FRESNEL LENS-TYPE ENERGY CONCENTRATOR FOR SPACE-BASED SOLAR POWER SYSTEMS

V. SERGENTU[1], V. URSAKI[2*], A. IOISHER[3], E. ADAR[3**]

[1]Institute of Applied Physics, Academy str. 5, MD-2028 Chisinau, Moldova,
E-mail: vsergentu@yahoo.com
[2]Institute of Electronic Engineering and Nanotechnology "D. Ghitu",
Academy str. 3/3, MD-2028 Chisinau, Moldova,
[*]*E-mail*: vvursaki@gmail.com
[3]WMT-Wire Machine Technologies, 12 Ha'ilan St, POB 203, Or Akiva, 30600, Israel

Received July 24, 2018

Abstract. In this paper a new concept of designing Fresnel lens concentrators on the basis of magnetic microwires with a complex spatial distribution of their density is proposed. The optical properties of microwires are analyzed in terms of their scattering indicatrix, and the design of the lens in the form of a sandwich consisting of two discs with concentric rings with current running inside and the microwires confined in between the discs is discussed. It is shown that such a design allows one to ensure the configuration of a complex spatial distribution of microwires and their effective control by changing the currents in the system. A comparative analysis is performed for microwires with diamagnetic, paramagnetic and ferromagnetic core.

Key words: Space-based solar power (SBSP) system, solar concentrator, Fresnel lens, magnetic microwire, scattering indicatrix, diffraction pattern, light spot on the target.

1. INTRODUCTION

The concept of Space-based solar power (SBSP) systems has been in research since the early 1970s [1, 2]. SBSP systems consists essentially of five functional units: (i) a solar energy collector to collect solar power in space, for example *via* solar concentrators, (ii) a solar cell or a heat engine to convert the solar energy into electricity, (iii) a unit to convert electricity to microwave or laser radiation, (iv) a large antenna array to beam the microwave power to the ground, and (v) a unit receiving power on earth, for example *via* microwave antennas called Rectenna. A variety of solar energy concentrator concepts have been proposed, such as an integrated symmetrical concentrator (ISC) using a two-dimensional mast to realize sun-tracking [3], an arbitrarily large phased array (ALPHA), which comprises a large number of individually pointed thin-film reflectors to intercept sunlight [4], a spherical solar power collector (OMEGA) [5], a concentrator based on zero-index metamaterial (ZIM) called Thin-film Energy Terminator (SSPS-TENT) [6], and a spherical condenser made of ε-near-zero (ENZ) metamaterial [7], to name a few.

[**] on issues of practical implementation please contact WMT director: adar@wmt-m.com

These concepts have many advantages, but also some drawbacks. For instance, multi-thousand-ton structure of the ISC project is difficult to control precisely in space [3]. The real-time adjustment of the thousands of reflectors in the ALPHA project is also an open problem [4]. To solve some of these problems, refractive property of a ENZ metamaterial are used to capture the sunlight and to redirect it to the center of the spherical condenser [7]. The SSPS-TENT concept using a concentrator made of metamaterials with properties of redirecting the energy propagation direction solves the problem of sun-tracking control with a large sunlight-collecting non-moving structure and a small-sized flexible reflector [6].

We propose in this paper to create a cosmic Fresnel lens in the Geostationary Earth Orbit on the basis of a cloud from pieces of glass-coated cast microwires with the core from magnetic materials. Fresnel thin film reflectors/concentrators have been previously proposed in the “Sun Tower” SBSP concept [8].

The microwire is a product of modern technologies that fully combines the mechanical, electrical, magnetic and optical properties necessary for materials used in outer space. One should note that there is some experience with placing metallic needles in the space. In 1963 a package containing 4.8×10^8 copper dipoles, each 1.8×10^{-5} m in diameter and 0.018 m in length, was placed into a nearly circular, nearly polar orbit at a mean altitude of 3650 km for the purpose of improving US military communications within a NASA Project West Ford (also known as Westford Needles or Project Needles) [9]. The experiment was only partially successful, since the needles were scattered due to mutual electrostatic repulsion as a result of charging effects of the electrons from the solar wind.

As compared to needles used in the West Ford Project, the cast microwires pieces used in our Fresnel lens are covered by glass insulation. Apart from that, they can be additionally coated with aluminum films. The configuration of the produced “lens” can be controlled by means of assemblies of concentric rings with electrical current, as described in section 3.

2. OPTICAL PROPERTIES OF MICROWIRES

First of all we will consider the optical properties of pieces of cast microwire in glass insulation. A medium with microwire particles will exhibit properties of a composite which requires taking into account the phenomenon of light scattering on inhomogeneities. For the calculation of the photon mean free path in the medium we will apply the scalar theory of the electromagnetic field for the complex amplitude A [10] on the basis of the following equation:

$$\Delta A + \varepsilon k^2 A = 0 \tag{1}$$

where the values of ε and A depend upon the spatial coordinates, $k = 2\pi/\lambda$ is the wave number of the radiation, and λ is the wavelength.

The mean free path l is a characteristic length that indicates the possible limiting values of some of the geometric dimensions of the lens. Further we will use the following equation for the photon mean free path in the direction perpendicular to the axis of cylindrical microwires, *i.e.* in fact for a two-dimensional configuration [11]:

$$l = 1/\sigma_{tr} n \tag{2}$$

where

$$\sigma_{tr} = \frac{2\lambda}{\pi} \sum_{m=-\infty}^{m} [|D_m|^2 - real(D_m^* D_{m-1})] \tag{3}$$

is the scattering cross-section of the microwire unit length in the direction perpendicular to the axis. This value is the scattering cross-section of a cylinder (microwire) unit length.

The two-dimensional concentration of microwire particles is as follows:

$$n = 1/d^2 \tag{4}$$

where d is the mean distance between the microparticles.

We will use the equations from ref. [12] modified for the case of the scalar theory for the determination of the D_m parameters. Figure 1 presents the scattering indicatrix in the case when the radiation is incident in the direction perpendicular to the axis of a microwire with a magnetic core with the diameter of 15 μm and a shell of glass insulation with the thickness of 20 μm and the refractive index $n = 1.5$, covered by an aluminum coating with the thickness from 0 to 3 μm. We will use the value of $n = 0.5$ for the magnetic core, and will not take into consideration the absorption, since its electrical resistivity is high. The value of the complex refractive index of the Al coating is taken from ref. [13]. The scattering indicatrix is plotted for the values of *log*(*I/min*(*I*)), in order to be able to analyze the relationship between the intensities of radiation scattered forward and the rest of the radiation. The common indicatrix $I = I(\varphi)$ is the angular dependence of scattered light intensity for a singular microwire.

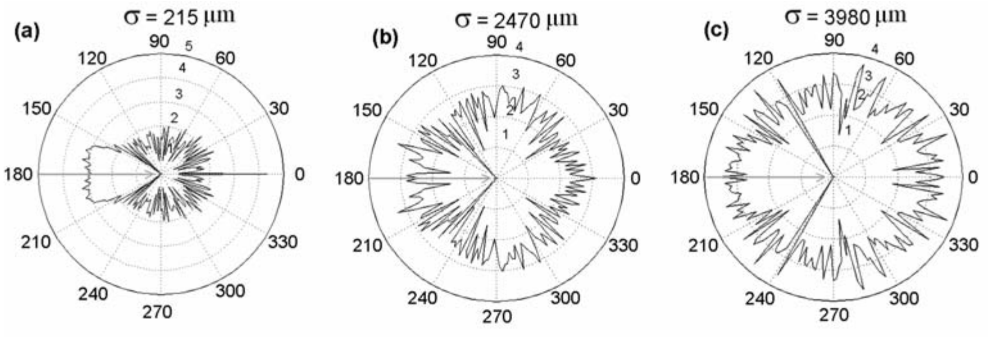

Fig. 1 – Scattering indicatrix for a microwire described in the text, with the Al coating thickness of 3 μm (a), 0.3 μm (b), and 0 μm (c).

One can see that, in the case of a thick Al coating, the backscattering and the strictly forward scattering predominates. The scattering passing through the screen contains a large part of the so called “snake” radiation [14, 15]. The medium composed of such a microwire can be used for creating a screen which is semitransparent for the radiation. Such a medium can be used for designing a big size diffraction lens. For the microwire without Al coating the scattering cross-section is larger as compared to a coated microwire. Apart from that, along with the strictly forward scattered radiation there is a significant scattering in different directions with respect to incident radiation [16, 17]. The selection of the main optical parameters is carried out for the wavelength of the light which gives the greatest contribution to the solar light intensity, *i.e.* $\lambda \approx 0.4$ μm.

3. DESIGN OF FRESNEL LENS ON THE BASIS OF MICROWIRES

Fresnel lenses are complex composed optical devices which are used in various fields [18]. We propose to assemble such a lens from concentric rings of microwires with various densities (Fig. 2a).

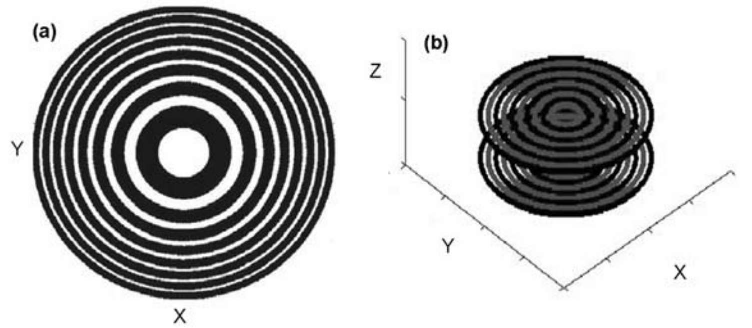

Fig. 2 – (a) A Fresnel lens assembled from concentric rings of microwires with various densities. (b) Design of a lens with concentric rings with current running inside for confining the magnetic microparticles.

The Fresnel diffraction equation, according to which the diffraction pattern is observed at a big, but finite distance L from the aperture or the diffracting object, is used for the calculation of lens parameters.

The physical system possesses cylindrical symmetry, therefore we will use further the cylindrical coordinate system (ρ, φ, z). The lens axis coincides with the z-axis, while its parameters are independent on φ. We will consider the lens as a two dimensional optical mask in our further calculations [10, 19]. Then, at a normal incidence of a plane wave on the lens, the amplitude behind $A(\rho, L)$ is generally a complex function of ρ. The Fresnel integral is expressed as [20]:

The main parameter of the system

$$A(\rho,L)=-[ik/2L\pi]\int_S d^2\rho' A(\vec{\rho}\,',0)\exp[i\,|\vec{\rho}-\vec{\rho}\,'|^2\,k/2L] \tag{5}$$

The main parameter of the system

$$K(\lambda,L)=\sqrt{k/L}=\sqrt{2\pi/L\lambda} \tag{6}$$

has the numeric value of $K \approx 100\ \mathrm{m}^{-1} = 1\ \mathrm{cm}^{-1}$ at the distance $L = 1$ km and $\lambda = 0.4$ μm.

By substituting the parameter L under the integral sign one obtains:

$$A(\rho,L)=-[iK^2/2\pi]\int_S d^2\rho' A(\rho',0)\exp[i\,|\vec{\rho}-\vec{\rho}\,'|^2\,K^2/2] \tag{7}$$

here

$$A(\rho,0)=S(\rho)\cos(W^2\rho^2/2)^2 \tag{8}$$

is the wavefront of the radiation formed behind the lens, which is represented as a periodic function of ρ^2 (the W quantity has units of the wave vector). The factor of

$$S(\rho)=\exp[-(\rho/R)^2]\,|_{R>>1/K} \tag{9}$$

allows one to take into account the influence of limited sizes of the lens R ~ 100 m upon the wave field formation process in the space behind the lens.

As a result of calculating the integral (7) taking into account the Eqs (8) and (9) one obtains the following equation [21]:

$$A^{(K)}(\rho,L)=-(\pi/4)\exp(i\rho^2K^2/2)\left[\begin{array}{l}\dfrac{iK^2/4\pi}{1/R^2-iK^2/2}\exp\left(-\dfrac{\rho^2K^4}{4(1/R^2-iK^2/2)}\right)+\\+\dfrac{iK^2/4\pi}{1/R^2+i(\pm W^2-K^2/2)}\exp\left(-\dfrac{\rho^2K^4}{4(1/R^2+i(\pm W^2-K^2/2))}\right)\end{array}\right] \tag{10}$$

We propose a design of the lens with concentric rings with current running inside (Fig. 2b). The lens is constructed of two discs consisting of such rings. The directions and values of currents in rings placed symmetrically with respect to the plane of symmetry (*i.e.* the middle between the discs) are the same, while the directions of the currents in neighboring rings of a disk (marked with different colors in Fig. 2b) are opposed to each other. In such a case, the magnetic field in the plane of symmetry (at $z = 0$) will be directed parallel to this plane and will change according to the Eq. (8) as a function of the distance from the center of the system. With such a configuration of currents, the fields controlling the magnetic particles will orient the microparticles predominantly in the direction perpendicular to the incident radiation. Apart from that, the magnetic fields will be concentrated exclusively inside the system, and will prevent the exit of the microwires into the open space. Such a design will allow one to create the necessary spatial distribution of microwires in the space, and will effectively control them by changing the value, the direction, and other characteristics of currents in the rings. The calculations of the magnetic fields were carried out by using the equations from ref. [22] for a ring with current. A calculated distribution of the magnetic field in the plane situated in the middle between the two discs, *i.e.* in the plane A-A oriented perpendicularly to the direction of incident radiation, is shown in Fig. 3a. The red color corresponds to high values of the field, while the blue color is for low values. However, apart from rings with high values of the magnetic field in this plane, regions with even higher magnetic fields will be concentrated around each of current conductor constituting the rings, as schematically illustrated in Fig. 3b. The direction of the current in conductors colored in yellow and labeled as "*a*" is opposed to that in conductors colored in green and labeled as "*b*". The dependence of the magnetic field at the surface of a current conductor (curve 1) and between the current conductors (curve 2) as a function of current is shown in Fig. 4.

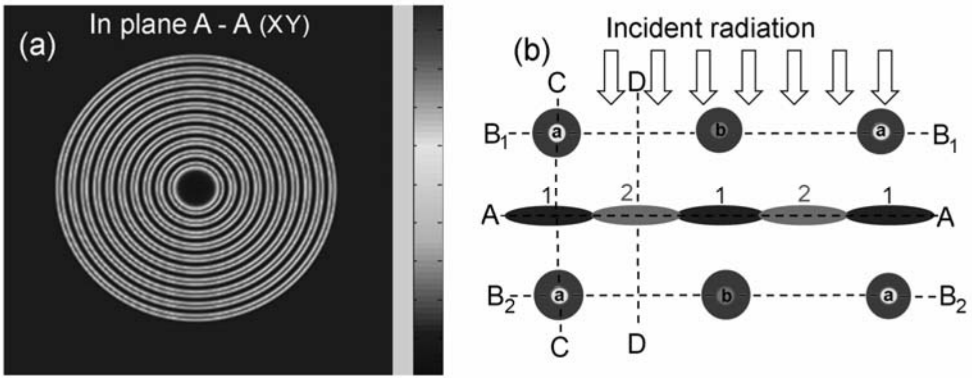

Fig. 3 – (a) Calculated configuration of the magnetic field within the lens in the plane of symmetry A–A perpendicular to the direction of incident radiation. (b) Schematic representation of several conductors in the cross section of rings forming the two disks. The direction of the current in conductors colored in yellow and labeled as "a" is opposed to that in conductors colored in green and labeled as "b". The red color corresponds to high values of the magnetic field (the darker the color, the higher the field). The blue color corresponds to low values of the magnetic field (color online).

The real spatial distribution of the magnetic field around the current conductors, in between them, and outside the two discs calculated for the schematic representation of Fig. 3b (*i.e.* in the plane perpendicular to the plane of symmetry and passing through the center of the system) for a value of the current of 1 A is shown in Fig. 5. The red spikes correspond to the locations of current conductors, while the blue color is for the outside of the two discs, *i.e.* upper than the first row of conductors ($B_1 - B_1$) in Fig. 3b and lower than the second row of conductors ($B_2 - B_2$). One can see from Fig. 5, that potential wells with low values of the magnetic field are also formed in between the two discs.

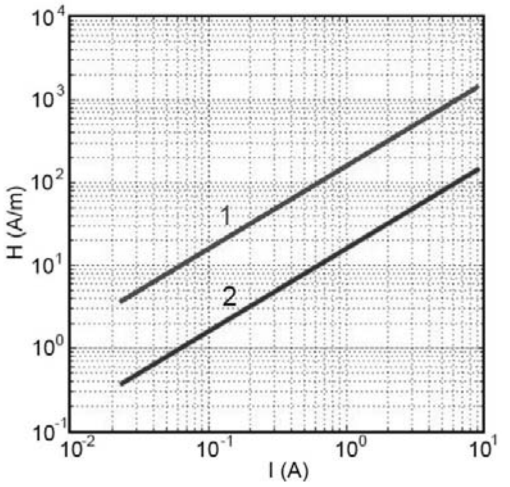

Fig. 4 – Dependence of the magnetic field at the surface of a current conductor (curve 1) and between the current conductors (curve 2) as a function of current.

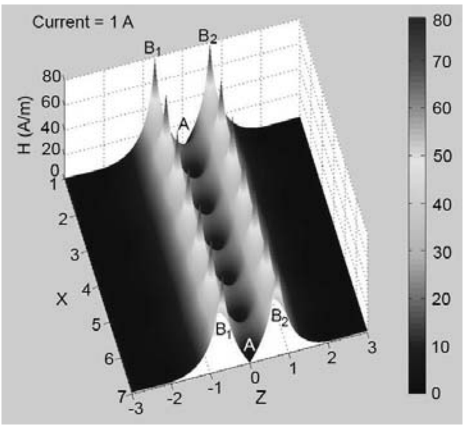

Fig. 5 – Calculated spatial distribution of the magnetic field in the system schematically illustrated in Fig. 3b for a value of the current of 1 A. The red spikes correspond to the locations of current conductors, while the blue color is for regions with low value of the magnetic field.

For the sake of clarity, in Fig. 8a the distribution of the magnetic field in the direction $B_1 - B_1$ and $B_2 - B_2$ is presented by curve 1, while the distribution of the field in the direction A – A is shown by curve 2. Apart from that, the distribution of the magnetic field in the direction marked as C – C in Fig. 3b is presented by curve 1 in Fig. 6b, while the distribution of the field in the direction D – D is shown by the curve 2.

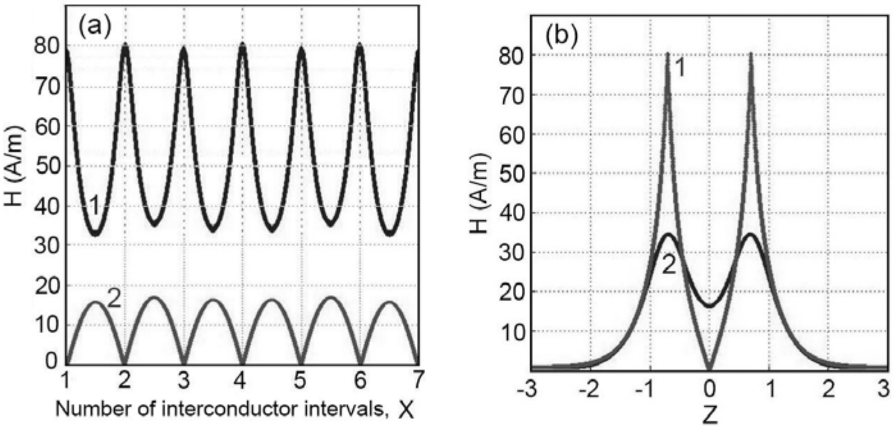

Fig. 6 – (a) Distribution of the magnetic field in the direction $B_1 - B_1$ and $B_2 - B_2$ (curve 1), and in the direction A – A (curve 2) for the schematic representation of Fig. 3b.
(b) Distribution of the magnetic field in the direction C – C (curve 1) and in the direction D – D (curve 2).

The spatial distribution of microwires in such a system will depend on the magnetic properties of the material of the microwire core. Note that the optical properties of microwires were discussed in the previous section of the paper. The potential energy E of a magnetic microwire dipole in a magnetic field is given by the following formula:

$$E = -dB = -\mu_0[\mu - 1]H^2V \tag{11}$$

where μ is the magnetic permeability of the microwire, V is its volume, and H is the external magnetic field.

If the core is made of a diamagnetic material with $\mu_r < 1$ (for instance of Bi), then the microwires will be expelled from regions with high values of the magnetic field and pushed to regions with low values of the field, *i.e.* they will be concentrated in regions marked as “1” in Fig. 3b, and will form concentric rings with high density of microwires in the plane perpendicular to the direction of incident radiation. The specific potential energy E/V of a Bi microparticle as a function of the external magnetic field is shown in Fig. 7. In such a case, the system will be suitable for designing Fresnel lenses. However, one should discuss the issue of ionizing the microparticles in the space. According to ref. [23], each microparticle with a size around 10 μm is subjected in orbit to one impact per month with particles from the magnetosphere (electrons, protons, etc) with energy E~1 MeV. This is not enough to significantly change the kinetic energy, but it is enough to ionize the microparticle [24]. The energy of interaction of diamagnetic microparticles with the magnetic field in the system is quite low, which implies the danger for microparticles to escape in the free space. We propose to create an additional electrical potential on the conducting rings with respect to the surrounding magnetosphere (the cosmic plasma in the geostationary orbit) for discharging the undesirable electrostatic charge. We mean surrounding magnetosphere is the one situated at a distance from our system much larger than its Debye length λ_D~100 m.

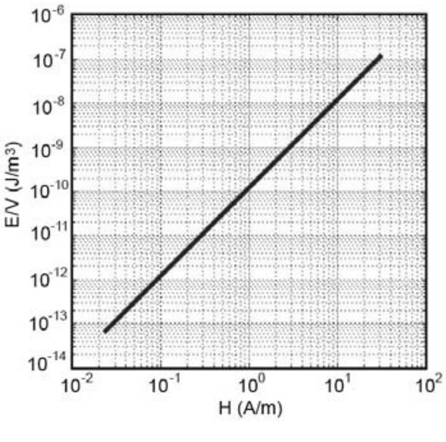

Fig. 7 – Specific potential energy *E/V* of a Bi microparticle as a function of the external magnetic field.

Therefore, Bi microwires are basically suitable for designing Fresnel lenses. Note that Bi microwires have been produced previously [25]. However, the Bi microwires are rather fragile, *i.e.* they are difficult to implement from the technological point of view of the capillary drawing process [26, 27].

If the core is made of a paramagnetic material with $\mu_r > 1$, then the microwires will tend to regions with high values of the magnetic field, *i.e.* they will stuck to the conductor rings. It means that such microwires are not suitable for producing lenses. Much more possibilities for designing Fresnel lenses could be provided by microwires with ferromagnetic cores. For a ferromagnetic material the magnetic flux density (B) is not a linear function of the magnetizing force (*H*), but it tends to saturation with increasing the magnetizing force, as shown in Fig. 8a for a typical ferromagnetic material. The relative permeability μ_r of such a material as a function of the magnetic field strength *H* will have a maximum at a certain value of the field strength $H(\mu_{rmax})$, as shown in Fig. 8b for Permalloy and for Armko iron. Apparently, in such a case, the microwires should tend to occupy spatial regions with that $H(\mu_{rmax})$ value of the magnetic field strength. Then, by adjusting the currents in the conductor rings "*a*" and "*b*", one could create conditions that the specified values of the field strength $H(\mu_{rmax})$ for a given material of the microwire core is reached in regions marked as "2" in Fig. 3b. Such a system could work again as a Fresnel lens, but with much more possibilities for designing as compared to the case of using microwires with cores of diamagnetic materials. However, there is a very slow decrease of the $\mu_r(H)$ function with increasing the magnetic field strength beyond the $H(\mu_{rmax})$ value, as deduced from Fig. 8. As a result, since according to formula (11) the potential energy is proportional to H^2, the value of the magnetic field, for which a minimum of the potential energy could be created, is shifted to very high value, or even no potential well exists. It means that the ferromagnetic microparticles will stuck again to the conductor rings similarly to paramagnetic ones. According to the analysis of literature data, there are no ferromagnetic material with a sharp decrease or the magnetic permeability beyond the $H(\mu_{rmax})$ value, which could be suitable for designing Fresnel lenses.

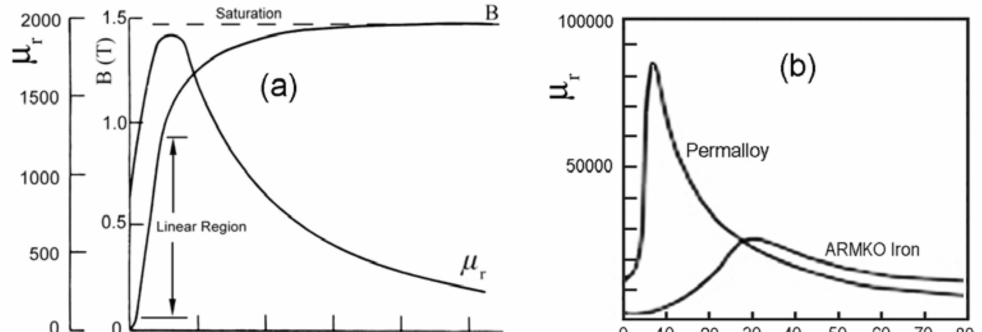

Fig. 8 – (a) The magnetizing curve of a ferromagnetic core and variation in permeability μ_r with B and H. (b) Relative permeability of Permalloy and ARMKO iron as a function of the field strength H.

To overcome these circumstances, we propose to make use of the Joule effect in the case of ferromagnetic microparticles, according to which the length of magnetic microparticle core placed in a magnetic field will change in correspondence with the following formula [28]:

$$\gamma(H) = \gamma_{\max}[1 - \exp(-x^2)] \tag{12}$$

where γ is the relative change of the length, x is a dimensionless quantity $x = M(H)/M_s$, $M(H) = [B(H) - \mu_0 H] / \mu_0$ is the magnetization, and M_s is the saturation magnetization.

Then, the total potential energy E (the energy of the magnetic dipole and the energy of elastic deformation) equals to:

$$E = V\{-\mu_0[\mu(H) - 1]H^2 + \gamma(H)^2 G\} \tag{13}$$

where $G \sim 10^{11}$ J/m^3 is the mean Young's modulus of the system (the glass envelope will also be subjected to deformation).

For estimative calculations (Fig. 9) we used formulae from ref. [29] with the following parameters $H_{\max} = 1$A/m, $\mu_{\max} = 10^4\mu_0$, $B_s = 2$T.

One can deduce from Fig. 9 the following:

- microparticles will stuck to conducting rings in the absence of deformation ($\gamma_{\max} \equiv 0$), since states with lower energies will correspond to large magnetic field on the surface of current conductors;
- microparticles should not stuck to conducting rings when there are deformations (at $\gamma_{\max} = 10^{-3}$), since states with lower energies will correspond to lower magnetic field in the regions between the current conductors;
- The potential barriers restraining (confining) the ferromagnetic microparticles are several orders of magnitude higher than in the case of Bi diamagnetic microparticles.

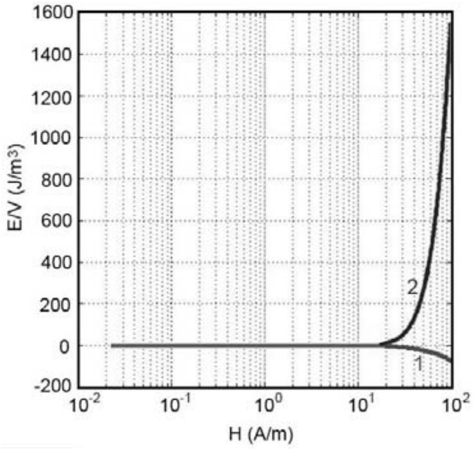

Fig. 9 – Calculated curves of the total specific energy (E/V) of a ferromagnetic microparticle in the absence of deformation $\gamma_{\max} \equiv 0$ (curve 1), and with a deformation of $\gamma_{\max} = 10^{-3}$ (curve 2). The parameters of the microparticles are as follows: $H_{\max} = 1$A/m, $\mu_{\max} = 10^4\mu_0$, $B_s = 2$T.

This analysis suggests that microwires with ferromagnetic magnetostrictive cores are more advantageous for designing Fresnel lenses than diamagnetic ones.

Finally, we will refer to possibilities of optimizing the number of rings constituting the Fresnel lens. The number of rings in Eq. (8) is given by the quantity $N = (RW)^2/2\pi$. However, one has to take into account that one deals with the solar radiation with inherent spatial dispersion, since the solar disc has a finite angular size of $\alpha \approx 0.01$. As a result, the size of the light spot on the target cannot be in any case less than

$$Q \cong \alpha L \tag{14}$$

Therefore, at $K >> 1/R$ one can neglect the first term in Eq. 10, as well as the second term with the sign "–" in the denominator. Then, the mean linear size of the light spot on the target will be as follows:

$$\begin{aligned} Q &= \sqrt{\int | A^{(K)}(\rho, L)|^2 \rho^2 d^2\rho / \int | A^{(K)}(\rho, L)|^2 d^2\rho} \approx \\ &\approx \sqrt{4[1/R^4 + (W^2 - K^2/2)^2]/(K^4/R^2)} = \alpha L \end{aligned} \tag{15}$$

Therefore, one can use the following values of the W quantity:

$$W \approx K\sqrt{(1-\alpha L/R)/2} \tag{16}$$

It means that one can decrease the value of W without losing the performance of the lens. Accordingly, one can reduce the number of rings N constituting the lens. These findings suggest that it is possible to simplify the design of the lens, which is extremely important for assembling a lens in the space.

4. CONCLUSIONS

The results of this study demonstrate that magnetic particles in the form of microwires can be used for the creation of large lenses in the space. The main issue to be addressed for this purpose is the formation of a complex spatial distribution of microwires density. The analysis of optical properties of cast microwires in glass insulation in terms of their scattering indicatrix suggest that they are suitable for designing Fresnel lenses provided a complex spatial distribution of microwires density in the form of concentric rings is achieved. On the other hand, the needed spatial distribution of microwires can be formed with microwires containing a magnetic core susceptible to a specific configuration of magnetic field. The calculations of magnetic fields in a sandwich structure consisting of two discs each of them being constructed from current conductors in the form of concentric rings demonstrate that similarly configured concentric rings with alternating high and low values of the magnetic field can be obtained in the plane of symmetry in between the two discs. In such a case, microparticles with specific magnetic properties can be confined in these circular regions, and this confinement is effectively controlled by changing the currents in the current conductors system. Therefore, such a design allows one to ensure the configuration of a complex spatial distribution of microwires. A comparative analysis performed for microwires with diamagnetic, paramagnetic and ferromagnetic cores shows that the microwires with cores made of paramagnetic materials will stuck to the conductor rings and they are not suitable for designing Fresnel lenses. On the other hand, concentric rings with high and low density of microwires will be formed at appropriate currents adjustment in the system with microwires made of diamagnetic or ferromagnetic materials. Therefore, the microwires with diamagnetic or ferromagnetic cores are suitable for producing Fresnel lenses, but ferromagnetic materials provide wider possibilities for designing as compared to diamagnetic ones, if their ferromagnetic properties are combined with magnetostrictive properties according to the Joule effect. Another important finding is related to the possibility to reduce to some extent the number of rings constituting the Fresnel lens without losing its performance, and therefore to simplify its design.

Acknowledgments. This work was supported by the Academy of Sciences of Moldova under Grants Nos. 15.817.02.04A and 15.817.02.08A.

REFERENCES

1. A. Anveshi, IOSR-JESTFT, Special issue **1(5)**, 01–03 (2015).
2. G. A. Landis, *Solar Power Satellites*. In: A. Sayigh, (ed.) *Comprehensive Renewable Energy*, vol 1, Oxford: Elsevier 767–774, 2012.
3. J. C. Mankins, Acta Astronautica **41**, 347–359 (1997).
4. J. R. Glaese, E. J. McDonald, *Space Solar Power Multi-Body Dynamics and Controls, Concepts for the Integrated Symmetrical Concentrator Configuration*, NASA Report Contract NAS8-00151, Bd Systems Inc., Huntsville, Alabama, 2000.
5. J. C. Mankins, *SPS-ALPHA: The First Practical Solar Power Satellite via Arbitrarily Large Phased Array*, NASA Report NIAC Project, Artemis Innovation Management Solutions LLC, Santa Maria, California, 2012.
6. Y. Yang, Y. Zhang, B. Duan, D. Wang, X. Li, Acta Astronautica **121**, 51–58 (2016).
7. X. Li, B. Duan, L. Song, Y. Yang, Y. Zhang, D. Wang, Acta Astronautica **136**, 182–189 (2017).
8. J. Huang, X.-M. Chu, J.-Y. Fan, Q.-B. Jin, Z.-Z. Duan, Adv. Space Res. **59**, 1460–1472 (2017).
9. I. I. Shapiro, H. M. Jones, C. W. Perkins, Proc. IEEE **52**, 469–518 (1964).
10. S. M. Rytov, Yu. A. Kravtsov, V. I. Tatarskii, *Principles of Statistical Radiophysics 4: Wave propagation through random media*, Springer-Verlag, Berlin Heidelberg, 1989.
11. K. Busch, C. M. Soukoulis, E. N. Economou, Phys. Rev. B **50**, 93–98 (1994).
12. X. Zhang, L.-M. Li, Z.-Q. Zhang, C.T. Chan, Phys. Rev. B **63**, 125114 (2001).
13. V. M. Zolotarev, V. N. Morozov, E. V. Smirnova, *Optical constants of natural and technical media* (in Russian) Leningrad, Khimiya, 1884.
14. M. Gu, X. Gan, D. Xiaoyuan, *Microscopic Imaging Through Turbid Media: Monte Carlo Modeling and Applications*, Springer, Berlin Heidelberg, 2015.
15. K. M. Yoo, B. B. Das, F. Liu, R. R. Alfano, in *Medical Optical Tomography: Functional Imaging and Monitoring*, G. Müller *et al.*, eds., SPIE, vol. IS **11**, 425–448, 1993.
16. S. Argon, R. Sergio, J. Chem. Phys. **73**, 1576–1580 (1980).
17. J. C. Ravey, J. Chem. Phys. **59**, 5221 (1973).

18. A. Rajkrishna, J. Fundam. Renewable Energy Appl. **6**, 205 (2016).
19. N. George, *Fourier optics*, University of Rochester, New York, 2012.
20. J. D. Jackson, *Classical Electrodynamics*, Wiley, New York, 1998.
21. I. S. Gradshteyn, M. Ryzhik, *Tables of Integrals*, Series, and Products, 6th edition, A. Jeffrey and D. Zwillinger, eds. Academic Press, Orlando, Florida, 2000.
22. L. D. Landau, E. M. Lifshitz, L. P. Pitaevskii, *Electrodynamics of Continuous Media*, Butterworth-Heinemann, Oxford, 1984.
23. I. P. Bezrodnyh, E. I. Morozova, A. A. Petrukovich, S. G. Kazantsev, V. T. Semenov, Voprosy Elektromehaniki (in Russian) **117**, 33–42 (2010).
24. E. K. Kolesnikov, Cosmic Research 39, 92–97 (2001).
25. D. Gitsu, T. Huber, L. Konopko, A, Nikolaeva, Proc. 25th Int. Conf. Thermoelectrics, 238–241 (2006).
26. E. Badinter, A. Ioisher, E. Monaico, V. Postolache, I.M. Tiginyanu, Materials Lett. **64**, 1902–1904 (2010).
27. A. M. Ioisher, E. Ya. Badinter, V. Postolache, E. V. Monaico, V. V. Ursaki, V. V. Sergentu, J. Nanoelectron. Optoelectron. **7**, 688–695 (2012).
28. A. G. Olabi, A. Grunwald, *Design and Application of Magnetostrictive "MS" Materials*, Dublin City University.
29. I. V. Pentegov, A. V. Krasnojon, Elektrotehnika i Electromehanika (in Russian) no. 1, 66–70 (2006).