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Evaluation of Optical Efficiency of Circular Cross-Section Torus Waveguide via Changing the Optical Parameters

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Abstract
The efficiency of solar systems was developed through the design of a torus waveguide, which provides high flexibility in the design of the solar system. The design was simulated using the optical design program (ANSYS Zemax Optic Studio 2022). The circular cross-section torus waveguide was shaped like the letters (U, S) to transmit solar radiation through total internal reflection inside the waveguide to the receiver (solar cell or thermal reservoir). To improve the solar system's efficiency, a group of optical parameters related to the waveguide's shape were changed to demonstrate the effect of changing them on the system's performance. These parameters include the radius of curvature of the waveguide, the width of the entry apertures, and the angle of rotation. The results showed that the designed waveguide shapes offer high flexibility in size and shape without significantly affecting the system's efficiency. This flexibility allows for greater diversity in the design of solar systems, depending on their intended purpose.
Keywords: Waveguide, Torus, Solar concentrator, Acceptance angle, Solar radiation, Circular cross-section.

1. Introduction
Solar energy is considered to be the primary source of energy for planet Earth. It is widely available in different parts of the world and is the source of life, either directly or indirectly. Solar energy comes in different forms, including direct solar radiation, wind energy, and biomass energy (1, 2). There are two methods of converting solar energy: Photoelectric conversion: This method directly transforms solar or light radiation into electrical energy through the use of materials like silicon and germanium in solar cells. Thermal conversion: This method converts solar radiation into thermal energy through solar concentrators. People use it to heat water for domestic and industrial purposes, as well as for heating, cooling, and drying crops (3, 4). Concentrated Solar Power (CSP) is a technology that uses the power of the sun to generate electricity without depending on fossil fuels. It functions by concentrating sunlight on mirrors or lenses to produce the heat required for electricity production. This

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technology is distinct as it captures the sun's energy and transforms it into electricity, making it an eco-friendly substitute for traditional power generation (5- 7).To enhance the performance of a solar system, it is important to transfer as much solar radiation as possible to the system through an effective area that is proportional to the size of the receiver (solar concentrators) (8, 9). These concentrators require a continuous sun-tracking system, which can be quite expensive and make the system bigger. The best design approach is to find a geometric shape that is ideal and allows for a large angle to accept sunlight, thus eliminating the need for a tracking system. A waveguide that uses total internal reflection to transmit rays at different angles to the receiver has been designed to transmit solar radiation with high efficiency (10, 11).There are three main types of waveguides, classified based on the optical system for which they are designed and engineered: slab waveguides, rectangular waveguides, and Circular Waveguides (12). Jason H. Karp and Joseph E. Ford (2009) introduced a new approach to solar concentrators that uses a thin lens array and a shared multimode waveguide (10). Jason H. Karp, Eric J. Tremblay, and Joseph E. Ford (2010) developed a solar concentrator model that uses a waveguide and lens array (convex-planar) to improve solar cell efficiency (13, 14). In 2018, Selvaraja, Shankar Kumar, and Purnima Sethi classified optical waveguides based on different factors and analyzed their propagation loss (15). Bauser, Haley C., et al. 2020 developed a new type of solar concentrator that achieves over 90% light trapping efficiency using quantum dots in photonic crystal slab waveguides (16, 17). The waveguide is a flat dielectric slab with a thin layer. It works by allowing radiation to travel in the z-direction through complete internal reflection from the left and right walls of the slab. On one side, it absorbs solar radiation and transmits it through the interior walls to the receiver on the other side, as shown in **Figure 1**. However, the conventional waveguide has a fixed size and shape that restricts its ability to transfer radiation to specific locations in the system (18, 19).

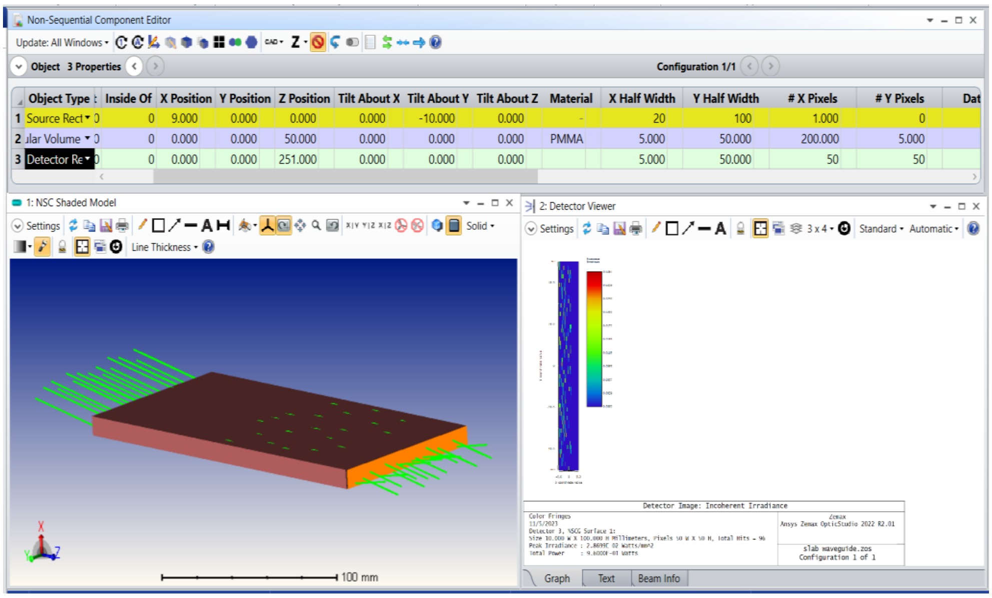

Figure 1. Slab waveguide model with data editor window and detector viewer window in Zemax program.

Solar systems that use a slab waveguide can experience a significant decrease in efficiency when solar rays hit the waveguide at an angle that doesn't allow for total internal reflection, causing a large portion of the rays to scatter outside the waveguide. This reduces the visual efficiency of the system, meaning that only a limited portion of the light reaches its intended receiver (20). To combat this, the solar system must have a relatively large acceptance angle (which is the angle of incidence of solar rays that allows for an efficiency of 80% or more). The torus waveguide was designed with a circular cross-section, and its shape is like the letters

U and S. This new model addresses the limitations of the traditional shape by allowing for higher flexibility in designing the solar system. By changing the location of the entry and exit openings for solar rays, we can improve the waveguide's efficiency and ensure that it functions optimally for the longest possible period of solar exposure (21- 23).

2. Materials and Methods

A circular cross-section torus waveguide of (U, S) shape has been designed to transmit solar radiation with high efficiency using the ANSYS Zemax Optic Studio 2022 optical design program. The waveguide transmits solar radiation to the receiver, such as a solar cell or thermal warehouse, through the total internal reflection of radiation within the waveguide. The program uses Non-Sequential Ray Tracing mode as its mathematical basis, which is suitable for designing a waveguide that functions on the principle of total internal reflection. This means that the solar ray travels inside the system without considering the sequence of the rays falling on the surfaces until they reach the detector's surface. In the software, a scale model of the waveguide is designed with uniform dimensions to match the shape of the torus waveguide (24, 25).The first design is the U-shape torus waveguide with a circular diameter (50 mm) and a length (100 mm), as shown in **Figure 2**. The second design, the S-shaped, has a circular diameter (50 mm) and a length (100 mm), as shown in **Figure 3**. The torus waveguide is made of polymethyl methacrylate (PMMA), which is a thermoplastic polymer that is characterized by thermal flexibility in shaping and rigidity to obtain the shape required for its design (26).

To design a waveguide, you need to input all the optical parameters, such as the aperture diameter, the external and internal curvature angle, the length, the material type, and the waveguide rotation angle, into the program's design data editor. It's important to determine the precise coordinates for every part of the waveguide component to ensure design uniformity (27, 28).For simulated visible light, the program uses a light source that replicates the sun's visible light using suitable wavelengths. Instead of the receiver, a photodetector is used at the exit aperture of the waveguide to measure the amount of radiation reaching it. The program uses a detector viewer to calculate optical efficiency for different incidence angles and any changes in the optical parameters. The Zemax program calculates efficiency by analyzing 1000 fixed rays as analysis rays only. Optical efficiency is the ratio of light intensity leaving the system to the light intensity entering it (29, 30). To determine optical efficiency, we calculate the number of rays received at the detector against the number of rays entering the system.

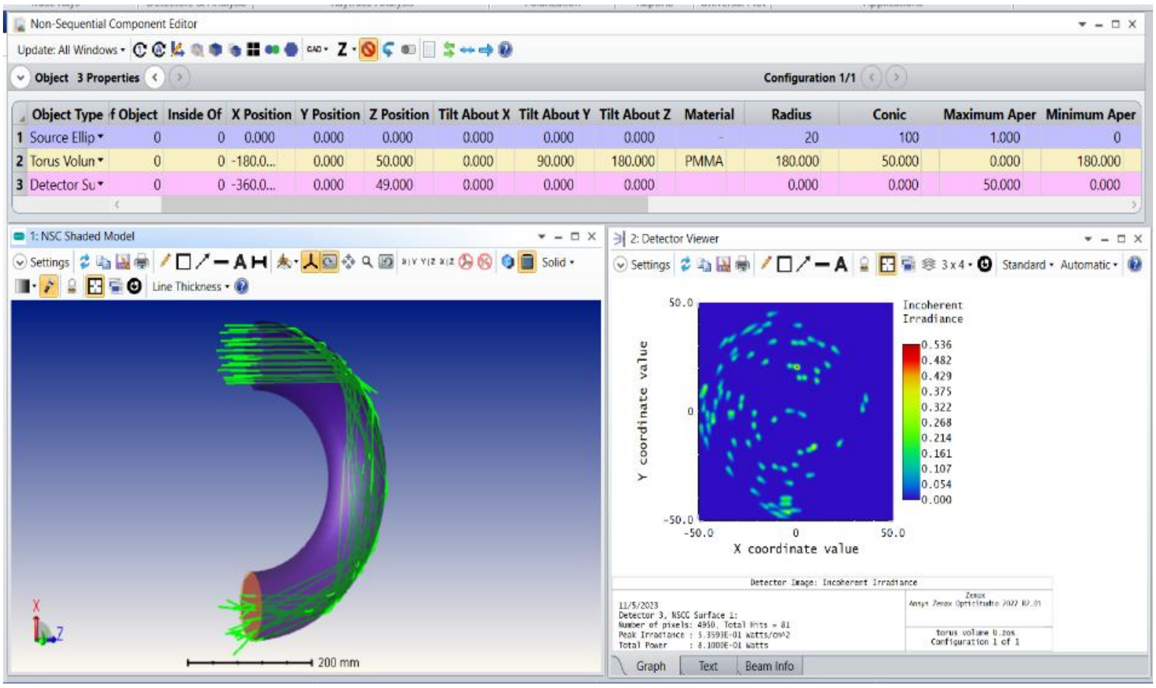

Figure 2. U-shape circular cross-section torus waveguide model with data editor window and detector viewer window in Zemax program.

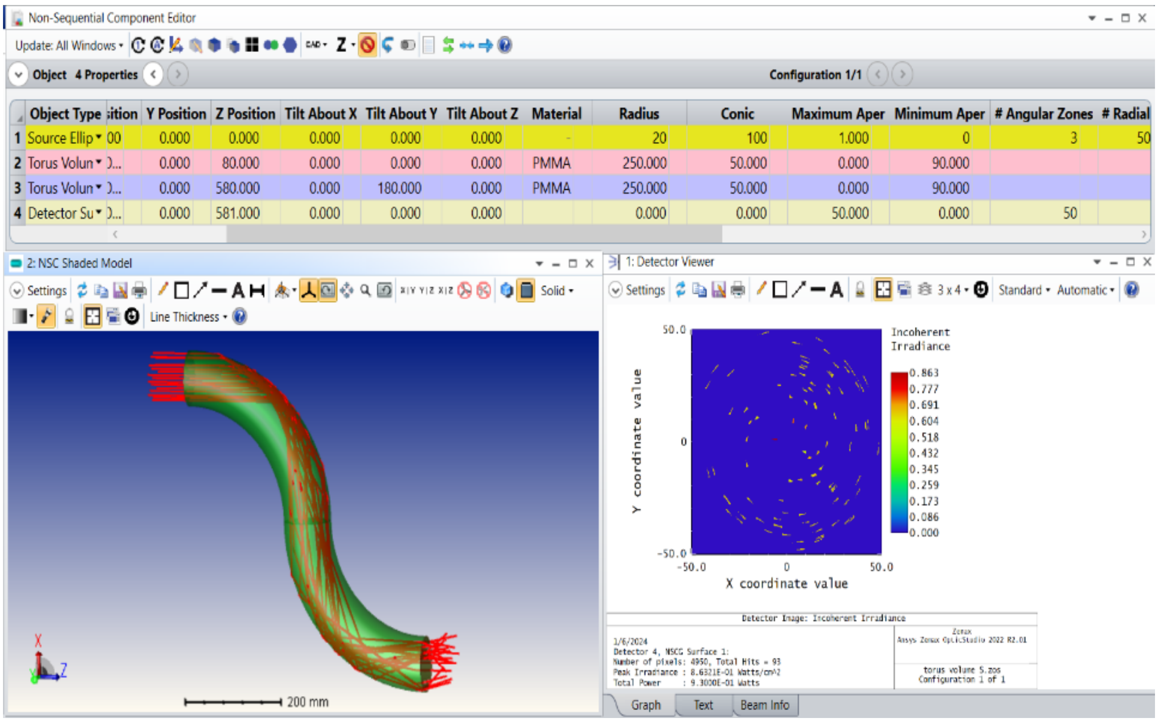

Figure 3. S-shape circular cross-section torus waveguide model with data editor window and detector viewer window in Zemax program.

3. Results and Discussion

The results obtained when changing a set of optical parameters, which include the radius of curvature, entry aperture, and angle of rotation of the waveguide on the performance of the waveguide, were shown as follows: When the radius of curvature changes, the path of rays inside the waveguide also changes. To maintain total internal reflection, the rays must not escape to the outside. The shape of the waveguide plays a crucial role in this matter. **Figures 4** and **5** display the efficiency values for a U-shaped waveguide circular cross-section. The efficiency values change according to the radius of curvature (r=50, 60, 70, 80, 90, 100 mm).

A decrease in efficiency occurs when the angle of incidence changes due to the alteration in the path of the rays inside the waveguide. For the model with a radius of curvature of 50 mm, an acceptance angle of around 20 degrees is achieved. **Figures 6** and **7** show an S-shaped waveguide circular cross-section, and the efficiency values also vary according to the radius of curvature (r=50, 60, 70, 80, 90, 100 mm). For the model with a radius of curvature of 50 mm, an acceptance angle of approximately 20 degrees is obtained. The radius of curvature values for both U and S models are restricted due to their design peculiarities. Changing the radius values results in a clear change in efficiency values due to the difference in the angle of reflection inside the waveguide walls. When changing the entry aperture, the size of the system changes, affecting the number of rays entering the waveguide. However, the concentration ratio remains the same, determined by the width of the entrance aperture to the width of the exit aperture. Changing the width of the entry hole is necessary if the system requires varying amounts of radiation to enter it according to work requirements. The circular cross-section design ensures that the optical efficiency remains similar for all cases when the width of the entrance aperture changes. **Figures 8 - 11** demonstrate that performance efficiency is not affected by changing the entrance aperture, providing an acceptance angle of around 35 degrees for all designs. The design of the models used provides engineering flexibility, even if the width of the entry hole changes. The efficiency value remains almost constant for all cases of change, allowing the entry aperture's area to be altered without affecting the system's efficiency. The waveguide rotation angle indicates the change in design rotation length, ranging from 30° to 270°. As the angle of rotation increases, the model's length changes, causing the exit opening's location to shift. **Figures 12** and **13** demonstrate the flexibility of changing the location of the entry and exit openings and the waveguide length to suit the system's needs. **Figures 14** and **15** show the optical efficiency values of the models used when the angle of rotation changes for different values of the angle of incidence. The optical efficiency values are similar to the circular cross-section model (types U, S), indicating that the length of the waveguide with its curvature does not significantly affect the amount of rays emerging from it. The radius of curvature of the waveguide remains constant, and as the curvature of its length increases, the angle at which the rays reflect inside the waveguide remains almost constant, resulting in total internal reflection and the rays reaching the recipient without much change. The almost constant value of the optical efficiency when changing the waveguide rotation length indicates the system's stability in performance. Therefore, the design allows for a wide range of freedom to alter its shape without affecting the optical efficiency value, giving ample geometric space to change the location of receiving the rays to and from outside the waveguide in the system.

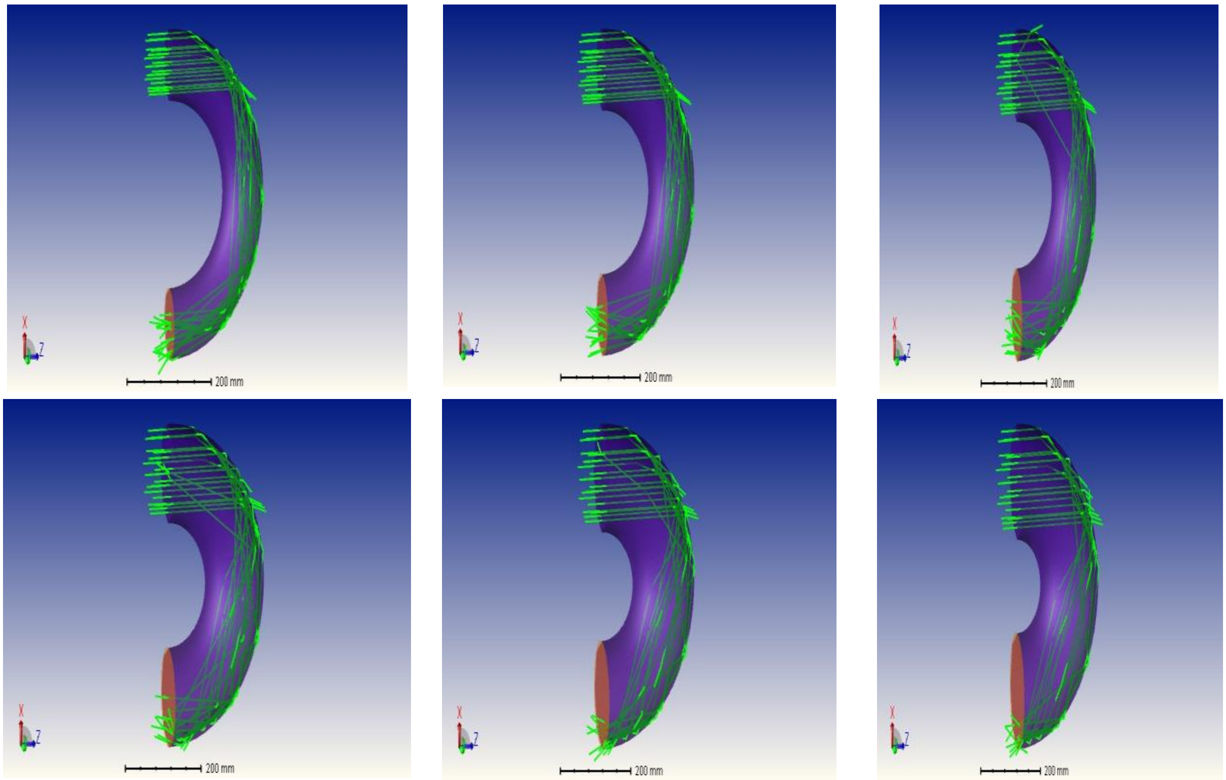

Figure 4. Changing of curvature radius of U-shape circular cross-section waveguide.

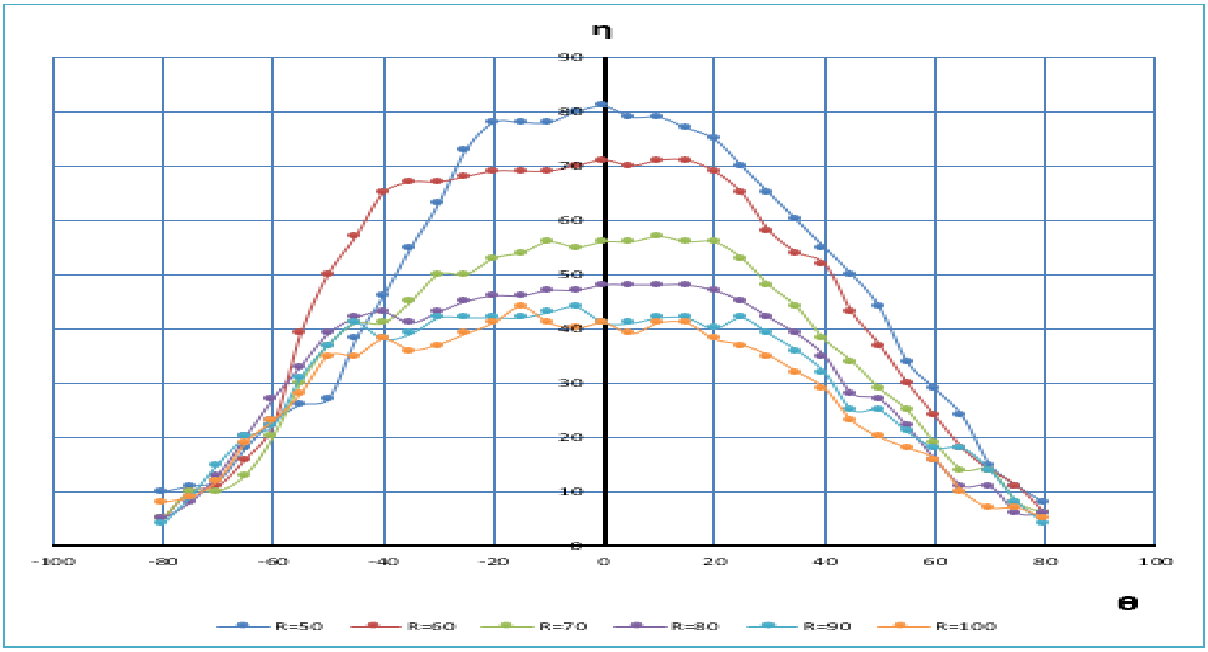

Figure 5. Optical efficiency of different incidence angle when changing the curvature radius of U-shape circular cross-section waveguide.

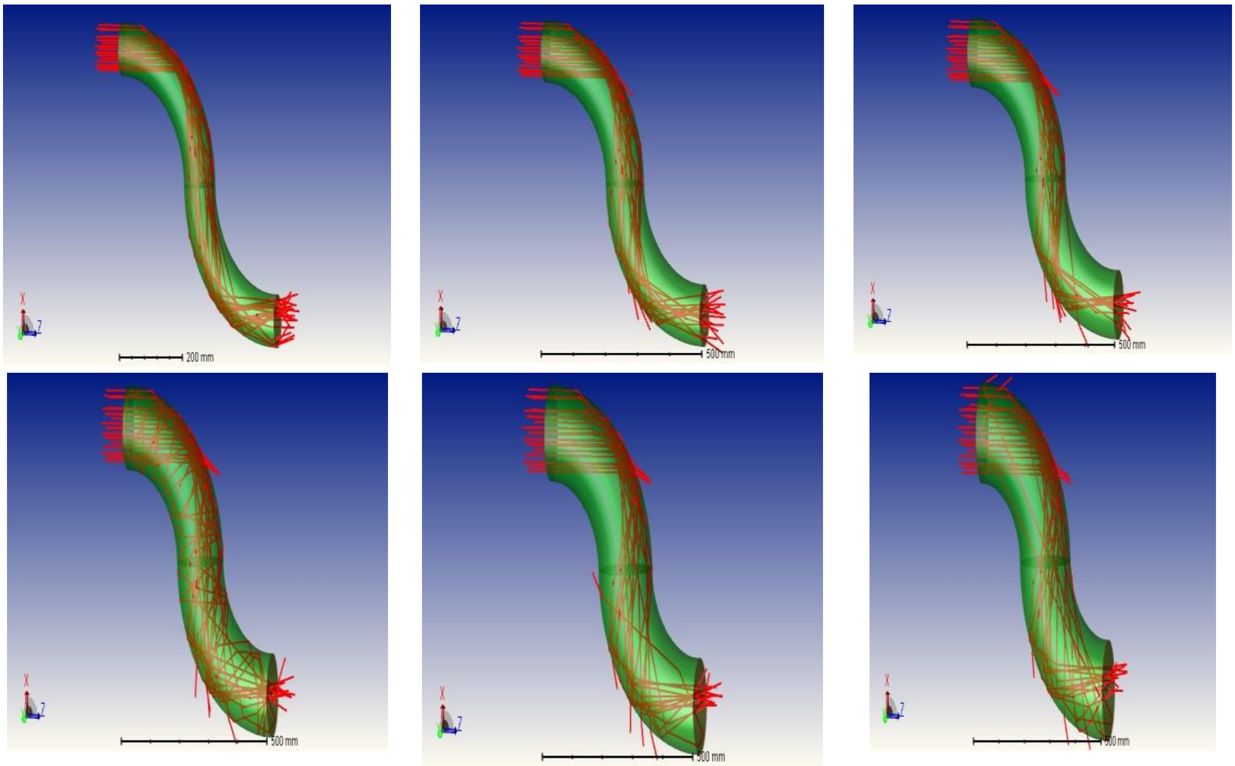

Figure 6. Changing of curvature radius of S-shape circular cross-section waveguide.

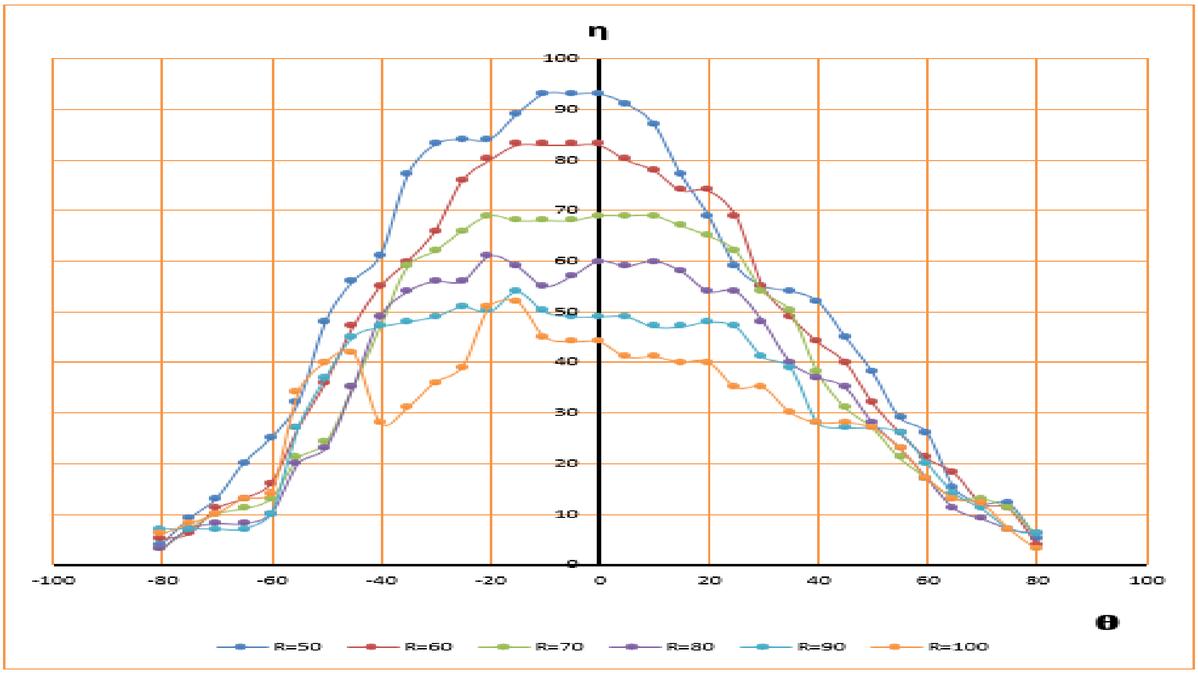

Figure 7. Optical efficiency of different incidence angle when changing the curvature radius of S-shape circular cross-section waveguide.

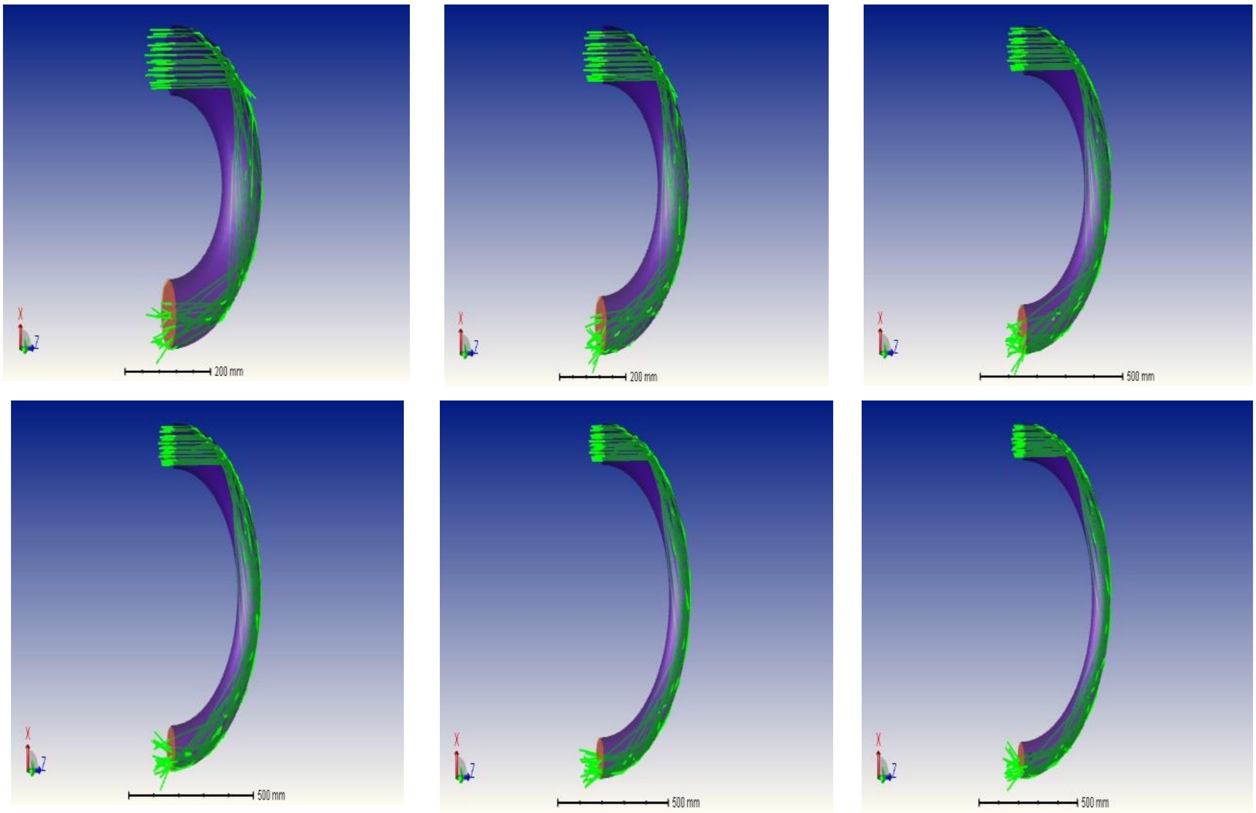

Figure 8. Changing of entrance aperture of U-shape circular cross-section waveguide.

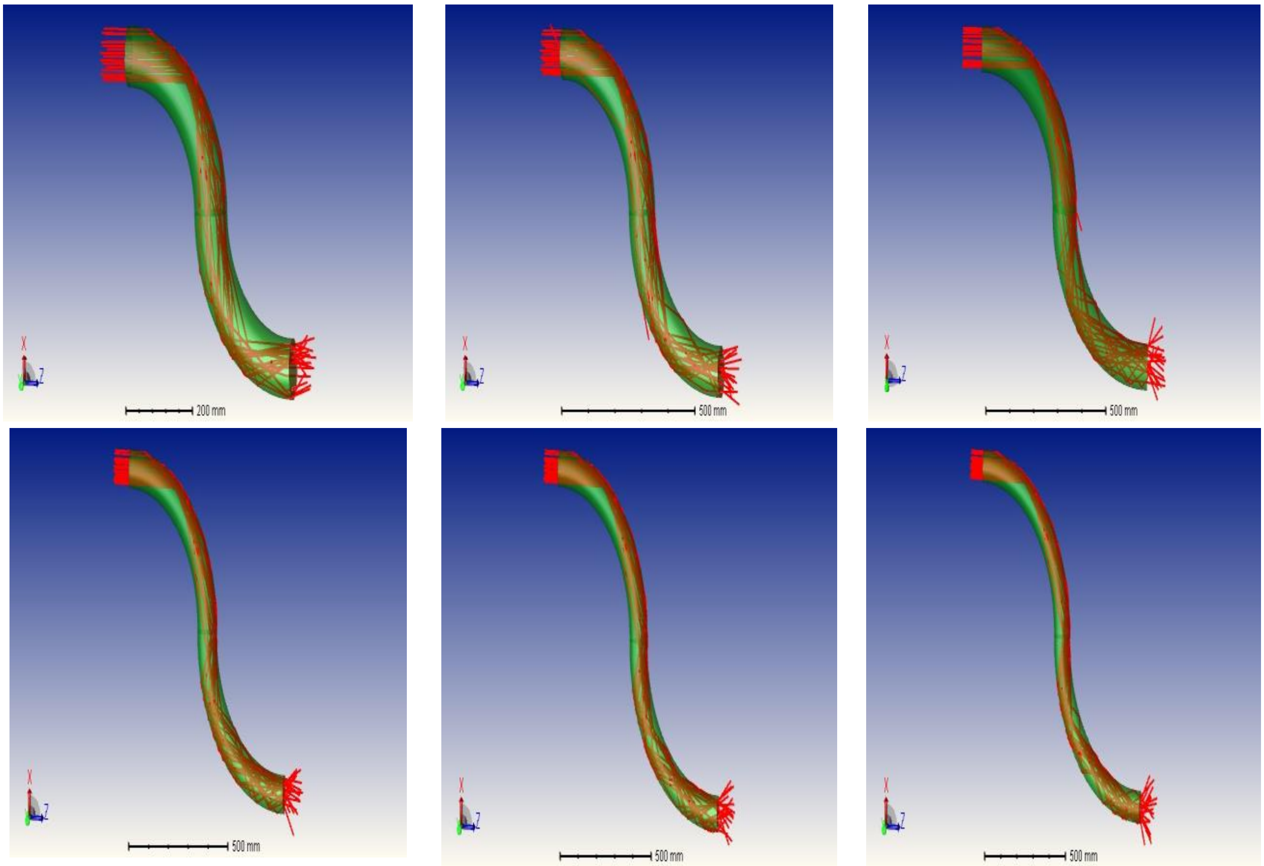

Figure 9. Changing of entrance aperture of S-shape circular cross-section waveguide.

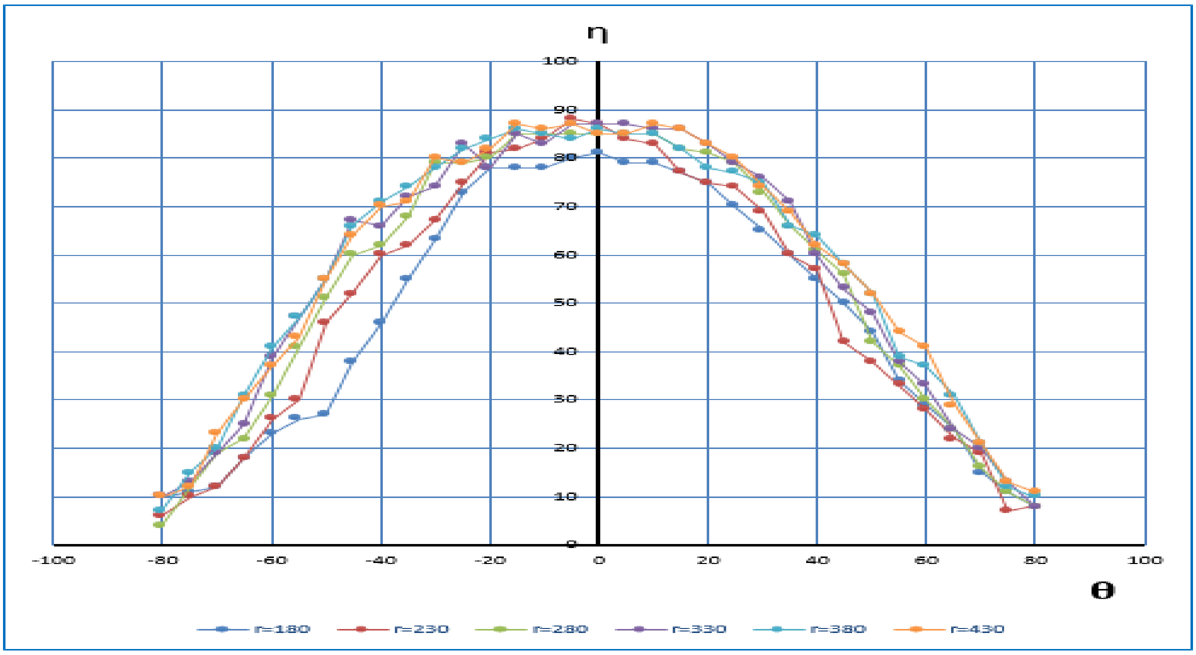

Figure 10. Optical efficiency of different incidence angle when changing the entrance aperture of U-shape circular cross-section waveguide.

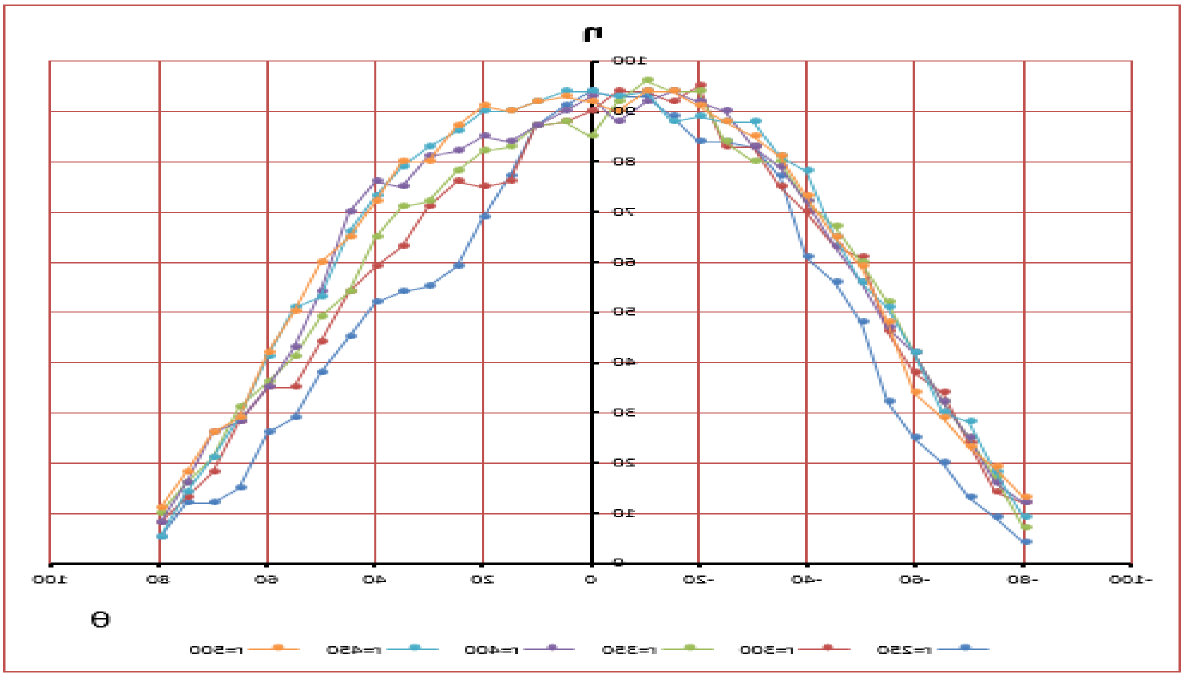

Figure 11. Optical efficiency of different incidence angle when changing the entrance aperture of S-shape circular cross-section waveguide.

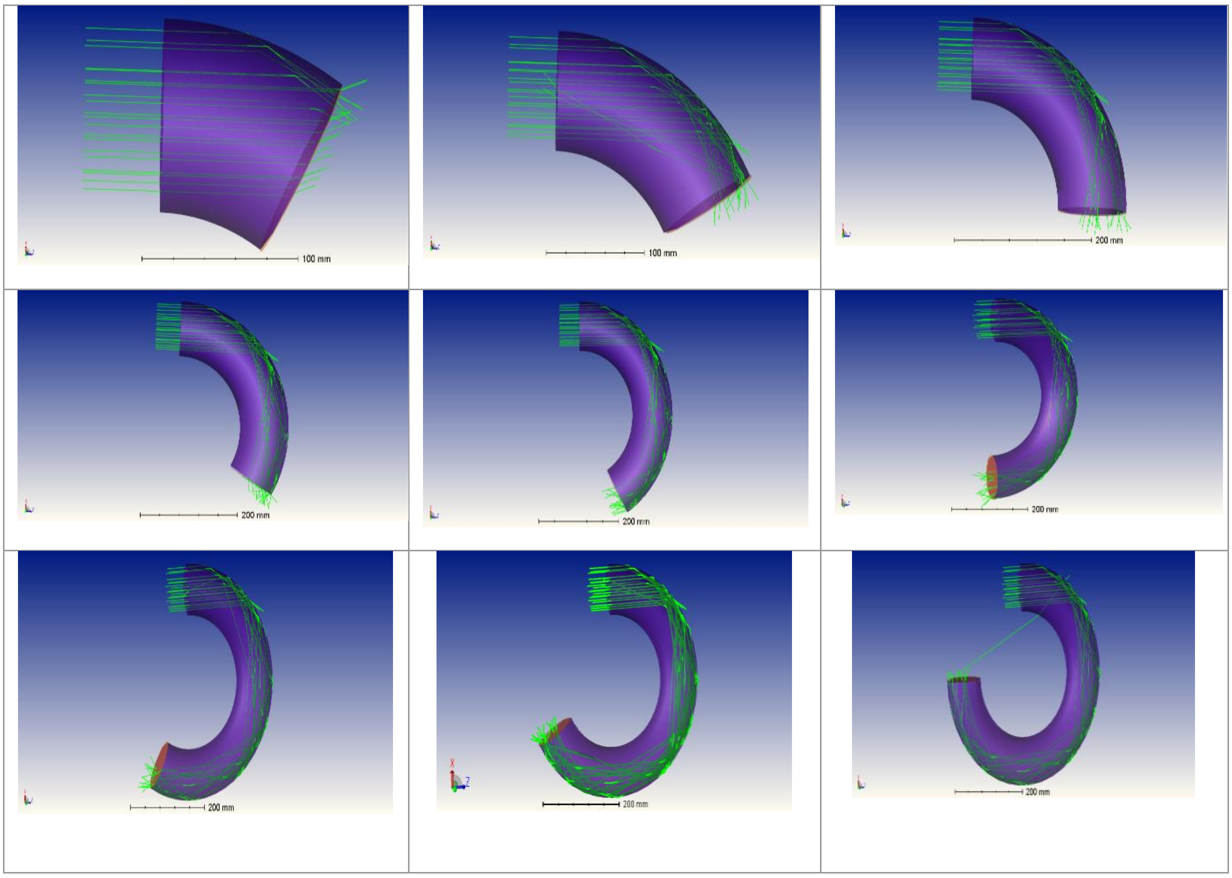

Figure 12. Changing of rotation angle (30º-270º) of U-shape circular cross-section waveguide.

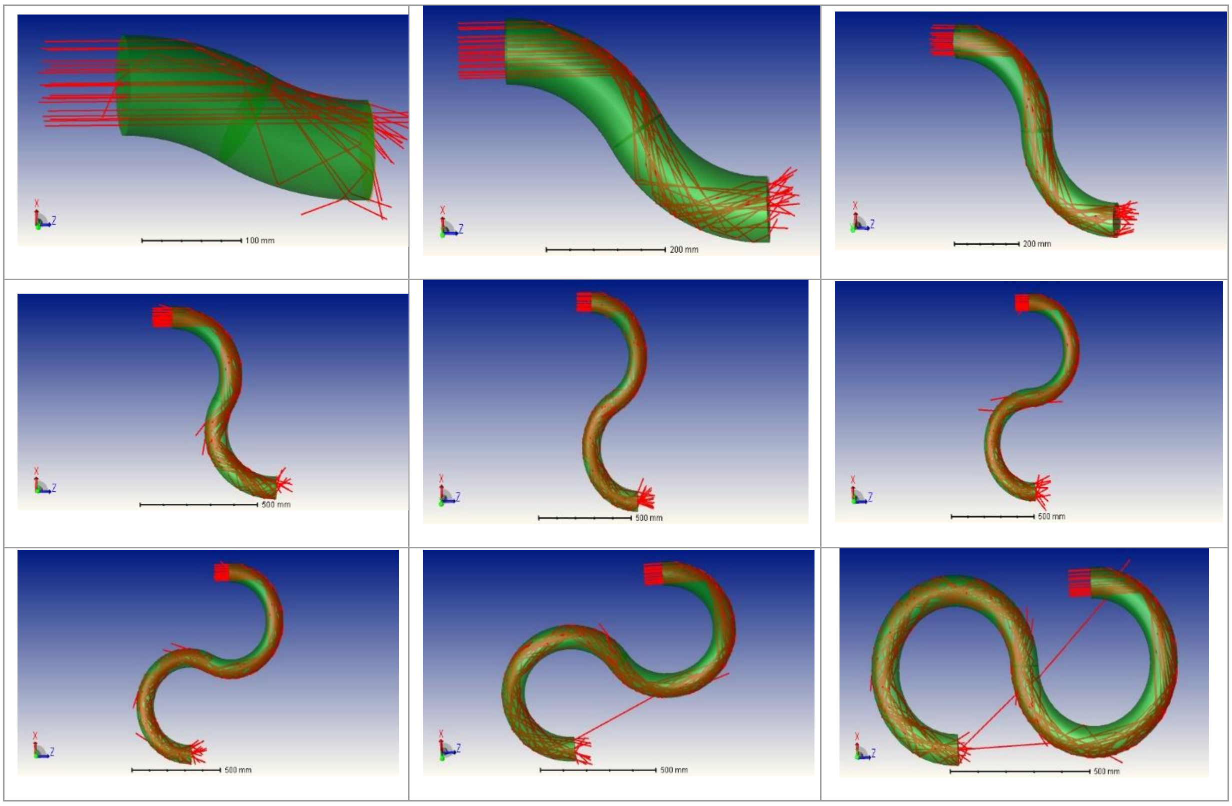

Figure 13. Changing of rotation angle (30º-270º) of S-shape circular cross-section waveguide.

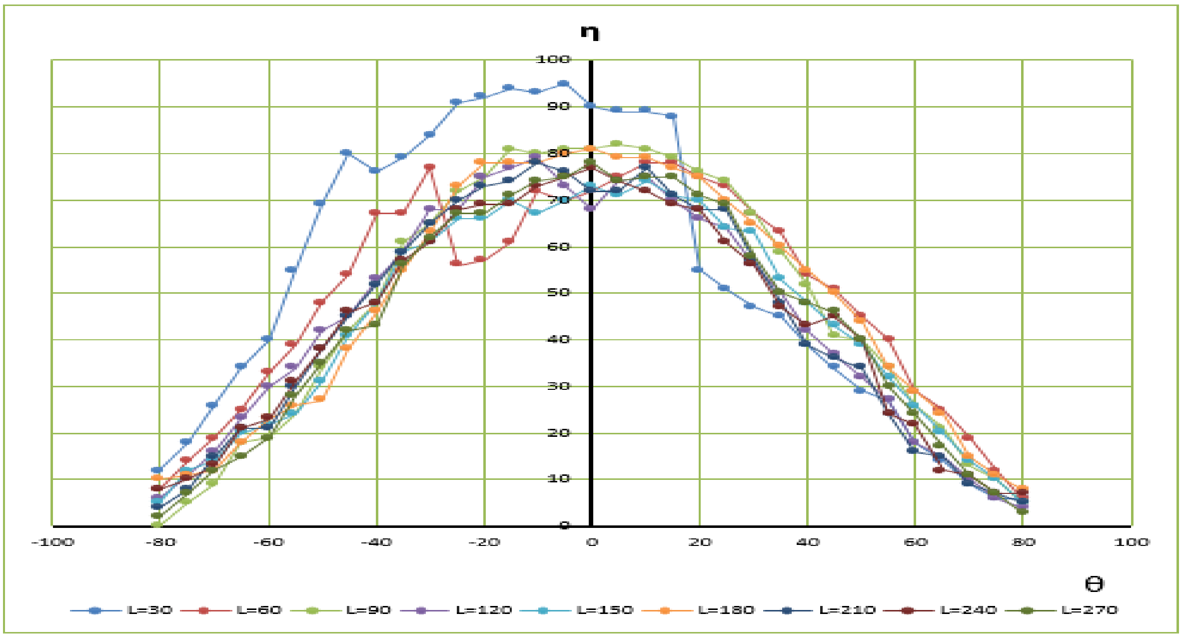

Figure 14. Optical efficiency of different incidence angle when changing the rotation angle of U-shape circular cross-section waveguide.

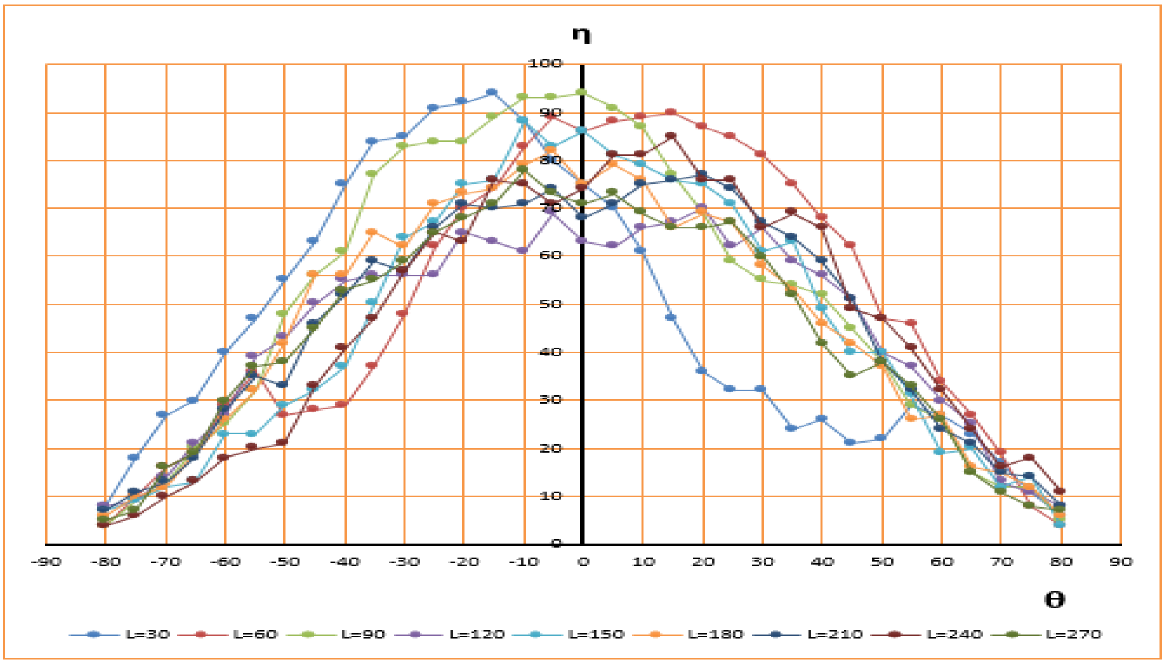

Figure 15. Optical efficiency of different incidence angle when changing the rotation angle of S-shape circular cross-section waveguide.

4. Conclusion

A waveguide for a solar radiation system was designed in the shape of the letter (U, S) with a circular cross-section to transmit solar radiation with high efficiency to any place within the solar system with great flexibility by changing the shape of the model according to the size and shape of the solar system. The design also gives a relatively large angle of acceptance, which gives adequate optical efficiency without the need for a solar tracking system. A group of optical parameters, namely the radius of the guide curvature, the diameter of the entry apertures, and the rotation angle, were changed without greatly affecting the efficiency of the system's performance to make the design possess high flexibility in changing its shape and length while maintaining its efficiency almost constant. The results showed that the efficiency value remained constant when the entry hole was changed. The rotation angle of the U-shaped design is greater than the S-shaped design, while the efficiency value changes significantly when the radius of curvature of the waveguide changes as a result of changing the angle of reflection of the rays inside the guide.

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Conflict of Interest

The authors declare that they have no conflicts of interest.

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References

1. Khaligh OC, Alireza S. Energy harvesting: solar, wind, and ocean energy conversion systems. CRC press. 2017;22:12-23. https://doi.org/10.1201/9781439815090
2. Heidari N, Pearce JM. A review of greenhouse gas emission liabilities as the value of renewable energy for mitigating lawsuits for climate change related damages, Renew. Sustain. Energy Rev. 2016;55(2):899–908. https://doi.org/10.1016/j.rser.2015.11.025
3. Ginley NR, Green A. Solar Energy Conversion Toward 1 Terawatt, Hornessing Mater. Energy. 2008;12(3):355–364. https:// doi.org/10.1557/mrs2008.71
4. Irena A. Renewable Energy Cost Analysis - Concentrating Solar Power, Int. Renew. Energy Agency Renew. 2012;23:1–41.
5. Rauschenbach S, Hans S. Solar cell array design handbook: the principles and technology of photovoltaic energy conversion, Springer Sci. Bus. Media .2012.
6. Dudley E, Kolb J, Mahoney A, Mancini T, Kearney D. Test results: SEGS LS-2 solar collector. Sandia National Laboratory. 1994;140:33-45.
7. Duffie WB, John A. Solar engineering of thermal processes. John Wiley & Sons, Appl. Opt. 2013;12: 55-67. https://dOI:10.1002/9781118671603
8. Zhang JX, Hoshino K. Optical molecular sensing and spectroscopy. Optical transducers. 2019;12(2): 23-45. https:// doi.org/10.1016/B978-0-12-814862-4.00005-3
9. Yoneda N, Miyazaki M, Matsumura H, Yamato M. A design of novel grooved circular waveguide polarizers, IEEE Trans. Microw. Theory Tech. 2000;48:2446–2452. https://doi.org/10.1109 /22.898996
10. Karp JH, Ford JE. Planar micro-optic solar concentration using multiple imaging lenses into a common slab waveguide, High Low Conc. Syst. Sol. Electr. Appl. IV. 2009;74(4):70-76. https://doi.org/10.1117/12.826531
11. Karp JH, Tremblay EJ, Ford JE. Radial coupling method for orthogonal concentration within planar micro-optic solar collectors. Opt. InfoBase Conf. Pap. 2010;12:9–11.
12. Cheng YL. Review on Optical Waveguides. Shankar, Intech. 2018;11(2):13-18. https://doi.org/10.5772/intechopen.77150
13. Bauser HC. Photonic Crystal Waveguides for >90% Light Trapping Efficiency in Luminescent Solar Concentrators. ACS Photonics. 2020;7:2122–2131. https:// doi.org/10.1021/acsphotonics.0c00593
14. Rühle S, Greenwald S, Koren E, Zaban A. Optical waveguide enhanced photovoltaics. Opt. Express. 2008;16(2):26-32. https:// doi.org/10.1364/OE.16.021801
15. Wang YM, Zheng G, Yang C. Characterization of acceptance angles of small circular apertures. Opt. Express. 2009;12(3):45-56. https://doi.org/10.1364/oe.17.023903

16. Murphy F, Tommy D. Analysing curved optical waveguides using the finite difference beam propagation method. Appl. Opt. 2020;11(2):67-78.
17. Farhan M, Adnan BI. The effect of temperature on polymethyl methacrylate acrylic (PMMA). Appl. Opt. 2013;17:22-34. https://doi.org/10.1016/j.polymertesting.2016.12.016
18. Hsu MY, Shenq TC, Ting MH. Thermal optical path difference analysis of the telescope correct lens assembly. Advanced Optical Technologies. 2012;6(4):447-453. https://doi.org /10.1515/aot-2012-0058.
19. Mahajan VN. Optical Imaging and Aberrations. Ray Geometrical Optics, Part I, II, By SPIE: Press Monograph. 1998;45:344-355. https://doi.org/10.1117/3.265735
20. Sanyal S, Ajay G. The factor of encircled energy from the optical transfer function. Journal of Optics A: Pure and Applied Optics. 2002;4:208-211. https://dOI.10.1088/1464-4258/4/2/316
21. Al-Saadi TM, Hussein BH, Hasan AB, Shehab AA. Study the structural and optical properties of Cr doped SnO_2 nanoparticles synthesized by sol-gel method. Energy Procedia. 2019;157:457–465. https://doi.org/10.1016/j.egypro.2018.11.210
22. Alaa BH, Husain SA. Design of Light Trapping Solar Cell System by Using Zemax Program. Journal of Physics: Conference Series. 2018;1003:25- 32. https://doi.10.1088/1742-6596/1003/1/012074
23. Alaa BH. Studying Optical Properties of Quantum Dot Cylindrical Fresnel Lens. NeuroQuantology 2022;20(2):97–104. https:// doi.org/10.14704/nq.2022.20.1.NQ22013.
24. Hamza HN, Alaa BH. Design of Truncated Hyperboloid Solar Concentrator by Using Zemax Program. Ibn Al-Haitham Jour. for Pure & Appl. Sci. 2022;35(2):1-7. https://doi.org/ 10.30526/35.1.2780.
25. Al-Hamdani AH, Rashid HG, Hasan AB. Irradiance distribution of image surface in microlens array solar concentrator. ARPN Journal of Engineering and Applied Sciences. 2013;5:23-31.
26. Karszewski KM, Stewen C, Giesen A, Huge H. Theoretical modeling and experimental investigations of the diode-pumped thin-disk Yb :YAG laser, Quantum Electron. Optica Mag. 1999;29:86-97. https://doi.10.1070/QE1999v029n08ABEH001555
27. Mohammad HS. Determination and suppression of back reflected pump power in Yb:YAG thin-disk laser. Optical Engineer. 2017;56(1):1-8. https:// doi.org/10.1117/1.OE.56.2.026109
28. Hariton V. Feasibility study and simulation of a high energy diode pumped solid-state amplifier. Tecnico Lisboa. 2016;12(3);1-94.
29. Kazemi SS, Mahdieh MH. Determination and suppression of back-reflected pump power in Yb:YAG thin-disk laser, Optical Engineering. 2017;56:026109. https:// doi.org/10.1117/1.OE.56.2.026109
30. Weichelt V, Von B. Experimental Investigations on Power Scaling of High-Brightness CW Ytterbium-Doped Thin-Disk Lasers, App. Opt. 2021;23:1–23.