

Investigation the hexagonal cylindrical absorber for bio-sensing in optical regime

Mohammad Mirzabeygi¹ · Mohammad Naser-Moghadasi¹

Received: 4 November 2017 / Accepted: 15 January 2018 / Published online: 18 January 2018
© Springer Science+Business Media, LLC, part of Springer Nature 2018

Abstract Optical absorber is important for various applications like solar-cell or optical sensing such as optical imaging. This paper has investigated the various formations of the cylindrical hollow structure such as triangular, rectangular and hexagonal cross-section and shows the benefit of the hexagonal absorber for 150 THz and the parametric studies investigated for the hexagonal structure. For achieving the multiband absorber, we have used another hexagonal particle inside of the first model the same as the co-axial formation and obtained dual-band characteristic. We show that by the asymmetric model we have the ability to obtain Fano response for the prototype absorber which can be noticed for the wideband application. The electric field shows that the prototype absorber has dipole mode. Finally, we have checked the external material effect on frequency shift as a factor for material recognition. We have compared the frequency shift in hexagonal, co-axial and Fano model for various refractive indexes. The studies show that the co-axial model is more suitable for material recognition, in comparison to hexagonal and Fano models.

Keywords Absorber · Plasmonic · Hexagonal · Fano · Optical sensing

1 Introduction

Absorber structures are widely used in many microwave and optical systems, which can be used for reducing radar cross section in the microwave range (Soheilifar and Sadeghzadeh 2015). Of course, with the advent of micro and the nanometer sized devices, new applications for absorbers in optical frequencies have been proposed, which could be widely used in solar cells and small components for medical applications (Zarrabi et al. 2017a). Optical absorbers are justified based on plasmonic phenomena (Bouchon et al. 2012). One of the metamaterial branches that have been considered in recent years is metamaterial

✉ Mohammad Naser-Moghadasi
mn.moghaddasi@srbiau.ac.ir

¹ Faculty of Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran

absorbers, which have high flexibility in the design process to improve the absorption properties in the wide range of microwave frequencies (Wang et al. 2017; Heydari et al. 2017b). A metamaterial absorber usually consists of a periodic array of unit cells that consist of a dielectric as a substrate, where the metallic particle and the ground layer are placed on two sides of the dielectric (Saeed Arezoomand et al. 2015; Hao et al. 2010). These structures are made based on different forms of the metal element and the gap between the elements is produced a capacitance, which results in a deep reflection and absorption of the near-unit in resonance frequencies (Guo-Dong et al. 2013; Tak et al. 2016).

Due to the fact that metamaterial absorber structures have operated based on resonance mechanism, these structures have the narrow absorption bandwidth and it's a drawback for these kinds of absorbers (Jiu-Sheng 2014; Li et al. 2011). Therefore, several methods such as multi-layer structures and an array of unit cells have been proposed to achieve broadband absorption bandwidth, each of which has advantages and disadvantages (Aydin et al. 2008; Cheng et al. 2015). The absorbers are used in the THz and infrared spectral range and the optical spectrum for medical applications. Today, designing, measuring, and manufacturing metamaterial absorber for THz and Microwave has become very important (Wen et al. 2009; Wang et al. 2011). Various models of metamaterials such as SRR have been proposed for designing of dual-band and multi-band metamaterial absorber at the THz range (Li et al. 2011).

With the advent of nanotechnology in the field of terahertz and the optical range of many devices, such as metamaterial switches, nano-antenna, sensors, and absorbers are introduced in the terahertz and optical range (Amiri et al. 2016; Liao and Zhao 2015; Heydari et al. 2017a).

Metamaterials are considered as an important part of plasmonic applications, which are based on nano-particles in order to concentrate and manipulate light in applications of subwavelengths through surface plasmons (Zarrabi et al. 2017b; Ghasemi and Choudhury 2016). Plasmonics is a new technology that can limit electromagnetic waves in areas that are much smaller than the wavelengths (Ghasemi et al. 2017). Plasmonic nano-particles structures include metal nanoparticles on a dielectric (Jahangiri et al. 2017). Its major applications include the construction of optical complex circuits, optical lithography with sub-wavelength accuracy, and high-resolution imaging (Liu et al. 2010). Plasmons are collected of the surface polaritons that are distributed surface between metal and dielectric (Fang et al. 2012). Based on the plasmonic property in electromagnetic structures, new devices are being developed in the THz and optic fields (Ghorbanian et al. 2016). The absorption properties of these structures have led to the design of THz-adsorbent structures with multi-band properties (Withayachumnankul et al. 2014).

In this paper, we have debated about cylindrical hollow plasmonic absorber with various shapes for the cross-section and we have checked the result for triangular, rectangular and hexagonal. In the second step, the parametric studies have presented for the hexagonal structure for height, width, and radius. In addition, the electric field is checked and compared for various suggested models. In the last part, the frequency shift by using various external materials with different refractive indexes have checked for hexagonal, coaxial and Fano models. The frequency shift can be noticed as a parameter for material recognition.

2 Absorber design

Figure 1a shows the top view of three steps of the designing of the prototype absorber. Fig. 1b shows the side view of the hexagonal absorber where the $h_1 = 120$ nm is heightened of the gold hexagonal particle and the outer and inner radius are 90 and 80 nm, respectively, which is placed over the dielectric material of SiN with the refractive index of 1.96 and $h_2 = 20$ nm is assumed for this layer. The gold layer is placed under the dielectric

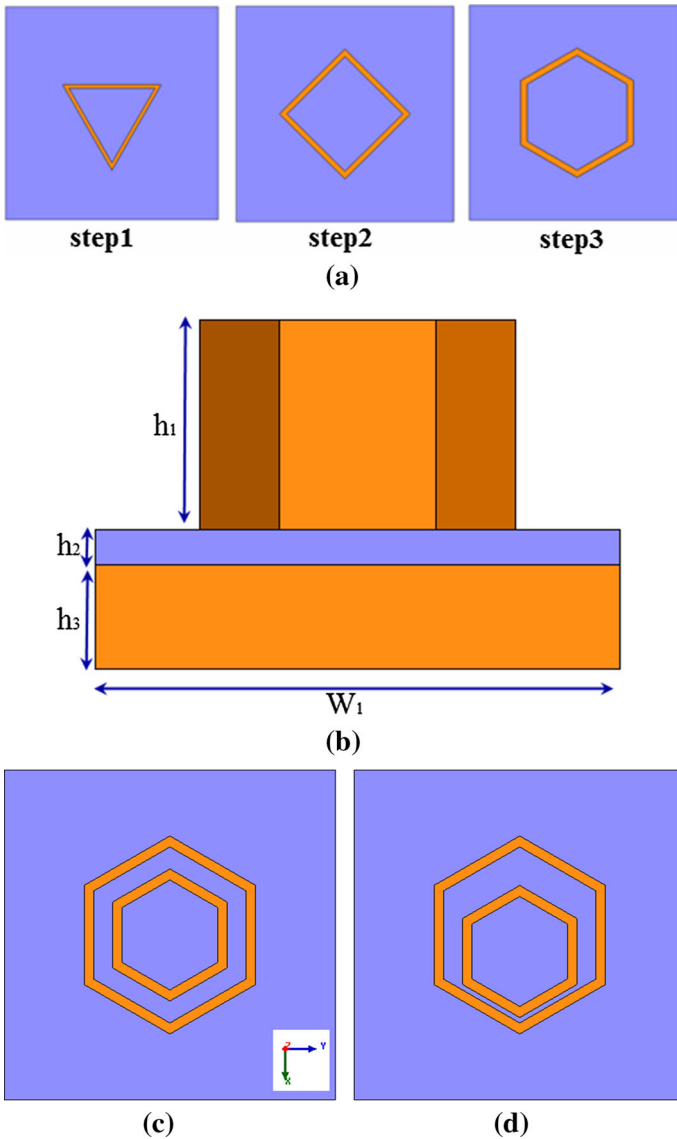


Fig. 1 The geometry of the prototype absorber **a** the top view of three basic steps for design absorber, **b** the side view of the prototype hexagonal absorber, **c** co-axial model hexagonal absorber and **d** Fano model hexagonal absorber

layer with the thickness of $h_3 = 120$ nm and for both gold layers we have used the Palik model in the CST microwave studio. The total size of the unit cell is chosen $W_1 = 300$ nm. In the second step, we have developed the hexagonal model by adding co-axial hexagonal structure with a radius of 90 nm as shown in Fig. 1c. For obtaining the Fano response, the displacement of the central hexagonal has noticed as presented in Fig. 1d while the asymmetrical formation has been noticed for Fano response in the nanoantenna before this (Cetin and Altug 2012; Zarrabi and Nasser-Moghadasi 2017b). Here, the TM mode is selected for the study with the periodic boundary condition based on the previous studies which have experimental and simulation (Wang et al. 2011).

3 Simulation of the particle

3.1 The shape effect on reflection

We have used the CST microwave studio for simulation of the suggested absorber based on time domain method (FIT). As shown in Fig. 2, we have compared the reflection in dB for triangular, rectangular and hexagonal cross sections with similar height (120 nm) and exactly the best result is obtained for the hexagonal absorbance. The triangular structure has a weak reflection at 150 THz and rectangular has a better reflection in comparison to triangular. However, the reflection is improved to -13 dB for hexagonal. Exactly, the hexagonal structure has high Q-factor which can be useful to improving the material recognition in optical sensor (Jahangiri et al. 2017).

3.2 The parametric studies of the hexagonal particle

The parametric studies for the hexagonal nanoparticle are presented in Fig. 3a–c, for the three parameters of height, width, and radius. As shown in Fig. 3a by increasing the height of the nanoparticle the reflection is reduced and it has limited effect on resonance frequency, so we can emphasize that by increasing the height of the particle, the absorbance is improved. The nanoparticle width effect on the reflection is presented in Fig. 3b for 10, 20

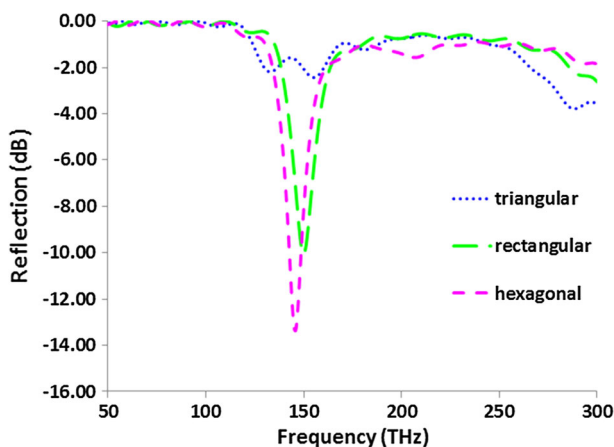
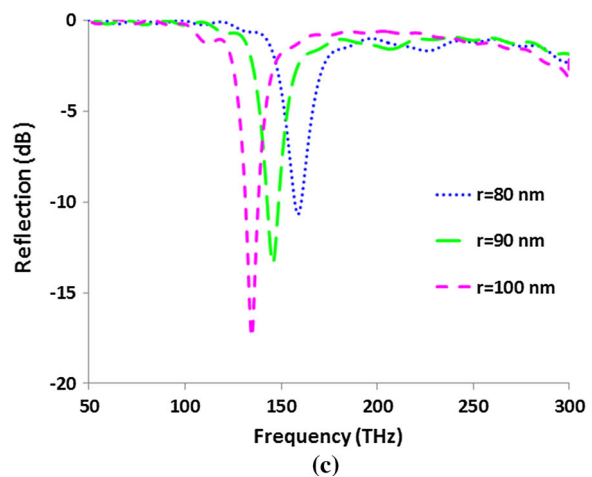
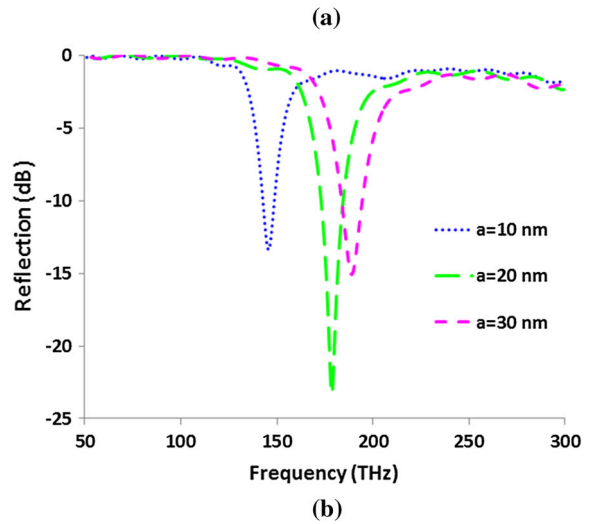
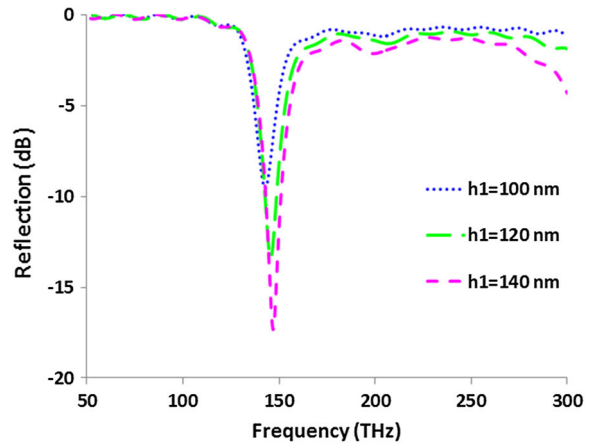


Fig. 2 The reflection of the three steps of design

Fig. 3 The reflection of the hexagonal absorber for **a** various heights, **b** various width and **c** various radios



and 30 nm while the outer radius is affirmed and 90 nm. As shown here, by increasing the width the frequency is shifted to the higher frequency and the best absorption is placed for 20 nm at 170 THz where the reflection is reduced to -23 dB. Figure 3c shows the radius effect of the hexagonal particle on the reflection with a constant width of the nanoparticle where the outer radius is 80, 90 and 100 nm. As shows here by increasing the outer radius, the reflection is reduced and the resonance is shifted to the lower frequency. For the hexagonal structure, by increasing the height of the particle, the Q-factor is increased too. However, for $a = 20$ nm the highest Q-factor is available. In addition, for $r = 100$ nm the Q-factor is more than the other studied cases such as $r = 90$ and $r = 80$ nm.

3.3 Co-axial model for dual band and Fano response reflection

In the third step, we have added the inner particle to the absorber as a coaxial structure. The coaxial structure shows the dual-band characteristic as shown in Fig. 4. For the basic model, the absorption frequencies are occurring at 140 and 190 THz. At the second model we have made some change in structure and in this case by 15 nm displacement of the central hexagonal in the X direction as presented in Fig. 1d the Fano response is appearing and to improve the reflection of the nanoparticle and in this situation the resonances are near to two each other and we have two absorption frequencies at 146 and 170 THz. Finally, in the modified structure, the height of the outer hexagonal is increased to 120 nm and the inner hexagonal width is increased to 20 nm. In this case, we have two absorption frequencies at 148 and 174 THz with the reflection of -6 and -12 dB respectively. For the Fano structure, by modifying the height and the width of the particle, the Q-factor is increased more than the both coaxial and Fano models.

3.4 The electric field distribution in simple structure

The electric field distribution of the various unit cells is compared in Fig. 5 and as shows here the plasmon polaritons are caused that most parts of the electric field are concentrated at the interface of the dielectric and nanoparticle. In addition, the thick gold layer under the dielectric reduces the transitions field by skin depth effect. Here we can see the dipole

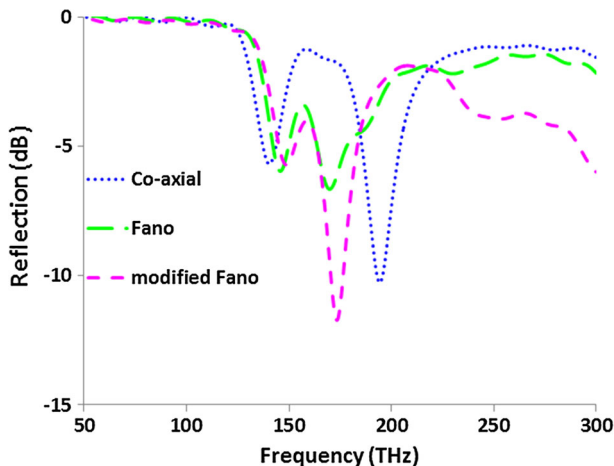


Fig. 4 The reflection of the hexagonal absorber for Fano, coaxial models

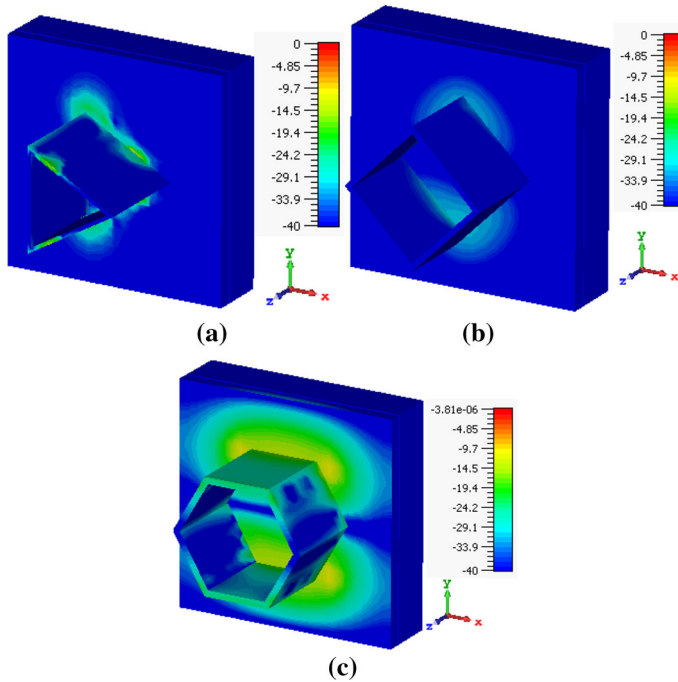


Fig. 5 Electric field distribution of the various unit cells **a** Triangular nanoparticle, **b** rectangular nanoparticle and **c** hexagonal nanoparticle

mode where the electric fields are dispensed in two sides of the nanoparticle. However, as is shown in Fig. 5a, in the triangular model, the asymmetrical shape of the nanoparticle is affected on electric field and the dipole distribution has some distortion, but in rectangular and hexagonal, we have the dipole mode as shown in Fig. 5b, c. Also, we should noticed that the surface plasmon are placed in the border between dielectric and metal while here we have height of the absorber is caused more surface plasmon are placed on substrate.

3.5 The electric field distribution in co-axial structure

The electric field distribution of the co-axial model is presented at Fig. 6a, b for 140 and 194 THz respectively, and as shown here, the structure has a tendency to save it dipole mode and then at Fig. 6c, d the electric field in the Fano response are checked and the electric field is presented for 146 and 170 THz respectively. However, in this case, the electric field tends to quad characteristic.

3.6 The material detection quality in the prototype absorber

For this step, we have placed the external materials with the height of the nano at inside and around of the nanoparticle. Here material with the various refractive indexes of 1.5, 1.75, 2 are checked for the hexagonal, co-axial and Fano model absorber and the frequency shifts are noticed as a detection factor (Ahmadvand et al. 2015; Zarrabi and Nasser-Moghadasi 2017a) and compared with the basic model where the refractive index is of 1. The frequency shifts are presented in Fig. 7a–c for these three cases. Figure 7a shows the

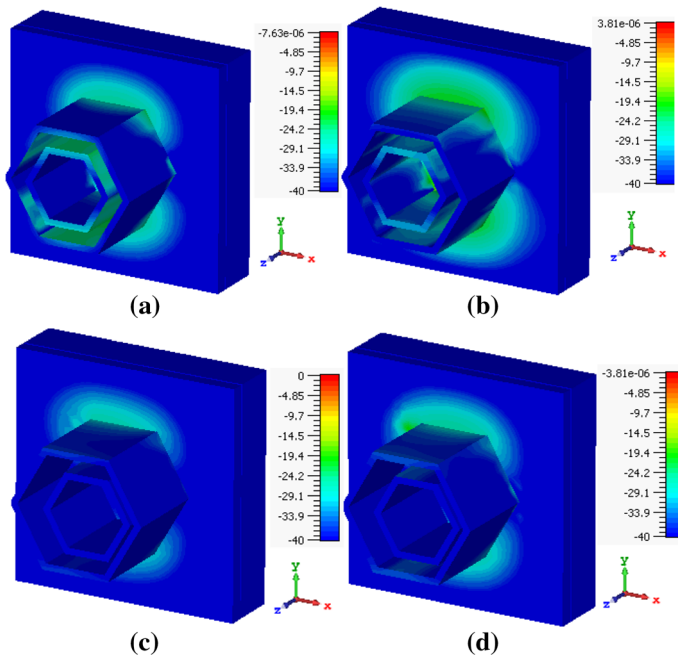


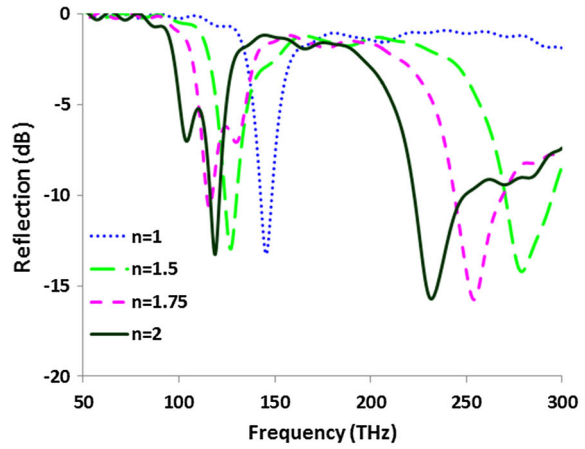
Fig. 6 Electric field distribution of the various unit cells **a** co-axial at 140 THz, **b** co-axial at 194 THz, **c** Fano model at 146 THz and **d** Fano model at 170 THz

reflection for the hexagonal absorber for various refractive indexes. As shown here, the absorber shows a dual-band characteristic and first resonances has a weak resonance too. In this case, the resonance is shifted from 140 THz for $n = 1$ –90 THz for $n = 2$. However, the main weakness is a distortion and overlaps of the first resonance for $n = 1.75$ and $n = 2$ at 110 THz which reduced the trust to this structure. The Co-axial model has studied at Fig. 7b and in this case, we have three resonances however the third resonance is placed over out studies range and so cannot be noticed. On the other hand, the first resonances value has good shifts, but the reflection value is reduced drastically and so we can neglect it and therefore only second resonance can be used for material detection in the range of 150 THz (for $n = 2$) to 194 THz (for $n = 1$).

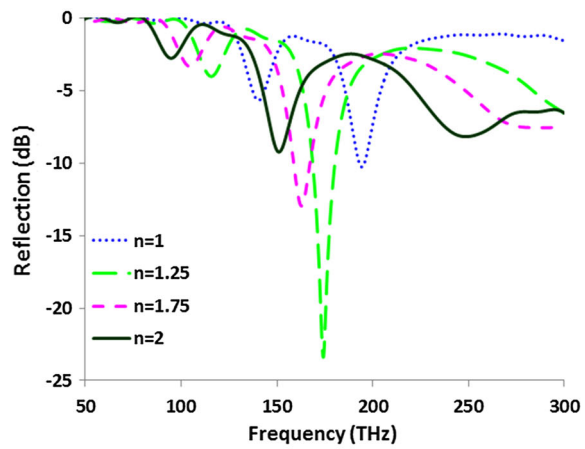
The Fano models have studied at Fig. 7c and in this case, we have three resonances the same as the co-axial model. However, this structure shows nonlinear manner and so it can make some distortion in material detection and so we cannot trust this model.

Exactly, here we should consider that the frequency shift for co-axial model is more than hexagonal and Fano model but on the other hand we should noticed that by increasing the index of material for the first resonance at co-axial model the reflection reduced drastically and it's a drawback of this structure where at Fano model we can see reflection enhancement and so absorbance is increased too. This factor can be considered for design solar-cell based on the biological material.

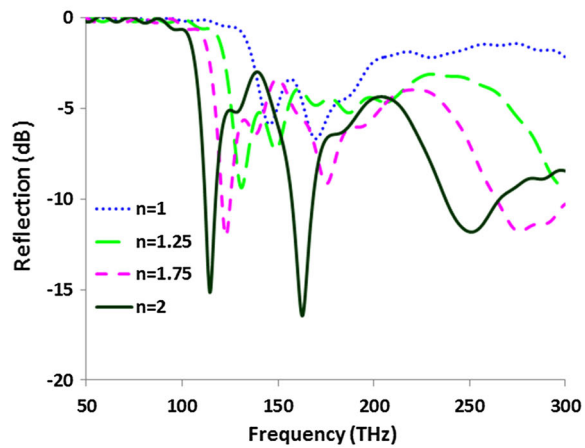
Fig. 7 The reflection of the absorbers for various materials for **a** the hexagonal absorber, **b** the co-axial absorber and **c** the Fano absorber



(a)



(b)



(c)

4 Conclusion

In this paper, we have studied the various shapes of the nanoparticle as the cylindrical plasmonic absorber. We have developed this absorber by using the coaxial model for obtaining dual-band characteristic and we show that by parametric studies we can optimize the basic model. Finally, we made a change in placement of the central element and with this change; the resonances are near together and show Fano shape in reflection. The frequency shifts by using various external materials were checked for hexagonal, coaxial and Fano models and we show that the coaxial model is more suitable for material recognition in comparison to Hexagonal and Fano model.

Acknowledgements The Authors would like to thank Ferdows B. Zarrabi (Science and Research Branch, Islamic Azad University, Tehran-Iran) for his helpful discussions and co-operation.

References

- Ahmadivand, A., Sinha, R., Pala, N.: Hybridized plasmon resonant modes in molecular metallodielectric quad-triangles nanoantenna. *Opt. Commun.* **355**, 103–108 (2015)
- Amiri, I.S., Ahmad, H., Ghasemi, M., Ismail, M.F., Aidit, S.N., Soltanian, M.R.K., Nafarizal, N.: Silicon-based microring resonators for multi-solitons generation for THz communication. *Opt. Quantum Electron.* **48**(8), 415 (2016)
- Aydin, K., Li, Z., Sahin, L., Ozbay, E.: Negative phase advance in polarization independent, multi-layer negative-index metamaterials. *Opt. Express* **16**(12), 8835–8844 (2008)
- Bouchon, P., Koechlin, C., Pardo, F., Haidar, R., Pelouard, J.-L.: Wideband omnidirectional infrared absorber with a patchwork of plasmonic nanoantennas. *Opt. Lett.* **37**(6), 1038–1040 (2012)
- Cetin, A.E., Altug, H.: Fano resonant ring/disk plasmonic nanocavities on conducting substrates for advanced biosensing. *ACS Nano* **6**(11), 9989–9995 (2012)
- Cheng, Y.Z., Withayachumnankul, W., Upadhyay, A., Headland, D., Nie, Y., Gong, R.Z., Bhaskaran, M., Sriram, S., Abbott, D.: Ultrabroadband plasmonic absorber for terahertz waves. *Adv. Opt. Mater.* **3**(3), 376–380 (2015)
- Fang, Z., Zhen, Y.-R., Fan, L., Zhu, X., Nordlander, P.: Tunable wide-angle plasmonic perfect absorber at visible frequencies. *Phys. Rev. B* **85**(24), 245401 (2012)
- Ghasemi, M., Choudhury, P.K.: Nanostructured concentric gold ring resonator-based metasurface filter device. *Opt. Int. J. Light Electron Opt.* **127**(20), 9932–9936 (2016)
- Ghasemi, M., Choudhury, P.K., Baqir, M.A., Mohamed, M.A., Md Zain, A.R., Majlis, B.Y.: Metamaterial absorber comprising chromium–gold nanorods-based columnar thin films. *J. Nanophotonics* **11**(4), 043505 (2017)
- Ghorbanian, A., Kashani, A.M., Javan, A.M.: The effects of silver slabs in nanodisk resonator of plasmonic tunable band-pass filter. *Opt. Int. J. Light Electron Opt.* **127**(4), 1884–1888 (2016)
- Guo-Dong, W., Ming-Hai, L., Xi-Wei, H., Ling-Hua, K., Li-Li, C., Zhao-Quan, C.: Multi-band microwave metamaterial absorber based on coplanar Jerusalem crosses. *Chin. Phys. B* **23**(1), 017802 (2013)
- Hao, J., Wang, J., Liu, X., Padilla, W.J., Zhou, L., Qiu, M.: High performance optical absorber based on a plasmonic metamaterial. *Appl. Phys. Lett.* **96**(25), 251104 (2010)
- Heydari, S., Bazgir, M., Zarrabi, F.B., Gandji, N.P., Rastan, I.: Novel optical polarizer design based on metasurface nano aperture for biological sensing in mid-infrared regime. *Opt. Quantum Electron.* **49**(2), 83 (2017a)
- Heydari, S., Jahangiri, P., Sharifi, A., Zarrabi, F.B., Saeed Arezomand, A.: Fractal broken-cross with Jerusalem load absorber for multiband application with polarization independence. *Microw. Opt. Technol. Lett.* **59**(8), 1942–1947 (2017b)
- Jahangiri, P., Zarrabi, F.B., Naser-Moghadas, M., Saeed Arezomand, A., Heydari, S.: Hollow plasmonic high Q-factor absorber for bio-sensing in mid-infrared application. *Opt. Commun.* **394**, 80–85 (2017)
- Jiu-Sheng, L.: Absorption-type terahertz wave switch based on Kerr media. *Opt. Commun.* **313**, 388–391 (2014)
- Li, L., Yang, Y., Liang, C.: A wide-angle polarization-insensitive ultra-thin metamaterial absorber with three resonant modes. *J. Appl. Phys.* **110**(6), 063702 (2011)

- Liao, Y.-L., Zhao, Y.: A wide-angle TE-polarization absorber based on a bilayer grating. *Opt. Quantum Electron.* **47**(8), 2533–2539 (2015)
- Liu, N., Mesch, M., Weiss, T., Hentschel, M., Giessen, H.: Infrared perfect absorber and its application as plasmonic sensor. *Nano Lett.* **10**(7), 2342–2348 (2010)
- Saeed Arezoomand, A., Zarrabi, F.B., Heydari, S., Gandji, N.P.: Independent polarization and multi-band THz absorber base on Jerusalem cross. *Opt. Commun.* **352**, 121–126 (2015)
- Soheilifar, M.R., Sadeghzadeh, R.A.: Design, fabrication, and characterization of stacked layers planar broadband metamaterial absorber at microwave frequency. *AEU Int. J. Electron. Commun.* **69**(1), 126–132 (2015)
- Tak, J., Jin, Y., Choi, J.: A dual-band metamaterial microwave absorber. *Microw. Opt. Technol. Lett.* **58**(9), 2052–2057 (2016)
- Wang, J., Chen, Y., Chen, X., Hao, J., Yan, M., Qiu, M.: Photothermal reshaping of gold nanoparticles in a plasmonic absorber. *Opt. Exp.* **19**(15), 14726–14734 (2011)
- Wang, L., Hu, C., Wu, X., Xia, Z., Wen, W.: Multi-band metamaterial absorber with arbitrary polarization and wide-incident angle. *Appl. Phys. A* **123**(10), 651 (2017)
- Wen, Q.-Y., Zhang, H.-W., Xie, Y.-S., Yang, Q.-H., Liu, Y.-L.: Dual band terahertz metamaterial absorber: design, fabrication, and characterization. *Appl. Phys. Lett.* **95**(24), 241111 (2009)
- Withayachumnankul, W., Shah, C.M., Fumeaux, C., Ung, B.S.-Y., Padilla, W.J., Bhaskaran, M., Abbott, D., Sriram, S.: Plasmonic resonance toward terahertz perfect absorbers. *ACS Photonics* **1**(7), 625–630 (2014)
- Zarrabi, F.B., Nasser-Moghadasi, M.: Plasmonic split ring resonator with energy enhancement for the application of bio-sensing and energy harvesting based on the second harmonic generation and multi Fano resonance. *J. Alloys Compd.* **706**, 568–575 (2017a)
- Zarrabi, F.B., Nasser-Moghadasi, M.: Investigated the Fano resonance in the nano ring arrangement. *Opt. Int. J. Light Electron Opt.* **138**, 80–86 (2017b)
- Zarrabi, F.B., Bazgir, M., Ebrahimi, S., Saeed Arezoomand, A.: Fano resonance for UI nano-array independent to the polarization providing bio-sensing applications. *J. Electromagn. Waves Appl.* **31**(14), 1444–1452 (2017a)
- Zarrabi, F.B., Bazgir, M., Naser-Moghadasi, M., Saeed Arezoomand, A.: Symmetrical metamaterial nano particle for improving the Fano mode for biological application at mid infrared. *Opt. Int. J. Light Electron Opt.* **130**, 1191–1196 (2017b)