Chapter 5

A metasurface-based broadband non-dispersive cross polarization converter for far infrared region

5.1 Introduction

Polarization is one of the most important characteristics of electromagnetic wave which plays an important role in several radio or optical devices such as radar remote sensing, optical fibre communication and imaging applications [91-93]. Conventionally the polarization state of an electromagnetic wave is controlled by the birefringence effect of anisotropic material which provides a retarding phase to one component referred to its orthogonal counterpart [94]. However, due to bulky size, narrow bandwidth and high losses these conventional polarizers restrict their applications in miniaturised electronic design. Such problem can be resolved using metasurfaces which enables to properly optimize the dimensions of the structure through which electromagnetic properties can be tailored artificially. The transmission or reflection amplitude, direction of wave propagation, dispersion characteristics, and state of wave polarization may be artificially manipulated [95-99]. The metasurface can provide large anisotropy due to its strong resonant response which helps in reducing the thickness of the structural design to large extent [100]. Among various polarization conversion devices, linear polarization converter is significantly used. A linear cross polarization converter (CPC) rotates the polarization direction of a linearly polarized incident wave to 90^o. Owing to its key role in many practical applications, various metasurface based CPC structures have been proposed which are mainly based on chirality effect, stacked grating effect, and polarization based resonance effect [101-

105]. Due to advancement in technology and diversified applications, terahertz science and technology has been emerged out as a region of interest for many research communities globally. Although previously, few transmissive as well as reflective polarization converters at terahertz region have been reported but either they are narrowband, dispersive, sensitive to angle of incidence, or limited by compactness [106-114]. Efforts have also been made to design non-dispersive polarization converter but they are lossy and suffer from fabrication complexities [115-116]. Hence there is still growing interest in designing a broadband non-dispersive polarizer having high polarization conversion efficiency.

In this chapter, a transmissive type broadband non-dispersive cross polarization converter has been proposed which operates in the far infrared region. The structure is working as a CPC in the frequency range 10.25 THz to 22.7 THz maintaining a high polarization conversion ratio (PCR) of more than 0.95 in the complete range. The structure consists of three layers where each one of them is mutually separated by air. The top and bottom layers consist of metallic patches oriented along vertical and horizontal directions respectively to allow only one component of the incident wave to pass; thereby preventing the propagation of other orthogonal component. The middle layer is a third order fractal structure which is a modification of T-square fractal [117]. The modification is done to make the structure chiral in nature which is necessary to make the structure anisotropic. The evolution of the geometry of the middle layer has been studied to validate the most optimized structural response as a broadband CPC. The fractional bandwidth has been computed as 75.6% with respect to 16.475 THz, the centre of the frequency band of the polarization conversion bandwidth having more than 0.9 PCR value. Furthermore, the electric field has been analysed at 17 THz, close to the centre frequency of the PCR bandwidth to show that the incident linearly polarized wave has undergone orthogonal rotation. The polarization conversion characteristics of the structure is also studied under oblique incidence. The result shows that the structure behaves as cross polarization converter for both TE and TM polarizations so long as the angle of incidence is within 45^0. The structure has been further studied in the light of Brewster angle concept [118]. It has been found that for the given set of media interface, when the wave is incident at Brewster angle the structure exhibits cross polarization conversion in the range of frequency 11.5 THz to 24.2 THz. The proposed structure is compact in thickness of (~λ/5) as well as periodicity (~λ/3) with respect to the centre frequency of the polarization conversion bandwidth

5.2 Design of the structure

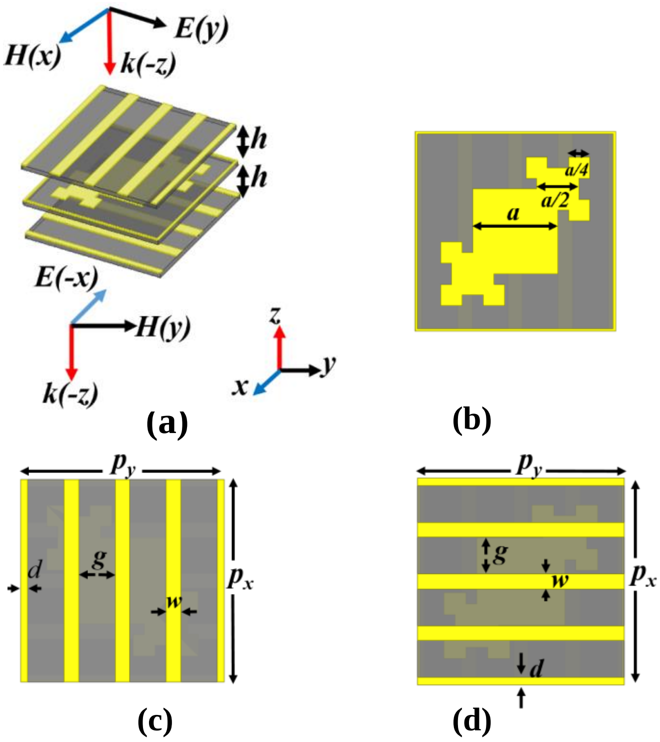

Fig. 5.1. (a) 3-D perspective view of three layered cross polarization converter (CPC) structure using metasurface along with incident electromagnetic wave directions where (b) middle layer as third order modified T-square fractal, (c) top layer with vertical strips and (d) bottom layer with horizontal strips.

The 3D perspective view of unit cell of proposed CPC structure along with electric field, magnetic field and wave vector directions is shown in Fig. 5.1(a). The proposed CPC is a three layered structure where each layer is mutually separated by air from each other as shown in

Fig. 5.1(a). The middle layer consists of a modified T-square fractal geometry of third order whose top view is shown in Fig. 5.1(b). The metallic strips at the top and bottom layers are aligned in the vertical and horizontal directions respectively as shown in Fig. 5.1(c) and Fig. 5.1(d) respectively. In the structural design, gold has been considered as metallic layer due to its good chemical stability and low ohmic losses. For each of the plate, ZnSe has been chosen as dielectric due to its optimized mechanical and thermal properties at infrared frequency regime. The dielectric constant of ZnSe in the desired frequency range is taken from the well-known experimental results. All the metallic structures possess thickness of 0.15 µm whereas each of the dielectric plate is 0.25 µm thick. The periodicity of the unit cell is $p_x = p_y = 8.0$ µm. The other geometrical dimensions of the unit cell as shown in Fig. 5.1 are optimized as h = 2.12 µm, a = 3.4 µm, g = 1.42 µm, w = 0.582 µm, d = 0.291 µm.

The design of the middle layer has been optimized to achieve a broadband linear polarization conversion of incident wave. The evolution of the middle layer's fractal geometry along with the effect on polarization conversion bandwidth is depicted in Table 5.1. Initially, the middle layer is considered as an array of square patch which is non-chiral in nature and hence does not offer anisotropy which is much needed for polarization conversion [119]. Chirality and anisotropy can be achieved by increasing the order of the geometry to 2nd for which polarization conversion from 14.8 THz to 19.8 THz has been achieved. For the 3rd order fractal geometry, a maximum polarization conversion bandwidth between 10.25 THz to 22.7 THz has been realized. Increasing the chirality to 4th fractal order however results in decrease of the polarization conversion bandwidth. This is due to the fact that increasing the fractal order increases the mutual coupling between the closely spaced metallic patches which can significantly decrease the resonating bandwidth of the whole structure. The design of the middle layer has been optimized to achieve a broadband linear polarization conversion of incident wave.

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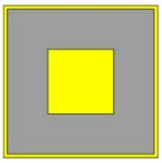
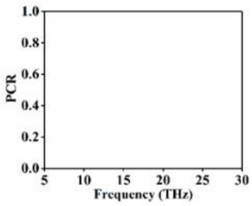
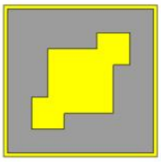
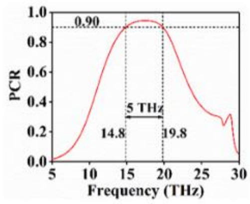
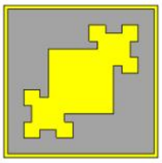
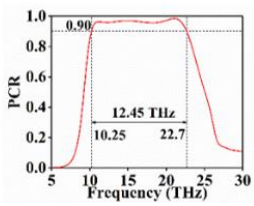
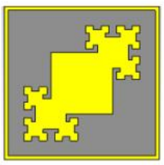
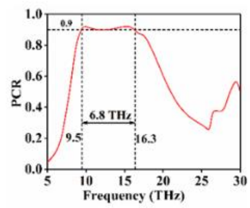
Table 5.1 Evolution of Geometry of The Middle Plate of The Structure

Fractal Order	PCR response	Comments
 1st		No polarization conversion observed
 2nd		Polarization conversion observed between 14.8 - 19.8 THz
 3rd		Polarization conversion observed between 10.25 - 22.7 THz
 4th		Polarization conversion observed between 9.5 - 16.3 THz

5.3. Simulated results

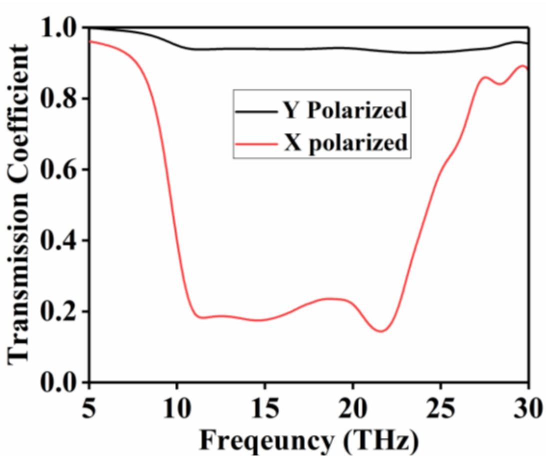


Fig. 5.2. X and Y polarized transmission coefficient response of the proposed CPC structure whose unit cell is shown in Fig. 5.1.

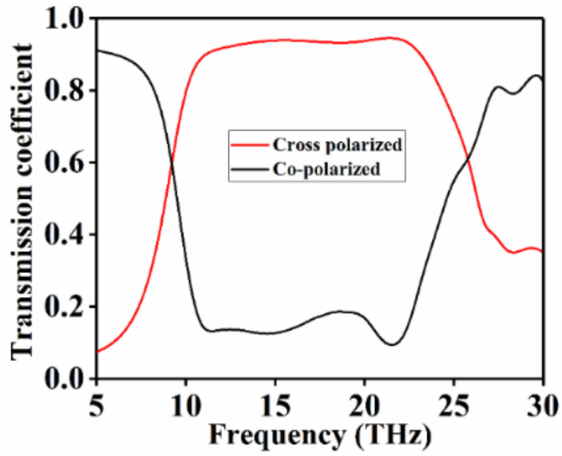
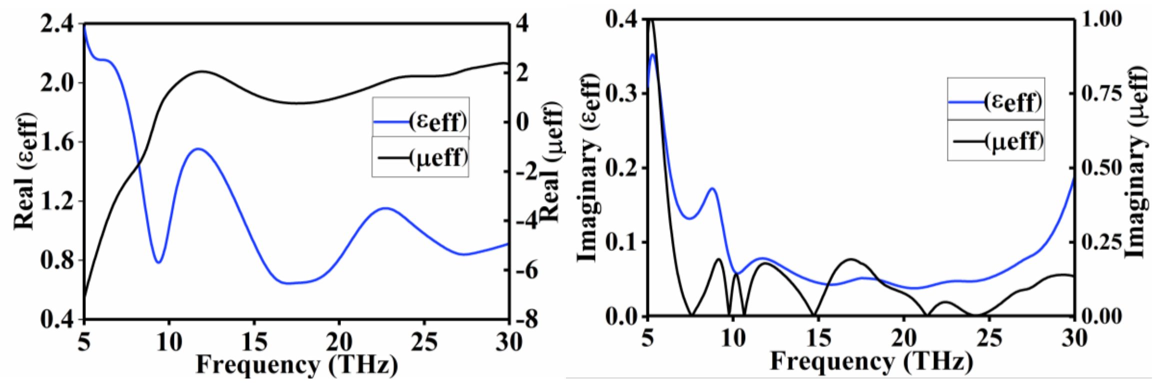


Fig. 5.3. Co and cross-polarized transmission coefficient responses of proposed CPC structure whose unit cell is shown in Fig. 5.1.

The proposed structure whose unit cell is shown in Fig. 5.1(a) is simulated using CST Microwave Studio under periodic boundary conditions. The transmission coefficients of X and Y polarized wave at the top layer is shown in Fig. 5.2. It is well evident from Fig. 5.2 that the structure allows only Y polarized wave to pass leaving X polarized waves totally reflected. For the X-polarized incident wave, the metallic strips are in same orientation; thereby making the transmitted wave evanescent in nature [121]. On the contrary, the Y-polarized incident wave being orthogonal to the metallic strips at the top plate can easily be transmitted as evident from Fig. 5.2. The transmitted field interacts with the middle layer comprising T-square fractal structure and only the X- polarized component of the outgoing transmitted field can be observed at the output end; thereby blocking the transmission of Y-polarized component. This phenomenon is nothing but the cross polarization conversion of the wave as it passes through the structure. The above physics is shown graphically as co-polarized and cross-polarized transmission responses in Fig. 5.3, which shows that cross polarization conversion of wave has taken place significantly between 10.25 THz to 22.7 THz. The fractional bandwidth with more than 0.9 PCR value has been evaluated as 75.6%.



(a) (b)

Fig. 5.4. Variations of (a) real and (b) imaginary parts of effective permittivity and permeability with respect to frequency.

From the co-polarized reflection and transmission coefficients, the effective medium parameters i.e., effective permittivity and effective permeability have been computed. The real and imaginary parts of computed parameters are illustrated in Fig. 5.4(a) and Fig. 5.4(b) respectively. The real and imaginary parts of the effective medium parameters are shown in Table II at three distinct frequencies of the band viz. 12 THz, 17 THz and 22 THz. They are found to be nearly equal to each other at all these frequencies; thereby satisfying impedance matching condition corresponding to incident wave.

Table 5.2. Constitutive parameters at three different frequencies of the polarization conversion bandwidth

Frequency (THz)	Real Part		Imaginary part	
	ε_{eff}	μ_{eff}	ε_{eff}	μ_{eff}
12	1.50	1.70	0.08	0.15
17	0.61	0.95	0.07	0.13
22	1.10	1.60	0.06	0.05

Furthermore, presence of small imaginary part of constitutive parameters corresponds to small imaginary refractive indices $n'_{eff} < n_{eff}$ signifying that the wave has not undergone decay during its progress. This is one of the reasons for achievement of high PCR of the structure. The polarization conversion property of the structure is determined in terms of polarization conversion ratio (PCR). The PCR of the structure is calculated from equation (5.1) where t_{xy} and t_{yy} are the cross-polarized and co-polarized transmission coefficients [122].

$$PCR = \frac{t_{xy}^2}{t_{xy}^2 + t_{yy}^2} \tag{5.1}$$

The frequency response of PCR is shown in Fig. 5.5. It is evident from the curve that the structure maintains a high PCR value of more than 0.95 in the entire frequency band between 10.25 THz to 12.27 THz.

The electric field orientation of the incident wave at the top layer and the transmitted wave from the bottom layer at 17 THz are shown in Fig. 5.6. It is clear from Fig. 5.6 that the wave incident at the top surface gets converted into its mutually orthogonal component during the transmission.

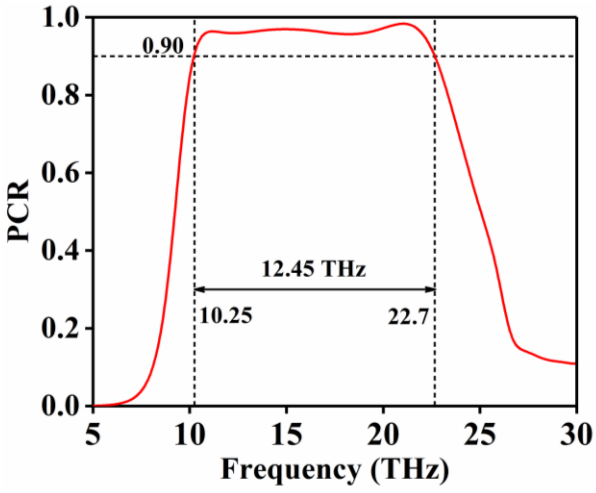


Fig. 5.5. PCR response of proposed CPC structure whose unit cell is shown in Fig. 5.1

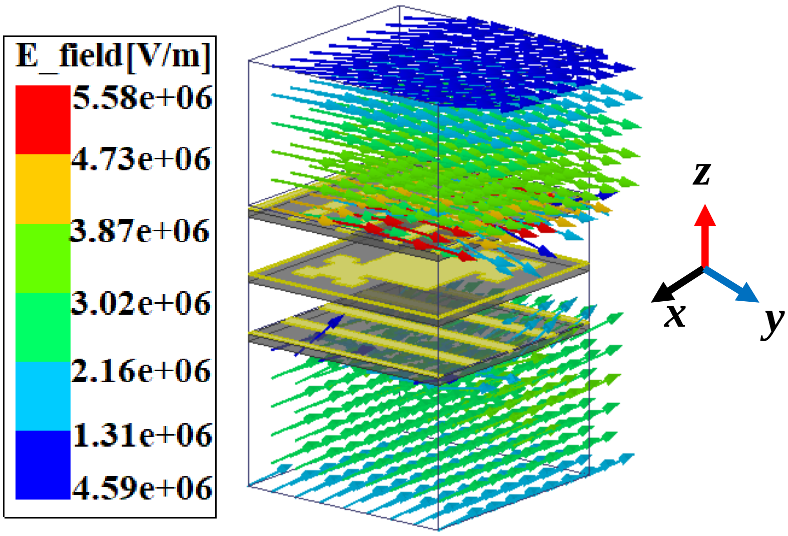


Fig. 5.6. Electric field of incident and transmitted waves of proposed CPC structure whose unit cell is shown in Fig. 5.1 at 17 THz.

The angle difference between the co-polarized and cross-polarized components in the entire frequency range is calculated as shown in Fig. 5.7. It is observed from Fig. 5.7 that the angle among the co-polarized and cross-polarized wave is close to 90º within the entire range of 10.25 THz to 22.7 THz which confirms the rotation of polarization of the incident wave by 90º.

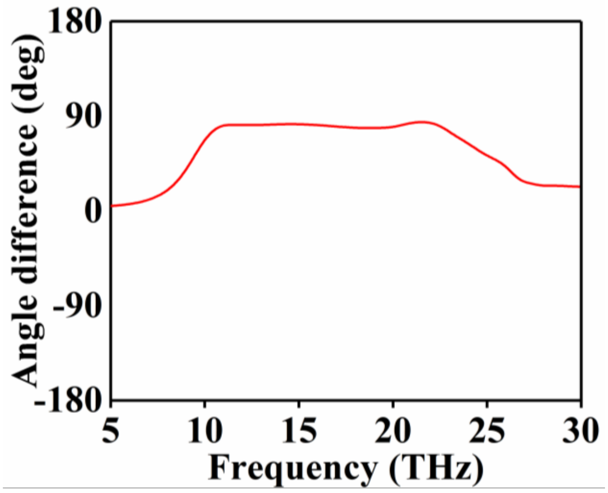


Fig. 5.7. Angle difference between the co-polarized and cross-polarized transmission coefficients of the incident wave.

5.4 Study of the structure under oblique incidences

The structure is studied for oblique incidence response under TE and TM polarization for which setup is shown in Fig. 5.8(a) and Fig. 5.8(b) respectively. The simulated PCR values under TE and TM polarizations for different θ values are shown in Fig. 5.9(a) and Fig. 5.9(b) respectively. The structure behaves as a bandwidth enhanced CPC structure up to 45° oblique incidences for both TE and TM polarization.

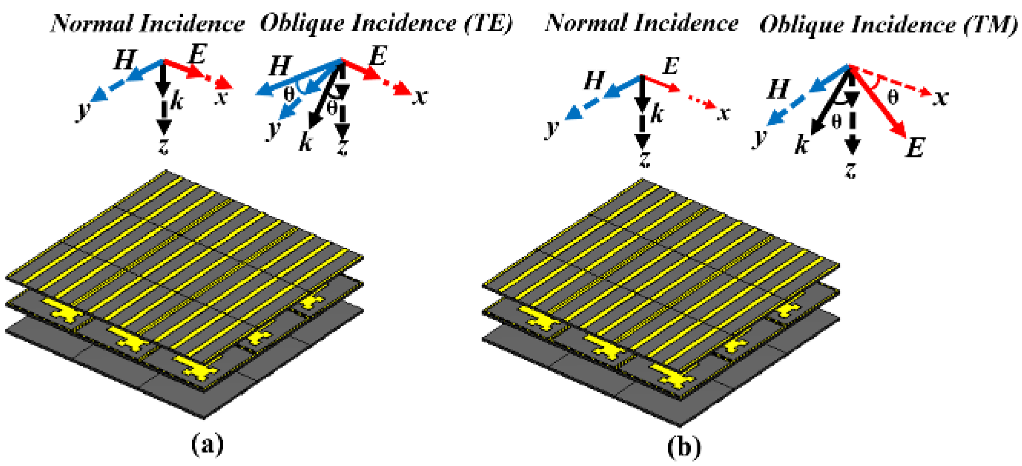


Fig. 5.8. Set-up of the oblique incidence responses under (a) TE polarization and (b) TM polarization.

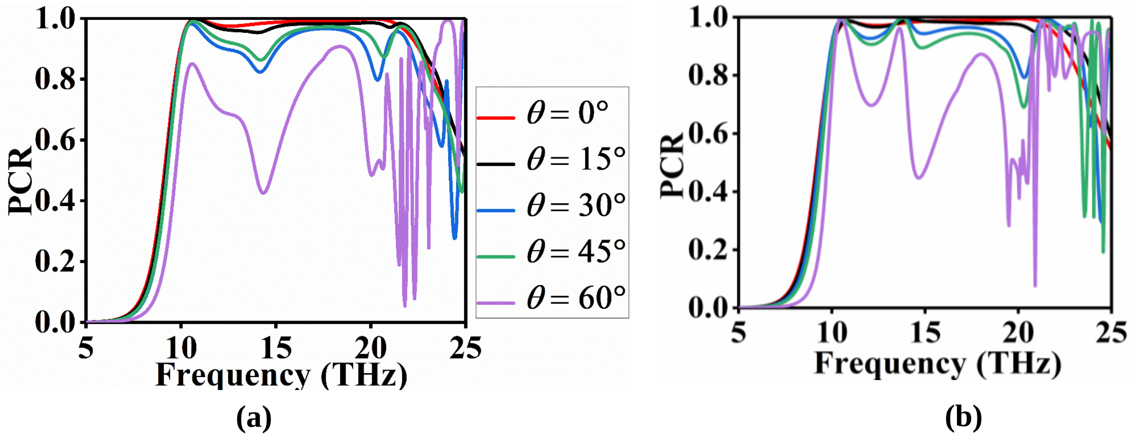


Fig. 5.9. Simulated absorptivity responses for oblique incidence response under (a) TE polarization and (b) TM polarization.

The PCR response of the proposed structure is also examined for different polarization angles where it has been found that when the polarization angle changes from ϕ =0º to ϕ =90º i.e., when the incident Y polarized component rotates to X polarized component the metallic strips oriented along *x*-direction will stop the transmission as evident from Fig. 5.10. Hence there is significant decrease in PCR response with increase of polarization angles (ϕ).

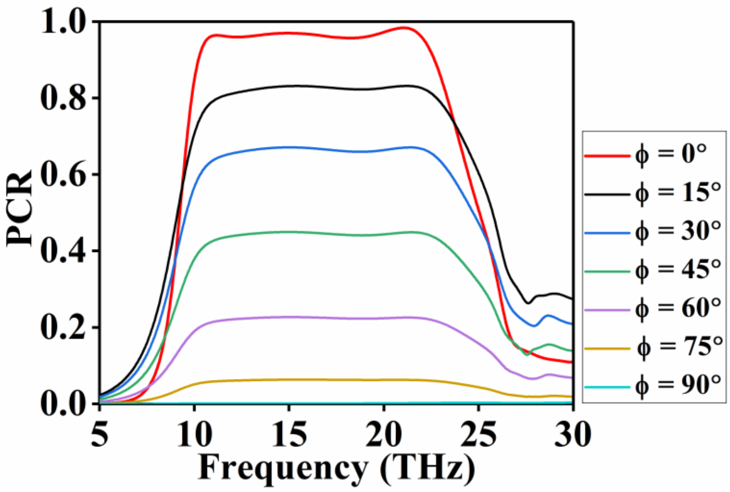


Fig. 5.10. PCR response of the structure at different polarization angles (ϕ).

The differential cross polarized transmission coefficient spectrum of the metasurface structure has been studied as shown in Fig. 5.11. The structure maintains a zero differential cross polarization transmission coefficient in the entire region of interest viz., from 10.25 THz to

22.7 THz which indicates that the cross-polarization transmission spectra of the meta device are non-dispersive in this region [123].

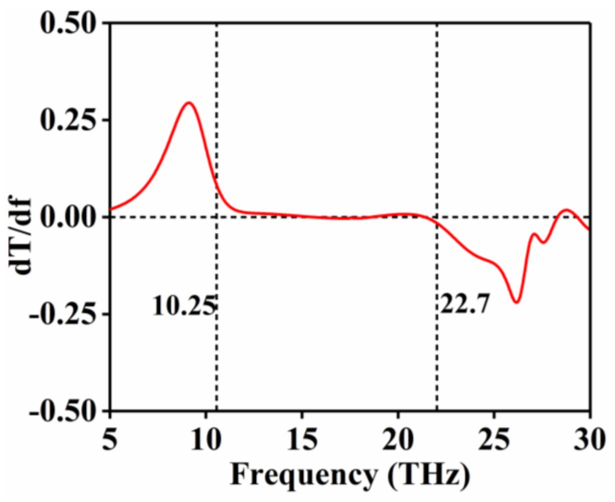


Fig. 5.11. Differentials of Cross-polarization transmission coefficients with frequency.

5.5. Polarization conversion under Brewster's angle incidence

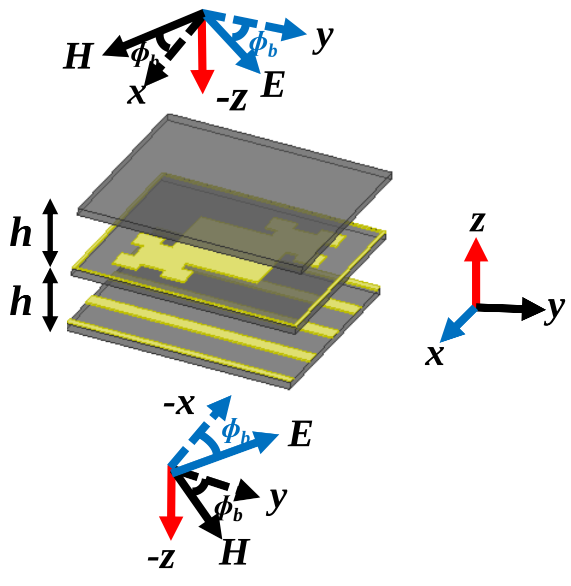


Fig. 5.12. 3-D perspective view of modified three layered cross polarization converter (CPC) structure along with incident electromagnetic wave directions considering Brewster angle incidence.

The structure has also been studied in the light of Brewster angle concept. The 3-D perspective view of the modified unit cell along with the direction of wave vector, electric field and magnetic field under Brewster's angle condition is shown in Fig. 5.12, where ϕ_b is the Brewster angle at which the wave is incident on the top surface. As the two media (air and ZnSe) are non-magnetic in nature, Brewster angle can be calculated by equation (5.2) where ε_1 is the relative permittivity of air is whereas ε_2 is the relative permittivity of ZnSe.

$$\phi_b = \tan^{-1}\sqrt{\frac{\varepsilon_2}{\varepsilon_1}} = 67^{\circ} \tag{5.2}$$

When an un-polarized light is incident on the top layer at 67º, then it is possible to separate two different polarization components. The structure will allow only the parallelly polarized component to pass whereas the perpendicularly polarized component will be totally reflected. The transmitted parallelly polarized component is then further rotated by 90º when it is transmitted through bottom layer. The above physics can be verified by analysing Fig. 5.13, which signifies that the structure exhibits cross polarization conversion in the range of frequency 11.5 THz to 24.2 THz. A slight shift in the transmission coefficient response has been observed which may arise due to the mutual coupling of the middle layer structure with metallic strips oriented perpendicular to incident electric field.

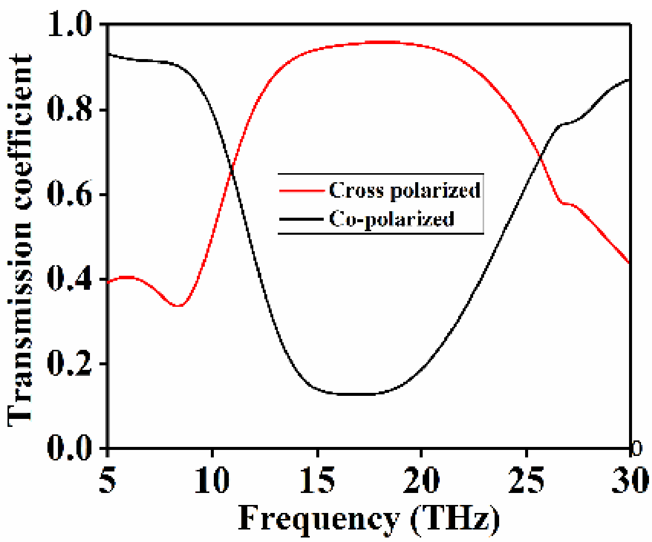


Fig. 5.13. Co-polarized and Cross-polarized transmission coefficient responses of proposed CPC structure whose unit cell is shown in Fig. 5.12.

Table 5.3. Comparison of The Performance of The Proposed Structure with Existing Cross Polarization Converter in Terahertz Region

Terahertz polarizer	PCR Bandwidth (in THz)	PCR	Periodicity
Cheng *et. al.* [21]	0.65-1.45 THz	>80%	~λ/2.5
Cong *et. al.* [22]	0.45-1.06 THz	>80%	~λ/1.3
Grady *et. al.* [23]	0.52-1.82 THz	<80%	~λ/3.7
Proposed Design	10.25-22.7 THz	>95%	~λ/2.8

The proposed design of the structure has been compared with a few existing metasurface based polarizer exhibiting cross polarization conversion as shown in Table 5.3. It is evident that the proposed design offers a broadband polarization conversion with a high PCR value over the complete range while maintaining the compactness.

5.6. Conclusion

We have proposed a non-dispersive broadband fractal CPC structure for far infrared wavelength application in this paper. The proposed polarizer is transmissive in nature which converts linear polarized wave to cross polarized by maintaining high PCR value above 0.95 in the desired band of frequency extending from 10.25 THz to 22.7 THz. The fractional bandwidth of 75.6% referred to the centre frequency of the polarization conversion bandwidth with more than 0.9 PCR value has been achieved. Further, the structure is studied for oblique incidence variations under TE and TM polarizations where it is behaving as a CPC structure with enhanced PCR bandwidth response up to 45° incident angle in both cases. A separate study on polarization conversion based on Brewster angle condition has been done in this paper. With excellent PCR response, broadband operating region and non-dispersive characteristics the proposed structure may found application in manipulating polarization states of the incident electromagnetic waves at far infrared region.