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Space-Based Nano-Material Enhanced Solar Laser System Simulation for Transferring Power onto the Earth

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A simulation model of a space-based solar-pumped laser system sensitized by a luminescent nano-crystal to transfer the power onto the earth is carried out. The system consists of a solar pumped laser by a concentration system set on a satellite. The laser material is coupled with a luminescent nano-crystal that acts as a sensitizer. The resulted laser is directed onto the earth surface, where it can be used to generate power. The intensity and the divergence of the laser are calculated in order to obtain the optimal solar laser system as a payload on the satellite and the optimal terrestrial applications in Egypt.

Keywords: Solar Laser; Space Power; Solar Concentration; Satellite Payload; Nano-crystal, Sensitizer; Nano-material.

1. INTRODUCTION

Space-based energy became one of the most important disciplines in the field of energy and technology. It is a matter of increasing the energy capacity needed for nowadays technology by harvesting the power from the space. He most important energy source in the space is the solar energy. In the outer space, we can receive the amount of energy equal to the solar constant before it undergoes many radiation interactions with the earth atmosphere such as: reflection, scattering, refraction and dispersion.

The idea of transferring the power from the outer space onto the earth began shortly after the beginning of space exploration in the 1950s and 1960s. The idea was sending great solar collectors to collect the solar energy to use it firstly in the space applications such as lighting and powering.

Solar energy is a promising energy source that can help reduce dependence on foreign oil, mitigate global climate change and improve the economy. Nanotechnology started recently to improve the use of the solar energy after testing some properties of the nano-materials. Many researchers started to think about the enhancing the solar energy devices by nano-materials.

Laser power beaming is the wireless transfer of energy from one place to another using laser light. The basic concept is the same as solar power, where a photovoltaic cell converts the sunlight to energy. Similarly, a photovoltaic cell converts the laser light to energy. The key differences are that laser light is much more intense than sunlight, it can be aimed at any desired location, and it can deliver a sustainable power. This power can be transmitted through air or space, or through optical fibers to everywhere. A sketch of the space-based solar laser is shown in Fig. (1).

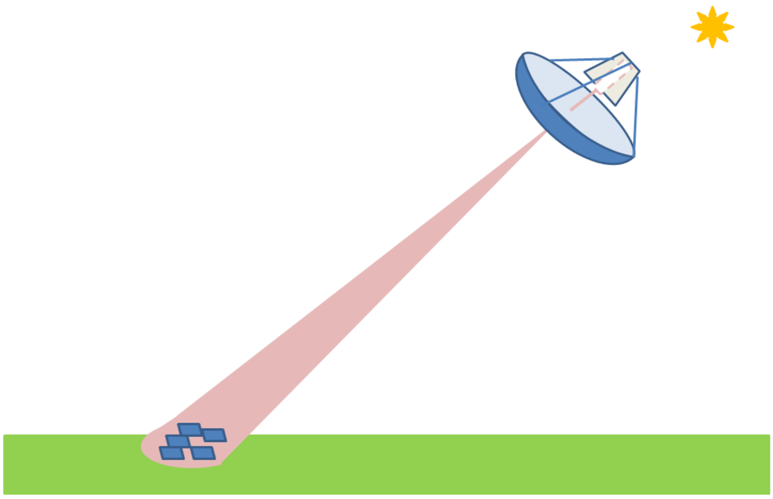

Figure. 1: A sketch of the space-based solar laser.

The benefits of wireless power beaming include:

- The narrow beam allows greater energy concentration at long distances;
- The compact size of the receiver allows easy integration into small devices;
- Power is transmitted with zero radio frequency interference (e.g. to wi-fi/cellular systems);

- Electrical power can be utilized for applications where it was previously uneconomical or impractical to run wires, including aerial refueling of unmanned aerial vehicles (UAVs) and other aircraft;

- Power beaming can use any existing power source to power the laser; and

- Power can be delivered through free space or over fiber optic cable.

Direct pumping uses sunlight developed for the first time by Young [1] as the source of the pumping light in order to generate the laser beam. In order to achieve the required power densities for the inversion process, sunlight at 1 a.u. needs to be concentrated from its natural 1387 W/m^2 to concentration values between 200 and a few thousands depending on the lasing medium.

De Young et al. [2], [3] and [4] started this trend in the National Aeronautics and Space Administration (NASA). The work of this group through the Space-Based Laser Research and Applications Program described a preliminary conceptual design of a space-based solar-pumped iodide laser emitting 1 MW of laser power for space-to-space power transmission. A near-parabolic solar collector focuses sunlight onto the t-C4FgI (perfluoret-butyl iodide) lasant within a transverse flow optical cavity. The preliminary design of a laser power station in Earth orbit did not reveal any major technical problems; thus, this type of power station remains a viable concept for future space applications.

Zepata [5] analyzed Nd^{3+}:Glass, Solar-Pumped, High-Power Laser Systems for the space applications. He evaluated the Nd^{3+} laser as a possible choice for a high-power, space-based laser. He reported that the main advantage of the solid-state media proposed is that the solar-pumped laser need not be refueled because sunlight, its primary source of power, is available on-site. One can easily envision a mosaic of 1000 of slabs of these materials, producing 1 MW of power. Using YAG, the calculations showed that an 80- × 80-cm mosaic would produce 1 MW of laser power at a solar concentration of 40000 with a 3.5-percent conversion efficiency.

Brauch, Schall and Wittwer [6] and [7] constructed a solar laser system in space. Solid state lasers pumped with electric power can currently reach 60% efficiency. If we assume a 30% efficiency for the solar arrays we can have an overall 18% efficiency. If a pumped laser is used, then the focal point can be close to the primary mirror and a high concentration factor can be obtained with a relatively small mirror. For example, if the mirror has an area of 314 m^2 (equivalent to a 10 m circular mirror), then the collected power at 1 AU is 429.5 kW. The solar array and laser system converts only 18% of this power, therefore only 77.3 kW are beamed to the surface of the asteroid, the rest needs to be dissipated.

De Young et al. [8] presented a conceptual design of a high-power, long-duration lunar rover powered by a laser beam. The laser transmitter in lunar orbit consists of an SP-100 reactor prime power source providing 100 kW of electricity to a laser diode array that emits 50 kW of laser radiation. The laser radiation is beamed to the lunar surface where it is received by a GaAlAs solid-state, laser-to-electric converter. This converter provides 22.5 kW of electrical power to the rover vehicle for science, locomotion, and crew needs. The mass of one laser transmitter is approximately 5000 kg, whereas the mass of the rover power system is 520 kg. The rover power system is significantly less massive (23 kg/kW) than alternative rover power units.

Williams et al. [9] described two systems for transmitting power by laser beam from two Lagrange points to the lunar surface. The systems consisted of satellites and a rover on the lunar surface. The systems differed in the two satellites used. The primary divergence between the two satellites was their prime power source. One satellite was powered by a nuclear reactor, while the other by solar photovoltaics (PV). The nuclear reactor was more massive than the photovoltaics and generates thermal and nuclear radiation, but the photovoltaics required continuous solar tracking, which may adversely affect satellite pointing and tracking. The rover was a large manned vehicle, of approximately 8 metric tons, powered by 30 kW of electrical power received by laser beam from a satellite. The power was used for locomotion (15 kW), environmental sustenance within the rover (16.5 kW maximum), scientific tasks (10 kW maximum), and energy storage (2 kW) aboard the rover for emergency use. The rover was roughly 7.5 m long by 3.2 m in diameter. It can travel at a rate of 10 km/h over very rough terrain and up inclines as great as 30°. The power satellite can beamed its power not only to lunar surface entities, but also to other satellites orbiting the Moon, satellites orbiting the Earth, or space vehicles within a radius of tens of thousands of kilometers.

Neal et al. [10] investigated the System requirements for Laser Power Beaming to Geosynchronous Satellites which use solar arrays as their primary source of electrical power. The system included the high energy laser device with laser power, the beam control system, the beam director, the atmosphere and the satellite. A specification has been established for a system which beams laser power to geosynchronous satellites using reactor pumped laser technology. Although only a few kW of power were finally delivered to the satellite, a 1 MW laser beam was required initially because of beam losses arising from sources such as laser beam jitter, thermal blooming, atmospheric turbulence and atmospheric isoplanatic angle. The adaptive optics requirement was for about 1000 adaptive optics segments over the 4-meter telescope aperture, all operating at about 1000 Hz. The most recent adaptive optics demonstrations corrected over significantly smaller apertures (1.5 m) and hence some development in adaptive optics technology was required.

Abdel-Hadi [11], [12], [13], [14] and [15] started a series of researches based on both mathematical simulation and experimental design of new concentration systems and devices for solar pumped solid state lasers. Nd:YAG and Nd:YVO_4 crystals were the laser active media in these studies. The published book of Abdel-Hadi (2006) and the articles published in 2007 and 2008 (a) reported designs of two main concentration systems of both mirror arrays and Fresnel lenses. Both systems were until that time unconventional in this field. These systems have been tested in the European weather in Berlin (Germany). The simulation model of the system of Fresnel lens has been tested for the weather of Helwan (Egypt). The efficiency of these systems was about 3%. For a Fresnel lens of about 60 cm × 60 cm, the output power of a 12 mm long laser rod reached to 6.8 W in the case a well selected summer day at Helwan.

Abdel-Hadi et al. [16] reported a comparative study of powering satellites supported by different types of solar cells during eclipse happening during the staellites rotation in the orbits. They reported that GaAs type is the well recommended type compared with Si type because of it higher output power per square unit (30% higher than Si type), smaller coefficient of efficiency change with temperature and its longer lifetime on orbits (40% - 60% longer than that of the Si type).

Summerer and Purcell [17] provided an overview about using lasers to transmit energy over large distances especially in space. Concepts and candidate technologies have been presented. They argued that due to recent advances in direct solar pumped lasers, the potential integration of space and terrestrial based solar power plants and potentially radical simplifications on the space system design, laser-based wireless power transmission concepts should be matured further in order to be involved as an alternative source of energy (Summerer and Purcell (2009)).

Almeida, Liang, Guillot and Abdel-Hadi [18] reported a significant improvement in solar laser collection efficiency by pumping the most widely used Nd:YAG single-crystal rod through a heliostat–parabolic mirror system. A conical-shaped fused silica light guide with 3D-CPC output end is used to both transmit and compress the concentrated solar radiation from the focal zone of a 2 m diameter parabolic mirror to a 5 mm diameter Nd:YAG rod within a conical pump cavity, which enables multi-pass pumping through the laser rod. 40 W cw laser power is measured, corresponding to 13.9 W/m^2 record-high collection efficiency for the solar laser pumped through a heliostat–parabolic mirror system. 2.9% slope efficiency is fitted, corresponding to 132% enhancement over that of our previous pumping scheme. A 209% reduction in threshold pump power is also registered.

Reusswig et al. [19] reported new results in the field of the nano-material-enhanced solar laser. They constructed a solar-pumped laser based on a conventional 1% atomic Nd^{3+}doped Yittrium Aluminum Garnet (YAG) gain medium to form a planar waveguide with length, width and thickness of 43 mm × 2 mm × 750 µm, respectively. The Nd:YAG waveguide was coated with a 15-µm-thick poly (vinyl butyral-co-vinyl alcohol-co-vinyl acetate) (PVB-CVA-CVAc) thin film containing 10% wt. colloidal CdSe/CdZnS nanocrystals of a quantum efficiency 75% when doped into PVB-CVA-CVAc [19].

Liang et al. [20] composed a 37.2 W multimode and a 9.3 W TEM00-mode solar-pumped Nd:YAG lasers of the first-stage heliostat-parabolic mirror solar energy collection and concentration system, the second-stage fused silica aspheric lens and the third-stage conical-shaped pumping cavity, within which the 4 mm diameter, 35 mm length grooved Nd:YAG rod was efficiently pumped. 37.2 W continuous-wave multimode solar laser power was firstly measured, corresponding to 31.5 W/m^2 multimode solar laser collection efficiency and 8.9% slope efficiency. By adopting the asymmetric large-mode laser resonant cavity, 9.3 W continuous wave TEM_{00}-mode solar laser power was measured. 7.9 W/m^2 TEM_{00}-mode collection efficiency is 2.6 times higher than the previous record by the Fresnel lens and nearly 2 times higher than the previous record by the parabolic mirror. Stable emission of the most efficient solar laser power from a stationary solar laboratory, both in multimode and fundamental mode regimes, could constitute one step futher for many interesting applications for solar-powered lasers.

Due to its natural four-level system, high emission cross-section, and long excited state lifetime, Nd:YAG laser is one of the most used materials in the field of sola-pumped laser. Therefore, we chose it in our investigation in this work.

1. Model Scenario

We modeled a solar-pumped laser of the same active media of Reusswig et al. [19] but put as a payload on a satellite or a space station in the space. The solar radiation of a value of the total solar constant (1387 W/m^2) falls on three-dimensional parabolic dish to be directed onto a laser rod in a three-dimensional compound parabolic concentrator (3D-CPC). Accordingly, a laser beam will be emitted and directed onto the earth surface where it will be detected by plants of photovoltaics modules and transformed into electricity.

The overlap between the solar spectrum and the absorption of the CdSe/CdZnS:PVB-CVA-CVAc thin film are seen in Fig. (2) (a) which shows the broad spectral absorption of the nanocrystals between 350 nm and 600 nm. The narrow emission and tunability of the nanocrystal photoluminescence increases the pumping efficiency through the narrow absorption peaks of Nd:YAG. Actually, as shown in Fig. (2) (b), the CdSe/CdZnS photoluminescence is tuned to neodymium's main absorption peak in the visible at 585 nm. The design of the laser cavity is shown in Fig. (3).

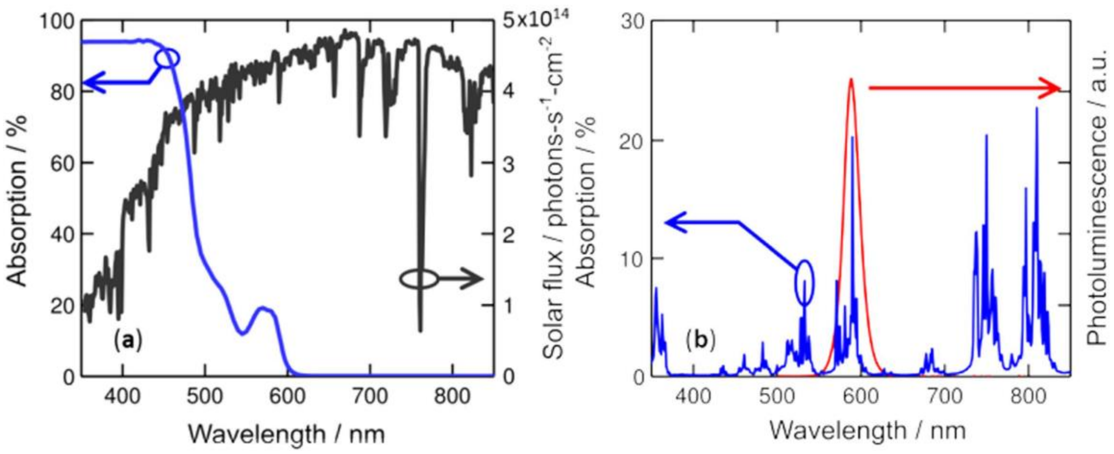

Figure. 2: (a) Absorption of the luminescent colloidal film, 10% wt. CdSe/CdZnS:PVB-CVACVAc (blue), overlaid on the AM1.5 solar flux (black). (b) The luminescence of the nanocrystal (red) is tuned to an absorption peak of the Nd^{3+}:YAG (blue), for efficient waveguided luminescent pumping of optical gain media [19].

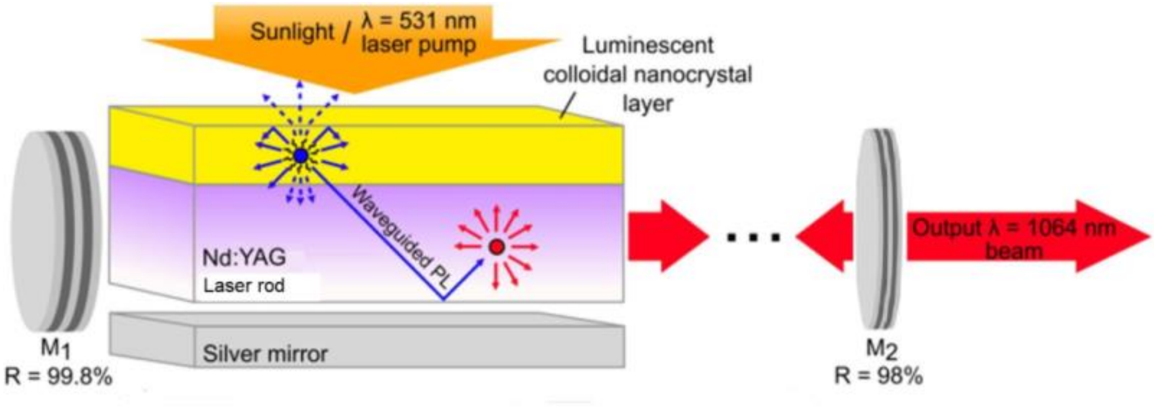

Figure. 3: The design of the laser cavity.

The threshold pumping power of the laser rod can be calculated from Equation (1) [21].

$$P_{th} = \frac{A_a I_s}{\eta_q \eta_{ovp} \alpha} \left(\frac{2\gamma_l - \ln(R)}{2\varepsilon}\right) \quad (1)$$

where A_a is cross-sectional area of the crystal (rod) and γ_l is the loss per pass in the laser. The other parameters are defined in Table (3).

We can also calculate the value of the slope efficiency (the efficiency above the threshold) using the Equation (2).

$$\eta_s = \eta_q \eta_{ovp} \alpha \varepsilon \left(\frac{T}{(2\gamma_l - \ln(R))}\right) \quad (2)$$

where the value η_q is the quantum efficiency (the mean wavelength of absorbed radiation divided by the lasing wavelength).

Put into a form that is often used when presenting solid-state laser performance data, the output power can also be written as in Equation (3).

$$P_{out} = \eta_s (P_{in} - P_{th}) \quad (3)$$

The measured laser threshold power, as a function of the output coupler mirror reflectivity *R*, can be used to determine both the loss per pass *L* and the mean pumping efficiency ε [22].

The parameters of the primary concentrator (three-dimensional parabolic dish), Laser rod and the nanocrystal are shown in Tables (1), (2) and (3) respectively.

Table 1: The parameters of the three-dimensional parabolic dish.

Parameter	Symbol	Value
Diameter	D	200 m
Focal length	f	121 m
Rim Angle	φ	44.866°
F-Ratio	F	0.606

Table 2: The parameters of the Nd:YAG laser rod.

Parameter	Symbol	Value
Rod Length	L_a	10 – 100 cm
Rod Diameter	D_a	2 - 20 mm
Absorption Coefficient	α	0.59
Quantum efficiency	η_q	0.63
Pumping efficiency	ε	0.67
Overlap Ratio	η_{ovp}	0.14
Loss across the rod	γ_l	0.016
Fluorescence of the crystal (Saturation flux)	I_s	12.5 W/mm^2
Transmissivity of the output coupler	T	0.02

Table 3: The parameters of the nano-crystal (CdSe/CdZnS).

Parameter	Symbol	Value
Quantum efficiency	η_q	0.75
Pumping efficiency	ε	0. 7
Overlap Ratio	η_{ovp}	0.14

Applying the model on the defined data in varying the dimensions of the laser rod (length and radius), we could get some curves showing the output power and intensity got initially from the system. Then we calculated the output intensity measured on the earth surface if the system is put on a satellite or a space station on an orbit of 300 km height, Low Earth Orbit (LEO) which is an orbit around Earth with an altitude of 2,000 km height, Geostationary Orbit (GEO) which is a circular orbit 35,786 km height. The purpose of testing the system in these cases is to find the optimum position for a solar laser system on the earth which can transmit a laser beam of optimum output for optimum energy receivers (solar cell plants) areas need for the needed applications on the earth.

Varying the length of the laser rod, the threshold pumping power for laser rod with and without the nano-crystal curves can be shown in Fig. (4). Accordingly, the output power and intensity diagrams can be shown in Figs. (5) and (6) respectively with and without the nano-crystal. Finally, a probability diagram of the output intensity received on the surface of the earth in the above-mentioned three orbits can be shown in Fig. (7).

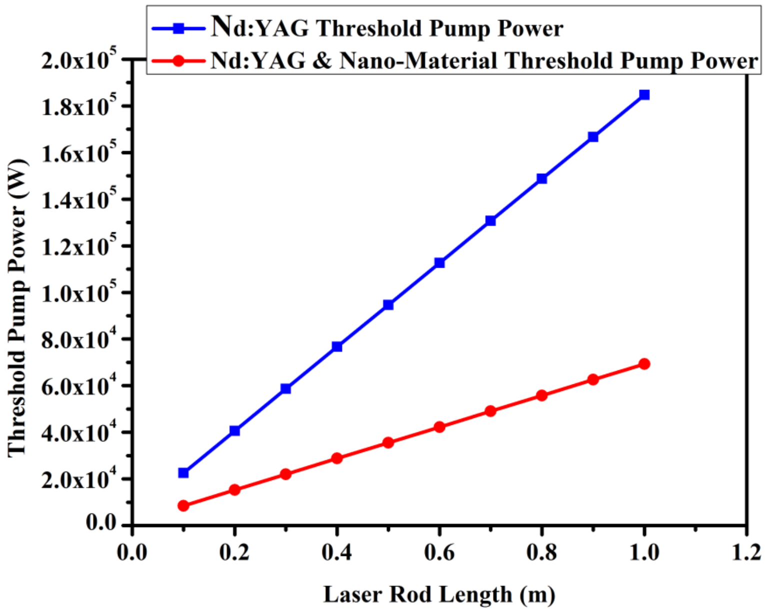

Figure. 4: The threshold pumping power of the Nd:YAG laser against the length of the rod with and without using the nano-material.

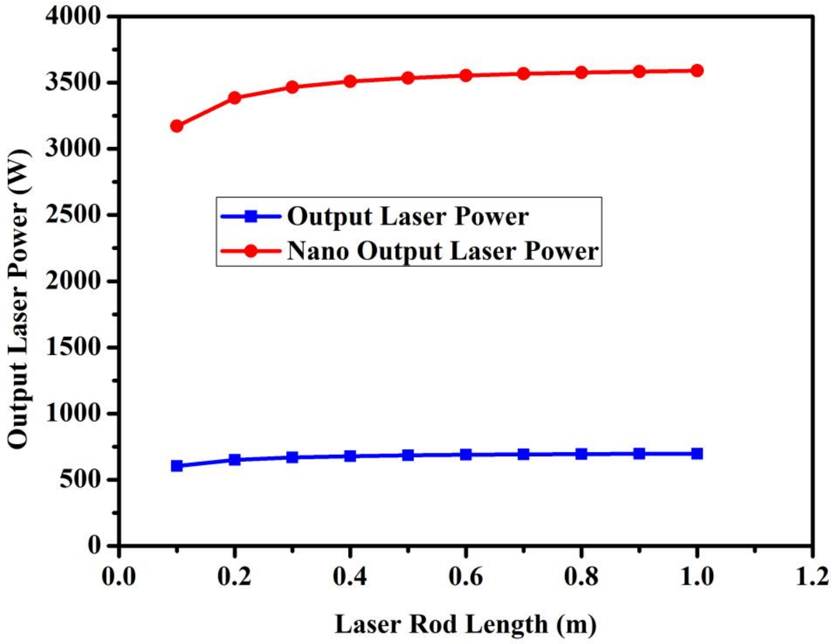

Figure. 5: The output power of the Nd:YAG laser against the length of the rod with and without using the nano-material.

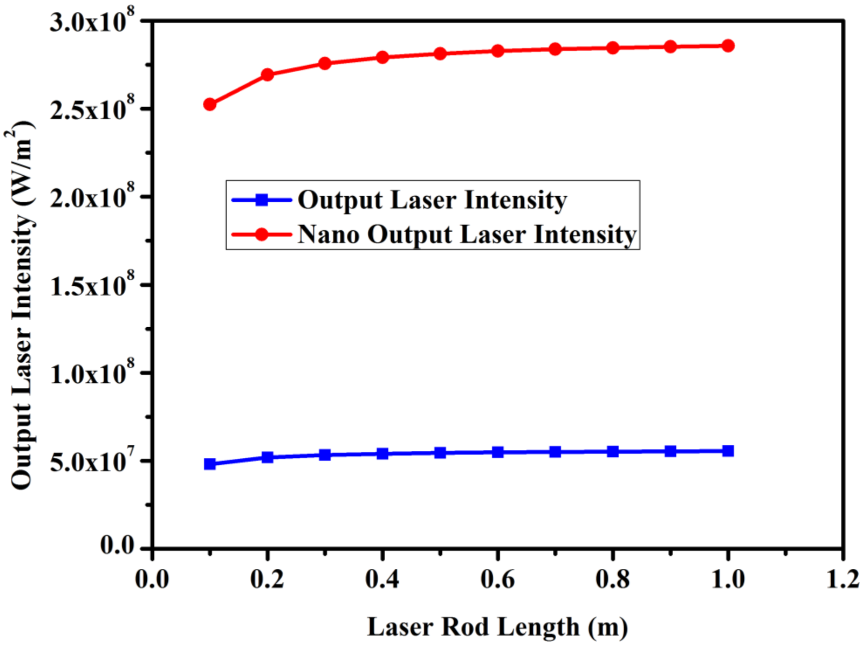

Figure. 6: The output intensity of the Nd:YAG laser against the rod length with and without using the nano-material.

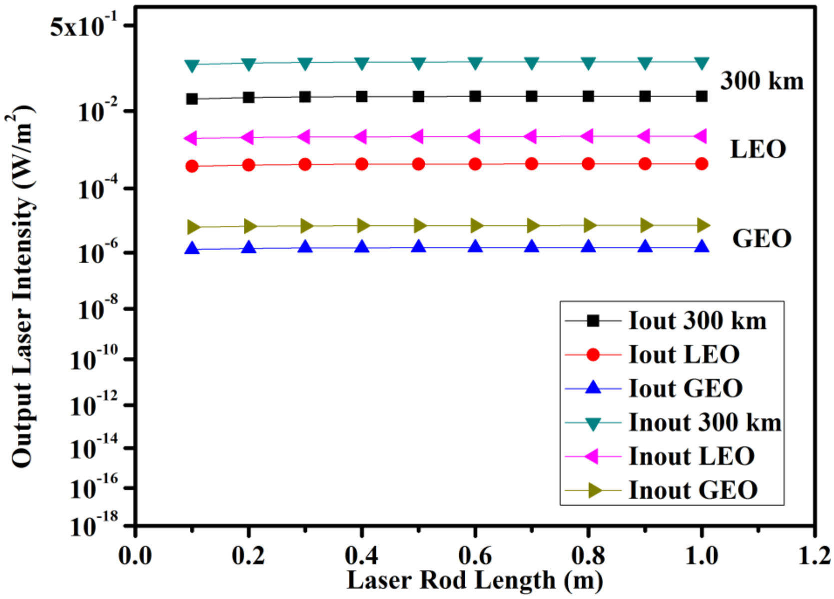

Figure. 7: A probability diagram of the output laser intensity against the length of the rod without using the nano-material on the three orbits; 300 km height, LEO and GEO respectively.

Similarly, varying the radius of the laser rod, the threshold pumping power for laser rod with and without the nano-crystal curves can be shown in Fig. (8). Accordingly, the output power and intensity diagrams can be shown in Figs. (9) and (10) respectively with and without the nano-crystal. Finally, a probability diagram of the output intensity received on the surface of the earth in the above-mentioned three orbits can be shown in Fig. (11).

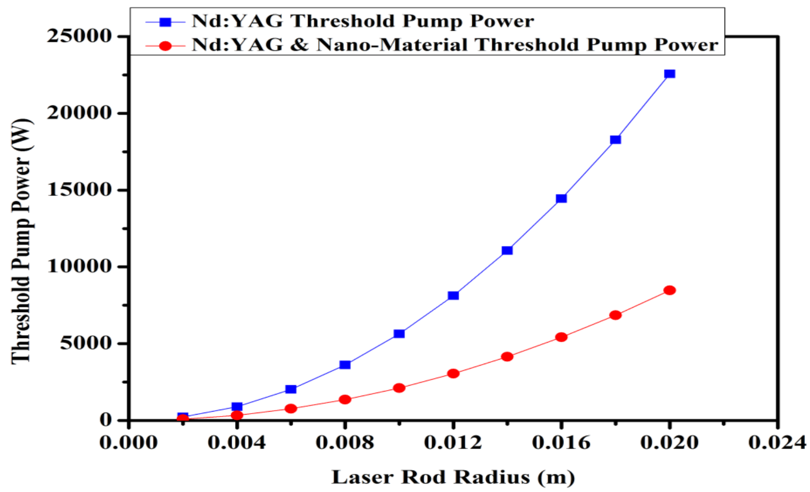

Figure. 8: The threshold pumping power of the Nd:YAG laser against the radius of the rod with and without using the nano-material.

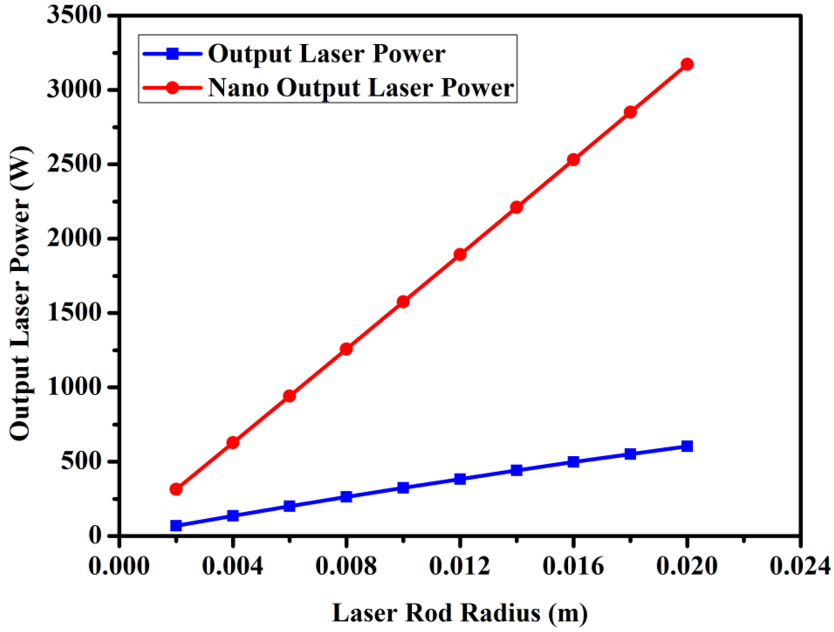

Figure. 9: The output power of the Nd:YAG laser against the radius of the rod with and without using the nano-material.

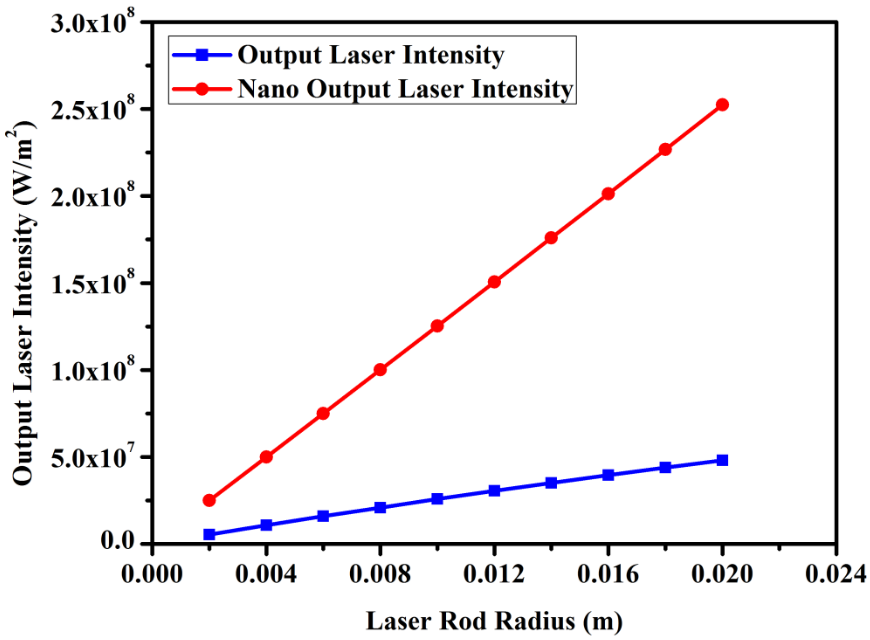

Figure. 10: The output intensity of the Nd:YAG laser against the radius of the rod with and without using the nano-material.

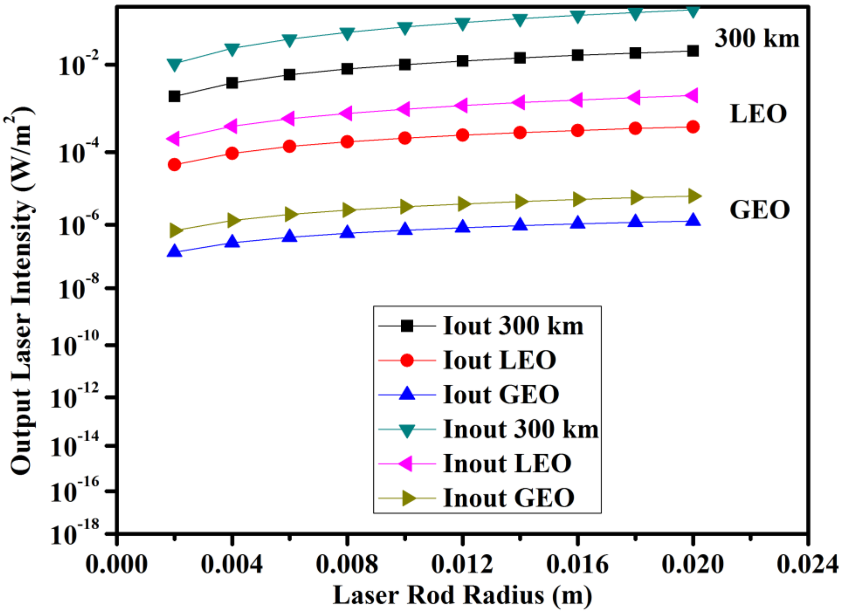

Figure. 11: A probability diagram of the output laser intensity against the radius of the rod without using the nano-material on the three orbits; 300 km height, LEO and GEO respectively.

2. Results and Discussion

From the resulted curves in Figs. (4), (5), (6), (7), (8), (9), (10) and (11), we can notice that the there is a remarkable reduction in the threshold pumping power of the laser system in the case of coating the laser crystal (Nd:YAG) with a 15-µm-thick poly (vinyl butyral-co-vinyl alcohol-co-vinyl acetate) (PVB-CVA-CVAc) thin film containing 10% wt. colloidal CdSe/CdZnS nanocrystals of a quantum efficiency 75% when doped into PVB-CVA-CVAc. The calculated threshold pumping power, in this case, was found to be 38% of its original value using the Nd:YAG crystal alone. Obviously, this will lead to a remarkable increase in the conversion (slope) efficiency and which was found to be about 4.5 times and the output power which was found to be ranging from 4.58 to 5.25 times depending on the laser dimensions. But the ratio between the output power in the case of nano-crystal coated laser rod and that of laser rod alone is decaying slightly by increasing the length of the rod due to the loss exceeding through the laser rod. On the contrary, the ratio between the output power in the case of nano-crystal coated laser rod and that of laser rod alone is increasing gradually by increasing the radius of the rod due to the gain exceeding through the laser rod.

Setting the system on a satellite on 300 km height over the surface of the earth is useful for getting relatively higher intensities but only for the short run because this orbit can be considered as a decaying orbit. This setting can be useful for relatively small solar panel fields which will receive relatively higher intensity output laser beams on narrower areas according to the divergence of the output laser beam. If the system is set on a satellite on LEO orbit, it will be useful for getting lower intensities but it is useful for the long run. Accordingly, the area of the solar panel fields will be larger in order to receive the output laser beam of a smaller intensity diverged on a wider area. But if the system is set on a satellite on GEO orbit, it will be useful for getting much lower intensities but it is useful for a much longer run and wider area. Accordingly, the area of the solar panel fields will be much larger in order to receive the output laser beam of a much smaller intensity diverged on a much wider area.

The transmission ratio of Nd:YAG laser beam in the earth's atmosphere is 0.92, while it is 0.7 for that frequency doubled Nd:YAG is 0.7. So, if the applications on the earth need lasers of higher frequency in the case of using Nd:YAG, it has to be known that the out laser power will be reduced by a value 0f 0.76. So, some possible modifications can be done to obtain a relatively higher laser output power such as increasing the radius of the rod, decreasing the height of the satellite carrying the system or using additional optical concentration devices like the light guides.

3. Conclusions

For the solar laser in general and specially that pumped in space onto the earth, nano-materials enhancement is good recommendation because of its reducing of the threshold pumping power and enhancing the slope efficiency and accordingly the output laser power.

Using Nd:YAG with the nano-crystal of the type CdSe/CdZnS, three main benefits can be attained:

1- Reduction of the threshold pumping power of 3 times.

2- Increasing the slope efficiency about 4.5 times (from 0.7% up to 3.1%).

3- Increasing the laser output power about 4.5 to 5 times (depending on the dimensions of the laser rod).

According to the chosen orbits in this research, we can say that setting the system on a satellite on 300 km height over the surface of the earth is useful for getting relatively higher intensities but only for the short run because this orbit can be considered as a decaying orbit, while setting the system on a satellite on LEO orbit is useful for getting lower intensities but it is useful for the long run, but setting the system on a satellite on GEO orbit is useful for getting much lower intensities but it is useful for much longer run and wider area.

Using frequency doubling Nd:YAG laser could readily give a laser beam of higher frequency but the total intensity will be reduced around 1.3 times according to the transmission in the earth's atmosphere. Therefore, the output intensities will be about 76% of the above results due to the atmospheric transmission through the earth's atmosphere.

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