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Novel optical polarizer design based on metasurface nano aperture for biological sensing in mid-infrared regime

Samaneh Heydari[1] · Maryam Bazgir[2] · Ferdows B. Zarrabi[3] ·
Navid P. Gandji[4] · Iman Rastan[2]

Abstract Since Metasurfaces are playing important roles in optical devices such as optical polarizers and detectors, in this article, we have proposed a novel shape of nano aperture antenna for mid-infrared applications such as bio-sensing and other potential optical applications based on plasmonic characteristic of the gold layer over the SiN substrate. The transmittance tensor is obtained for vertical and horizontal linear polarization and base on boundary condition of the metasurface, the circular polarizations are extracted which are confirmed by the electric field distributions. We have shown by the parametric studies that the phase difference is altered by the gap and slot width and so with the dimension modification, we are able to achieve circular polarizer in the optical range. The biological materials with a thickness of 80 nm have then been placed over the metasurface layer and the figures of merits have been obtained. We have revealed that when the circular polarization is osculated to the metasurface at a special frequency the linear polarization is obtained in the other side of the metasurface. The nano aperture has been modeled and the finite difference time domain calculations are performed in CST Microwave Studio as a commercial full wave simulation software.

Keywords Metasurface · Infrared · Nano aperture antenna · Plasmonic · Optical polarizer

✉ Samaneh Heydari
  samanehheydari7@gmail.com

  Ferdows B. Zarrabi
  ferdows.zarrabi@yahoo.com

1 Department of Electrical engineering, Isfahan (Khorasgan) Branch, Islamic Azad University, Isfahan, Iran

2 Faculty of Engineering, Arak Branch, Islamic Azad University, Arāk, Iran

3 Young Researchers and Elite Club, Babol Branch, Islamic Azad University, Babol, Iran

4 Electrical and Computer Engineering Department, Michigan Technological University, Houghton, MI, USA

1 Introduction

Over the last decade, Metasurfaces or metafilms have attracted a great deal of research attentions due to their exceptional abilities to control the flow of light and optical radiation at subwavelength scales utilizing uncomplicated planar structure with various shapes for different applications specially optical polarizers (Aieta et al. 2012; Dabidian et al. 2015). New advances in nonmanufacturing technologies have allowed manipulating the light polarization which is playing a main role in optical applications because of their inherent capability to scatter and diffract light in the frequency range of which, the plasmonic attribution is used based on meta-atom with two-dimensional (2D) metasurfaces (Meinzer et al. 2014). With the fast development and growing of technology, plasmonic subwavelength systems based on metallic nano apertures or nano particle with different shapes and size have been one of the most fascinating topics to create new opportunities to manipulate light polarization at the nano meter scale (Schuller et al. 2010).

Metasurfaces or single layers of metamaterial are two-dimensional Metamaterial with subwavelength thickness, which possess unusual and beneficial optical properties that may not be available in nature. They are being more attractive mostly because they are not costly and as well as having low ohmic loss they can be easily fabricated. These metasurfaces have found numerous applications in optical imaging (Adams et al. 2016), invisibility cloaking (Semouchkina et al. 2016), circular polarization filter (Cadusch et al. 2014), compact cavity resonators (Caiazzo et al. 2004), Second-harmonics generation as a significant method for sensitive optical characterization of nano structures (Valev 2012), Holographic leaky-wave metasurfaces (Fong et al. 2010), wave front shaping (Sievenpiper et al. 2003), and Lenses for surface waves (Wan et al. 2014). Metasurfaces were so-called nano-island metal films, and were in use for sensing applications. Silver or gold nano-islands on a dielectric substrate possess a localized plasmon resonance and in the frequency range of this resonance the local electric field is strongly enhanced. The field-enhancement mechanism is used in many sensing schemes, among which the most known is the so-called surface enhanced Raman scattering (SERS). The property of electromagnetic wave polarization provides an additional information channel in radio and optical systems for different purposes like MIMO communications, polarimetric measurements, fiber-optic communications, and dual-polarized radars (Kildishev et al. 2013).

There is a special class of devices manipulating waves localized in vicinity of a flat layer. Such devices are mostly used as a part of flat lens antennas producing a fan-beam radiation pattern at microwaves, but can also be employed as components of optical circuits (Park et al. 2001). A full control of the reflected and transmitted field can be presented by metasurface (Gordon et al. 2009) and since they have planar structures, they can merge with planar antennas in order to produce circular polarization (Zhu et al. 2013, 2014). In spite of diffraction grating which provides multiple diffraction lobes, metasurfaces similar to homogeneously polarisable sheets can reflect and transmit plane waves (Falcone et al. 2004). Metasurface capabilities to make an abrupt phase modification and control the propagation of light have made these devices incomparable especially in optical applications (Aieta et al. 2012; Chen et al. 2013).

On the other hand, nano aperture antennas based on plasmonic structures are recently being noticed for bio-medical applications. Various shapes of nano antennas are suggested to produce single or dual band resonance such as subwavelength H-shaped apertures (Cetin et al. 2015a), bowtie apertures (Cetin et al. 2015b), On-chip sensing platform with plasmonic microarrays and lens-free computational imaging (Cetin et al. 2014), and fractal

Fig. 1 a The prototyped
metasurface array formation,
b metasurface unit cell geometry

(a)

(b)
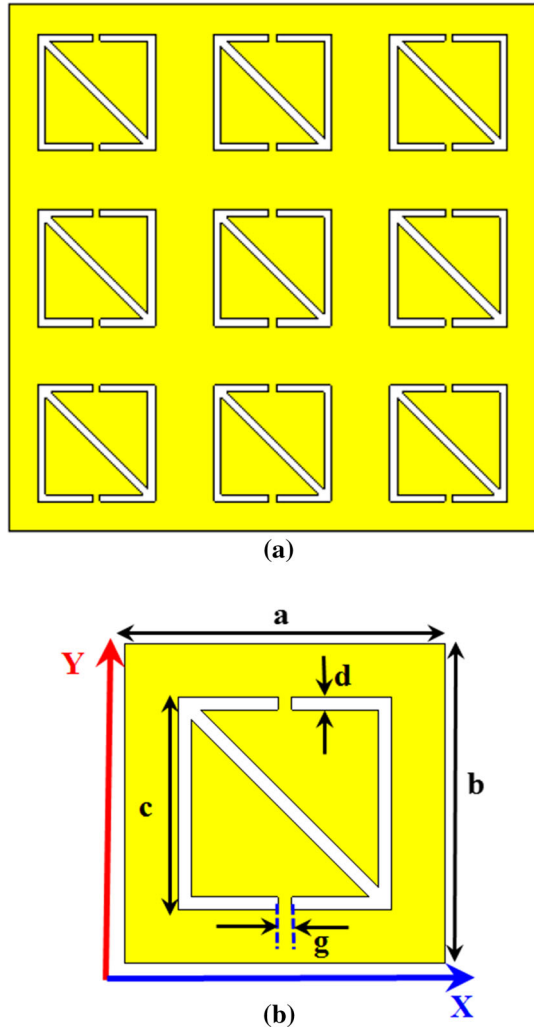
formation for dual band applications (Cetin et al. 2015c). 2D periodical arrangement of slotted unit cells and their complementary formations are noticed for metasurfaces. However, various complementary structures are also suggested for optical polarizer (Kildishev et al. 2013; Zhao et al. 2012).

In this paper, we have considered ultrathin metasurface based on nano aperture method which exhibits some benefits in comparison to complementary formations such as their application in spectroscopy for bio sensing in the mid infrared. Based on previous research and theories, we have debated about transmittance and phase manner in our basic model and then by parametric studies, we are looking for the best choice in the structure. In addition, the Electric field has revealed the effect of the prototype metasurface on the incident wave with circular polarization and converting to linear polarization. At last, FOM factors are studied for various biological materials.

2 Design particle

A novel shape of nano antenna based on rectangular aperture has been proposed in Fig. 1 as a metasurface which can be utilized for biological sensing applications. Figure 1a illustrates the prototype metasurface in array form, and Fig. 1b shows the geometry and dimension of each unit cell. The structure contains a plasmonic gold layer with split ring resonator (SRR) shape aperture with a length and width of 2400 nm for each unit cell with a thickness of 30 nm for gold layer in the design of the proposed nano antenna, the gold layer is placed on an 80 nm thick SiN substrate with n = 1.98 for optical regime and the Palik's model of gold is selected in the simulation for the metallic parts. In addition, all dimensions in Fig. 1b are set to a = b = 2400 nm, c = 600 nm, d = 100 nm, g = 100 nm.

3 Design theory

When an incident wave is emitted normally on a desired surface, depending on being in TE or TM mode, the electric field or magnetic field is parallel to the surface, respectively. As the field reaches the surface, inducing actions take place generating current intensity (surface flow) and this current consequently generate the field. It is shown by Alu et al. that the electric field divided into two component x and y, so the reflection (R) and transmission (T) coefficient obtained by relevant formula. In this study, they use Tensor for both TE and TM modes. These Tensors are generally functions of the incidence angle. By utilizing the concept of the Tensor, the reflection and transmission coefficients can be acquired (Zhao and Alù 2011; Zhao et al. 2011). They show that transmission matrix **T** can be described by complex amplitudes of transmitted waves (Zhao and Alù 2011).

$$T = \begin{pmatrix} T_{xx} & T_{yx} \\ T_{xy} & T_{yy} \end{pmatrix}$$

We have assumed the phases of $\mathbf{E}_x$ and $\mathbf{E}_y$ are described by ϕ_1 and ϕ_2, and when the difference between phase of $\mathbf{E}_x$ and $\mathbf{E}_y$ ($\Delta\phi = \phi_1 - \phi_2$) is 90° and 180° then the linearly-polarized is converted to circularly-polarized (Ma et al. 2014).

We have used subwavelength characteristic of the plasmonic in the proposed Meta-surface and described a circular polarization with combination of two perpendicular linear polarizations.

**Fig. 2** The electric field for $\mathbf{E}_x$ and $\mathbf{E}_y$
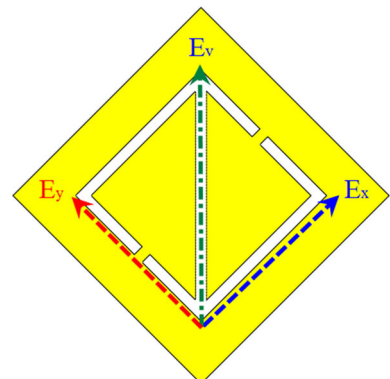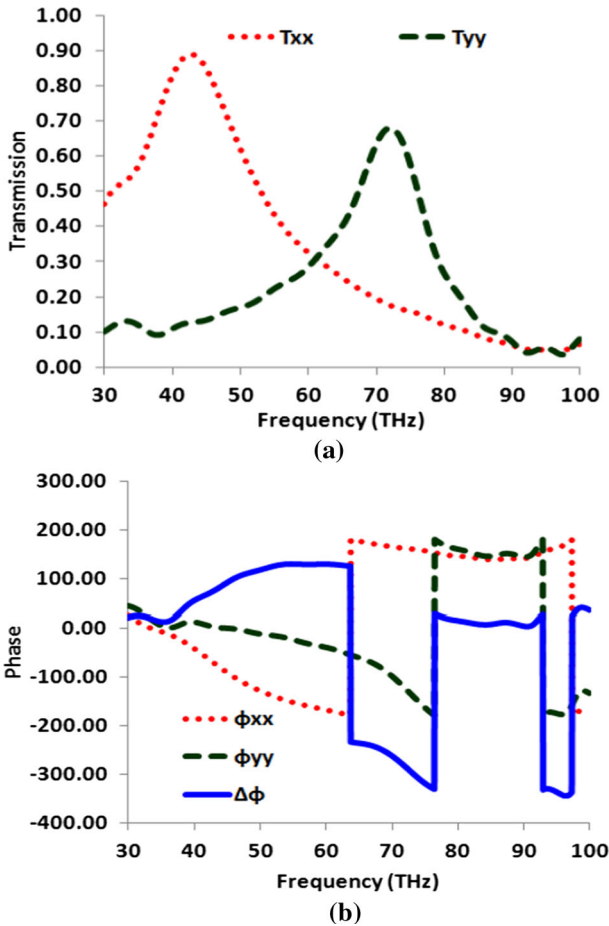
Fig. 3 a The transmittance of the metasurface layer, **b** the phase variation and $\Delta\phi$ in metasurface

The gap is behaving as a capacitor and slots are made to produce inductive properties in the nano antenna which is theoretically a parallel resonance circuit and the related wavelength would be $\lambda = 2\pi c_0 \sqrt{LC}$ where c_0 is the speed of light in free space (Zarrabi et al. 2016). The quality factor for this parallel circuit can be obtained by $Q = \omega_r Z_0 C / 2$, where ω_r is the angular frequency of resonance and $Z_0 = 120\pi = 377\,\Omega$ is known as the free space impedance.

4 Simulation result

In order to numerically analyze the aperture system we have used commercial full-wave simulation software (CST microwave studio) by using two-port analyzing with open boundaries for side walls and open boundary with space for Z-direction and wave-ports are placed in Z direction. Figure 3 shows the transmission of a simple structure in X and Y direction which is shown by $\mathbf{T_{xx}}$ and $\mathbf{T_{yy}}$ where both excitation ports are emitting wave in
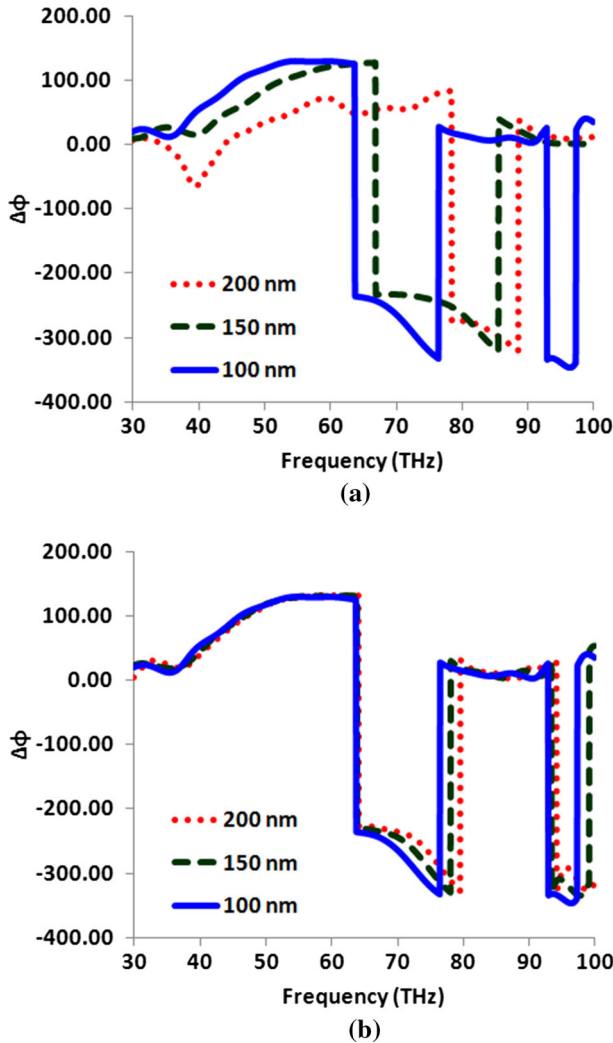
Fig. 4 The phase variation in metasurface for **a** slot variation, **b** gap variation

X and Y direction and they made $\mathbf{E_x}$ and $\mathbf{E_y}$ (Fig. 2). It is shown in Fig. 3a that the prototyped nano-antenna shows a single resonance at 40 THz for the transmission along X-direction (T_{xx}) and at this frequency, the maximum of the transmission is around 0.88, and when considering transmission along Y direction a single resonance at 72 THz appears with the maximum transmission of about 0.67. Figure 3b illustrates the phase variation in metasurface for X and Y directions. As shown here, a phase difference in the 45 THz exactly equal to 90°, verifying that its operation is achieved as an ideal ultrathin low-loss quarter-wave and we have circular polarization as told for obtaining the circular polarization we should obtained $\Delta\phi = \phi_1 - \phi_2$ of 90° (Ma et al. 2014).

Figure 4a, b shows the phase variation studies for prototype structure by variation in slot (d) and gap (g) of the unit cells. Exactly the phase in this structure is sensitive and aperture
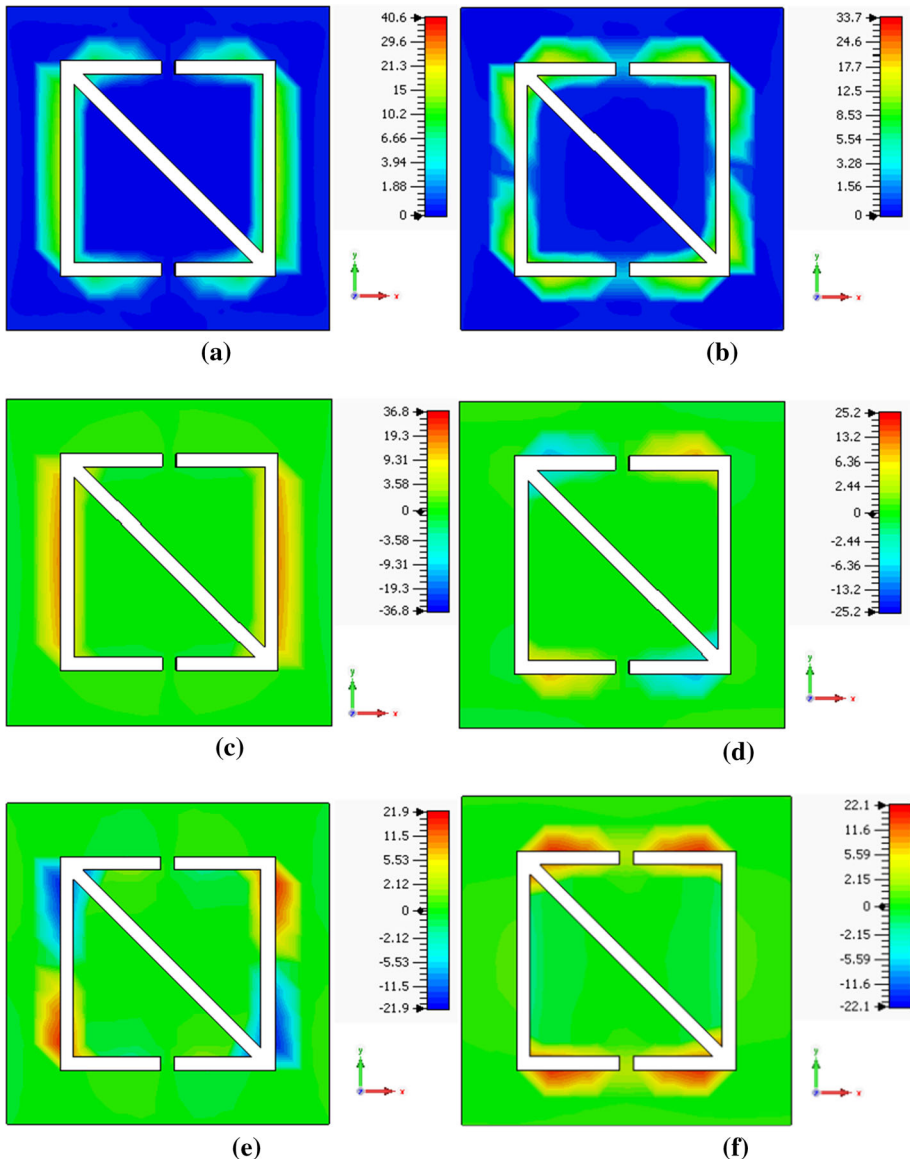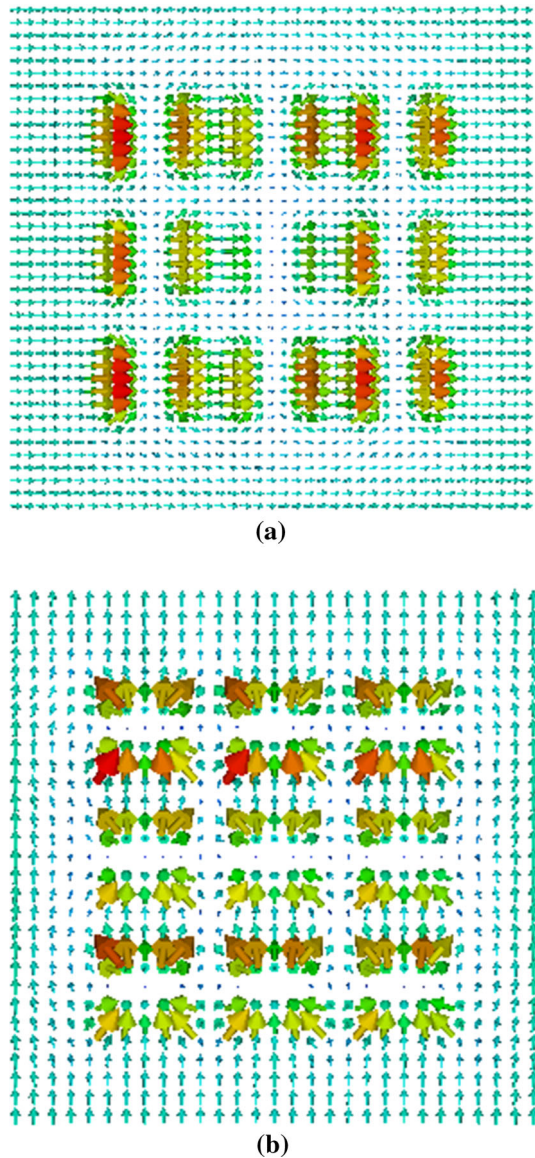
Fig. 5 The nano antenna field intensity enhancement distribution for the main resonance modes **a** total E-field excited in X-direction at 40 THz, **b** total E-field excited in X-direction at 72 THz, **c** E_x-field when excited in X-direction at 40 THz, **d** E_y-field when excited in X-direction at 40 THz, **e** E_x-field when excited in Y-direction at 72 THz, and **f** E_y-field when excited in Y-direction at 72 THz

parameters have effect on the inductance and capacitance and therefore the phase would be altered.

Figure 4a shows the slot alteration effect on the phase response and presented here that by increasing the slot width from 100 to 150 and 200 nm, the phase changes drastically and the phase difference of the 90 is not occurring. On the other hand, the phase difference in

Fig. 6 The effect of the
metasurface on the incident wave
with circular polarization
a linearly polarized field
observed at 45 THz, **b** circular
polarization at 70 THz

(a)

(b)

the gap variation shows limited change and the result shows more stability when the gap
changed from 100 to 200 nm as shown in Fig. 4b.

The antenna field intensity enhancement distribution is shown in Fig. 5 for the main
resonance modes of the proposed nano antenna in X and Y direction when the Electric field
is incident with the amplitude of 1 V/m in each X and Y direction. Figure 5a exhibits the
total electric field distribution which excited in X-direction at 40 THz whereas Fig. 5b
shows the total electric field distribution which excited in Y-direction at 72 THz. As shown
in Fig. 5a, b, total $\left|E^2\right|/\left|E_{int}^2\right|$ ratio in X- and Y-directions are approximately around 1648
and 1135, respectively. Figure 5c, d illustrate E_x field and E_y field for incident wave in X-
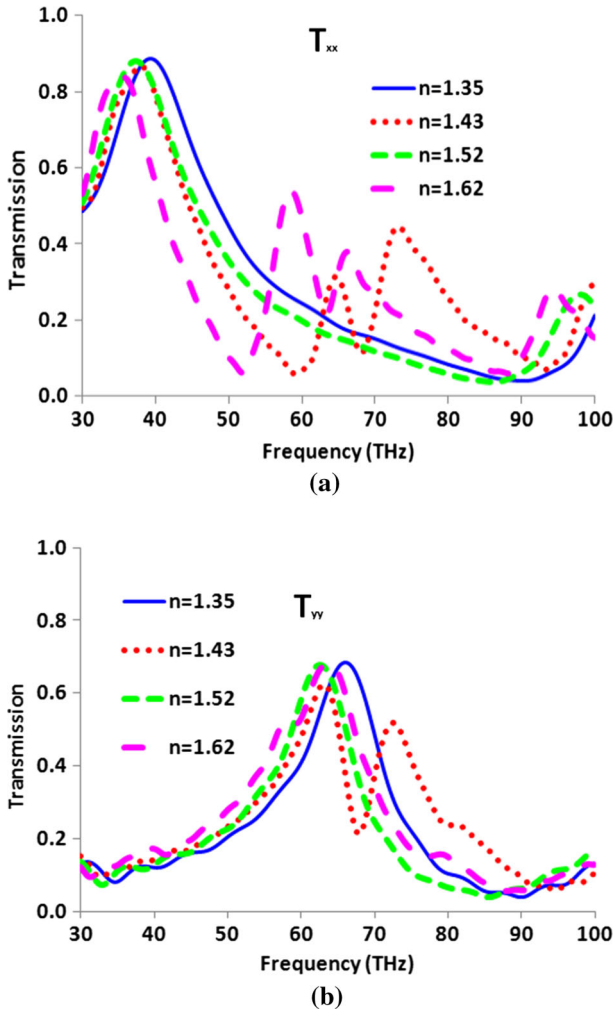
Fig. 7 Nano antenna transmittance in presence of additional material **a** for X direction, **b** for Y direction

direction at 40 THz, respectively and while Fig. 5e, f exhibit E_x field and E_y field for incident wave in Y-direction at 72 THz, respectively. As can be seen in Fig. 5e, f, the electric field are concentrated at the nano apertures and at 72 THz the E_x and E_y are equal where the $\left|E^2\right|/\left|E_{int}^2\right|$ ratio are 479.6 and 488.4.

It has been discussed in Fig. 3b that the metasurface shows circular polarization at 45 THz and now in Fig. 6 for showing that the metasurface can be used as polarizer, we have radiated a circular polarized field to the metasurface at 45 and 70 THz where we have circular and linear polarization and observed the field on the other side of the metasurface. The results in Fig. 6a revealed that at 45 THz the observed fields are distributed in linear form at X direction and it means the metasurface is converted the circular polarization to linear. Figure 6b shows the field is dispensed in the slant form with angle of 45° at 70 THz and it revealed that the metasurface does not have any effect on this frequency on the
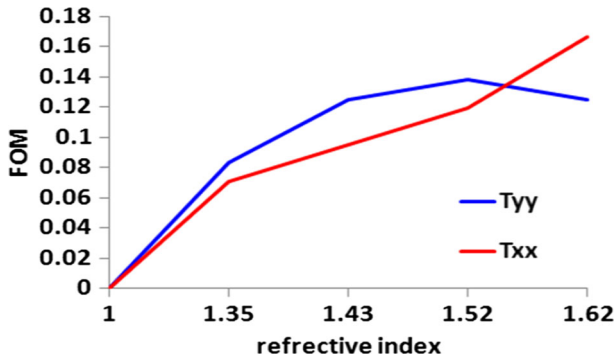
Fig. 8 FOM profile for X and Y direction of incidence

incident wave polarization. This is because although the equal value is obtained for E_x and E_y at 70 THz, $\Delta\phi$ is not 90° and therefore we do not have variation in the polarization.

We have also studied the transmission coefficient of the prototyped nano structures surrounded by various conventional biomaterials. For this aim, Surface Enhanced Infrared Absorption (SEIRA) spectroscopy is a normal method to identify material such as Ether (R–O–R′) with n = 1.35, Ethylene glycol (HO–CH$_2$CH$_2$–OH) with n = 1.43, Chlorobenzene (C$_6$H$_5$C1) with n = 1.525, and Quinoline (C$_6$H$_7$N) with n = 1.627 (Zarrabi et al. 2016). In this article, the thickness of biomaterial is assumed to be 80 nm. Figure 7a, b exhibit the result of material loading of the proposed nano antenna for X and Y direction, respectively. As shown in Fig. 5a, b, by increasing the refractive index of biomaterial in X and Y direction the peak resonances are reduced, but the shift in the high frequencies for X direction is more pronounced than those in Y direction.

Figure 8 shows the figure of merit (FOM) factor by considering $\Delta f/f$ when the incidence is in X and Y direction for various refractive indices. When the direction of incidence is in X-direction, changes in FOM with various indices have risen considerably. However, considering the incidence in Y direction, the FOM changes also has increased slightly and reached a peak of about 0.14 for n = 1.52, but gradually fell for higher indices to approximately 0.12. Thus, by the analysis in X direction there would a better possibility to detect homogenous isotropic materials.

5 Conclusion

In this current work we have developed a new form of the slotted nano antenna for bio sensing with metamaterial shape. The transmission amplitude and phase of the structure has been simulated in both X- and Y-directions and it was concluded that since this structure has a different phase response in two directions it can change the polarization of the incident wave for instance when the circularly polarized wave at 45 THz is emitting in X direction the output would have only linear components, however for the Y-propagating wave The circular polarization is conserved. The feasibility of using the proposed structure for sensing bio-materials has also been investigated by considering transmission in both X- and Y-directions and also calculating the FOM factor, it could be seen that the x-directed transmission coefficient gives a better opportunity as a biomaterial sensor.

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