Phase Distribution Analysis of Reflectarray Resonant Elements based on Linear and Non-linear Materials

*M. Hashim Dahri and M.Y. Ismail
Wireless and Radio Science Centre (WARAS),
University Tun Hussein Onn Malaysia, 86400 Parit Raja, Johor, Malaysia
muhammadhashimdahri@yahoo.com, yusofi@uthm.edu.my

Abstract— **Properties of substrate material play an important role in the design of reflectarray antenna. In this work linear and non-linear dielectric properties of substrate materials are discussed thoroughly. Rogers RT/d 5880 and K-15 nematic are used as linear and non-linear dielectric materials respectively, to design different reflectarray resonant elements in X-band frequency range. Simulated and measured results of different reflectarray resonant elements printed on Rogers substrate are discussed thoroughly. Simulations based on CST computer model are performed to analyze dynamic response of three different reflectarray resonant elements printed on K-15 nematic material. It has been demonstrated that the ring element based on linear material offers higher static phase range of 310° as compared to dipole and rectangular elements which offer 285° and 200° respectively. Furthermore the rectangular element based on non-linear material is observed to offer a narrower dynamic phase range of 90° as compared to dipole and ring elements which offer 190° and 200° respectively.**

Keywords- reflectarrays; resonant elements; linear materials; non-linear materials; dynamic phase range.

I. INTRODUCTION

A flat surface reflectarray antenna can be a possible alternative of conventional parabolic systems. It consists of printed reflecting elements on a grounded flat dielectric surface, illuminated by a feed antenna. But the limited phase ranges and higher reflection losses are the main performance limitations of reflectarray antennas [1]. Parabolic antenna requires mechanical movement for beam steering, especially in radar systems. An electronically tunable reflectarray antenna can overcome this flaw of mechanical movement. Selection of suitable dielectric materials is a crucial factor to determine the performance of reflectarray antenna particularly phase range and bandwidth [2]. Furthermore different types of resonant elements can also used to enhance the performance of reflectarray antenna in terms of wider phase ranges and higher bandwidths [3]. In this work a thorough investigation on the phase distribution characteristics of different reflectarray resonant elements has been carried out. Dielectric isotropic and anisotropic substrate materials are used to design different types of reflectarray resonant elements such as rectangular, dipole and ring at X-band frequency range. The unit cell reflectarray configuration for rectangular, dipole and ring as resonant elements is shown in Fig. 1. Reflection loss and static phase range of reflectarray resonant elements are analyzed using 0.787 mm thick Rogers as a linear substrate material.

This project is funded by the Best Fundamental Research Grant Scheme (FRGS VOT 0983), awarded by Ministry of Higher Education of Malaysia.
*Corresponding Author

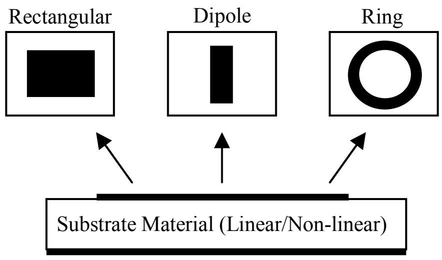

Figure 1. Design configuration of unit cell reflectarray element with different resonant elements

Waveguide simulator approach [4] is used to perform the measurements of fabricated samples by Vector Network Analyzer (VNA) at X-band frequency range. The non-linear properties of LC materials are mostly exploited in phase shifter designs [5, 6]. The same technique can be employed to design a tunable reflectarray antenna. A 1.0 mm thick non-linear LC material is used as the substrate for the three different elements. Simulations are carried out by CST computer model in order to investigate the effect of non-linear material properties on reflectarray antenna performance. Reflection loss, frequency tunability and dynamic phase range for rectangular, dipole and ring elements are discussed thoroughly. Finally a comparative analysis between linear and non-linear material properties in conjunction with reflectarray antenna performance has been discussed.

II. LINEAR AND NON-LINEAR MATERIAL PROPERTIES

An isotropic or linear material is one in which the dielectric permittivity (ε) and dissipation factor (tanδ), are uniform in all directions of the medium [7]. In other words the material which does not change its properties by the influence of any external effect is isotropic material [8]. Table I shows the properties of Rogers, which has been used as a linear substrate material for X-band reflectarray antenna design. It has been shown from Table I that the linear material holds fix values for dielectric constant and dissipation factor. Liquid crystals are non-linear dielectric materials in which the dielectric constant can be changed between two extreme states that are described by the orientation of LC molecules, being either parallel or perpendicular to the excited electric field [8, 9]. Table I shows the properties of K-15 nematic, which has been used as a non-linear substrate material for reflectarray antenna design. Table I shows that the non-linear material contains variable values for dielectric constant and dissipation factor.

TABLE I. PROPERTIES OF LINEAR AND NON-LINEAR SUBSTRATE MATERIALS

Substrate Materials	Type	Dielectric Constant (ε)	Dissipation Factor (tanδ)
Rogers	Linear	2.2	0.0009
K15 Nematic	Non-linear	2.1 – 2.27	0.072 – 0.06

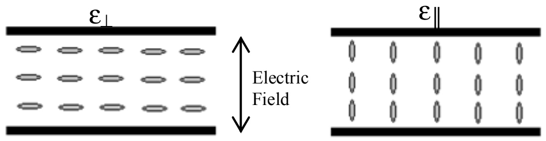

Figure 2. Alignment of molecules of non-linear LC material without and with external DC voltage

It is possible to vary the dielectric constant of non-linear dielectric materials by applying a controlled DC bias voltage across the substrate. In the presence of a DC voltage the molecules of anisotropic material are oriented parallel to the incident field to attain a maximum dielectric permittivity value ($\varepsilon_{\|}$). 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 [9] as shown in Fig. 2. The difference between maximum and minimum values of dielectric permittivity is called dielectric anisotropy of material and is given by equation (1).

$$\Delta\varepsilon = \varepsilon_{\|} - \varepsilon_{\perp} \qquad (1)$$

Where, Δε = Dielectric anisotropy
$\varepsilon_{\|}$ = Dielectric constant with applied DC voltage
$\varepsilon_{\perp}$ = Dielectric constant without DC voltage

Dielectric anisotropy is used as the figure of merit for non-linear dielectric materials. It can be observed from Table I that K-15 nematic has a dielectric anisotropy of 0.17.

III. SIMULATIONS AND MEASUREMENTS

The design layout of reflectarray resonant elements as shown in Fig. 1, has been modeled in CST MWS with proper boundary conditions suitable for infinite array analysis. Simulated results are compared with measured results which are obtained for fabricated samples of three different resonant elements. Fig. 3 shows the layout of two patch rectangular element unit cell where "d" is the element spacing between the patches. The element spacing should be taken as half of the incident wavelength to avoid the mutual coupling between the adjacent elements [10]. It has been shown in Fig. 3 that an E and H wall waveguide simulator technique can be used to excite the unit cell rectangular element in an infinite reflectarray environment [3]. The scattering parameter measurements have been performed by connecting waveguide simulator to the vector network analyzer through a coaxial cable. A 0.787 mm thick Rogers substrate material is used for both simulations and measurements.

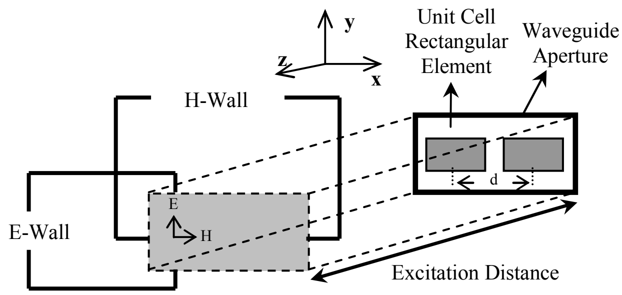

Figure 3. Excitation of unit cell rectangular element in waveguide simulator technique

IV. RESULTS AND DISCUSSION

A. Comparison of Reflection Loss Performance

The linear materials have fixed dielectric properties therefore they offer a single reflection loss curve at a particular resonant frequency. While non-linear materials have a range of dielectric constant values from its perpendicular ($\varepsilon_{\perp}$) to parallel ($\varepsilon_{\|}$) component therefore they offer a frequency agility characteristic. Fig. 4 shows the measured and simulated reflection loss curves of three different resonant elements printed above Rogers. As depicted in Fig. 4 it has been shown that ring element is observed to offer a higher measured reflection loss performance of 3.6 dB as compared to dipole and rectangular elements which offer 3.3 dB and 1.6 dB respectively. The reflection loss performance of reflectarray antenna for selected resonant elements printed on K-15 nematic material is shown in Fig. 5. As depicted in Fig. 5, it has been observed that rectangular element offers minimum reflection loss values of 9.09 dB and 10.74 dB for its maximum and minimum dielectric constant values respectively, followed by dipole and ring elements which offer 21.16 dB – 33.51 dB and 23.06 dB – 56.54 dB values respectively. This dissimilarity between reflection loss performance of three elements in X-band is due to the different reflecting areas of these elements [11]. Fig. 1 shows that the rectangular element acquires wider reflecting area as compared to dipole and ring elements respectively.

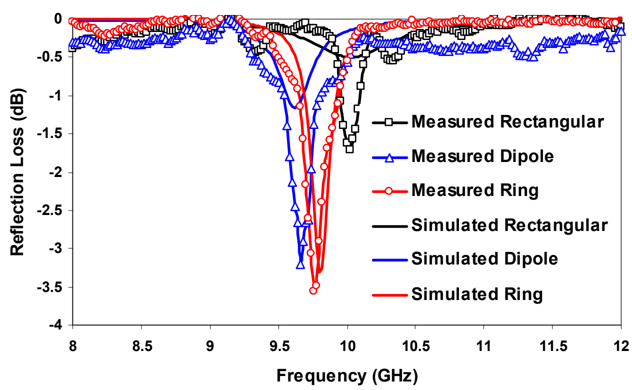

Figure 4. Reflection loss performance of reflectarray resonant elements based on a linear material

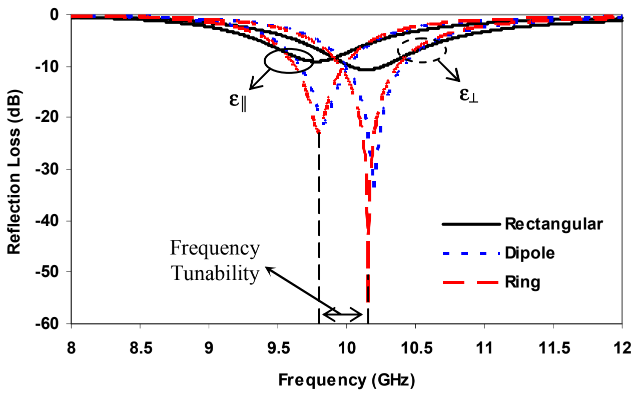

Figure 5. Reflection loss performance of reflectarray resonant elements based on a non-linear material

TABLE II. REFLECTION LOSS PERFORMANCE OF DIFFERENT RESONANT ELEMENTS PRINTED ON LINEAR AND NON-LINEAR MATERIALS

Resonant Element	Reflection Loss (dB)			
	Linear Material		Non-linear Material	
	Simulated	Measured	at $\varepsilon_\perp$	at $\varepsilon_\parallel$
Rectangular	0.5	1.6	10.74	9.09
Dipole	1.2	3.3	33.51	21.16
Ring	3.31	3.6	56.54	23.06

Therefore rectangular element reflects back most of the incident signals and offers lowest reflection loss performance of 1.6 dB and 9.09 dB for linear and non-linear materials respectively. Alternatively due to narrower reflecting area of ring element most of the incident signals interacts with the substrate region and as a result highest reflection loss performance of 3.6 dB and 56.54 dB is obtained. Table II summarizes all the reflection loss values for linear and non-linear materials. It has been shown from Table II that non-linear material offers higher reflection loss performance as compared to linear material. This is because the non-linear material attains higher values of dissipation factor as compared to linear material, as depicted in Table I. For linear material a good agreement has been found between measured and simulated resonant frequencies and reflection loss performance. It has been observed from Table II that the measured results offer higher values of reflection losses as compared to the simulated results. The losses in the connectors and waveguide simulator are the main possible contributions of the discrepancy in the measured and simulated reflection losses. Another reason for this difference can be due to the manufacturing errors occurred in fabrication process [4].

B. Comparison of Static and Dynaimc Phase Ranges

The static phase range performance of three different elements namely rectangular, dipole and ring has been analyzed using measured and simulated results. For the comparison of static phase range performance of different resonant elements, a Figure of Merit (FoM) has been defined as the ratio of the change in reflection phase to the change in the frequency [2] and can be expressed as;

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

The non-linear LC materials attain a range of dielectric constant values from minimum ($\varepsilon_\perp$) to maximum ($\varepsilon_\parallel$). Therefore when a non-linear LC material is used as a reflectarray antenna substrate, a phase agile characteristic occurs due to the change in the frequency. The maximum variation in the reflection phase occurs at resonant frequency which is known as dynamic phase range as shown in Fig. 8. The dynamic phase range is given by equation (3) [9].

$$\Delta\varphi = \varphi(\varepsilon_\parallel) - \varphi(\varepsilon_\perp) \qquad (3)$$

The measured and simulated reflection phase curves of rectangular, dipole and ring elements based on Rogers substrate are shown in Fig. 6. As shown in Fig. 6 it has been observed that ring element is observed to offer a wider measured static phase range of 310° as compared to dipole and rectangular elements which offer 285° and 200° respectively. The wider static phase range performance of ring element is due to the higher slop of the reflection phase which is 0.52°/MHz as compared to 0.48°/MHz and 0.31°/MHz of dipole and rectangular elements respectively. On the other hand the dynamic phase range performance of rectangular, dipole and ring elements printed on 1.0 mm thick K-15 nematic substrate material are shown in Fig. 7. As depicted in Fig. 7 it has been shown that ring element has steeper reflection phase curves as compared to other two resonant elements therefore it offers wider dynamic phase range of 200°. This is because the narrower reflecting area of ring element allows rapid multiple bounces of energy into the substrate region and offers a high reflection loss, hence resulting in a steeper and increased phase range. The comparison between simulated and measured results for linear material is shown in Table III where static phase ranges and FoM of three elements are summarized. A good agreement has been found between simulated and measured results. Table III shows that the measured results offer slightly higher values of static phase ranges as compared to the simulated results.

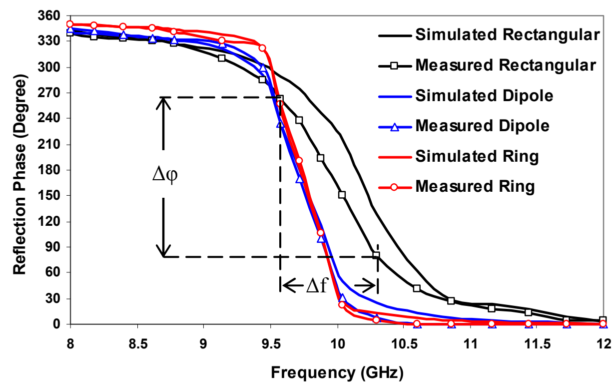

Figure 6. Static phase range performance of reflectarray resonant elements based on a linear material

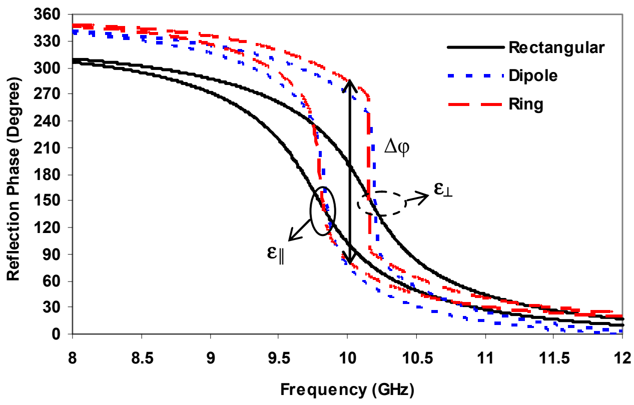

Figure 7. Dynamic phase range performance of reflectarray resonant elements based on a non-linear material

TABLE III. REFLECTION PHASE AND FOM VALUES OF DIFFERENT RESONANT ELEMENTS PRINTED ON ROGERS

Resonant Element	Static Phase Range (°)		FoM (°/MHz)	
	Simulated	Measured	Simulated	Measured
Rectangular	190	200	0.27	0.31
Dipole	255	285	0.44	0.48
Ring	295	310	0.49	0.52

This minor discrepancy is due to the high loss performance of measured results which increases the slope of reflection phase and overall phase range.

A change in dielectric constant of non-linear dielectric materials can also cause a significant change in resonant frequency [12] which is known as the frequency tunability. Rectangular, dipole and ring elements have different reflecting sizes therefore these elements also have different frequency tunability performance. Table IV summarizes the dynamic phase range and frequency tunability values for all three resonant elements. It has been shown from Table IV that rectangular element offers a higher frequency tunabiltity of 372 MHz as compared to dipole and ring elements which offer 364 MHz and 360 MHz respectively. This is due to the fact that wider reflecting area of rectangular element allows most of the incident signals reflect back and attains a higher frequency tunability.

TABLE IV. DYNAMIC PHASE RANGE AND FOM VALUES OF DIFFERENT RESONANT ELEMENTS PRINTED ON K-15 NEMATIC

Resonant Element	Dynamic Phase Range (°)	Frequency Tunability (MHz)
Rectangular	90	372
Dipole	190	364
Ring	200	360

V. CONCLUSION

A detailed analysis based on different reflectarray resonant elements printed on linear and non-linear materials respectively, is presented in this work. Different types of resonant elements such as rectangular, dipole and ring can enhance the performance of reflectarray antenna in terms of wider phase ranges and lower losses. It has been observed that in order to enhance the reflection phase range of reflectarray antenna, an element with narrower reflecting area can be used. Linear materials are good for fixed reflectarray response whereas non-linear materials have dynamic reflectarray response but at the cost of higher reflection losses. Furthermore a non-linear dielectric material offers rapid dynamic phase change behavior for designing an electronically tunable reflectarray antenna. The static and dynamic phase range performance of different reflectarray resonant elements discussed in this work is required particularly for beam steering applications in radar and satellite communication systems.

ACKNOWLEDGMENT

We would like to thank the staff of Wireless and Radio Science Centre (WARAS) of University Tun Hussein Onn Malaysia (UTHM) for the technical support.

REFERENCES

[1] J. Huang, and J. Encinar, Reflect Array Antennas, Wiley Inter Science, USA, ISBN 978-0-470-08491-5, 2007.

[2] M. Y. Ismail and M. Inam, “Analysis of Design Optimization of Bandwidth and Loss Performance of Reflectarray Antennas Based on Material properties”, Modern Applied Science, January 2010, Vol. 4, No. 1, pp. 28-35.

[3] C. A. Balanis, Antenna Theory Analysis and Design, 3rd edition ISBN 0-471-66782-X. copyright @ 2005 John Willey and Sons.

[4] 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 January 2011.

[5] A. Moessinger, C. Fritzsch, S. Bildik, R. Jakoby, “Compact Tunable Ka-Band Phase Shifter based on Liquid Crystals”, Microwave Symposium Digest (MTT), 2010 IEEE MTT-S International.

[6] H. Kamoda, T. Kuki, H. Fujikake, and T. Nomoto, “Millimeter-wave Beam Former Using Liquid Crystal”, 34th European Microwave Conference - Amsterdam, 2004 pp. 1141-1144.

[7] M. Golio, J. Golio, “RF and Microwave Passive and Active Technologies”, 2nd edition CRC Press, ISBN-10: 0849372208, 2007.

[8] D. Dunmur, A. Fukuda, G. Luckurst, “Physical Properties of Liquid Crystals: Nematics”, IEE Inspec publication 2001, ISBN 0 85296 784 5.

[9] M. Y. Ismail and R. Cahill, “Beam Steering Reflectarrays Using Liquid Crystal Substrate”, Tenth IEEE High Frequency Postgraduate Student Colloquium, 5 & 6 September 2005. University of Leeds, pp. 62-65.

[10] J. Huang, “Analysis of microstrip reflectarray antenna for microspacecraft applications”, Spacecraft Telecommunications Equipment Section, TDA Progress Report, pp: 42-120.

[11] M. Y. Ismail, M. F. M. Shukri, Z. Zakaria, A. F. M. Zain, “Investigation of Static Phasing Distribution Characteristics of Passive Reflectarray Antenna Elements”, PIERS Proceedings, Moscow, Russia, August 18-21, 2009.

[12] M. Y. Ismail, M. Inam and A. M. A. Zaidi “Reflectivity of Reflectarrays based on dielectric substrates” American J. of Engineering and applied Sciences 3 (1): ISSN 1941-7020, 2010, pp. 180-185.