Abstract: In pursuit of infrared (IR) radiation absorbers, we examine icosahedral graphite wires. An array of graphitic cages and cage-within-cage, and whose overall thickness is smaller than the radiation wavelength exhibit a flat absorption spectrum, $A$~0.83 between 10-30 microns and a quality loss factor of $L$~0.83 ($L=A/Q$, with $Q$ – the quality factor). Our simulations suggest that these quasi-crystal structures are capable of trapping electromagnetic energy within them. Applications are envisioned as anti-fogging surfaces, EM shields and energy harvesting.

Introduction: There is a growing interest in perfect absorbers [1], which do not transmit, nor reflect electromagnetic (EM) radiation. In the past [2], we analyzed metallo-dielectric screens as highly absorbing structures in the near infrared (near IR). Here we extend this analysis to mid-IR wavelengths with graphite wires.

Conductive-dielectric absorbers on a sub-wavelength scale may broadly fall into several categories: resonating structures such as meta-materials [3-5], interferometric devices [6-8] and lossy thin film or surface guides [9-10], most of which are quasi-two dimensional. Our structures are based on hollow frameworks, which are made of graphitic wire cages. Their overall thickness is less than a wavelength. Our simulations suggest that at the minimum, an array of quasi-crystal frameworks exhibits a large absorption coefficient ($A$=0.83) with a very large bandwidth of 20 microns, centered at $\lambda_\text{center}$=20 microns and are capable of trapping electromagnetic energy within them. A cage-within-cage framework exhibits a similar absorption coefficient ($A$~0.83), similar spectral width and funnels the radiation further towards its inner cage.

A metric, by which one compares all absorbers, regardless of their frequency of operation or their dielectric loss factor is defined as: the absorption-bandwidth product, normalized by the center frequency of operation. The bandwidth-to-frequency ratio is just the inverse of the quality factor $Q$, thus, $L=A\Delta\lambda/\lambda=A/Q$. For example, an ultimate absorber, such as a frequency independent black body with an absorption coefficient of $A^{\text{max}}$=1, has very large bandwidth response and its center frequency is at the bandwidth center. In this case, the bandwidth is twice its center frequency: $Q^{\text{max}}$=0.5 and $L^{\text{max}}$=2. In the Yablonovitch limit [11], a frequency independent, mirror-clad, weakly absorbing film ($\alpha d$=0.02, $n$=3.5) in which the mirror suppresses the transmission, has it: $A=4n^2\alpha d/(1+4n^2\alpha d)$=0.5; $Q$~0.5; and $L$~1. Resonators allow both transmission and reflection modes and are made of metal films on a slightly lossy dielectric. They are typically narrow band. For example [3,4], an excellent absorption coefficient of $A$~0.99 with $Q$~25 at the microwave frequencies exhibits $L$~0.04. We emphasize though, that the effect in [3,4] is due to the lossy nature of the dielectric filler itself and less to do with the structured surface metal electrodes. We have shown that a bilayer structure can achieve 97% of absorption ($A$=0.97) in the near infrared without the necessity for a lossy dielectric material [12]. Here too, we do not include lossy dielectric material, though the conductor exhibits complex permittivity. Our graphitic
Icosahedral cages exhibit a Quality Loss Factor, L, where L=A/Q~0.83, and Q=1 (since the bandwidth equals the center frequency).

A Faraday Cage [13], a hollow structure made of knitted conductive wires, shields its inner domain from external electromagnetic radiation through current loops at its surface. The openings in the wire mesh are typically very small compared to the effective radiation wavelength; thus, the radiation energy is dissipated at the cage’s surfaces. Here, we concentrate on cages whose dimensions and openings are in the order of the radiation wavelength. The excited dipoles in the wire mesh generate an internal field, which is not fully frustrated as for its homogeneous surface counterpart [2]. Our quasicrystals structures take advantage of the interplay between the negative dielectric constant of graphite and its moderate conductive losses in the IR wavelength region. At longer wavelengths, the conductive wires behave as perfect electric conductors and if the icosahedral array is filled with a lossless dielectric, then the array becomes reflective.

Periodic metallo-dielectric structures (also known as screens, or metal meshes) have been studied in the past, and in particular in the long wavelength region – the wavelength region where the array pitch is of the order of, or smaller than the radiation wavelength [12, 14-16] – and thus, is above the diffraction region. Stacked periodic metal screens resemble photonic crystals with a large index of refraction ratio [17]. Conductive screens may be divided into two categories: inductive screens (conductive films with a periodic array of holes which portray a transmission band) and capacitive screens (the complementary structure where conductive structures are embedded in a dielectric and portray a reflection band). The screens exhibit negative index of refraction, or NIR. For inductive screens the NIR is exhibited throughout the wavelength band pass. For capacitive screens, the NIR region lies in the longer wavelength region beyond the reflection resonance. Our array of graphitic mesh structures may be viewed as capacitive screens.

Simulations: As indicated earlier, the structure takes advantage of the negative dielectric constant of graphite at the mid IR – the same effect that leads to surface plasmons polaritons (SPP) in that spectral range and the relatively low conduction losses [18]. The icosahedral edge and wire thickness varied. A CAD tool (Comsol) was employed in the analysis of the array. Periodic boundary conditions between the icosahedrons and perfect matching layers (PML) on top and bottom of the computation cell were used. Optimizations with edge-length to wire-thickness ratio may be made. The cell size was 10 x 10 x 100 micron$^3$. The incident intensity of 1 W is linearly polarized plane wave. The fluence of radiation is, therefore, 0.01 W/micron$^2$. Periodic boundary conditions are used with a perfect matched layer on the top and bottom of the cell. As for the thermal simulations, we used periodic boundary conditions around the edges of the unit cell. For example, we set the temperature along the x-direction, temperature(x,-g/2,z)=temperature(x,g/2,z), and along the y-direction, temperature(-g/2,y,z)=temperature(g/2,y,z). The simulation works in one direction: the electromagnetic simulator affects the currents on the conductive layers, which result in heat. One may go one step further to assess how the resultant heat affects the electromagnetic absorption in a positive feedback manner; while it is worth exploring in future works, we found earlier that such approach only marginally affect the outcome [2]. The full-wave finite element solver with appropriate boundary conditions provides a complete solution to electromagnetic problems and was found in line with previous experimental results [19].

Plots of the intensity coefficients for the transmission, T, reflection, R, and total absorption A (which is defined here as, A=1-T-R) are provided in Fig. 1. The icosahedral array was illuminated
by a plane wave, propagating along the negative z-direction with y-polarization. As shown in the figure, the absorption coefficient is substantial and flat across a wide range of wavelengths.

Fig. 1. (a) Icosahedral array made of a graphitis framework: the pitch is 10 microns and the edge is 6 microns. The wire thickness is 0.3 microns. (b) Coefficients for the transmission intensity, T, reflection intensity, R, and absorption A (defined as, A=1-T-R) as a function of wavelength in microns.

An aligned, cage-within-cage framework is shown in Fig. 2. Here, the enclosing (larger) icosahedron edge measures 6 microns and the enclosed (smaller) icosahedron edge measures 3 microns while the array pitch remains at 10 micron. The wire thickness are 0.3 and 0.15 microns for the outer and inner frameworks, respectively. Here, too, the absorption is quite flat across a large band of wavelengths.

Fig. 2. (a) Aligned graphite-made cage-within-cage. (b) Coefficients for the transmission intensity, T, reflection intensity, R, and absorption A (defined as, A=1-T-R) as a function of wavelength in microns.

Capturing energy within the structure leads to heat and a quick rise in temperature. The temperature rise exhibits a linear trend over the time-scale studied, from 0 to 1 ns. Fig. 3 also
indicates the funneling of energy from the outer towards the inner cage. The electromagnetic intensity distribution is shown for the middle cross-section. Since the dielectric is made of air, the rise in temperature is seen on the conductive wires. Specifically, the inner cage becomes hotter. Both distributions were evaluated at a wavelength of 14.9 microns. The value of the trapped energy varies is a function of wavelength, though. For the cage-within-cage in the near infrared we found [2] that most of the trapped radiation energy at the peak absorption wavelength resides in between the cages as seems to be the case here.

Fig. 3. Temperature and electromagnetic intensity distributions at $\lambda=14.9$ microns. (a) A single cage array and (b) a cage-within-cage array. The electromagnetic fluence is 0.01 W/micron$^2$. The simulation was captured after 1 ns. The electromagnetic intensity distribution is shown only for the middle cross-section whereas the temperature is developed on the conductive wires.

Can we further extend the absorption wavelength region? Preliminary simulations indicate that at longer wavelengths - longer than used here, the absorption coefficient drops to 50%. Furthermore, at microwave frequencies, one needs to interface the structure with a lossy dielectric, similarly to [3] for the absorption coefficient to become $A=0.3$.

In summary, an array of graphitic icosahedrons was found to be a very effective radiation absorber in the 10 to 30 microns wavelength range.

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