Phase Distribution Analysis of Reflectarrays Based on Isotropic and Anisotropic Substrate Materials

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Abstract

Reflectarray antennas provide a low cost and low profile way for different type of applications, but their use is limited particularly in satellite and earth observatory systems, due to limited phase ranges and high reflection loss performance. In this paper an X band rectangular patch reflectarray constructed on 1mm thick isotropic and anisotropic substrates is proposed to be employed as a dynamic phase control strategy for terrestrial systems. A number of isotropic and anisotropic materials, including liquid crystals, have been used to investigate the tunability capability of reflectarray antenna design. A detailed analysis of reflection losses, static and dynamic phase ranges with respect to dielectric constant and dielectric anisotropy are presented for different substrate materials. The preliminary analysis results demonstrate that Teflon and Polystyrene are observed to offer minimum reflection losses of 0.026dB and 0.0159dB for isotropic and anisotropic materials respectively compared to Silicon and Zircon which generate wider static and dynamic phase ranges of 215° and 315° and a minimum figure of merit (FoM) value of 0.14°/MHz and a maximum dielectric anisotropy of 3.4 respectively. Moreover it is also shown that an increase in dielectric anisotropy can also rise the dynamic phase and resonant frequency ranges. The dielectric isotropic and anisotropic properties of materials presented in this work are shown to considerably affect the reflection loss and phase range of reflectarray antenna performance particularly for rapid dynamic phase change of satellite and earth observatory systems.

Keywords: Anisotropic, dielectric anisotropy, dynamic phase range, figure of merit, isotropic, reflectarray, reflection loss, resonant frequency.

1. INTRODUCTION

Reflectarray antenna consists of printed reflecting elements on a flat surface and an illuminating feed antenna [1]. The printed reflectarray combines some of the best features of microstrip array antenna and the traditional parabolic reflector antenna. It can be designed to have very high gain with relatively good efficiency, as well as to have its main beam tilted/scanned to large angles from its broadside direction [2]. Such an antenna would be an attractive option for mobile communications, satellite communication and radar beam scanning systems [3]. Recently, some potential applications of reflectarrays in space have also been registered, such as counter beam antennas for direct broadcast satellites and very large inflatable antennas [1]. Apart from these advantages however the bandwidth and the loss performance of reflectarrays are considered as the main performance limitation of the reflectarray antennas. The narrow bandwidth is mainly due to the differential spatial phase delays [4]. These limitations can be decreased by the selection of a proper dielectric substrate [5]. Many researchers have been working on the investigation of alternative materials for the realization of efficient low-loss radiating systems at millimeter frequencies but it requires minimal increase in cost [6]. This work provides a thorough study on different substrate materials, used in X-band reflecarrays, based on isotropic and anisotropic material properties.

1.1 Isotropic Materials

An isotropic material is one such that the dielectric permittivity ε and permeability μ, are uniform in all directions of the medium [7]. The materials that do not change their properties by the influence of any external effect are isotropic materials [15]. Table 1(a) shows some isotropic materials that are used for the reflectarray antenna design.

Table 1(a): Isotropic materials with dielectric permittivity and loss tangents [7], [8]

Isotropic Materials	ε_r	Tan δ
Teflon	2.1	0.0004
Roger5880	2.2	0.0004
Roger5870	2.33	0.0012
Milar	3.1	0.003
CEM	4.5	0.025
Mica	5	0.0003
Arlon AR600	6	0.0035
Alumina 99.5%	9.9	0.0001
Silicon	12	0.005

Table 1(b): Anisotropic materials with dielectric permittivity and dielectric anisotropy [4], [7], [9]

Anisotropic Materials	ε_r Perpendicular	ε_r Parallel	Dielectric Anisotropy
ABS	2.9	3.4	0.5
Polycarbonate	2.9	3.8	0.9
Polystyrene	2.4	2.7	0.3
PPO	2.4	3.1	0.7
BL006	2.2	2.38	0.18
BL037	2.25	2.45	0.2
K15 Nematic	2.1	2.27	0.17
LC-B1	2.6	3.05	0.45
Polypropylene	2.3	2.9	0.6
Corderite	4.5	5.4	0.9
Procelain dry	6	8	2
Procelain wet	6	7	1
Zircon	7.1	10.5	3.4
Steatite	5.5	7.5	2

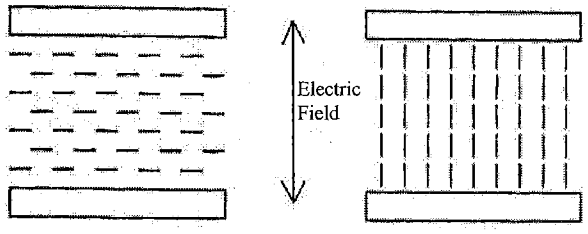

Fig. 1 Alignment of Molecules of anisotropic material without and with external DC voltage [14]

1.2 Anisotropic Materials

The materials that are being directionally dependent are anisotropic materials. Anisotropy means materials which have variation in values of a property in any direction [15]. Table 1(b) shows some anisotropic materials that are used in designing X-band reflectarray antenna. A dielectric anisotropic material is such that, dielectric permittivity ε, varies in one direction of medium [7]. Materials with large tunability of dielectric properties and low loss in the microwave region are required for the microwave engineering industry with application areas in telecommunications, remote sensing and global navigation systems [10]. It is possible to vary the dielectric permittivity of anisotropic materials simply by applying a DC 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 [11] as shown in Fig. 1. The difference between maximum and minimum value of dielectric permittivity is called dielectric anisotropy of material as given in Equation (1) [15]. The tunability capability in dielectric permittivity is required in order to realize dynamic phase distribution of reflectarrays.

$$\Delta\varepsilon_r = \varepsilon_{r\parallel} - \varepsilon_{r\perp} \tag{1}$$

2. REFLECTARRAY DESIGN

Different types of substrate materials, including isotropic and anisotropic, listed in Table 1(a) and Table 1(b) respectively, are used to design a rectangular patch reflectarray at X band, resonating at 10 GHz. Series of simulations of rectangular patch reflectarray have been performed in CST MWS computer model in order to characterize the reflectivity phenomenon of reflectarray patch element, based on reflection loss and reflection phase curves.

3. RESULTS AND DISCUSSION FOR ISOTROPIC MATERIALS

3.1 Reflection Loss

Fig. 2 shows the reflection curves of isotropic materials, which illustrates that Teflon is observed to offer minimum reflection loss value of 0.026dB followed by Alumina99.9% and Mica which offers the reflection losses of 0.047dB and 0.083dB respectively. This is because Teflon has very low values of loss tangent and dielectric permittivity as compared to the other materials as shown in Table 1(a). The difference in the reflection loss values for different materials is due to the difference in the reflectivity of reflectarrays as discussed in [5]. Table 2 shows the reflection loss values of all isotropic materials used for reflectarray simulation in CST MWS. From Table 2 it has been observed that the reflection loss increases from

0.026dB to 2.79dB as the dielectric permittivity increased from 2.1 to 12.

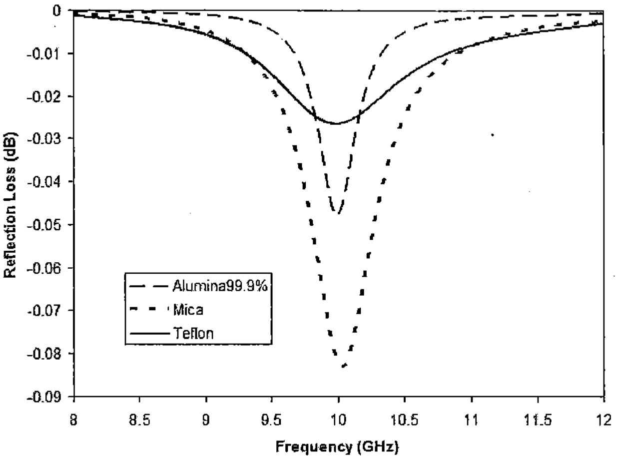

Fig. 2 Reflection loss curves of isotropic materials

Table 2: Reflection loss values of different isotropic substrate materials used for reflectarray design

Isotropic Materials	ε_r	Reflection Loss (dB)
Teflon	2.1	0.026
Roger5880	2.2	0.124
Roger5870	2.33	0.174
Milar	3.1	0.557
CEM	4.5	7.99
Mica	5	0.083
Arlon AR600	6	1.13
Alumina 99.5%	9.9	0.047
Silicon	12	2.79

3.2 Static Phase Range and Bandwidth

Another important parameter that can be used to analyze the reflectivity of reflectarrays is reflection phase performance. The reflection phases for some isotropic materials that can be used for reflectarray antenna designed at 10 GHz constructed above a 1mm substrate thickness are shown in Fig. 3. The slope of the reflection phase versus reflection frequency curve is a measure of the bandwidth of reflectarrays [12]. The steeper the slope of the reflection phase curve the lesser will be the bandwidth of the reflectarrays. From Fig. 3 it has been observed that Teflon shows a smoother phase curve as compared to the phase curves of other two isotropic substrates. For comparison of bandwidth performances in terms of reflection phase curves 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 [16].

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

Table 3 (a) shows the static phase range and FoM values of different isotropic materials that are used as substrate for reflectarray design. From Table 3(a) it has been observed that Silicon having minimum FoM value of 0.14°/MHz, offers a maximum static phase range of 215°. Table 3(b) contains the 10% and 20% bandwidth of different isotropic materials used as substrate. It has been observed from Table 3(b), that Teflon offers a maximum 10% bandwidth of 400 MHz followed by Roger5880 and Roger5870, having bandwidth of 384 and 368 MHz respectively. This is because these materials have lower values of dielectric permittivity which can also affect the bandwidth performance. It has been observed from Fig. 4 that as dielectric permittivity increases from 2.1 to 12 the bandwidth decreases from 400MHz to 100MHz.

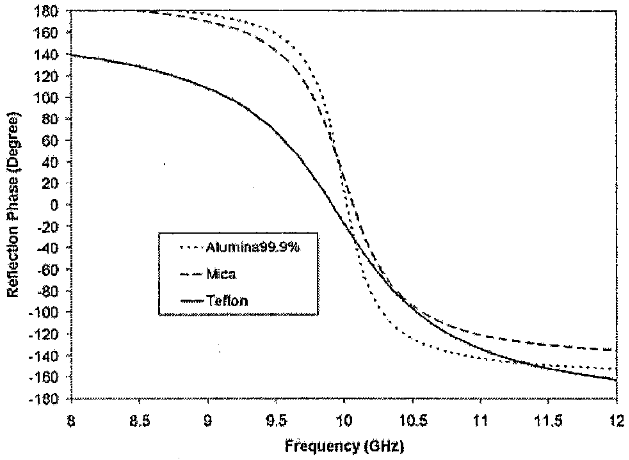

Fig. 3 Static Phase Range of isotropic materials

Table 3(a): Static phase Range and FoM of different isotropic substrate materials

Isotropic Materials	Phase Range (°)	FoM (°/MHz)
Teflon	190	0.29
Roger5880	190	0.27
Roger5870	195	0.16
Milar	210	0.53
CEM	190	0.15
Mica	210	0.45
Arlon AR600	175	0.35
Alumina 99.5%	150	0.26
Silicon	215	0.14

Table 3(b): Bandwidth of different isotropic substrate materials

Isotropic Materials	Bandwidth 10% (MHz)	Bandwidth 20% (MHz)
Teflon	400	588
Roger5880	384	560
Roger5870	368	548
Milar	292	432
CEM	188	272
Mica	200	292
Arlon AR600	172	252
Alumina 99.5%	116	172
Silicon	100	148

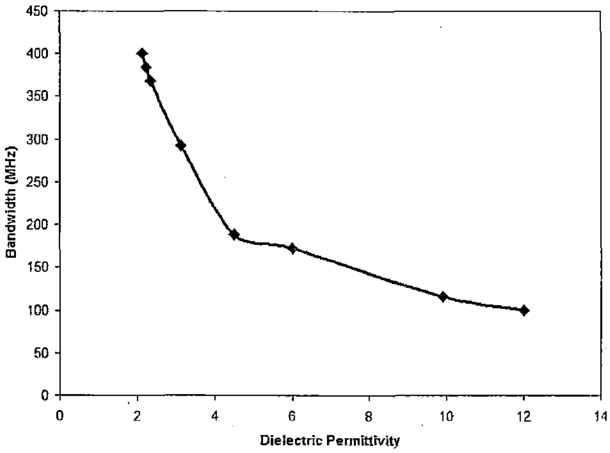

Fig. 4 Dielectric permittivity Vs Bandwidth of different isotropic substrates

4. RESULTS AND DISCUSSION FOR ANISOTROPIC MATERIALS

4.1 Reflection Loss

As described earlier anisotropic materials have a range of dielectric permittivity values according to the alignment of their molecules with respect to the incident field as shown in Table 1(b). In this work, the minimum and maximum dielectric permittivity values are considered for each material, therefore each material holds two different values for reflection loss, centered at 10 GHz. The reflectivity performance of reflectarray antenna for selected anisotropic materials is shown in Fig. 5. As depicted in Fig. 5, it has been observed that polystyrene offers a minimum reflection loss values of 0.0159dB and 0.0492dB for their maximum and minimum dielectric permittivity values respectively, followed by polypropylene and PPO which have 0.081dB – 0.071dB and 0.067dB – 0.104dB values respectively. This is because these materials have lower values of dielectric permittivity, as shown in Table 1(b). Table 4 contains the reflection loss values of all anisotropic substrate materials including some liquid crystals, used for reflectarrays.

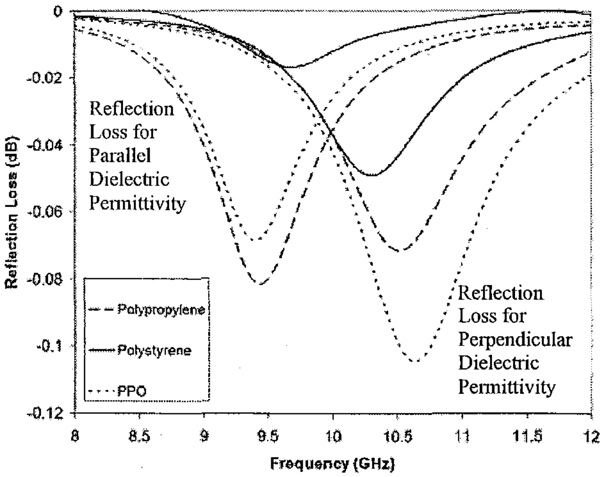

Fig. 5 Reflection loss curves of anisotropic materials

Table 4: Reflection loss values of different anisotropic substrate materials used for reflectarray design

Anisotropic Materials	Dielectric Anisotropy	Reflection Loss $\varepsilon_{r\perp}$ (dB)	Reflection Loss $\varepsilon_{r\|}$ (dB)
ABS	0.5	3.376	0.96
Polycarbonate	0.9	1.761	0.135
Polystyrene	0.3	0.0492	0.0159
PPO	0.7	0.104	0.067
BL006	0.18	8.306	5.37
BL037	0.2	7.11	3.76
K15 Nematic	0.17	10.74	9.09
LC-B1	0.45	3.54	1.22
Polypropylene	0.6	0.071	0.081
Corderite	0.9	11.613	3.397
Procelain dry	2	6.78	0.111
Procelain wet	1	3.268	2.1
Zircon	3.4	3.024	0.0892
Steatite	2	0.12	0.07

It is clearly observed from Table 4 that parallel component of dielectric permittivity offers overall low values of reflection loss as compared to the perpendicular component.

4.2 Dynamic phase Range and Bandwidth

As anisotropic materials cover a range of dielectric permittivity values, the possibility of realizing a variation in the phase distribution has been further investigated based on dynamic phase range. Therefore by changing the value of dielectric permittivity of anisotropic materials a wider phase range is achievable. Dynamic phase range can be defined as

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

Dielectric permittivity of anisotropic materials can be changed by simply applying a DC voltage across the substrate as described in [11]. The dynamic phase range of materials is a measure of dielectric anisotropy. The maximum phase variations of the reflected signal occur at frequencies close to resonance. The dielectric anisotropy is often used as figure of merit for anisotropic materials [13]. The dynamic phase ranges for some anisotropic materials that can be used for design at 10 GHz center frequency with 1mm substrate thickness, are shown in Fig. 6. The results as depicted in Fig. 6 shows that Zircon has a wider dynamic phase range of 315° with a maximum value for dielectric anisotropy of 3.4 followed by the Steatite and Procelain dry having dynamic phase ranges of 295° and 290° respectively, with dielectric anisotropy of 2. Table 5(a) summarizes the results of dynamic phase range with dielectric anisotropy for all the anisotropic materials that are used as substrate, including some liquid crystals. As shown in Table 5(a), it can be observed that dynamic phase range increases from 90° to 315° with an increase in dielectric anisotropy from 0.17 to 3.4. The summary of the relationship between dynamic phase change and bandwidth performance is shown in Fig. 7. Table 5(b) shows the range of operational frequencies or bandwidth for all anisotropic substrate materials along with their dielectric anisotropy, it can be observed from here that Zircon has a maximum bandwidth of 1.916 GHz followed by Steatite and Procelain dry which having bandwidth of 1.687 GHz and 1.535 GHz respectively, this is because these materials have higher values of dielectric anisotropies. The results shown in Fig. 7 demonstrate that bandwidth increases from 0.377GHz to 1.916GHz with an increase in dielectric anisotropy of materials from 0.17 to 3.4.

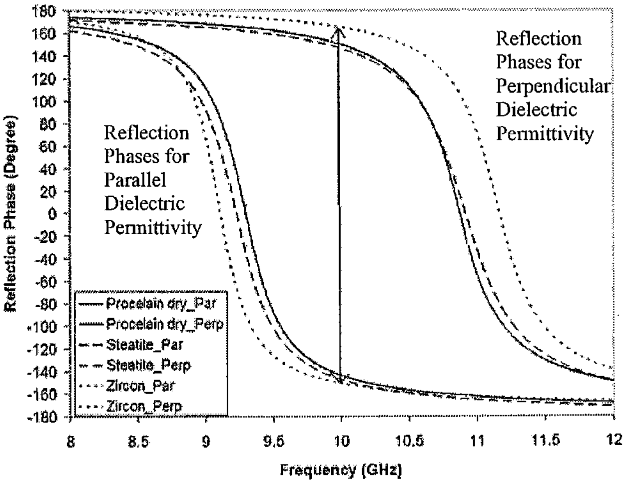

Fig. 6 Dynamic Phase Range of Anisotropic Materials

Table 5(a): Dynamic Phase Range of different anisotropic substrate materials

Anisotropic Materials	Dielectric Anisotropy	Phase Range (°)
ABS	0.5	175
Polycarbonate	0.9	230
Polystyrene	0.3	120
PPO	0.7	210
BL006	0.18	90
BL037	0.2	95
K15 Nematic	0.17	90
LC-B1	0.45	165
Polypropylene	0.6	190
Corderite	0.9	245
Procelain dry	2	290
Procelain wet	1	255
Zircon	3.4	315
Steatite	2	295

Table 5(b): Bandwidth of anisotropic substrate materials

Anisotropic Materials	Dielectric Anisotropy	Bandwidth (GHz)
ABS	0.5	0.775
Polycarbonate	0.9	1.36
Polystyrene	0.3	0.61
PPO	0.7	1.24
BL006	0.18	0.387
BL037	0.2	0.397
K15 Nematic	0.17	0.377
LC-B1	0.45	0.77
Polypropylene	0.6	1.066
Corderite	0.9	0.898
Procelain dry	2	1.535
Procelain wet	1	0.873
Zircon	3.4	1.916
Steatite	2	1.687

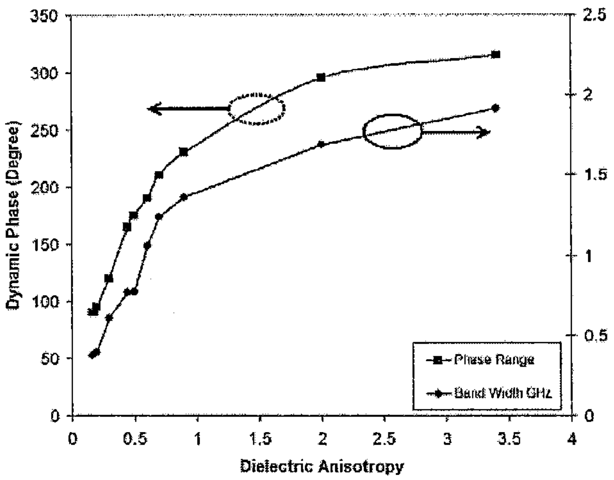

Fig. 7 Dynamic Phase and Bandwidth Vs dielectric anisotropy of anisotropic materials

5. CONCLUSION

The results obtained from Finite Integral Method analysis, demonstrate that the losses in the dielectric substrate of the reflectarray can be optimized by the selection of a proper dielectric material. A suitably selected material can also increase the bandwidth performance of reflectarray. It has been shown that materials having low dielectric permittivity values offer low losses and higher bandwidths. Dielectric anisotropic materials offering the rapid dynamic phase change behavior and wider bandwidths which are essential for designing a tunable reflectarray antenna that plays an important role in the field of satellite and earth observations. Moreover it has also been shown that different material properties including the dielectric anisotropy are shown to be a crucial factor to achieve an optimized reflection loss performance with enhanced phase and bandwidth characteristics.

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