Amplifying Reflectarrays", IEEE Transactions on Antennas and Propagation, Vol. 50, No.8, pp. 1065-1076, 2002.
[5] M. Y. Ismail and M. Inam, "Resonant Elements for Tunable Reflectarray Antenna Design" International Journal of Antennas and Propagation, Vol. 2012, Article ID 9148686, pages 6, 2012.
[6] M. E. Biallowski and J. Encinar, "Reflectarray: Potential and Challenges" *International Conference on Electromagnetics in Advanced Applications*, pp. 1050-1053, (ICEAA) 2007.
[7] D. M. Pozar and S. D. Targonski, "A Shaped-Beam Microstrip Patch Reflectarray" *IEEE Transactions on Antennas propogation*, Vol. 47, No. 7, pp. 1167-1173, 1999.
[8] J. Huang and J. Encinar, Reflectarray Antennas: Broadband Techniques, Wiley, interscience, 2007.
[9] 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.
[10] K. Y. SZE and L. Shafal, "Analysis of Phase Variation Due to Varying Patch Length in a microstrip Reflectarray" *IEEE Trans. Antennas and Propagation*, Vol. 46, No. 7, pp. 1134-1137.
[11] S. V. Hum, M. Okoniewski and R. J. Davies, "Realizing an Electronically Tunable Reflectarray Using Varactor Diode-Tuned Elements". *IEEE Microwave and Wireless Components Letters*, Vol. 15, pp. 422-424, 2005.
[12] 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". *Proc. IET Microw. Antennas Propag.*, Vol. 1, No. 4, pp. 809-814, 2007.
[13] W. Hu, M. Y. Ismail, R. Cahill, H. S. Gamble, R. Dickie, V. F. Fusco, D. Linton, S. P. Rea and N. Grant, "Tunable Liquid Crystal Patch Element". *IET Electronic Letters*, Vol 42, No 9, 2006.
[14] A. Mossinger. R. Marin, S. Mueller, J. Freese and R. Jakoby, "Electronically Reconfigurable Reflectarrays with Nematic Liquid Crystals". *IET Electronics Letters*, Vol. 42, No. 16, 2006.
[15] H. Rajagopalan, Y. Rahmat and W. A. Imbriale, "RF MEMES Actuated Reconfigurable Reflectarray Patch-Slot Element". *IEEE Trans. Antennas Propag.*, Vol. 56, No. 12, pp. 369-3699, 2008.
[16] F. A. Tahir, H. Aubert and E. Girard, "Equivalent Electrical Circuit for Designing MEMS-Controlled Reflectarray Phase Shifters". P*rogress in Electromagnetics Research*, Vol. 100, pp. 1-12, 2010.
[17] L. Boccia, F. Venneri, G. Amendola and G. D. Massa, "Application of Varactor Diodes for Reflectarray Phase Control". *IEEE International Symposium of Antennas and Propagation Society*, Vol 4, pp. 132-135, 2002.
[18] S. V. Hum, M. Okoniewski and R. Davies, "Modeling and Design of Electronically Tunable Reflectarrays". *IEEE Trans. Antennas Propag.*, Vol. 55, No. 8, pp. 2200-2210, 2007.
[19] M. Riel and J. J. Laurin, "Design of an Electronically Beam Scanning Reflectarray Using Aperture-Coupled Elements". IEEE Transactions on Antennas and Propagation, Vol. 55, No. 5, pp. 1260- 1266, 2007.
[20] 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.