Dual band Vis-IR absorber using bismuth based helical metamaterial surface

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Abstract
In this study authors worked to attain a metamaterial absorber for visible and infrared region using bismuth as its main constituent material. Proposed absorber would be used for various applications; solar cell, communication etc. To model the metamaterial surface, two different sets of materials are used to observe and compare the absorption, having metal-insulator-metal structure to observe the metamaterial. It is observed that proposed metamaterial layer having Al/TiO$_2$/Bi, displays high absorption for two bands in different wavelength region with wide bandwidth. Absorption peaks are observed at 510 nm and 1590 nm. However, apart from the peaks, absorption is not less than 0.5 a.u. anywhere in the absorption spectrum, which depicts that this absorber can be used for whole wavelength range varies from 200 to 2500 nm. Designed absorber in this study also ensures the easy fabrication of the metamaterial surface due to its less complex design and small geometry, which ensures the stability of three dimensional structure.

Keywords Absorber · Bismuth · Metamaterial · Broadband · Polarization independent

1 Introduction

Since the first realization of the metamaterial, there are a lot of interesting properties and applications catch the eyes of researchers. In recent years, paradigm of research industry is shifted from microwave to infrared (IR) (Tsutsumi et al. 2021; Song et al. 2015) due to its numerous advantages over higher wavelengths. IR industry attracts the attention
of researcher due to their unprecedented ability of low interference, high performance, smaller device size etc. (Song et al. 2015; Lamont et al. 2019). While discussing lower wavelength devices, metamaterial is the most used term/material due to its unique abilities such as, negative refractive index, absorption, negative Doppler shift etc. (Xiao et al. 2020). These extraordinary ability of metamaterial, dragged it at the center of interest to push the boundaries of nano-devices up to next level ranging form communication devices; antennas (Johnson et al. 2015), modulators (Ahmed et al. 2018), wireless devices (Kindness et al. 2019; Alibakhshikenari et al. 2018) to energy efficient conversion devices; solar cells (Kim and Lee 2019), absorbers (Zou and Cheng 2019). The most interesting feature of metamaterial is its sub-wavelength size for visible and IR applications and absorption of various bands of electromagnetic spectrum. Metamaterial term was first proposed by Veselago (1968) in 1968 but at that time interest was very limited, then after study of Schurig et al. (2006) draw a lot of attention due to the experimental verification of metamaterial.

Since Landy et al. (2008) proposed the first ever perfect metamaterial absorber in 2008, a lot of groups start working on metamaterial based absorbers for different application and wavelength regions. The operating region of metamaterial is basically decided based on the unit cell structure and the dimensions of the structure. Considering, metamaterial is a artificial material made of repeated unit cell structure in $x$ and $y$ direction. Where, unit cell is the smallest design structure of metamaterial. Based on the different shapes, features, constituent material, and thickness of material etc. properties of designed metamaterial get change, which is the key feature of metamaterial.

Ring type resonator is the most used technique of metamaterial formation in various wavelength range, ranging from millimeter to IR (Chen et al. 2018). In 2012, Alves et al. (2012) proposed a micro-electro-mechanical systems (MEMS) sensor made of the metamaterial surface having 90% absorption. Operating region of this proposed absorber is 3.8 THz which is based on a bimetallic approach. In 2016, Carranza et al. (2016) designed a cross-shaped ring resonator absorber. This is a very advanced paper, proposing integration of metamaterial surface with commercial CMOS technology for imaging system with wide resonance spectrum, peak at 2.5 THz. Then in 2018, Li et al. (2018) designed a dual band resonance metamaterial absorber working in near-infrared (NIR) region with metallic layer on top. However, utilization of metal-insulator-metal (MIM) combination can improve the benefits of metamaterial a lot due to its simpler built and wide variety of available materials. This structure consists of a cavity which respond in terms of narrow operating region, although this traditional disadvantage can be mitigated through different strategies, such as change in material, multi-dimensional structure, and multi-shape etc.

In conventional approach, gold (Au), silver (Ag) etc. are most used noble metals in MIM design, but use of titanium (Ti) and other materials (Ghobadi et al. 2018) can broaden the operating spectrum. In various studies, concept of multilayer planar structure of MIM is already been studied to achieve ultra broadband absorption. Nevertheless, bandwidth is still limited, for instance, a simple plus shape metamaterial surface can provide the maximum (96%) absorption at 19.24 THz with small narrow bandwidth (Zhong 2020). Thus, exploration of new materials for MIM structure is required. In 2019, Ghobadi et al. (2019) explored the use of bismuth (Bi) metal for perfect absorber having MIM structure. This study is proposed for the use of Bi based metamaterial as wide band absorber as well as narrow band reflective filter. Different combinations of metal thicknesses and repetitive combinations are studied to optimize the absorbance from the absorber. This absorber has a very large absorption range with the simple structure, however, tunability of the wavelength region is a problem which can not be achieved by modifying the layer thickness. In some applications tunability is most
important property. To achieve the same, authors proposed a three-dimensional (3-D) absorber with the possibility of tuning of center wavelength. In the present study, utilization of Bi metal is done for MIM metamaterial structure having 3-D design at top. The proposed absorber ensures the broad bandwidth and tunability based on the application of the device.

2 Design and modeling of proposed absorber

Present study includes two combinations of materials, first combination includes Au base metal over it Magnesium fluoride (MgF$_2$) layer is placed and at the top helices are placed made of Bi. Second combination consists of aluminum (Al) as the base metal over it Titanium dioxide (TiO$_2$) is placed and the top helices are made of Bi, Fig. 1(a) has the top view of the absorber with the proposed combinations. Figure 1(b) displays the 3-D view of the same.

Thickness of substrate material is chosen such that light would not escape/ transmit rather absorbed. To achieve such property, skin depth is calculated and the thickness put is more than the skin depth. To achieve the desired absorption, 120 nm thickness of dielectric/insulator is used, whereas lower metal thickness is 20 nm in both the cases. Thickness of the top most structure depends on helix parameters, such as pitch of helix, fiber diameter. For the detailed study, structural parameters of helix are varied and their effect is observed on the wavelength and absorption. Wavelength region, is defined as the region where the absorption is more than 0.5 a.u. Based on these two parameters, optimization of the 3-D structure is done for good absorption. Lumerical FDTD tool is used for the simulation purpose which is based on finite-difference time domain (FDTD) mathematical model. Calculation of transmission and reflection from the absorber can be done as follows:

**Fig. 1** (a) Two-dimensional (2-D)/top view of the proposed absorber (b) 3-D view of the same
where, \( \varepsilon \) is permittivity of the material, \( \beta \) is propagation constant, and \( z \) is direction of light incidence. After calculating the reflection and transmission coefficients, absorbance can be calculated as follow;

\[
A = 1 - R - T
\]

where \( A \) is absorbance in a.u. For the analysis, full width of half maximum (FWHM) would also be calculated to define the width of the absorbance in terms of wavelength region. In the next section, results are discussed and compared with the existing work.

### 3 Results and discussion

Analysis starts with the determination of the combination of materials for MIM metamaterial surface. To decide the substrate metal, various different metals are analyzed by observing their absorbance individually as shown in Table 1;

From the analysis, it is observed that all the considered metals have absorbance more than 0.90 a.u., however only two metals are picked from the table, i.e. Au and Al because of their other properties such as inertness (Pishkenari et al. 2018), easy availability, non toxic nature Pishkenari et al. (2018) etc. After the determination of the substrate layer, intermediate dielectric layer material has to be decided. MgF\(_2\) and TiO\(_2\) are chosen due to their high optical absorption (David, Glocker 2018) in visible wavelength region. Thickness for the dielectric material layer is chosen to be 120 nm (Ghobadi et al. 2018). The upper most layer is the 3-D helix structure and made of Bi. Bi is used as the structural metal due to its high absorbance/ near perfect absorption. From various designs for metamaterial layer, helix structure is decided due to its high absorbance and tunability. Properties would be tuned by changing the structural parameters of helix. Since, the aim here is to design a polarization insensitive absorber, unit cell has four helices; having two right handed and two left handed helices. Both handed helices are placed side by side, to achieve polarization insensitive nature. Due to the symmetry of the unit cell, absorption spectrum

| Metal    | Peak absorbance (a.u.) | Peak wavelength (nm) |
|----------|------------------------|----------------------|
| Au       | 0.92                   | 420                  |
| Bi       | 0.98                   | 450                  |
| Al       | 0.90                   | 378                  |
| Tin (Sn) | 0.91                   | 514                  |
are same for both left handed and right handed circularly polarized light (Agarwal et al. 2016).

Since, helices can be of different types based on their upper and lower radius, i.e. uniform, tapered etc. Uniform helices (top and bottom radius’s are same) are well studied for absorbance, however, absorbance can be improved if helices are tapered. Tapering can be of two types, either bottom radius large or top radius large. Based on the tapering, absorbance of the helix gets affected. On keeping smaller top radius of helix, same as in this study, less reflection radiation escape from the structure and thus more absorption (Agarwal et al. 2016). For the analysis of structural parameters, both the combinations are studied together.

First, the effect of fiber radius has been observed by changing the radius value from 10 nm to 20 nm is step of 5 nm. Figure 2 has the absorption spectrum for both the combinations.

It would be observed that, absorption starts at 0.58 a.u. for all the fiber radius’s, however, the maximum absorption reaches till 0.82 a.u. It is observed that higher fiber radius provides better absorption for both the absorption bands. Nevertheless, absorption for Al/TiO$_2$/Bi is much better than the other combination, because of the higher absorption

Fig. 2 Absorption spectrum for different fiber radius (a) Au/MgF$_2$/Bi (b) Al/TiO$_2$/Bi
absorption of Al. Thus, it is to be concluded that higher fiber radius is good, but radius lesser than 10 nm is not an option, since it might make structure less stable. After deciding the fiber radius, pitch of the helix is analyzed, with the fixed value of fiber radius, i.e. 20 nm. Figure 3 has the absorption spectrum for both interested combinations.

Pitch length is varied from 150 nm to 200 nm. Three values are observed, i.e. 150 nm, 170 nm, 200 nm. Maximum achieved absorption is 0.78 a.u. at 490 nm for MgF$_2$ combination, whereas, maximum absorption is 0.845 a.u. for TiO$_2$ combination. However, the second band for both the combinations is not much emphasized because of the lower absorption of individual materials in that range. Nonetheless, helical structure helped to get the absorption for the longer wavelength region. For the current analysis, pitch length of 150 nm is the optimized value, since, it gives the maximum absorption for both combinations. The reason behind this absorption is the interaction of light with helical structure is better for lower pitch value and stability is also there. Lengthy helical structure may cause the instability in overall structure. Thus, 150 nm is decided as the optimized value of pitch. Afterward, top and bottom radius are varied but with the

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**Fig. 3** Absorption spectrum for different pitch length (a) Au/MgF$_2$/Bi (b) Al/TiO$_2$/Bi
fixed ratio, the values chosen for the analysis are, 15/150 nm, 17/170 nm, and 20/200 nm respectively. Figure 4, has the absorption spectrum for different helical radius.

It is observed that absorption spectrum has the highest absorption for 17/170 nm value of top/bottom radius. Table 2 and Table 3 has the comparative data for the geometrical parameter analysis of the proposed absorber.

From the above Tables 2 and 3, it is depicted that optimization of combination of geometrical parameters is very important. Based on the absorption spectrum for both combinations, optimized parameters are decided and a comparative optimized absorption spectrum is plotted and included in Fig. 5. It is observed that on optimization absorption spectrum for Al/TiO$_2$/Bi is better than Au/MgF$_2$/Bi.

However, it is also observed that for Al/TiO$_2$/Bi combination, maximum absorption achieved is more than 0.8 a.u. and it represents dual band absorption spectrum. One peak is around 510 nm and the second peak is achieved around 1590 nm, thus visible and infrared both regions are covered through this absorber layer combination. For this combination, absorption is always higher than 0.5 a.u. for whole considered wavelength region. Whereas, for Au/MgF$_2$/Bi, first peak is achieved around 600 nm and second is
around 1850 nm. Thus, metamaterial layer made of Al/TiO$_2$/Bi is better than the other combination. This should also be pointed out here that the proposed metamaterial layers are not complex thus, easy to realize through available fabrication and characterization tools. Characteristics of proposed absorber is compared with the existing research work given in Table 4. It is observed that the proposed absorber has very large absorption region with high absorbance. It is also noticed that only proposed absorber has absorbance more than 0.5 a.u. for wavelength range 200–2500 nm, whereas, for the existing work absorption decreases less than 0.5 a.u. outside the peak absorbance region. Thus, it can said that the proposed work has best performance and it can be used for various

Table 2 Comparative analysis of peak absorption and wavelength for different geometrical analysis for Au/MgF$_2$/Bi metamaterial combination

| Pitch length (nm) | Fiber radius (nm) | Top/bottom helix radius (nm) |
|------------------|------------------|-------------------------------|
| 150              | 170              | 200                          |
| 10               | 15               | 20                           |
| Band 1 Peak absorption | 0.78           | 0.77                         | 0.75 |
| Band 2 Peak absorption | 0.7          | 0.63                         | 0.69 |
| Band 1 Peak wavelength | 490           | 490                          | 350  |
| Band 2 Peak wavelength | 2100          | 2150                         | 1950  |

Table 3 Comparative analysis of peak absorption and wavelength for different geometrical analysis for Al/TiO$_2$/Bi metamaterial combination

| Pitch length (nm) | Fiber radius (nm) | Top/bottom helix radius (nm) |
|------------------|------------------|-------------------------------|
| 150              | 170              | 200                          |
| 10               | 15               | 20                           |
| Band 1 Peak absorption | 0.845          | 0.82                         | 0.81 |
| Band 2 Peak absorption | 0.64          | 0.58                         | 0.70 |
| Band 1 Peak wavelength | 530           | 550                          | 500  |
| Band 2 Peak wavelength | 1650          | 2200                         | 2100  |

Table 4 Comparative analysis of proposed work with the existing work (Higher absorption peak considered)

| Research study             | Peak absorbance (a.u.) | Peak wavelength | Wavelength region         |
|----------------------------|-------------------------|-----------------|---------------------------|
| Shuvo et al. (2022)        | 0.99                    | 340 nm          | 300–1600 nm               |
| Zhong (2020)               | 0.98                    | Multiband (614, 741, 1072, 1312 nm) | 400–1500 nm               |
| Cen et al. (2020)          | 0.15                    | 24.5 $\mu$m     | –                         |
| Bilal et al. (2020)        | 0.96                    | 550 nm          | 400–750 nm                |
| Mudachathi and Tanaka (2019)| 0.90                     | 1.7 $\mu$m      | 1.5–4.5 $\mu$m           |
| He et al. (2020)           | 0.90                    | 27.50 GHz       | 8–40 GHz                  |
| Proposed work              | 0.845                   | 510 nm          | 200–2500 nm               |
communication as well as other applications. Along with the theoretical approach it is also very important to comment on the physical feasibility aspect of the proposed structure. Since, the proposed absorber is a 3-D structure, thus direct laser writing is the best fabrication method to develop the absorber with accuracy. There are some other techniques also present such as 3-D printing, electron beam lithography etc, however, direct laser writing is the best solution because this is already been used for this type of structures (Tsutsumi et al. 2021; Lamont et al. 2019). Thus, feasibility of the proposed absorber is not a problem at all.

4 Conclusion

The proposed study is focused to design metamaterial absorber layer for wide wavelength region to cover. Bi is used as the structural material due to its high absorbing property. Materials are chosen carefully to improve the absorbance and keep the cost optimized. It is observed from the study, that both the combinations provide good enough absorption for the entire wavelength range starting from 200 to 2500 nm. However, for Au/MgF$_2$/Bi, absorption is less than 0.5 a.u. for small part of wavelength range. With Al/TiO$_2$/Bi combination, very good absorption is achieved for whole wavelength range. Thus, the proposed absorber is suitable for many communication and thermophotovoltaic applications. Less complicated unit cell structure ensures the stabilizability of the absorber with the available high end sophisticated fabrication tools.

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**Declarations**

**Conflict of interest** The authors have no financial or proprietary interests in any material discussed in this article.
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