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# Incidence Angle Sensitive Broadband Metamaterial Perfect Absorber

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***Abstract***—In this paper a novel configuration of metamaterial perfect absorber (MMPA) is proposed to enhance the spectral broadband performance. A combination of squares and circles of Au structures made on Si are used for the purpose. An Au thin layer at the bottom is used to minimize the transmission through the MMPA. The observed strong absorbance are due to the overlap between TE and TM polarization states from 250 nm to 600 nm and 1100 nm to 1700 nm. The design is validated by measuring the reflectance, transmittance and absorbance at different angle of incidence of source using Lumerical FDTD commercial software. Results show incidence angles sensitive broadband MMPA.

***Keywords*—**Absorbance, Broadband, Metamaterial Perfect Absorber (MMPA), Lumerical FDTD, Solar Band

## I. INTRODUCTION

Artificially structured materials known as metamaterials are studied in the past as it shows many exotic properties not achieved using naturally occurring materials, compounds and alloys. Design of metamaterial means patterning the subwavelength unit cells known as meta-atoms or meta-molecules. These meta-atoms may have novel electric and/or magnetic responses for the incident electromagnetic waves. Development of metamaterials design has many applications in engineering and applied science.

Since the theoretical prediction of the existence of metamaterials the search of it for a specific application has been the active area of research [1]. Few applications of metamaterials for specific applications have been demonstrated through experiments [2-4]. Experiments have shown potential applications of metamaterials in sensing, imaging and focusing [5-6]. Among various applications the design for a metamaterial as a perfect absorber has been the active area for the researcher [7-12].

Various experimental and/or numerical simulations reported in the literature for MMPA in different spectral range of electromagnetic spectrum show absorption band narrow enough on the electromagnetic spectral region. This is because of the different design of structures that is only resonant in a narrow band of spectral region and non-resonant in a wide region of spectrum [13-21]. However, few works shown the broadband performance of absorption having single type of unit cell.

Here, in this work a design having the combination of the structures is presented which has the spectral broadband performance in the solar band of spectral region [22]. The design (finite array of structures) is, however, complex but could be very useful for MMPA. Optimized parameters such as the size and periodicity of the structures may result broadband performance for the designed metamaterial.

For MMPA, idea is to create multiple resonances in each unit cell of the structure for each pattern of Au on the top layer of the proposed design for MMPA (as shown in Fig. 1).

## II. METHODOLOGY

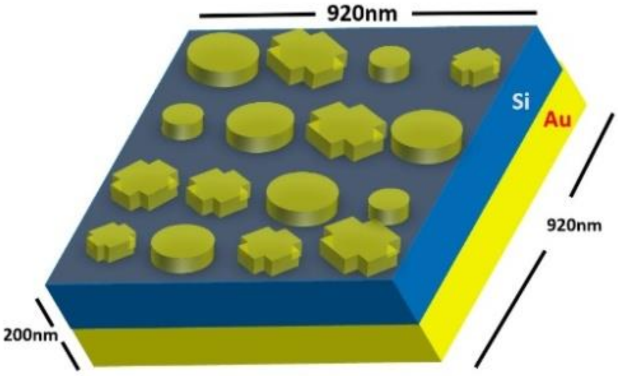

Fig. 1: Dimensions of the proposed MMPA is 920 nm × 920 nm × 280 nm. The top Au complex structures comprising circles and crosses with thickness of 80 nm and separation of 230 nm (distance between centers of the two consecutive structures) are taken. Bottom layer of Au has thickness of 120 nm.

We use the combination of individual structure of different size and shape to create multiple resonance through the individual unit cell at different wavelength. Our proposed MMPA is composed of periodically arranged complex metallic pattern of Au as shown in Fig. 1. Proposed design of MMPA is patterned over a dielectric layer of Si followed by a metallic plate of Au at the bottom [22]. Proposed design of MMPA is useful to tune the impedance-matching condition to achieve almost zero reflection and transmission with maximum absorption at resonant wavelength range. To dissipate the electromagnetic wave the dielectric layer of Si is used. To minimizes the transmission of incident electromagnetic waves through the MMPA bottom metallic ground layer of Au blocks are used. The dimensions of the proposed MMPA is 920 nm × 920 nm × 280 nm with top designed structure of Au as circles and crosses as shown in the Fig. 1.

Origin of functioning the proposed design as a perfect absorber is based on the localization of electric and magnetic dipolar resonances in the Au-Si-Au structure. The top Au complex structures having circles and crosses have thickness of 80 nm with periodicity of 230 nm (distance between centres of the two consecutive structures). The diameter of smallest circle is 40 nm and the largest circle is 140 nm. Length of crosses type structures varies from 140-200 nm. Thickness of Si layer selected for both impedance matching and strong absorbance and the bottom layer of Au concentrating the electromagnetic energy to work as an absorber are kept equal to 120 nm each.

Structures like circles and crosses are used for the multiple resonances in the different region of spectrum to achieve the broadband performance of the absorber.

Full wave numerical simulations using Lumerical FDTD software is performed using commercial software. Simulations were carried out using appropriate boundary conditions. Dielectric constants for the studied wavelength region of 250 nm to 2500 nm for the Au and Si have been taken from the Lumerical FDTD. In all simulations monitors are placed in the far-field region. Lumerical FDTD simulations are performed for the various angles of incidence ($0^0$, $45^0$, $60^0$) for the proposed design of MMPA. Both *p*-polarized and *s*-polarized electromagnetic source are used to study the performance of MMPA in wavelength range of 250 nm to 2500 nm.

In our simulations, we calculate the *S* parameters by changing the angle of incidence of electromagnetic source falling on MMPA (*S*21 for transmission and S11 for reflection) and the absorption was derived using, (1-*S*11) considering transmission (*S*21) as negligibly small equal to zero. Electric field pattern have also been simulated to verify the observed absorption behaviour of absorption in the observed spectral band of incident electromagnetic source. Furthermore, simulations have been performed using both the *s*-polarisation and *p*-polarisation of electromagnetic source of incident light. All the parameters are calculated using simulations and results are analysed and interpreted in subsequent sections.

## III. RESULTS AND DISCUSSION

Simulations results in the wavelength range of 250 nm to 2500 nm for the absorption, transmission and reflection are shown in Fig. 2 for different angle of incidence of electromagnetic source. It is observed that normalized absorption band is increasing as we increase the angle of incidence from $0^0$ to $45^0$ for the source as shown in the Fig. 2. At $60^0$ of source incidence broadband performance is even less broader in the spectral region than that of $45^0$ of source incidence. At $45^0$ of source incidence, it has been found to have the almost 80% of absorption is taking place while reflection and transmission is within the range of 20% in the wavelength range from 1100 nm to 1700 nm.

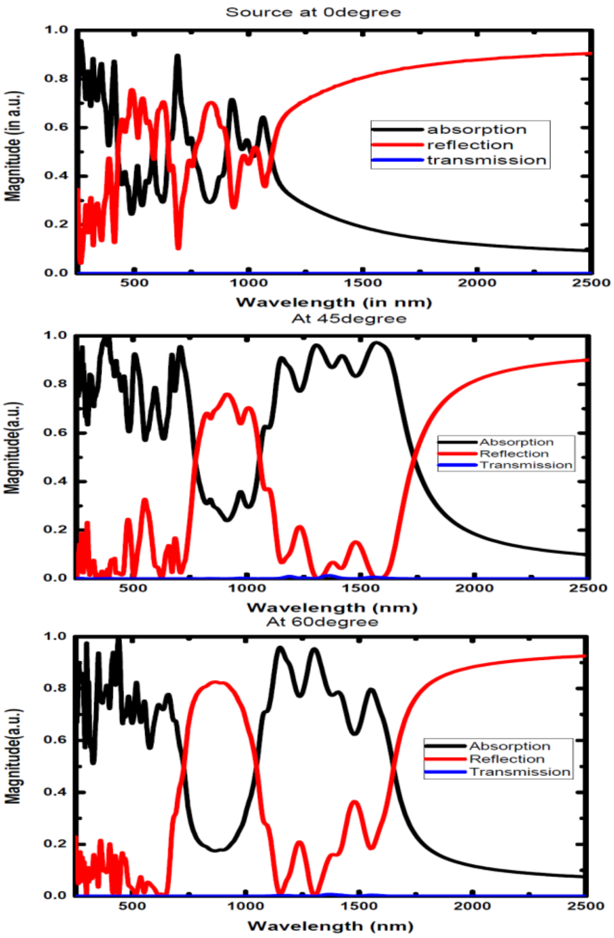

Fig. 2: Simulation results of transmission, reflection and absorption for MMPA at different angle of electromagnetic wave falling on the designed MMPA.

Proposed design has the complex structures as circles and crosses are resonantly excited and concentrate the electromagnetic source energy in the broader range of spectrum of wavelength because of differently sized and shaped structures excited at different wavelengths.

Further, we show the electric field pattern over the surface of Au using Lumerical FDTD software package. We have compared the performance of our proposed metasurface structure with the other structures which has either completely cross structures or circled structures keeping the size of the single kind of structures unchanged (for circle structure radius is same as length of corresponding cross structures) at respective place of the structure for source wavelength of 1000 nm at different angle of incidence. We plot the electric field distribution at the surface of Si and just below the nanostructures for the incidence source of electromagnetic wave at normal incidence. We found that at wavelength of 1000 nm both the bigger sized and smaller sized structure are contributing in the absorption and similar observations of electric field distributions are observed as shown in Fig. 3(a) and (b) for the other angle of source incidence (e.g. for $45^0$ and $60^0$). However, for our designed metasurface structure having combinations of crosses and circles structure contribution in the absorption is found due to both kind of structures with different sizes as shown by the electric field distribution patterns shown in Fig. 3(c), (d), (e) and (f) for the wavelength of 1000 nm, 400 nm, 1600 nm and 2500 nm, respectively.

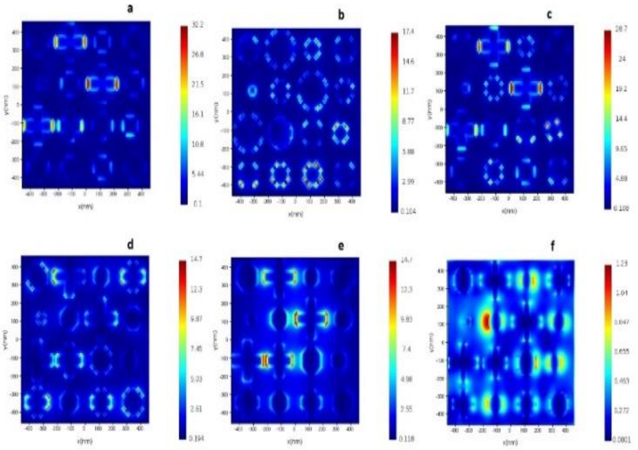

Fig. 3: Simulated electric field pattern on the surface of MMPA for wavelengths of 1000 nm a) only cross structures b) only circles structures in the units of electric field of $\times 10^{12}$ V/m c) a combination of cross and circle structures as our designed metasurface and electric field on the surface of the broadband metasurface absorber for wavelength of d) 400 nm e) 1600 nm f) 2500 nm. Units of electric field are in $\times 10^{13}$ V/m.

**Discussion**

Our results validate that a combination of structures result into the better performance in terms of broad band absorption of metamaterials. To further optimize the performance of the design genetic algorithm may be used to get the optimized parameters for size of the circles, crosses and the periodicity of the structures.. Our results are found to be almost insensitive *w.r.t.* the light polarization plane as change of polarization plane only induces change in the direction of the electric field pattern on the surface of the MMPA without affecting much in the magnitude (slight change) of electric field as shown in the Fig. 4 at wavelength of 1000 nm for *p*- and *s*-polarization. Similar observations are found for other wavelength for the *p*- and *s*-polarization. These observations may be due to the symmetry of the individual structures as in the unit cell we have the combination of individual symmetric structures of circle and cross structures.

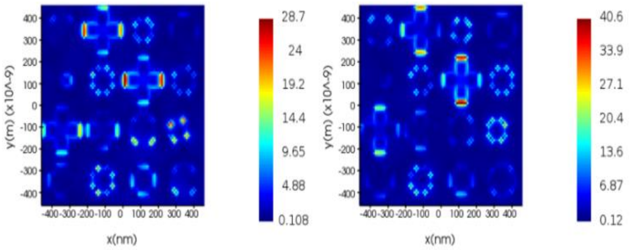

Fig. 4: Simulated electric field pattern on the surface of MMPA for wavelengths of 1000 nm for both polarisation a) *p*-polarisation and b) *s*-polarisation in the units of electric field of $\times 10^{13}$ V/m.

Complex structures having crosses and circles resonate to achieve dispersion enabling Fabry-Pérot destructive interference in reflection at multiple wavelengths. Consequently, incident electromagnetic source trapped resulting high absorption [22]. However, at other wavelengths range the conditions Fabry-Pérot destructive interference are not satisfied  Due to the limited number of resonance modes where Fabry-Pérot destructive interference conditions are not satisfied, absorption dips are observed as shown  in Fig. 2 for the wavelength range of 600 nm to 1100 nm and in the range of 1700 nm onwards. Our simulation results show the design as absorber with average percentage of absorption close to 75 % in the wavelength range of 250 nm to 600 nm. Broadband absorption from 250 nm to 1700 nm is observed except in the range of 600 to 1100 nm. In the range of 600 to 1100 nm relatively weak absorption is observed compared to the reflectance.

## IV. CONCLUSION AND FUTURE SCOPE

An MMPA in the solar band (250 nm to 2500 nm) is demonstrated to enhance the spectral broadband performance. Our results using Lumerical FDTD simulation shows that proposed design is optimized at $45^0$ of electromagnetic source incidence for the wavelength range of 1100 nm to 1700 nm and 250 nm to 600 nm. As we change the angle of incidence of the electromagnetic source falling on the complex structure of MMPA, *e.g.* either $60^0$ or $0^0$ absorption band gets changing. Therefore, we conclude that broadband performance of the designed MMPA is sensitive *w.r.t.* the incidence angle of the electromagnetic source falling on the surface of the MMPA.

In these spectral regions, absorption is dominant in nature compared to reflection with negligibly small transmittance through the sample and thus our design works as perfect absorber. The observed strong absorbance may be attributed because of substantial overlap between TE and TM polarization states and are seen through the simulations of electric field patterns on the top surface of the Si as shown in Fig. 3. Our results are insensitive against the state of polarization of the incident electromagnetic source as shown by the simulation results for the both the *s*-polarized and *p*-polarized electromagnetic source as shown in Fig. 4. Complex nature of structures consisting of combinations of squares and circles of Au makes the performance better for the broadband applications as compared to single kind of structures used in many studies.

Our simulation results may find useful application for the proper design of ultrathin solar absorber with optimized performance in the broader range of electromagnetic spectrum. Perfect absorption properties shown here for our designed metasurface may find applications in many in energy harvesting, scattering reduction as well as in thermal sensing.

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### REFERENCES

[1] Peng Yu, Lucas V. Besteiro, Yongjun Huang, Jiang Wu, Lan Fu, Hark H. Tan, Chennupati Jagadish, Gary P. Wiederrecht, Alexander O. Govorov, and Zhiming Wang,, "Broadband Metamaterial Absorbers", *Adv. Optical Mater*., Vol. **7,** pp**. 1800995**, **2019**.

[2] D. R. Smith, W. J. Padilla, D. Vier, S. C. Nemat-Nasser, S. Schultz, "Composite Medium with Simultaneously Negative Permeability and Permittivity", ***Phys. Rev. Lett.***,Vol. **84**, pp. **4184**, **2000**.

[3] H. Chen, B.-I. Wu, B. Zhang, J. A. Kong, "Electromagnetic Wave Interactions with a Metamaterial Cloak", ***Phys. Rev.*** *Lett.*,Vol. **99**, pp. **063903**, **2007**.

[4] N. Seddon, T. Bearpark, (2003), "Observation of the Inverse Doppler Effect", *Science*, Vol. **302**, pp. **1537, 2003**.

[5] X. Liu, T. Starr, A. F. Starr, W. J. Padilla, "Infrared Spatial and Frequency Selective Metamaterial with Near-Unity Absorbance", *Phys. Rev. Lett.*, Vol. **104**, pp. **207403**, **2010**.

[6] N. Liu, M. Mesch, T. Weiss, M. Hentschel, H. Giessen, "Infrared perfect absorber and its application as plasmonic sensor", *Nano Lett.*, Vol. **10**, pp. **2342**, **2010**.

[7] N. I. Landy, S. Sajuyigbe, J. Mock, D. Smith, W. Padilla, "Perfect Metamaterial Absorber", ***Phys. Rev. Lett.***, Vol. **100**, **207402**, **2008.**

[8] C. Kurter, J. Abrahams, S. M. Anlage, "Miniaturized superconducting metamaterials for radio frequencies", *Appl. Phys. Lett.*, Vol. **96**, pp. **253504**, **2010**.

[9] B. Edwards, A. Alu, M. E. Young, M. Silveirinha, N. Engheta, "Experimental Verification of Epsilon-Near-Zero Metamaterial Coupling and Energy Squeezing Using a Microwave Waveguide", *Phys. Rev. Lett.*, Vol.**100**, pp. **033903**, **2008**.

[10] G. Scalari, C. Maissen, D. Turcˇinkova, D. Hagenmuller, S. De Liberato, C. Ciuti, C. Reichl, D. Schuh, W. Wegscheider, M. Beck, "Ultrastrong Coupling of the Cyclotron Transition of a 2D Electron Gas to a THz Metamaterial", *Science*, Vol. **335**, pp. **1323**, **2012**.

[11] I. Sersic, M. Frimmer, E. Verhagen, A. F. Koenderink, "Electric and Magnetic Dipole Coupling in Near-Infrared Split-Ring Metamaterial Arrays", ***Phys. Rev. Lett.***, Vol. **103**, pp. **213902**, **2009**.

[12] A. Christ, O. J. Martin, Y. Ekinci, N. A. Gippius, S. G. Tikhodeev, "Symmetry Breaking in a Plasmonic Metamaterial at Optical Wavelength", *Nano Lett.*, Vol. **8**, pp. **2171**, **2008**.

[13] P. Yu, J. Wu, E. Ashalley, A. Govorov, Z. Wang, "Dual-band absorber for multispectral plasmon-enhanced infrared photodetection", *J. Phys. D: Appl. Phys.*, Vol. **49**, pp. **365101**, **2016**.

[14] Z. H. Jiang, S. Yun, F. Toor, D. H. Werner, T. S. Mayer, "Conformal Dual-Band Near-Perfectly Absorbing Mid-Infrared Metamaterial Coating", *ACS Nano*, Vol. **5**, pp. **4641**, **2011**.

[15] Tun Cao, Shuai Wang, and Chen Wei Wei**,** "Simulation of tunable metamaterial perfect absorber by modulating Bi2Se3 dielectric function", *Mater. Express*, Vol. **6**, No. **1**, pp. **45-52**, **2016**.

[16] Lee, D., Hwang, J. G., Lim, D., Hara, T. & Lim, S. "Incident angle- and polarization-insensitive metamaterial absorber using circular sectors", *Sci. Rep* Vol. **6**, pp. **27155**, 2016.

[17] Cheng, Y., Yang, H., Cheng, Z. & Wu, N., "Perfect metamaterial absorber based on a split-ring-cross resonator", *Applied Physics A: Materials Science and Processing*, Vol., **102**, pp. **99–103, 2011**.

[18] Lim, D., Lee, D. & Lim, S., "Angle- and polarization-insensitive metamaterial absorber using via array". *Sci. Rep*, Vol. **6**, pp. **39686**, **2016**.

[19] Yoo, M., Kim, H. K. & Lim, S,. "Angular- and polarization-insensitive metamaterial absorber using subwavelength unit cell in multilayer technology", *IEEE Antennas Wirel. Propag. Lett*, Vol. **15**, pp. **414–417 2016**.

[20] Zhu, B. et al., "Polarization insensitive metamaterial absorber with wide incident angle" *Progress in Electromagnetics Research*, Vol. **101**, pp. **231–239**, **2010**.

[21]S. Selvakumar, T.R. Rajasekaran, V.Sabarinathan, R.V. Jeba Rajasekhar, "Energy Collection Efficiency of Solar Collector with Nano Carbon-Cr2O3 Coated Absorber", *International Journal of Scientific Research in Physics and Applied Sciences*, Vol.**6**, Issue.**6**, pp.**127-128**, **2018.**

[22] Abul K. Azad, Wilton J. M. Kort-Kamp, Milan Sykora, Nina R. Weisse-Bernstein, Ting S. Luk, Antoinette J. Taylor, DiegoA. R. Dalvit & Hou-Tong Chen, "Metasurface Broadband Solar Absorber", *Scientific Reports***,** Vol. **6**, pp. **20347**, **2016**.

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