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W-AlON nanocermet thin film based metamaterials for multi-band absorption at infra-red frequencies

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Abstract

Developing cermet composites are highly desirable for solar thermal technologies for their selective solar absorptions. Inserting a thin film of these cermets in a metamaterial perfect absorber allows for a flexible control over the multiple bands of large absorption over the visible to LWIR frequencies bands.

1 Introduction

Metal-dielectric composites known as cermets have been the subject of interest as efficient absorbers of visible and near infra-red light since the 1970's [1]. These exhibit good thermal stability for mid and high temperature applications and show characteristics of a ceramic in the visible spectrum and metallic properties in the infra-red (IR) frequencies.

Metamaterial perfect absorbers (MPA) [2] consists of artificially designed structures to resonantly absorb the incident light. A typical MPA consists of three layers, with the top layer consisting of highly resonant structures that are separated from a bottom metallic layer by an dielectric spacer layer to result in an optimal impedance match to free space. The electric field component of the incident electromagnetic wave excites current densities on the top resonant structure with the corresponding mirror charges and currents being excited in the bottom ground plane [3]. The current on the top disc along with the anti-parallel current on the bottom Cu ground plane and a displacement current inside the spacer layer gives rise to a circulating current loop and a consequent magnetic resonance.

MPA's have found their applications in different devices such as sensors [4], bolometers [5], solar cells [6], and thermal emitters [7] etc. Applications such as imaging devices and solar cells the band width of absorption plays a vital role. Multi-band MPA has been developed to increase the bandwidth of the MPA. One way to demonstrate a multi band absorber is to make use of multiple resonant structures within the top layer array [8]. However with the increase number of resonators in the unit cell, the fill factor and absorption efficiency decreases. So MPA with single resonating elements giving rise to multiple bands, which are almost independent of each other are highly desirable.

In this work, we present the design of a multi-band MPA with embedded cermet materials to give rise absorption bands covering from visible to long wave infra-red (LWIR) bands. The multilayer stack of Cu/cermet/ZnS create absorption bands at visible and NIR frequencies, while the metamaterial structures produce independent high absorption bands of any desired band.

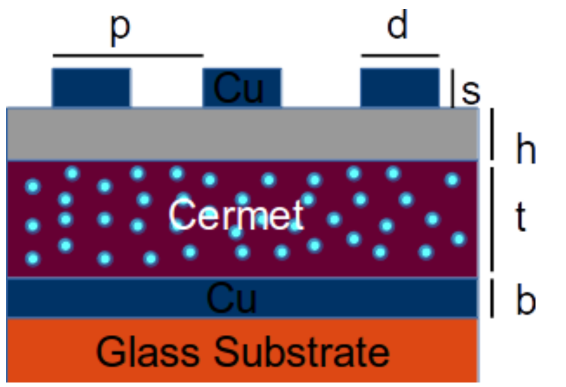

Figure 1. Unit cell depicting unit cell of a MPA with bottom Cu as a ground plane with thickness b= 200 nm, cermet and ZnS as dielectric spacer layers with thickness t= 80 nm and h=100 nm respectively, the top Cu disc has thickness s= 120nm, diameter d= 2μm and period p=4 μm

2 Choice of materials and metamaterial design

Our design of cermets consist of tungsten (W) nanoparticles embedded in the ceramic matrix of aluminium oxinitride (AlON). The volume fraction of tungsten in AlON has taken to be 0.304. These materials can withstand in a high temperature environment and can resist oxidation [9]. These cermets along with a metal base (copper) can effectively serve as spectrally selective absorbers for visible to short wave infra-red (SWIR) wavelengths with high reflectivity for larger wavelengths in the longer part infra-red wavelengths. Here, we make use of an additional layer of zinc sulphide as an anti reflection coating (ARC) on top of cermet to minimize the surface reflection from the top. The

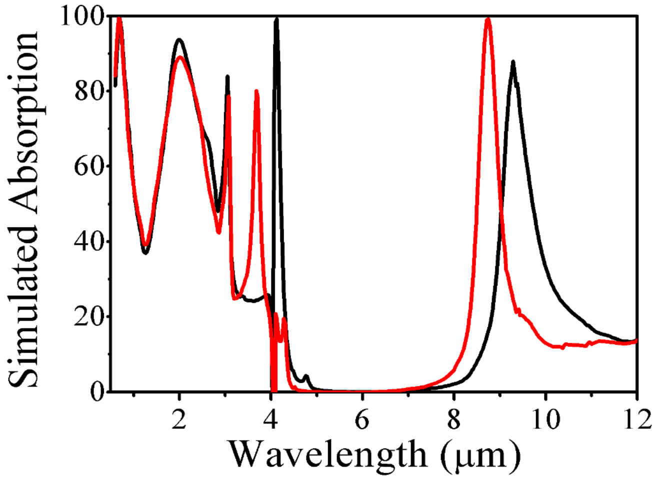

Figure 2. Red curve shows the absorption of a MPA with top disc diameter d= 2 μm and black curve shows the absoption with diameter d= 2.3 μm

MPA here, consists of an array of periodic circular metal discs of Cu separated from a continuous metal film of Cu by thin films of ZnS and cermet (see Figure 1). The top structured disc of Cu has thickness b=200 nm, diameter d= 2 μm for one design and d= 2.3 μm for another design with an array period of 4 μm. 80 nm thick film of Cermet and 100 nm thick film of ZnS are sandwiched between the top Cu discs and bottom continuous ground plane.

3 Simulation and Discussions

We perform numerical simulations using a Finite Element method based software package, COMSOL multi physics [10]. Wave port boundary conditions are used to excite a transverse electromagnetic wave from the top of the metamaterial structure with normal angle of incidence. Periodic boundary conditions are used to replictae the unit cell so that the structure can be considered as an infinite two-dimensional arrays. The absorption was calculated as A(ω)=100-R(ω)-T(ω), where R(ω) is the reflection and T(ω) is the transmission. The thick Cu ground plane makes sure, there is no transmission through the MPA.

A Lorentz- Drude dielectric function is used for the frequency dependent permittivity of Cu given by equation (1)

$$\varepsilon(\omega) = \varepsilon_b + \sum_{j=1}^{5} \frac{f_j \omega_p^2}{(\omega_j^2 - \omega^2 - i\gamma_j \omega)} \tag{1}$$

where where f_j is strength of oscillators, ω_p as the plasma frequency, ω_j as the resonant frequencies with γ_j as the damping frequencies. The value of the above mentioned parameters for Cu is taken from [11] and are summerized in Table.1. ε_b is the background contribution given by 1. The refractive index of the cermet is considered to be dispersive and has been taken from [12], whereas for ZnS it has been taken to be 2.24 for the entire wavelength considered.

Table 1. Permittivity for Cu

Term	Strength	Plasma Frequency (Rad/s)	Resonant Frequency (Rad/s)	Damping Frequency (Rad/s)
1	0.575	0.164×10^{17}	0	0.455×10^{14}
2	0.061	0.164×10^{17}	0.442×10^{15}	0.574×10^{15}
3	0.104	0.164×10^{17}	0.449×10^{16}	0.16×10^{16}
4	0.723	0.164×10^{17}	0.805×10^{16}	0.488×10^{16}
5	0.638	0.164×10^{17}	0.169×10^{17}	0.654×10^{16}

In figure 2 (red curve) we have plotted the absorption spectrum of a design consisting of top layer of discs made up of Cu with thickness s=120 nm, diameter d=2 μm and array period p=4 μm, separated from a continuous layer of Cu of thickness b=200 nm by dielectric spacer layers of cermet and ZnS of thickness t=80 nm and h=100 nm respectively. Two distinct absorption peaks are obtained at 8.7 μm and 3.65 μm with peak absorption nearly 100 % in the former case and 80 % in the later case. The first peak at 8.7 μm corresponds to fundamental dipole mode, where there is a simultaneous excitation electric and magnetic resonances. The second peak at 3.65 μm arises from the higher order mode excitation. In these wavelengths where the peak absorption happens, a circulating current is generated by the accumulation of opposite charges on the edge of the top discs and the corresponding charges are mirrored at the bottom Cu film. Along with the above resonance peaks, a propagating surface plasmon (PSP) resonance is observed at 3.05 μm , propagating at the interface of Cu and cermet. These PSP resnance is excited by the top two dimensional grating structure. Two other resonances that are obtained, one peaked at 2 μm with absorption nearly 90 % and another peaked at 0.7 μm with almost 100 %. These absorption bands are essentially originates from the interference in the multilayer stack of Cu/cermet/ZnS. These resonances, which are mainly originating from the multilayer reflection are almost independent of the size and periodicity of top Cu structured layer. To demonstrate this, we have shown in Figure. 2(black curve), the absorption of another deisgn of the MPA with disc diameter 2.3 μm and all other material dimensions same as the above case. With the increase of the disc diameter, the fundamental dipole as well as the higher order band got red shifted peaking at wavelength 9.3 μm and 4.13 μm (see black curve in Figure 3). The peak at 3.05 μm doesn't change as the PSP resonance is independent of the size of the disc. The absorption bands at NIR frequencies still peaks at, 2 μm and 0.7 μm, as these absorption bands essentially originates from the multilayer reflections and nothing to do with the top discs.

4 conclusion

In conclusion, a multi-band perfect absorber has been demonstrated based on a embedded cermet material. Reflections coming from the multilayer stack of Cu/cermet/ZnS gave rise to high absorption bands at visible to NIR frequencies. The top structure on the MPA independently control the absorption band at LWIR frequencies. It has been shown that by changing the size of the top disc the absorption bands at LWIR can be tuned without altering the bands at visible/NIR frequencies. Therefore, with this approach there is a complete freedom of selecting bands at specified IR frequencies while keeping the visible/NIR behaviour the same.

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