Simple trilayer metamaterial absorber associated with Fano-like resonance

Raghwendra Kumar
S. Anantha Ramakrishna
Simple trilayer metamaterial absorber associated with Fano-like resonance

Raghwendra Kumar a,b,* and S. Anantha Ramakrishna a

aIndian Institute of Technology, Department of Physics, Kanpur, India
bPatna University, Bihar National College, Department of Physics, Patna, India

Abstract. A simple trilayer metamaterial absorber suitable for large area fabrication associated with a Fano-like resonance is numerically investigated and presented at infrared frequencies. The finite-element method-based COMSOL Multiphysics is used for numerical simulations and to understand the mechanism of absorption in the system. The absorber consists of photoresist disk arrays on a silicon substrate followed by a consecutive trilayer of gold, ZnS, and gold. The absorption is caused by the simultaneous excitation of the cavity and guided-mode resonances in the structures, whereas the Fano-like resonance arises due to the interference of these two modes. The coupled mode theory is used to describe the Fano-like resonance in the system. The design can easily be implemented for large area fabrications as it separates the structuring and deposition processes and makes them sequential, and avoids expensive and complex lift-off or etching processes. The spectral position of the resonance can be tuned by just controlling the thickness of the trilayer instead of the structural size and shape modification of the micro/nanostructures as is usually done in conventional metamaterial absorbers. © 2020 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.JNP.14.016011]

Keywords: metamaterial absorber; Fano resonance; guided-mode resonance; cavity mode resonance.

Paper 19124 received Sep. 16, 2019; accepted for publication Jan. 22, 2020; published online Mar. 18, 2020.

1 Introduction

Electromagnetic metamaterials are artificial nano/microstructured composites of subwavelength-sized metallic and dielectric components that depend on their structures to give rise electromagnetic responses. These composites exhibit exotic electromagnetic responses such as complete absorption of electromagnetic waves, invisibility cloaking, negative refraction, and subdiffraction limited imaging using super lenses, which are not available in natural occurring materials. These composites usually consist of identical structured unit cells, arranged typically in a periodic fashion, and can be considered as bulk homogeneous media described as an effective medium through effective medium parameters. Among these responses, the perfect absorption of electromagnetic wave as metamaterial absorbers has received considerable attention due to their potential applications for radar stealth at microwave frequencies, controllable thermal emitters, sensitive infrared detectors and microbolometer arrays, thermophotovoltaics at infrared frequencies, etc. A perfect metamaterial absorber with nearly perfect absorption caused by simultaneous excitation of electric and magnetic resonances to create an impedance match of a resonant medium with the surrounding medium was first proposed by Landy et al. Many absorbers based on different physical mechanisms such as antireflection coating, resonant/impedance matching, localized surface plasmons resonance, cavity mode resonance, guided-mode resonance (GMR), ohmic losses in the visible regime, and lossy dielectric in the microwave regime have been demonstrated theoretically and experimentally in a wide spectral range. Due to the scale invariance of Maxwell’s equations, it has been possible to easily adapt metamaterials for different frequencies. The main purpose of a metamaterial absorber is to reduce reflections and increase absorption within a given spectral range.
Generally, metamaterial absorbers show symmetric (Gaussian) absorption profiles, but asymmetric absorption profiles have also been observed due to the interference of different modes arising in the system. Fano resonance is used to describe the asymmetric resonance arising due to the constructive and destructive interference of a discrete resonance state with a broadband continuum state. This phenomenon and the underlying mechanisms are common and appear in many domains of physical sciences in a variety of micro/nanostructures such as plasmonics and metamaterials, quantum dots, and photonic crystals. The asymmetric Fano resonance profile promises a variety of applications in a wide range of photonic devices, such as sensors, optical filters, detectors, nonlinear devices, and slow-light devices. In the last few years, with advancements in micro/nanofabrication techniques and the development of integration techniques, Fano resonance has been widely investigated in micro/nanostructured systems.

The metamaterial perfect absorbers based on impedance matching typically involve a complex geometrical design and their fabrication tolerance is quite severe. However, for many infrared applications, such as solar thermal devices or thermal camouflage, control of the emissivity and the absorptivity is required over very large surfaces ranging from a few square meters to even square kilometers. It is a great manufacturing challenge to produce metamaterials that have complex micrometric or even submicrometric structures containing metallic as well as dielectric constituents over these large areas with good fidelity and over realistic time scales. In this work, we present numerical studies on an innovative design of a trilayer metamaterial absorber suitable for large area fabrication. The absorber consists of a trilayer of Au/ZnS/Au thin films on photoresist microstructures and depends on the cavity and GMR of the structure to produce high absorptivity. The design can be easily implemented for sequential patterning and deposition processes without lift-off or etching and makes the process applicable for large area metamaterial surfaces.

2 Design of the Metamaterial Absorber by Electromagnetic Simulations

The unit cell of the metamaterial absorber is shown in Fig. 1. It consists of a photoresist disk of height \( h \) 500 nm and diameter \( d \) 1.68 \( \mu \)m on a silicon substrate with consecutive layers of bottom gold of thickness \( t_1 \) (160 nm), ZnS of thickness \( t_2 \) (300 nm), and top gold of thickness \( t_3 \) (30 nm) on the top of photoresist disk as well as on the other parts of the silicon substrate not covered by the photoresist disk. In essence, the structure consists of three disks of gold and ZnS. Of these three, two are of gold and one is of ZnS placed on the photoresist disk with continuous layering.
thin films of Au/ZnS/Au at a lower level on the substrate. Due to the trilayer, a cavity is formed between the bottom layer of gold on the top of the photoresist disk and the silicon substrate, because the refractive index of the photoresist is lower than that of silicon and gold is itself highly reflecting. A waveguide is formed in the ZnS layer between the gold layers on the silicon substrate and the ZnS itself.

The numerical simulation is carried out using the radio frequency module of the COMSOL Multiphysics software. The design is optimized on the basis of trial and error methods. We tried many designs of the metamaterial absorber suitable for large area fabrication and finally came up with this simplified design. Periodic boundary conditions are used along the transverse x and y directions to simulate an infinite array of unit cells to reduce the complexity of the simulation. Perfectly matched layers are used along the propagation direction (z direction) of the waves at a sufficient distance from the structure to prevent their reflection from the top and bottom domain boundaries. The dispersive refractive indices (real and imaginary parts) of ZnS, gold, and silicon are taken from Refs. 43–45, respectively. The refractive index of the photoresist in the simulations is considered as 1.58. The transmittance (T) and reflectance (R) of the structure are calculated using port conditions at a plane above the structure in the air and below the structure in the substrate. The absorbance is calculated using energy conservation as $A(\omega) = 1 - R(\omega) - T(\omega)$ at the corresponding wavelength.

The simulated reflectance, transmittance, and absorbance spectra of the metamaterial are shown in Fig. 2(a). The transmittance spectrum consists of two peaks at wavelengths 9 and 9.8 $\mu$m. The reflectance spectrum consists of three dips at wavelengths of 6.4, 9.1, and 9.85 $\mu$m. The absorbance spectrum consists of three peaks at wavelengths of 6.4, 9.1, and 10 $\mu$m. Color maps of the normalized magnetic field at different resonant wavelengths 9.1, 6.4, 9.6, and 10 $\mu$m, are shown in Figs. 2(b)–2(e), respectively. It is clear from Fig. 2(b) that the fields are strongly confined in the waveguide as well as in the cavity at the 9.1 $\mu$m wavelength. The field is highly localized in the ZnS layer between the two layers of gold on the top of the photoresist disk at the 6.4 $\mu$m wavelength. Figures 2(d) and 2(e) show the normalized magnetic field maps at resonant wavelengths 9.6 and 10 $\mu$m, respectively. It is clear from Fig. 2(d) that the fields are distributed along the Au/Si interface and not localized within the cavity. The fields are distributed along the Au/Si interface and weakly within the cavity. There is no contribution of the resonance at wavelength 6.4 $\mu$m in the resultant interfering resonances at the 9.1 $\mu$m wavelength. In order to understand the contribution of the

![Fig. 2](image-url)
different resonances in the interference at 9.1 μm, we note that the resonance at 6.4 μm, which is not close to 9.1 μm, can be eliminated by removing the top layers of gold and ZnS from the photoresist disk.

The simulated reflectance, transmittance, and absorbance spectra of the metamaterial absorber without the top ZnS and gold layers on the photoresist disk with the corresponding unit cell as the inset are shown in Fig. 3(a). The normalized time average power flow in a color map with its arrow volume plot to understand the power flow in the system is shown in Fig. 3(b). It is clear that the power flows into the cavity and the waveguide as well as along the interface of gold and silicon. The color maps of the normalized magnetic fields at wavelengths of 9.1 and 10 μm are shown in Figs. 3(c) and 3(d), respectively.

Figure 4 shows the transmittance, reflectance, and absorbance spectra for different periodicities of the photoresist disk array. The other parameters, such as the thickness of the bottom and top gold layers, ZnS layer, and height of the photoresist disk are kept constant. An extra resonance appears upon increasing the periodicity of the disk array, and it shifts toward longer wavelengths. But the resonance corresponding to the cavity mode remains almost independent of the periodicity of the disk array. There is an asymmetric resonance for a particular value of periodicity of 2.8 μm that arises due to the interference of a fixed resonance (cavity mode resonance) and the resonance caused by changing the periodicity (guided mode and Wood’s anomaly resonances) of the disk array [Fig. 4(b)]. The interfering resonances corresponding to the different modes separate for the 4 μm periodicity of the disk array [see in Fig. 4(c)]. At periodicity of 2 μm, only one resonance appears, which arises due to the confinement of fields into the cavity, whereas at 5 μm periodicity, an extra resonance appears around 12.4 μm.

Figure 5 shows the color maps of the normalized magnetic field and arrow volume plot of the normalized time average power flow at different resonance wavelengths for the 4 μm periodicity of the disk array. Figure 5(a) shows the color plot of the normalized magnetic field at the 8.8 μm wavelength, where the field is only localized in the cavity formed between the gold layer on the photoresist disk and the Si substrate. The corresponding color map of the normalized time average power with its arrow volume plot is shown in Fig. 5(d). Figure 5(b) shows the color map of the normalized magnetic field at the 13.7 μm wavelength, where the field is only extended into the silicon substrate from the gold layer side. The corresponding color map of the normalized time average power with its arrow volume plot is shown in Fig. 5(e). The arrow volume power flow indicates the flow of power into the substrate along the gold and silicon interface.
Figure 5(c) shows the color map of the normalized magnetic field at the 10.3 μm wavelength, where the field is confined in the sandwiched ZnS layer between the bottom gold layer on the substrate and the top gold layer on ZnS itself. The corresponding color map of the normalized time average power with its arrow volume plot is shown in Fig. 5(f). It is clear that most of the power flows into the sandwiched ZnS layer.

Figures 6(a) and 6(b) show the simulated reflectance spectra at different incident angles for the TE and TM polarizations, respectively. There is a slight decrement in the minimum of reflectance spectra around the 9 μm wavelength upon increasing the angle of incidence in case of the TE polarization, whereas it remains almost constant with a slightly longer wavelength shift in the case of the TM polarization. The minimum at around 10 μm wavelength in case of the TE polarization slightly decreases in amplitude upon increasing the angle of incidence, whereas it slightly decreases in amplitude with longer wavelength shifts in the case of the TM polarization. An extra minimum appears in the reflectance spectra around the 7.5 μm wavelength in the case of the TM polarization, and it shifts toward longer wavelengths upon increasing the
angle of incidence. The minimum in the reflectance spectra around the 6.5 μm wavelength remains almost constant upon increasing the angle of incidence in both polarizations. The minimum in the reflectance spectrum around the 4.5 μm wavelength slightly increases in amplitude upon increasing the angle of incidence for both polarizations, but increases faster in the case of the TM polarization compared to that of the TE polarization. Splitting in the resonance minimum at the 4.5 μm wavelength appears upon increasing the angle of incidence in case of the TM polarization, whereas there is no such splitting in case of the TE polarization.

Figure 7 shows the simulated electromagnetic response of the metamaterial absorber for different values of the $g$ at normal incidence. The value of $g$ is changed by changing the thickness of the bottom gold layer, and the other parameters are kept constant. In the reflectance spectra [see Fig. 7(a)], the minimum at the 9.1 μm wavelength shifts toward shorter wavelengths, and the minimum at the 9.8 μm wavelength remains almost constant upon increasing the value of $g$, whereas the minimum at the 6.4 μm wavelength increases upon increasing the gap. In the transmittance spectra [see Fig. 7(b)], the fundamental order transmission amplitude at the 9.8 μm wavelength decreases, whereas the higher order transmission amplitude at the 6.4 μm wavelength increases upon increasing the gap. The transmission peak at the 9.1 μm wavelength shifted toward shorter wavelengths upon increasing the gap. In the absorbance spectra [see Fig. 7(c)], the absorption peak around the 10 μm wavelength decreases with a minimal shift toward shorter wavelengths upon increasing the gap. There is a shift in the absorption peak.
around 9 μm toward shorter wavelengths and an increase in the absorption peak around the 6.4 μm wavelength upon increasing the value of g.

Figure 8 shows the simulated electromagnetic response of the metamaterial absorber for different heights of the photoresist disk at normal incidence. The height of the photoresist disk is varied by changing the thicknesses of the ZnS layer and the bottom gold layer to maintain the value of g. The dips in the reflectance spectra at resonance wavelengths 9.1 and 9.8 μm decrease in magnitude with a slight shift in position toward longer wavelengths upon decreasing the height of the disk. The peaks in transmittance spectra at 9.1 and 9.8 μm remain almost constant in magnitude with a slight shift in position toward longer wavelengths upon decreasing the height of the disk. The localized spoof surface plasmon resonance at 6.4 μm is also shifted toward longer wavelengths upon decreasing the height of the photoresist disk.

Figure 9(a) shows the simulated reflectance spectrum (black line) at normal incidence of the metamaterial absorber with the corresponding Fano fit profile (red line) using the coupled mode theory (CMT) of one port and two modes. There are two minima at 9.1 and 9.8 μm wavelengths in the reflectance spectrum, which correspond to the cavity mode resonance and GMR, respectively. Figure 9(b) shows the individual Fano fitted profiles corresponding to the two

![Fig. 8](image-url)

**Fig. 8** The simulated (a) reflectance, (b) transmittance, and (c) absorbance spectra of the metamaterial for different heights of the photoresist disk as 200 nm ($t_1 = 100$ nm, $t_2 = 60$ nm, and $t_3 = 30$ nm), 300 nm ($t_1 = 160$ nm, $t_2 = 100$ nm, and $t_3 = 30$ nm), 400 nm ($t_1 = 160$ nm, $t_2 = 200$ nm, and $t_3 = 30$ nm), and 500 nm ($t_1 = 160$ nm, $t_2 = 300$ nm, and $t_3 = 30$ nm) at normal incidence. The other parameters used for simulations: periodicity of the disk array and diameter of the disk are 2.8 μm and 1.68 μm, respectively.

![Fig. 9](image-url)

**Fig. 9** (a) Simulated reflectance spectrum (black line) with Fano fit (red line) and (b) Fano fitted reflectance spectra corresponding to the individual resonance. The parameters used for simulations: periodicity of the disk array, disk height, disk diameter, bottom gold layer thickness, ZnS layer thickness, and top gold layer thickness are 2.8 μm, 0.5 μm, 1.68 μm, 160 nm, 300 nm, and 30 nm, respectively. The fitting parameters: $\omega_1 = 65.6$ THz, $\omega_2 = 60.73$ THz, $\gamma_1 = 6.42$ THz, $\gamma_2 = 1.86$ THz, $\gamma_1 = 6.4$ THz, $\gamma_2 = 3.0$ THz, and $\gamma_0 = 6.53$ THz.
coupling modes. This is plotted using the same fitting parameters as are used to fit the asymmetric reflectance spectrum in Fig. 9(a). The individual profile is plotted by switching off the other corresponding resonance. For example, for the cavity mode resonance, the value of \( \omega_2 = 0 \), and similarly for GMR, the value of \( \omega_1 = 0 \) [see Eq. (1)].

3 Discussion

The mechanism of absorption of electromagnetic waves can be understood from the illustration of different exciting modes as shown in the schematic diagram of the unit cell of the metamaterial absorber (see Fig. 1). A part of the diffracted electromagnetic waves from different disks enters into the different modes through the gap (\( g \)) between the bottom layer of gold on the photoresist disk and the top gold layer on the ZnS layer on uncovered portions of the substrate by the photoresist disk. The part coupled into the cavity mode gets multiply reflected between the gold layer and the silicon substrate and causes trapping inside.\(^{46}\) Similarly, the part coupled into the waveguide mode propagates in the ZnS layer of the waveguide,\(^{47}\) and the rest of it just propagates at the interface of the gold and silicon layers. The same happens by coupling through the gap with other disks. Thus the waves in the ZnS layer travel in forward and backward directions in the waveguide and cause the formation of standing waves. The waves propagating along the plane at the interface of gold and silicon are absorbed and do not contribute to the transmittance, and the corresponding phenomenon is known as Wood’s anomaly.\(^{48}\)

Figure 2(a) shows the simulated electromagnetic response of the metamaterial absorber. The asymmetric electromagnetic response is caused by the simultaneous excitation and interaction of the cavity mode, guided mode, and Wood’s anomaly resonances, which result in a Fano-like resonance. The Fano-like resonance arises due to the interference of the continuum mode (cavity mode resonance) and the discrete modes (GMR and Wood’s anomaly) resonances. The simulated absorption spectrum consists of three peaks at wavelengths 6.4, 9.1, and 10 \( \mu \)m. The peak at the wavelength of 6.4 \( \mu \)m corresponds to the metamaterial absorption peak due to the presence of the trilayer (Au/ZnS/Au) on the top of the photoresist disk.\(^{49}\) There is no contribution of this resonance in the Fano-like resonance, so it is neglected in the further simulations by not including the top gold and ZnS layers on the photoresist disk.

Figure 3 shows the simulated electromagnetic response without considering the top gold and ZnS layers on the photoresist disk. However, there is still an appearance of a peak in the absorption spectrum at 6.4 \( \mu \)m, which is due to the localized spoof surface plasmons at the corner of the gold disk placed on the top of the photoresist disk. There is no effect of the removal of the top gold and ZnS layers from the photoresist disk on the other resonances, as is seen in Fig. 3(a). The arrow volume plot of the normalized time average power flow with its color map is shown in Fig. 3(b). The simultaneous excitation of the cavity mode, guided mode, and Wood’s anomaly can be seen through the coupling of power flow into each mode. The simultaneous excitation of all these modes can be seen in the color map of the normalized magnetic fields in Fig. 3(c). The propagation of the diffracted wave at the interface of gold and silicon can be seen in Fig. 3(d).

To understand the Fano-like resonance better and to elucidate the contribution of different modes in the Fano resonance, simulations are carried out for different periodicities of the photoresist disk array, which are shown in Fig. 4. Only the cavity mode resonance exists in the case of the photoresist disk array with 2 \( \mu \)m periodicity. The existence of this mode is independent of the periodicity of the disk array and is always associated with the unit cell, and hence is regarded as the continuum mode, whereas the existence of the GMR and Wood’s anomaly are conditional and hence regarded as discrete modes. Interference of the continuum and discrete modes is conditional, and it only happens at 2.8 \( \mu \)m periodicity [Fig. 4(b)]. For a periodicity of 4 \( \mu \)m, these interfering modes separate in frequency [Fig. 4(c)], and the modes corresponding to the resonance wavelengths of 8.8, 10.3, and 13.7 \( \mu \)m are the cavity mode, guided mode, and Wood’s anomaly, respectively. The existence of the cavity mode can be seen even at 5 \( \mu \)m periodicity [Fig. 4(d)].

The color maps of the normalized magnetic field and normalized time average power flow with its arrow volume plot at different resonant wavelengths corresponding to 4 \( \mu \)m periodicity of the disk array are shown in Fig. 5. Excitation of cavity mode resonance can be understood by
the confinement of the magnetic field in the cavity and arrow volume plot of the time average power from Figs. 5(a) and 5(d), respectively. Excitation of the GMR can be understood by the confinement of the magnetic field in the waveguide and arrow volume plot of the time average power from Figs. 5(c) and 5(f), respectively. Similarly, excitation of the Wood’s anomaly resonance can be understood from Figs. 5(b) and 5(e).

The effect of spoof surface plasmon polaritons can be understood from the angle-dependent reflectance spectra of the metamaterial absorber for the TE and TM polarizations [see Figs. 6(a) and 6(b)]. In case of the TE polarization, the magnitude of the electric field remains constant, so there is only a slight variation in the magnitudes of dips and peaks in the reflectance spectra at different incident angles. In case of the TM polarization, the magnitude of the electric field changes due to which the coupling condition for the spoof SPPs changes, and hence there is a finite variation in the magnitudes of dips and peaks as well as a spectral shift in the corresponding resonance.50

The minimum in the reflectance spectra as well as the corresponding peak in absorbance and transmittance spectra around the 9 μm wavelength shift toward shorter wavelengths upon increasing the value of $g$ (Fig. 7). This can be understood from the circuit model theory of a metamaterial absorber. The resonance frequency is defined as $\omega = 1/\sqrt{LC}$ on the basis of the circuit model, where $L$ and $C$ are the effective inductance and capacitance corresponding to the metamaterial absorber.31 In the proposed metamaterial absorber, upon increasing the value of $g$, the effective capacitance decreases, which results in an increase in the resonance frequency, and hence a shorter wavelength shift in the resonance.

The decrease in magnitude of the absorbance with decreasing the height of the disk is attributed to less diffraction of the wave from the disks and hence less coupling in different resonance modes (Fig. 8). The slightly longer wavelength shift of the resonances corresponding to the cavity and guided mode arises due to the coupling of the wave at different angles in the cavity and waveguide. Since the refractive index of the photoresist is less than that of gold and ZnS, with the decrease in the height of photoresist disk, there is an overall increase in the refractive index around the localized spots of the field. Hence, there is a longer wavelength shift in the localized spoof surface plasmon resonance.

The CMT has also been used to describe the Fano asymmetric line profile that arises due to the interference of continuum and discrete mode resonances in metamaterial absorbers.52 Since this metamaterial absorber has two main resonances; one is the cavity mode resonance and the other is GMR, the CMT with the one-port and two-modes resonator model can be used to describe the asymmetric reflectance spectra of the metamaterial absorber.53 The reflectance $r$ corresponding to the metamaterial absorber can be written as

$$r = -1 + \frac{2(W_1\gamma_2 + W_2\gamma_1 - 2\gamma_0\sqrt{\gamma_1\gamma_2})}{(W_1W_2 - |\gamma_0|^2)}, \quad (1)$$

where $W_i = j(\omega - \omega_i + \gamma_i + \gamma'_i)$, $(i = 1, 2)$ $\omega_i$ is resonant frequency corresponding to the $i$’th mode, $\gamma_i$ is the radiation loss rate due to the interaction between the $i$’th mode and the outgoing wave, $\gamma'_i$ is the intrinsic loss rate associated with the $i$’th mode, and $\gamma_0$ is the coupling coefficient between the modes. The first two terms of the numerator of the second part of Eq. (1) describe the responses of two modes independently after coupling modulation, whereas the last term $\sqrt{\gamma_1\gamma_2}$ describes the response of the cross coupling between the two modes after coupling modulation. For the metamaterial absorber, the fitted parameters are: the radiation loss rates for the two modes are $\gamma_1 = 6.42$ THz and $\gamma_2 = 1.86$ THz; the intrinsic loss rates of the two modes are $\gamma'_1 = 6.4$ THz and $\gamma'_2 = 3.0$ THz; the coupling between modes occurs at $\gamma_0 = 6.53$ THz; the resonant frequencies of the corresponding modes are $\omega_1 = 65.6$ THz and $\omega_2 = 60.73$ THz.

The fitted parameters match well with the expected parameters such as the spectral position of resonances and bandwidth of the individual resonances. It is clear that the asymmetric profile is mainly caused by the interference of the cavity mode resonance and the GMR. The response of the individual resonance using the same fitted parameters as for the fitting of the reflectance spectrum [see in Fig. 9(a)] is plotted in Fig. 9(b).
4 Conclusions

We have proposed a very simple design of a trilayer metamaterial absorber with band selective absorptivity/ emissivity suitable for large area fabrication. The origin of absorption as well as the asymmetric nature of the absorption profile has been understood. The absorption is caused due to the simultaneous excitation of the cavity and GMRs in the structures, whereas the asymmetric profile is caused due to the interference of the continuum mode (cavity mode) and discrete modes (guided mode and Wood’s anomalies). This design can be easily implemented for large area fabrications by separating the structuring and deposition processes and making them sequential, as well as avoiding expensive and complex lift-off or etching processes. This approach can be easily adapted for the rapid production of large area fabrications on the industrial level. The spectral position of the resonance can be tuned without structural shape and size modification by changing the thicknesses of the gold and ZnS layers.

Acknowledgments

R. K. would like to thank the Council of Scientific and Industrial Research (CSIR), India, for a fellowship.

References

1. S. A. Ramakrishna and T. M. Grzegorczyk, Physics and Applications of Negative Refractive Index Materials, CRC Press, Boca Raton (2008).
2. H. Durmaz, Y. Li, and A. E. Cetin, “A multiple-band perfect absorber for Seira applications,” Sens. Actuators B 275, 174–179 (2018).
3. D. Schurig et al., “Metamaterial electromagnetic cloak at microwave frequencies,” Science 314(5801), 977–980 (2006).
4. R. A. Shelby, D. R. Smith, and S. Schultz, “Experimental verification of a negative index of refraction,” Science 292(5514), 77–79 (2001).
5. J. B. Pendry, “Negative refraction makes a perfect lens,” Phys. Rev. Lett. 85(18), 3966–3969 (2000).
6. V. G. Veselago, “The electrodynamics of substances with simultaneously negative values of and μ,” Sov. Phys. Usp. 10(4), 509–514 (1968).
7. S. A. Ramakrishna, “Physics of negative refractive index materials,” Rep. Prog. Phys. 68(2), 449–521 (2005).
8. X. Liu et al., “Taming the blackbody with infrared metamaterials as selective thermal emitters,” Phys. Rev. Lett. 107(4), 045901 (2011).
9. S. Ogawa et al., “Wavelength selective uncooled infrared sensor by plasmonics,” Appl. Phys. Lett. 100(2), 021111 (2012).
10. E. Aslan et al., “Experimental and numerical characterization of a mid-infrared plasmonic perfect absorber for dual-band enhanced vibrational spectroscopy,” Opt. Mater. 73, 213–222 (2017).
11. C. Wu et al., “Metamaterial-based integrated plasmonic absorber/emitter for solar thermophotovoltaic systems,” J. Opt. 14(2), 024005 (2012).
12. N. I. Landy et al., “Perfect metamaterial absorber,” Phys. Rev. Lett. 100(20), 207402 (2008).
13. B. Zhu et al., “Dual band switchable metamaterial electromagnetic absorber,” Prog. Electromagn. Res. 24, 121–129 (2010).
14. N. Mattiucci et al., “Impedance matched thin metamaterials make metals absorbing,” Sci. Rep. 3, 3203 (2013).
15. D. Wu et al., “Ultra-narrow band perfect absorber and its application as plasmonic sensor in the visible region,” Nanoscale Res. Lett. 12(1), 427 (2017).
16. K. Bhattacharai et al., “Metamaterial perfect absorber analyzed by a meta-cavity model consisting of multilayer metasurfaces,” Sci. Rep. 7(1), 10569 (2017).
17. W. Zhou et al., “Extraordinary optical absorption based on guided-mode resonance,” Opt. Lett. 38(24), 5393–5396 (2013).
18. R. Ameling et al., “Cavity-enhanced localized plasmon resonance sensing,” *Appl. Phys. Lett.* **97**(25), 253116 (2010).
19. S. Xiao et al., “Tunable anisotropic absorption in hyperbolic metamaterials based on black phosphorous/dielectric multilayer structures,” *J. Lightwave Technol.* **37**(13), 3290–3297 (2019).
20. T. Liu et al., “Black phosphorus-based anisotropic absorption structure in the mid-infrared,” *Opt. Express* **27**(20), 27618–27627 (2019).
21. X. Jiang et al., “Tunable ultra-high-efficiency light absorption of monolayer graphene using critical coupling with guided resonance,” *Opt. Express* **25**(22), 27028–27036 (2017).
22. S. Guddala, R. Kumar, and S. A. Ramakrishna, “Thermally induced nonlinear optical absorption in metamaterial perfect absorbers,” *Appl. Phys. Lett.* **106**(11), 111901 (2015).
23. M. Pu et al., “Investigation of Fano resonance in planar metamaterial with perturbed periodicity,” *Opt. Express* **21**(1), 992–1001 (2013).
24. U. Fano, “Effects of configuration interaction on intensities and phase shifts,” *Phys. Rev.* **124**(6), 1866–1878 (1961).
25. A. E. Miroshnichenko, S. Flach, and Y. S. Kivshar, “Fano resonances in nanoscale structures,” *Rev. Mod. Phys.* **82**(3), 2257–2298 (2010).
26. B. Luk’yanchuk et al., “The Fano resonance in plasmonic nanostructures and metamaterials,” *Nat. Mater.* **9**(9), 707–715 (2010).
27. F. Tavakoli, F. B. Zarrabi, and H. Saghaei, “Modeling and analysis of high-sensitivity refractive index sensors based on plasmonic absorbers with Fano response in the near-infrared spectral region,” *Appl. Opt.* **58**(20), 5404–5414 (2019).
28. A. Johnson et al., “Coulomb-modified Fano resonance in a one-lead quantum dot,” *Phys. Rev. Lett.* **93**(10), 106803 (2004).
29. M. Rybin et al., “Fano resonance between Mie and Bragg scattering in photonic crystals,” *Phys. Rev. Lett.* **103**(2), 023901 (2009).
30. F. Hao et al., “Symmetry breaking in plasmonic nanocavities: subradiant LSPR sensing and a tunable Fano resonance,” *Nano Lett.* **8**(11), 3983–3988 (2008).
31. K. Nozaki et al., “Ultralow-energy and high-contrast all-optical switch involving Fano resonance based on coupled photonic crystal nanocavities,” *Opt. Express* **21**(10), 11877–11888 (2013).
32. L. Zhou and A. W. Poon, “Fano-resonance-based electrically reconfigurable add-drop filters in silicon microring resonator-coupled Mach–Zehnder interferometers,” *Opt. Lett.* **32**(7), 781–783 (2007).
33. C. Wu et al., “Fano-resonant asymmetric metamaterials for ultrasensitive spectroscopy and identification of molecular monolayers,” *Nat. Mater.* **11**(1), 69–75 (2012).
34. M. Kroner et al., “The nonlinear Fano effect,” *Nature* **451**(7176), 311–314 (2008).
35. C. Wu, A. B. Khanikaev, and G. Shvets, “Broadband slow light metamaterial based on a double-continuum Fano resonance,” *Phys. Rev. Lett.* **106**(10), 107403 (2011).
36. A. B. Khanikaev, C. Wu, and G. Shvets, “Fano-resonant metamaterials and their applications,” *Nanophotonics* **2**(4), 247–264 (2013).
37. J. Gu et al., “Active control of electromagnetically induced transparency analogue in terahertz metamaterials,” *Nat. Commun.* **3**, 1151 (2012).
38. R. Singh et al., “Coupling between a dark and a bright Eigenmode in a terahertz metamaterial,” *Phys. Rev. B* **79**(8), 085111 (2009).
39. N. Liu et al., “Infrared perfect absorber and its application as plasmonic sensor,” *Nano Lett.* **10**(7), 2342–2348 (2010).
40. F. B. Zarrabi, M. Bazgir, and R. Hekmati, “Reconfigurable optical heptamer disk absorber based on an optical switch,” *IEEE Photonics Technol. Lett.* **31**(10), 779–782 (2019).
41. R. Kumar, A. K. Agarwal, and S. A. Ramakrishna, “Development of a metamaterial structure for large-area surfaces with specified infrared emissivity,” *Opt. Eng.* **57**(8), 087109 (2018).
42. “Comsol Multiphysics 4.4, finite element methods simulation software” (2014).
43. M. Debenham, “Refractive indices of zinc sulfide in the 0.405–13-μm wavelength range,” *Appl. Opt.* **23**(14), 2238–2239 (1984).
44. R. L. Olmon et al., “Optical dielectric function of gold,” *Phys. Rev. B* **86**(23), 235147 (2012).
45. D. Chandler-Horowitz and P. M. Amirtharaj, “High-accuracy, midinfrared (450cm$^{-1} \leq \omega \leq 4000$cm$^{-1}$) refractive index values of silicon,” *J. Appl. Phys.* **97**(12), 123526 (2005).
46. A. Artar, A. A. Yanik, and H. Altug, “Fabry–Pérot nanocavities in multilayered plasmonic crystals for enhanced biosensing,” *Appl. Phys. Lett.* **95**(5), 051105 (2009).
47. D. Rosenblatt, A. Sharon, and A. A. Friesem, “Resonant grating waveguide structures,” *IEEE J. Quantum Electron.* **33**(11), 2038–2059 (1997).
48. D. Maystre, “Theory of Wood’s anomalies,” in *Plasmonics*, S. Enoch and N. Bonod, Eds., pp. 39–83, Springer, Berlin, Heidelberg (2012).
49. G. Dayal and S. A. Ramakrishna, “Design of highly absorbing metamaterials for infrared frequencies,” *Opt. Express* **20**(16), 17503–17508 (2012).
50. R. Kumar and S. A. Ramakrishna, “Enhanced infra-red transmission through subwavelength hole arrays in a thin gold film mounted with dielectric micro-domes,” *J. Phys. D Appl. Phys.* **51**(16), 165104 (2018).
51. B. J. Lee, L. Wang, and Z. Zhang, “Coherent thermal emission by excitation of magnetic polaritons between periodic strips and a metallic film,” *Opt. Express* **16**(15), 11328–11336 (2008).
52. S. Fan, W. Suh, and J. D. Joannopoulos, “Temporal coupled-mode theory for the Fano resonance in optical resonators,” *J. Opt. Soc. Am. A* **20**(3), 569–572 (2003).
53. W. Suh, Z. Wang, and S. Fan, “Temporal coupled-mode theory and the presence of non-orthogonal modes in lossless multimode cavities,” *IEEE J. Quantum Electron.* **40**(10), 1511–1518 (2004).
54. J. Xu et al., “Design of triple-band metamaterial absorbers with refractive index sensitivity at infrared frequencies,” *Opt. Express* **24**(22), 25742–25751 (2016).

Raghwendra Kumar received his MSc degree from Department of Physics, B. R. A. Bihar University, Muzaffarpur, India, and his PhD from Department of Physics, IIT Kanpur, India. Currently, he is working as an assistant professor at Department of Physics, Bihar National College, Patna University, India. His research interests include plasmonics, metamaterials, non-linear metamaterials, and multiphoton polymerization.

S. Anantha Ramakrishna is a professor at Department of Physics, IIT Kanpur, India. He received his PhD from RRI, Bangalore, and carried out postdoctoral research with Sir John Pendry at Imperial College, London. He has authored over 110 peer-reviewed journals and a research monograph titled *Physics and Applications of Negative Refractive Index Materials*. His research interests include negative refractive index, near-field imaging using negative index, development of metamaterials and plasmonic surfaces for applications from microwave to optical frequencies.