Characterization of Material Properties for Tunable Reflectarray Antenna Design

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Abstract. The emerging field of communications has increased the demand of electronically tunable reflectarray antennas. Substrate material properties play an important role in the design of reflectarray antennas. Variable permittivity materials such as liquid crystals and ferroelectrics have received great deal of attention due to their non-linear material properties. A comparative analysis between the properties of liquid crystals and ferroelectrics for tunable reflectarray antenna design has been carried out by using Finite Integral Method (FIM). A thorough investigation based on reflectarray design analysis and tunable bias voltages of different non-linear materials is provided. It has been shown that due to higher dielectric permittivity values of non-linear materials, ferroelectrics require higher bias voltages for electronic tunability, as compared to liquid crystal materials. Barium strontium titanate (BST) with a dielectric permittivity ranging from 300 to 360 has been used as a ferroelectric substrate material to design a rectangular patch reflectarray which offers a frequency tunability of 3 GHz. The results show that ferroelectrics are only applicable for high frequency reflectarray operation due to materials' higher permittivity values. Furthermore a rectangular patch reflectarray antenna printed on 1 mm thick different liquid crystal materials has also been designed based on FIM. It has been shown that as the dielectric anisotropy of substrate material increases from 0.17 to 0.45, the frequency tunablity and dynamic phase range of reflectarray antenna also increase from 372 MHz to 795 MHz and 90° to 160°, respectively.

Keywords: Reflectarrays, Non-linear Materials, Dielectric Anisotropy, Dynamic Phase Range, Frequency Tunability.
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INTRODUCTION

Mechanical movement of parabolic antenna especially in radar systems has increased the demand of an electronically tunable antenna [1]. Therefore a flat surface reflectarray antenna is gaining significant primary importance because of its lower cost and miniaturized size. Reflectarray antenna consists of printed reflecting elements on a grounded flat dielectric surface, illuminated by a primary feed horn [2]. The properties of dielectric substrate play an important role in the designing of reflectarray antenna [3]. Non-linear dielectric properties of substrate materials are mostly exploited in phase shifter designs for electronic tunability [4, 5]. The same technique can be employed to design an electronically tunable reflectarray antenna. In this work, different types of non-linear dielectric materials namely ferroelectrics and Liquid Crystals (LC) are used to design X-band rectangular patch reflectarray antenna. Table 1 summarizes some of the non-linear dielectric materials which have been used in reflectarray antenna design. Moreover, measurements of a passive reflectarray rectangular element printed on a linear material (Rogers 5880) were carried out by waveguide simulator approach. Measured reflection loss and static phase range values are compared with simulated results in order to ensure the validity of simulations. Furthermore a comparative analysis based on required tunable bias voltage between ferroelectric and LC materials has been performed. The reflection loss performance is comparatively analyzed with frequency tunablilty and dynamic phase range of different non-linear dielectric materials based on FIM.

TABLE 1. Different types of non-linear dielectric materials which have been used as reflectarray substrate

Non-Linear Dielectric Materials	Type	$\varepsilon_\perp$	$\varepsilon_\parallel$	Dielectric Anisotropy ($\Delta\varepsilon = \varepsilon_\parallel - \varepsilon_\perp$)	$\tan\delta_\perp$	$\tan\delta_\parallel$
K15 Nematic	LC	2.1	2.27	0.17	0.072	0.06
LC-B1	LC	2.6	3.05	0.45	0.022	0.007
Barium Strontium Titanate (BST)	ferroelectric	300	360	60	0.05	0.06

NON-LINEAR DIELECTRIC MATERIAL PROPERTIES

The materials that are being directionally dependent are non-linear/anisotropic materials in which the variation in values of a property may occur in any direction [6]. A non-linear dielectric material is such that, dielectric permittivity ε, varies in one direction of medium [6] whereas a dielectric linear/isotropic material has a fixed dielectric permittivity value. It is possible to tune the dielectric permittivity of anisotropic materials simply by applying a bias voltage across the substrate, which allows the molecules of anisotropic material to be oriented parallel to the incident field which results in an increase in the dielectric permittivity [7] as shown in Figure 1. The tunability capability in dielectric permittivity is required in order to realize dynamic phase distribution of reflectarrays. The difference between maximum and minimum value of dielectric permittivity is called dielectric anisotropy of material as given in Equation 1.

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

where, $\Delta\varepsilon$ = Dielectric anisotropy, $\varepsilon_{||}$ = Dielectric constant with applied DC voltage, $\varepsilon_{\perp}$ = Dielectric constant without DC voltage
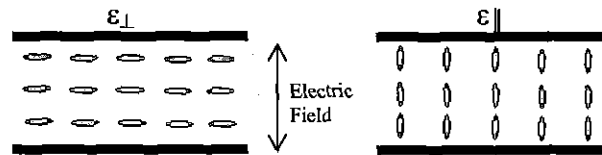

FIGURE 1. Alignment of molecules of dielectric anisotropic material without and with external bias voltage

According to the dielectric and physical properties which have been used in reflectarray antenna design, the non-linear dielectric materials can be categorized into two types.

Ferroelectrics

Ferroelectric materials posses a molecular property called ferroelectricity. Ferroelectricity is an electrical phenomenon whereby certain materials may exhibit a spontaneous dipole moment, the direction of which can be switched between equivalent states by the application of an external electric field. The internal electric dipoles of a Ferroelectric material are physically tied to the material lattice. Consequently, a change in the physical lattice results in change in the strength of the dipoles causing currents to flow into or out as a capacitor [8]. In the presence of an external bias voltage across the material, ferroelectrics attain variable dielectric permittivity values [4]. As shown in Table 1, ferroelectrics usually have very high dielectric constant values as compared to LC which is usually the main reason behind the limited use in reflectarrays.
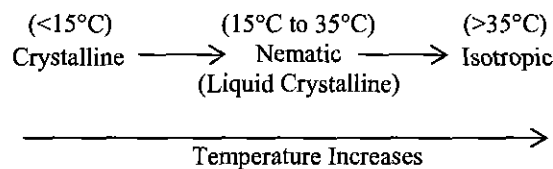

FIGURE 2. Effect of temperature on three physical states of K-15 Nematic liquid crystal

Liquid Crystals

The LC materials have two melting points in which after the first melting point they convert from solid crystal state to liquid crystal state and after second melting point they convert to pure liquid state. This shows that the liquid crystal state is the intermediate state between liquids and solids [6, 9]. It has been shown in Table 1 that the perpendicular components of dielectric constant have higher dissipation factor values as compared to the parallel components for all LC materials. The three states of liquid crystal materials are temperature dependent [7] as shown in Figure 2. For K-15 Nematic, it can be observed from Figure 2 that below 15°C, it posses a solid crystalline state,

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between 15°C and 35°C it is a pure liquid crystal having anisotropic properties whereas above 35°C it converts into liquid state which have linear/isotropic dielectric properties.

Comparison of Tunable Bias Voltage between Ferroelectrics and Liquid Crystals

The performance of both types of non-linear dielectric materials can easily be compared by the variation in the tunable bias voltage, required for electronic tunability in reflectarrays. Table 2 depicts some of the ferroelectric and LC materials with bias voltages. The anisotropic LC materials require a bias voltage from 0V to 20V as compared to ferroelectrics which require a higher voltage variation from 0V to 350V (Table 2). This is because the LC materials have very low dielectric constant values as compared to ferroelectric materials resulting in requirement of lower voltages [10].

TABLE 2. Comparison of bias voltage between Liquid Crystals and ferroelectric materials

Non-Linear Dielectric Materials	Type	Maximum Dielectric Permittivity	Bias Voltage Range (V)
K15 Nematic	LC	2.27	0-20
LC-B1	LC	3.05	0-20
Barium Strontium Titanate (BST)	ferroelectric	360	0-40
Strontium Titanate	ferroelectric	320	0-350

RESULTS BASED ON LINEAR DIELECTRIC MATERIAL

In order to investigate the scattering properties of passive reflectarray unit cells, reflectarray rectangular element operating at 10 GHz has been fabricated using 0.787 mm thick Rogers 5880 as a linear substrate material. Rogers 5880 has a dielectric permittivity of 2.2 with a dissipation factor of 0.0009. The waveguide simulator approach [11] has been used to perform the scattering parameter measurements of fabricated two patch unit cell element by Vector Network Analyzer (VNA) at X-band frequency range. This work has been used as a baseline stage for active reflectarray elements design.

Reflection Loss and Static Phase Range

The linear materials have fixed dielectric properties therefore they offer a single reflection loss and reflection phase curve at a particular resonant frequency. Figure 3(a) shows the measured and simulated reflection loss curves of a two patch reflectarray rectangular element printed above Rogers 5880 substrate.
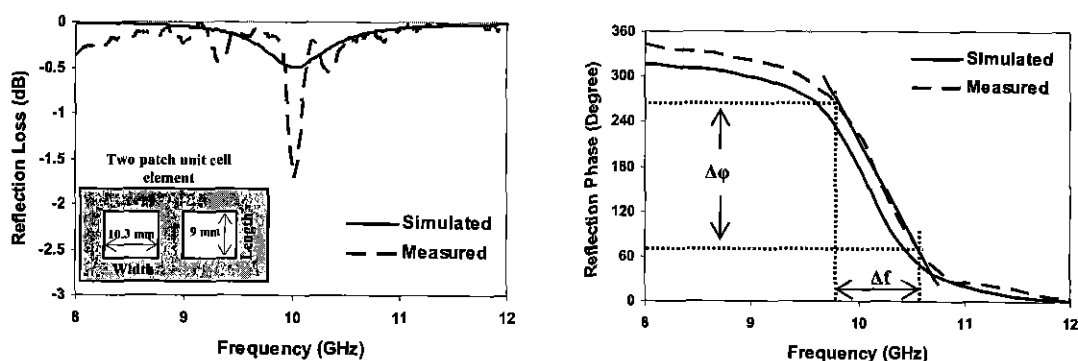

FIGURE 3. (a) Reflection loss performance of linear material with design configuration of two patch unit cell element
(b) Reflection phase performance of a linear material

As depicted in Figure 3(a) it has been shown that a rectangular element is observed to offer a sharp resonance at 10 GHz with a measured and simulated reflection loss performance of 1.6 dB and 0.5 dB respectively. Table 3 summarizes the simulated and measured reflection loss values which show some variance between them. The additional losses in the connectors and waveguide simulator are the main possible contributions of the discrepancy

in the measured and simulated results. Furthermore the surface roughness in fabrication process and substrate material tolerance also causes variation in the measured results. In order to analyze static phase range performance of passive reflectarray element, a Figure of Merit (FoM) has been defined as the ratio of the change in reflection phase to the change in the frequency and can be expressed as;

$$FoM = \frac{\Delta\varphi}{\Delta f} (° / MHz)$$ (2)

TABLE 3. Measured and simulated reflection loss and reflection phase performance of linear material

Rogers 5880	Simulated	Measured
Reflection Loss (dB)	0.5	1.6
Static Phase Range (°)	190	200
FoM (°/MHz)	0.27	0.31

The measured and simulated reflection phase curves of passive reflectarray element based on Rogers 5880 substrate are shown in Figure 3(b). As shown in Figure 3(b), it has been observed that rectangular element is observed to offer a measured and simulated static phase ranges of 190° and 200° respectively. The comparison between simulated and measured results for linear material is shown in Table 3 where static phase range and FoM values are summarized. A good agreement has been found between simulated and measured results. Table 3 shows that the measured reflection phase has a FoM value of 0.31°/MHz as compared to simulated phase which has 0.27°/MHz. This minor discrepancy is due to the high loss performance of measured results which increases the slope of reflection phase and overall phase range.

RESULTS BASED ON NON-LINEAR FERROELECTRIC MATERIAL

The properties of a ferroelectric material named barium strontium titanate (BST) have been used to design a rectangular patch reflectarray in CST computer model. According to Balanis [12], substrates with dielectric constant in between 2.2 and 12 are suitable for reflectarray antenna design. As described in Table 1, BST has dielectric constant values ranging from 300 to 360 therefore rectangular patch reflectarray unit cell has very small dimensions of 0.41 mm by 0.17 mm with a substrate thickness of 0.1 mm. A higher value of dielectric constant leads to the smaller dimensions of patch element which are comparable with the lower wavelengths of incident signal. As a result smaller patch element reflects higher frequency signals therefore this antenna has a resonant frequency of 33.5 GHz.

Reflection Loss and Frequency Tunability

Figure 4(a) shows the reflection loss curves and frequency tunability of reflectarray antenna printed on BST substrate material. It has been shown from Figure 4(a) that reflectarray antenna offers a reflection loss of 1.45 dB and 1.21 dB for perpendicular and parallel component of dielectric permittivity respectively.
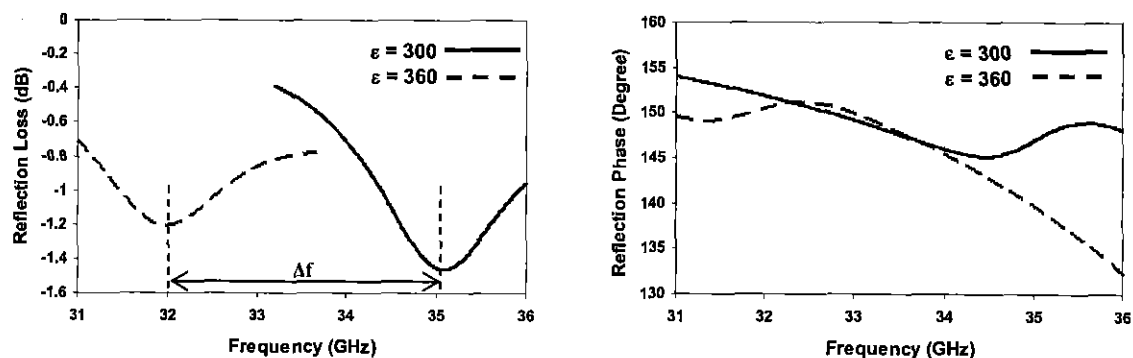

FIGURE 4. (a) Reflection loss and frequency tunablity (b) Distorted reflection phase curves of rectangular patch reflectarray unit cell based on BST substrate

Another important parameter to analyze the performance of non-linear dielectric materials is frequency tunability. With a dielectric anisotropy of 60, BST is shown to give a wider frequency tunability of 3 GHz. A bias

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voltage across a ferroelectric substrate can provide a very good frequency tunability performance for reflectarray antenna but higher values of dielectric permittivity is the main performance limitation for ferroelectric materials.

Reflection Phase Performance

As depicted in Figure 4(b) it has been observed that BST has a distorted phase response. Smaller dimensions of patch element affect the surface current distributions on the surface of the patch. Indistinct surface currents lead to have miss-behaved reflections from reflectarray antenna which causes a distorted phase curve in response [13]. Furthermore, due to thinner substrate used in this work the ground plane and patch element is comparatively severe. Thin substrate affects the electric field distribution and hence weaker electrostatic fields are generated within the substrate region, which causes higher dielectric absorption and consequently a distorted phase of reflectarray antenna.

RESULTS BASED ON NON-LINEAR LC MATERIALS

Reflection Loss Performance

The reflectivity performance of reflectarray rectangular patch element based on selected LC materials named LC-B1 and K-15 Nematic is shown in Figure 5(a). As depicted in Figure 5(a), it has been observed that perpendicular component of dielectric permittivity offers higher reflection loss performance as compared to parallel component. It is because of the reason that, the perpendicular component has a higher dissipation factor as compared to the parallel, as described earlier in Table 1. Table 4 contains the maximum and minimum reflection loss values of both anisotropic LC materials that are used to design reflectarray antenna. It has been observed from Table 4 that, K-15 Nematic offers the highest reflection loss performance of 10.74 dB as compared to LC-B1 which attains 3.54 dB. The reason behind that is, K-15 Nematic has a maximum dissipation factor or tangent loss value of 0.072 whereas LC-B1 has 0.022 which leads to have lower reflection losses.
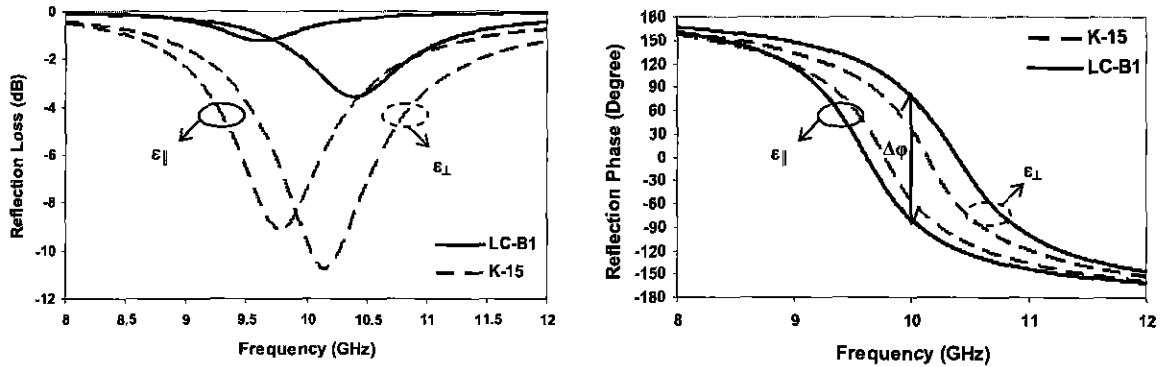

FIGURE 5. (a) Reflection loss performance of non-linear LC materials (b) Reflection phase performance of non-linear LC materials

Dynamic Phase Range and Frequency Tunability

Non-linear LC materials attain a range of dielectric permittivity values from minimum ($\varepsilon_\perp$) to maximum ($\varepsilon_\parallel$). Therefore when a non-linear LC material is used as a reflectarray substrate a phase agile characteristic occurs which is known as dynamic phase distribution. The maximum phase variations of the reflected signal occur at resonant frequency. Dynamic phase range can be defined as.

$$\Delta\varphi = \varphi(\varepsilon_{//}) - \varphi(\varepsilon_\perp) \qquad (3)$$

The dynamic phase range of LC materials is a measure of dielectric anisotropy. Figure 5(b) shows the dynamic phase ranges for reflectarray antenna printed on LC-B1 and K-15 Nematic LC material. As shown in Figure 5(b), it has been observed that LC-B1 offers wider dynamic phase range of 160° as compared to K-15 Nematic which attains 90°.

TABLE 4. Reflection loss, dynamic phase range and frequency tunability performance of anisotropic LC materials

Non-Linear LC Materials	Dielectric Anisotropy	Reflection Loss (dB)		Dynamic Phase Range $\Delta\varphi$ (°)	Frequency Tunability Δf (MHz)
		at $\varepsilon_{\perp}$	at $\varepsilon_{\parallel}$		
K15 Nematic	2.27	10.74	9.10	90	372
LC-B1	3.05	3.54	1.22	160	795

Table 4 also contains the values of dynamic phase ranges for reflectarray antenna printed on 1 mm thick dielectric anisotropic materials. It has been observed from Table 4 that, as the dielectric anisotropy increases from 0.17 to 0.45 the dynamic phase range also increases from 90° to 160°. This shows a relationship between dielectric anisotropy and dynamic phase range of non-linear LC materials.

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. Table 4 summarizes the frequency tunability values for rectangular reflectarray element printed above different anisotropic LC materials. It has been shown from Table 4 that, as the dielectric anisotropy increases from 0.17 to 0.45, the frequency tunability also increases from 372–795 MHz. Frequency tunability response of reflectarray antenna corresponds to the flexibility in the value of dielectric anisotropy of anisotropic materials.

CONCLUSION

A detailed analysis based on rectangular patch reflectarray antenna printed on different linear and non-linear materials is presented in this work. The results obtained from this work demonstrate that different types of non-linear materials such as ferroelectrics and LC can enhance the performance of reflectarray antenna in terms of wider phase ranges and higher frequency tunability. It has been observed that due to higher dielectric permittivity ferroelectrics require higher bias voltages as compared to LC materials. Furthermore it is observed that BST has a distorted phase response because of thinner substrate and reduced dimensions of the patch element. A non-linear LC material offers rapid dynamic phase change behavior for designing an electronically tunable reflectarray antenna. A rapid dynamic phase range with a high frequency tunability performance of different non-linear dielectric materials discussed in this work is required particularly for beam steering applications in radar and satellite communication system.

ACKNOWLEDGMENTS

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