Design of All-Dielectric Half-wave and Quarter-wave Plates Microwave Metasurfaces Based on Elliptic Dielectric Resonators

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Abstract **─** In this paper, we propose a numerical study for the design of Quarter-Wave Plate (QWP) and Half-Wave Plate (HWP) all-dielectric metasurfaces of relative permittivity 10.2, loss tangent 0.003 and thickness 5.12 mm. The devices based on Elliptic Dielectric Resonators (EDRs) may operate in the microwave band 20-30 GHz. First, we have studied the variation of the metasurface transmission, under x- and y-polarizations of the incident electric fields, when we vary the resonator ellipticity τ in the range 1:1.94. Next, we have optimized the resonator orientation (the rotation angle θ is situated in the range 0:45°) to improve further the moduli of transmission coefficients. Finally, from these previous parametric studies, we have designed QWP and HWP metasurfaces with the selected ellipticities τ_1=1.4 and τ_2=1.6. For example, we have obtained for ellipticity τ_1 that the metasurface may acts as HWP device at frequencies 26.08 GHz and 28.03 GHz with bandwidths 175 MHz and 75 MHz, respectively and as QWP device at 29.02 GHz with a bandwidth of 150 MHz. In addition, the transmission bandwidths of HWP metasurface was increased from 75 to 225 MHz when we vary the rotation angle of the EDR from θ=0° to 10°.

Index Terms **─** All-dielectric, dielectric resonator, half-wave plat, metasurface, quarter-wave plate, transmission coefficient.

I. INTRODUCTION

Control of the propagation of electromagnetic waves is an exciting topic in applied electromagnetics, and the complete control is still a challenge. Recently, metasurfaces have emerged as effective means for controlling the amplitude, phase and polarization of electromagnetic waves, see e.g. [1].

Metasurfaces [2-3], which are the 2-D version of metamaterials [4-7], are artificial structures designed by arranging a set of scattering elements in a regular pattern throughout a two-dimensional surface. These scattering elements can alter the propagation properties of incident electromagnetic waves, equipping metasurfaces with desirable functionalities and permitting the realization of innovative microwave devices such as cloaks, lens, absorbers, and polarizers [1].

Contrary to metasurfaces designed with conducting elements, characterized by high metallic losses especially in optical range, all-dielectric metasurfaces have emerged as a potential alternative for designing new microwave and optical devices with novel performances, due to their inherent advantages notably low-losses, high-refractive-index material, high overall efficiency and especially the possibility of realizing new functionalities by controlling both electric and magnetic resonances through optimization of the dielectric resonators' shape and spacing [8]-[12].

The majority of designed all-dielectric metasurfaces use dielectric resonators due to their particularity to excite both electric and magnetic resonant modes and to obtain miniaturized structures by using high dielectric constant materials. In addition to the possibility of using various canonical shapes such as spheres, cubes, cylindrical/elliptical disks and rods offering more flexibility in the design process.

In this paper, employing the Ansys-HFSS software package, we have investigated numerically the design of

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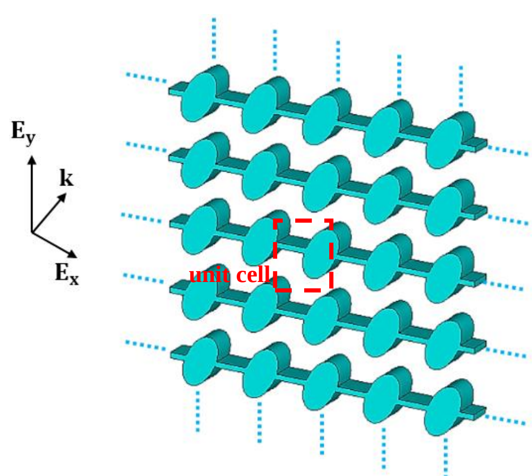
QWP and HWP all-dielectric metasurfaces based on Elliptic Dielectric Resonators (EDRs), operating in the microwave band 20-30 GHz. We have first studied the effects of the EDR ellipticity and orientation on the transmission through the determination of both x- and y-polarized transmission coefficients (moduli and phases). Then, selecting proper frequency sub-bands, with the moduli being equal, and the phase shift between x- and y-transmission coefficients being close to ±90° and ±180°, we have designed Quarter-Wave Plate (QWP) and Half-Wave Plate (HWP) metasurfaces. Next, we have presented examples of metasurfaces having particular values of the EDR ellipticity and orientation. Finally, we have analyzed the resonances of the proposed QWP and HWP metasurfaces based on the electric field distribution at their resonating frequencies.

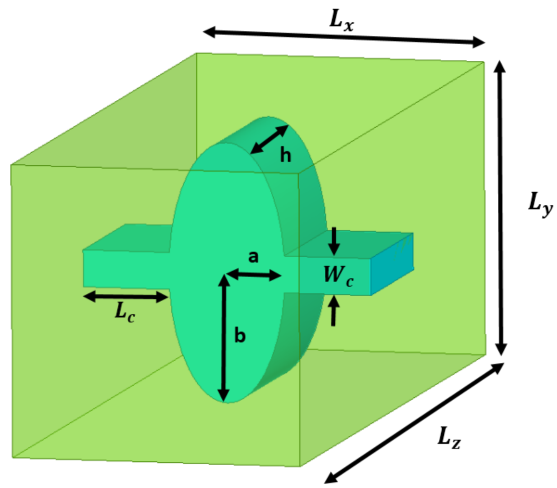
II. METASURFACE DESIGN

Employing the ANSYS-HFSS software package we have designed the proposed all-dielectric metasurface for operation in the frequency range 20-30 GHz. The structure is composed of an infinite 2D-array of connected dielectric resonators (Rogers RO3210) of relative permittivity 10.2, loss tangent 0.003 and thickness 5.12 mm (Fig. 1 (a)).

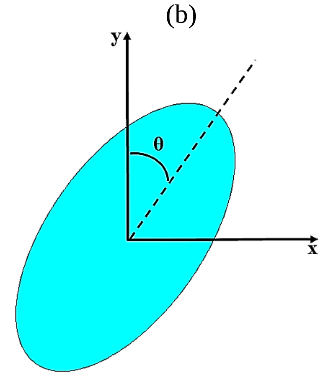
The used resonator is characterized by an elliptic shape of minor axis “a” along the x-direction, major axis “b” along the y-direction, and an ellipticity factor τ = b/a. The unit cell (Fig. 1 (b)) considered in the simulations is a box of longitudinal dimension Lz = 160 mm along the z-direction (Lz > λ), and transverse dimensions Lx and Ly along the x- and y-directions, respectively (Lx < λ and Ly < λ), with λ being the free-space wavelength associated with the upper frequency of the band 20-30 GHz (λ=10 mm). The connection (along the x-direction) between resonators were ensured with dielectric strips of thickness 5.12 mm, length Lc=(Lx/2)-a and width W_c=0.5 mm.



(a)



(b)



(c)

Fig. 1. Sketch of the proposed all-dielectric metasurface: (a) 2D connected EDR array with x- and z-polarizations of the electric field, (b) HFSS-model for the unit cell, and (c) definition of the rotation angle θ.

The influence of the ellipticity of the resonator was studied by varying only the major radius b, without changing the cell size; to this end τ is assumed to be in the range 1:1.94. The minor radius was kept constant (a = 2.5 mm (λ/4)). The orientation of the resonator was studied by modifying the angle θ (0 ≤ θ ≤ 45°) between the EDR major axis and y-direction (see Fig. 1 (c)).

III. RESULTS AND DISCUSSIONS

In order to design QWP and HWP all-dielectric metasurfaces, we have analyzed their transmission properties when excited under normal incidence waves having orthogonal polarizations parallel to the x- and y-axis. From moduli and phases of incident and transmitted electric fields, we have defined $T_{xx} = \frac{|E_x^t|}{|E_x^i|}$ and $T_{yy} = \frac{|E_y^t|}{|E_y^i|}$ as the transmission moduli of the x- and y-polarization, respectively, where E_x^i is the x-polarized incident electric field, E_x^t is the x-polarized transmitted electric field, E_y^i is the y-polarized incident electric field, and E_y^t

y-polarized transmitted electric field. $\Delta\phi = \phi_x - \phi_y$ is the phase difference between x- and y-polarizations. Then, the moduli T_{xx} and T_{yy} vary from 0 to 1, and the phase difference from -360° to +360°.

In the design process, we have first fixed the thickness of the resonator to be 5.12 mm, and its minor radius to be 2.5 mm. Then, we have determined the values of resonator ellipticity τ resulting in high transmission moduli and phase shift around ±90° for the QWP and ±180° for the HWP metasurfaces. Next, we have selected two ellipticity values ($\tau_1 = 1.4$ and $\tau_2 = 1.6$), and we have studied the effect of the rotation angle θ on the metasurface transmission in order to improve further the obtained transmission moduli and phases. Finally, we have represented the transmission coefficients and determined the bandwidth obtained with the optimized structures, over the frequency band 20-30 GHz.

For illustration of achieved results, we have selected two configurations; the first shows the possibility to design a unique metasurface with both QWP and HWP effects, and the second illustrates the possibility to improve a QWP or HWP metasurface transmission by adjusting the orientation of the resonators.

A. Effect of the EDR ellipticity

In this section, we have investigated the effect of the resonator ellipticity on the metasurface transmission. We have first simulated the variation of the transmission coefficients T_{xx} and T_{yy} (moduli and phases) when the ellipticity τ is varied from 1 to 1.94. Then, we have deduced the moduli ratio in logarithm scale and the phase shift $\Delta\phi$. Finally, we have filtered these values to keep only high and equal transmission moduli ($0.7 \leq T_{xx} \leq 1$ and $0.7 \leq T_{yy} \leq 1$) and phase shifts $\Delta\phi$ close to ±90° and ±180° for both QWP and HWP behaviors, respectively.

In Fig. 2, we have presented the effect of the resonator ellipticity on the metasurface transmission in colored maps. From these values, we have deduced (see Fig. 2 (b)), the logarithm of ratio between the moduli (log (T_{xx}/T_{yy})) and the phase difference $\Delta\phi$, then filtered values of the moduli corresponding to $0.7 \leq T_{xx} \leq 1$ and $0.7 \leq T_{yy} \leq 1$, and phases corresponding to $\Delta\phi = \pm 90° \pm 5°$ and $\Delta\phi = \pm 180 \pm 5°$. In fact, the QWP and HWP metasurfaces are obtained when the moduli are equal ($T_{xx} = T_{yy}$) and the phase shift is $\Delta\phi = \pm 90°$ for QWP and $\Delta\phi = \pm 180°$ for HWP.

The highest values of the moduli T_{xx} and T_{yy} are given with red color in Fig. 2 (a), and the equality between them ($T_{xx} = T_{yy}$) is represented with green color (log (T_{xx}/T_{yy}) close to 0) in Fig. 2 (b) (left graph), while high and equal moduli are given in the right graph of Fig. 2 (b).

For the phase, Fig. 2 (a) gives all phases ϕ_x and ϕ_y, the left graph of Fig. 2 (b) gives all values of the phase difference $\Delta\phi$, whereas right graph of Fig. 2 (b) gives the filtered values close to ±90° and ±180°.

In the two graphs of Fig. 2 (b) related to filtered moduli and phases, each couple (f, τ) which has a color in both figures is a possible solution for the design of QWP or HWP metasurface.

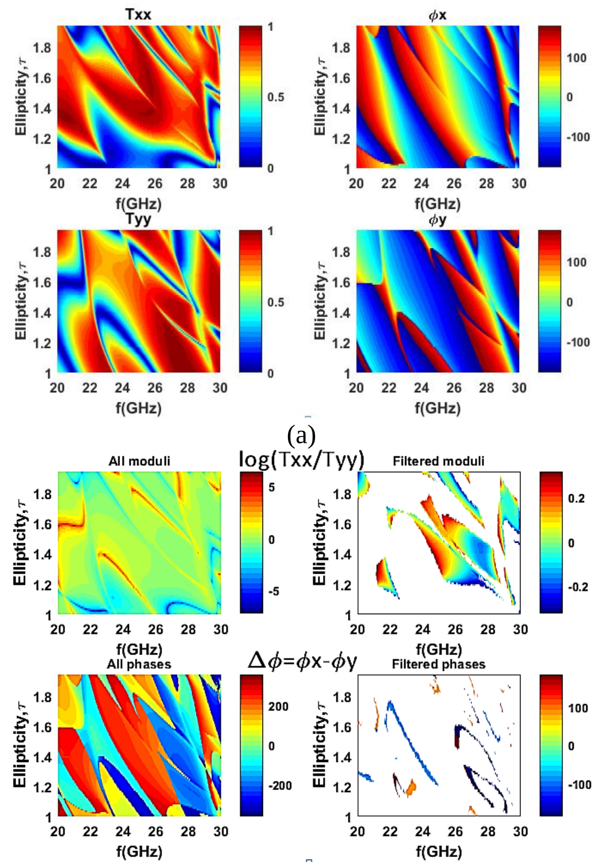


Fig. 2. Effect of the resonator ellipticity on the all-dielectric metasurface transmission: (a) moduli and phases of the x- and the y-polarized transmission coefficients; (b) all and filtered values of both moduli ratio and phase difference.

B. Effect of the EDR orientation

After establishing the color map (Fig. 2) illustrating the best ellipticity values giving high transmission, we have investigated the possibility to improve further the metasurface transmission by optimizing the resonator orientation, and rotating it in the x-y plane around z-axis. To conduct this parametric study, we have selected from the previous study (Fig. 2) two resonators of ellipticities τ_1=1.4 and τ_2=1.6 showing high transmission levels.

Again, for each resonator, we have first simulated the variation of the transmission coefficients T_{xx} and T_{yy} (moduli and phases) when its rotation angle θ is varied from 0° to 45° with a step of 5°. Then, we have deduced the moduli ratio in logarithm scale and the phase shift

$\Delta\phi$. Finally, we have filtered these values to keep only high and equal transmission moduli ($0.7 \leq T_{xx} \leq 1$ and $0.7 \leq T_{yy} \leq 1$) and phase shifts $\Delta\phi$ close to ±90° and ±180° for both QWP and HWP behaviors, respectively.

In Figs. 3 (a) and 4 (a), we have presented moduli and phases of the x- and the y-polarized transmission coefficients, in the frequency range 20-30 GHz, for different rotation angles θ. The equality between the moduli T_{xx} and T_{yy}, and the phase shift $\Delta\phi$ variation with the EDR orientation are given in Fig. 3 (b) and Fig. 4 (b), as well as the filtered values corresponding to high and equal moduli, and particular values of the phase shift corresponding to $\Delta\phi = \pm 180°$ or $\Delta\phi = \pm 90°$.

The right graphs of Fig. 3 (b) and Fig. 4 (b) give the useful parameters for the design of QWP and HWP metasurfaces with EDRs. Each couple (f, θ) represented with a color in both right graphs of Fig. 3 (b) or Fig. 4 (b), is a possible solution for the design of QWP or HWP metasurface with resonators of ellipticity 1.4 or 1.6, respectively.

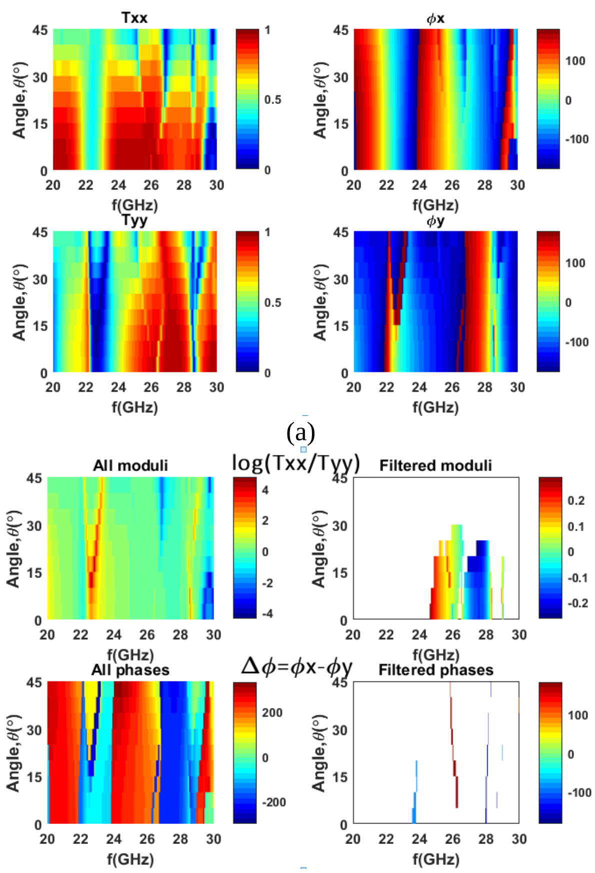


Fig. 3. Effect of the rotation angle of a resonator of ellipticity τ_1=1.4 on the all-dielectric metasurface transmission: (a) the moduli and phases of the x- and the y-polarized transmission coefficients; (b) all and filtered values of both moduli ratio and phase difference.

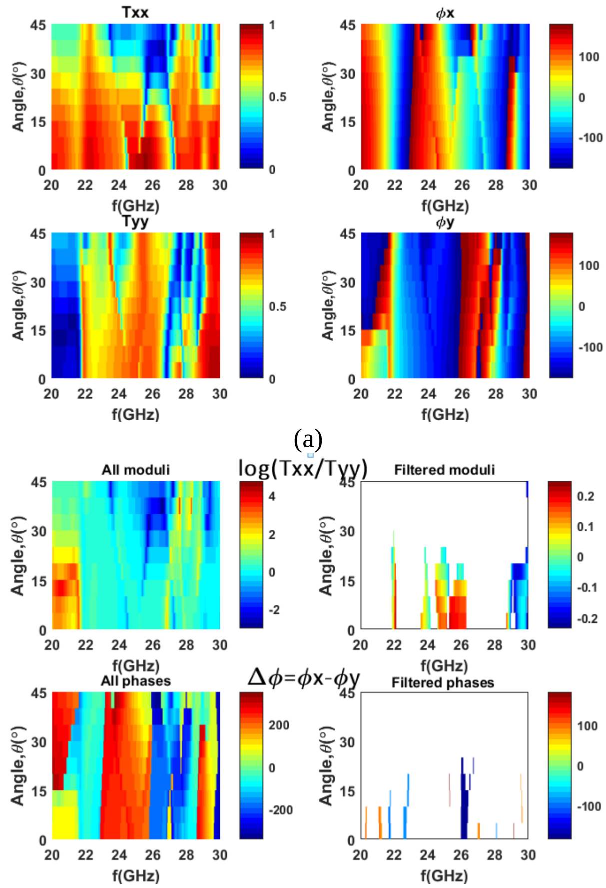


Fig. 4. Effect of the rotation angle of a resonator of ellipticity τ_1=1.6 on the all-dielectric metasurface transmission: (a) the moduli and phases of the x- and the y-polarized transmission coefficients; (b) all and filtered values of both moduli ratio and phase difference.

We conclude from the color distribution in Fig. 3 (b) and Fig. 4 (b), that we have more possibility to design QWP or HWP metasurface with EDR ellipticity 1.6 than 1.4 since we have more superposition between filtered values of moduli and phases in Fig. 4 (b) (τ_2=1.6) than in Fig. 3 (b) (τ_1=1.4). In fact, each superposition between filtered values of moduli and phases means that we have the possibility to design QWP or HWP metasurfaces with high transmission ($0.7 \leq T_{xx} \leq 1$ and $0.7 \leq T_{yy} \leq 1$) and phase shifts $\Delta\phi$ close to ±90° or ±180°.

C. Application: QWP and HWP metasurfaces

Table 1 summarizes the main obtained results in sections A and B, for the design of all-dielectric QWP and HWP metasurfaces based on EDRs. For each resonator of ellipticity τ (τ_1=1.4 or τ_2=1.6), we have presented different orientations (angles θ) (in column 2) giving QWP or/and HWP behaviors. In columns 3 and 4, we have indicated respectively, the central frequency f_0

and the bandwidth BW of the frequency sub-band in which the designed metasurfaces may operate.

Table 1: Main QWP and HWP metasurfaces properties deduced from Figs. 3 (b) and 4 (b)

Ellipticity, τ	Rotation Angle, θ(°)	Central Frequency, F_0 (GHz)	Bandwidth, BW (MHz)	QWP	HWP
τ_1=1.4	0	27.98	75		√
	5	26.25	150		√
		27.98	75		√
	10	26.16	225		√
		28.01	75		√
	15	26.08	175		√
		28.03	75		√
		29.02	150	√	
	20	26.05	150		√
		28.06	75		√
	25	25.93	125		√
	30	25.91	75		√
τ_2=1.6	0	26.13	325		√
		29.60	-	√	
	5	26.13	325		√
		29.12	-		√
		29.60	50	√	
	10	26.15	350		√
		27.87	-		√
		29.12	-		√
		29.58	75	√	
	15	25.22	50		√
		26.06	175		√
		29.10	-		√
		29.51	75	√	
	20	25.07	-		√

The main conclusion from Table 1 is that, for a fixed ellipticity, the metasurface behavior depends on the resonator orientation. For example, the bandwidth may be improved by varying the rotation angle θ, in addition to the possibility of realizing both QWP and HWP with a unique metasurface for certain orientations.

We remark also that ellipticity τ_1 is more adequate for the realization of HWP metasurfaces (θ=0, 5, 10, 15, 20, 25 and 30°), whereas ellipticity τ_2 is more adequate for realization of both QWP and HWP metasurfaces (θ=0, 5, 10 and 15°).

In Fig. 5, we have illustrated the dual-effect (QWP and HWP) by giving the variation, over the range 20-30 GHz, of moduli ratio (in log scale) and phase shift $\Delta\phi$ for two metasurfaces based on EDRs of fixed orientation (θ=15°) and ellipticity's τ_1 and τ_2, respectively.

In Fig. 5 and Fig. 6, the yellow and blue strips correspond to sub-bands with QWP and HWP behaviors, respectively. Therefore, we can note that the metasurface based on EDRs of ellipticity τ_1 may acts as HWP device at frequencies 26.08 GHz and 28.03 GHz with bandwidths 175 MHz and 75 MHz, respectively and as QWP device at 29.02 GHz with a bandwidth of 150 MHz. Whereas for ellipticity τ_2, we have obtained the HWP behavior at frequencies 25.22 GHz and 26.06 GHz with bandwidths 50 MHz and 175 MHz, respectively and the QWP behavior at 29.51 GHz with a bandwidth of 75 MHz.

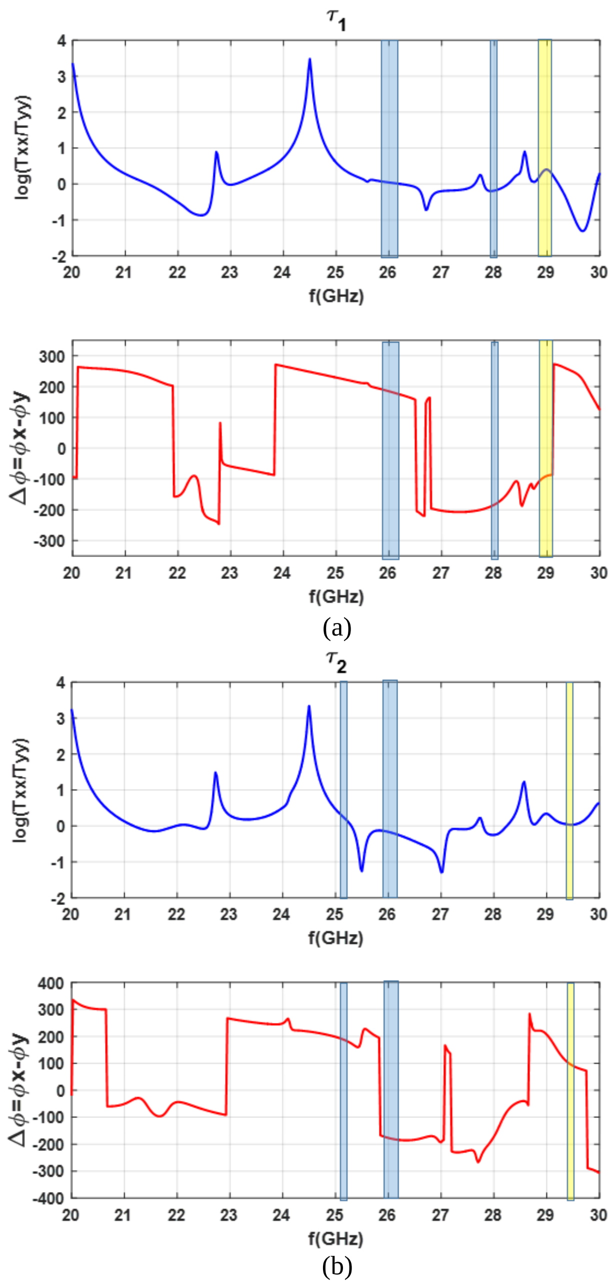


Fig. 5. Variation, over the frequency band 20-30 GHz, of the x- and y-polarized moduli ratio and phase shift for an all-dielectric metasurface based on EDRs of rotation angle θ=15° and ellipticity: (a) τ_1=1.4; (b) τ_2=1.6.

The effect of EDR orientation on the metasurface transmission is shown in Fig. 6. We note from Fig. 6 (a) that the transmission bandwidths are 75, 150 and 225 MHz for rotation angles θ=0°, 5° and 10°, respectively, which means that the bandwidth of the HWP metasurface designed with ellipticity τ_1 was ameliorated by simple optimization of the angle θ. Similarly, for the QWP metasurface designed with ellipticity τ_2 (Fig. 6 (b)), the transmission bandwidth was increased by varying the resonator orientation.

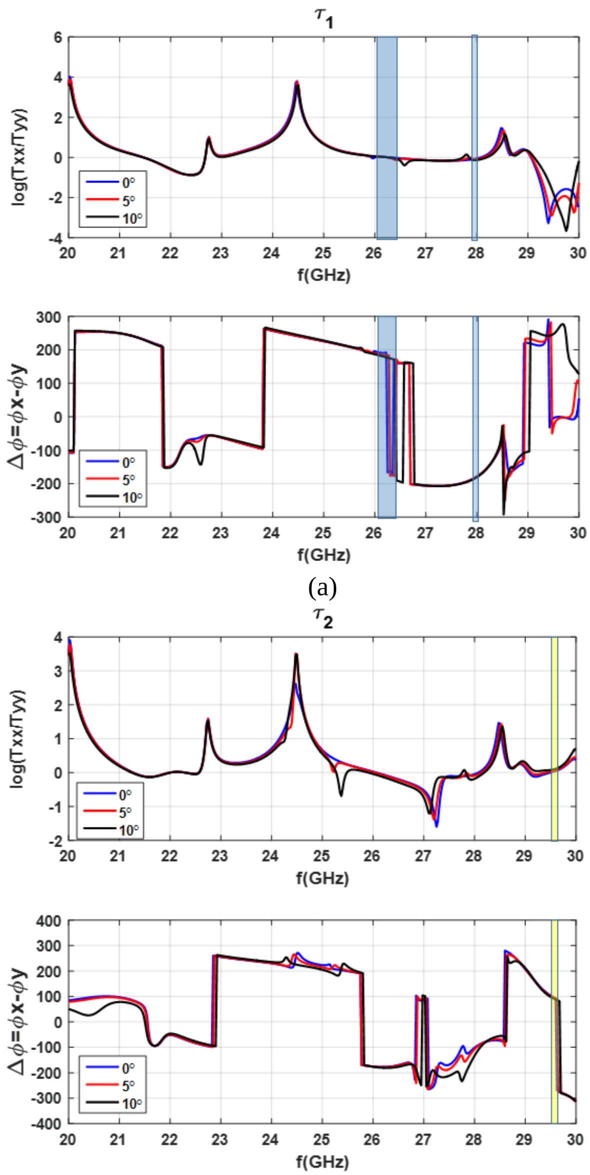


Fig. 6. Variation, over the frequency band 20-30 GHz, of the x- and y-polarized moduli ratio and phase shift for an all-dielectric metasurfaces based on EDRs of rotation angles θ=0°, 5° and 10°, and ellipticity: (a) τ_1=1.4; (b) τ_2=1.6.

The electric field distributions in the yz-plane at the middle of the resonator (cut plane (x=0) of both QWP and HWP all-dielectric metasurfaces (excided with the y-polarization) based on EDRs of ellipticity τ_1=1.4 and for different orientations are given in Figs. 7 and 8, respectively. For each device (QWP or HWP), the structure was selected to resonate at the same frequency with two different rotation angles θ; permitting the analysis of the effect of the EDR orientation on the electric field distribution.

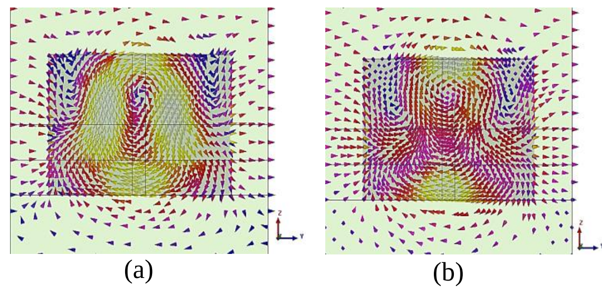


Fig. 7. Electric-field distribution on the yz-plane at the middle (cut plane x=0) of the unit cell for a QWP-metasurface based on EDRs of ellipticity τ_1=1.4 and rotation angle θ, resonating around the frequency f=29 GHz: (a) θ = 0°; (b) θ = 15°.

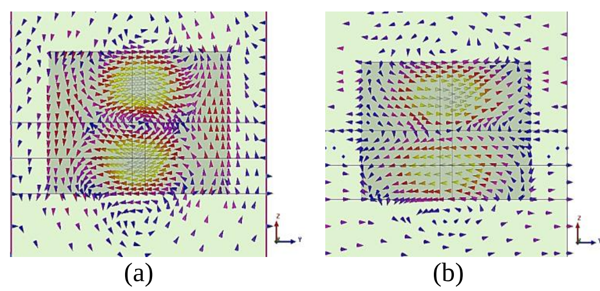


Fig. 8. Electric-field distribution on the yz-plane at the middle (cut plane x=0) of the unit cell for a HWP-Metasurface based on EDRs of ellipticity τ_1=1.4 and rotation angle θ, resonating around the frequency f=26.15 GHz: (a) θ = 0°; (b) θ = 10°.

Analysis of Figs. 7 and 8 reveals that rotation of the resonator about the z-axis within it, which in turns may reduce the resonance strength of the structure excited with-y-polarization. This result may be explained by the decrease of the exciting the y-electric field component with the rotation of the resonator. However, we note a slight improvement of the useful bandwidth for both QWP and HWP devices.

IV. CONCLUSION

In this work, we have investigated numerically the design of QWP and HWP all-dielectric metasurfaces based on EDRs operating in the microwave frequency band 20-30 GHz. We have investigated first the effect of the EDR ellipticity on the metasurfaces transmission; then we aimed at improving the resulting transmission by rotation of the resonator about its z-axis. It is found that by optimizing the rotation angle we can improve the bandwidth of both QWP and HWP metasurfaces in addition to the possibility of realizing a unique device with both QWP and HWP behaviors at some selected frequencies.

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