

Ultra-Broadband Thermal Radiation Management Using a Plasmonic Metamaterial Absorber for Thermophotovoltaic Applications and Solar Sails

Himu Sheik

erfanhimu@gmail.com

Nagoya Institute of Technology

Fayzul Bari Shikder

International Islamic University Chittagong

Md Raihan

International Islamic University Chittagong

Md. Imtiaz Uddin

International Islamic University Chittagong

Arman Ahamad Akib

International Islamic University Chittagong

Md. Ismail Haque

International Islamic University Chittagong

Research Article

Keywords:

Posted Date: October 20th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11257380/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Ultra-Broadband Thermal Radiation Management Using a Plasmonic Metamaterial Absorber for Thermophotovoltaic Applications and Solar Sails

¹Himu Sheik Erfan Ahmed, ²Fayzul Bari Shikder, ²Md Raihan, ²Md. Imtiaz Uddin, ²Arman Ahamad Akib, ²Md. Ismail Haque

¹Department: Electrical and Mechanical Engineering, Nagoya Institute of Technology, Showa Ward, Nagoya, Aichi 466-0062, E-mail: erfanhimu@gmail.com),

²Department of Electrical and Electronic Engineering, International Islamic University Chittagong, Chittagong, Bangladesh, E-mail: fayzulbarictg@gmail.com , mohammedraihan133@gmail.com imtiazanam56@gmail.com , ahamadakibarman@gmail.com , ismail07rueteeeee@iiuc.ac.bd

(corresponding author: Himu Sheik Erfan Ahmed)

Abstract: Metamaterial absorbers show a path towards produce greener energy without noise, toxic waste, or carbon dioxide emissions. Optical metamaterial absorber can achieve significant absorption with compact dimensions. However, achieving high efficiency, with an average rate of 97% and ultrabroadband absorption from UV to IR, using a three-layer sandwich structure is still under research. In this work, we present a compact three-layer metal-dielectric-metal absorber that achieved a total 98.43% average absorption rate. This efficiency remains stable from 230 nm to 4000 nm. In this region, the absorption remains above 92%. Our study shows its suitability at higher temperatures, as we have used low-cost, high-temperature-stable materials: tungsten and silicon dioxide. Polarization angle and incident angle also varied from 0° to 70°, and showed no variation. Under AM 1.5 irradiance, the absorber performs also evaluated. Under 973K temperature the MMA shows 96.7% thermal conversion efficiency at C= 400 which maintains 97.41% at C= 2000. We verified the absorption with the interference theory model, which shows almost similar results. We also conducted a comparative analysis of the last two years' work, where our present work significantly stands out in terms of efficiency and bandwidth. The demonstration of solar absorber implementation illustrates how this MMA can be used for solar energy harvesting.

Introduction

Since the demonstration of the first metamaterial perfect absorber (MPA) by Landy et al. in 2008, which achieved near-unity absorbance at a single microwave resonance through independently tunable electric and magnetic resonators [1], the field has expanded from narrowband microwave devices toward broadband optical absorbers explicitly engineered for solar-spectrum coverage. Concerning solar energy harvesting with a metamaterial absorber, a few studies have focused on achieving optimal absorption in a variety of frequency bands. For the visible spectrum (400nm to 700nm), R.M.H. Bilal suggested [2] an elliptical ring-shaped absorber. They employed tungsten metal in their design, which means they had a 90% absorption, with about 70% absorption when the light fell at an angle of 0° to 70°. Some research

focused on structural changes to select the spectral absorption. Yubin et al. [3] focused on this context. This absorber's absorption rate was 99.9%, which was attained with Gold and silicon dioxide with four identical circular resonators. However, for solar absorption, it is generally required to have wide-bandwidth absorption; thus, improving the bandwidth coverage is crucial in this research field. To broaden the absorption, this study [4] worked on a visible absorber operating from 400 nm to 700 nm. It maintained its absorption at about 80% at the incident angle of 60° . A numerical study in this range was reported to improve the bandwidth and efficiency from 320 nm to 982 nm [5]. Both in TE and TM mode it showed 90% absorption. The broadband metamaterial absorber designed in [6] is based on a novel hybrid dual-resonator structure in a metal–dielectric–metal (Al/SiO₂/Al) sandwich structure. This work achieved 95% absorption over the visible wavelength range of 450 - 600 nm. To overcome the narrowband limitation, some research work also conducted in recent years. Qi et al. [7] reported an all-refractory titanium-based selective absorber with 98.68% average broadband absorptivity across the wavelength range of 200–2620 nm and 95.88% photothermal conversion efficiency at 700 °C, explicitly pointing out that this broadband response comes from strong intrinsic absorption loss in the refractory metal itself, rather than the noble-metal plasmonics. This work [8] achieved a 95% average rate from 300 nm to 2000 nm a 1576 nm bandwidth of absorption above 90%. The absorber exhibited polarization- and incident angle-independent characteristics. Qi *et al.* [9] proposed a dual-dielectric-layer tungsten-based selective absorber (DDMSA) that was designed to have an above-90% absorption rate in the spectral range of 280–2280 nm. Recently a double Ni ring MDM metamaterial solar absorber was proposed [10], achieving broadband absorption of 96.75%, from 300–2500 nm. They used Ti substrate, a Si₃N₄ spacer layer and an array structure of double Ni rings for their work. In another work [11] researchers feature a three-layer MXene-SiO₂-MXene structure with square and circular nano disk resonators. It achieves over 90% absorption across the 200–3000 nm range, including two ultra-wideband (1510–3000 nm and 1810–2550 nm) and >91% absorption under solar AM 1.5 conditions. The design is polarization-independent, maintains performance at wide angles, however their bandwidth is continuous from 1510 nm to 3000 nm. This [12] study presents a Metamaterial MXene/W-based Resonator Solar Absorber (MMRSA) designed to optimize solar energy harvesting. They utilized a wire and cylindrical ring geometry using MXene and Tungsten on an MgF₂ substrate, the absorber achieves over 94% absorptance across the 200–3000 nm range. In terms of absorption efficiency for solar absorber there is a need for improving absorbance more than 96% of total average absorption.

A number of recently developed designs are structurally close relatives of the present three-layer W/SiO₂ absorber and a detailed comparison of these is warranted. A W–SiO₂–Ti broadband metamaterial perfect absorber (BMPA) with the tungsten layer periodically patterned by the etched cavity was demonstrated to enable a mean absorption of 96.07% over 280–2500 nm at normal incidence due to the interaction of the magnetic resonance, cavity resonance and surface plasmon resonance, and was shown to be polarization-independent and mostly incidence-angle independent, with a photothermal conversion efficiency close to 90% at 1000 K [13]. To alleviate CTE mismatch failure issues mentioned in the previous work at temperatures above 873 K, Xue et al. proposed a three-layer solar absorber: titanium cubes, SiO₂ cubes, and a hollow, symmetrical, pentagonal tungsten top layer, realizing a high-efficiency absorption in the range of 200–2300 nm [14]. Concentric ring cavity absorbers with tungsten–alumina–graphite absorber material showed that the material has an absorption band which covers more than 90% across the range 200–2000 nm, a high solar-thermal efficiency of 93%, and a total thermal emissivity of 93%, the choices of thermally stable refractory metals enabling such operation, demonstrated by Prasad and Gupta [15]. In another work a tungsten substrate has also been coupled to a GaInAsP staircase resonator to take advantage of tungsten's

high thermal conductivity for heat extraction besides the absorption [16], and elliptical-ring tungsten fractal metasurfaces have been employed to shift the absorption in the visible band over 90% [17].

The proposed three-layer tungsten–SiO₂–tungsten metamaterial absorber achieves broadband absorption over the 230–4000 nm wavelength range, with an average absorbance of 98.43%. throughout this bandwidth the absorption remains above 92%. The work shows polarization insensitivity and maintains the absorption rate throughout the operating region. Its ultrawide operating bandwidth is realized using a simple sandwich-type architecture, demonstrating that a compact three-layer design can deliver performance comparable to or better than recent state-of-the-art broadband absorbers. We verified the absorption attained from numerical simulation with interference theory model.

Methodology

Theoretical Analysis

As we know, MTMs are artificial structures designed differently. Meta-absorbers are required to absorb incoming electromagnetic waves, storing the energy within the structure. When EM waves pass through any object, three things can happen, i) the wave passes through the object, ii) it can reflect back into the medium or in another direction, and iii) the wave can be absorbed by the structure if it does not reflect or pass through. Conservation of energy links these three quantities through equation 1

$$A = 1 - R(\lambda) - T(\lambda) \quad (1)$$

Here A, R, and T denote the fractional absorptance, reflectance, and transmittance at wavelength λ . So, for absorption, we need minimal reflection and transmission, which will increase absorption. If we make transmission and reflection close to zero, we can get optimal output or absorption. There is one way we can

make transmission zero, and it is using a metal plate with a thickness of skin depth $\delta_s = \sqrt{\frac{2\rho}{2\pi f\mu R\mu_0}}$.

Therefore, if we place a metal plane block at the bottom of the structure, it will block the incoming electromagnetic wave. In our design, the bottom metallic ground layer is made several skin depths thick across the entire operating band, so no appreciable field tunnels through it and the transmittance can be taken as vanishing, $T(\lambda) \rightarrow 0$. The energy balance then becomes to the simpler form

$$A = 1 - R(\lambda) \quad (2)$$

Equation (2) reframes the entire absorber-design problem as a reflection-suppression problem: absorption is high precisely where reflection from the top interface is low.

3.1.1 Impedance Match Theory

Two complementary mechanisms explain why a patterned metasurface can suppress reflection far more effectively than a bare metal or dielectric film impedance matching between free space ($=377\Omega$) and the effective medium presented by the structure, and coherent destructive interference among multiple internally reflected waves. Both are examined below, followed by a discussion of how the underlying material parameters, permittivity and permeability, govern them. Now in equation form impedance of free

space is, $Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}}$ and the same way effective impedance is denoted as, $Z_{eff\omega} = \sqrt{\frac{\mu_0 \mu_r}{\epsilon_0 \epsilon_r}}$. If we look at

this relation, it becomes clear that impedance is related to permeability and permittivity, and which is also frequency dependent.

$$R(\lambda) = \frac{Z_s(\lambda) - Z_f}{Z_s(\lambda) + Z_f} \quad (3)$$

Here, in equation 3, Z_s is denoted as the system's impedance, R represents the reflection, and Z_f is the impedance of the free space. Equation (3) contains the central design principle of any resonant metasurface absorber: whenever the effective impedance of the structure equals that of free space, $Z_s(\lambda) = Z_f$, the numerator of Equation (3) vanishes and $R(\lambda) \rightarrow 0$, forcing all of the incident power essentially into the structure rather than back into the surrounding medium. This condition of impedance matching is the electromagnetic counterpart of matching a load to a transmission line to eliminate standing-wave reflections. Here, the “load” is the patterned resonator layer backed by a lossy dielectric spacer and a metallic ground plane, and the “line” is free space itself. Crucially, $Z(\lambda)$ is not an independent design handle; it is fixed by the effective constitutive parameters of the metasurface, the effective permittivity $\epsilon_{\text{eff}}(\lambda)$ and effective permeability $\mu_{\text{eff}}(\lambda)$, through

$$Z_s(\lambda) = Z_f \left(\frac{\mu_{\text{eff}}(\lambda)}{\epsilon_{\text{eff}}(\lambda)} \right) \quad (4)$$

Equation (4) is the bridge that connects the macroscopically observed reflection behaviour of Equation (3) to the underlying material's response. Because a sub-wavelength resonator array is not a bulk medium in the conventional sense, ϵ_{eff} and μ_{eff} are retrieved, rather than intrinsic, quantities; they are extracted numerically from the complex scattering parameters (S_{11} , S_{21}) obtained from full-wave simulation. Both parameters are strongly dispersive near a resonance, which is precisely what endows a metasurface absorber with spectral selectivity: $Z_s(\lambda)$ can be steered toward Z_f over a broad or narrow wavelength window purely through geometric tailoring of the unit cell, without requiring any single natural material whose intrinsic impedance happens to equal 377Ω .

Using the CST simulation, we developed the full unit cell structure. The dimensions and the parameter values used in this design are presented in Table 01. The structure is a cone shaped symmetrical absorber which is enclosed by a split-ring resonator. Fig. 1 illustrates the front view and side view of the MMA

Simulation setup

Electromagnetic simulations were performed in CST Microwave Studio utilizing the Finite Integration Technique (FIT) on a discretized tetrahedral mesh using the Frequency Domain solver to solve Maxwell's continuous equations over complicated geometries. Floquet ports along the Z axis created open-space limits for front-side excitation, while periodic unit cell conditions were given along the X and Y axes as illustrated in Fig 2. The tetrahedral mesh component is utilized in conjunction with FIT and the Frequency Domain solver by CST. To inject electromagnetic waves into the model and record the resulting response, an excitation port is required. For a single periodic unit cell, a Floquet port is used instead of a standard waveguide port. Standard waveguide ports cannot be positioned on faces with active periodic boundary conditions, making them unsuitable for this geometry. In contrast, Floquet ports support periodic boundaries while accurately modeling plane waves at both normal and oblique incidence angles. Consequently, Floquet ports were applied to excite the unit cell along the vertical axis across all simulation runs.

Table 01: Parameter values

Parameters	a	tb	ts	tcr	R	C	tr1
Value (nm)	452	150	65	900	165	10	450

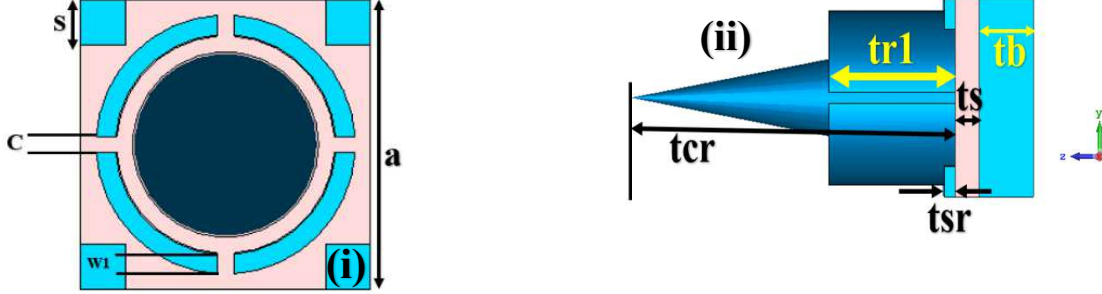


Fig. 1: Illustration of the proposed meta-absorber's design (i) front view (ii) side view

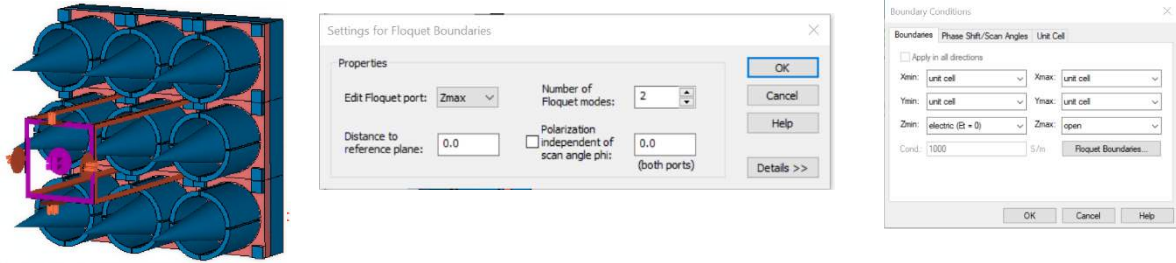


Fig. 2: Simulation setup and boundary conditions of the metamaterial absorber

Result analysis:

Absorption and Reflection

The optimized broadband optical meta-absorber absorption performance is shown in Fig 2. The proposed structure shows very good optical absorption in the wavelength range 230 to 4000 nm covering the deep-ultraviolet (DUV), visible (VIS), near-infrared (NIR) and part of the mid-infrared (MIR). The absorbance is slightly wavelength dependent, but its value is always high in the entire operating band, so that the absorber can effectively suppress optical loss over a very large spectral range. It peaks at 99.93% at 422 nm, and drops below approximately 92.4% only at this single weakest frequency, which is deep in the near-ultraviolet. The structure has an averaged absorption of the incident wave over the entire window which is quoted throughout this thesis as 98.43 %. We also performed TE and TM mode analysis for the efficient utilization of each incoming type of electromagnetic wave. As Fig 3 demonstrates, its absorption in TE mode remains the same as in TM mode, which makes it effective in these two modes. In transverse

electric mode, the electric field is perpendicular to the propagation direction, and in TM mode the magnetic field is circulating in the propagation direction.

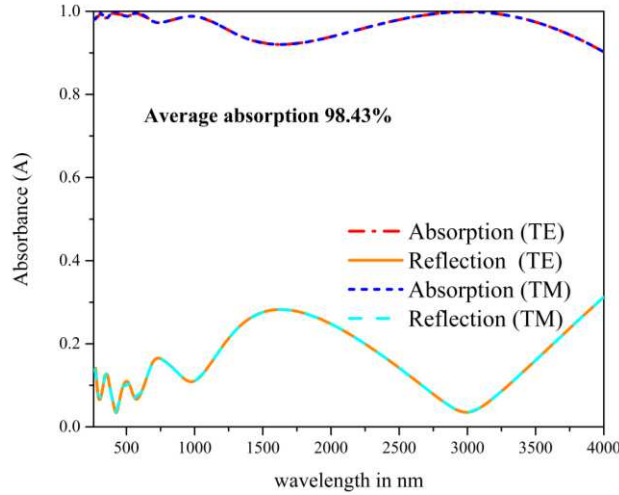


Fig 3: Absorption response of the MMA throughout the bandwidth

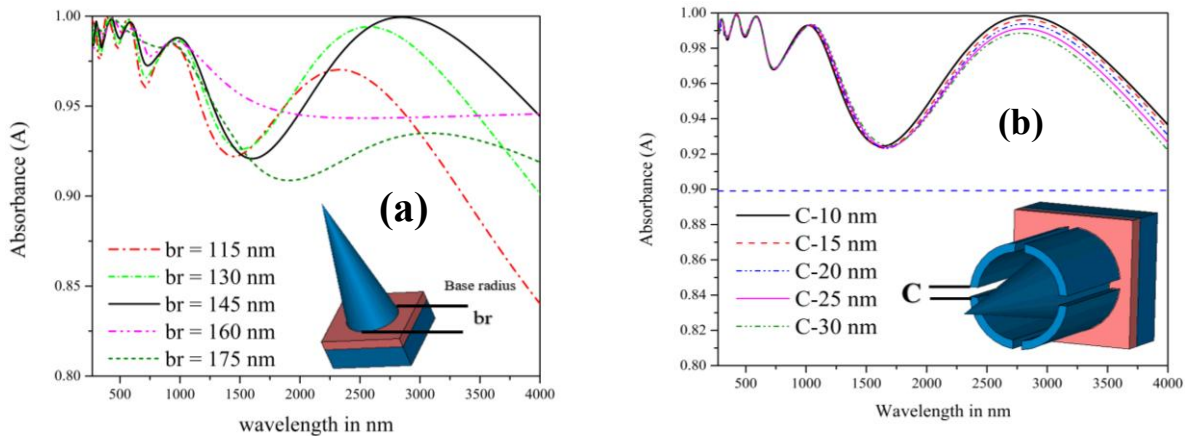
Geometrical sweep analysis:

The parametric examination was conducted by altering four geometric parameters independently while maintaining the other parameters constant: the base radius of the top cone resonator br , the cut gap width $c1$, the height of the cone resonator tcr , and the height of the circular resonator $tr1$. The impacts of these variables on the absorption response are examined individually hereunder, starting with the most significant parameter.

The bottom radius br significantly affects the absorption spectrum, particularly at the lower-frequency range, where noticeable changes in the spectral shape are observed, as shown in Figure 4. The radius was varied from 145 to 175 nm in 15 nm increments. The average absorption increased from 97.85% at 145 nm to 98.17% and 98.43% as the radius increased, but then decreased to 98.29% and 97.96% for larger radii. Considering both absorption and bandwidth, a bottom radius of 145 nm was selected as the optimum value for the proposed structure. When compared with br , the cut gap width $c1$ has a comparatively negligible impact on the overall absorption response. With the increase of $c1$ from 10 to 30 nm, the average absorption alters just minimally, transitioning from 98.41% to 98.44%, and the plots in **Figure 4** exhibit almost identical characteristics across most of the spectrum. A specific absorption dip is detected across all analyzed values of $c1$. The dip incrementally advances toward longer wavelengths, ranging from 1626 nm at 10 nm to 1682 nm at 30 nm, while the absorption percentage alters marginally from 92.44% to 92.48%. On the other hand, the near-UV peak shows no alteration, presenting at 422, 417, 423, 421, and 420 nm, respectively. The results demonstrate that $c1$ primarily effects one resonance, having a negligible effect on the total spectral response. Thus, it can function as a tuning parameter to alter the resonance wavelength while minimally influencing the other absorption properties. Fig (4b) demonstrates the absorption curve under parameter sweep “ $c1$ ”.

Fig 4(b) illustrates the change in absorption with change in the value of gap 'g'. By changing the inter-element gap (g) from 10 to 30 nm, the effect was examined. The average absorption falls from 98.41% to 98.15% when the inter-element gap (g) rises from 10 to 30 nm. Fano-type interference may be the cause of the abrupt dip that appears at $g=15$ nm about 258 nm, but it has minimal impact on the average absorption. The near-field coupling between neighboring resonators is likewise weakened by increasing g, which lowers the minimum absorption in the 1550–1600 nm regions from 92.44% to 91.70%. Therefore, even if the overall effect of g is rather tiny, a narrower gap offers strong coupling and slightly larger resonant absorption.

tr1 has the biggest impact on the total absorption performance out of the four parameters. Both the average absorption and the bandwidth above 90% gradually diminish as tr1 rises from 350 to 550 nm. The whole 230–4000 nm range keeps absorption above 90% at tr1=350 and 400 nm, with average values of 98.41% and 98.19%, respectively. A dip in the 1718–2218 nm range occurs at 500 nm, lowering the average absorption to 97.57% and the minimum absorption to 88.24%. The dip widens to 1767–2415 nm and the minimum absorption drop to 87.38% with an average of 97.26% when tr1 is further increased to 550 nm. Additionally, the resonant wavelength changes from 422 nm at tr1=350 nm to 3874 nm at 550 nm, suggesting that resonances move toward longer wavelengths as resonator size increases. As a result, tr1 largely regulates the absorber's spectral location and bandwidth. For the final design, tr1 was chosen within the 450 nm range in order to keep broadband absorption above 90%.



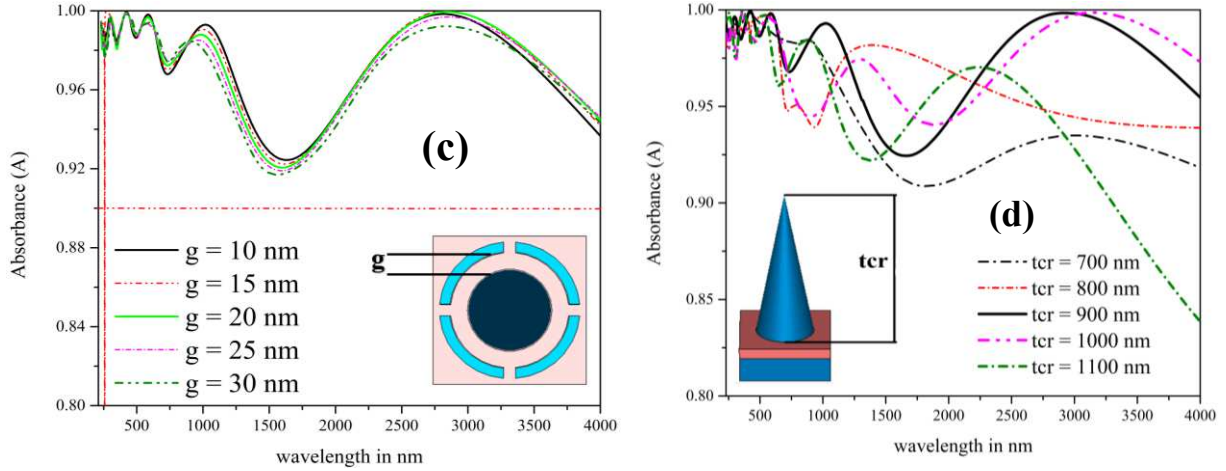


Fig: Absorption curve of attained for (a) changing the parameter “br” , (b) changing the parameter “C”,(c) changing the parameter, “g”, (d) change of cone resonator thickness trl

Co and Cross Polarization

The polarization conversion ratio (PCR) is one of the common parameters to measure the polarization change amount of reflected electromagnetic wave from the incident wave. It is simply the ratio of the power of the reflected rays which is polarized down to the total reflected power and is given below.

$$PCR_{TE} = \frac{R_{xy}^2}{(R_{yy}^2 + R_{xy}^2)} \quad (5)$$

$$PCR_{TM} = \frac{R_{yx}^2}{(R_{xx}^2 + R_{yx}^2)} \quad (6)$$

In the case of the proposed metamaterial absorber, both co-polarized and cross-polarized reflection coefficients can be used to describe the reflection response. The co-polarized reflection coefficients R_{xx} and R_{yy} are the reflected field that has the same polarization as the incident field, while the reflected field with the polarization rotated is the cross-polarized coefficients R_{xy} and R_{yx} . The cross polarized reflection coefficients are also low and significantly lower than the co-polarized ones as seen in Fig.5(a) through the operating frequency band. The values of R_{xy} and R_{yx} are very small, meaning that the polarization of the incident electromagnetic wave is almost unchanged after reflection. This is a desirable behavior because it reduces the polarization conversion ratio (PCR), and indicates that the absorber maintains the polarization state of the incident wave. This is also confirmed by the PCR results in Fig.5 (b) for both TE and TM polarization modes. The calculated PCR is very close to zero over the entire operating band, indicating a polarization-independent behavior of the proposed metamaterial absorber with almost no cross-polarization conversion. The results confirm that the superior performance of the absorber is a result of efficient absorption and not from the polarization rotation.

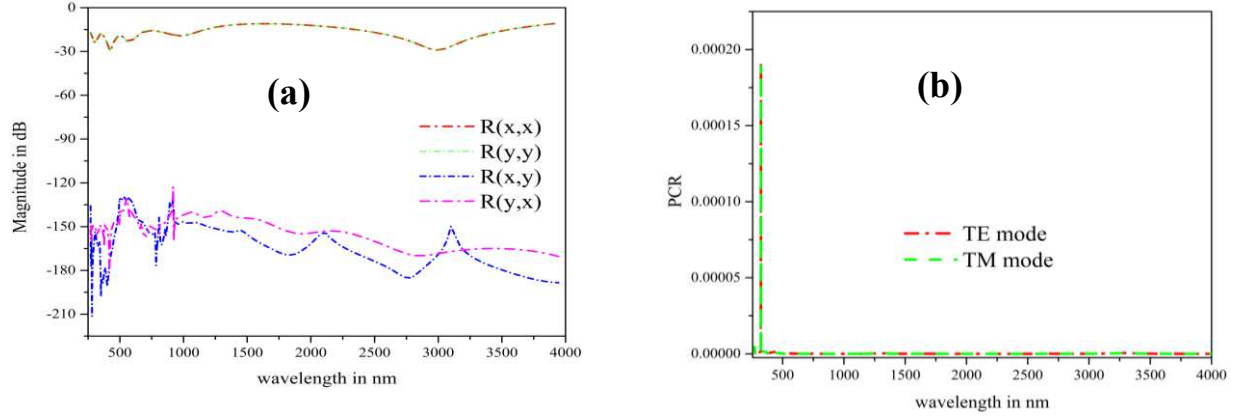


Fig 5: The illustration of the proposed absorber's (a) Cross polarization and Co polarization, (b) Polarization Conversion Ratio (PCR)

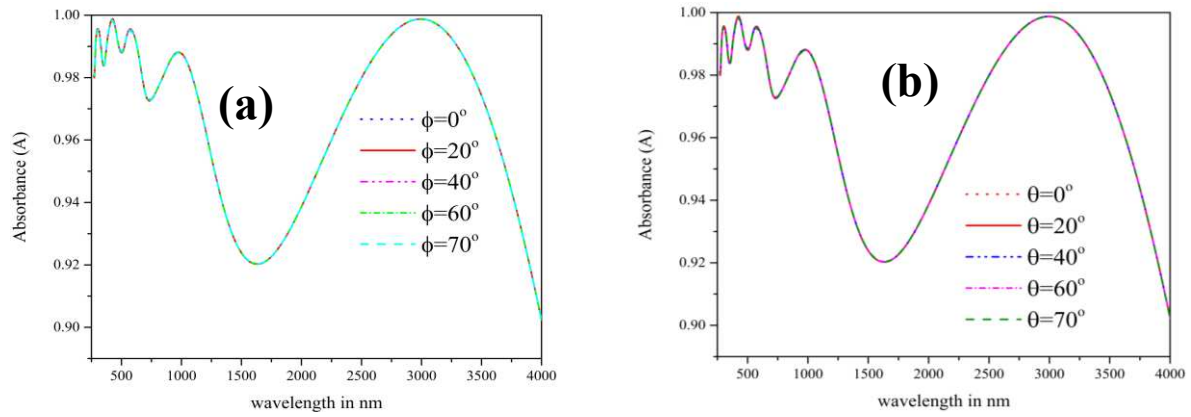


Fig. 6: Absorption response under (a) different incident angle, (b) different polarization angle

Polarization angle and incident angle stability

We also performed polarization and angular stability analysis for different angles. The absorber remains stable for either polarization change or a change of the angle of the incoming light. The shape of the resonator is very symmetrical, so the absorption is almost unchanged regardless of the polarization of light, thus proving that the resonator is not sensitive to polarization. It is seen from Fig. 6 that the absorption spectrum does not change significantly with the increase in the incidence angle and the presence of strong absorption region remains even at large incidence angles. This is because the electromagnetic coupling and the confinement of the fields in the resonator-dielectric system remains optimum even when light is tilted. We studied the design for different polarization angle from 0° to 70° where the graph shows stable absorption in each variation. In the same way we analyze the effect of different incident angle of incoming wave which also shows the similar results as we can see from Fig 6.

Verification of result through Interference theory:

Interference theory demonstrates how the process of absorption occurs. The wave is reflected and deflected back and forth between the top resonator and the bottom plane, alternately changing phase. These bouncing

reflections do not add up in the end, resulting in almost no reflection and near total absorption. The interface between the patterned top resonator and the dielectric spacer underneath it is where the incoming electromagnetic wave is incident. At that point, part of the wave reflects but does not pass through the structure. This directly reflected portion is a complex reflection coefficient, which can be expressed as $R_{f12} = R_{f12} e^{j\phi_{12}}$, where ϕ_{12} is the phase and R_{f12} is the amplitude of the reflection. When the transmission coefficient has the same form as $R_{f12} = R_{f12} e^{j\phi_{12}}$, the remainder of the incident wave transmits into the dielectric spacer instead of reflecting. The transmitted portion then travels to the solid tungsten ground plane at the bottom via the dielectric layer. When it does, it develops a propagation phase that depends on the distance traveled and the characteristics of the dielectric itself, i.e., $\beta_A = \beta_N + i\beta_P = \sqrt{\epsilon_d} K_0 d$. In this relation, k_0 is the free space wavenumber, " β_P " is the absorptivity that happens directly in the dielectric material as the wave propagates through it, and β_N is the propagation phase, which is essentially the amount of phase change the wave experiences when it travels a distance "d" through a medium of permittivity " ϵ_d ." The wave is now characterized by $R_{f21} = R_{f21} e^{j\phi_{21}}$, since it cannot pass through the ground plane without reflecting back up. A portion of this reflected wave transmits back into free space, $T_{R12} = T_{R12} e^{j\theta_{12}}$, after traveling back up through the dielectric and striking the underside of the top layer. The remainder bounces back down, restarting the cycle. Therefore, it is not just the initial bounce that departs the structure. It is the total of all the smaller waves that leak out after one, two, or more round trips, plus the initial reflection. These departing waves are "out of phase" due to an extra "phase delay" introduced on each trip. The majority of the wave that would otherwise reflect away is canceled out by their destructive interference. The net reflection coefficient is the sum of this infinite set of bouncing waves. It is the critical number that lets us know just how much energy is lost rather than absorbed. If we now connect this interference picture with the S-parameters that we simulated in CST, we get,

$$R_{Total} = R_{f12} - \frac{T_{R12} T_{R21} e^{j2\beta}}{1 + R_{f21} e^{j2\beta}} \quad (7)$$

Fig. 7 illustrates the absorption attained from ITM theory in comparison with the result from CST simulation. The result from calculation is almost similar to the simulated one which verifies the efficiency of our simulation.

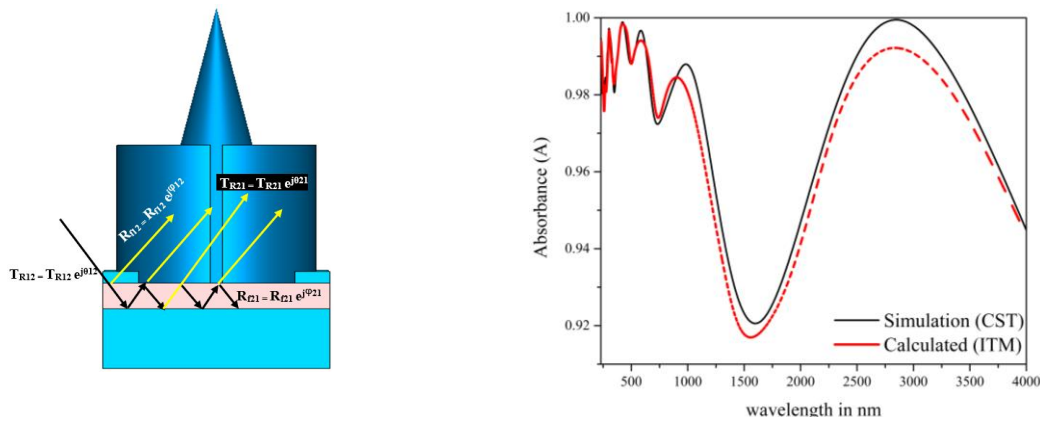


Fig 7: The illustration of how light strikes and is divided into fractions, part of which travels through the layer and scatters outside, (b) Absorption curve attained from simulation result and from the interference theory calculation

Field distribution analysis:

The Electric Field (E-field) and Magnetic Field (H-field) distributions were obtained by numerical full-wave simulations in order to assess the underlying physical mechanisms responsible for the broadband and high-efficiency absorption performance of the suggested metamaterial absorber. Four important operational wavelengths were used to study the resonant modes and localized electromagnetic field improvements.

Overall, the broadband absorption behavior of the suggested structure can be explained physically by the electric and magnetic field distributions. The wavelength-dependent localization of these fields shows that the broad absorption response is a result of many electromagnetic interactions within the metallic and dielectric areas rather than a single resonance.

The E-field and H-fields of the MMA can be approximated using the following Maxwell equations:

$$\int_c^a E \cdot dl = 0 - \frac{\partial}{\partial t} \int_S \int B \cdot dS \quad (8)$$

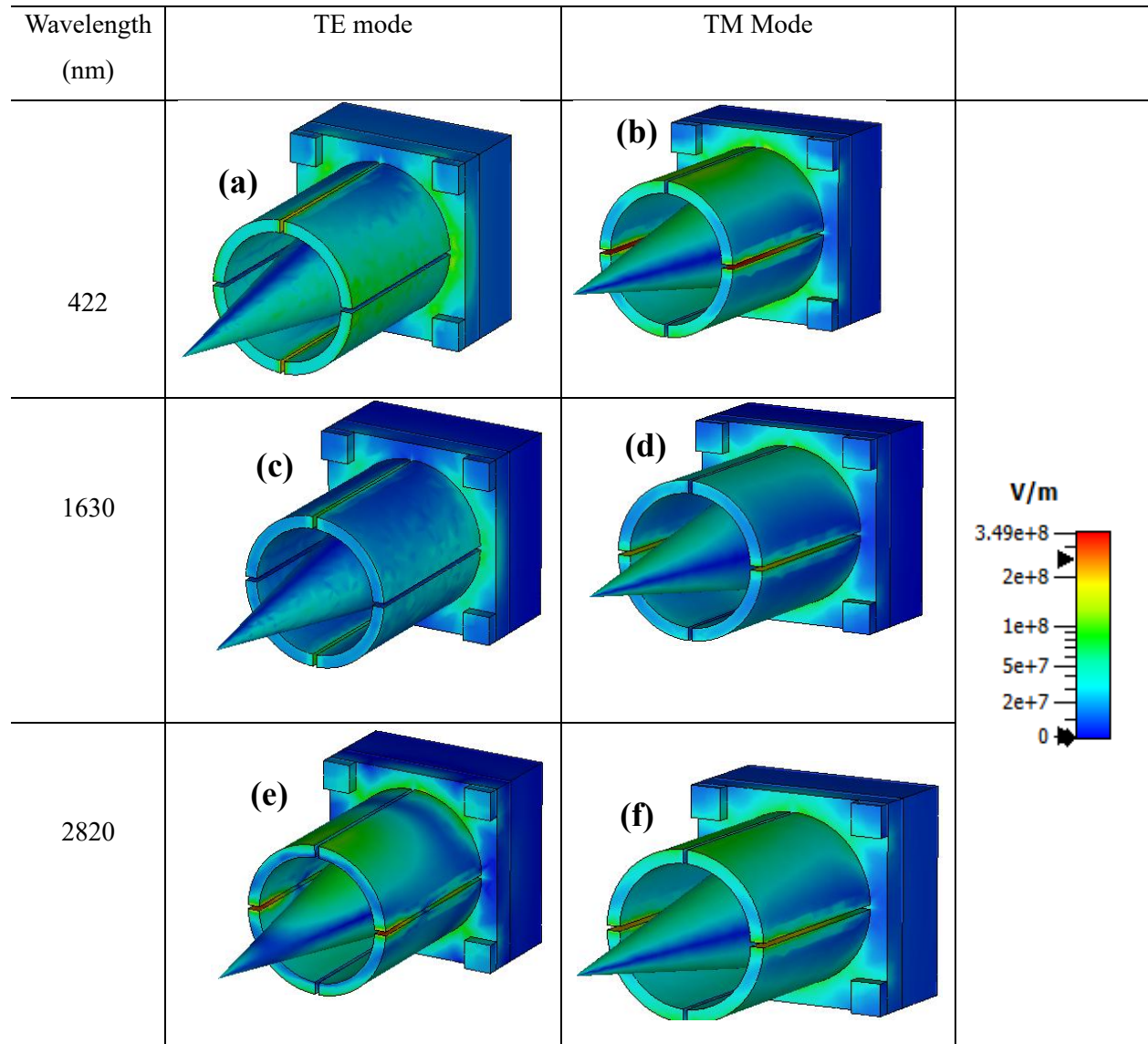
$$\int_c^a H_F \cdot dl = 0 - \frac{\partial}{\partial t} \int_S \int D_F \cdot dS \quad (9)$$

In the equation above, the magnetic flux is denoted as ‘B’. ‘E’ represents the electric field density, and ‘D_F’ represents electric flux density. Here, magnetic flux is denoted as ‘H_F’. We can find D_F and H_F from these two relationships $D_e = \epsilon_{effective} \epsilon_0 E_F$ and $B = \mu_{effective} \mu_0 H_F$. These equations actually show that the flux densities of the electric field and the magnetic field are connected with two material properties, ‘μ’ and ‘ε’. These are called permittivity and permeability, and the spatial distributions of the electric and magnetic fields can vary considerably with wavelength, particularly near resonant conditions.

Field distribution analysis:

The electric- and magnetic-field distributions of the suggested absorber were analyzed at four representative wavelengths—422 nm, 1630 nm, 2820 nm, and 4000 nm, as illustrated in Figures 8 and 9 in order to look into the source of the broadband absorption. At the apex of the core conical structure and along the longitudinal slots of the outer cylindrical shell, the E-field displays an extraordinary local maximum of 3.49×10^8 V/m. Intense LSPR excitation is demonstrated by this strong electric dipole moment, which efficiently traps shorter-wavelength light within the subwavelength tip, resulting in nearly complete absorption. The absorption is 92% over the bandwidth at 1630 nm. Despite a modest decrease in total absorption, the E-field distribution shifts from the conical tip toward the inner and outer cylindrical sidewalls, exhibiting balanced cavity modes that maintain strong power dissipation. Compared to other wavelengths, this one has a smaller field spread. The cut gap, the adjoint of the dielectric layer, and the metal cut gap all exhibit a small amount of field intensity. In this case, the location is rotated while the TM mode changes at the same wavelength because TE and TM behave inversely with field rotation. The absorption rose to 99.28% at 2820 nm. Therefore, as shown in Fig. 8 (e) and (f), the field intensity also rose. The field intensity rose at this wavelength in the vicinity of the ring gap and the dielectric spacer. The gap displays the highest field intensity that extends in the direction of the dielectric, indicating the existence of LSPR and CSPR. At 422 nm resonance, the magnetic field is at its strongest. The existence of LSPR is explained by the spacer and joint space with metal resonator, which spread the majority of the field intensity. Additionally, as Fig. 9 (a) and (b) show, the field color ramp moves toward the bottom layer, which stands for PSPR. Because there is less absorption at 1630 nm, the magnetic field marginally diminishes at this wavelength. Thus, in

comparison to others, the field intensity likewise appears to be lesser. Fig 9 (b) and (c) display a little LSPR at the top of the ring resonator. The field distribution at 2820 nm is shown in Fig.9 (e), (f). The graphic shows that there is a small amount of PSPR and LSPR near the top of the ring resonator. As seen in Fig. 9(g) and (h), PSPR and LSPR are most visible at a wavelength of 4000 nm. The highest concentration of LSPR, which promotes absorption, is seen at the top of the ring resonator. This is the second-lowest peak absorption point, with absorption at 94%. Thus, Fig 9 illustrates how the structure's overall absorption is influenced by the LSPR, PSPR, and CSPR.



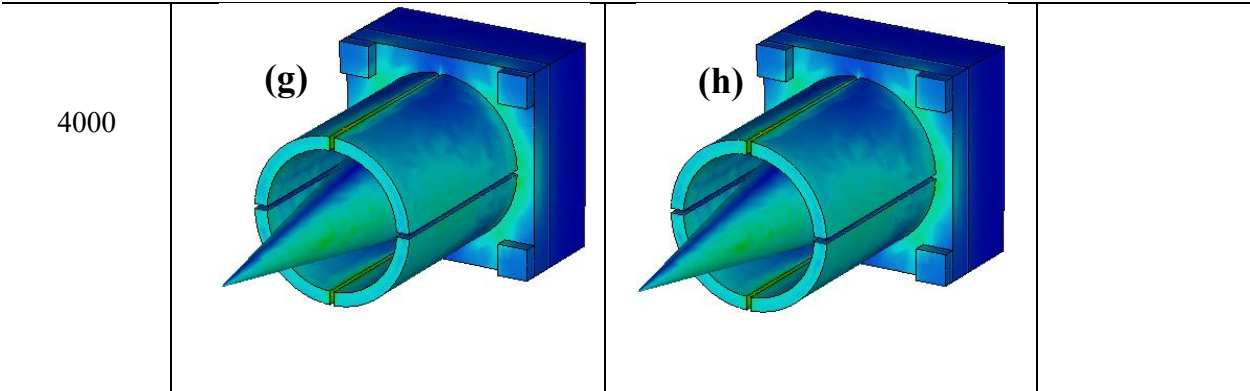
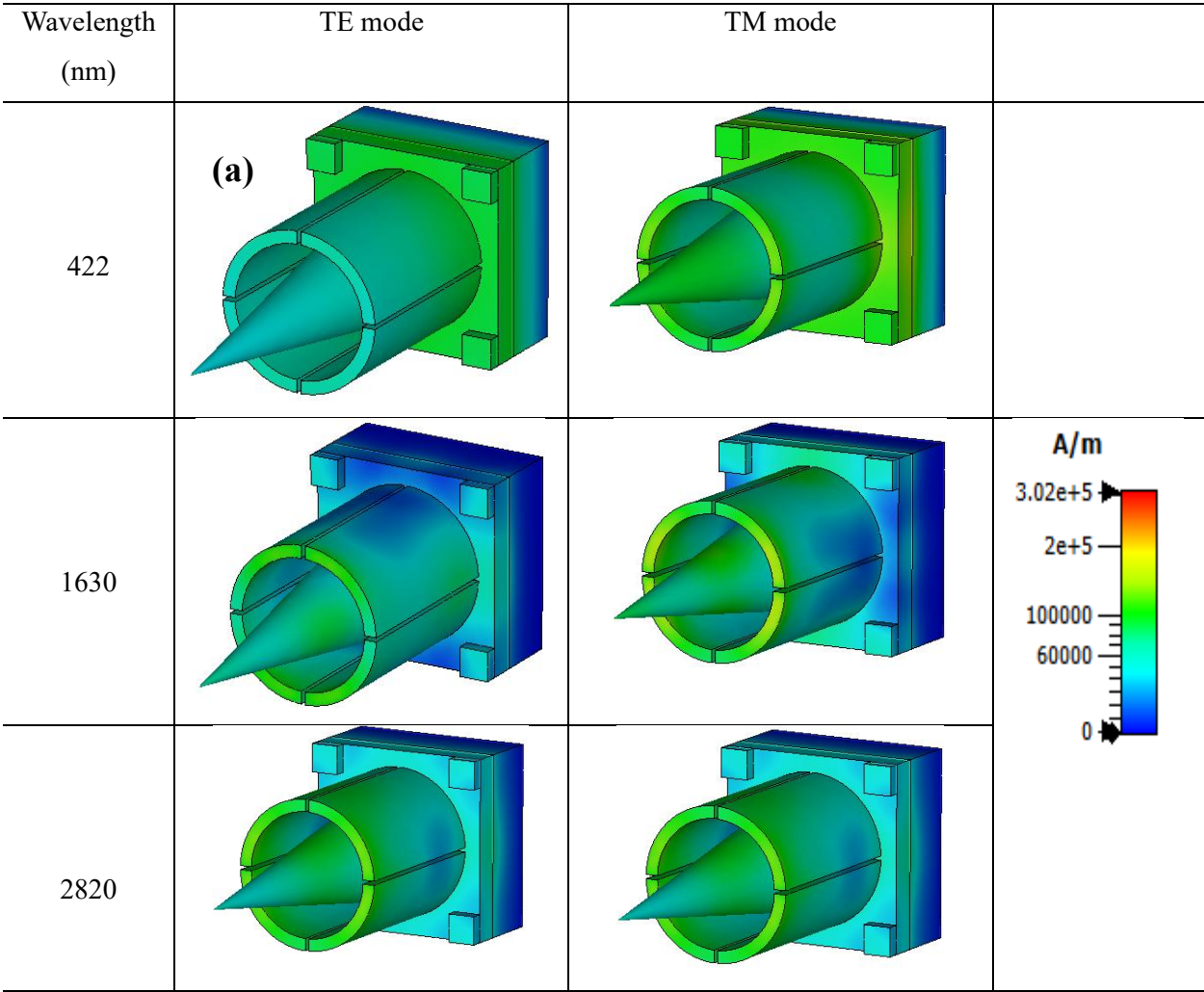


Fig 8: Electric field distribution at 4 distinct wavelengths in TE mode and TM mode



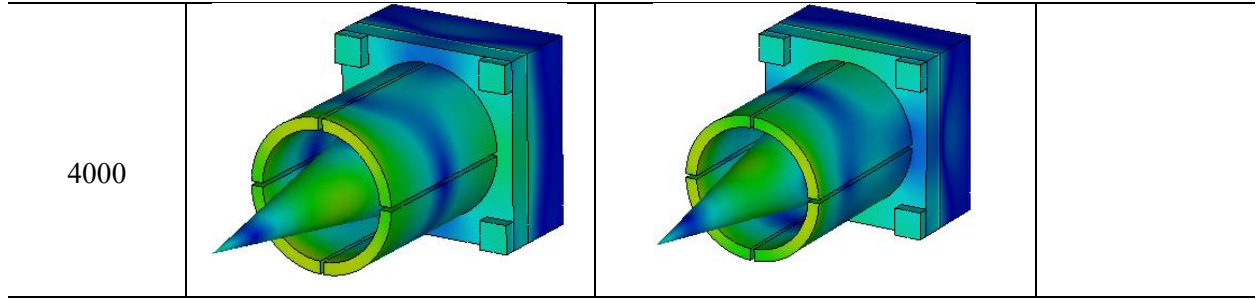


Fig. 9: Illustration of magnetic field distributions on absorber structure

Absorber as Solar Harvesting Application

The collection of solar energy is a crucial method for sustainable energy transformation. This work proposes a subwavelength metamaterial absorber (MMA) for broadband solar energy absorption. Its potential as an optical front-end layer in solar-energy conversion systems is shown by its high absorption over a wide wavelength range. The performance is assessed theoretically using the simulated absorption spectrum, $A(\lambda)$, weighted in accordance with the standard solar spectrum, as no practical solar cell or photocurrent measurement was included in this work. This offers a standard framework for evaluating the absorber's potential for solar-thermal and photovoltaic applications.

Instead, then relying solely on absorption, solar energy harvesting requires evaluating absorption based on the incident solar power's spectral distribution. The three primary parts of a typical solar thermophotovoltaic (STPV) system are a photovoltaic (PV) cell, a thermal emitter, and a solar absorber. The incident solar radiation is captured by the absorber, transformed into thermal energy, and then released again as photons by the thermal emitter. The PV cell subsequently absorbs these photons to produce electrical energy and electron-hole pairs. Thus, the solar-weighted absorptance provided by the following formula [18, 19] can be used to calculate the percentage of incident solar energy absorbed by the suggested construction under normal illumination:

$$\alpha_{MAT} = \frac{\int_{230 \text{ nm}}^{4000 \text{ nm}} \alpha_{A\lambda} I_{AM1.5}(\lambda) d\lambda}{\int_{230 \text{ nm}}^{4000 \text{ nm}} I_{AM1.5}(\lambda) d\lambda} \quad (10)$$

Here, α_{MAT} denotes the total solar absorptance of the absorber, $\alpha\lambda$ is the spectral absorptance at wavelength λ , and $I_{AM1.5}(\lambda)$ represents the standard solar spectral irradiance [20]. The thermal emissivity as a function of temperature and wavelength is then determined using Equation (11), where ε_{ET} is the total integrated emissivity and ε_{ST} is the spectral emissivity of the unit cell at the selected wavelength.

$$\varepsilon_{ET} = \frac{\int_{370 \text{ nm}}^{1070 \text{ nm}} \varepsilon_{ST} V_{BR}(\lambda, T_{AB}) d\lambda}{\int_{370 \text{ nm}}^{1070 \text{ nm}} V_{BR}(\lambda, T_{AB}) d\lambda} \quad (11)$$

The blackbody radiation $V_{BR}(\lambda, T_{AB})$, is calculated using Equation (12) based on Planck's constant (h), Boltzmann's constant (k), and the speed of light (c) [21]. Since the absorber temperature

strongly affects its thermal emission, the photon-to-heat conversion efficiency is evaluated using Equation (13), assuming convective and conductive losses are equal to 1.

$$V_{BR}(\lambda, T_{AB}) = \frac{2\pi hc^2}{\lambda^5} \times \frac{1}{e^{hc/\lambda kt} - 1} \quad (12)$$

$$\eta_E = \frac{\alpha_T D \times h - \varepsilon_{TO}(\sigma T_W^4 - \sigma T_C^4)}{D \times C} \quad (13)$$

For the analysis, the ambient temperature (T_c) is set to 25 °C, while (T_w) represents the steady-state absorber temperature. Under one-sun illumination, the incident solar intensity is assumed to be 1000 W/m². Radiative heat loss is considered through the solar concentration factor (C) and the Stefan–Boltzmann constant (σ). The photothermal conversion efficiency is then calculated from the absorbed solar energy converted into thermal energy using Equation (16). The schematic of the solar energy harvesting mechanism, using the proposed metamaterial absorber, is presented in Figure 10. Figure 11 presents the conversion efficiency for different concentration factors at absorber temperatures of 573, 973, and 1273 K.

The weighted solar irradiance solar AM1.5 is compared to our archived absorption. Our work shows excellent conversion and absorption efficiency. In figure12 it is clearly seen that most of the available solar wave under standard irradiance is absorbed. A very little energy is missed which depicted in fig 12 with a blue covered area.

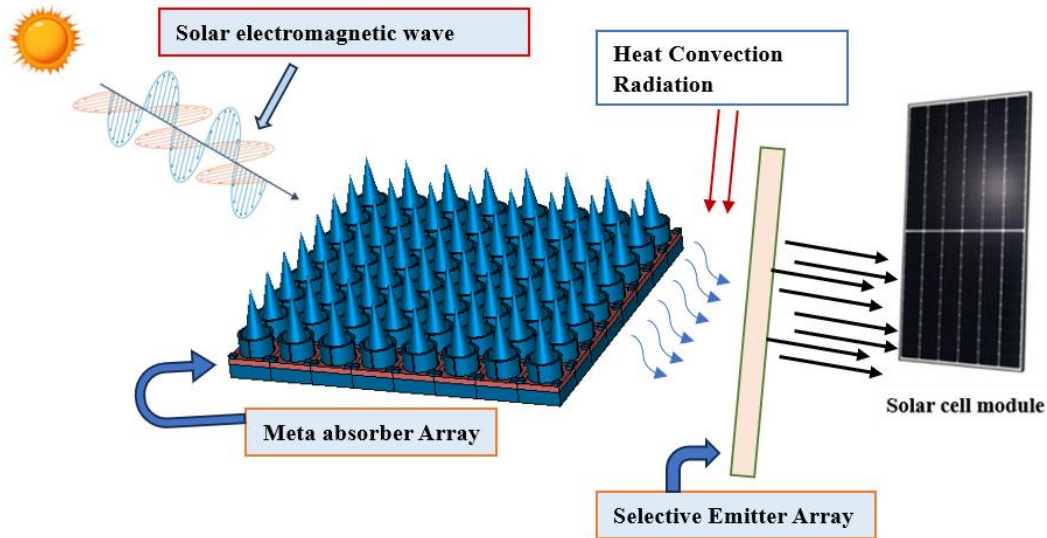


Fig. 10: Demonstration of solar energy harvesting system of the meta absorber

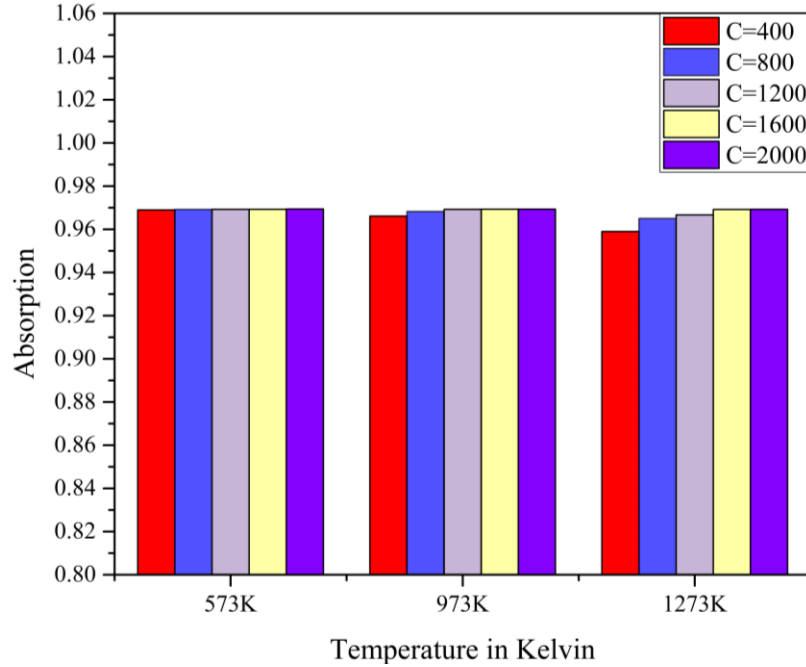


Fig 11: Bar graph showing solar photothermal conversion efficiency under different solar concentration factors (C)

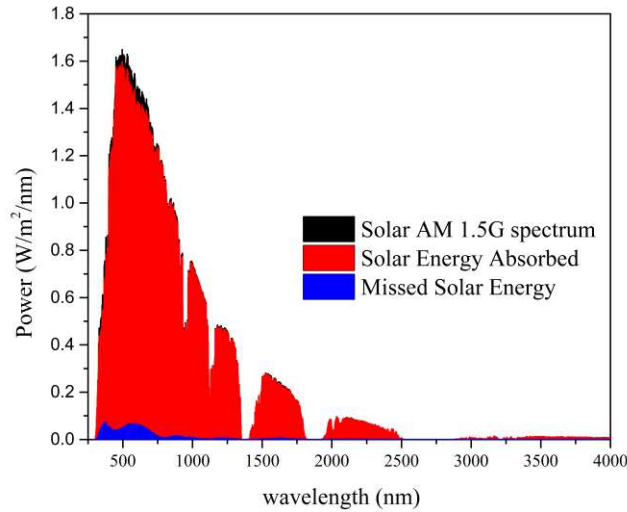


Fig.12 : Demonstration of absorber performance under standard Solar irradiance solae AM 1.5

Potential implementation of absorber as Solar Sail:

MMA can be used in solar sail applications in addition to absorption in solar energy harvesting. Without the need for a traditional propellant, solar sailing uses the velocity of sunlight to produce a constant propelling force. A radiation-pressure force is created when electromagnetic radiation interacts with a sail surface and transfers momentum through absorption, reflection, and transmission. Lightweight optical structures are especially appealing for solar-sail applications since the force's amplitude is dependent on the sail's optical response and mass-to-area ratio. Because their optical response may be controlled using

subwavelength resonators, metamaterial absorbers (MMAs) offer an alternative to traditional reflective solar sails. It is possible to modify the absorption, reflection, polarization response, and angular properties over a chosen spectral range by adjusting the unit cell's geometry and material composition. As a result, broadband MMAs have drawn attention for solar energy harvesting and, more recently, solar sail applications. NASA's recent research demonstrates how they function in space without the need for a thrust generator or other propulsion technology. This extreme metamaterial project as a solar sail is shown in Fig. 13 (a). The earlier studies on metamaterial absorbers for solar sail applications are shown in Fig. 13 (b), (c). Fig 14 (a), (b) represents our proposed absorber as solar sail.

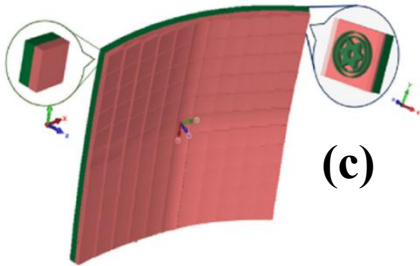
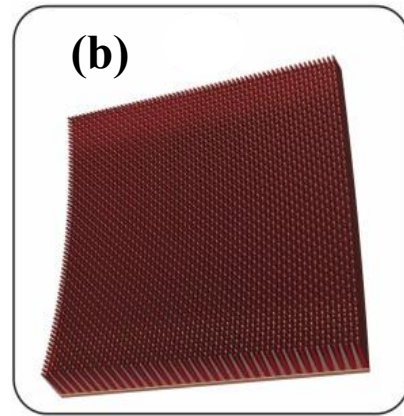
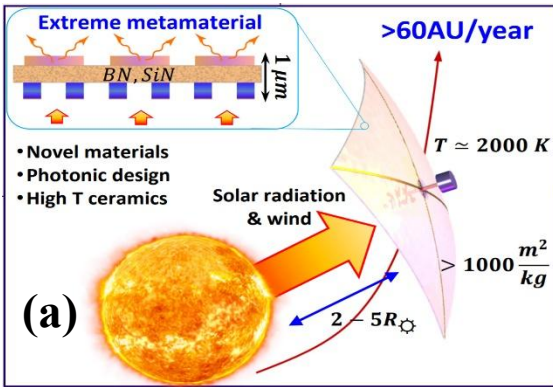


Fig 13: Graphical representation of (a) a concept of NASA, representing an extreme metamaterial for solar sailing application, (b), (c) recent meta-absorber works as solar sail.

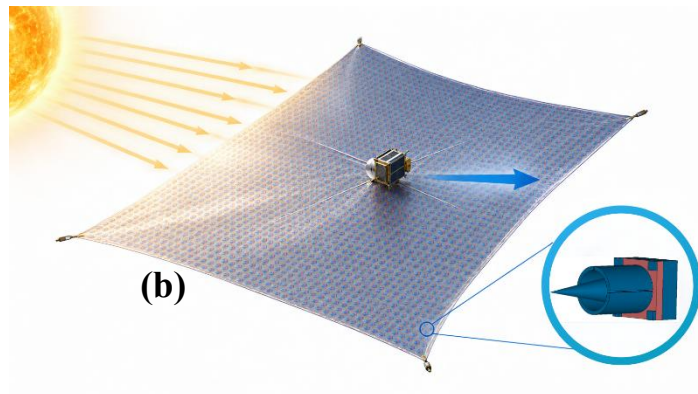
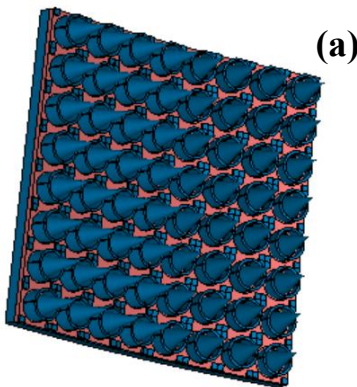


Fig 14: Illustration of (a) proposed absorber bulk array for solar sail, (b) potential practical implementation of proposed large metamaterial absorber array solar sail

Comparative analysis

The suggested absorber has a maximum absorption of 92.4% at any point in the band and an average absorption of 98.30% for the range of 230 nm to 4000 nm. This entire process is accomplished utilizing a solitary unit cell that measures 452 x 452 x 1115 nm. Table 2 compares these numbers with eight metamaterial solar absorbers from the most recent research to help understand them.

The development of meta-absorbers to capture solar electromagnetic waves has been significantly impacted by recent research. Only three-layer works that attained broad absorption are included here; several multilayer works that also attempted to do so are not. The table illustrates that while the majority of earlier research attempted to increase the bandwidth and absorption efficiency, the average absorption rate did not surpass 97% and the bandwidth remained below 1000 nm in optical frequencies (UV, Vis, and IR). Although references [22] and [23] demonstrated absorption efficiency of above 97%, their bandwidth was still insufficient to span the wide spectrum. Reference [24] attained a wide bandwidth of 2800 nm and a 96.7% absorption rate in 2025. A 96.7% rate was achieved with a 2300 nm bandwidth later in 2026, but none of the works listed here surpass the suggested rate. A small absorber with complete polarization, angular insensitivity, and 98.43% absorption efficiency is shown in our work. Additionally, the coverage bandwidth, which is 3770 nm from 230 nm to 4000 nm, is better than that of other previous studies.

Table 2: Comparison table of previous works						
Ref	Year	Layer	Material	Bandwidth	Absorption rate	Polarization and Angular stability
[22]	2026	3	Ni, Al, Ni	900	97.45	Yes, up to 60°
[23]	2026	3	W-SiO ₂ -W	580	97.36	Yes, up to 50°
[24]	2025	3	Ni, SiO ₂ , Ni	2800	95.21 %	Yes, up to 60°
[25]	2025	3	W, SiO ₂ , W	840	96.27	Yes, up to 80°
[26]	2025	3	Ni, SiO ₂ , Ni	900	96.63	Yes, up to 60°
[27]	2026	3	TiN , Si ₃ N ₄ , W	2300	96.7	Yes, up to 60°
[28]	2026	3	Ni, Au, Quartz,	850	88.49	Yes, up to 30°
[29]	2026	3	W, Quartz, Au	375	91.27	Yes, up to 90°
[30]	2025	3	W, Quartz, W	515	90.8	Yes, up to 60°
Proposed	2026	3	W-SiO₂-W	3770	98.3%	Yes, totally unchanged

Conclusion

A three-layer tungsten and silicon dioxide (W/SiO₂) optical meta-absorber with a compact unit cell measuring 452 × 452 × 1115 nm³ was designed and numerically analyzed in this work. Over a broadband absorption range of 3770 nm, the optimized structure demonstrated an average absorptance of 98.43%; over the examined spectrum of 230–4000 nm, the absorption was above 92.4%. It offers huge opportunities for solar energy harvesting and other related photothermal applications due to its broad UV-to-mid IR wavelength range. The metal–dielectric–metal structure's numerous reflections, resonant coupling, and impedance matching all contribute to the broadband response. A SiO₂ spacer and patterned tungsten resonator are utilized to limit electromagnetic polarization and dissipate energy, while a tungsten ground plane is employed to block transmission. The parametric and material analyzes identified the geometrical

and material characteristics that govern the absorption response, and the appropriateness of the W/SiO₂ parameter was confirmed. Additionally, the absorber's TE and TM responses were very identical, indicating polarization insensitivity. Stable absorption was achieved for oblique incidence up to 70° in the examined angle of incidence. The suggested design offers a high absorption, an incredibly broad spectral range, and a comparatively straightforward 3-layer architecture with just two materials when compared to the recently reported broadband absorbers. Because of these qualities, it can be used for high-temperature photonic applications, photothermal conversion, and broadband solar energy harvesting.

Acknowledgement: Authors received no funding for this research

Data Availability Statement: The simulation data analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest: The authors declare no conflict of interest

REFERENCES

- [1] N. I. Landy, S. Sajuyigbe, J. J. Mock, D. R. Smith, and W. J. Padilla, "Perfect metamaterial absorber," *Physical review letters*, vol. 100, no. 20, p. 207402, 2008.
- [2] R. Bilal *et al.*, "Elliptical metallic rings-shaped fractal metamaterial absorber in the visible regime," *Scientific reports*, vol. 10, no. 1, p. 14035, 2020.
- [3] Y. Zhang *et al.*, "Dual band visible metamaterial absorbers based on four identical ring patches," *Physica E: Low-dimensional Systems and Nanostructures*, vol. 127, p. 114526, 2021.
- [4] M. Luo, S. Shen, L. Zhou, S. Wu, Y. Zhou, and L. Chen, "Broadband, wide-angle, and polarization-independent metamaterial absorber for the visible regime," *Optics express*, vol. 25, no. 14, pp. 16715-16724, 2017.
- [5] T. S. Tuan and N. T. Q. Hoa, "Numerical study of an efficient broadband metamaterial absorber in visible light region," *IEEE Photonics Journal*, vol. 11, no. 3, pp. 1-10, 2019.
- [6] Y.-C. Lai, C.-Y. Chen, Y.-T. Hung, and C.-Y. Chen, "Extending absorption edge through the hybrid resonator-based absorber with wideband and near-perfect absorption in visible region," *Materials*, vol. 13, no. 6, p. 1470, 2020.
- [7] B. Qi, W. Chen, T. Niu, and Z. Mei, "Ultra-broadband refractory all-metal metamaterial selective absorber for solar thermal energy conversion," *Nanomaterials*, vol. 11, no. 8, p. 1872, 2021.
- [8] Z. Huang and B. Wang, "Ultra-broadband metamaterial absorber for capturing solar energy from visible to near infrared," *Surfaces and Interfaces*, vol. 33, p. 102244, 2022.
- [9] B. Qi *et al.*, "A near-perfect metamaterial selective absorber for high-efficiency solar photothermal conversion," *International Journal of Thermal Sciences*, vol. 194, p. 108580, 2023.
- [10] Y. Sun *et al.*, "Absorption and photothermal conversion analysis of metamaterial solar absorber based on double Ni rings," *Applied Thermal Engineering*, p. 129851, 2026.
- [11] R. Agravat, S. K. Patel, Y. Sharma, and F. A. Al-Zahrani, "Smart broadband thermal absorption across solar spectrum using machine learning-optimized nanodisk slotted resonator metamaterial solar thermal absorber for industrial heating applications," *Case Studies in Thermal Engineering*, vol. 77, p. 107585, 2026.
- [12] N. B. Ali, R. Agravat, S. K. Patel, A. Armghan, M. Kouki, and O. P. Kumar, "Optimization of ultra-wideband metamaterial MXene-based polarization-insensitive solar absorber using machine learning for solar heater application," *Scientific Reports*, vol. 15, no. 1, p. 10429, 2025.
- [13] J. Zhang, Y. Chen, S. Chen, J. Hou, and J. Liu, "A simple ultra-broadband metamaterial solar perfect absorber with highly efficient photothermal conversion performance," *Physica B: Condensed Matter*, vol. 699, p. 416845, 2025.

- [14] Z. Xue, S. Cheng, H. Zhang, J. Zhu, and Z. Yi, "Three-layer metamaterial solar absorber based on tungsten metal for broadband high absorption and high-temperature thermal radiation stability," *International Journal of Thermal Sciences*, vol. 223, p. 110648, 2026.
- [15] C. S. Prasad and M. Gupta, "Tungsten-alumina-graphite based metamaterial absorber with concentric ring cavities for efficient solar energy harvesting," *Optical and Quantum Electronics*, vol. 57, no. 6, p. 338, 2025.
- [16] J. Wu, Y. Sun, B. Wu, C. Sun, and X. Wu, "Perfect metamaterial absorber for solar energy utilization," *International Journal of Thermal Sciences*, vol. 179, p. 107638, 2022.
- [17] V. Khichar, N. Hozhabri, and A. R. Koymen, "Solar energy harvesting using new broadband metamaterial solar absorbers for generation of heat," *APL Energy*, vol. 2, no. 1, 2024.
- [18] H. Wang and L. Wang, "Perfect selective metamaterial solar absorbers," *Optics express*, vol. 21, no. S6, pp. A1078-A1093, 2013.
- [19] M. Raihan *et al.*, "Concentric square and circular patch metamaterial absorber for solar absorber and optical wavelength applications," *Micro and Nanostructures*, p. 208476, 2025.
- [20] M. Soliman, M. Rahman, A. K. Zilani, A. M. Alenezi, M. A. Alawad, and M. T. Islam, "Nanostructured star symmetric metasurface absorber for solar and optical applications: Attaining close-complete absorption from ultraviolet to near-infrared a numerical approach," *Photonics and Nanostructures-Fundamentals and Applications*, p. 101454, 2025.
- [21] M. M. Soliman *et al.*, "Wideband close perfect meta surface absorber for solar photovoltaic and optical spectrum applications," *Surfaces and Interfaces*, vol. 45, p. 103849, 2024.
- [22] M. M. K. Nipun, S. R. Rana, M. G. Morshed, I. Jahan, and F. S. Ahamed, "Machine learning-driven metamaterial absorbers for solar energy harvesting and UV to infrared radiation shielding," *Journal of Science: Advanced Materials and Devices*, p. 101172, 2026.
- [23] H. S. E. Ahmed, F. B. Shikder, M. J. Uddin, and M. Raihan, "Nano-structured efficient meta-absorber for optical applications: solar thermophotovoltaic and solar sail," *Journal of Engineering and Applied Science*, vol. 73, no. 1, p. 214, 2026.
- [24] K. Nath, F. Islam, and M. Mahdy, "A tri-layered Fibonacci spiral-inspired metamaterial absorber exhibiting enhanced solar energy harvesting with an emphasis on thermophotovoltaic cells," *Energy Conversion and Management: X*, p. 101448, 2025.
- [25] M. Raihan *et al.*, "Wideband absorption with polarization and angular insensitive metamaterial for optical applications based on Tungsten-SiO₂ composites," *Journal of Science: Advanced Materials and Devices*, vol. 10, no. 2, p. 100878, 2025.
- [26] M. M. K. Nipun, S. R. Rana, M. G. Morshed, K. M. R. Amin, F. S. Ahamed, and H. F. Khan, "Broadband solar energy harvesting with a machine-learning-optimized nickel-quartz metamaterial absorber," *Journal of Nanophotonics*, vol. 19, no. 4, pp. 046003-046003, 2025.
- [27] N. Singh, R. Kumar, B. K. Singh, and P. C. Pandey, "High-temperature photothermal conversion and spectrally tailored thermal emission using selective refractory metamaterial absorber for efficient solar energy harvesting," *Solar Energy Materials and Solar Cells*, vol. 303, p. 114397, 2026.
- [28] M. J. Hossain, A. Shaha, M. H. Rahman, S. Haydar, and M. R. I. Faruque, "Ultra-wideband polarization-incident angle insensitive nano-scale metamaterial absorber for solar energy harvesting and infrared detection," *Journal of Science: Advanced Materials and Devices*, p. 101140, 2026.
- [29] A. Sharkar *et al.*, "Nanoscale optical-regime metamaterial absorber for enhanced photon absorption in thermal emitters," *Journal of Science: Advanced Materials and Devices*, vol. 11, no. 1, p. 101078, 2026.
- [30] A. A. M. Rahman, M. T. Islam, M. Moniruzzaman, H. Alsaif, A. A. Maash, and M. S. Soliman, "A highly absorptive ultra-wideband nanoscale metamaterial absorber for solar energy harvesting from ultraviolet to Infrared spectrum," *Ain Shams Engineering Journal*, vol. 16, no. 2, p. 103229, 2025.