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Design of Liquid Crystal Based Tunable Reflectarray Antenna Using Slot Embedded Patch Element Configurations

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Abstract**—**This paper presents the design and analysis of Liquid Crystal (LC) based tunable reflectarray antenna with different design configurations within X-band frequency range. The effect of LC volume used for unit cell element on frequency tunability and reflection loss performance has been investigated. Moreover different slot embedded patch element configurations have been proposed for LC based tunable reflectarray antenna design with enhanced performance. The detailed fabrication and measurement procedure for different LC based unit cells has been presented. The waveguide scattering parameter measured results demonstrated that by using the circular slot embedded patch elements, the frequency tunability and dynamic phase range can be increased from 180MHz to 200MHz and 120° to 124° respectively. Furthermore the circular slot embedded patch element can be designed at 10GHz resonant frequency with a patch volume of 2.71mm^3 as compared to 3.47mm^3 required for rectangular patch without slot.

Keywords**—**Liquid crystal, Tunable reflectarray, Frequency tunability, Dynamic phase range.

I. Introduction

A low profile printed reflectarray introduced by D. G. Berry, R. G. Malech and W. A. Kennedy in 1963 [1] has evolved as a promising alternative to the bulky parabolic reflectors and expensive phased array antennas for radar and long distance communications. Reflectarray consists of a flat reflector and an array of microstrip patch elements printed on a thin dielectric substrate illuminated by a primary feed horn placed at a particular distance from the array.

The most important aspect of reflectarray antenna design is the design of printed microstrip elements which can be used for the performance appraisal of the antenna. The individual elements of the periodic array have to be designed with progressive phase distribution so that the spherical beam from the horn antenna can be converted into a planar wavefront. The required reflection phase values from individual elements of an array also depend on the location of the feed horn. For proper phase requirements, different techniques such as, identical patches of variable-length stubs [2], square patches of variable sizes [3], identical planar elements of variable rotation [4] and identical rectangular patches with different types of slot configurations have been used [5], [6]. All these phasing techniques increase the possibility of reflectarrays to become an alternative option to the parabolic reflectors. However, the main concerns of a reflectarray antenna are its limited bandwidth and high loss performance as compared to the parabolic reflector antennas [7]-[9]. Different configurations have been proposed by researchers in the past few years for the bandwidth and loss performance improvement of reflectarray antennas [10], [11] but considerable efforts are still required to improve the bandwidth performance of reflectarrays.

In order to steer the main beam of an activereflectarray, 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 [12]. There have been a considerable research in beam steering antennas such as the use of non-linear dielectric materials [13]-[15], the integration of Radio Frequency Micro Electro Mechanical Systems (RF MEMS) as switches [16], [17], loading varactor diodes with the patch elements and varying the varactor capacitance by using various biasing [18], [19] 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 [20].

In this paper a novel design of slot embedded patch element configuration integrated with the LC based cells has been proposed. 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. The scattering parameters measurements have been carried out using X-band rectangular waveguide simulator and vector network analyzer where an improvement in frequency tunability and dynamic phase range performance has been demonstrated by the use of proposed slot embedded patch elements.

II. Design and Analysis

A. Unit Cell Reflectarray Design

The basic design topology of unit cell reflectarray has been maintained where periodic boundary conditions have been used in Ansoft HFSS to represent a single patch element as an infinite array. The resonant patches,as shown in Fig. 1 (a), have been fabricated on a thin supporting layer of Rogers

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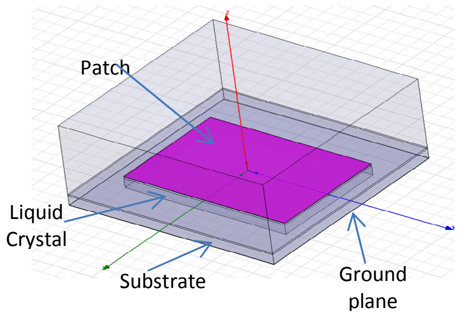
RT/Duroid 5880 with substrate thickness of 0.127mm. K-15 nematic LC has been depositedwithin a cavity made in dielectric substrate of Rogers RT/Duroid 5880 with substrate thickness of 0.787mm backed by a ground plane. The dimensions of resonant patch element are kept 8.4mm x 11.8mm (LxW) for resonance within X-band frequency range. It can be observed from Fig. 1 (b) that the E-fields are sinusoidaly distributed with maximas 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).



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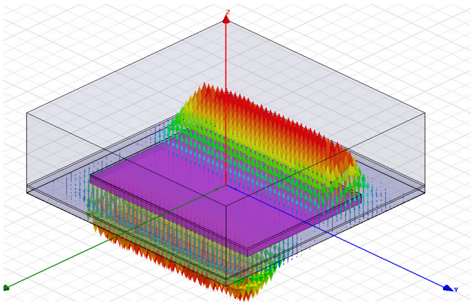

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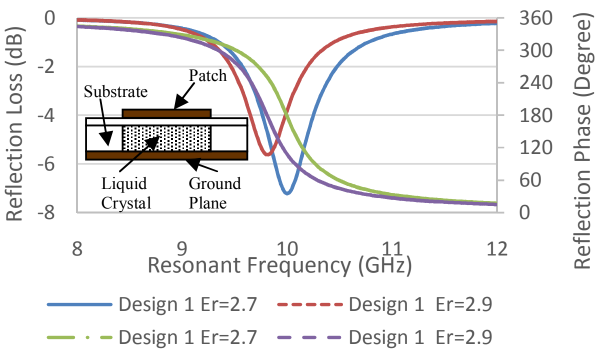
Fig. 1 Design configuration (a) Unit cellreflectarray design configuration and (b) E-field distribution for LC based unit cell



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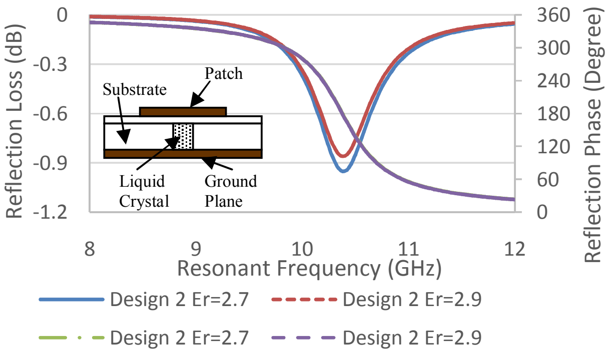

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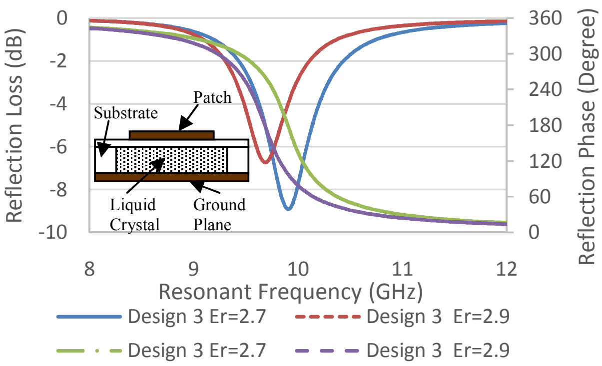

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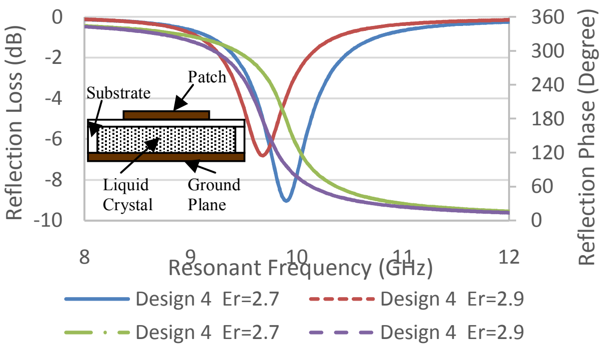


(d)

Fig. 2 Reflection loss and reflection phase curves for different designs depending on the volume of LC used, (a) Design 1: LC under full patch, (b) Design 2: LC under partial patch, (c) Design 3: LC under patch and substrate 1, (d) Design 4: LC under patch and substrate 2

B. Effect of LC Volume

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 its molecules from perpendicular (ε_r=2.7 and tanδ=0.04) to parallel (ε_r=2.9 and tanδ=0.03). Four different designs have been investigated in this work based on the volume of deposited LC as shown in Fig. 2. Reflection loss and reflection phase curves have been observed to characterize frequency tunability and dynamic phase range characteristics.

It can be observed from Fig. 2 (a) that in Design 1, where LC is deposited under full patch, the resonant frequency changes from 10GHz to 9.80GHz while the reflection loss decreases from 7.22dB to 5.62dB as the properties of LC are varied. On the other hand, in Design 2, shown in Fig. 2 (b), with lesser amount of LC under patch element, the resonant frequency varies only from 10.39GHz to 10.38GHz with reflection loss of 0.95dB and 0.85dB respectively. Design 3 in Fig. 2 (c) consists of LC deposited under patch and a small portion of substrate while Design 4, shown in Fig. 2 (d) contains LC under patch and larger portion of substrate. In Design 3, the frequency varied from 9.91GHz to 9.67GHz with reflection loss variation of 8.91dB to 6.73dB and in Design 4 a frequency variation of 9.90GHz to 9.6GHz with reflection loss variation of 9.03dB to 6.81dB has been observed by variation of LC properties. In all these results the resonant frequency decreases because of increase in dielectric permittivity from ε_r=22.7 to ε_r=22.9 while reflection loss decreases because of loss tangent variation of k-15 nematic LC from tanδ=0.04 to tanδ=0.03 at two different molecular states of operation. Table I shows the dimensions of LC cavity and volume of LC deployed for different designs. The effect of variation of LC volume on frequency tunability and dynamic phase range is shown in Fig. 3. It can be observed from Fig. 3 that a maximum frequency tunability of 240MHz can be achieved with dynamic phase range of 139° when maximum volume of LC (130.1mm^3) has been used.

TABLE I
DIMENSIONS OF LC CAVITY AND VOLUME OF DEPLOYED LC

Design Configuration	LC Dimensions (L x W x H) (mm)	LC Volume (mm^3)
Design 1	7.4 x 10.5 x 0.787	61.15
Design 2	3.7 x 5.25 x 0.787	15.28
Design 3	9.4 x 12.5 x 0.787	92.47
Design 4	11.4 x 14.5 x 0.787	130.1

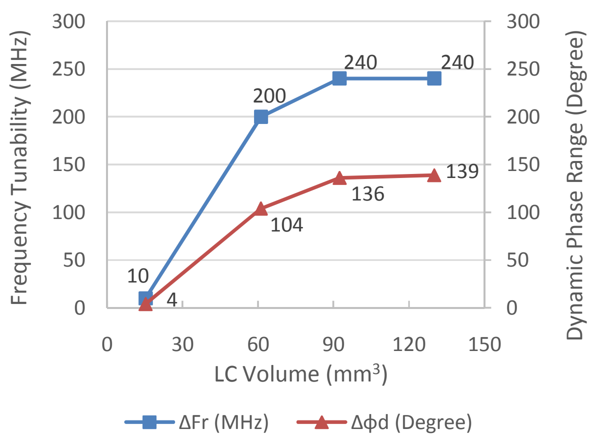
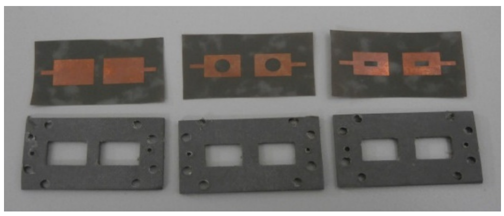


Fig. 3 Trend of frequency tunability (ΔFr), dynamic phase range (Δφd) and loss variation (ΔRl) with variation in LC volume

On the other hand a minimum frequency tunability of 10MHz with dynamic phase range of 4° has been demonstrated when a minimum volume of LC (15.28 mm^3) is encapsulated. However the maximum reflection loss performance has been observed to increase from 0.95dB to 9.03dB with an in increase in LC volume from 15.28 mm^3 to 130.1mm^3. Therefore there exists a trade-off between frequency tunability and reflection loss performance with variation in LC volume because of high loss dielectric properties of K-15 nematic LC.

III. Fabrication and Measurements

Based on the investigation carried out in Section II, it can be concluded that an optimum design of LC volume has to be chosen for the design of LC based reflectarray antenna. Hence in this work, a design with LC under full patch element has been selected. Apart from rectangular patch element, different rectangular slots and circular slots embedded unit cell patch elements have also been fabricated for X-band frequency range operations as shown in Fig. 4 (a). Encapsulations made of Aluminum as 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. Fig. 5 (a) shows the measurement procedure and LC filling inside the cavity under the resonant patch element. The complete assembly of unit cell patch elements filled with LC has been inserted in the aperture of waveguide as shown in Fig. 5 (b) and scattering parameter measurements have been carried out using waveguide simulator with vector network analyzer. The voltage from to 0V to 20V has been supplied by a function generator to the resonant patch elements as shown in Fig. 5 (c).



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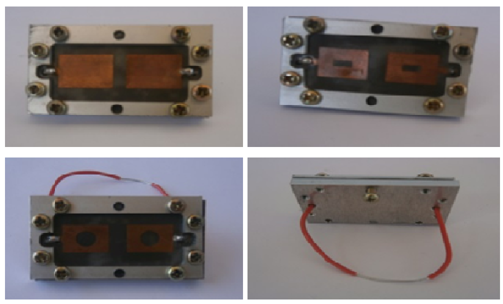
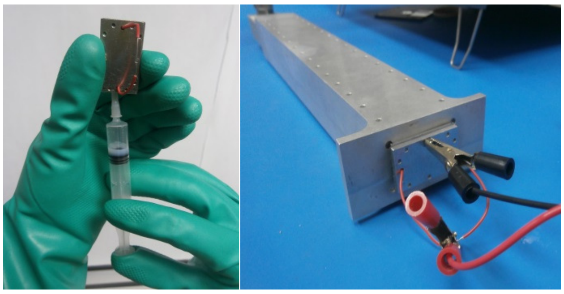


(b)

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



(a) (b)

(c)

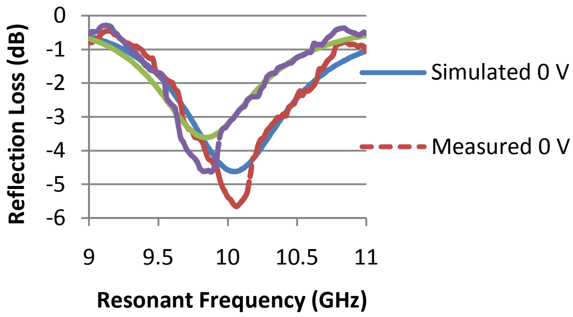
Fig. 5 Scattering parameter measurements of reflectarray unit cells (a) LC filling in cavity, (b) unit cell inserted in waveguide simulator and (c) complete measurement setup

IV. Results and Discussion

The scattering parameter measurements have been carried out for different design configurations in X-band frequency range for performance comparison. Figs. 6 (a) and (b) show the comparison between measured and simulated results of reflection loss and reflection phase curves respectively for rectangular patch element configuration. A close agreement between the two results has been observed and a variation from 10.06GHz to 9.88GHz for measured resonant frequency has been demonstrated with an increase in voltage from 0V to 20V.

Similarly in the case of rectangular slot embedded patch element, as shown in Figs. 7 (a) and (b), the measured resonant frequency varied from 10GHz to 9.88GHz while in the case of circular slot embedded patch elements a frequency variation from 10.2GHz to 10.0GHz has been observed with an increase in voltage from 0V to 20V as shown in Figs. 8 (a) and (b).

Table II provides the summary of measured results for slot embedded LC based reflectarray design. It can be observed from Table II that introduction of slots in the patch element reduces the volume of patch elements from 3.47mm^3 to 2.71mm^3 as compared to element without slot. Moreover the introduction of circular slot in patch element has increased the frequency tunability from 180MHz to 200MHz while the dynamic phase range is shown to increase from 120° to 124°. Therefore the circular slot embedded patch elements can be categorized as the most suitable LC based reflectarray design investigated in this work.



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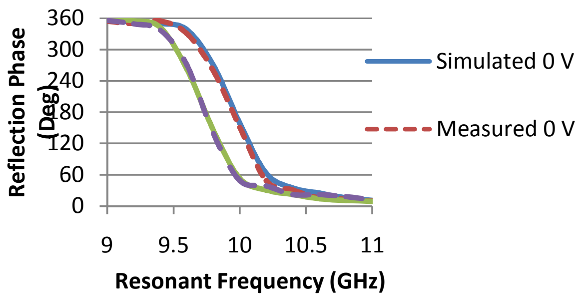

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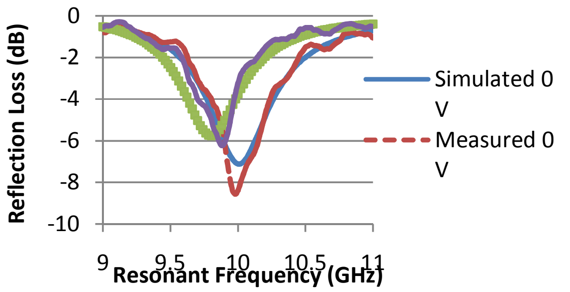
Fig. 6 Comparison of measured and simulated results for rectangular patch element (a) reflection loss curve and (b) reflection phase curve



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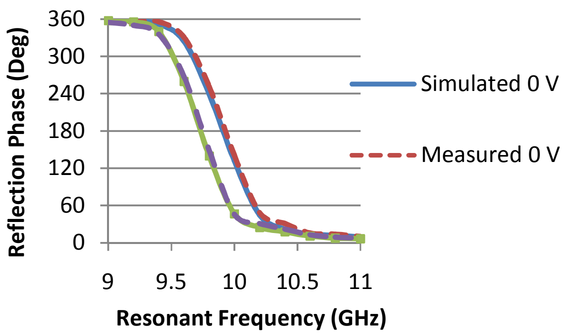
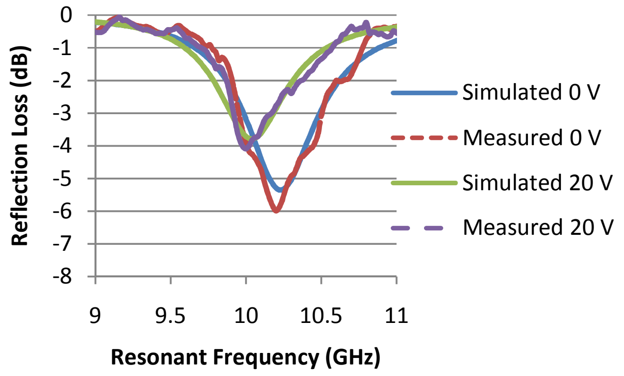


(b)

Fig. 7 Comparison of measured and simulated results for rectangular slot embedded patch element (a) reflection loss curve and (b) reflection phase curve



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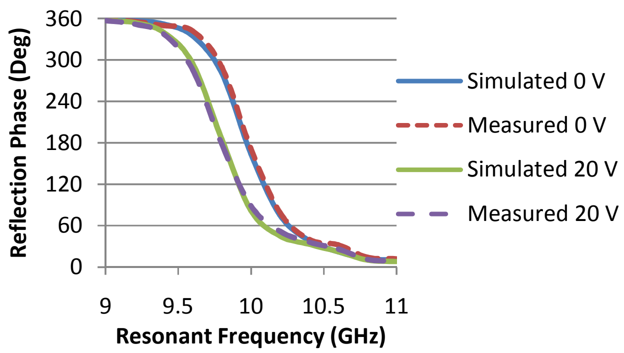

(b)

Fig. 8 Comparison of measured and simulated results for circular slot embedded patch element (a) reflection loss curve and (b) reflection phase curve

TABLE II
PERFORMANCE COMPARISON OF DIFFERENT PROPOSED DESIGN CONFIGURATIONS

Design Configuration	Patch Volume (mm^3)	Frequency Tunability (MHz)	Dynamic Phase Range (°)
Rectangular Patch	3.47	180	120
Rectangular Slot Embedded Patch	2.71	120	103
Circular Slot Embedded Patch	2.71	200	124

V. CONCLUSION

Volume of the nematic LC has a significant effect on the performance of LC based reflectarray design where a trade-off between frequency tunability and reflection loss performance occurs because of LC properties. Therefore selection of optimum design in terms of LC volume has to be identified prior to finalize a suitable LC based reflectarray design. Slot embedded patch elements provides an edge over the conventionally used rectangular patch element tunable reflectarray antenna design. Introduction of circular slots not only reduces the patch volume but also increases the frequency tunability and dynamic phase range in LC based reflectarray designs.

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