Grating Structure Broadband Absorber Based on Gallium Arsenide and Titanium

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Abstract: We designed a broadband absorber based on a multilayer grating structure composed of gallium arsenide and titanium. The basic unit is a grating structure stacked on top of a semiconductor of gallium arsenide and titanium metal. We used the finite difference time domain method to simulate the designed model and found that the absorber absorption efficiency exceeded 90% in the range from 736 nm to 3171 nm. The absorption efficiency near perfect absorption at 867 nm was 99.69%. The structure had good angle insensitivity, and could maintain good absorption under both the TE mode and TM mode polarized light when the incident angle of the light source changed from 0° to 50°. This kind of metamaterial grating perfect absorber is expected to be widely used in optical fields such as infrared detection, optical sensing, and thermal electronics.

Keywords: surface plasmons; metamaterials; grating structure; FDTD method

1. Introduction

Surface plasmon resonance has been widely used in many fields over the past decades [1–3] such as photodetectors and infrared absorbers. Among them, the metamaterial absorber based on surface plasmon resonance has attracted the interest of researchers. The first metamaterial perfect absorber was proposed in 2008 and had perfect light absorption performance. More scientific researchers have noticed this high potential absorber and have joined in their research up to now [4–19].

Most of the proposed perfect absorbers only absorb specific frequency bands that cannot be adjusted [20–26]. The absorption bandwidth of this type of absorber is not wide enough, which means that the designed absorber has limited functions. In 2017, a scientific research team designed an ultra-thin perfect absorber based on titanium nitride material [27]. The physical principle is that the designed titanium nitride and titanium dioxide structures can excite a variety of resonances under light, resulting in strong coupling to achieve ultra-wideband absorption. The absorption wavelength ranges from 316 nm to 1426 nm, and the perfect absorption bandwidth above 90% reaches 1110 nm. However, the structure of this kind of absorber is complicated [28,29], so it is difficult to realize it under the current equipment level. The laminated structure based on their work is one of the
causes of broadband absorption, so we considered designing a laminated structure with a simpler structure.

In recent years, gallium arsenide has been used as a material in solar cells because of its high energy conversion efficiency. Previously, a scientific research team broke the record for the energy conversion efficiency of gallium arsenide solar cells. They grew a high-quality surface passivation layer on the gallium arsenide nanowire core and doubled the energy conversion efficiency of solar cells [30]. Another research team started from the theoretical direction and proved that the conversion efficiency of gallium arsenide photonic crystal solar cells exceeded 30% [31]. These theories and experiments have proven that gallium arsenide materials have great potential in electromagnetic absorption.

We designed a multilayer grating structure absorber based on a stacked layer of gallium arsenide and titanium metal. It is a simple structure composed of four layers. On the top is a grating structure composed of gallium arsenide and titanium; the bottom is a thick titanium barrier layer; and in the middle is a layer of gallium arsenide film. This absorber can achieve near-perfect absorption in a wide range of wavelengths because the structure will excite the surface plasmon resonance when exposed to light. In addition, the absorption capacity of this absorber will not be weakened due to changes in incident light. It can maintain excellent absorption performance under incident light of any polarization angle, and can adapt to various environmental conditions.

2. Design and Structures

This section mainly introduces the structure of the absorber we designed. As shown in the Figure 1, the top layer is a stacked grating structure of gallium arsenide and titanium metal, a layer of gallium arsenide thin film and the bottom layer of anti-transmission thick titanium metal. The structure of this broadband absorber was designed with a periodic array.

![Three-dimensional structure of our absorber](image1)

**Figure 1.** (a) Three-dimensional structure of our absorber. (b) The cross-sectional view of the absorber.

We set the grating constant to P, set the width of the top layer to W, and set the bottom layer of titanium to 290 nm to prevent transmission. The thickness of the structure from top to bottom was set to h1, h2, and h3 in sequence.

We used FDTD Solutions software for simulation. We set the grating period P = 400 nm, the top width W = 275 nm, and the structure thickness from top to bottom is h1 = 140 nm, h2 = 30 nm, and h3 = 80 nm. We added a transmission monitor and a reflection monitor when using the numerical simulation. T represents the transmittance, R represents the reflectance, and the structural absorptivity can be expressed as A = 1-R-T [32–36]. The bottom layer of 290 nm titanium film can prevent transmission, so the absorbance can be simplified to A = 1-R.

In the simulation, the dielectric constants of the gallium arsenide semiconductor and titanium were derived from the data in Palik. The calculation accuracy was set to 5, the calculation step length in the x direction and the y direction was set to 10 nm, and the calculation step length in the z direction was set to 5 nm. Light source type selection: plane wave light source.
3. Results

The absorption range of the absorber is shown in Figure 2. The light transmittance was close to zero because our bottom layer was thick enough [37–39]. Figure 2b marks the absorption band with an absorption rate greater than 90% of the structure from 736 nm to 3171 nm. The total bandwidth reached 2435 nm. The best absorption wavelength was at 867 nm and the absorption efficiency reached 99.69%.

We set the incident light in TM mode for simulation, and we obtained the electromagnetic distribution of the three absorption peaks (528 nm, 871 nm, and 2847 nm) of the absorber. We can explore the physical mechanism of the metamaterial structure absorber through the phenomena shown in these figures. Through the two Figure 3a,d, we can observe that at the wavelength of 528 nm, the slit of the grating was the main distribution area of the electric field, and the surface of the gallium arsenide material on the top layer was the distribution area of the electric field. At this time, the local surface plasmon resonance is excited on the surface of the absorber [40–44]. Figure 3b,e shows that the electric field in the slit still exists at this time, and there is a very strong magnetic field between the slits and grooves. This is because the free electrons on the surface of the structure interact with light waves under illumination, which excites local surface plasmon resonance. It also excites the propagating surface plasmon resonance at the material junction. The coupling between them gives a good absorption effect at 871 nm. Figure 3c,f shows the electromagnetic effect of the absorber at 2847 nm. The four corners of the grating were the areas where the electric field was mainly distributed, and the magnetic field appeared between the two material layers of gallium arsenide and titanium inside the grating. This is because the light irradiation excites the propagation surface plasmon between the materials [45–47].

We modified various parameters many times during the simulation process to explore the influence of material thickness on the entire device. As shown in Figure 4, we adjusted the parameters of each layer except for the anti-transmission layer, and found that the absorption effect of the absorber was different. As shown in Figure 4a, when the GaAs thickness h1 is changed, the change of spectrum is not obvious, indicating that h1 is universal. In Figure 4b, with the thickening of the titanium metal layer and Palki by layer, the absorption valley between 1216 nm and 1964 nm gradually rose to more than 95%, but the absorption rate began to decrease in the part greater than 1970 nm. When we changed the thickness of h3, we also found that the absorption capacity of the absorber changed. Figure 4c shows that with the gradual increase of h3, the absorption performance of the part larger than 1426 nm was weakened and could not be absorbed well. The reason for this phenomenon is that the change in the thickness of the material caused the change in the strength of the internal resonance, which led to the change in the absorption capacity [48–50]. Adjusting the size of h1 (in Figure 4a) and W (in Figure 4d) had little effect.

Figure 2. (a) The transmission, reflectivity, and absorption spectra of the absorber. (b) The absorption wavelength range of our absorber.
on the overall absorption result because the structure and material determine its absorption capacity. Its performance could not be greatly improved by changing the grating constant or grating height.

Figure 3. Distribution of the electric (a–c) and magnetic (d–f) fields inside the absorber.

Figure 4. Comparison of absorption curves of changing (a) h1; (b) h2; (c) h3 and (d) w.

In order to gain insight into the impact of each layer on the structure, we removed a portion of it and explored the results of absorption. We found that after removing the structures of h2 and h3, as shown in Figure 5a, the wavelength bands after 1200 nm and 2000 nm showed a significant decrease in the absorption capacity. Integrating the information shown in Figure 5b,c, it can be concluded that the presence of h2 led to the
excitation of surface plasmon resonance between GaAs and Ti, which may be the main reason for the enhanced absorption at 1200 nm. The existence of h3 was equivalent to increasing the area of gallium arsenide on the surface of the structure, which can make up for the poor absorption in the long wavelength band. The two synergies resulted in the broad absorption of the absorber. This notion was confirmed by the phenomenon in Figure 4b, where the absorption around 1200 nm was gradually enhanced with the increasing thickness of h2. It can also explain the variation produced by the absorption waveform in Figure 4c. With the increase in the thickness of h3, the excitation band became longer and the absorption band gradually redshifted. This caused the short-wave and long-wave absorption peaks to be separated from each other. This led to the phenomenon that the absorption in the wavelength band shorter than 1500 nm became stronger, and the wavelength band longer than 1500 nm weakened. There was an absorption peak around 800 nm, which was due to the excitation of the grating coupling mode, which localized the energy to the top of the grating.

Figure 5. Changes in the light absorption capacity of the structure after removing h2, (a) h3; (b) h2; and (c) h3.

In order to compare the performance of different materials, we replaced heat-resistant metal materials and semiconductor materials for simulation. The replacement material had the same chemical properties as the previous material. The dielectric constant was taken from the data in Palik [51–53].

As shown in Figure 6a, after replacing the platinum metal material, we found that there was a narrow band absorption peak at 813 nm, 1642 nm, and 3884 nm, but the overall absorption effect was poor, and the absorption curve changed greatly. This means that in this structure, platinum metal does not guarantee broadband absorption. After replacing it with tungsten metal, there was a very narrow absorption peak in the 871 nm band, and then the absorption curve dropped significantly. Therefore, the titanium metal we selected was the most suitable metal material under this structure. We also replaced the semiconductor dielectric material to test the absorption effect produced by other materials, as shown in Figure 6b, when we used aluminum oxide, which absorbed almost perfectly in the 852 nm to 1553 nm band. However, the fly in the ointment is that the absorption
curve plummeted after this waveband, and the effective absorption range was very narrow. Indium arsenide material and gallium arsenide material have similar effects [54,55]. When replacing gallium arsenide material with indium arsenide material, we found that the absorption curve was almost the same. In a comprehensive comparison, gallium arsenide material is the best choice.

![Figure 6.](image-url) (a) Absorption curves of different metal materials. (b) Absorption curves of different semiconductor materials.

By adjusting the incident angle of the light source, it is found in Figure 7, that the absorption capacity of our designed structure is basically unaffected. In addition to angular insensitivity, polarization insensitivity is also a key characteristic that affects the performance of the absorber [56–60]. We can observe the absorption effect of the absorber under different polarization angles in Figure 8. We found that when the polarization angle changed from 0° to 40°, the absorption effect of the absorber was maintained at a fixed level. However, when the polarization angle was greater than 40°, the position of the absorber in the 900–1200 nm band changed and weak absorption occurred, while light in other bands could be absorbed as usual. This is because the structure of the absorber is not strictly symmetrical. The absorption capacity will change when the polarization angle turns to about 45°. In general, the absorber we designed has polarization insensitivity in a large angle range.

![Figure 7.](image-url) (a) Absorption spectra at different incident angles in TE mode. (b) Absorption spectra at different incident angles in TM mode.
4. Conclusions

In summary, the absorber we designed is composed of a stack of gallium arsenide and titanium, which will excite surface plasmon resonance under light irradiation. The absorber could achieve a nearly perfect absorption effect in the range of 736 to 3171 nm. The best absorption band had an absorption rate of 99.69% at 867 nm. Our proposed metamaterial grating structure absorber not only had a large absorption bandwidth, but the absorption band of the absorber was not affected by the change in the polarization angle. Even when the incident angle changed from 0° to 50°, the absorber always maintained good absorption performance. This type of absorber is less restrictive and can be used in many fields. Compared with other absorbers of the same type, the absorber we propose is simpler in structure and has a larger absorption range. This kind of metamaterial grating perfect absorber is expected to be widely used in optical fields such as infrared detection and infrared filtering.

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