Broadband Negative Refractive Index in the Visible Spectrum

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Abstract: In this paper, a composite medium based metamaterial with random distribution of nanoparticles in vacuum host to achieve negative effective refractive index in the visible wavelength range is suggested for invisibility purposes. Our calculations show that structures including single metal (dielectric) spheres and core-shell structures with metallic core and dielectric shell, which consists two-layer particles with uniform sizes cannot support negative effective refractive index. For this purpose the structures consist of two-layer nanospheres with different sizes and fill fraction has been proposed. Since, band width of negative refractive index is narrow, the three layer nanospheres has been studied and investigated. We show that in this case with increasing the refractive index of middle and outer layers, negative value of effective refractive index can be increased. Also, we show that using different sizes of nanomaterials in host medium, band width is increased. Finally, superposition of three layer spherical nanoparticles with different outer radius and applied single doped semiconductor spheres, has been proposed. We show that Band width with negative permittivity and permeability can be optimized.

1 INTRODUCTION

Nowadays the metamaterials has very interesting applications such as applications in super lenses and invisibility and also hot topic for researchers recently (Cai, Genov and Shalaev, 2005, Cai and Shalaev, 2010). Although, metals such as silver, gold and copper can produce the negative permittivity in the optical range but finding natural elements with negative permeability is limited to the hundred gigahertz frequencies (Cai and Shalaev, 2010). In this way different media consists of nanorods and split ring resonators (SRRs) in order to achieve negative effective parameters have been proposed in different wavelength ranges (Cai and Shalaev, 2010, Zhang, Fan, Panoiu, Malloy, Osgood and Brueck, 2005, Smith, Padilla, Vier, Nemat-Nasser and Schultz, 2000). The complex fabrication methods to produce these media and limitations of SRRs related to the saturation magnetic response in the optical wavelength ranges (Zhang, Fan, Panoiu, Malloy, Osgood and Brueck, 2005) lead to designing of the media with random distribution of nanoparticles (Zhou, Koschny, Kafesaki, Economou, Pendry and Soukoulis, 2005, Dominguez, Tejeiara, Marques and Gil, 2011) . The random distribution of nanoparticles also can produce broad band negative permittivity that it was not possible with the previous structures. In this paper, we propose single, two and three layer spherical nanoparticles with random distribution to exhibit negative effective refractive index in visible wavelength range. In this regard first single nanospheres consist of metal (Ag, Au, Cu, Al…) and dielectric with high relative refractive index and two layer spherical nanoparticles which possess of metal core (Ag) and dielectric shells (Si) with different sizes and fill fractions will investigate. After that to produce negative refractive index, we will consider three layer spherical nanoparticles (such as proposed in (Dajian, Shumin, Ying and Xiaojun, 2011)). then, the effect of electrical permittivity of middle layer and the refractive index of the outer layer on increasing of the wide of wavelength range with negative optical parameters has been studied and at the end structure consist of three layer nanoparticles with different size and the same filling fraction has been proposed to broaden the wavelength range with negative effective permeability. Since, the wavelength range with negative effective permittivity is narrow, finally in order to broaden of this range, we have applied the semiconductor doped spherical nanoparticles with a proper plasma frequency and electrical permittivity (obtained by Drude model) in the structure. To calculate the effective parameters Clausius-Mossotti relations have been used.

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2 THEORETICAL BACKGROUND AND SIMULATIN

First, structures including metal (Ag, Au, Cu, Al …) and high refractive index dielectric (Si, Ge, GaAs …) as single spheres to produce electric and magnetic activity in the desired wavelength range have been studied. The medium has been shown as bellow:

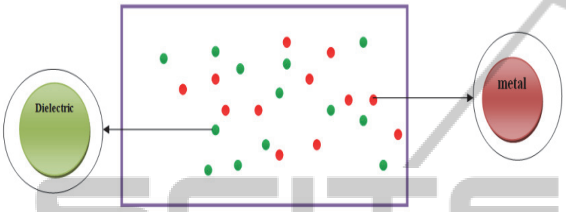

Figure 1: Single layered spheres with metal and dielectric spheres in vacuum host.

Although the metal spheres show negative electric permittivity (since, electric resonance condition for metal spheres surrounded in a media with electric permittivity ε_m is $(\varepsilon_{res} = -2\varepsilon_m)$) the electric resonance of metal nanoparticles in vacuum doesn't occur in the visible wavelength range. However, the dielectric with high refractive index with proper radius produces the magnetic activity in the desired range. Therefore, the electric and magnetic resonance don't occur in the desired wavelength range simultaneously. The media including two spherical- layer nanoparticles with metallic core and dielectric shell with same size are considered and shown as follows.

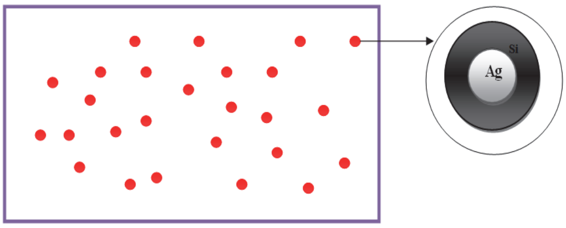

Figure 2: Two layered spheres with Ag as core and Si as shell in vacuum host.

Scattering and extinction efficiencies for these structures can be obtained as (Craig, Bohren and Donald, 1983):

$$Q_{sca} = \frac{2}{y^2}\sum_{l=0}^{\infty}(2l+1)\left(|a_n|^2 + |b_n|^2\right)$$
$$Q_{ext} = \frac{2}{y^2}\sum_{l=0}^{\infty}(2l+1)\,\mathrm{Re}(a_n + b_n) \qquad (1)$$

Where electric and magnetic scattering coefficients a_n and b_n for two layer nanoparticles can be obtained from (Craig, Bohren and Donald, 1983). Since, the size of nanoparticles is small related to the incident wavelength, therefore only a_1 and b_1 can be considered for simulations.

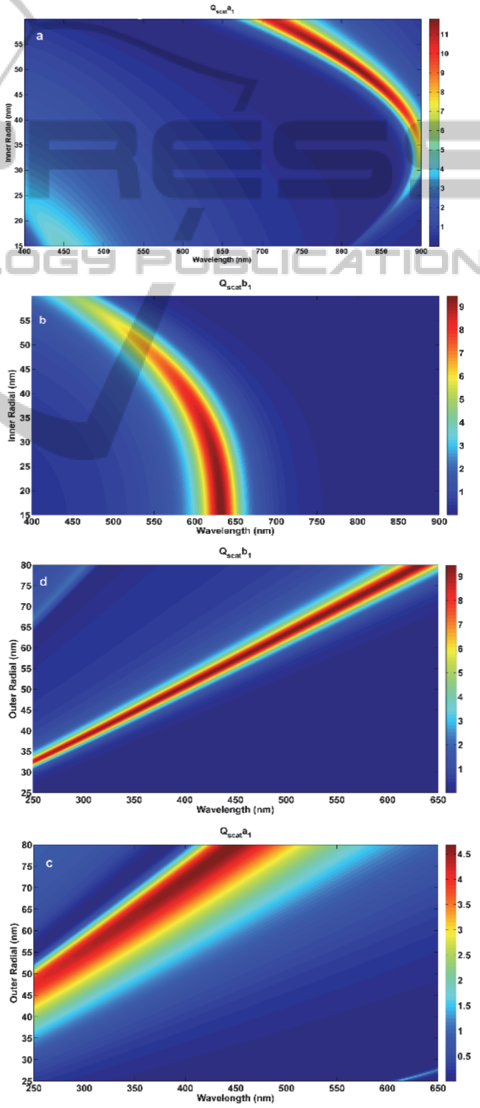

Figure 3: (a) and (b) electric and magnetic scattering efficiencies for the particles with fixed Rout in terms of Rin and incident light, (c) and (d) electric and magnetic scattering in the case of fixed Rin versus different Rout and incident light respectively.

Figure 3 (a) and (b) show electric and magnetic scattering efficiencies for the particles with fixed outer layer radii (R_{out}=70nm) in term of inner layer radii (R_{in}) and incident light and (c), (d) indicate scattering efficiencies corresponded to the case of specific inner layer radius (R_{in}=15nm) versus outer layer radii (R_{out}) and incident light wavelength.

It is clear from the figure that with the uniform particles, it is impossible to adjust inner and outer radii to resonance both electric and magnetic dipoles in a specific wavelength range to produce negative n_{eff}. To resolve this problem, we can apply a medium consists nanoparticles with different sizes (R_{in}=20nm, R_{out}=70nm for f_1=0.30 and R_{in}=25nm, R_{out}=35nm for f_2= 0.15).

By using the Clausius-Mossotti equation, Effective permittivity (ε_{eff}) and magnetic permeability (μ_{eff}) of a host medium with electrical permittivity (ε_h) and magnetic permeability (μ_h) related to the filling fraction $f = N\,4\pi r^3/3$ where N is the number of particles per unit volume, and polarizabilities of the nano-particles.

$$\frac{\varepsilon_{eff}-\varepsilon_h}{\varepsilon_{eff}+2\varepsilon_h} = f\,\frac{\alpha_E}{4\pi R^3}$$

$$\frac{\varepsilon_{eff}-\varepsilon_h}{\varepsilon_{eff}+2\varepsilon_h} = f\,\frac{\alpha_E}{4\pi R^3} \qquad (2)$$

Where the electric and magnetic polarizabilities, α_E and α_M respectively, are directly proportional to the scattering coefficients a_1 and b_1 (factor $i(k^3/6\pi)^{-1}$. As can be seen in Figure 4, n_{eff} is negative for a narrow wavelength range.

Broader wavelength range with negative n_{eff} can be produced by using three layered spherical nanoparticles according to (Dajian, Shumin, Ying and Xiaojun, 2011). This goal can be achieved by applying the middle layer with the refractive index, smaller than the outer layer in order to increasing the Plasmon resonance frequency. In this condition the electric and magnetic resonance simultaneously occur in a specific wavelength ranges, too. Effective optical parameters for this structure have been obtained as (Dajian, Shumin, Ying and Xiaojun, 2011). Since, the magnetic polarizability of the particle enhances by increase the refractive index of the outer layer; the effective negative permeability of the structure will be broader in the desired wavelength range. This effect can be seen in Figure5 as is shown increase the refractive index of outer layer leads to broader negative wavelength range.

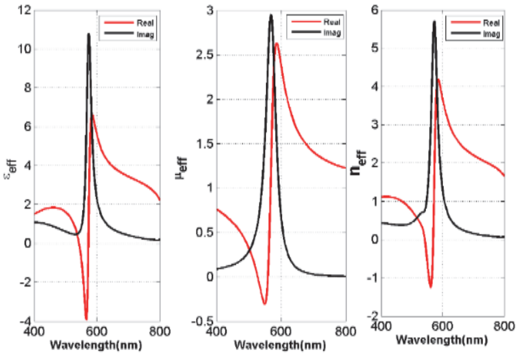

Figure 4: Effective parameters for a medium consists of nanoparticles with different sizes (Rin=20nm, Rout=70nm for f1=0.30 and Rin=25nm, R_{out} =35nm for f2= 0.15).

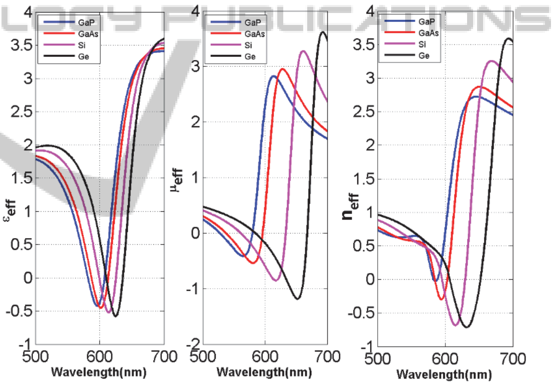

Figure 5: The effect of different materials for outer layer on effective optical parameters.

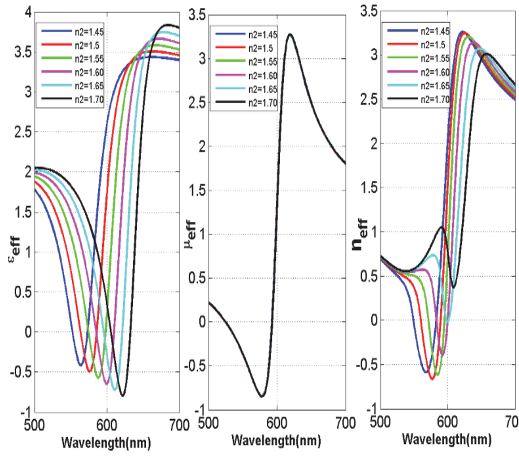

Figure 6: The effect of changing refractive index middle layer on the effective parameters.

Increasing of the electric permittivity of the middle layer leads to a shift in the electric resonance to the longer wavelength and broaden the wavelength band with negative effective permittivity but the effective permeability isn't influenced as shown in Figure 6.

Figure 7 shows the effect of increase of the refractive index of middle and outer layer that broad wavelength band with negative refractive index can be achieved.

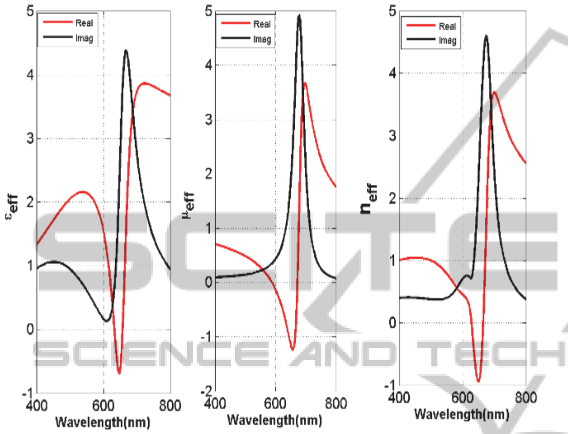

Figure 7: effective parameters plotted for a medium contains three layered spheres with n2=1.7 and n3=nGe=4.

Since, the electric and magnetic resonance simultaneously in the other hand, the magnetic resonance is influenced by changes in the outer layer radius, so in order to broadening the wavelength range with negative permeability the idea of superposition can be useful as discussed in the following section.

2.1 Superposition Effect

In this part, we study the influence of outer layer radius on the broadening band width for negative refractive index. We use the particles which have the middle and outer layer with high refractive index. The results show the change in the outer layer radius causes the magnetic resonance shifts to longer wavelength. In fact a particle can be considered as a cavity which increase in the size of cavity results in the resonance wavelength shifts to longer wavelength ranges. So, by using superposition of nanoparticles with different outer layer radius the broader wavelength range with negative permeability, can be achieved. The structure is shown in Figure 8 and effective parameters are shown in Figure 9.

The results indicate that the wavelength range with negative permittivity is narrow and it leads to a narrow band negative refractive index and by applying spherical doped semiconductor nanoparticles (which electric permittivity follows the Drude model and have plasma frequency in the desired wavelength range) in the three layer nanoparticles (As shown in Figure 10) the wavelength range with negative refractive index can be broaden.

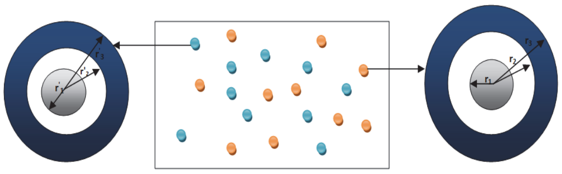

Figure 8: Three layer nanoparticles with different dimension in vacuum media.f1 and f are fill factors of the three layer nano particles with r1, r2, r3 radiuses (orange spheres) and r_1', r_2', r_3' radiuses (blue spheres).

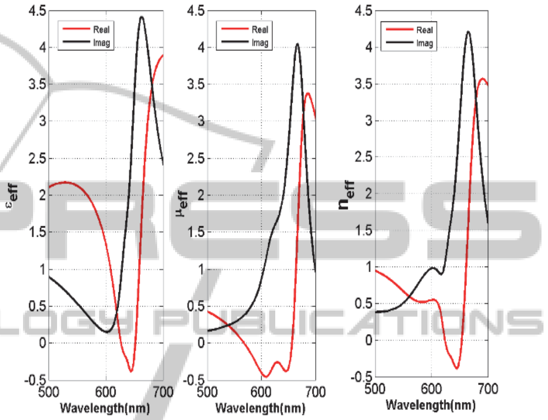

Figure 9: The effective optical parameters for a medium consist of two layer nanoparticles with different outer size and doped semiconductor.

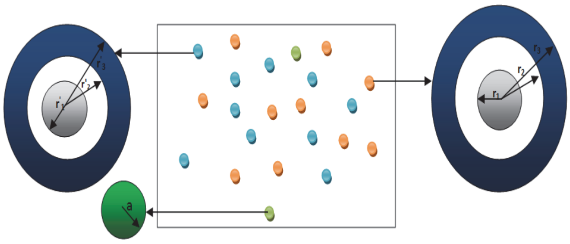

Figure 10: Three layer nanoparticles with different dimension and a single layer doped semiconductor nanoparticles in vacuum media. f1, f2 and f3 are fill factor of the three layer nano particles with r1, r2, r3 radiuses (orange spheres) and r_1', r_2', r_3' radiuses (blue spheres) and the fill factor of doped semiconductor nanoparticles with a radius (green sphere).The Materials in core, middle layer and outer layer are Ag, SF5 and Ge respectively.

The effective parameters for this structure are illustrated in Figure 11.

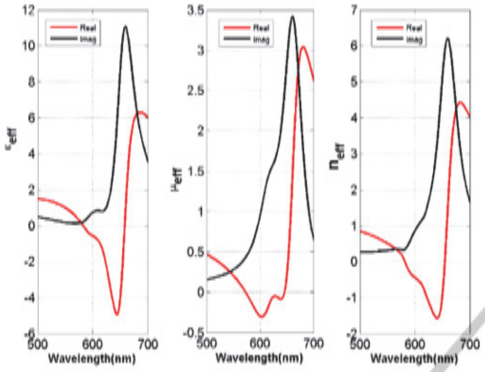

Figure 11: The effective optical parameters for a medium consist of two layer nanoparticles with different outer size and doped semiconductor.

3 CONCLUSIONS

We proposed single, two and three layer spherical structures with random distribution in order to achieve broad band effective refractive index in this paper. The particles are in vacuum media and sizes of them are in the small nanometer ranges. The results show Non-overlapping of the scattering efficiencies for single layer particles (metal and dielectric nanosphers) and two layer spherical nanoparticles consist of metal core (Ag) and dielectric shell (Si) with uniform size causes no negative n_{eff} in the visible wavelength range. To solve the problem we proposed the structure with different size and fill fraction of two layered nanoparticles. Since, the wavelength range with negative n_{eff} is narrow in these conditions; we used a three layer structure. Increase the electrical permittivity of middle layer and the refractive index of the outer layer lead to broadening of the negative n_{eff} range. Using different size of three layered nanoparticles with the same filling fraction to broadening of the wavelength range with negative effective permeability was introduced by superposition idea. In order to increase the negative refractive index, we applied the doped spherical semiconductor layer which has proper plasma frequency and electrical permittivity confirmed by Drude model.

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