THE PUBLISHING HOUSE
OF THE ROMANIAN ACADEMY

PROCEEDINGS OF THE ROMANIAN ACADEMY, Series A,
Volume 20, Number 2/2019, pp. 151–157

SOLAR ENERGY CONCENTRATORS IN GEOSTATIONARY ORBITS

Vladimir SERGENTU[1], Veaceslav URSAKI[2,*], Anatolii IOISHER[3], Eliezer ADAR[3]

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

Abstract. An important component of Space-based solar power (SBSP) systems is the solar energy concentrator that collects solar power in space and focusses it on solar cells or heat engines to produce electricity, which is consequently beamed to the earth by means of microwave or laser radiation. A variety of solar concentrator concepts proposed up to now are briefly reviewed in this paper, such as an integrated symmetrical concentrator (ISC), an arbitrarily large phased array (ALPHA), a spherical solar power collector (OMEGA), a thin-film energy terminator (TENT) concentrator based on zero-index metamaterial (ZIM), and a spherical condenser made of ε-near-zero (ENZ) metamaterial. A special attention is paid to a new concept proposed recently for designing Fresnel lens concentrators on the basis of magnetic microwires with a complex spatial distribution of their density. Methods of achieving relevant configurations of microwires density are discussed in connection with variations of their magnetic properties.

Key words: space-based solar power (SBSP) system, solar concentrator, Fresnel lens, magnetic fields, magnetic microwires, diamagnetic, paramagnetic, and ferromagnetic microparticles.

1. INTRODUCTION

The issues of the gradual reducing of the fossil fuels combined with environmental concerns impose stringent needs for the development of alternative energy resources. One of the global solutions of this problem would be a progress with the controlled thermonuclear fusion. However, the hard conditions imposed by the figure of merit [1,2], *i.e.* the "triple product" of density, confinement time, and plasma temperature, results in a low feasibility of any known thermonuclear fusion reactions for now. Therefore, these problems are far from being solved at the moment, in spite of considerable efforts and investment spent [3-5], even taking into account a recent communication from the Massachusetts Institute of Technology (MIT) and Commonwealth Fusion Systems (CFS) in Cambridge about discovering a new class of super high-temperature superconductors and small, ultra-powerful magnets, which would strengthen the magnetic field to hold the fusion reaction in place without it touching anything solid – thus solving the meltdown problem [6].

Wind, water, and solar are alternative renewable energy sources [7]. Among other renewable energy sources, solar photovoltaic plants, for instance, can operate without much of operation and maintenance costs as compared to conventional power technologies [8]. Apart from that, they can also reduce the use of grid electricity during the peak hours, and do not require extensive power line construction, which is especially important for remote sites. However, an important drawback of photovoltaic plants and other renewable energy technologies as compared to traditional energy generation is their inherent instability and limited possibilities to control the output, which depends on the weather and climatic conditions [8]. The solar energy cannot be collected during the night. This drawback can be overcome if the solar harvesting system is placed into the space.

Space-based solar power (SBSP) systems convert sunlight to microwaves or laser radiation outside the atmosphere, avoiding these losses, and the downtime due to the Earth's rotation. In geosynchronous orbit, i.e. 36,000 km, a Solar Power Satellite (SPS) would face the sun over 99% of the time, except for few days at spring and fall equinox when the satellite would be in shadow. The concept of SBSP collecting has been in research and has been gathering momentum since the early 1970s [9,10]. 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. It was shown that a hybrid laser-microwave system is a more appropriate means of transmitting power to earth [11]. Such a system uses laser power transmission in space to a receiver high in the atmosphere that relays the power to Earth by microwave power transmission. Such hybrid systems have the advantages of a reduction in the mass of equipment required in geostationary orbit and avoidance of radio frequency interference with other satellites and terrestrial communications systems, as compared to pure microwave power transmission from the one hand, and the advantage of avoiding absorption in atmosphere and outages due to clouds and precipitation, as compared to purely laser power beam transmission on the other hand.

The main major problem of developing SBSP systems is the high costs of putting the required materials in orbit. In 1997, NASA conducted a "Fresh Look" feasibility study, which revealed that SBSP are feasible provided the costs of earth to orbit transportation are driven down dramatically [12]. Some of the key issues associated with cost-competitive space solar power in terrestrial markets, and some relevant SBSP concepts have been later-on introduced, see for instance Ref. [13]. Nowadays, with the emergence and remarkable evolution of SpaceX, Blue Origin and other private aerospace companies, the SBSP activities are expected to gain new momentum. Particularly, SpaceX launched its 50th Falcon 9 rocket, and is on track for a record-breaking 30 missions in 2018.

We will focus in this paper on the first of the above mentioned elements of a SBSP system – *i.e.* on the development of solar energy concentrators.

2. CONCEPTS OF COSMIC SOLAR ENERGY CONCENTRATORS

A variety of solar energy concentrator concepts have been proposed, such as an integrated symmetrical concentrator (ISC) (Fig. 1a) using a two-dimensional mast to realize sun-tracking [14], an arbitrarily large phased array (ALPHA) (Fig. 1b), which comprises a large number of individually pointed thin-film reflectors to intercept sunlight, mounted on the non-moving structure [15], a spherical solar power collector (OMEGA) (Fig. 1c) [16], a concentrator based on zero-index metamaterial (ZIM) called Thin-film Energy Terminator (SSPS-TENT) (Fig. 1d) [17], and a spherical condenser made of ε-near-zero (ENZ) metamaterial (Fig. 1e) [18], to name a few.

ISC uses large, symmetrically placed off-axis parabolic reflectors, which concentrate the light on the focal plane where the PV cell arrays are placed. The sunlight is concentrated to a high efficiency PV array by thousands of individually pointed light weight thin-film mirrors in the ALPHA concept. However, assembling and exploitation of these designs in space conditions poses many problems. For instance, the multi-thousand-ton structure of the ISC project is difficult to control precisely in space. The real-time adjustment of the thousands of reflectors in the ALPHA project is also an open problem. A spherical solar power collector is concentrating the light on hyperboloid PV cell array in the OMEGA project. The concentrator is made of metamaterials with low loss and high transmittance, with properties of redirecting the energy propagation direction, in the SSPS-TENT concept. This design solves the problem of sun-tracking control with a large sunlight-collecting non-moving structure and a small-sized flexible reflector. The concept based on ENZ metamaterial uses the refractive property of the metamaterial to capture the sunlight and to redirect it to the center of the spherical condenser, in contrast to the OMEGA project, in which the sunlight is condensed by means of a reflective concentrator.

The light trace in the OMEGA project, the project with ENZ metamaterial, and the SSPS-TENT project are illustrated in Fig. 2. The sunlight in the OMEGA project passes through opening thousands of individual thin-film reflectors that face to the sun in the spherical condenser, it being captured and reflected to the PV arrays, as shown in Fig. 2a. On the other hand, the sunlight is directed to the PV arrays by making use of the special property of metamaterial to redirect the light as shown in Fig. 2b and Fig. 2c for the ENZ concept and the SSPS-TENT project, respectively.

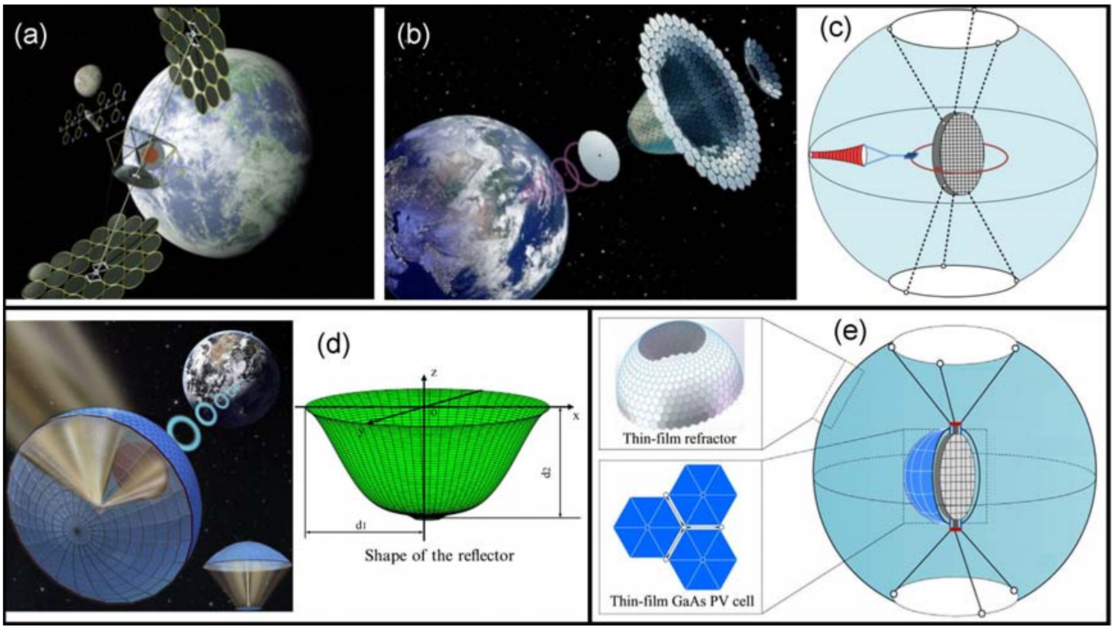

Fig. 1 – The design of the solar energy concentrator in the ISC project (a – adapted from Ref. [14]); ALPHA project (b – adapted from Ref. [15]); OMEGA project (c – adapted from Ref. [16]); SSPS-TENT project (d – adapted from Ref. [17]), and the concept of ENZ) metamaterial (e – adapted from Ref. [18]).

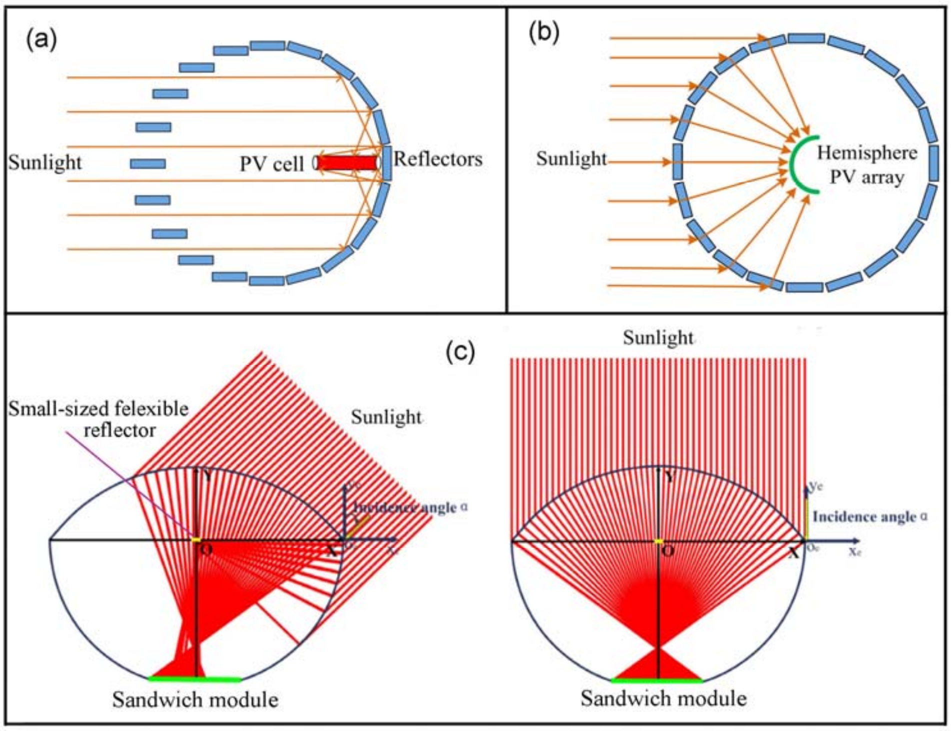

Fig. 2 – Light trace in the OMEGA project (a – adapted from Ref. [16]); the project with ENZ metamaterial (b – adapted from Ref. [18]), and the SSPS-TENT project (c – adapted from Ref. [17]).

The solar light can also be concentrated by Fresnel thin film reflectors/concentrators as previously proposed in the “Sun Tower” SBSP concept [12]. Another concept of a solar concentrator has been recently proposed by creating a 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 [19]. In this regard, it is worth to mention that microparticles have been used in other type of projects in the space. For instance, a cloud of metallic needles with the dimensions of 1.8×10^{-5} m in diameter and 0.018 m in length was placed in 1963 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) [20]. However, this 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.

3. FRESNEL LENS ON THE BASIS OF MICROWIRES

As compared to needles used in the West Ford Project, the cast microwires pieces used in Ref. [19] 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 illustrated in Fig. 3.

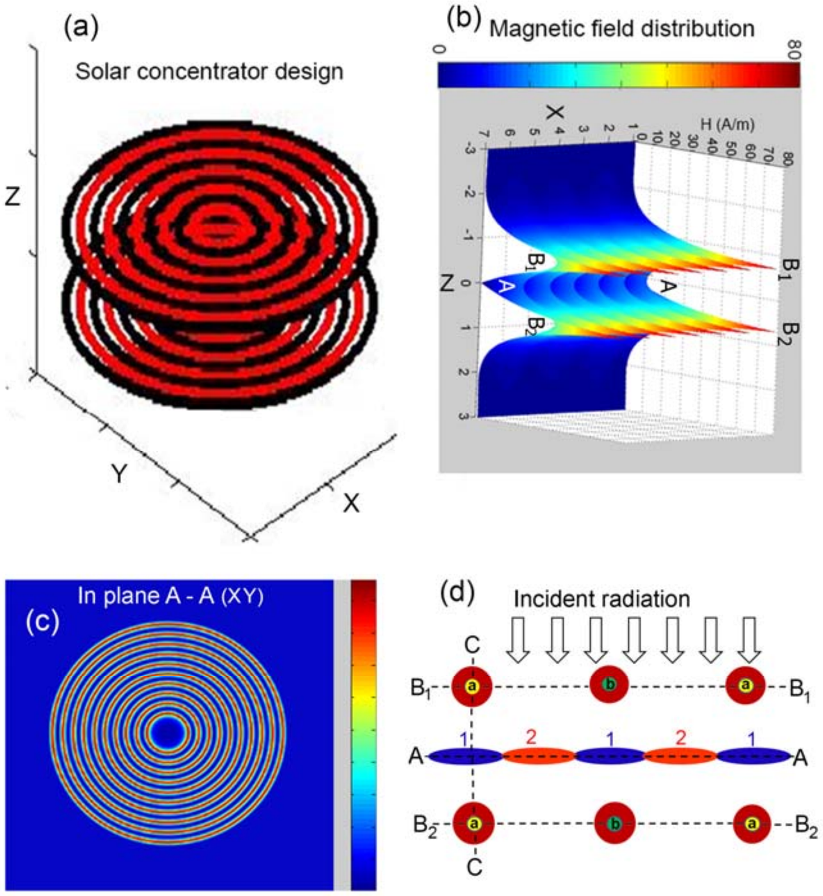

Fig. 3 – a) Design of a lens with concentric rings with current running inside for confining the magnetic microparticles. b) Calculated spatial distribution of the magnetic field in the system for a value of the current of 1 A. The red spikes correspond to the locations of current conductors, while the blue color is for regions with low value of the magnetic field. c) Calculated configuration of the magnetic field within the lens in the plane of symmetry A–A perpendicular to the direction of incident radiation. d) 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 (Adapted from Ref. [19]).

The calculations of optical properties of microwires showed that a medium composed of microwires with a thick Al coating can be used for creating a screen that is semitransparent for the radiation [19]. Such a medium can be used for designing a big size diffraction lens. Fresnel lenses are complex composed optical devices that are used in various fields [21]. It was proposed to assemble such a lens from concentric rings of microwires with various densities (Fig. 3a). 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. 3a) are opposed to each other. In such a case, the magnetic field in the plane of symmetry (at $z=0$, in the plane A–A) will be directed parallel to this plane and will change as illustrated in Fig. 3c. The red color corresponds to high values of the field, while the blue color is for low values. 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. 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. 3d.

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. 3d (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. 3b. 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. 3d and lower than the second row of conductors (B_2-B_2). One can see from Fig. 3b, that potential wells with low values of the magnetic field are also formed in between the two discs.

The spatial distribution of microwires in such a system was found to depend on the magnetic properties of the material of the microwire core [19]. Particularly, microwires of paramagnetic materials with $\mu_r > 1$ were found to be unsuitable for producing lenses, since they will tend to regions with high values of the magnetic field, i.e. they will stuck to the conductor rings. In contrast to this, microwires with the core made of a diamagnetic material with $\mu_r < 1$ (for instance of Bi) 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. 3d, and will form concentric rings with high density of microwires in the plane perpendicular to the direction of incident radiation. Taking into account the dependence of the specific potential energy E/V of a Bi microparticle upon the external magnetic field (as shown in Fig. 4a), it was concluded that such a system will be suitable for designing Fresnel lenses. However, it was suggested to take care about the issue of ionizing the microparticles in the space, which can pose danger for microparticles to escape in the free space. Apart from that, in spite of the fact that Bi microwires have been produced previously [22], they are rather fragile, which can create difficulties with their implementation from the technological point of view of the capillary drawing process [23,24].

Much more possibilities for designing Fresnel lenses were suggested to be offered by microwires with ferromagnetic cores. Since the relative permeability μ_r of ferromagnetic materials as a function of the magnetic field strength H have a maximum at a certain value of the field strength $H(\mu_{r,\max})$, the microwires could tend to occupy spatial regions with that $H(\mu_{r,\max})$ 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 $H(\mu_{r,\max})$ for a given material of the microwire core is reached in regions marked as “2” in Fig. 3d. Such a system could eventually work as a Fresnel lens. However, basically all the known ferromagnetic materials exhibit a very slow decrease of the $\mu_r(H)$ function with increasing the magnetic field strength beyond the $H(\mu_{r,\max})$ value. As a result, there are no attainable values of the magnetic field, for which a minimum of the potential energy could be created, i.e. there are no potential wells where the ferromagnetic microwires could be captured.

To overcome this bottleneck, is was proposed 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 [19]:

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

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

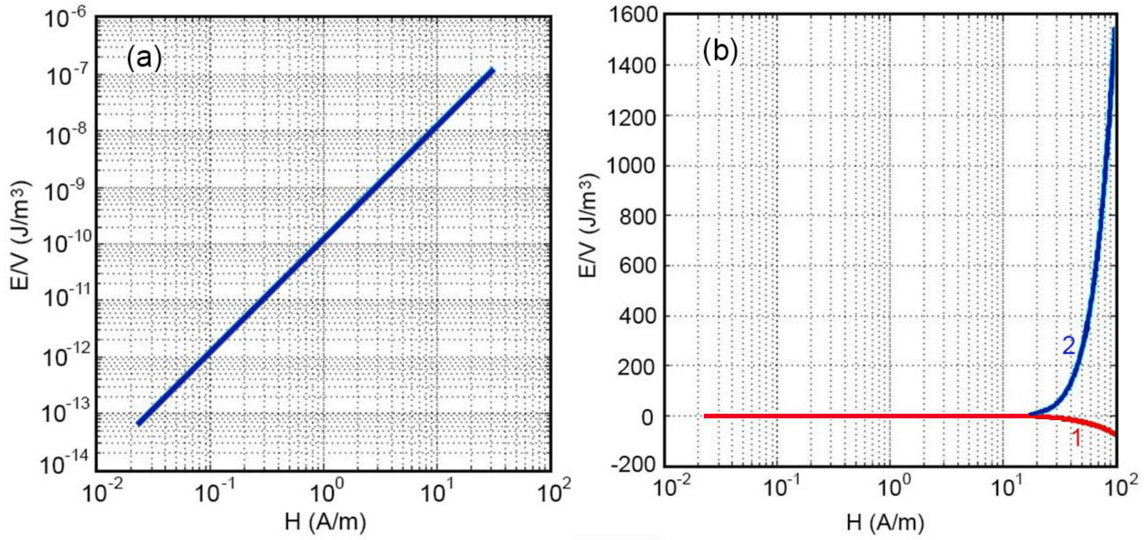

Fig. 4. a) Specific potential energy E/V of a Bi microparticle as a function of the external magnetic field (E is the energy, and V is the volume of the microparticle); b) calculated curves of the total specific energy (E/V) of a ferromagnetic microparticle in the absence of deformation $\gamma_{\max}\equiv 0$ (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, $\mu_{\max}=10^4\mu_0$, $B_s=2T$ (adapted from Ref. [19]).

In such a case, the total potential energy E (the energy of the magnetic dipole and the energy of elastic deformation) equals to:

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

where $G\sim10^{11}$ J/m³ is the mean Young's modulus of the system (the glass envelope will also be subjected to deformation).

The calculations of the total specific energy of certain ferromagnetic microparticles (Fig. 4b) demonstrated that microparticles will stuck to conducting rings in the absence of deformation ($\gamma_{\max}\equiv0$), since states with lower energies will correspond to large magnetic field on the surface of current conductors. On the other hand, the nanoparticles will be confined in regions between the current conductors when they are subjected to deformations (at $\gamma_{\max}=10^{-3}$), since states with lower energies will correspond to lower magnetic field in those regions. It was found that the potential barriers restraining (confining) the ferromagnetic microparticles are several orders of magnitude higher than in the case of Bi diamagnetic microparticles. That means that microwires with ferromagnetic magnetostrictive cores are more advantageous for designing Fresnel lenses than diamagnetic ones.

4. CONCLUSIONS

This analysis shows that using large, symmetrically placed off-axis parabolic reflectors in the ISC solar concentrator, or thousands of individually pointed light weight thin-film mirrors in the ALPHA concept poses many problems in assembling and exploitation of such designs in space conditions. Difficulties to control precisely the multi-thousand-ton structure in space and the real-time adjustment of the thousands of reflectors are among them. Making a spherical solar power collector from metamaterials with low loss and high transmittance and with properties of redirecting the energy propagation direction in the SSPS-TENT concept, or using the refractive property of a metamaterial to capture the sunlight and to redirect it to the center of a spherical condenser in the ENZ metamaterial concept offer many advantages as compared to the OMEGA project. Even more prospects are offered by designing Fresnel lens solar energy concentrators on the basis of clouds of magnetic microparticles. This design is flexible enough by effectively controlled spatial distribution of magnetic microparticles density by means of magnetic fields in the system. This concept provides even more flexibility by possibilities to model the magnetic properties of microparticles from diamagnetic to ferromagnetic ones.

REFERENCES

1. J.D. LAWSON, *Some criteria for a power producing thermonuclear reactor*, Technical Report, Atomic Energy Research Establishment, Harwell, Berkshire, U.K., 1955.
2. A.E. COSTLEY, *On the fusion triple product and fusion power gain of tokamak pilot plants and reactors*, Nucl. Fusion, **56**, 066003, 2016.
3. S.O. DEAN, *Search for the ultimate energy source: A history of the U.S. Fusion Energy Program*, Springer, New York, 2013.
4. D. CLERY, *A piece of the Sun the quest for fusion energy*, Overlook Duckworth, 2013.
5. R.L. HIRSH, *Necessary and sufficient conditions for practical fusion power*, Physics Today, **70**, *10*, pp. 11–13, 2011.
6. J. TOLLEFSON, *MIT launches multimillion-dollar collaboration to develop fusion energy*, Nature, **555**, pp. 294–295, 2018.
7. S. VEZMAR, A. SPAJIC, D. TOPIC, D. SLJIVAC, L. JOZSA, *Positive and negative impacts of renewable energy sources*, Int. J. Electr. Comp. Eng. Syst., **5**, pp. 15–23, 2014.
8. S. SHARMA, K. JAIN, A. SHARMA, *Solar cells: in research and applications – A review*, Mater. Sci. Appl., **6**, *12*, pp. 1145–1155, 2015.
9. A. ANYESHI, *A study on space-based solar power system*, IOSR-JESTFT, Special issue **1**, *5*, pp. 01–03, 2015.
10. G.A. LANDIS, *Solar power satellites*, in: *Comprehensive renewable energy*, vol. 1 – ed. A. Sayigh, pp. 767–774, Elsevier, Oxford, 2012.
11. C.A. SCHAFER, D. GRAY, *Transmission media appropriate laser-microwave solar power satellite system*, Acta Astronautica, **79**, pp. 140–156, 2012.
12. J.C. MANKINS, *A fresh look at space solar power: New architectures, concepts and technologies*, Acta Astronautica, **41**, pp. 347–359, 1997.
13. J.C. MANKINS, *New directions for space solar power*, Acta Astronautica, **65**, pp. 146–156, 2009.
14. 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.
15. JOHN 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.
16. Y. YANG, Y. ZHANG, B. DUAN, D. WANG, X. LI, *A novel design project for space solar power station (SSPS-OMEGA)*, Acta Astronautica, **121**, pp. 51–58, 2016.
17. X. LI, B. DUAN, L. SONG, Y. YANG, Y. ZHANG, D. WANG, *A new concept of space solar power satellite*, Acta Astronautica, **136**, pp. 182–189, 2017.
18. J. HUANG, X.-M. CHU, J.-Y. FAN, Q.-B. JIN, Z.-Z. DUAN, *A novel concentrator with zero-index metamaterial for space solar power station*, Adv. Space Res., **59,** pp. 1460–1472, 2017.
19. V. SERGENTU, V. URSAKI, A. IOISHER, E. ADAR, *Fresnel lens-type energy concentrator for space-based solar power systems*, Romanian Journal of Physics, **63**, paper 908, 2018.
20. I.I. SHAPIRO, H.M. JONES, C.W. PERKINS, *Orbital properties of the West Ford dipole belt*, Proc. IEEE, **52**, pp. 469–518, 1964.
21. A. RAJKRISHNA, *Solar Geyser using spot Fresnel lens*, J. Fundam. Renewable Energy Appl., **6**, 205, 2016.
22. D. GITSU, T. HUBER, L. KONOPKO, A, NIKOLAEVA, *Thermoelectric power of single Bi microwires at Helium temperatures*, Proc. 25th Int. Conf. Thermoelectrics, pp. 238–241, 2006.
23. E. BADINTER, A. IOISHER, E. MONAICO, V. POSTOLACHE, I.M. TIGINYANU*, Exceptional integration of metal or semimetal nanowires in human-hair-like glass fiber*, Materials Lett., **64**, pp. 1902–1904, 2010.
24. A.M. IOISHER, E.Ya. BADINTER, V. POSTOLACHE, E.V. MONAICO, V.V. URSAKI, V.V. SERGENTU, I.M. TIGINYANU, *Filiform nanostructure technologies based on microwire stretching*, J. Nanoelectron. Optoelectron., **7**, pp. 688–695, 2012.

Received October 20, 2018