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RESEARCH PAPER

Linear to left- and right-hand circular polarization conversion by using a metasurface structure

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By using a metasurface (MS) structure, a linearly polarized wave is converted to circularly polarized waves. Both right- and left-handed circular polarizations (RHCPs and LHCP) are obtained by a simple configuration in the proposed structure which consists of 16 unit cells arranged in a 4 × 4 layout. Each unit cell contains five horizontal and parallel strips embedded in a rectangular frame in which a single diagonal strip is placed from one corner to the opposed one. It is shown that the orientation of the diagonal line determines the handedness of the converted signal to be either LHCP or RHCP. In order to show the working conditions of the MS structure, scattering parameters are found for both co-polarized and cross-polarized responses. Axial ratio, an indicator for polarization conversion, is then obtained by dividing cross-polar response to co-polar response to demonstrate the transformation. The structure works for horizontally and vertically polarized linear waves in a wide band frequency range which is approximately 510 MHz. Since the suggested MS model is composed of a simple geometry for polarization conversion, it can be easily adjusted in any desired frequency bands for a variety of applications from the defence industry to medical, education, or communication areas.

Keywords: Antenna design, modeling and measurements, Meta-materials and photonic bandgap structures

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I. INTRODUCTION

After 30 years from Veselago's theoretical work [1] in which he theoretically showed that negative permeability and permittivity can be obtained simultaneously by using periodic structures, Pendry *et al.* and Smith *et al.* [2–4] realized such structures and successfully obtained negative refraction index. They also called these kinds of materials as metamaterials (MTMs) because of their unusual electromagnetic properties. With the realization of MTMs, the interest in these materials having distinctive electromagnetic properties has grown exponentially in both scientific and industrial fields. With their unusual electromagnetic behaviors, MTMs offer a wide variety of applications including perfect lenses, filtering, absorption, antennas, sensors, etc. [5–18]. Metasurfaces (MSs), a single-layer MTM, can be considered as two-dimensional (2D) versions of MTMs. MSs having the ability to manipulate electromagnetic wave polarizations under particular boundary conditions have focused on the control and change the direction of an EM wave. This is not only attracting the scientific community, but it has started to be used in the industrial applications such as antennas, sensors, wave polarization rotators, etc. [19–25]. MS structures have two unusual characteristics. One is the MTM property which cannot be realized by ordinary materials. The other one is the frequency selection which behaves differently in various frequency ranges. The materials which demonstrate both properties are denoted as MSs [26]. Hence, the MTM approach is mentioned in the study. Nowadays, many scientists examined MSs in different aspects. Hao *et al.* [27] presented an MS to achieve narrowband polarization conversion activity depending on the incident angle of the signal, dimension parameters, and operating frequency of the structure. Besides, Hao *et al.* [28] observed a linear polarization rotation by controlling optical polarization of the reflected signal from a structure. Fedotov *et al.* [29] offered a planar chiral MS structure to provide asymmetric transmission up to 40% for circular polarization activity. Zhao *et al.* [30] examined a resonance-based dielectric MS to obtain subwavelength resonator structures by using high dielectric constant materials. Lee *et al.* [31] proposed a gate-controlled graphene MS to obtain THz wave modulation. Lee *et al.* [32] studied phase-matching conditions in non-linear phenomena by using an MS as it can eliminate the thickness problem. Hence, it can be concluded that MSs can be used to achieve various signal applications.

In this study, an MS structure including five parallel copper lines enclosed by a rectangular frame is used to achieve polarization rotation from linear to circular. The proposed MS structure also includes a diagonal line placed across the

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corners of the enclosing rectangle in order to control the handedness of the circularly polarized wave. By simply changing the orientation of the diagonal line, left- or right-hand circularly polarized waves can be obtained. The efficiency of the conversion can be assessed by computing the axial ratio (AR), which is the ratio of cross and co-polarized responses. The proposed model offers relatively wide bandwidth, which is approximately equal to 500–600 MHz which means that it can be safely used as a polarization converter within this frequency bandwidth. Having a wide bandwidth is of course an advantage for the polarization converter studies. In this study, the resonance is set at around 4 GHz, but it can easily be adjusted to any required or desired working frequency range by simply changing the dimensions of the structure. Another advantage of this method is that it does not require any extra space next to the RF source since it is placed in front of the source which can also be considered another method for minimizing antennas. Manufacturing of antenna radomes using the proposed model does not require any extra space in front of the antenna, which can also be considered as another advantage of the proposed design.

II. DESIGN OF THE PROPOSED MS POLARIZATION CONVERTER

The proposed structure designed for both left- and right-handed rotation is shown in Figs 1(a) and 1(b). As seen in Fig. 1, the structure consists of parallel microstrip lines with a thickness of "*a*", which are equally separated and enclosed by a frame with the same thickness. The proposed structure also includes a diagonal line drawn between the opposite corners of the outer frame to provide cross-polarization component. The diagonal line is drawn from the upper left corner to the bottom right corner to obtain right-handed polarization converter (RHPC). For left-handed polarization converter (LHPC) application, the diagonal line is drawn from the upper right corner to the bottom left corner of the structure. The detailed information about the dimension of the unit cell of the MS model is shown in Fig. 1(c). The MS structure used in this work consists of 16 unit cells arranged in a 4 × 4 layout, which is quite appropriate when considering the electrical length of the frequency range we are working with. Table 1 shows the detailed dimensions of 4 × 4 layout.

RT5870 Substrate with a thickness of 1.575 mm is used as the base of the structure. The relative permittivity and the loss tangent of the substrate are 2.33 and 0.012, respectively.

Table 1. The dimensions of the unit cell (mm).

Lx	*Ly*	*x*	*y*	*a*	*tx*	*ty*	*tz*
56.80	69.584	14.20	17.396	1.528	9.752	8.46	14.526

III. NUMERICAL ANALYSIS OF THE PROPOSED MS

As the title stands, the purpose of this design is to control the polarization of a linearly polarized incident wave. The designed structure can convert the polarization from linear to circular, which is either LHCP or RHCP wave. This feature can be shown by examining the AR of the wave passed through the structure. AR is the ratio of the cross-polarized wave to the co-polarized wave, so for a perfect circular polarization conversion, the AR should be equal to one. The AR can be written as:

$$\mathrm{AR(dB)} = Mag(20\log(\mathrm{AR}(\omega))), \tag{1}$$

where $\mathrm{AR}(\omega)$ represents;

$$\mathrm{AR}(\omega) = \frac{T(\omega)(\text{cross-polar})}{T(\omega)(\text{co-polar})} \tag{2}$$

and

$$T(\omega) = Mag(S_{12}). \tag{3}$$

Simulation of the proposed design is performed by using a commercial 3D software, CST Microwave Studio based on Finite Integration Technique. In order to plot the AR, the floquet port modes are chosen and the co-polarized and cross-polarized waves are obtained by adjusting the ports.

A 3 dB point can be considered as the reference point for polarization conversion. When the values of AR are smaller than 3 dB, the structure can be used as a polarization converter. On the other hand, the frequency range for which the AR value is smaller than the reference value is called bandwidth of the structure. As seen in Figs 2 and 3, the designed structure has considerably large bandwidths. For the optimization, the effects of microstrip lengths (*tx*, *ty*, and *tz*) are analyzed. Furthermore, the cell size and the strip thickness are also changed for the parametric study and the results are shown in Figs 2 and 3. As seen in Fig. 2, the cell dimension affects the behavior of the structure significantly while the microstrip thickness only shifts the working band. The

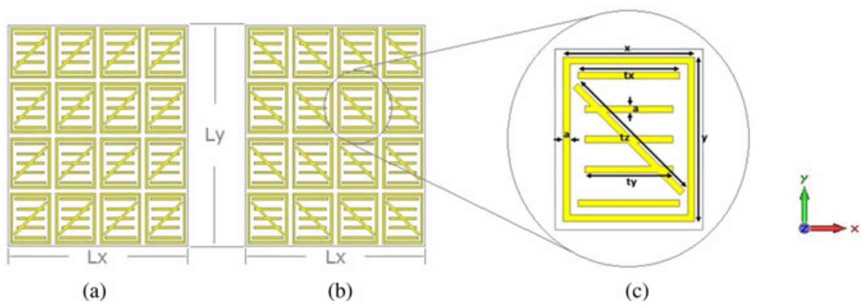

Fig. 1. Layout of (a) the linear to left-handed circular (LHPC design), (b) the linear to right-handed circular polarization (RHPC design), (c) unit cell of the MS polarization converter.

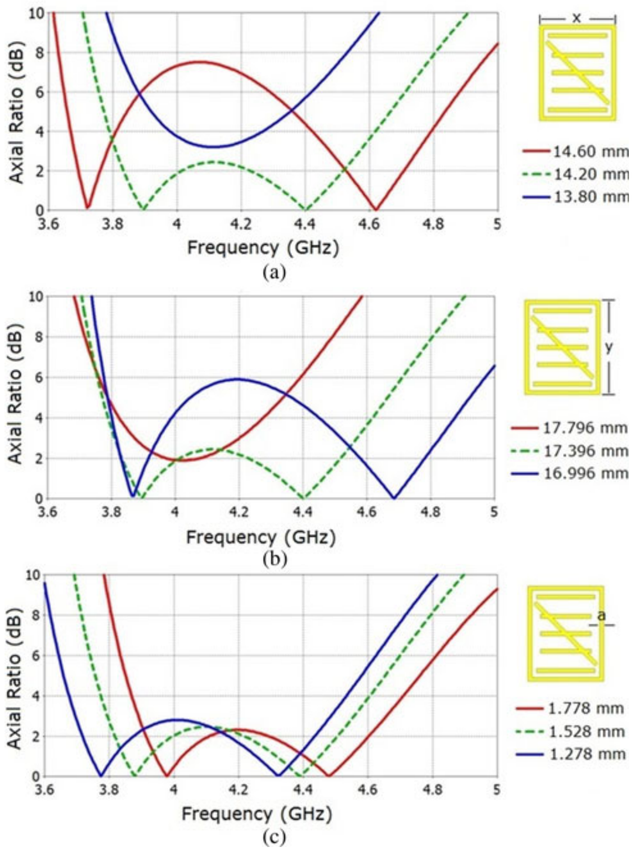

Fig. 2. Effect of the unit-cell width, height, and strip thickness on axial ratio: (a) unit-cell width, (b) unit-cell height, (c) strip thickness.

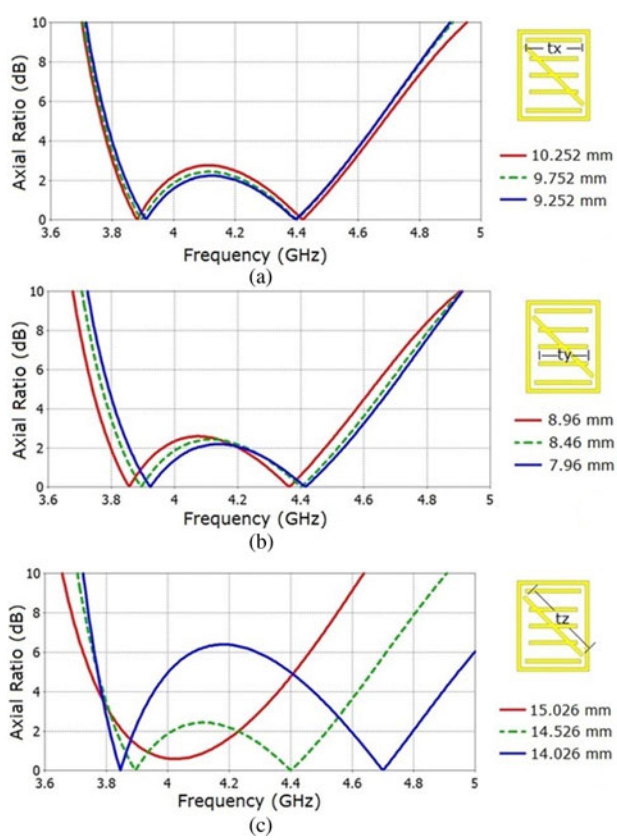

Fig. 3. Effect of horizontal strip length (a) *tx*, (b) *ty* and crossed strip length, (c) *tz* on axial ratio.

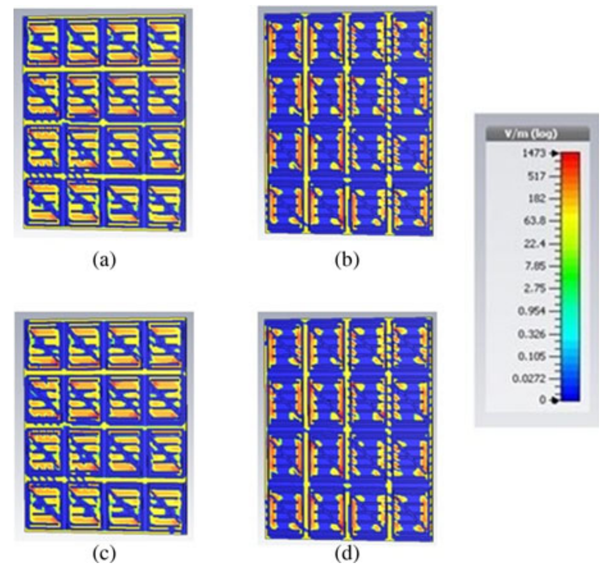

Fig. 4. E-field distribution of the proposed MS structure at various incident angles (a) 0°, (b) 90°, (c) 180°, (d) 270°.

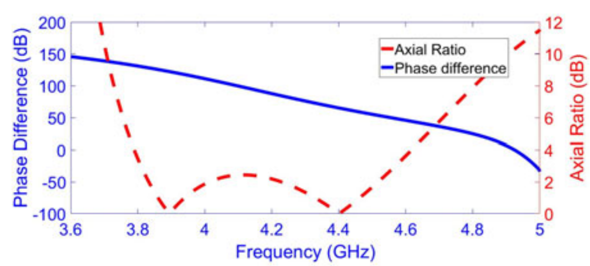

Fig. 5. Axial ratio and phase difference between two perpendicular field components.

variation of *x* dimension affects both the bandwidth and the magnitude of the AR. The best value range is obtained between 3.9 and 4.4 GHz with a maximum AR of 2.4 dB for $x = 14.2$ mm. Since the AR of upper and lower *x* dimensions does not provide proper polarization conversion, the structure acts as a resonator only for the middle value of *x*. The vertical dimension of MS also affects the AR. The resonance is obtained at $y = 17.396$ mm. The change of the vertical component only breaks the resonance and the structure cannot behave as a polarizer. The thickness variation of the strip slightly affects the AR. The increment of the "*a*" does not change the bandwidth and maximum AR but shifts the resonance band to the higher frequencies. The unit cell can be assumed as the combination of an L-C circuit. The capacitance of two strips is inversely proportional with the distance between them. Therefore, increment of "*a*" decreases the interval between adjacent strips and increases the capacitance. The resonance frequency also increases due to its direct proportionality with the capacitance value. In Fig. 3, it can be concluded that the effect of the horizontal strip lengths on the AR is small; however, the effect of diagonal line is remarkable. Therefore, the length of the diagonal line has to be chosen carefully.

To elaborate the study, the electric field distribution within the layout is obtained and plotted for various incident angles as shown in Fig. 4. When the incident angle is 0 or 180°, the horizontal lines become more sensitive and scatter most of the

(a) (b)

Fig. 6. (a) Fabricated MS structure sample; (b) experimental setup.

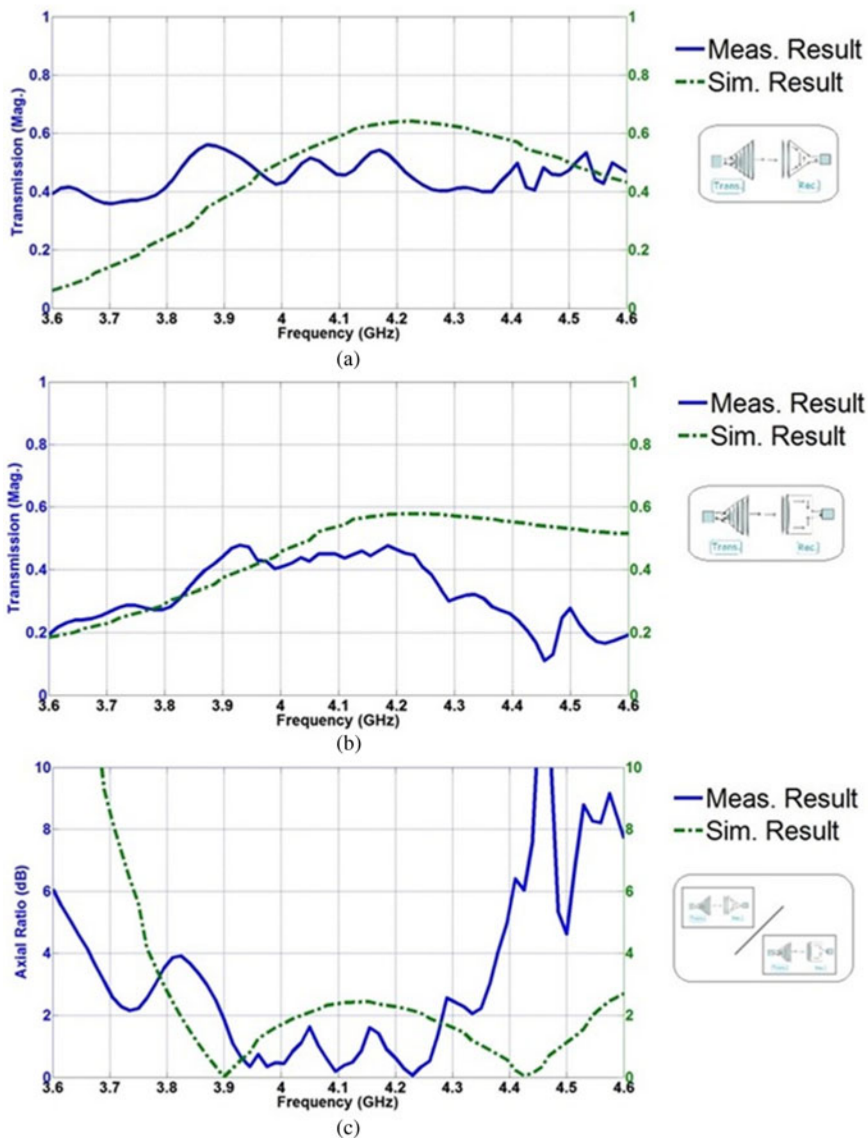

Fig. 7. Numerical and measured (a) co-polar transmission results, (b) cross-polar transmission results, and (c) AR results of the proposed MS polarization converter.

incident E-fields. On the other hand, the vertical lines become more active when the incident angle is 90 or 270°. These results are already expected due to the polarization axis. In other words, when the incident wave is vertically polarized, the vertical side of the structure will respond and emit most of the E-field and *vice versa*. Hence, the proposed structure can be used as a circular polarizer for both horizontally and vertically polarized waves.

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AR and phase difference between two perpendicular field components are shown in Fig. 5. For the efficient AR range, the phase difference is in quadrature as it is expected [33]. The phase difference is between 130 and 70°, which is around quadrature value in the frequency range of 3.8–4.4 GHz.

IV. EXPERIMENTAL RESULTS OF THE PROPOSED MS

Experimental study is also carried out by using a vector network analyzer and two horn antennas for the specific frequency range. The manufactured structure consisting of 64 unit cells arranged in an 8 × 8 layout is shown in Fig. 6(a). Horn antennas are calibrated first in the free space to obtain more accurate results and the structure is placed between them. The co- and cross-polarized incident waves are then obtained by simply changing the orientation of one of the horn antennas (Fig. 6(b)). Both transmitting and receiving antennas are kept vertically polarized to obtain co-polarized response but just one of them is rotated 90° in order to get the cross-polarized response. As we expect from the numerical studies, we have successfully obtained both co- and cross-polarized responses, which means that the structure converts the incident wave from linear- to circular-polarized waves.

In short, the operating principle of MS is based on the transformation of half of the incident energy propagating along horizontal (vertical) direction into the signal traveling along vertical (horizontal) direction. This wave power division is due to the geometrical properties of the MS. As seen in Fig. 7, the incident wave is divided into two nearly equal perpendicular waves, which result in linear to circular polarization conversion without incident angle dependency. Beside this, it is well known that the frequency-selective surfaces (FSSs) are mostly used to filter microwave signals, i.e. FSSs can be used as low, high, band pass or band stop filters in free space applications. The fundamentally used types of FSSs are patch and aperture. The patch type of FSSs behaves as band stop filter, the aperture shapes act as band pass filter. Hence, these types of structures are named as MS if it involves in both MTM and FSS [26]. Furthermore, the proposed MSs are exactly used to convert linear wave to circular one. As it can be seen from the measurement results, approximately 95% of the incident wave is transmitted with an AR below 3 dB. This high transmission coefficient is due to standard intrinsic impedance matching characteristics of the MS, and high-level radiation properties of the metallic lines.

For a better understanding, the transmission values and AR results are also measured, plotted and compared with the numerical ones as shown in Fig. 7. The bandwidth of the AR is between 3.87 and 4.38 GHz. This means that the AR values are below 3 dB at this frequency range. Hence, the structure can be used as a circular polarizer with a bandwidth of 510 MHz range. Besides, almost all co- and cross-polar transmission values are around 0.5. In other words, half of the linearly polarized wave is co-polar directed and other half part is cross-polar directed with respect to the incident wave. One can see from Fig. 7 that we almost have the same bandwidth with the simulation except for some small oscillations that are probably caused by the noise on the cables and laboratory conditions. It should also be stated that the frequency range is high enough to be affected by small quality and length changes in the cable and the environmental laboratory conditions. As a result, the experimental results agree well with the numerical ones.

V. CONCLUSION

In this work, we have successfully designed and analyzed a polarization converter based on MS structure. The proposed design allows having both RHCP and LHCP waves by simply changing the orientation of the diagonal strip. The performance of the structure is tested both numerically and experimentally and the results are found to be supporting each other. The proposed design has a simple geometry and gives a strong conversion from linearly to circularly polarized (both LH and RH) waves with a bandwidth of 510 MHz and it can be adjusted to any desired frequency range. The model can be implemented with very high efficiency and wide bandwidth to any application area where both circularly and linearly polarized waves are used.

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