Structures for Metamaterial Superlenses Used in Medical Imaging

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Abstract The metamaterial superlenses for imaging proteins, viruses, and DNA have to present a high resolution, which cannot be ensured by classical lenses. Such a material for lenses exceeds the Abbe-Rayleigh diffraction limit, leading to a nanoscale level of resolution, a several times better than the classical diffraction limits. We have illustrated here a hotspot size of ca. 0.25 – 0.28 λ, corresponding to a numerical aperture of about 1.4. The used metamaterial structures are isotropic negative index metamaterials (NIMs), with negligible losses. Material combinations of metallic nanoparticles (with dimensions of tens of nm) inserted in a dielectric slab have been considered for study. Microcomponents periodicity in the layer is of a few hundred of nanometers. Material properties evolve in function of the constituent’s nature and dimensions. Refraction index in function of wavelength was determined and represented on graphs in order to illustrate the domain of negative values and the manner in which it can be controlled at structure level. Analysis was performed in visible and IR range by simulation methods, using the HFSS program and a proper algorithm based on physical considerations.

1. Introduction
A high resolution is necessary for imaging proteins, viruses, and even DNA molecules, which cannot be ensured by classical lenses. The metamaterial structures used for lenses exceeds the Abbe-Rayleigh diffraction limit and nanoscale level of resolution can be achieved, a several times better than the classical diffraction limits [1], [2].

The metamaterial slab compensates the wave decay and images can be reconstructed in the near field. The negative index metamaterial gives us the possibility to recover evanescent waves from the object in the image plane. The material amplifies the evanescent waves that carry information at very small scales [1], [3]. Superlens with a negative refractive index are obtained, working at frequencies in visible range [7]. Sub-wavelength metasstructures has to be included inside the metamaterial in order to obtain subwavelength foci and resolution close to the size of the focus [9]. We have illustrated here a hotspot size of ca. 0.25 – 0.28 λ, corresponding to a numerical aperture of about 1.4.

2. Structure Description
We have analyzed a negative index metamaterial (NIM) for lenses, with a particular structure. The material with ε > 0 and μ < 0 supports evanescent waves and represents an MNG (μ negative material). If the object and the lens are placed along the z-axis, the rays from the object are traveling in
the +z direction. Due to the negative refraction index, transport of energy in the +z direction requires the \( z \) component of the wave vector to have opposite sign \([2], [4], [5]\):

\[
k_z = -\sqrt{\frac{\omega^2}{c^2} - (k_x^2 + k_y^2)}
\]  

Consequently, the evanescent waves are transported and amplified.

The unit cell of the considered metamaterial is a type of split ring resonator (SRR). This ensures the negative permeability in a limited frequency domain, which can be modified by dimensions tuning. A regular distribution of the unit cells (SRRs) inside a nonmagnetic dielectric has been considered.

The material is isotropic, with negligible losses. The SRR segments are metallic, with dimensions of tens of nm inserted in the dielectric slab (Fig. 1). Microcomponents periodicity in the layer is of a few hundred of nanometers.

The SRR were structured from cylindrical rods of Ag with length \( L \) of 100 nm to 120 nm and diameter \( d \) of 20 to 30 nm. Number of segments of each SRR can be 3, 5 or 7- odd number was chosen in order to ensure the negative permeability of the sample. The considered dielectric was GaP. Analysis has been performed for similar sets of materials given in literature. E.g. of material combinations: Au, Ag, Cr on Si; Ag on Al_{2}O_{3}, Si_{3}N_{4}, SiO_{2}, TiO_{2}, GaP, GaAs, InP \([10] - [13]\).

The spatial structure of the lenses metamaterial is given in Fig. 1.

![Figure 1. Structure of the metamaterial. The two successive layers represent the negative of each other regarding the metal / dielectric constituents.](image)

One remarks the opposite orientation of the successive units (individual SRR), in the same layer, either in successive ones. This type of unit orientation was chosen in order to obtain the maximum inductive effect of the SRRs when they interact with the applied field. The geometry was tested until a convenient domain of negative permeability has been obtained.

Material properties evolve in function of the constituents nature and dimensions (size and shape of the metallic nanostructures). Subwavelength confinement and strong field enhancement have been achieved.

The wave vector of the surface plasmon polaritons is given by the relation \([12], [14]\):

\[
k_p(\omega) = \frac{\omega}{c} \sqrt{\frac{\varepsilon_d \varepsilon_m}{\varepsilon_d + \varepsilon_m}}
\]  

where \( \varepsilon_m \) and \( \varepsilon_d \) are the frequency dependent permittivity of the metal, respectively dielectric, \( \omega \) is the pulsation of the incident field, and \( c \) is the light speed. In the same time,

\[
k_p = k_0 n = \frac{2\pi}{\lambda} n_{\text{eff}}
\]  

where \( k_0 \) is the free-space wavenumber, \( n_{\text{eff}} \) is the effective refraction index of the propagation medium and \( \lambda \) is the wavelength. The imaginary part of the wavenumber expresses attenuation per unit distance and is useful in the study of evanescent fields with exponential decaying.
3. Analyzing Method
The test configuration is represented in Figure 2. Exposure of the metamaterial slab has occurred in a multi-mode ridge channel waveguide, with dimensions of \( w = 2.8 \) µm, \( h = 1.6 \) µm. With help of the HFSS program, the samples analysis was performed in the domain of 600 … 840 nm for the incident field wavelength.

![Figure 2. The ridge channel waveguide with the metamaterial sample.](image)

The normalized frequency (\( V \) number, which determines the number of modes) of this rectangular waveguide can be written as:

\[
V = \frac{2\pi}{\lambda} w \sqrt{n_{\text{meta}}^2 - n_{\text{cladding}}^2}
\]

where \( n_{\text{meta}} \) and \( n_{\text{cladding}} \) are the refraction index of the metamaterial slab, respectively substrate and \( w \) is the metamaterial slab width (Fig. 2).

For the TE mode, \( E_z = 0 \), \( E_x \gg E_y \), and \( H_z \neq 0 \). The considered channel waveguide is a nonplanar one and has strong optical confinement because it is surrounded on three sides by a low-index material - air.

The S-parameters have been determined by simulation with help of the HFSS program. Then the reflection coefficient \( \Gamma \) and the transmission coefficient \( T \) have been calculated using the simulation data, for the TE\(_{10} \) mode.

The following expressions have been used [12], [15]:

\[
S_{11} = \frac{\Gamma (1 - T^2)}{1 - \Gamma^2 T^2} ; \quad S_{21} = \frac{T (1 - T^2)}{1 - \Gamma^2 T^2}
\]

\[
\Gamma \approx \frac{n_{\text{meta}} - n_{\text{air}}}{n_{\text{meta}} + n_{\text{air}}} ; \quad T \approx \frac{2n_{\text{meta}}}{n_{\text{meta}} + n_{\text{air}}}
\]

The effective refraction index of the metamaterial sample has been calculated at different frequencies in the considered domain.

4. Results for the Negative Parameters
For the superlenses material, the refraction index in function of wavelength has been determined and represented on graphs in order to illustrate the domain of its negative values. We are interested in the manner to which the refraction index can be controlled at structure level. Analysis was performed in visible and IR range (600 … 840 nm) by simulation methods, using the finite element method and a proper algorithm based on physical considerations.

Results for \( n(\lambda) \) were illustrated in Fig. 3, 4 and 5 below. Different structural parameters have been varied in order to observe the \( n \) dependence on the geometry of the metamaterial constituents.

In Fig. 3 the shape of the rings of the SRRs has been modified by varying their segments number (odd, 3, 5, 7) in the unit cell.
Figure 3. Refraction index evolution for $\lambda = 600 \ldots 840$ nm, for the metamaterials having metallic SRRs with different number of segments, $s$, included in the dielectric volume.

One observes that the segments number do not influence significantly the results, the recommendation is for the segments loop to be rather almost closed than open, for leading better the field lines.

The refraction index evolution in frequency range is characterized by a negative peak (a valley) and in a narrow frequency range is possible to have negative values. This fact depends on the structure, the nature and geometry of the metamaterial constituents. Excepting this valley, negative values for $n$ are achieved when $\lambda$ increases and is close to IR region. These results are in agreement with the data presented in literature [1], [6], [8], etc. The decreasing trend of the refraction index is limited in practice, $n$ presenting positive values over the most of the electromagnetic spectrum. The simulation model has to be perfected in order to reproduce the real behavior of the material in a more wide frequency range that the domain considered for analysis.

The negative peak is caused by a resonant phenomenon inside the metamaterial sample and a correlation can be pointed out between the SRR dimensions, respective periodicity and the wavelength corresponding to this peak central frequency. Simulations are indicating very easy modification of the position of this negative peak when SRR perimeter, respectively the distance between the metamaterial layers are changed.

Fig. 4 indicates variation of the refraction index when the SRR segments length vary.

![Graph](image-url)

**Figure 4.** Refraction index in function of the wavelength, for different values of the SRR segments length, $L$. 
A maximum for negative values more deep and wide have been obtained when the perimeter of the SRR loop increases. But in the same time, the domain of the negative values for \( n \), which succeeded this maximum, is smaller. This effect is valuable for an increasing of \( L \) up about 140 – 150 nm, then the maximum is rising to positive values, not convenient for a metamaterial. The interval of values for \( L \) in which the negative peak can be obtained is correlated to the wavelength and is linked to the resonant phenomena inside the material sample.

In Fig. 5 are represented the curves for \( n \) when the metal of the SRR rings modify its thickness. The interval of possible modifications it is not too large, limited by a rising of the curve to positive values when the rings are thicker (see the example of the curve for a SRR segments diameter \( d = 30 \) nm). Variation of the metal thickness does not modify the position of the resonant peak, but it’s magnitude. Finer the SRR ring, deeper is the negative peak, but also very narrow. The ring diameter is limited in practice by the technology.

![Figure 5](image)

**Figure 5.** Refraction index in function of the wavelength, for different values of the SRR segments diameter, \( d \).

If we denote the maximum negative value of the refraction index on graphs with \( n^* \) and the domain of the negative values, which succeeded this maximum, with \( \Delta \lambda \), the results obtained for different internal structure of the considered metamaterial for lenses are given in Table I. Results were obtained for the five segments SRR structures (\( s = 5 \)). Arrows indicate the increasing of the parameter in the table column. The lenses resolution using slabs of metamaterial with characteristics given in the table lines has been determined.

| No. | \( d \) [nm] | \( L \) [nm] | \( n^* \) negative peak | \( \Delta \lambda \) [nm] for \( n \) negative | Resolution |
|-----|-------------|-------------|------------------------|---------------------------------|------------|
| 1   | 20          | 100         | -0.66                  | 156                             | 0.23 \( \lambda \) (min 138nm) |
| 2   | 20          | 110         | -0.82                  | 133                             | 0.24 \( \lambda \) |
| 3   | 20          | 120         | -0.74                  | 87                              | 0.26 \( \lambda \) |
| 4   | 25          | 100         | -0.26                  | 124                             | 0.25 \( \lambda \) |
| 5   | 25          | 110         | -0.52                  | 81                              | 0.28 \( \lambda \) |
| 6   | 25          | 120         | -0.73                  | 45                              | 0.32 \( \lambda \) |
| 7   | 30          | 100         | 0.18                   | 98                              | 0.27 \( \lambda \) |
| 8   | 30          | 110         | 0.05                   | 82                              | 0.30 \( \lambda \) |
| 9   | 30          | 120         | -0.24                  | 76                              | 0.33 \( \lambda \) (max 277nm) |
One observes that the obtained resolution values exceed the classical diffraction limit and can be adjusted by modifying the metamaterial geometrical configuration. For obtaining finer spots, finer SRR rings have to be used (e.g. \( d = 20 \) nm), with a perimeter correlated with the wavelength, in agreement with the resonant phenomena which accompany the propagation. Yellow lines in the table are indicating possible preferable solution for the metamaterial synthesis.

5. Conclusions

A model of structure for metamaterial used for superlenses have been proposed here, in order to improve the resolution and control the lens properties by modifying the geometrical parameters of the samples.

Superlens resolution of fraction of wavelength can be achieved, using metamaterial structures conceived with periodic metal SRRs included in a proper dielectric background, alternating in volume, on layers, with similar components but inverting the metal / dielectric materials.

Resonant phenomena occur in the metamaterial. A maximum recovering of the evanescent wave energy can be achieved when a periodical dimension of the metamaterial structure is a multiple or submultiple of a half wavelength of the propagating field. This determines the maxim focalization effect of the superlens.

The adopted configuration of the metamaterial which represents a mirror positive / negative structure (Fig. 1) increases significantly the amplification of the evanescent wave, in comparison with the structure with only metal SRRs inside the dielectric.

Concerning the material nature of the components, it can be pointed out that the metal nature influences the foci, while the dielectric nature influences absorption and losses inside the superlens material.

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