Some design considerations for nanomembrane-based fishnet metamaterials operating at optical frequencies

Dragan Tanasković, *Member,* Zoran Jakšić, *Senior Member, IEEE*, and Jovan Matović

***Abstract* — We designed a metal-dielectric-metal laminated freestanding structure with ordered nanoaperture arrays acting as fishnet-type negative index metamaterials. We utilized finite element analysis to define the geometry and consider the influence of various parameters. The structures are based on our experimental building blocks which utilize freestanding, self-supported nanomembranes (5-50) nm thick and focused ion beam technique to shape the nanoaperture arrays.**

***Keywords* — Applied Electromagnetics, Nanophotonics, Optical Metamaterials, Nanomembranes, Surface Plasmons, Optical Waveguides, Nanoplasmonics.**

I. Introduction

ELECTROMAGNETIC metamaterials are a wide group of artificial structures with electromagnetic properties not readily found in nature. The best known among them are metamaterials with negative refractive index (LHM, short for "left-handed material" – related to the fact that the wavevector, electric and magnetic field are here connected with the rule of the left hand) [1-3]. The LHM structures host a plethora of unusual and sometimes counter-intuitive properties like the reversal of the direction of the wavevector and the Poynting vector, negative group velocity, reversal of the Snell's law, reversal of Doppler Shift, etc. [3].

One of the properties of the LHM of a great practical importance is the phase shift compensation: if a LHM structure is combined with a conventional material having a positive refractive index (RHM, right-handed material), the phase shift introduced by the positive material will be compensated and even annulled by the LHM part. This effect is the basis of superlenses with resolution below the diffraction limit [4], subwavelength resonant cavities with the dimensions much smaller than the operating wavelength [5], subwavelength antennas and delay lines [6], etc. The LHM are thus finding nowadays a rapidly increasing application in microwave and communications technology.

The interest for the LHM in the optical frequency range is large, one of the reasons being the possibility to combine optical components with conventional VLSI circuitry and to use the same metal structure both for optical waveguiding and for the transmission of the controlling low-frequency electrical signals [8]. Due to their nonlinear dispersion dependence, the operating wavelengths in the LHM and generally in plasmonic structures can be much smaller than those in free space at the same frequencies. In this manner they offer the possibility to operate devices at frequencies of the order of hundreds of terahertz and yet to retain extremely short length scales, a property very convenient for miniaturization of photonic circuitry and the fabrication of ultra-compact devices. It is thought that plasmonic components and metamaterials may ensure the bridge between the conventional circuitry and the emerging all-optical circuitry at the nanometer scale and thus merge photonics and electronics [9], [10].

The fabrication of the LHM for the optical range poses formidable challenges. Among the problems are the development of sufficiently accurate nanotechnology procedures for the fabrication of the material building blocks. Various parasitic effects appear at very large frequencies, for instance the ballistic inductance [3]. Also, some material properties like magnetic permeability lose their sense when reaching the visible. As a consequence, many structures functional in the e.g. microwave (for instance the well-known double split ring resonators) lose much or all of their function at the frequencies near the visible range [3]. Among the various designs proposed for the LHM in the optical range, probably the best performance to date has been achieved utilizing the double fishnet structures [11], [12]. These are LHM with the highest operating frequencies to date, even entering the visible [13], [14].

In this paper we investigate the possibility to fabricate fishnet metamaterial structures for the optical range utilizing the freestanding, self-supported nanomembranes as their basic building blocks. Recently we proposed a method to fabricate (5-50) nm thick nanomembranes with very large aspect ratios, even exceeding 1,000,000 [15], as well as methods to functionalize them using surface sculpting [16], [17], adsorption [18] and nanohole drilling [19].

Dragan Tanasković, IHTM – Institute of Microelectronic Technologies and Single Crystals, Njegoševa 12, 11000 Belgrade, Serbia, (phone 381-11-2630757, fax 381-11-2182995, e-mail: dragant@nanosys.ihtm.bg.ac.rs)

Zoran Jakšić, IHTM – Institute of Microelectronic Technologies and Single Crystals, Njegoševa 12, 11000 Belgrade, Serbia, (phone 381-11-2630757, fax 381-11-2182995, e-mail: jaksa@nanosys.ihtm.bg.ac.rs)

Jovan Matović, Institute of Sensors and Actuators, Faculty of Electrical Engineering & Information Technology, Technical University Vienna, Austria, (e-mail: Jovan.Matovic@tuwien.ac.at)

Here we present the results of the finite element simulation of nanomembrane-based fishnet structures designed for the optical frequency range. We investigate the influence of the main design parameters and the resulting electromagnetic behavior of our structures. The design is oriented to enable and facilitate the experimental fabrication of nanomembrane-based fishnet structures which is already underway.

II. Theory

A unit cell of a fishnet LHM consists of two parallel metal sheets with a rectangular shape separated by a dielectric layer along the direction perpendicular to it. The sheets are discontinuous at each edge of the square. Each metal sheet is thus basically a superposition of a thin wire along one in-plane direction and a short slab along the other in-plane direction. If a large number of such unit cells is observed simultaneously, the structure has an appearance of a fishnet, where the discontinuities at the edges form the openings of the fishnet. These apertures may be e.g. rectangular, circular or ellipsoidal. An example of a fishnet with circular holes is shown in Fig. 1.

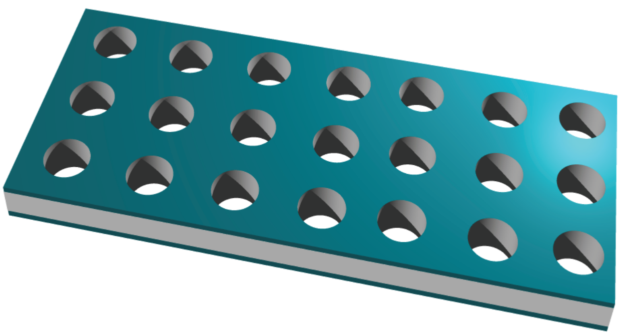


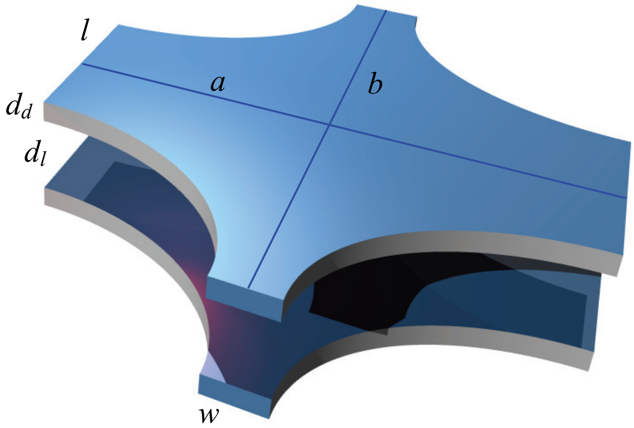
Fig. 1. Basic configuration of a fishnet-type DNG metal-dielectric-metal structure based on a freestanding nanomembrane

Among the advantages of the fishnet LHMs is their ability to generate left-handed response for a light beam incident perpendicularly to the plane of the metal sheets. In this way both lateral and normal coupling is ensured. Thus one is able to obtain a strong left-handed response using a single metal-dielectric-metal structure.

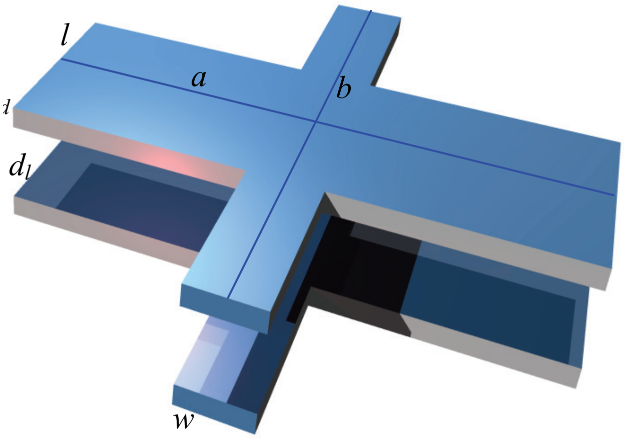
Geometry of a single unit cell of our fishnet MM is shown in Fig. 2. The width and the length of the unit cell are a and b, respectively. Fig. 2 shows the two generic cases of the fishnet LHM geometry, that of elliptical holes (Fig. 2a) and of rectangular ones (Fig. 2b). The spacing between the metal sheets in Fig. 2 is empty, i.e. the dielectric is air (vacuum), however in a general case the spacing may be filled with any dielectric (and actually with any material whatsoever).

The apertures define the minimum widths of the fishnet unit cell l and w (which are identical in the special cases of circular and square openings). The thickness of the metal part is d_m, and the dielectric spacing between the two metal sheets is d_d.

In our specific case, owing to the nanomembrane base, the structures are fully symmetrical in electromagnetic sense, with two identical metal surfaces at each side.



a)



b)

Fig. 2. Geometry of a single unit cell of a fishnet structure. a) elliptical apertures; b) rectangular apertures.

III. Results

We modeled a single unit cell consisting of a metal-dielectric-metal sandwich structure as shown in Fig. 2a. The values of l and w are identical, i.e. the shape of the apertures is circular (see Fig. 1). The dimensions of the structures were a=320 nm, b=280 nm and the radius of the apertures was r=100 nm. In our simulations we varied the values of the thickness of the dielectric of (20, 50, 75, 100, 150, 200) nm. We introduced the perfect matching layer boundary conditions. We investigated the case when an electromagnetic wave propagates so that its wavevector is parallel to the metal surface and is TM-polarized. The central frequency for the chosen set of parameters was 300 THz. We calculated spectral reflection and transmission of the structure using full 3D finite element analysis.

Our goal was to perform simulations for various values of metal and dielectric thickness, as well as for different dielectric and metal materials, in order to be able to chose the values which best suite our available experimental facilities and possibilities. The idea was first to establish general trends, then to perform calculations for real materials. Thus we first performed our calculations for

PEC (perfect electric conductor) sheets. After that we utilized the optical constants of real metals. Typically we used silver, which is more convenient than other plasmonic materials since its absorption losses in the frequency range of interest are the lowest (for instance, it is 4 times lower than in gold, which is the second best). It should be mentioned, however, that no real dispersion has been taken into account and the real part of the relative dielectric permittivity of silver was kept at 1. The imaginary part was taken into account through metal conductance, and the assumed value was $6.1\cdot 10^7$ Siemens/m. Since we operate at optical frequencies, we assumed that the relative magnetic permeability was always 1. We utilized tetrahedral finite elements and typically the sides of the elements were of the order of 1 nm.

Figs. 2-4 shows the spectral reflection of a fishnet with a PEC-dielectric-PEC sandwich where the metal thickness was d_m=5 nm (Fig. 2), d_m=10 nm (Fig. 3) and d_m=20 nm (Fig. 4). The dielectric thickness was varied as parameter. The relative permittivity of the dielectric was always ε=2. The frequency of the reflection dip shifts toward lower frequencies with the increasing thickness of the dielectric middle layer. It is also interesting to note that the dip is sharpest at some optimum dielectric thickness, which is in the case shown in Fig. 2 equal to 75 nm.

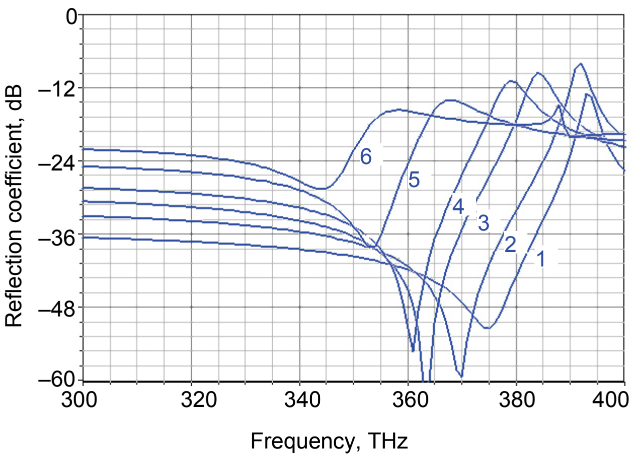


Fig. 2. Spectral reflection for a fishnet PEC-dielectric-PEC with d_m=5 nm and various values of dielectric thickness, 1) 20 nm, 2) 50 nm, 3) 75 nm, 4) 100 nm, 5) 150 nm and 6) 200 nm. Relative permittivity of dielectric ε=2.

A similar dependence is observed in Figs. 3 and 4. Fig. 3 shows the spectral reflection for the same range of dielectric layer thickness values, but the metal layer thickness is 10 nm. In Fig. 4 the metal layer thickness is 20 nm. It is seen that an increase of the metal film thickness shifts the dependence towards higher frequencies. Thus one can optimize the spectral characteristics of the structure by independently tuning the thickness of the metal and of the dielectric parts.

Fig. 5 was calculated for the case of silver top and bottom layers. The dielectric thickness was kept constant at 100 nm, and the metal sheet thickness was varied from 5 nm to 20 nm, which are realistic values for our freestanding nanomembranes.

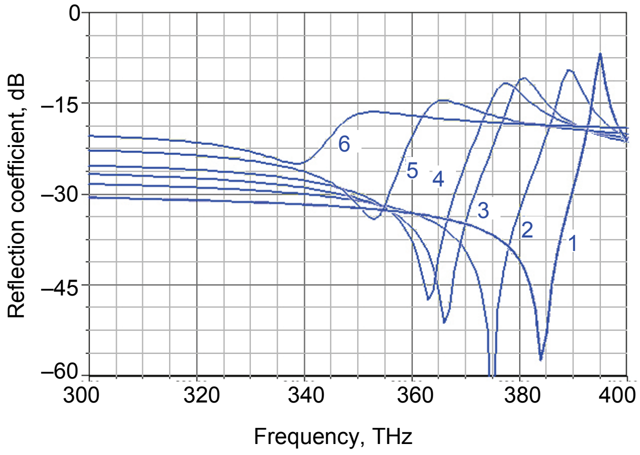


Fig. 3. Spectral reflection for a fishnet PEC-dielectric-PEC with a metal thickness d_m=10 nm and various values of dielectric thickness, 1) 20 nm, 2) 50 nm, 3) 75 nm, 4) 100 nm, 5) 150 nm and 6) 200 nm. Relative permittivity of dielectric ε=2.

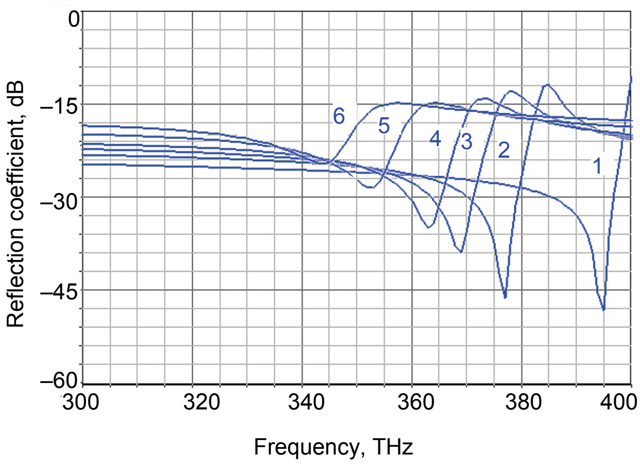


Fig. 4. Spectral reflection for a fishnet PEC-dielectric-PEC with a metal thickness d_m=20 nm and various values of dielectric thickness, 1) 20 nm, 2) 50 nm, 3) 75 nm, 4) 100 nm, 5) 150 nm and 6) 200 nm. Relative permittivity of dielectric ε=2.

The relative dielectric permittivity of the dielectric part was varied from 2 to 6. It is readily observed that higher values of dielectric permittivity tend to shift the curves towards lower frequencies; thus it appears desirable to keep the difference between the real parts of dielectric permittivity between layers at its maximum. This situation in metamaterials is hardly, since a similar condition is valid for photonic crystals, a similar class of artificial electromagnetic materials with periodically varying optical constants.

It is readily observed that the reflectance dips are much smaller and "smeared" over frequencies in the case of real metal. It is also seen that thinner metal shifts the curves towards lower frequencies.

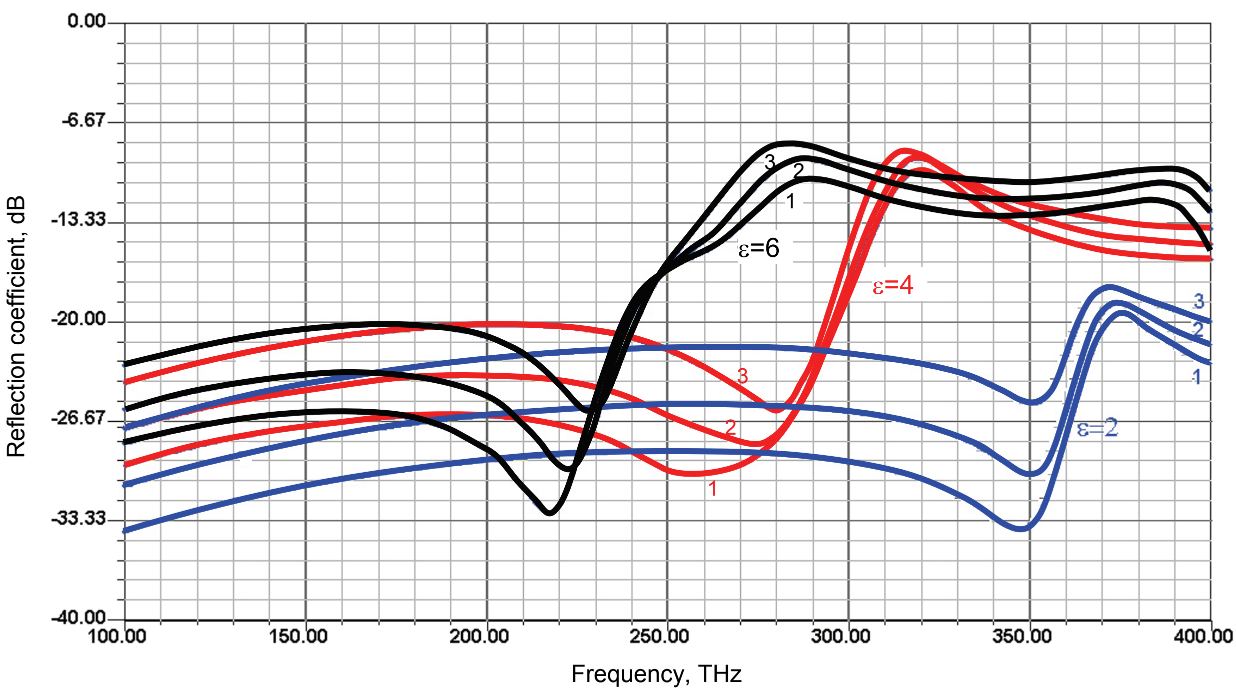


Fig. 5. Comparative diagram for a silver-dielectric-silver fishnet for various metal thickness values. 1) 5 nm, 2) 10 nm, 3) 20 nm and a dielectric thickness of d_d = 100 nm, while the relative permittivity of the dielectric is ε = 2, 4, 6.

I. Conclusion

Our simulation results show that it is feasible to utilize the nanomembranes we recently developed [15] as the basic building block for the fishnet-based LHM structures for the optical range. Parallel with the presented design and simulation calculations we started performing experiments with fabrication based on sputtering of nanomembrane precursors [15], laminar structuring of thus obtained structures using vacuum evaporation [18], while the approach chosen for the fabrication of the apertures is focused ion beam method [19]. The results of our experiments will be published elsewhere.

Acknowledgment

This work was funded by the Austrian Science Fund (FWF) within the project L521 “Metalcomposite Nanomembranes for Advanced Infrared Photonics” and by the Serbian Ministry of Science and technology within the project 11027 “Microsystem and Nanosystem Technologies and Devices”.

References

[1] V. Veselago, "The electrodynamics of substances with simultaneously negative values of ε and μ," *Sov. Phys. Uspekhi*. 10, pp. 509–514, 1968.

[2] J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart, “Magnetism from conductors and enhanced nonlinear phenomena,” *IEEE Trans. Microw. Theory Tech*. Vol. 47 pp. 2075-2081, 1999

[3] S. A. Ramakrishna, T. M. Grzegorczyk, "*Physics and Applications of Negative Refractive Index Materials*", SPIE Press, 2008

[4] J. B. Pendry, "Negative refraction makes a perfect lens," *Phys. Rev. Lett*. 85, pp. 3966–3969, 2000.

[5] N. Engheta, "An idea for thin subwavelength cavity resonators using metamaterials with negative permittivity and permeability", *IEEE Ant. Wireless Propag. Lett*. 1, pp. 10-13, 2002

[6] G. V. Eleftheriades, K. G. Balmain, "*Negative Refraction Metamaterials: Fundamental Principles and Applications*", Wiley-IEEE Press, 2005

[7] C. Caloz, T. Itoh, "*Electromagnetic Metamaterials: Transmission Line Theory and Microwave Applications*", Wiley-IEEE Press, 2005

[8] W. L. Barnes, A. Dereux, T. W. Ebbesen, “Surface plasmon subwavelength optics,” *Nature*, vol. 424, no. 6950, pp. 824–830, 2003.

[9] E. Ozbay, "Plasmonics: Merging Photonics and Electronics at Nanoscale Dimensions", *Science* 311, 5758, pp. 189 - 193, 2006.

[10] S. A. Maier, "*Plasmonics: Fundamentals and Applications*", Springer, Berlin, 2007

[11] S. Zhang, W. Fan, N. Panoiu, K. Malloy, R. M. Osgood, S. R. J. Brueck, " Experimental demonstration of near-infrared negative-index metamaterials", *Phys. Rev. Lett.* 95, pp. 137404-4, 2005.

[12] M. Kafesaki, I. Tsiapa, N. Katsarakis, Th. Koschny, C. M. Soukoulis, E. N. Economou, "Left-handed metamaterials: The fishnet structure and its variations", *Phys. Rev. B* 75 (23), 235114, 2007.

[13] G. Dolling, M. Wegener, C. M. Soukoulis, S. Linden, "Negative-index metamaterial at 780 nm wavelength", *Opt. Lett*. 32, 53-55, 2007.

[14] G. Dolling, "*Design, fabrication, and characterization of double-negative metamaterials for photonics*", Ph. D. Thesis (2007)

[15] J. Matović, Z. Jakšić, "Simple and reliable technology for manufacturing metal-composite nanomembranes with giant aspect ratio", *Microel. Eng*., 86, pp. 906-909, 2009

[16] J. Matović, Z. Jakšić, "Three-dimensional surface sculpting of free-standing metal-composite nanomembranes", *Proc. 35th Internat. Conf. on Micro and Nanoengineering MNE 09*, Ghent, Belgium, Sep. 28 – Oct 1, 2009, P-NANO-99, pp. 1-2.

[17] Z. Jakšić, J. Matović, "Coupling between propagating and evanescent modes in freestanding nanomembrane-based plasmon sensors using surface sculpting", *3rd Vienna International Conference Nano-Technology – VIENNANO'09*, March 18-20, 2009, Vienna, Austria, pp. 187-194

[18] Z. Jakšić, D. Tanasković, J. Matović, "Fishnet-based metamaterials: spectral tuning through adsorption mechanism", Acta Physica Polonica A, Accepted for publication, 2009.

[19] J. Matović, J. Kettle, E. Brousseau, N Adamovic, "Patterning of Nanomembranes with a Focused-Ion-Beam", *Proc. 26th Internat. Conf. on Microelectronics (MIEL 2008)*, Niš, 11-14 May, 2008, vol. 1, pp. 104-108.