

# Broadband Absorber Using Ultra-thin Plasmonic Metamaterials Nanostructure in the Visible and Near-Infrared Regions

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## Research Article

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# Abstract

In this work, an ultra-thin plasmonic metamaterial nanostructure absorber is simulated using finite difference time domain method in the visible and near infrared regions. A metamaterial, metal-insulator-metal, of a periodic structure of titanium-silica cap mounted on a top of a silver substrate covered by glass substrate is introduced in this paper. The glass substrate is used to enhance the absorption bandwidth by 276%, from 510 nm to 1410 nm. An almost perfect absorber, over 90% of the incident light, has been obtained for wavelengths from 440 nm to 1850 nm which produces an absorption bandwidth of 1410 nm. The square base unit cell dimensions of the silver substrate and of the cap are simulated and found as 250 nm and 200 nm consequently. The effect of using different materials for the top of the cap and for the insulator are also tested. The considered materials are titanium, nickel, silver, aluminum, and gold; however, the insulators are silica, quartz, vanadium dioxide, methyl methacrylate, and aluminium dioxide. In addition, aluminium, silver, copper, and gold are then simulated as a substrate metal. The optimum structure, which produce the maximum absorber bandwidth, 1410 nm, with a higher absorption, over 90%, is Glass- $Ti-SiO_2-Ag$ . Finally, the absorption bandwidth is calculated using different polarization angle, from  $10^0$  to  $70^0$  with a step  $10^0$ .

## I. Introduction

Plasmonic metamaterials absorber has drawn the attention in the last decade for its variety applications such as solar cells, nano-antennas, ultra-sensitive sensors, photovoltaic, thermal emitters, optical devices, optical switches, photoresistors, filters, and modulators [1–5]. Recently, the enhancement of the light absorption bandwidth of the nanostructure plasmonic metamaterials is the trend need to be achieved [6–9]. Many techniques have been used to obtain perfect metamaterial absorbers such as cylinder array, hole array and multilayer structure [10–12]. However, these techniques have some problems such as need noble metals or produce narrow bandwidth. A metal-insulator-metal metamaterial nanostructure is the most common structure used as a perfect absorber for its simplicity and highly efficient specially in the ultraviolet, visible, and infra-red regions [12–14]. Metamaterials are structured as a top metal periodic layer followed by insulator as a spacer layer on the top of a perfect refractor metal [9]. Many up-to-date works have been carried to obtain a wideband absorber using plasmonic metamaterials structure as illustrated below:

J. Hao and *et al.* introduced theoretical and numerical periodic structure of plasmonic metamaterial using three layers as  $Ag-Al_2O_3-Ag$  of  $250\text{ nm}^2$  based area of the unit cell. The absorbed light is in the visible region with very low bandwidth (less than 50 nm) [16].

An ultra-broadband absorber has been obtained using  $Ti-SiO_2-Al$  structure from visible to near-infrared regions with a bandwidth of 712 nm by L. lie and *et al.* [12]. They used different materials on the top cap such as  $Ni$  and  $Al$  which produced a lower bandwidth than using  $Ti$  material.

Multiband plasmonic metamaterials absorber using  $Ti-SiO_2-Al$  structure in the infrared region is given by C. Fann and *et al.* [13]. The proposed structure has been simulated and experimentally tested at two main bands 4.8–7.5  $\mu m$  and 9.7–10.5  $\mu m$  with high absorption.

1. M. Hedayati and *et al.* introduced a plasmonic nanocomposite metamaterial absorber structure with different nanocomposite concentration [17]. A gold nanoparticle with different concentrations is distributed on the top of the  $SiO_2$  spacer which placed on  $Au$  layer. The maximum obtained bandwidth in the visible region is around 500 nm at gold concentration of 40%.
2. H. Gao and *et al.* gives a plasmonic absorber based on insulator-metal-insulator-metal structure of  $SiO_2-TiN-SiO_2-TiN$ . The absorption bandwidth is almost 1  $\mu m$ , from 200 nm to 1200 nm, from ultraviolet to near infrared band for an absorption over 90% [18].

In this work a unit cell of a plasmonic metamaterial has been simulated using Finite Difference Time Domain method FDTD using Lumerical tool to calculate the absorption from visible to near-infrared region, 0.3-3  $\mu m$ . The absorption of the proposed structure is simulated with and without a glass cover substrate. The optimum base dimensions of the bottom substrate,  $L$ , and the cap insulator,  $W$ , are also calculated. The absorbance is tested for different top layer metal; Nickel ( $Ni$ ), Titanium ( $Ti$ ), Aluminium ( $Al$ ), and Silver ( $Ag$ ). A Silicon Dioxide ( $SiO_2$ ), Aluminium Oxide ( $Al_2O_3$ ), Quartz, ploy (methyl methacrylate), and Vanadium Dioxide ( $VO_2$ ) are used as a spacer material while  $Al$ ,  $Ag$ ,  $Au$ , and  $Cu$  are tested as a bottom layer of the proposed structure. Finally, the absorption of the broadband absorber is simulated at different polarization angles of the incident light.

## ii. Maximum Absorption Wavelength And Absorber Structure

A metamaterial is a man-made material generates a subwavelength which can be tailored using different structure and unit cell dimensions. For insulator-metal stack, the maximum absorption occurs at wavelength,  $\lambda_{max}$ , which can be calculated using Equation (1) [13].

$$\lambda_{max} = 2\pi n_i t \left( n_i \sqrt{\frac{(n_m - n_o)}{n_o(n_i^2 - n_m n_o)}} \right) \quad (1)$$

where  $n_m$  is the refractive index of the metallic substrate,  $n_i$  is insulator refractive index,  $n_o$  is the superstrate refractive index, and  $t$  is the dielectric material thickness.

The introduced plasmonic metamaterial absorber nanostructure is consists of a periodic structure cubes of metal-insulator placed on a metal substrate using glass substrate as a top cover. The periodicity in both x and y coordinates and in the z direction is Perfect Matched Layer, PML, as a boundary conditions. A plan wave source with Bloch/Period signal and wavelength bandwidth from 0.3 nm to 3 nm is used in the simulation. The operating wavelength is in Visible and near infrared regions. The Lumerical FDTD is

an electromagnetic wave solver which used to measure absorbed wave by the proposed structure. The proposed structure is illustrated in Figure 1.

The absorbed wave is calculated in this simulation by subtracting the transmitted and the reflected signal from the incident signal power using Equation (2).

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

where  $A$  is the absorbed signal,  $T$  is the transmitted signal and  $R$  is the reflected signal. To obtain the maximum absorption bandwidth, different metals are used as a cap of the periodic structure such as  $Ni$ ,  $Ti$ ,  $Al$ , and  $Ag$  and different insulators are used as  $SiO_2$ ,  $Al_2O_3$ , Quartz, ploy, and  $VO_2$ . Finally,  $Al$ ,  $Ag$ ,  $Au$ , and  $Cu$  are used as a substrate material.

## iii. simulation Results And Discussion

To calculate the reflected signal from the plasmonic metamaterial absorber nanostructure, a square shape base unit cell of  $Ag$  has been simulated, bottom layer, with pitch  $L = 250$  nm and thickness  $t = 200$  nm with a periodic structure in both  $x$  and  $y$  direction and PML in  $z$  direction. A square base periodic cap of length  $W = 200$  nm is illustrated in Fig. 1. The cap is consisting of  $SiO_2$  as a spacer with height  $t_1 = 80$  nm and a top metal layer of  $Ti$  with height  $t_2 = 20$  nm. In this simulation, the air is considered as a surrounding medium and the complex dielectric constants of the used metals are modelled by a Drude-Lorentz model.

The structure is proposed to be  $Ti-SiO_2-Al$  without a glass cover, then the structure is covered by a glass material layer with thickness  $t_3 = 100$  nm to enhance the absorption as shown in Fig. 2. The absorption bandwidth, over 90% of the absorption, is 510 nm without using a glass cover, however the bandwidth is extended to be 1315 nm when the structure covered by a glass substrate. The glass substrate enhances the light absorption bandwidth by more than 257% for absorbance more than 90% of the incident light.

The effect of cap base dimensions,  $W$ , on the absorption is calculated by simulate different base values, started from 180 nm to 220 nm with 10 nm step, as clearly shown in Fig. 3. As shown in the figure, the absorption bandwidth is getting wider and the absorbance getting lower as the base length and width increases. The maximum obtained absorption bandwidth is 1584 nm at  $W = 220$  nm for absorbance higher than 87%, however the minimum bandwidth is 1126 nm for absorption more than 90% at  $W = 190$  nm.

The optimum base dimension is found to be 200 nm with absorbance bandwidth 1315 nm when the simulated structure was glass-  $Ti-SiO_2-Al$ .

An opposite behaviour is noticed when the unit cell base dimension is changed,  $L$ , from 210 nm to 270 nm with 20 nm step. The absorbance bandwidth of 270 nm is 1274 nm for absorption over 90% and 1490 nm for  $L = 210$  nm over 60% absorption as illustrated in Fig. 4. For  $L = 230$  nm, the bandwidth is 1610 nm at absorbance over 87% however the bandwidth is 1315 nm at  $L = 250$  nm over 90% absorbance. Hence, the base dimension  $L = 250$  nm is more efficient and has been chosen for higher absorption and comparable bandwidth.

Figure 5 shows the absorbed light for different cap top metals. The maximum absorbance, blue curve, is obtained when  $Ti$  material is used as a top metal of the cap.  $Au$ ,  $Al$ , and  $Ag$  give a very low absorption and high reflection in the visible and NIR regions, however their absorbance is very high in the 0.3–0.6 nm band. On the other hand, using  $Ni$  material as top metal gives a high bandwidth with lower absorbance than obtained by  $Ti$  specially in near infrared region.

Insulator layer is playing an important role in the absorption bandwidth and absorbed light ratio, according to the insulator material. In Fig. 6, the absorbance of the proposed nanostructure using the most common materials, used as a spacer, are simulated. Vanadium dioxide,  $VO_2$ , produced an almost total absorption, over 98%, with bandwidth 814 nm, however, the bandwidth is 885 nm over 90% absorbance for  $Al_2O_3$  material. Also, the absorbance bandwidth of quartz is 577 nm over 88% absorption and 1125 nm for ploy for absorbance over 90%. The optimum material used as an insulator is the  $SiO_2$  which gives 1315 nm absorption bandwidth over 90% of the absorbed light.

As most of the light either reflected or absorbed from the glass or cap structure, the portion of light transmitted to the bottom substrate is very limited which means the effect of using different bottom substrate is also limited. Figure 7 illustrates the absorption when different metals are used as a bottom metal substrate.

The most common metals used as a bottom substrate are  $Al$ ,  $Ag$ ,  $Au$ , and  $Cu$ . Table 1 shows the absorption bandwidth, over 90%, for the given four used metals and the minimum absorption in the absorption range.

Table 1  
Spectrum bandwidth for different bottom metal layer substrate.

Bottom metal layer material	BW ( $\mu\text{m}$ )	Minimum absorption in the BW range (%)
Al	1.35	93.92
Ag	1.41	92.55
Au	1.27	89.87
Cu	1.37	92.70

The maximum absorption bandwidth is obtained when silver is used, 1410 nm, over 90% absorbance and the minimum absorption in the measured band is 92.5%, as shown in Fig. 8, where the maximum absorbance is 99% in the same range. Copper material, which considered as a cheap material to use in the fabrication process, has a very interesting comparable bandwidth, 1370 nm, with high absorbance.

Figure 8 illustrates the overall absorption bandwidth of the proposed nanostructure, Glass- $Ti-SiO_2-Ag$ , which gives a 1410 nm bandwidth over 90% absorbance and high absorbance in the visible and near-infrared band.

A plane wave light source is used in the simulation as a source of light with incident angle  $\theta = 0^0$  as shown in Fig. 9. The absorbance of the proposed structure is also simulated for different polarization angle,  $\theta$ , from  $0^0$  to  $70^0$  with step of  $10^0$  as illustrated in Fig. 10.

As clearly shown in Fig. 10, the absorber bandwidth is increasing as the polarization angle increases but it is getting more fluctuating. For  $\theta = 70^0$ , the bandwidth is almost 2  $\mu m$  for absorbance almost over 50%.

Table 2 gives an overall comparison between similar techniques and the introduced techniques. In [16], the structure was  $Ag-Al_2O_3-Al$  with a very low bandwidth, less than 50 nm, in the visible region with almost 100% absorption. The bandwidth increased to be 715 nm over 90% absorbed light in the visible and NIR regions for  $Ti-SiO_2-Al$  structure as given in reference [12]. The same structure was introduced but with different dimensions in reference [13] which gives a wide range of absorption in Mid-IR region. Two different bands are introduced, the first one from 4.8  $\mu m$  to 7.5  $\mu m$  and the second is from 9.7  $\mu m$  to 1.05  $\mu m$ . In [18], the proposed structure was  $SiO_2-TiN-SiO_2-TiN$  with an absorption bandwidth of almost 1  $\mu m$ , from 0.2–1.2  $\mu m$ , in ultraviolet, visible, and near infrared bands over 90% absorbance.

Table 2  
Comparison between the introduced nanostructure and what mentioned in the related works.

Ref	Materials	Region	BW (nm)	Absorption ratio
[16]	$Ag-Al_2O_3-Al$	Visible	< 50	Almost 100%
[12]	$Ti-SiO_2-Al$	Visible-NIR	712	> 90%
[13]	$Ti-SiO_2-Al$	Mid-IR	4800–7500 and 9700 – 1050	> 30%
[18]	$SiO_2-TiN-SiO_2-TiN$	Ultraviolet-NIR	1000	> 90%
Proposed structure	Glass- $Ti-SiO_2-Ag$	Visible-NIR	1410	> 90%

The proposed structure, Glass- $Ti-SiO_2$ - $Ag$ , gives absorption bandwidth of 1410 nm for absorption over 90% in the visible and NIR regions.

## Conclusion

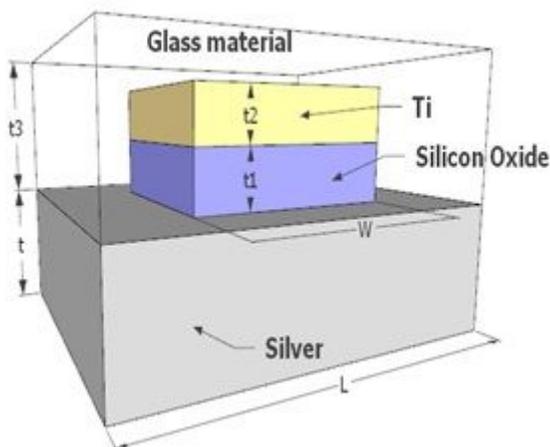
A high absorber periodic ultra-thin plasmonic metamaterial nanostructure is produced in this work. The proposed structure is consistence of a periodic cap of a metal-insulator structure,  $Ti-SiO_2$ , which placed on a top of a metal substrate,  $Ag$ , with and without top glass layer. The absorption bandwidth is enhanced by 276%, from 510 nm to 1410 nm, when using a glass substrate as a top cover over the proposed structure. The base dimensions of both the bottom substrate, unit cell dimensions, and the periodic cap have been studied and optimized to be 250 nm and 200 nm for bottom substrate and the cap consequently. Different top cap metal materials have been simulated such as  $Ni$ ,  $Ti$ ,  $Al$ , and  $Ag$ . Titanium material gives the best performance as a top cap metal and  $SiO_2$  as an insulator material over  $Al_2O_3$ , Quartz, ploy and  $VO_2$  materials. On the other hand, silver material as a bottom substrate gives a wide bandwidth, 1410 nm, over  $Al$ ,  $Au$ , and  $Cu$  which produce a 1350 nm, 1270 nm, and 1370 nm absorption bandwidth consequently for absorbance over almost 90%. In addition, the absorption as a function of the incident light polarization is also studied and notice that, increasing the incident angle leads to increase the bandwidth and decrease the absorption to less than 50% of the incident light.

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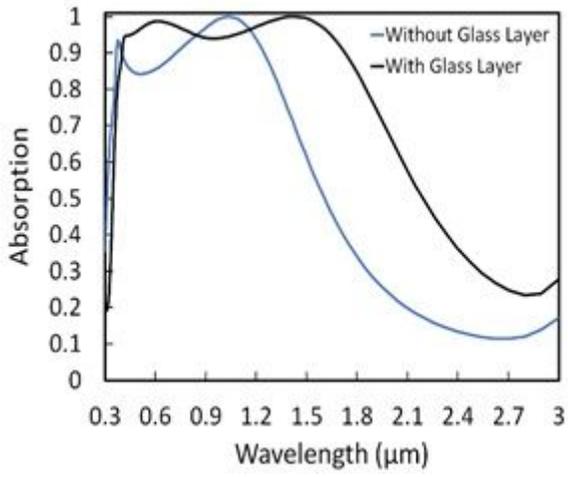
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## Figures



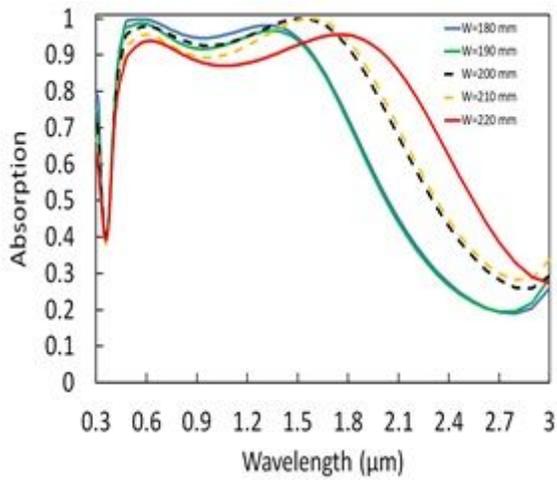
**Figure 1**

Schematic diagram of the proposed broadband plasmonic metamaterial structure.



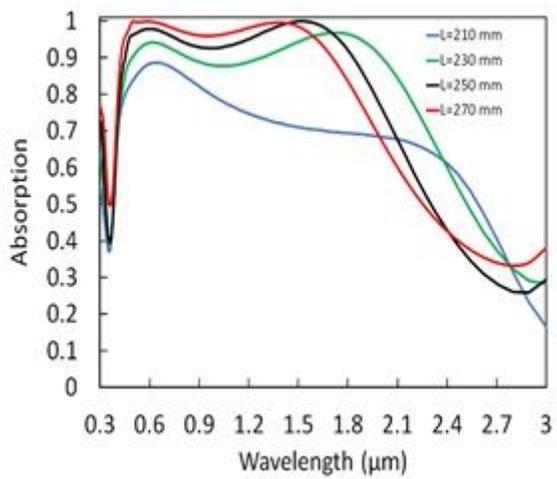
**Figure 2**

Absorbance spectra with and without top glass cover layer.



**Figure 3**

Absorbed spectra versus wavelength for the cap base dimensions.



**Figure 4**

Absorbed spectra versus wavelength for unit cell base dimension.

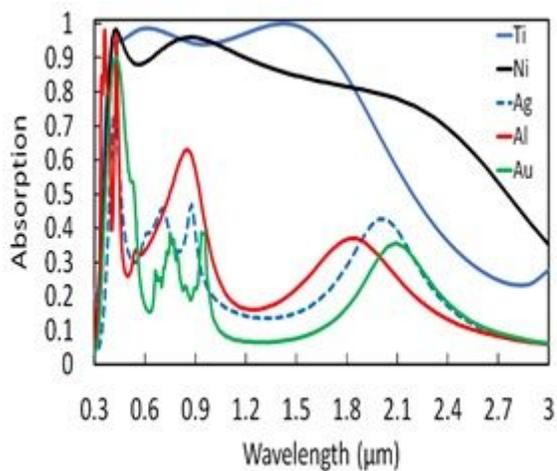


Figure 5

Absorption versus wavelength for different cap top metals (Ti, Ni, Ag, Al and Au).

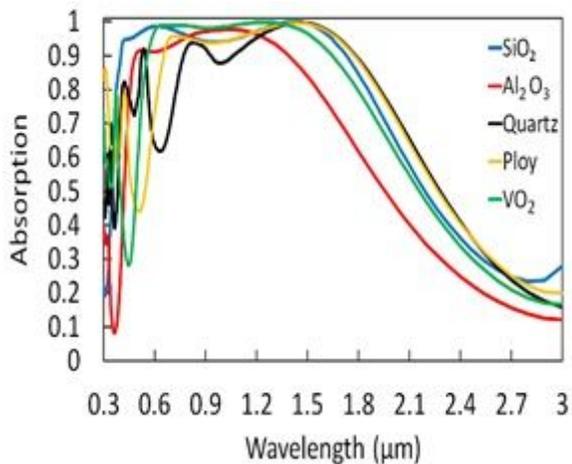
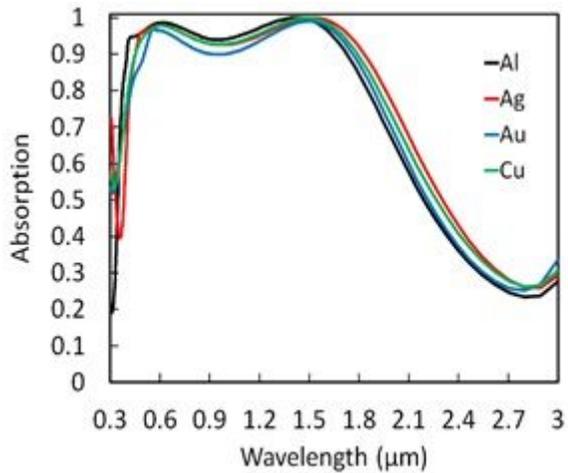


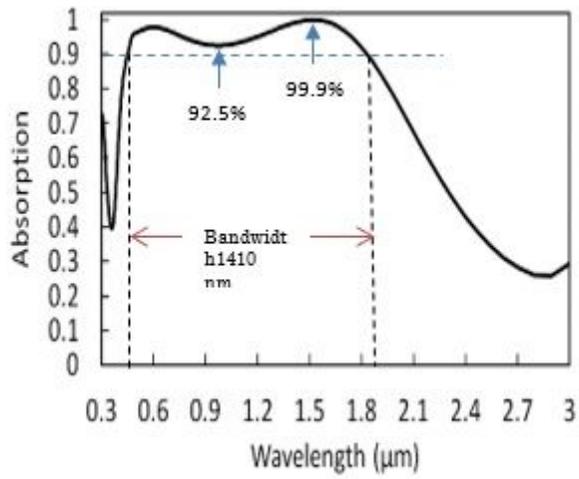
Figure 6

Absorbance spectra for different insulators (SiO2, Al2O3, Quartz, ploy, and VO2).



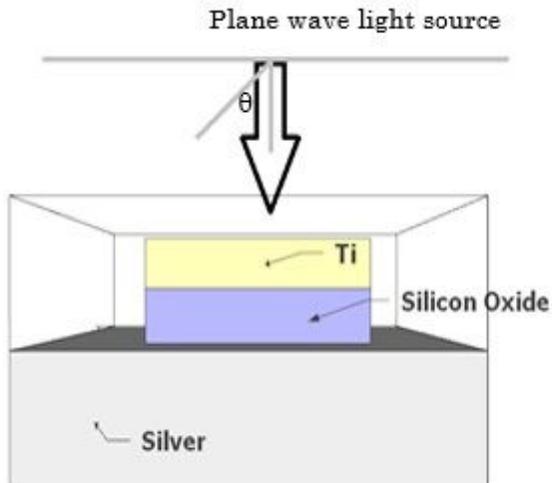
**Figure 7**

Absorbance spectra for different bottom metal substrate (Al, Ag, Au, and Cu).



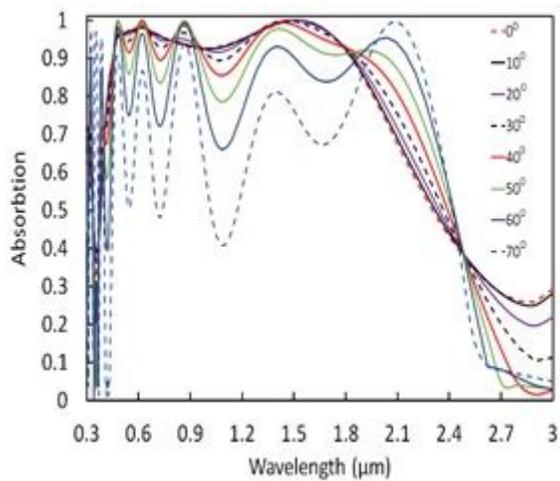
**Figure 8**

Absorbance spectra Bandwidth for the proposed Glass-Ti-Sio2-Ag nanostructure.



**Figure 9**

Incident light polarization angle.



**Figure 10**

Absorbance spectra for different light incident angle.