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Design of CNT-based perfect absorbers over SWIR to LWIR frequencies for sensing applications.

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Abstract

Carbon nanotubes (CNT) are known for their use in solar thermal technologies due to their high absorption across the solar band. We design structural arrays of circular shaped CNT disc on conducting metallic film (Ag) that give rise to specified absorption bands at short-wavelength infrared (SWIR) to long-wavelength infrared (LWIR) frequencies. We note that nearly 99 % of absorbance occurs at the wavelength of 11.8 μm in the absorbance spectrum. In addition to that, other two peaks are at the wavelength of 5.6 μm and 7.8 μm with nearly 70 % and 80 % of absorbance respectively. The high absorbance at the wavelength of 11.8 μm is primarily due to the dipolar resonance while other peak positions in the spectrum are due to the higher mode and the vertical cavity mode resonances. Further, it is been shown that the simple design of CNT based perfect absorber can be used as sensing application at the infrared frequencies.

1 Introduction

The unique optical properties of subwavelength metal-dielectric nanostructurs have attracted considerable attention due to their wide applications in micro-bolometers, photo-detectors, thermal emitters, high sensitivity imaging, solar cells, biological sensing, non-linear enhancements, etc [1]. When electromagnetic wave irradiates a periodic arrays of metal-dielectric structures it results either in enhanced light transmission or light absorption through different modes of excitations. The basic principle to obtain a perfect absorber in any frequency band is to minimize the reflection through an impedance matched to free space and to simultaneously create strong absorption by resonant processes. The most common metamaterial absorbers consist of trilayered metal-dielectric-metal thin films, where the top metal layer is patterned so that it acts as an array of electrical resonators [2]. The bottom metal layer is kept thick enough so that the charge and current distribution on the top pattern layer are appropriately mirrored in it and the two layers together form a magnetic resonator. The electric and magnetic responses can then be tuned independently to match the impedance of the structure to that of free space at any desired frequency by making a proper choice of top metallic pattern and the thickness of the spacer layer of an appropriate material [3, 4]. The electric resonance is sensitive to the shape, size of the top periodic pattern of metallic nanostructures, whereas the magnetic resonance depends primarily on the spacer material and its thickness. The coupling of electromagnetic wave in a single layer metal/dielectric structures on a thick metallic film can also be achieved by a unit absorption in a desired frequency range.

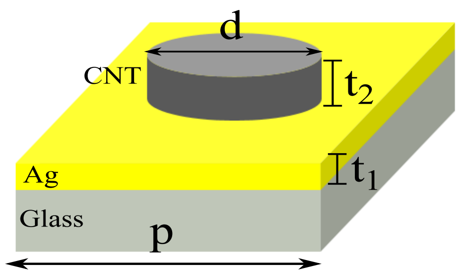

Figure 1. The schematic diagram of the proposed model for unit absorption in wavelength range of SWIR to LWIR. The dimensional parameters like diameter of the disc, thickness of the metal film, thickness of the CNT film and lattice are denoted as d, t_1, t_2 and p, respectively.

Recently, carbon nanotubes (CNT) have attracted significant attention due to their exciting electrical, optical and mechanical properties as well as novel applications in various fields [5]. Here, our aim to achieve unit absorption in both visible and infra-red frequencies. So, we choose single wall carbon nanotube (SWCNT) which has unique electro-optical properties at the visible and the infra-red frequencies. SWCNT films are the potential candidates in replacing the metallic electrode in the solar cells application to enhnace absorption efficiency. In addition, they are also used in bolometers and other micowave devices applications [6]. In the Ref. [7], it has been reported that 980 nm thick film of SWCNT deposited on 100 nm Au film shows a nearly unit absorption in visible to short-wavelength infrared range and a high reflection in the long infra-red frequency range. The high reflectivity that is observed at high wavelength range is due to metallic behaviour of CNT films. Recently, several groups [8] have proposed different models of metamaterial absorber which consist of structured metal layer top, continuous metal at bottom while these two layers are separated by a suitable dielectric layer. The physical mechanism to achieve high absorbance was described in the previous paragraph. Since CNT have high absorbance at the visible frequencies and also a good metallic behaviour at the infra-red frequencies, that motivate us

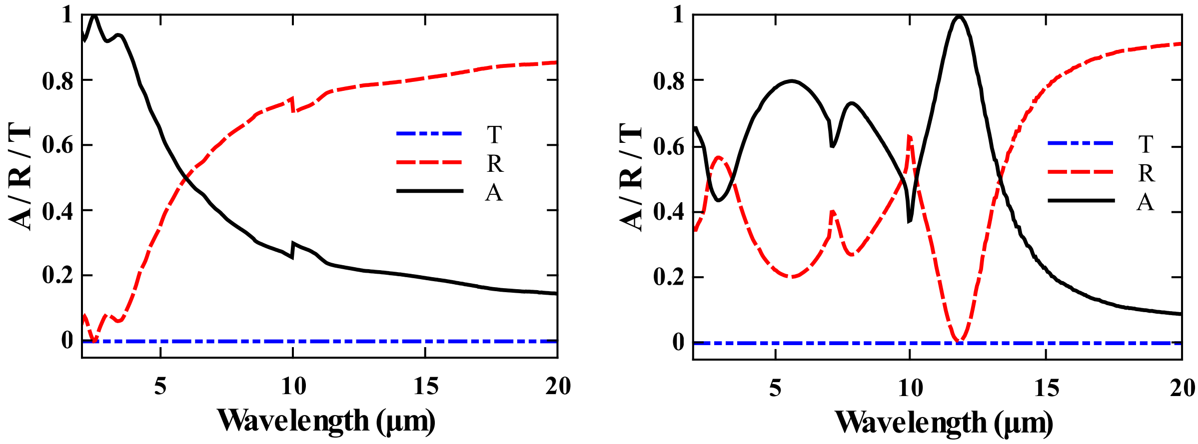

Figure 2. The reflectance, transmittance and absorbance for plane CNT film of thickness 1.8 μm and structured CNT disc array are shown in left and right panel. The diameter of CNT disc (d), and lattice period (p) for this study are taken as 3 μm and 10 μm. The thickness of the bottom Ag film is taken as 0.2 μm.

to choose CNT as our material choice and design a simple model to achieve high absorbance not only at the visible but also at infra-red frequencies range. In the present work, we propose a theoretical model for SWCNT-based perfect absorber that shows unique absorption in the visible to near infra-red frequencies due to its material properties and the unit absorption at the long-infra-red frequencies due to its structural effect. Further, we show that such structured SWCNT film on metal film can be used in the infrared sensing applications. This integration of simultaneous high absorptivity bands at SWIR wavelengths and specified IR bands in a common structure could be of use in various applications, as particularly given the robust and stable nature of the SWCNT layers.

2 Proposed model

The schematic of the unit cell of the proposed multiband perfect absorber is illustrated in Fig. 1. Our proposed design to realise unit absorption in the desired wavelength range consists of an array of periodic circular CNT microdiscs placed on a continuous metal film. The whole structural array of CNT and continuous metallic film is supposed to be fabricated on glass substrate. The dimensional parameters of the structural arrays are defined as: d, t and p are the diameter, thickness and lattice period of the CNT disc array, respectively. In order to investigate the optical response of the proposed model, we have performed the numerical simulation by using commercial software Comsol multiphysics based on the fine element method[9]. A transverse electromagnetic wave travelling perpendicular to the $x-y$ plane is incident on the top layer of the structure. Perfectly matched layers (PMLs) are used at the edges of the computational domain along the direction of propagation to avoid unwanted reflections. The unit cell was simulated using periodic boundary conditions along the $x-y$ directions to replicate the unit cell in the transverse direction so that the structure can be considered as an infinite two-dimensional array. The wavelength dependent reflection and transmission of the structure were calculated from the S-parameters. The absorption are calculated as A(λ)=1-R(λ)- T(λ), where R(λ) is the reflection and T(λ) is the transmission. The frequency-dependent dielectric permittivity of silver is modelled by the Drude model[10]. The refractive index of CNT films are taken from Ref. [7].

3 Results and discussion

To compare the reflection, transmission and absorption coefficient from a plane SWCNT film and the structured SWCNT film, we have plotted the respective spectrums for plane CNT film and the structured CNT film in Fig.2. Here, we have taken the thickness of the SWCNTs as 1.8 μm which are deposited on Ag film for both structured and unstructured CNT films. The radius and lattice period of the CNT array for this study are taken as 3 μm and 10 μm. In case of the SWCNT film (shown in left panel in Fig. 2), we noticed nearly unit absorption in the absorption spectra below 3 μm, after that the absorption spectra monotonically decreases with increasing wavelengths of the incident radiation. The refection spectra is complementary to the absorption spectra. The transmittance spectra is zero for the entire spectrum due to the high thick metallic layer below the CNT layer. The high absorption noticed occurs below 3 μm is due to the material properties of the CNT film (see in Ref.[7]). Again, we have plotted the refection, transmission and absorption spectra for the structured SWCNT film on the thick Ag film in Fig.2 (right panel). In this plot, we noticed that both reflection and the transmission spectra are complementary to each other and the transmission plot is zero in entire wavelength range. In addition to that we notice that there are three resonant peaks in the absorption spectra at the wavelength of 5.6 μm, 7.8 μm and 11.8 μm.

In order to understand the underlying physics behind the enhanced absorption peak position mentioned above, we have plotted the electric and magnetic field distributions in xy

plane and *yz* plane at the respective wavelengths in Fig. 3. The top panel and bottom panel show the electric and magnetic field distributions. At the wavelength of 5.6 μm which was plotted in Fig. 3 (a) , the electric fields and magnetic field are concentrated more on the gap between the adjacent CNT disc. Further, we see that the electric and magnetic fields are more concentrated in the gap and the top edge of the CNT disc at the wavelength of the 7.8 μm in Fig. 3 (b). In Fig.3 (c), we have plotted the field distributions at the wavelength of the 11.8 μm and observe that the electric fields are more localized at the top edge of the CNT disc. Hence, the absorption at this wavelength is primarily due to the localised dipolar mode of excitation of the CNT disc. The CNT films act as perfect metal at the infra-red frequency range. We used scaling laws which was derived by Novotny[11] as $\lambda_{eff} = n_1 * \lambda + n_2$, where n_1, n_2 are coefficients that depend on the antenna geometry and static dielectric properties. λ is wavelength of incident radiation and effective wavelength (λ_{eff}) that obey the resonant condition as $m * \lambda_{eff} = 2\ L$, where L is the length of antenna with m = 1, 2, 3, 4 etc. Our simulated peak positions at the wavelength 11.8 μm is in agreement with the resonance peak obtained analytically.

4 Sensing application

Recently, the local field enhancements obtained in such metallo-dielectric systems have been found attractive for ultra-sensitive sensor applications to detect and quantify biological and chemical agents with spectral lines at mid-infrared frequencies. For example, these structures can be perfect absorbers for resonances at 3000 cm^{-1} for C-H bonds, and were shown to effectively sense bio-molecules with monolayer sensitivity. Similarly, the extraordinary transmission in an array of holes in an aluminium film enabled sensing few-molecule layers of phospholipids and allowed for label-free sensing[12].

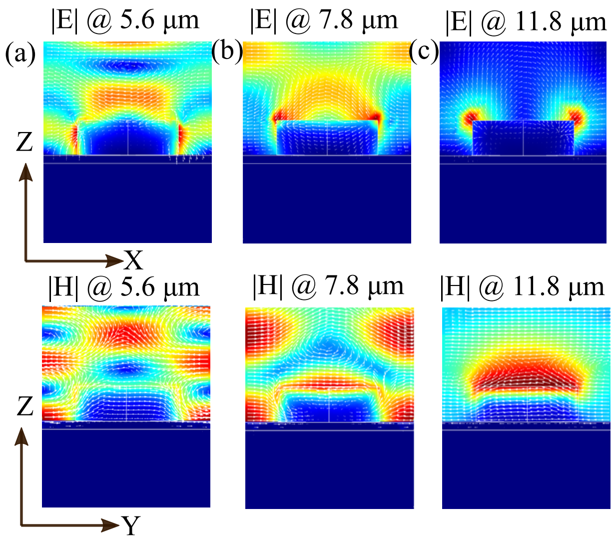

Figure 3. The electromagnetic field distribution at the respective peak position in the absorbance spectrum.

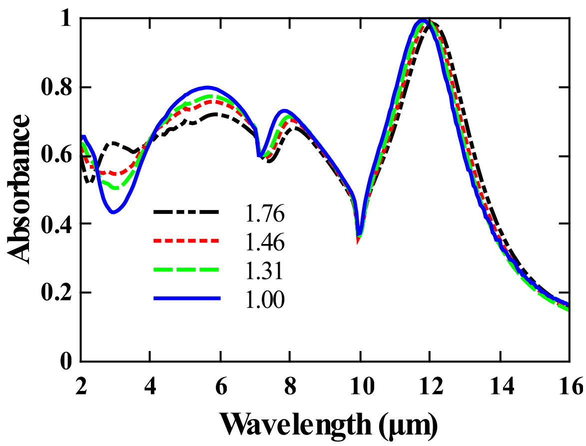

Figure 4. shows the effect of the changing in refractive index of the surrounding medium on the absorbance spectra.

The electromagnetic field distributions for the proposed model discussed above show a clear indication of the different mode of excitations and allow for spectral sensitivity. To analyse whether these structures can be useful for sensing application, we numerically simulated the change in the refractive index of the ambient surrounding medium on the absorbance spectrum. The influence of the refractive index of the surrounding medium on the absorbance spectrum can be seen in Fig.4, where we found that the resonance peaks at all positions are shifted towards higher wavelengths with an increase in the refractive index of the medium. The refractive index sensitivity is calculated by using the formula $S = \triangle\lambda/(n_{med} - n_{air})$, where $\triangle\lambda$ is the change in the resonant wavelength, and n_{med} and n_{air} are the refractive indices of the given medium and the air. The resonant peak at the wavelengths (λ_R) of 11.8 μm for n = 1 are shifted as 11.9, 11.95 and 12.1 μm for refractive index of the medium of 1.31, 1.46 and 1.76. The refractive index sensitivity to the above changes is 0.31, 0.48, and 0.98 μm per unit index, respectively.

5 Conclusion

In this paper, we propose a simple design of CNT-based perfect absorber with absorptance values above 70% in the whole 4 μm - 9 μm wavelength region. The absorbance peak is noticed at around the wavelength 11.8 μm with absorbance exceeding 99 %. The enhanced absorption peak positions at the different wavelengths in the desired wavelength range are due to the vertical cavity mode and the localised dipolar mode of the CNT film. From the electromagnetic field distributions, we noticed at the major peak, the fields are more localised at the top edge of the CNT disc, so it gives clear indication that this structures may be useful for the sensing application. Thereafter, we investigated the effect of changing the refractive index of the surrounding medium to the peak location at the unit absorbance point in the spectrum. We registered a significant change in the peak position by this effect. Hence we draw a conclusion that it can be used for the sensing application at the infrared frequencies range. Further, we proposed that our findings are potentially significant because of the opportunity of integration of such designs into different infrared devices like bolometer and also other infrared imaging systems.

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