Avrupa Bilim ve Teknoloji Dergisi
Özel Sayı, 34, S. 773-777, Mart 2022
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Araştırma Makalesi

www.ejosat.com ISSN:2148-2683

European Journal of Science and Technology
Special Issue 34, pp. 773-777, March 2022
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Research Article

Metasurface Based Reflection Type Linear Polarization Conversion for X Band Applications

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(2nd International Conference on Applied Engineering and Natural Sciences ICAENS 2022, March 10-13, 2022)

(**DOI:** 10.31590/ejosat.1086520)

ATIF/REFERENCE: Ozturk, G. (2022). Metasurface Based Reflection Type Linear Polarization Conversion for X Band Applications. *European Journal of Science and Technology*, (34), 773-777.

Abstract

Polarization conversion describe the propagation behavior of the electric field component of the electromagnetic wave. Polarization converters are widely used to improve the performance of microwave devices. In recent years, polarization converters have been produced on a metasurface basis, as they have relatively great advantages over polarization converters produced by conventional methods. In this study, a metasurface-based reflection type polarization converter operating in the microwave X band is proposed. The proposed design has a linear polarization conversion rate (PCR) of over 90% in the 9.1 GHz-12 GHz frequency range. In addition, the proposed design provides linear polarization conversion performance over 80% up to 45 degrees under oblique angle. The design consists of metal termination, easily accessible FR4 and metasurface. In order to better understand the physical mechanism of the proposed metasurface-based polarization transducer, its analysis in the u-v axes was performed as well as the surface current behaviors at resonance frequencies. Since the proposed design shows the same behavior in both TE and TM modes under normal incidence, the converter behaves polarization independent. The Design CST was created in the Microwave Studio program and the simulation results were processed by the Matlab program. The results were compared with other X band polarization converters and it was seen that the proposed design is superior to existing metasurface polarization converters in oblique angle performance, single design, cost-effective and thickness.

Keywords: Metasurface, Polarization, Convertion, Lineer Polarization, X-band

X Band Uygulamaları için Metasurface Tabanlı Yansıma Tipi Lineer Polarizasyon Dönüşümü

Öz

Polarizasyon dönüştürücüler elektromanyetik dalganın elektrik alan bileşenin yayılma davranışını tanımlar elektromanyetikte. Polarizasyon dönüştürücüler mikrodalga cihazların performansının artırılması için yaygın bir şekilde kullanılmaktadır. Son yıllarda polarizasyon dönüştürücüler metayüzey temelli olarak üretilmektedir, geneleksel yöntelerle üretilen polarizasyon dönüştürücülere nispeten büyük avantajlara sahip oldukları için. Bu çalışmada metayüzey temelli mikrodalga X bandında çalışan yansıma tip polarizasyon dönüştürücü önerildi. Önerilen dizayn 9.1GHz- 12 GHz aralığında %90 üzerinde lineer polarizasyon dönüşüm oranına (PCR) sahiptir. Ayırca eğik açı altında 45 dereceye kadar %80 üzerinde lineer polarizasyon dönüşüm performansı sağlar. Dizayn metal sonlandırma, kolay erişilebilir FR4 ve metayüzeyden oluşmaktadır. Önerilen metayüzey temelli polarizasyon dönüştürücünün fiziksel mekanizmasının daha iyi anlaşılması için u-v eksenlerinde analizi yapıldı hem de rezonans frekanslarında yüzey akım davranışları incelendi. Önerilen dizayn normal geliş altında hem TE hem de TM modda aynı davranışı gösterdiği için polarizasyon bağımsız olarak davranmaktadır. Dizayn CST mikrowave Studio programında yaratıldı ve simülasyon sonuçlar Matlab programı vasıtasıyla işlendi. Sonuçlar diğer X bant polarizasyon dönüştürücüler ile karşılaştırıldı ve önerilen tasarımın mevcut metasurface polarizasyon dönüştürücülere göre eğik açı performansı, tek tasarım, uygun maliyetli ve kalınlık açısından üstün olduğu görüldü.

Anahtar Kelimeler: Metayüzey, Polarizasyon, Dönüşüm, Lineer Polarizasyon, X-bant

1. Introduction

Polarization shows the behavior of the electric field components of electromagnetic waves. Polarization is of great importance for the manipulation of electromagnetic waves and for improving the performance of microwave devices. Polarization transducers are effectively used in areas such as radar cross-section reduction, sensors, and optical communication [1]. Polarization converters obtained by traditional methods such as Faraday effect, photo-elastic modulators, optical grating and birefringence effect have disadvantages such as large volume, difficulty in production, narrow bandwidth, use only in one conversion type, and lack of oblique angle performance [2]. In order to eliminate these disadvantages, metasurface structures in polarization converters have been actively used in recent years [3]. Metasurface structures are widely used in microwave devices such as sensors [4], antenna [5], absorber [6] with their negative refractive index feature, which is not found in nature. In addition, these structures are widely used in polarization converter devices at GHz [7], THz [8] and optical frequencies [9]. Metasurface polarization converters can be used as reflective type by placing anisotropic structures [10] diagonally, or as transmitting type by using chiral structures [11]. In addition, the produced polarization converters diversified with the choice of optically transparent materials [12] such as glass, PET, good conductor materials in metasurface part such as graphene, gold [13], and dielectric materials in substrate part such as FR-4, FB-4 [14]. Metasurface-based polarization converters are also diversified from linear to linear (LP-LP) [1,14], from linear to circulara (LP-CP) [1] and from circular to circular (CP-CP) [15] according to polarization conversion types. Microwave X band is widely used in various microwave devices, such as radar [16], antenna [17], sensor [18]. In recent years, metasurface-based polarization converter designs have been made in the literature for this bandwidth [14,19-22]. It is observed that some of these works have been produced using multi structures [19] and have complex production difficulties. The oblique angle performance of some X band polarization converters [14, 19] shows sensitivity over 30 degrees. In addition, some X band polarization converters are produced with substrates such as FB-4 [14], rogers [19], which are not economically preferred. In addition, the thickness of some studies in terms of wavelength is up to 0.110 λ [14]. In order to overcome these disadvantages, a metasurface polarization converter with over 90% PCR performance for the X band applications was proposed at the 9.2 GHz - 12 GHz range in this study. The proposed design also has over 80% PCR performance up to 45 degrees under oblique angle. The proposed design is produced with easily accessible FR-4 material. The proposed design compared with other studies and it is noted that the proposed design has superior characteristics with thickness, oblique angle, substrate and single production structures compared to other studies.

2. Material and Method

The front and side views of the proposed design are as given in Figure 1(a) and figure 1(b). As seen in Figure 1, the lower part of the design consists of metal termination, the middle part consists of FR-4 substrate and the upper part consists of metasurface. Copper with a conductivity of 5.8x108 S/m was chosen as the metal. The dielectric constant of FR-4 with h=1.6 mm thickness selected as substrate is ε_r=4.3 and its loss tangent is δ=0.025. In addition, the unit cell of the metasurface polarization transducer is L=7.6 mm. Also, ri=1.6 mm, a=3.9 mm and g=0.6 mm.

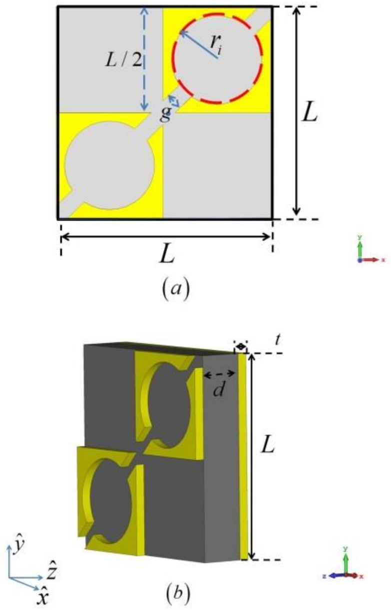


Fig. 1 (a) Front and (b) side view of proposed design

In order to understand the working principle of the polarization converter, if electromagnetic wave with y-polarized electric field intensity propogate to the metasurface polarization converter in the +z direction, the incoming wave is expressed as follows.

$$\vec{E}_i = \hat{y}E_y e^{-jkz} \tag{1}$$

The waves reflected from the metasurface polarization converter in the -z direction are expressed by electric field components as follows.

$$\vec{E}_r = (\hat{y}E_y R_{yy} + \hat{x}E_y R_{xy})e^{jkz} \tag{2}$$

For linear polarization conversion, the incoming wave with the +y polarized must be reflected as x polarized. Hence it will transform the polarization of the incoming wave as x-polarized. For the x-polarized incident wave case, the electric field component of the reflected wave must be reflected as y-polarized. If the incident wave is x and y polarized, the incident and reflected waves can be written in matrix format as follows.

$$\begin{bmatrix} \vec{E}_{rx} \\ \vec{E}_{ry} \end{bmatrix} = \begin{bmatrix} R_{xx} & R_{xy} \\ R_{yx} & R_{yy} \end{bmatrix} \begin{bmatrix} \vec{E}_{ix} \\ \vec{E}_{iy} \end{bmatrix} \tag{3}$$

Here, E^i and E^r denote the incident and reflected waves, $R_{xx} = \vec{E}_{rx}/\vec{E}_{ix}$ and $R_{yy} = \vec{E}_{ry}/\vec{E}_{iy}$ the co-reflection coefficients, and $R_{xy} = \vec{E}_{rx}/\vec{E}_{iy}$ and $R_{yx} = \vec{E}_{ry}/\vec{E}_{ix}$ the cross reflection coefficients.

Using the reflection coefficients, the polarization conversion ratio (PCR) can be obtained for the y-polarized incident wave as follows [1].

$$PCR = \frac{|R_{xy}|^2}{|R_{xy}|^2 + |R_{yy}|^2} \tag{4}$$

The PCR value for the x-polarized incident wave can be obtained by swapping the x and y indices in Equ. 3.

In order to understand the physical mechanism of the proposed design, the y-polarized incoming wave was decomposed in the u-v axes as shown in figure 2.

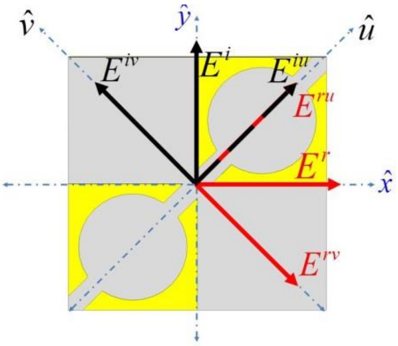


Fig. 2 Decomposing of incident and reflected field in u-v axes

For a y-polarized incoming wave to be reflected x-polarized, the component in the +u axis must be reflected in the +u direction, and the component in the +v direction must be reflected in the –v direction. In this case, E^{ru} and E^{rv} components will provide x-polarized reflection as in figure 2. Therefore, the incoming wave can be expressed as follows in the u-v axes

$$\vec{E}_i = \hat{u}\vec{E}_{iu}e^{-j\varphi_{uu}} + \hat{u}\vec{E}_{iv}e^{-j\varphi_{vv}} \tag{5}$$

The reflected wave can be expressed in the u-v axes as follows.

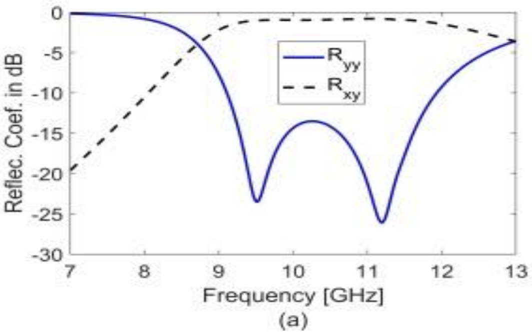
$$\begin{bmatrix}\vec{E}_{ru}\\ \vec{E}_{rv}\end{bmatrix} = \begin{bmatrix}r_{uu} & r_{uv}\\ r_{vu} & r_{vv}\end{bmatrix}\begin{bmatrix}\vec{E}_{iu}\\ \vec{E}_{iv}\end{bmatrix} \tag{6}$$

Here r_{uu} and r_{vv} are the co-reflection coefficients in the u and v directions. In order for the entire y-polarized wave to be x-polarized, its components in the +u and +v directions must be reflected in the +u and –v directions with the same amplitude. So |r_uu|=|r_vv| must be 1. Also, since the incoming wave in the +u direction is reflected in the +u direction, φ_{uu} must be 0^o. Similarly, for the incoming wave in the +v direction to be reflected in the –v direction, φ_{vv} must be $=-180^o$. Therfore, this will ensure that the angle between the two reflection components is $\Delta\varphi = 180^o$ for linear polarization conversion.

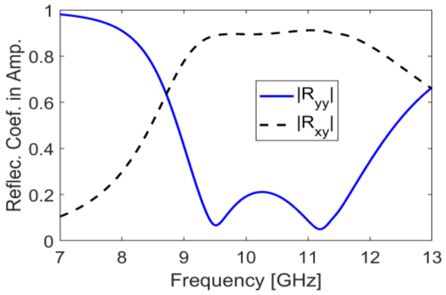
3. Results and Discussion

3.1. Simulation Results

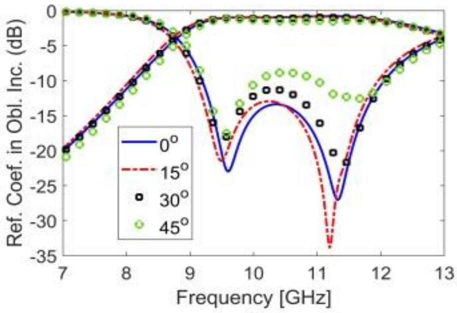
The proposed metasurface-based polarization converter was created in the CST Microwave Studio program as shown in Figure 1. The boundary conditions in the frequency domain were selected as the unit cell. Co and cross reflection coefficients under normal incidence were obtained by simulation in dB as given in figure 3(a). As seen in Figure 3(a), the metasurface resonates at the 9.5 GHz and 11.2 GHz. In addition, in figure 3(a), the co-reflection coefficient is below -10 dB and the cross-reflection coefficients are above -0.98 dB in the range of 9-12 GHz. In Figure 3(b), the co- and cross-reflection coefficients are given in amplitude. As seen in Figure 3(b), the co-reflection coefficients are below 0.218 and the cross-reflection coefficient is below 0.897 in amplitude. In Figure 3(c), the co and cross reflection coefficients are given in dB up to 45 degrees under oblique angle. As seen in Figure 3(c), co-reflection coefficients are above – 8.88 dB, and cross reflection coefficients are below -1.7 dB up to 45 degrees. In Figure 3(d), the PCR by using equation .. is given. As seen in Figure 3(d), PCR is over %90 in the 9-12 GHz range. In addition, PCR reached % 98.7 at 9.5 GHz resonance frequency and %99.6 at 11.2 GHz resonance frequency.



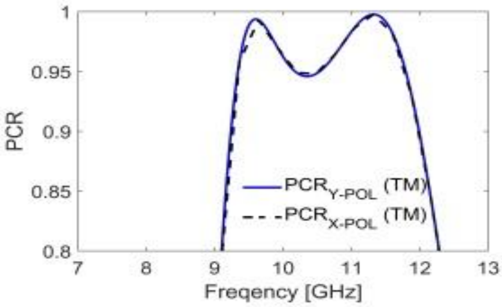
(a)



(b)



(c)



(d)

Fig. 3 Reflection coefficient of proposed design (a) in dB (b) in amplitude (c) under oblique incidence up to 45 degrees (d) PCR of proposed design

The reflection coefficients and phases in the u-v directions of the proposed design are given in figure 5(a,b). Figure 5a shows that the reflection coefficients in the u-v axes are approximately equal to 1 in the 9-12 GHz range where linear polarization is achieved. Also, Figure 5(b) shows the phase differences in the u and v directions. As seen in Figure 5(b), the phase difference in the u – v directions is approximately 180 degrees in the 9-12 GHz range.

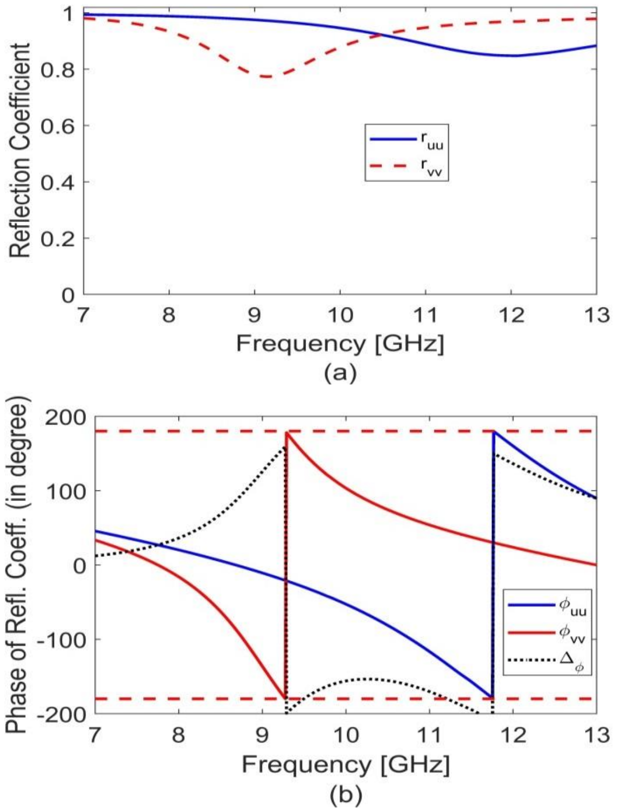


Fig. 4 Reflection coefficient of proposed design in u-v direction (a) in amplitude | (b) phase and phase differents

When the electromagnetic wave is sent to the metasurface polarization converter, electrical and magnetic polarizations are formed on the material. This polarization causes the formation of electrical and magnetic currents. In order to understand the physical mechanism of the proposed design, the surface current behaviors on the metal parts were investigated at resonance frequencies. Current behavior at resonant frequencies in the top and bottom layers of the proposed design is as given in Figure 6(a-c). In Figure 6(a-c), it is seen that the surface currents are parallel in the metasurface and metal termination parts. Also, in Figure 6(b-d), the surface currents are anti-parallel at the metasurface and metal termination parts. The anti-parallel behavior of the currents indicates that magnetic polarization occurs at these frequencies, on the contrary, the parallelism of the currents indicates that there is electrical polarization at this frequency.

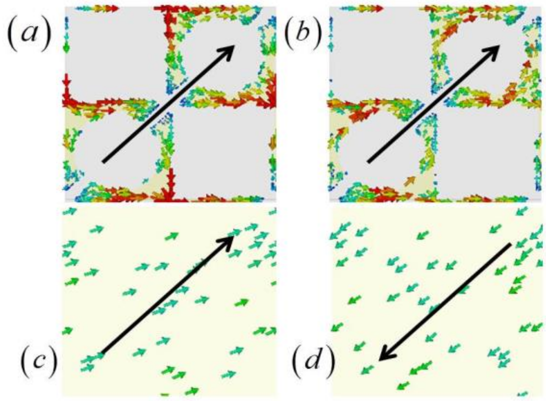


Fig. 5 Surface current distrubition (a-c) for 9.5 GHz (b-d) for 11.2 GHz

3.2. Discussion

For the analysis of linear conversion performance of the proposed design, the proposed design and other X-band polarization transducers were compared as given in Table 1. Table 1 will be used for performance analysis in terms of bandwidth, oblique angle performance, thickness, substrate type and layer thickness. Considering the studies for the X band [14,19], the proposed design provides linear polarization conversion for a wider band gap in the 9-12 GHz range than the reference [19]. For incoming wave in oblique angle condition, reference [19] shows sensitivity up to 30 degrees, while the proposed design shows sensitivity up to 45 degrees. When the studies made according to the thickness in terms of wavelength are examined, the proposed design is at least 55% less thick than the reference [14]. Therefore, the proposed design allows it to be used for applications that require thinner application. In addition, some X band applications [19] performing multiple structures increase the manufacturing complexity. In addition, the applications performed by choosing Rogers and FB-4 materials [14,19] are more expensive than the FR-4 material. Therefore, the proposed design has less complexity than ref [19] and can be produced cost-effectively according to ref [14,19].

Table 1. Comparison of the proposed design with other X band polarization converters

Ref.	**BW (GHz)**	**Angle**	**Thickness**	**Layer**
[14]	9.1-12.9	N.A	3 mm (0.110 λ)	Single (FB-4)
[19]	8.9-11.1	30°	1.27 mm (0,042 λ)	Multi (Ro4003)
Prop.	9.2-12	45°	1.6 mm (0,056 λ)	Single (FR-4)

4. Conclusions and Recommendations

In this study, a linear polarization converter operating in the 9-12 GHz band is proposed for microwave X band applications. The proposed polarization converter provides over %90 PCR at 9-12 GHz bandwidth. For this bandwidth, the design provides linear polarization for both the TE (x-polarized) and TM (y-polarized) modes, and the design behaves polarization independent. . The proposed design shows over %80 PCR performance up to 45 degrees under oblique angle of incidence. The substrate of the proposed design consist of easily accessible 1.6 mm FR-4 material. The dizayn can be used in cases where very thin applications are required with its 0,056 λ thickness. The design is achieved with a single structure and the production complexity is less than the existing studies. The proposed polarization converter was created and simulated with the CST Microwave Studio program.

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