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Tunability Performance of Reflectarrays Based on Non-Linear Material Properties

Ismail, M.Y. and M. Hashim Dahri

Wireless and Radio Science Center (WARAS),
Faculty of Electrical and Electronics Engineering,
University Tun Hussein Onn Malaysia (UTHM), 86400 Parit Raja, Johor, Malaysia

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ABSTRACT

Limited phase range and narrower bandwidth are the main performance limitations of reflectarray antennas for high gain applications which result in the performance to be restricted particularly in satellite and earth observatory systems. This study provides a thorough investigation on the tunability performance of reflectarrays designed in X-band frequency range using different non-linear dielectric substrates. An investigation of phase agility characteristics of reflectarray rectangular patch antenna printed above non-linear materials ($0.17\leq \Delta\varepsilon \leq 0.45$) is thoroughly presented. A detailed analytical study on dynamic phase range and frequency tunability of the reflectarrays is carried out based on the analytical investigation which is validated by Finite Integral Method (FIM). As the dielectric anisotropy of non-linear materials increases from 0.17-0.45 the frequency tunability performance of the reflectarray antenna is shown to increase from 372-796 MHz. The results show that LC-B1 with a dielectric anisotropy of 0.45 contributes a maximum dynamic phase range and frequency tunability performance of 160° and 796 MHz respectively. The dielectric non-linear properties presented in this study are shown to considerably affect the frequency and phase range performance of reflectarray antenna particularly for rapid dynamic phase change of terrestrial systems.

Keywords: Phase Agility, Dielectric Anisotropy, Dynamic Phase Range, Tunability

1. INTRODUCTION

Reflectarray antenna has been acknowledged as a potential alternative solution to the traditionally used high gain antennas such as parabolic reflectors or phased arrays (Huang and Encinar, 2007). It consists of printed reflecting elements on a flat dielectric substrate. Apart from the low cost and low profile structure, the phase range and bandwidth performance of reflectarrays are considered as the main performance limitations (Huang, 1995). These limitations can be reduced by the selection of a suitable dielectric substrate (Ismail *et al*., 2010). Non-linear dielectric materials are required for the microwave engineering industry particularly in telecommunications, remote sensing and global navigation systems (Trushkevych *et al*., 2010). Liquid Crystal (LC) materials have dielectric anisotropic properties which can be used to enhance the reflectarray performance in terms of frequency tunability and dynamic phase control strategy (Kamoda *et al*., 2004). The tunabilty in dielectric constant of LC materials can be achieved simply by applying a DC bias voltage across the substrate. With an applied bias voltage the molecules of anisotropic material are oriented parallel to the incident field to attain a maximum dielectric permittivity value ($\varepsilon_{\parallel}$). A minimum dielectric permittivity value ($\varepsilon_{\perp}$) is achieved without applied bias voltage when molecules of anisotropic material are oriented perpendicular to the incident field (Ismail and Cahill, 2005) as shown in **Fig. 1**. The dielectric anisotropy of non-linear LC materials can be realized by the difference between the maximum ($\varepsilon_{\parallel}$) and minimum ($\varepsilon_{\perp}$) values of dielectric permittivity as given in Equation 1:

Corresponding Author: M.Y. Ismail, Wireless and Radio Science Center (WARAS), Faculty of Electrical and Electronics Engineering, Universiti Tun Hussein Onn Malaysia (UTHM), 86400 Parit Raja, Johor, Malaysia

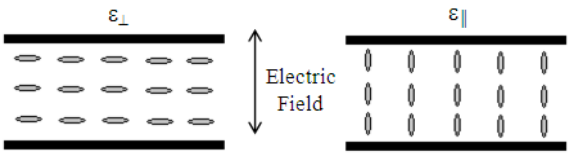

Fig. 1. Alignment of molecules of anisotropic material without and with external DC voltage

$$\Delta\varepsilon_r = \varepsilon_{r\parallel} - \varepsilon_{r\perp} \quad (1)$$

Where:

$\Delta\varepsilon$ = Change in dielectric constant

$\varepsilon_\parallel$ = Dielectric constant with applied DC voltage

$\varepsilon_\perp$ = Dielectric constant without applied DC voltage

In this study the effect of non-linear material properties on the tunabilty performance of reflectarrays is discussed in details. Different non-linear dielectric substrates are used to design a rectangular patch reflectarray at 10 GHz in order to investigate the dynamic phase range and frequency tunabilty performance using numerical equations and Finite Integral Method (FIM).

2. MATERIALS AND METHODS

2.1. Analytical Investigation

The existence of electromagnetic fields E in a dielectric anisotropic material causes the polarization of the molecules to create electric dipole moment P. This dipole moment is a vector quantity and directed from negative electric charge to positive electric charge presented in the material (Pozar, 2005). The electric dipole moment is also subject to Torque τ, which is a vector quantity represented by the turning effect of the molecules of the material (Serway and Jewett, 2009). The Torque τ can be obtained by the cross product of electric dipole moment P and electric field E as given in Equation 2:

$$\bar{\tau} = \bar{P} \times \bar{E} = |P||E|\sin\theta \quad (2)$$

where, θ is the angle between incident electric field and generated dipole moment as shown in **Fig. 2**.

Electric flux is a quantity that represents the amount of displacement current D in the dielectric material caused by the applied electric field (Pozar, 2005). For a non-linear dielectric material the displacement current in terms of electric field is given by the Equation 3:

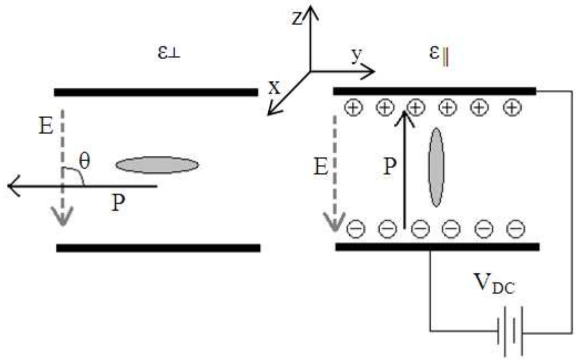

Fig. 2. Dipole moment P inside the non-linear dielectric material without and with external DC voltage

$$D = [\varepsilon]\bar{E} \Rightarrow \begin{bmatrix} D_x \\ D_y \\ D_z \end{bmatrix} = \begin{bmatrix} \varepsilon_\perp & 0 & 0 \\ 0 & \varepsilon_\perp & 0 \\ 0 & 0 & \varepsilon_{//} \end{bmatrix} \begin{bmatrix} E_x \\ E_y \\ E_z \end{bmatrix} \quad (3)$$

The displacement current measured in Coul/m^2 signifies the directional characteristics of non-linear material properties, where [ε] is known as the complex dielectric permittivity tensor of non-linear dielectric materials (Dankov *et al*., 2005). Equation 3 shows that the dielectric permittivity of non-linear dielectric materials is a vector quantity having different parameters in x, y and z directions. As shown in **Fig. 2**, when an external DC voltage is applied across the non-linear substrate material the dipole moment vector P changes its direction and points towards the higher potential side. A change in dipole moment P causes a change in torque **τ** by the Equation 2. Torque τ corresponds to the turning effects of the molecules of the non-linear material. Therefore a change in Torque τ also results in the change in the position of molecules as depicted in **Fig. 2**.

It is shown in Equation 3 that dielectric permittivity of non-linear dielectric materials is a directional dependent property. Therefore a changing molecular position refers to a different value of dielectric permittivity. This is the reason behind the variable dielectric properties of non-linear dielectric materials.

2.2. Phase Agility

Non-linear dielectric materials attain a range of dielectric constant values from minimum ($\varepsilon_\perp$) to maximum ($\varepsilon_\parallel$). Therefore when a non-linear dielectric 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:

$$\Delta\varphi = \varphi(\varepsilon_{\parallel}) - \varphi(\varepsilon_{\perp}) \quad (4)$$

The dynamic phase range of non-linear dielectric materials is a measure of dielectric anisotropy. It has been shown from Equation 4 that the dynamic phase range increases with the increase in dielectric anisotropy ($\Delta\varepsilon$). Therefore an equation for dynamic phase range based on non-linear material properties has been established as shown in Equation 5:

$$\Delta\varphi = C\frac{2\pi\Delta\varepsilon}{\lambda_g} \quad (5)$$

Where:

$\Delta\varepsilon = \varepsilon_{\parallel}-\varepsilon_{\perp}$ = Dielectric anisotropy of non-linear material
λ_g = Guided wavelength
C = A conditional arbitrary constant and its value depends on the dielectric anisotropy of non-linear material

2.3. Frequency Agility

A change in dielectric constant of non-linear dielectric materials can also cause a significant change in resonant frequency which is known as the frequency tunability of reflectarray. In order to calculate the frequency tunability the minimum and maximum values of resonant frequencies are required. Therefore the frequency tunability can be obtained by Equation 6:

$$\Delta f = f_{\perp} - f_{//} = \frac{c\left\{\sqrt{\varepsilon_{eff//}} - \sqrt{\varepsilon_{eff\perp}}\right\}}{2L_{eff}\sqrt{\varepsilon_{eff//}\varepsilon_{eff\perp}}} \quad (6)$$

Where:

$\varepsilon_{eff\parallel}$ and $\varepsilon_{eff\perp}$ = Maximum and minimum effective dielectric permittivity of non-linear material respectively
L_{eff} = The Effective length of resonant element

2.4. Reflectarray Design

Table 1 shows different types of non-linear dielectric substrate materials listed with dielectric permittivity and loss tangent values. These materials are used to design a rectangular patch reflectarray at X-band, using commercially available CST MWS computer model with 1mm substrate thickness.

Table 1. List of non-linear dielectric substrates and their properties

Non-Linear LC Materials	$\varepsilon_{\perp}$	$\varepsilon_{\parallel}$	Dielectric anisotropy ($\Delta\varepsilon = \varepsilon_{\parallel} - \varepsilon_{\perp}$)	$\tan\delta_{\perp}$	$\tan\delta_{\parallel}$
K15 Nematic	2.10	2.27	0.17	0.072	0.060
Merck BL037	2.25	2.45	0.20	0.048	0.025
Chisso JB-1017	2.50	2.90	0.40	0.015	0.005
LC-B1	2.60	3.05	0.45	0.022	0.007

In order to characterize the phase agile characteristics of reflectarrays, the dynamic phase range and frequency tunability were obtained using dielectric substrates having a variety of dielectric anisotropy ranging from 0.17-0.45. Furthermore the equations given above are also analyzed to find out the dynamic phase range and frequency tunability for the reflectarrays using non-linear dielectric properties listed in **Table 1**.

3. RESULTS AND DISCUSSION

3.1. Electric Field and Displacement Current

Due to the dielectric anisotropic nature of non-linear properties, these materials generate ranges of maximum electric fields and displacement currents. It is because anisotropic materials contain a range of dielectric permittivity values from its perpendicular state to its parallel state. Electric fields should reach at their peaks in order to realize a phase change at the resonant frequency (Dahri and Ismail, 2011). This can easily be verified from **Fig. 3** in which every material has a peak value of electric field at its resonant frequency but as graph moves forward or backward from resonant frequency it again starts decreasing gradually. It is also clearly shown from **Fig. 3** that K-15 Nematic offers the lowest electric field intensity of 62×10^3 V/m compared to Chisso which offers the highest electric field intensity of 112×10^3 V/m. This is due to the fact that electric field is a directional dependent quantity which depends on the orientation of the molecules of non-linear material as described earlier in Equation 3.

The electric characteristics of non-linear materials can be viewed from **Table 2** where every material offers a range of values for electric field intensity and displacement current. These values can be calculated by subtracting maximum value (at $\varepsilon_{\parallel}$) from minimum value (at $\varepsilon_{\perp}$) for each electrical quantity. It has been shown that as dielectric anisotropy increases from 0.17-0.45, the ranges of values of the electrical field intensity and displacement current are shown to increase from 11072-54790 V/m and 8980-100990 Coul/m^2 respectively.

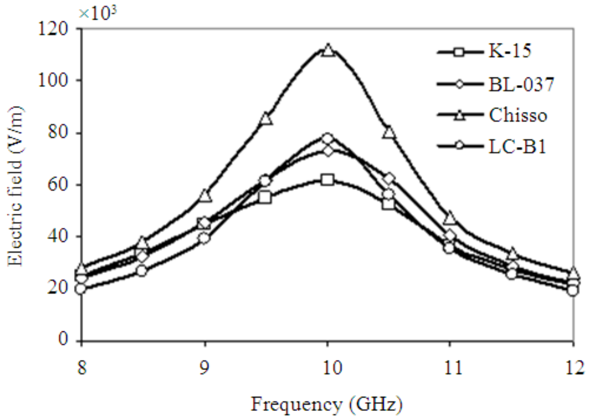

Fig. 3. Electric field Vs frequency for different non-linear materials

Table 2. Values of electric field and displacement current for different non-linear materials

Non-linear LC Materials	Values of Dielectric Anisotropy (Δε)	Values of Electric Intensity (V/m)	Displacement Current (Coul/m^2)
K-15 Nematic	0.17	11072	8980
BL037	0.20	27972	84408
Chisso	0.40	37280	64792
LC-B1	0.45	54790	100990

This is because the variation in the values of dielectric permittivity corresponds to the change in the electric field and hence displacement current as shown in Equation 3. Consequently the effect of dielectric anisotropy on electric field intensity and displacement current enhances the tunability characteristics of non-linear materials.

3.2. Reflection Loss Performance

The non-linear materials have a range of dielectric permittivity values according to the alignment of their molecules with respect to the incident field. The maximum dielectric permittivity and dissipation factor of each non-linear material are shown to be crucial factors in the loss performance of reflectarray antenna. **Table 3** summarizes maximum reflection loss values for all non-linear materials that are used for reflectarray antenna design. It has been shown from **Table 3** that K-15 Nematic offers a higher reflection loss of 10.74 dB compared to Chisso which offers reflection loss of 2.36 dB. This is because the K-15 Nematic has a higher dissipation factor value of 0.072 compared to Chisso which has a lower dissipation factor.

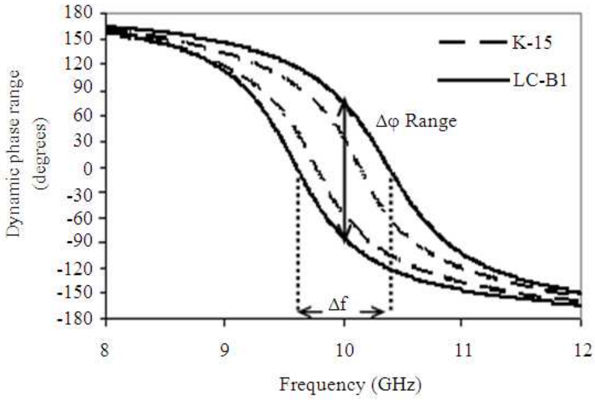

Fig. 4. Dynamic phase range and frequency tunability of two different non-linear materials

Table 3. Maximum reflection loss performance of non-linear materials

Maximum Non-Linear LC Materials	Maximum Dielectric Permittivity (ε)	Maximum Dissipation Factor (tanδ)	Reflection Loss (dB)
K15 Nematic	2.27	0.072	10.74
Merck BL037	2.45	0.048	7.11
Chisso JB-1017	2.90	0.015	2.36
LC-B1	3.05	0.022	3.54

3.3. Dynamic Phase Range

Dielectric constant of non-linear dielectric materials can be changed by simply applying a DC voltage across the substrate (Ismail and Cahill, 2005). Therefore by changing the value of dielectric permittivity of anisotropic materials a dynamic phase range is achievable. The dynamic phase range of materials is a measure of dielectric anisotropy which can be used as Figure of Merit (FoM) for anisotropic materials (Ismail *et al*., 2007).

The dynamic phase ranges for selected non-linear substrate materials are shown in **Fig. 4**. As depicted in **Fig. 4** it has been shown that LC-B1 has a higher dynamic phase range of 160° as compared to K-15 with a dynamic phase range of 90°. **Table 4** summarizes the results of simulated and formulated dynamic phase ranges with dielectric anisotropy for all non-linear LC materials that are used as dielectric substrates. The formulated analysis is done by considering the properties of non-linear materials as explained in Equation 5. The results as depicted in **Table 4** show that LC-B1 has a maximum formulated dynamic phase range of 172° for a maximum dielectric anisotropy of 0.45 as compared to K-15 Nematic which has a minimum formulated dynamic phase range of 93° with dielectric anisotropy of 0.17.

Table 4. Simulated and Formulated dynamic phase ranges of different non-linear materials

Non-Linear LC Materials	Dielectric Anisotropy (Δε)	Dynamic Phase Range (°) Simulated	Formulated
K15 Nematic	0.17	90	93
Merck BL037	0.20	90	113
Chisso	0.40	150	150
LC-B1	0.45	160	172

Table 5. Simulated and Formulated frequency tunability of different non-linear materials

Non-Linear LC Materials	Dielectric Anisotropy (Δε)	Frequency Tunability (MHz) Simulated	Formulated
K15 Nematic	0.17	372	358
Merck BL037	0.20	404	401
Chisso	0.40	736	680
LC-B1	0.45	796	752

Furthermore it has also been observed that as dielectric anisotropy increases from 0.17-0.45 dynamic phase range also increases from 93-172°. This is because the variation in the values of dielectric anisotropy (Δε) corresponds to the phase agility at resonant frequency of reflectarrays which is known as dynamic phase range as described earlier in Equation 5. From **Table 4** it can also be observed that a good agreement has been found between simulated and formulated results.

3.4. Frequency Tunability

Dielectric anisotropic nature of non-linear materials causes the resonant frequency of reflectarray to be varied which results in the frequency tunability as shown in **Fig. 4**. **Table 5** summarizes the results of simulated and formulated frequency tunability with dielectric anisotropy for all non-linear LC materials. Formulated tunable frequency ranges have been calculated by using Equation 6.

The results depicted in **Table 5** show that LC-B1 has a maximum simulated frequency tunability of 796 MHz for a maximum dielectric anisotropy of 0.45 whereas K-15 nematic has a minimum frequency tunability of 372 with dielectric anisotropy of 0.17. Furthermore it has also been observed that as dielectric anisotropy increases from 0.17-0.45 frequency tunability also increases from 372-796 MHz and 358-752 MHz for simulated and formulated results respectively. This change in frequency tunability performance with change in dielectric anisotropy expresses a relationship between frequency tunability and non-linear material properties.

4. CONCLUSION

A detailed analysis of reflectarray cells based on molecular alignment of non-linear materials presented in this work demonstrates that a suitably selected dielectric non-linear material can enhance the phase range performance of reflectarray. Non-linear dielectric materials are shown to offer a rapid dynamic phase change behavior for designing an electronically tunable reflectarray antenna particularly for terrestrial systems. It has been shown that the dielectric anisotropy of non-linear materials can affect the phase agility characteristics and frequency tunability of reflectarray antenna particularly for space technology. Furthermore the phase agility and frequency tunability characteristics of reflectarray antenna elements can also be optimized by numerical equations based on substrate material properties.

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