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TITLE: A review of optical concentrators for portable solar photovoltaic systems for developing countries.

YEAR: 2018

A Review of Optical Concentrators for Portable Solar Photovoltaic Systems for Developing Countries

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Abstract: Worldwide, over 1.1 billion people have no access to electricity. The consequences for the affected people include health hazards from fuels used for lighting, limits to learning when it gets dark, a short productive day and high expenditures on lighting alternatives. Since 85% of affected people live in rural areas in developing countries, increasing access to electricity through grid supply is logistically and financially challenging. As a potential solution to this issue off-grid solar chargers have been gaining popularity. This technology is under continuous development to achieve lower costs, faster battery charge and more electricity generation to prolong light hours. This review contains a comprehensive analysis of possible improvements to solar lights and the role solar PV concentrators can play in it. It aims to provide the reader with a critical comparison of existing solar PV concentrators and to consider the advantages and drawbacks if applied to portable solar systems used in developing countries. From this review, static nonimaging concentrators have been identified as best suited since they are easy to operate and maintain and have shown high reliability. A detailed comparison of existing static nonimaging concentrators is presented in this work and their suitability for being deployed in portable solar systems in developing countries is evaluated. It concludes that the existing designs need adjustment if to be used for this purpose. Thus, novel concentrator designs for portable solar systems for developing countries are needed to facilitate more off-grid solar power generation. It is the aim therefore of this review to stimulate more research in this field.

Key words: solar PV concentrator, concentrated portable solar systems, rural electrification, solar lamps

1. Introduction

Worldwide, over 1.1 billion people have no access to electricity and thus no access to clean lighting [1]. The poor quality of light from alternative sources such as kerosene lamps, candles or burning switchgrass limits the ability of the affected people to study or work after the sunset. Furthermore, these light sources have associated health risks such as poisoning from the inhaled fumes, chronical lung diseases, eye irritation as well as increasing the potential for burns from accidental fires. These hazards mostly affect women and children since they are predominantly involved in household chores like cooking [2].

Not having access to clean electricity has a negative impact on people and the environment. Kerosene (for lighting) is responsible for 3% of global black carbon emissions and the contribution of black carbon to global warming is stronger than CO_2. One kilogram of black carbon produces a "positive forcing"[1] during its atmospheric lifetime[2] equivalent to 700 kg of CO_2 over 100 years [3]. Burning local biomass on the other hand leads to erosion and reduces the fertility of the local land.

In Sub-Saharan Africa (SSA) the rural electrification ratio is only 14% [4] whilst in Malawi it is just 1% [5]. Despite progress in the electricity supply has been made in SSA, the population not connected to the grid is expected to increase in the future. This is due to electrification happening at a slower rate than population growth [4].The gap between supply and demand has further increased with the introduction of mobile phones. In rural Zambia, 50% of homes own mobile phones [6] whilst the electrification ratio is only 3% [7]. Consequently people have to walk to the nearest town to charge their phones [8]. The resulting high electricity prices lock communities into energy poverty, as fuel-based lighting is up to 150 times more expensive than efficient lighting [4].

Approximately 85% of the affected people live in rural communities in developing countries [1]. The lack of infrastructure is one of the main obstacles to the electrification of rural areas. Low electricity demand, small population density and long distances to the nearest substation make the connection of remote areas extremely challenging. In Kenya for example, when a household is further in distance than 600 m to the nearest substation, the full cost of the grid extension has to be met by the household [9]. Additionally, in many Sub-Saharan countries the electricity supply is characterised by increasing prices and frequent blackouts . This is mostly due to insufficient generating capacity and a high reliance on fossil fuels [4].

It is however not the grid connection that people want, but the potential benefits the energy provides. This suggests the way towards electrification does not need to be a centralised solution. Whilst Baurzhan et al. [10] state there is little evidence that off-grid solar systems contribute to poverty alleviation, the World Bank identified that the benefits of off-grid renewable energy solutions in rural areas are low costs, environmental sustainability, a contribution to Millennium Development Goals[3] and a faster service provision than grid supply [11]. For instance, access to clean lighting has helped improve children's education, facilitated longer working hours (e.g. by illuminating a kiosk); and enabled households to make financial savings [12,13]. Since SSA has an abundance of solar radiation throughout the year [14], solar systems are seen as the way forward to decentralised electrification.

The options for local renewable energy generation include mini- and microgrids as well as solar home systems (SHS). Since microgrids involve larger capital costs and are more complex to operate [9], SHSs have been regarded as a more viable solution. Yet, investment costs remain high [10], and SHSs are primarily targeted at middle and high income families [15–17]. A further problem with SHSs and microgrids, as argued by Baurzhan et al. [10], is the underestimated operation and maintenance costs, which are not given sufficient consideration in financial schemes. Furthermore, the authors argue that repaying a solar installation over multiple years as fixed debt, does not offer the same flexibility as purchasing kerosene, which can be done according to the financial constraints.

As a smaller solution, solar lights have been introduced into the market. The main components are a solar panel, a rechargeable battery, a light-emitting diode (LED) lamp and more commonly a USB charger with phone adapters [4]. These have the advantage of smaller upfront costs, do not involve

[1] Measure of atmospheric warming

[2] Atmospheric lifetime of black carbon is estimated as 4 - 12 days [114]

[3] Eight targets set by the UN nations to reduce extreme poverty by 2015 and extended to 2030 [115]

operational and maintenance costs [4] and are easier to stock and distribute by non-specialist shops. Solar lights retail at different prices according to the amount of electricity they generate, therefore more solar lights can be purchased when the demand or financial means increase. This makes them more scalable than SHSs and microgrids.

In this paper the performance, affordability and sustainability of solar lights is discussed and potential ways to improve the systems are highlighted. This work focuses on a new approach of using solar PV concentrators to improve the properties of solar lights. While other reviews of solar PV concentrators are available in literature [18–21], this article presents a comprehensive review of existing concentrator types and discusses their potential and suitability specifically for portable solar systems for rural areas in developing countries. Conclusions and recommendations are drawn and discussed.

2. Solar lights and solar chargers

While some people are highly satisfied with their solar lights, others feel the low quality of the light compared to grid power further reinforces their poverty and low social status[5]. A solar lantern at the lowest range provides a luminous flux of 20 lumens [22,23], only twice as much as a kerosene lamp and just enough to illuminate a small area. However, compared to a kerosene lamp where light is emitted in all directions and only a half to a third of it is usable light [24], LED light is directional and therefore more efficient. Furthermore, current lamps take 5 to 10 hours to charge to provide 4 to 6 hours of light at high intensity. In addition, solar lights are still considered expensive to purchase. A low range study light providing 20 lumens currently costs USD 5 (Table 1) [23,25–31], and whilst USD 5 might not seem a large investment, the financial possibilities of the poorest of a rural community need to be taken into account. In Malawi for example, only a quarter of a million people have an income above USD 5 per day and around 74% of the total population live below the poverty line of USD 1.25 per day (effective 2010) [32,33].

Table 1 Current price range of solar lamps, data from [23,25–31]

To be an efficient solution, a solar light needs to generate more electricity, store it more quickly while being low cost and highly portable. This can be achieved by improving different parts of the design: the LED light, the battery and the solar module.

Higher efficiency LED light

LED light sources have a longer life span and a higher luminaire efficacy than compact fluorescent lamps (CFL) and incandescent light sources. The main drawback is the price per lumen, which is currently considerably higher than other light sources. The relative cost however is predicted to fall by 70% between 2013 and 2020 while the luminaire efficacy is expected to increase by 36% by 2020 [34].

Quicker charging battery

[4] The only operational cost is the battery replacement, which is due around every 5 years [23,25–31] The battery cost at the moment are around 25% of the overall cost.

[5] Joanna Gentili, Founder and CEO, Team Planet (http://www.goteamplanet.com/), pers. comm with Glasgow Caledonian University, Centre for Climate Justice (7May15)

Lithium-iron-phosphate ($LiFePO_4$) batteries are most commonly used for portable solar devices and have several advantages over the alternatives. These benefits include not requiring specific recycling facilities which is crucial for applications in rural areas; a long life time of up to 2000 cycles and a low self-discharge [4]. Furthermore, they are chemically more stable and are best suited for outdoor usage. The drawbacks are: higher costs than nickel-metal-hydride (NiMH) and nickel-cadmium (NiCd) batteries and a lower mass-energy density than lithium-cobalt-oxide ($LiCoO_2$) batteries [35]. A comparison of batteries most commonly used for portable solar systems is shown in Table 2 (not including sealed lead acid batteries).

Table 2 Comparison of rechargeable batteries most commonly used for portable solar systems, data from [4]

The charging time of a $LiFePO_4$ battery depends on the charging current. An 800 mAh 3.2 V battery for example takes 6 hours to charge at 160 mA and 3 hours at a 400 mA [36]. Thus increasing the charging current would be an advantage. Additionally, overvoltage can be applied without damage to $LiFePO_4$ batteries to reduce charging time by 1/3 [35]. Further improvements in battery technology are expected in the near future; MIT researchers for instance fabricated a single cell which can be charged within 10 - 20 seconds instead of 6 minutes [37,38].

Higher solar module output

To suggest improvements for the photovoltaic (PV) module, the PV materials currently used in the systems need to be examined. The following section shows a comparison between the PV technologies currently being used and available alternatives. Their advantages and limitations are highlighted.

The PV material most commonly used for solar lights is crystalline silicon (c-Si) [23,25–31]. Having benefited from parallel development in the semiconductor industry, c-Si based PV modules have been dominating the photovoltaic market for the last decades [39]. Mono c-Si solar cells are produced from high purity single crystal ingots; they are therefore more expensive than poly c-Si solar cells but also more efficient, with a laboratory efficiency of 25.6% [39] and a commercial efficiency of ~19% [40,41]. Poly c-Si was developed to reduce production cost of silicon solar cells by using multi grain silicon ingots. Due to increased recombination losses at grain boundaries, the laboratory efficiency is reduced to 21.3% [39] and the commercial efficiency to 14% [40,41]. Besides high efficiencies, c-Si solar cells have the advantage of high durability under outdoor conditions and non-toxic components [42]. Considering the lack of maintenance and the lack of appropriate recycling facilities in rural areas in developing countries, c-Si solar cells are highly suitable for solar lights. The only obstacle is the high cost.

Given that the efficiency limit for silicon based solar cells with an energy gap of 1.1 eV is 30% [43] and that efficiency improvements of silicon solar cells have been stagnating over the last two decades [44], research into new materials and device structures has been increasing. Second generation solar cells are thin film technologies which were developed to exceed the efficiency limit of silicon solar cells and to cut costs by reducing the active layers from ~100 μm to < 10 μm [45]. These technologies include: amorphous silicon, copper indium diselenide (CIS), copper indium gallium diselenide (CIGS), cadmium telluride (CdTe) and gallium arsenide (GaAs). Amorphous silicon solar cells only require 1% of the silicon material needed for mono c-Si solar cells and therefore have low cost per W_p [46]. However, due to its low efficiency, which is 14% laboratory [44] and 8% commercially [40], amorphous silicon is mostly used where low cost is more important than space efficiency. It is therefore rarely used for solar lights. CIGS, CdTe, GaAs have band gaps closer to the ideal of 1.5 eV and achieve high laboratory conversion efficiencies of 21%, 21%, 29% respectively [44–48]. They contain toxic materials which can be a problem during the manufacturing process, but in particular during disassembly, since specific recycling facilities are required [49–51]. Furthermore, CIGS solar cell producers have benefited from indium being a by-product of zinc smelting and refining. If increased production will exceeds the amount of indium available as a by-product, more costly resources will need to be used, which will increase the cost of CIG and CIGS PV [52].

Third generation or emerging technologies include dye sensitized solar cells, perovskite cells, organic cells and multiple junction solar cells. The most recent and promising PV technology is hybrid perovskite PV, due to an efficiency jump to 17.9% within only four years [53]. They have the advantage of low material costs and bandgap tenability but the material is highly sensitive to moisture and the cells are not stable [54]. As a possible market niche, tandem cells from large band gap perovskite and Si are suggested [55]. Dye sensitized and organic solar cells on the other hand are favoured due to their less complex manufacturing process and cost effective materials [56]. Efficiencies of 11% have been recorded for both technologies [47]. However, efficiency and stability of these solar cells needs further improvement to gain a higher market share [56]. Hybrid perovskite, dye sensitised and organic solar cells are therefore not currently used in portable solar systems.

Multijunction solar cells achieve high efficiencies by stacking material layers with different band gaps to absorb a larger part of the light spectrum. A record efficiency of 46% has been achieved by Fraunhofer ISE / Soitec with a quadruple junction solar cell [44]. A different approach for the same idea is used in split-spectrum solar cells. A pre-optical setup splits the spectrum into energy bands, which are then guided and absorbed by solar cells with a matching band gap. It has been shown that a 50% efficiency can be obtained using this technology [57]. However, multijunction and spilt-spectrum solar cells are extremely expensive to manufacture and are therefore not suitable for portable solar systems [53].

Solar cells for portable solar systems for developing countries need to have a low ecological footprint since recycling facilities are limited or non-existant. Additionally, the material needs to be widely available on the market so that solar lights can be assembled locally. From the PV materials discussed in this section it can be concluded, that silicon based solar cells remain best suited for this application.

Another method of improving the electrical output of the module is simply to increase its size. However, this will result in a direct increase in price, since the solar module contributes approximately 20 - 25% of the overall cost of a small solar lantern. From an environmental perspective it is also advantageous to use less PV material. Albeit silicon based solar cells do not include toxic materials, quartz for silicon needs to be mined putting the workers and local population at risk. The manufacturing process of silicon solar cells also involves toxic substances and elements such as silicon tetrachloride, hydrofluoric acid and cadmium, which when not treated at high safety levels can harm workers and the environment [58]. Thus, increasing the output without increasing the amount of PV material used is preferable.

An alternative approach to increasing the electrical output of the solar module is to use solar PV concentrators. A solar PV concentrator increases the electrical output of the system whilst using the same amount of PV material. This is not only beneficial for the environment but also has the potential to reduce the overall costs, given that the cost for the concentrator is lower than the PV material cost it replaces[6]. Furthermore, concentrated light on the cell results in an increased photo-generated current, which enables a quicker battery charge.

The solar PV concentrator design depends on the application. A solar PV concentrator for portable PV systems for developing countries needs to meet the following requirements: (i) low complexity; (ii) minimum maintenance; (iii) high reliability; (iv) low cost; and (v) non-toxic materials. The following section gives an overview of existing solar concentration types including their advantages and disadvantages. Their suitability to be used for portable solar systems for developing countries is analysed according to the outlined requirements.

3. Solar PV concentrators

A solar PV concentrator is a device which redirects light rays from a large area onto a small area [59]. Optical concentrators can be categorised by their concentration ratio. Systems with a concentration ratio <10 x are low concentration devices. They require neither tracking nor cooling, have generally a large light acceptance angle[7] and concentrate more diffuse light. However, 1-axis tracking can be used to prolong light collection hours [18]. Systems with concentration ratios between 10 x and 100 x are medium concentration systems requiring cooling and at least 1-axis tracking. Systems with a concentration ratio >100 x are considered as high concentration systems requiring cooling and high precision 2-axis tracking with tolerances below 0.2° [18,60].

For solar concentration, a PV material with high stability is required due to increased heat from additional thermal losses within the PV material [53]. For concentration ratios below 40 x, c-Si solar cells have been used in building integrated photovoltaics (BIPV). Nevertheless, silicon solar cells show a reduction in generated power at temperatures above 25 ºC at a reduction rate of up to 0.65% K^{-1}. Active cooling is therefore particularly important for medium and high concentration systems. For low concentration systems on the other hand, the solution depends on the concentration factor. F. Muhammad-Sukki [61] reported a power decrease of 13% in a silicon solar cell at concentration ratios of ~4 x at a maximum temperature of 58 ºC. For concentrating systems of a similar range, the temperature increase can be managed by passive cooling.

The categorisation used in this work is based on the concentration method (reflective, refractive, hybrid, luminescent) and on the optics type (imaging, nonimaging) (Figure 1). Additionally, the concentrators can be divided into 2D and 3D designs, depending on whether the concentration is performed on one plane or on two planes [62].

[6] Cost saving depend on various parameters, see section 4.2

[7] The acceptance angle specifies the range of angles of incidence within which light rays are accepted by the system

Figure 1 Characterisation of solar PV concentrators

3.1 Reflective-imaging concentrators

Imaging solar PV concentrators focus rays from a light source onto a focal point, thus creating an image of the light source. The image gets dispersed when the incident light rays are not parallel to the axis of the concentrator. Hence, high accuracy tracking to sharply reproduce the image and to achieve high concentration is required.

The best example of imaging reflective concentrators is the paraboloid where parallel rays are reflected onto a focal point (Figure 2). 2D concentration is achieved by a parabolic trough where rays are focused onto a line and 3D concentration is achieved by a parabolic dish where rays are focused onto a point, using 1-axis and 2-axes tracking respectively [63]. The concentration limit of a parabolic trough is ~70 x as reported by Canavarro et al. [64] which is due to the emerging compromise of optical efficiency, acceptance angle and irradiance distribution [19]. However, in combination with a secondary optic, concentration ratios of ~200 x have been achieved [64–66]. Since the reflector requires high precision manufacturing [67], the high costs, the required manufacturing know-how and the operation and maintenance costs are prohibitive for reflective-imaging concentrators to be used in portable solar systems in developing countries.

Figure 2 Parabolic concentrator, redrawn from [68]

3.2 Reflective-nonimaging concentrators

While imaging optics maintain the interior order of the light rays, nonimaging optics consider solely the boundary of the transmitted light beam without paying attention to the interior order of the transmitted light rays. The light rays within the specified acceptance angle are focused onto an area in the exit aperture. Due to their larger acceptance angle than imaging optics, nonimaging concentrators have a higher capability to capture diffuse light [69].

The ***compound parabolic concentrator*** (CPC) is the most common example of nonimaging optics. It was proposed and developed by Winston and Welford [69]. The CPC consists of two segments of parabolas and all the rays incident within the acceptance angle are reflected towards the exit aperture (Figure 3). The CPC comes close to be an ideal concentrator with a high concentration ratio, a high optical efficiency[8] and a large acceptance angle compared to imaging systems with similar concentration ratios [70]. However, CPCs are not used for high concentration applications due to their excessive heights at high concentration ratios. The height can be reduced by truncation, however, only along with the concentration ratio [69]. A further problem of CPCs is the non-uniform light distribution on the solar cell [70], but which has been reported to be insignificant for concentration ratios <10 [19]. Variations of the CPC have been proposed to achieve better irradiance distribution [71,72] While a reflective, CPC with a low concentration ratio fulfils the

[8] The ratio of radiant flux at the entrance aperture to the radiant flux at the exit aperture [116]

requirements of low complexity, low maintenance and high reliability; the manufacturing costs of a reflective surface for low concentration systems are prohibitive.

Figure 3 Compound parabolic concentrator

The design proposed by Rabl [20] is a reflective solar PV concentrator for a bifacial solar cell. It focuses the light with a concentration ratio of up to 3.4 x within the half-acceptance angles of ± 36º. This concentrator design has been proposed for building integrated photovoltaics, therefore the system can be installed for maximum output in either summer or winter (Fig. 4). Due to the low market availability of bifacial solar cells [73,74] and the required knowledge on appropriate orientation, this design is less suitable for portable solar system for developing countries.

Figure 4 Sea Shell concentrator

Another reflective, nonimaging concentrator is the ***hyperboloid*** concentrator which consists of two hyperbolas reflecting all incident rays within the acceptance angle to the exit aperture of the concentrator (Figure 5). It has a compact design when truncated and the efficiency can be increased by incorporating an additional lens at the entrance aperture [21]. However, on its own, it is not suitable for infinite light sources [69].

Figure 5 Hyperboloid concentrator

A similar approach is used in the ***cone*** concentrator which guides incident light rays towards the exit aperture by total internal reflection (Figure 6). Compared to the CPC, the V-trough concentrator has been reported to be less prone to hot-spots [18]. However, it is far from being ideal, due to a maximum transmission of 80% within its acceptance angle [69].

Figure 6 Cone concentrator

Linear Fresnel reflectors use an arrangement of individual mirrors to focus light onto a receiver. This gives freedom in tracking where either the entire system, the receiver or the individual mirrors can be moved to track the sun [18]. Due to the large size, high manufacturing costs of the mirrors, high precision tracking and the required cooling, this concept is not considered for portable solar systems for developing countries.

3.3 Refractive concentrators

Refractive concentrators use optical refraction between materials with different refractive indices to focus light and do not require expensive reflecting materials. The main example is the ***Fresnel lens*** where parallel rays are refracted and focused onto a focal point (Figure 7) achieving concentration ratios >100 x. To reduce material cost, volume and weight, one side of a Fresnel lens is facetted, where each facet approximates the curvature of an imaging lens. A high concentration Fresnel lens can have up to 100 facets per mm, thus high accuracy in manufacturing is necessary.

Furthermore, Fresnel lenses suffer from chromatic aberration. Various designs have been proposed to improve the flux distribution on the solar cells by either altering the facets or by incorporating a secondary optic [75–78]. Further designs are proposed combining a Fresnel lens with mirrors redirecting the focused light from multiple Fresnel lenses onto one solar cell. However, low optical efficiencies due to reflection losses and imperfect alignment have been reported [79].

Refractive imaging concentrators are less suitable for portable solar systems for developing countries because of their small optical tolerances, the large focal distance, high precision manufacturing and tracking.

Figure 7 Fresnel Concentrator, redrawn from [68]

3.4 Hybrid nonimaging concentrators

Hybrid concentrators use refraction and total internal reflection (TIR) to focus light. For the same concentrator design, a higher acceptance angle or a higher concentration ratio can be achieved when using the dielectric. This is due to light refraction at the boundary of two materials with different refractive indices [80]. The main examples of hybrid concentrators are flat high concentration devices, dielectric totally internally reflecting concentrators (DTIRC), wedge prisms, dielectric compound parabolic concentrators (CPCs) and dielectric hyperboloid concentrators.

Various designs of the ***flat high concentration nonimaging devices*** have been proposed since 1995, namely the RR, XX, XR, RX and the RXI concentrators. The acronyms stand for “R” refractive, “X” reflective and “I” totally internally reflective. Thus, an RXI concentrator incorporates all three features where rays are refracted at the entrance surface, experience internal reflection at the bottom side of the concentrator and total internal reflection at the inside of the entrance surface towards the solar cell (Figure 8). The RXI is a very compact design achieving the theoretical maximum concentration. However, due to the solar cell position, it is difficult to collect electricity and heat from the solar cell and it is complex to manufacture [21,81]. The resulting high costs as well as the requirement for tracking and cooling make the flat high concentration imaging devices not suitable for portable solar systems for developing countries.

Figure 8 Flat high concentration nonimaging concentrator of the RXI type, redrawn from [69]

Further compact optics for high concentration were developed by Minano et al. [69] by using a stepped flow line method. The compact concentrator uses multiple small CPCs and a parabolic reflector to give a compact design, incorporating mirroring and refracting materials. The high complexity in manufacturing of such concentrators means this design method does not meet the outlined requirements for portable solar systems for developing countries.

The ***dielectric totally internally reflecting concentrator*** (DTIRC) consists of three main parts; a curved entrance aperture, a totally internally reflecting side profile and an exit aperture (Figure 9). At a smaller height than the CPC, higher concentration can be achieved approaching the theoretical maximum [82]. For a CPC and a DTIRC fabricated from the same material, with the same refractive index, height and exit aperture, the CPC will always have a larger acceptance angle [83]. The DTIRC can be designed using the phase conserving method or the maximum concentration method, enabling more uniform light distribution and higher concentration ratios respectively [82]. Although the DTIRC fulfils the requirements of low complexity, maintenance and high reliability, the concentrator height, which is determined by the design algorithm, increases with the concentration ratio making it cost prohibitive [84].

Figure 9 Dielectric totally internally reflecting concentrator, redrawn from [85]

The ***wedge prism*** concentrator directs the light within the lens towards the exit aperture using TIR (Figure 10). This lens design is more commonly used for light direction rather than light concentration due to its low concentration ratio compared to other concentrator designs as presented in this work. It is therefore not given further consideration.

Figure 10 Wedge prism concentrator

A ***luminescent concentrator*** uses transparent materials to absorb and redirect light to a solar cell, which is commonly attached at the side of a window glass (Figure 11). The transparent material is a mixture of glass, dye molecules and aluminium based tris-(8-hydroxyquinoline) molecules. Photons absorbed by the dye molecules are reemitted and directed to the solar cell by total internal reflection. To increase the efficiency, aluminium molecules were introduced which cause the photons to be reemitted at different wavelengths than the dye molecules can absorb. In combination with a GaAs solar cell, overall efficiencies in excess of 7% have been achieved.

Figure 11 Luminescent concentrator, redrawn from [86]

A similar concept is used in the quantum-dot concentrator where quantum dots from crystalline semiconductors are used instead of the luminescent dye. Their advantage is higher UV-stability and the ability to control the size of the dots. The latter influences the absorption and luminescence of photons and minimises losses from reabsorption [18]. On the other hand, their efficiency is lower than that of the luminescent concentrator comprising 3.5% in conjunction with GaAs solar cells [87,88]. Further research into material stability and an increase in efficiency are both necessary.

A further alternative is the light guide concentrator proposed by Morgan Solar and the University of Rochester [89]. The systems uses precisely manufactured features within a dielectric lens to deflect light into a light-guide where the light is trapped. By TIR the light reaches the centre of the light-guide where a secondary concentrator focuses the light onto a solar cell [89]. While theoretical concentration ratios of 700 x – 1400 x have been reported possible, a suitable material which can incorporate complicated moulded geometries and does not degrade quickly under high concentrations has proven difficult to develop. Due to the complexity of manufacturing, this design method does not comply with the outlined requirements for portable solar systems for developing countries.

4. Concentrator designs for portable PV for developing countries

To date very little research has been undertaken on concentrators for portable solar systems in general. The two main concepts have been proposed by Lewis Fraas et al. [90,91] from JX Crystals and Barnett et al. [92]. The first design by JX Crystals was a concentrated solar generator using linear Fresnel lenses in combination with 32% efficient solar cells. JX Crystals proposed a design with folding legs, to enable a particular focal distance for the Fresnel lenses. At a concentration ratio of 10 x, an output of 15 V was achieved altough the device orientation needed to be adjusted every two hours. A follow up design incorporated point focus Fresnel lenses instead of linear focus lenses and GaInP/GaInAs/Ge triple junction solar cells of 39% efficiency to charge a 12 - 24 V battery. Single axis electronic tracking and daily manual adjustments were required and the cooling of solar cells was recommended to maintain performance. Although the size of the device when folded was suitable for portability, the device was space consuming when deployed, having a stand and folding legs to allow for tracking and a focal distance respectively. A technical limitation factor as stated by Fraas et al. [90] is the non-uniform flux distribution and the increased heat on the solar cell.

Since these systems were designed with the US army as a customer in mind, complexity of operation and cost of such devices was not an issue. If they were to be deployed in rural areas in developing countries, several disadvantages become obvious. Firstly, the implementation of high efficiency solar cells is costly as well as the required tracking and cooling. Secondly, materials from used solar cells are toxic and require disposal facilities, which are not available in most developing countries. Lastly, the use of the proposed systems requires knowledge on appropriate orientation, and since the opportunities for knowledge transfer and training are limited in remote areas, the design is not suitable for use there.

Spectrum splitting for solar energy conversion has contributed to achieving high energy efficiencies, yet, manufacturability and cost remain a problem [93]. The design proposed by Barnett et al. [92] is compact using solar concentration and spectrum splitting to redirect and focus light bands on a low energy and a medium energy solar cell. The design incorporates a refractive front lens, a hollow pyramidal reflective concentrator, a dichroic lens and a nonimaging solid concentrator. Light below 1.4 eV is passed by the dichroic lens onto the silicon solar cell, while light between 1.4 eV and 2.4 eV is reflected onto the nonimaging concentrator and focused onto a GaInP/GaAs solar cell. The overall thickness between the front lens and the solar cell is 11 mm. An overall system efficiency of 50% was achieved at a concentration ratio 20 x. However, the optical efficiency drops rapidly outside an angle of incidence of ± 3° reaching 34% optical efficiency at incident angles of ± 18°. It is therefore designed for fast battery charge in 1 - 2 hours. The narrow acceptance angle, the complexity in manufacturing and the high cost make this design less suitable for portable systems in rural areas in developing countries.

This review concludes that static nonimaging refractive concentrators are best suited for portable concentrated PV systems in developing countries. They are easy to operate, maintain, have shown a high reliability and capture more diffuse light. These types of concentrators have been widely considered for building integrated concentrated photovoltaics (BICPV) but to date no applications in portable solar systems have been reported. The following paragraph presents the designs and characteristics of existing nonimaging static concentrators. Their suitability is analysed based on the criteria of low complexity, low cost and portability (Table 3):

Table 3 Essential requirements of a solar PV concentrator designed for portable solar systems for developing countries

4.1 Suitability of existing nonimaging concentrator designs proposed for portable solar systems for developing countries

4.1.1 2D nonimaging static concentrators

For BICPV, solar PV concentrators need to be installed at a certain angle of inclination according to the latitude in order to achieve maximum concentration over the year. The ***truncated symmetric CPC*** proposed by Zacharopolos et al. [94] incorporates this angle of inclination. With an acceptance angle of 36.4º and a height of 29.4 mm for a 10 mm wide absorber[9], the geometrical concentration ratio[10] is 2.96 x. The optical efficiency remains above 90% for azimuth angles between 20° and 50° and altitude angles between 45° and 90°. A further design proposed by Zacharopolos et al. [94], the ***truncated asymmetric CPC***, has a higher truncation resulting in a height of 17.7 mm for a 10 mm wide absorber. Designed with a 37° acceptance angle, the geometrical concentration ratio is 2.46 x. The optical efficiency remains above 90% for azimuth angles between 0° and 55° and altitude angles between 5° and 60°.

The ***truncated dielectric asymmetric compound parabolic concentrator*** (DiACPC-55) proposed by Sarmah et al. [95] was designed for building integration for locations with latitudes of 55°N and above. At half-acceptance angles of 0°/55° and a height of 14.5 mm for a 6 mm wide absorber (Figure 12), the geometrical concentration ratio is 2.8 x. Since the truncated CPCs need to be installed at a specific angle, this type of design is less suitable for portable solar systems. Furthermore, all three truncated CPCs are 2D designs which have a lower concentration ratio than 3D designs, since the maximum concentration ratio limit for 3D and 2D designs is $1/\sin^2\theta$ and $1/\sin\theta$ respectively.

Figure 12 Truncated dielectric asymmetric compound parabolic concentrator (DiACPC-55), adapted from [96], copyright permission has been granted

[9] Definition of concentrator height and cell width as used in this work is illustrated in Figure 11

[10] Defined as the ratio of the area of the entrance aperture to the area of the exit aperture

4.1.2 3D nonimaging static concentrators

The dielectric ***3D crossed compound parabolic concentrator*** (3D CCPC) proposed by Sellami et al. [62] was designed by taking the intersection of two 2D-CPC extrusions resulting in a concentrator with a rectangular entrance and exit aperture (Figure 13). At a height of 16.16 mm to a 10 mm wide absorber and half-acceptance angles of ± 40º, the concentrator has a geometrical concentration ratio of 3.61 x. The simulated optical efficiency remains around 73% within the acceptance angle. Due to its small height, same concentration ratio and similar acceptance angles at all vertical planes, the dielectric 3D CCPC design is suitable for portable solar systems. An improvement for the use in portable devices would be an increase in the optical concentration ratio.

Figure 13 3D crossed compound parabolic concentrator, adapted from [97], copyright permission has been granted

A further design proposed by Sellami et al. [62] is the ***square elliptical hyperboloid*** (SEH). Its geometry was obtained by the construction of different hyperbolic branches which connect the elliptical entrance aperture with the square exit aperture (Figure 14). The concentrator was designed for a geometrical concentration ratio of 4 x while the acceptance angle varies with the "height to exit aperture width" ratio. For a "height to exit aperture width" ratio ≥ 2, the maximum simulated optical efficiency is above 60% however it drops to below 30% at an angle of incidence of 60°. The acceptance angle and the geometrical concentration ratio are sufficiently high for portable solar systems, however, the wide acceptance angle is only along one axis requiring knowledge on appropriate orientation. A further improvement for its portable solar applications would be a higher optical concentration ratio by either improving the optical efficiency or the geometrical concentration ratio. This can be achieved by adding a lens therefore making it suitable for infinite sources [69].

Figure 14 Square elliptical hyperboloid, adapted from [98], copyright permission has been granted

While the designs presented above incorporate either reflective or refractive materials, the ***novel lens walled compound parabolic concentrator*** uses both. The design was carried out by rotating the cross sectional parabolic curves of a common CPC around their top end points, pointing inwards by a certain angle and filling the space between the original CPC and the new CPC. A reflective coating was applied to the outside of the created lens. For a geometrical concentration ratio of 4 x and a half-acceptance angle of about 28°, the height for a 10 mm base is 97 mm (Figure 15) [99]. The improvement to this design is an air gap between the reflecting coating and the lens which maximises the total internal reflection and leads to an increase in optical efficiency by 10% [100]. The advantage of this design compared to a dielectric CPC is less material use and compared to a mirror CPC a more uniform flux distribution. Considering the geometrical concentration ratio is 4 x, the concentrator needs to be more compact if it is to be used for portable solar systems.

Figure 15 Novel lens walled compound parabolic concentrator, adapted from [100], copyright permission has been granted

Ramirez-Iniguez et al. [101] developed the ***rotationally asymmetrical dielectric totally internally reflective concentrator*** (RADTIR) with a geometrical concentration ratio of 4.91 x and half-acceptance angles of ± 30° and ± 40°, which allows for variations in the solar altitude and solar azimuth angle respectively [31]. The entrance aperture is therefore faceted enabling a different acceptance angle on each plane parallel to the axes of symmetry. For a square cell of 10 mm per side, the total height is 30 mm (Figure 16) [59]. The RADTIRC has a high concentration ratio and a compact design which are two important features for a portable concentrator. However, compared to other concentrators, the appropriate orientation of the concentrator is even more important because of the facetted entrance aperture. Furthermore, the concentrator is not designed for concentrator array moulding which makes the array assembly more time and cost intensive.

Figure 16 Rotationally asymmetrical dielectric totally internally reflective concentrator, adapted from [59], copyright permission has been granted

The ***rotationally asymmetrical compound parabolic concentrator*** (RACPC) developed by Abu-Bakar et al. [102], has a geometrical concentration ratio of 3.67 x and a half-acceptance angle of ± 43°. To facilitate concentrator array moulding integration, the concentrator has a flat entrance aperture (Figure 17). With the same acceptance angle and concentration ratio at all vertical planes, the RACPC is suitable for portable solar systems for developing countries. However, a smaller height to lower the cost and weight would be preferrable.

Figure 17 Rotationally asymmetrical compound parabolic concentrator, adapted from [102], copyright permission has been granted

Saitoh et al. [103,104] proposed a ***refractive static 2D lens and a 3D lens***. The 2D lens has a half-acceptance angle of ± 25° and an optical concentration ratio of 1.75 x while the height of the concentrator is 17 mm for a 10 mm wide absorber. The follow up 3D lens has half-acceptance angles of ± 30° and ± 45° and an optical concentration ratio of 2.3 x. The height for a 20 mm x 30 mm cell is 28 mm (Figure 18). The experimental optical concentration ratio is 2.3 and remains above 2.0 until the angle of incidence reaches 60°. Because of the small height and large half-acceptance angles, the 3D lens is particularly suitable for portable solar systems. A possible enhancement would be a similar acceptance angle at all vertical planes.

Figure 18 Refractive static 3D lens, adapted from [104], copyright permission has been granted

In a similar approach to using a single refractive surface, an ***aspheric lens*** has been optimised by Ota et al. [105] for the use a as a static solar PV concentrator for automobiles. The design requirements are very similar to those needed for portable solar systems in developing countries. These include: a large acceptance angle, the highest possible concentration ratio and being light weight using a small area. The optimised aspheric lens together with an InGaP/InGaAs/Ge triple-junction solar cell achieves an optical efficiency of 46.7% at a geometrical concentration ratio of 4 x. However, the optical efficiency has a strong drop between the angles of incidence of 30º and 60º. This design is highly attractive due to its thickness of only 4 mm and could also be used for silicon based solar cells. However, the angular acceptance and the optical efficiency need to be improved.

Various nonimaging concentrator designs have been proposed as secondary optical elements (SOE) for high concentration appliances [19,75,84,106–108]. They are used to further increase the concentration ratio, enhance the optical tolerance and improve flux distribution on the solar cell. The designs include CPCs, elliptical and hyperbolic concentrators, v-troughs, inverted cones and pyramids [19], which are all specifically designed for the small acceptance angles for imaging optics. Because of their application, the particular SOE designs are not further discussed in this work. However, related design concepts with application in BIPV have been discussed in section 3.

A comparative table of the concentrators discussed above is presented in Table 4. It can be concluded that the most suitable designs when considering height, concentration ratio and the potential for concentrator array moulding, are the 3D CCPC by Sellami et al. [62], the 3D refractive lens proposed by Saitoh et al. [103] and the aspheric static concentrator proposed by Ota et al. [105]. These designs would require further development for successful application in portable solar systems in developing countries.

Table 4 Comparison of static nonimaging concentrators and their suitability for portable solar systems

4.2 Financial aspect of solar PV concentrators

As mentioned previously, the PV module contributes 20-25% to the overall cost of a small solar lantern. The inclusion of solar PV concentrators influences the overall cost depending on the following factors:

- Concentrator geometry
- Manufacturing method (casting, injection moulding, machining)
- Design complexity (3-axis machining or 5-axis machining of concentrator or mould)
- Material type of the concentrator
- Concentrator volume
- Array moulding or manual assembly
- Number of orders
- Labour cost in the manufacturing country

While all the above authors of the static nonimaging concentrators presented above have focused on the performance of the concentrators, only two completed an analysis on the financial viability of the specific concentrator design. Sarmah et al. [95] stated that if the solar cell price drops below £1.75/W, the cost of the DiACPC-55 module would be higher than the cost of the non-concentrating module. Abu-Bakar [83] on the other hand concluded that compared to a 0.94 m^2 non-concentrating module, the RACPC module saves 31.75% of the PV module costs when using solar cells at the price of £0.64 for a 12.5 cm x 12.5 cm square solar cell.

Without detailed information on the precise geometries of the solar PV concentrators, it is not possible to draw a cost comparison between the different concentrator designs. With changing prices for PV material [109], concentrator material and with improvements being made in manufacturing techniques, the cost analyses by the aforementioned authors are only valid for a short period of time. Nevertheless, it is possible to comment on the cost competitiveness of the above nonimaging concentrator designs, based on material and manufacturing methods as suggested by their authors.

Abu-Bakar [2] and Ota et al. [105] suggested injection moulding as the manufacturing process and Abu-Bakar [83] concluded that PMMA has better optical properties and is cheaper than polyurethane. While polyurethane and casting was chosen by Sellami [62] and Sarmah [111] for the manufacturing of the prototype; Sellami [62] suggested using injection moulding for mass production of SEH and 3D CCP concentrators, since casting is more cost effective for small production amounts [112]. When using injection moulding it should be recognised that the cost per unit is dependent on the maximum wall thickness of the lens [113]. Lenses with small and uniform wall thicknesses, as is the case of the aspheric lens by Ota et al. [105], have a short cooling period and are therefore more financially viable. The cooling period increases quadratically with the lens thickness leading to increased cycle costs and larger costs per unit [113].

Consequently, the cost advantages from using solar concentrators depend of various factors and it is essential to have knowledge of the precise concentrator geometry to calculate the change in total cost. When designing a concentrator for portable solar systems for developing countries, the factors influencing the manufacturing cost need to be considered for a solar PV concentrator to be cost competitive.

5. Conclusion

The lack of electricity has a significant health impact, it limits the potential of the poorest people in society and is adverse for the country's economic and social development. Since 85% of the affected people live in rural areas in developing countries, an increase in electrification rate through grid supply is extremely challenging. As a result, off-grid solar chargers have been gaining popularity, however, lower cost, faster battery charge and more electricity generation need to be achieved to increase the product uptake. It has been found that the implementation of concentrators in portable solar systems allows a reduction in photovoltaic material used, it enables a faster battery charge and the potential to reduce the overall cost and environmental impact of the system. Different solar PV concentrator types have been reviewed in this paper, exploring their advantages and disadvantages in portable solar systems in developing countries. The review concludes that the most suitable concentrator type for portable solar systems for developing countries is the static nonimaging concentrator. This is due to its ease of operation and maintenance and high reliability since no tracking or cooling is required. Important features for a concentrator design have been outlined and the essential requirements can be summed up as: (i) a similar acceptance angle on all vertical planes to reduce complexity in operation; (ii) a sufficiently high concentration ratio to offset photovoltaic material cost; (iii) a minimum height / volume to reduce weight and manufacturing cost, and (iv) the suitability of the design for concentrator array moulding to minimise manufacturing and assembly cost. From the review of existing nonimaging solar PV concentrator designs it has been concluded that there are currently no designs which meet the outlined requirements. Novel concentrator designs for portable solar systems for developing countries are needed to achieve more renewable energy generation through off-grid solar power.

Acknowledgments

The authors would like to thank Glasgow Caledonian University, for funding this research activity.

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Figure Descriptions

Number	Caption	Suggested width in mm
1	Characterisation of solar concentrators	140
2	Parabolic concentrator (redrawn from [46])	60
3	Compound parabolic concentrator	29
4	Sea Shell concentrator	80
5	Hyperboloid concentrator	41
6	Cone concentrator	44
7	Fresnel Concentrator (redrawn from [46])	42
8	Flat high concentration nonimaging concentrator of the RXI type (redrawn from [47])	80
9	Dielectric totally internally reflecting concentrator (redrawn from [54])	40
10	Wedge prism concentrator	52
11	Luminescent concentrator (redrawn from [55])	75
12	Truncated dielectric asymmetric compound parabolic concentrator (DiACPC-55), adapted from [60]	54
13	3D crossed compound parabolic concentrator, adapted from [61]	54
14	Square elliptical hyperboloid, adapted from [62]	57
15	Novel lens walled compound parabolic concentrator, adapted from [64]	36
16	Rotationally asymmetrical dielectric totally internally reflective concentrator, adapted from [41]	53
17	Rotationally asymmetrical compound parabolic concentrator, adapted from [66]	47
18	Refractive static 3D lens, adapted from [67]	58

Table description

Number	Caption	Suggested width in mm
1	Current price range of solar lamps, data from [18–25]	80
2	Comparison of rechargeable batteries most commonly used for portable solar systems, data from [2]	160
3	Essential requirements of a solar PV concentrator designed for portable solar systems for developing countries	170
4	Comparison of static nonimaging concentrators and their suitability for portable solar systems	170

Figure 1 Characterisation of solar concentrators

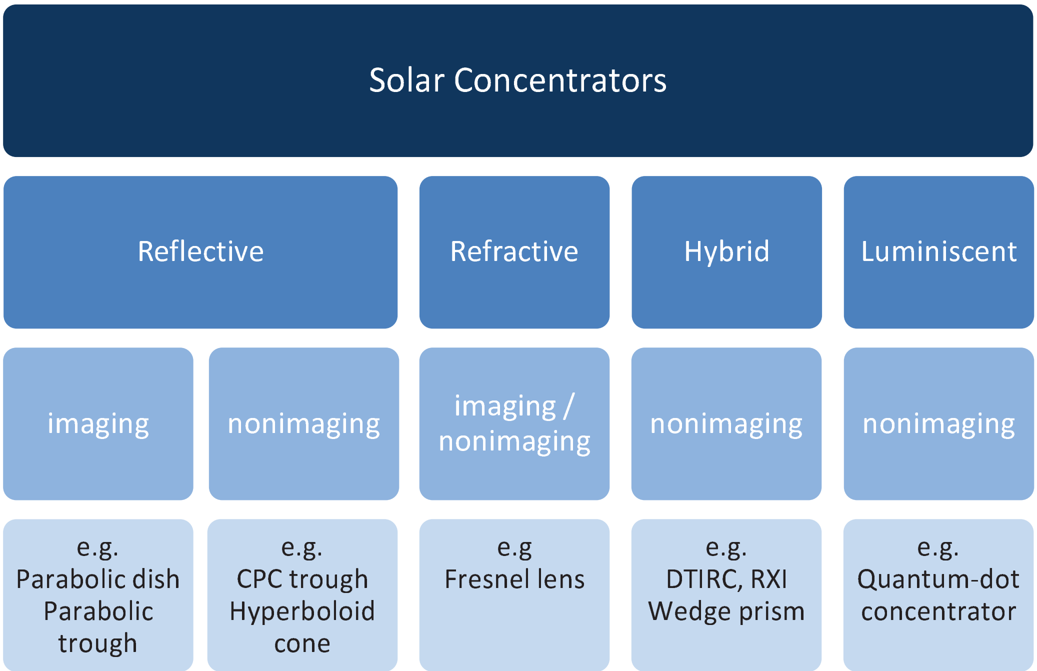

Figure 2 Parabolic concentrator (redrawn from [46])
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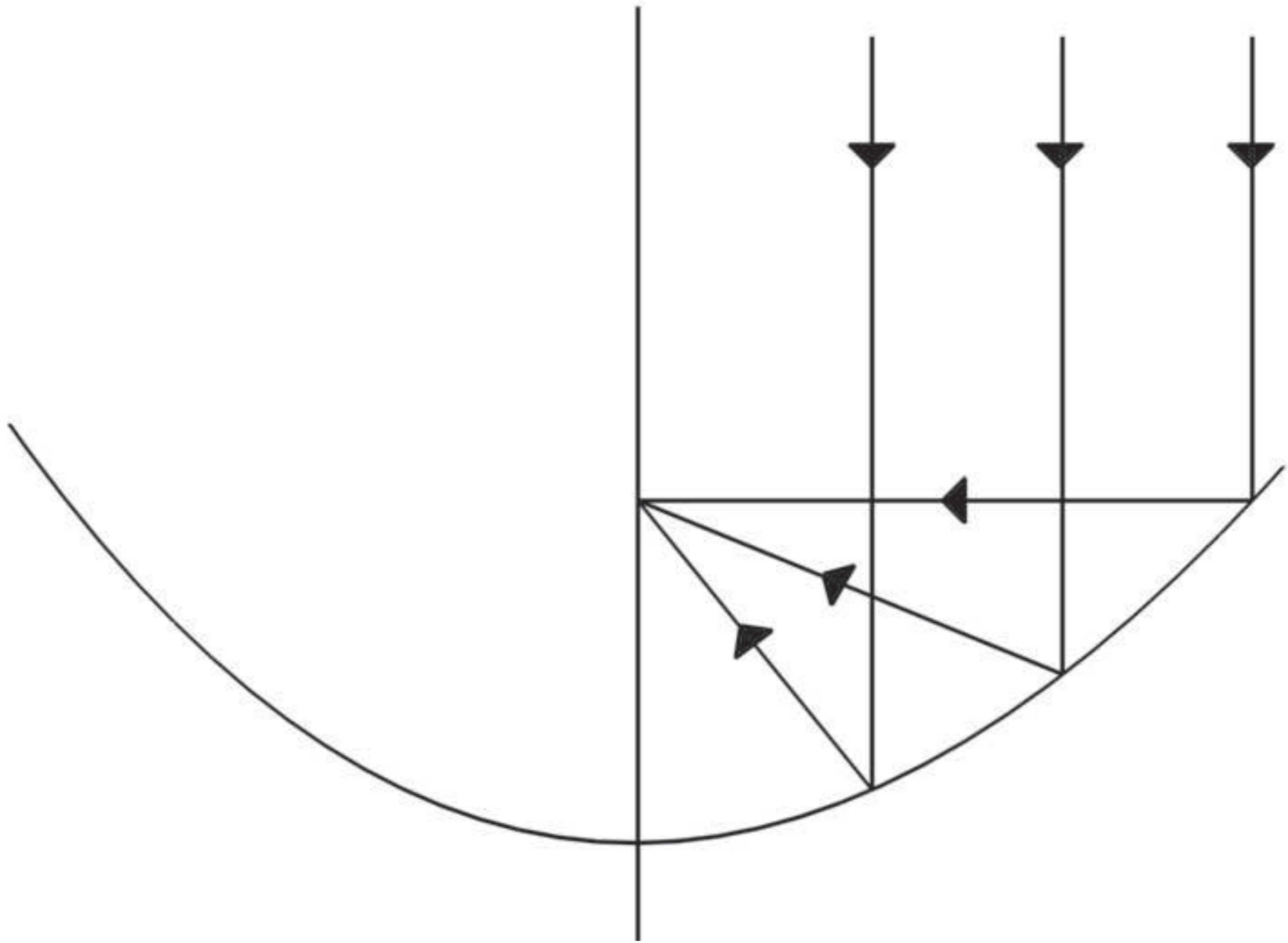

Figure 3 Compound parabolic concentrator
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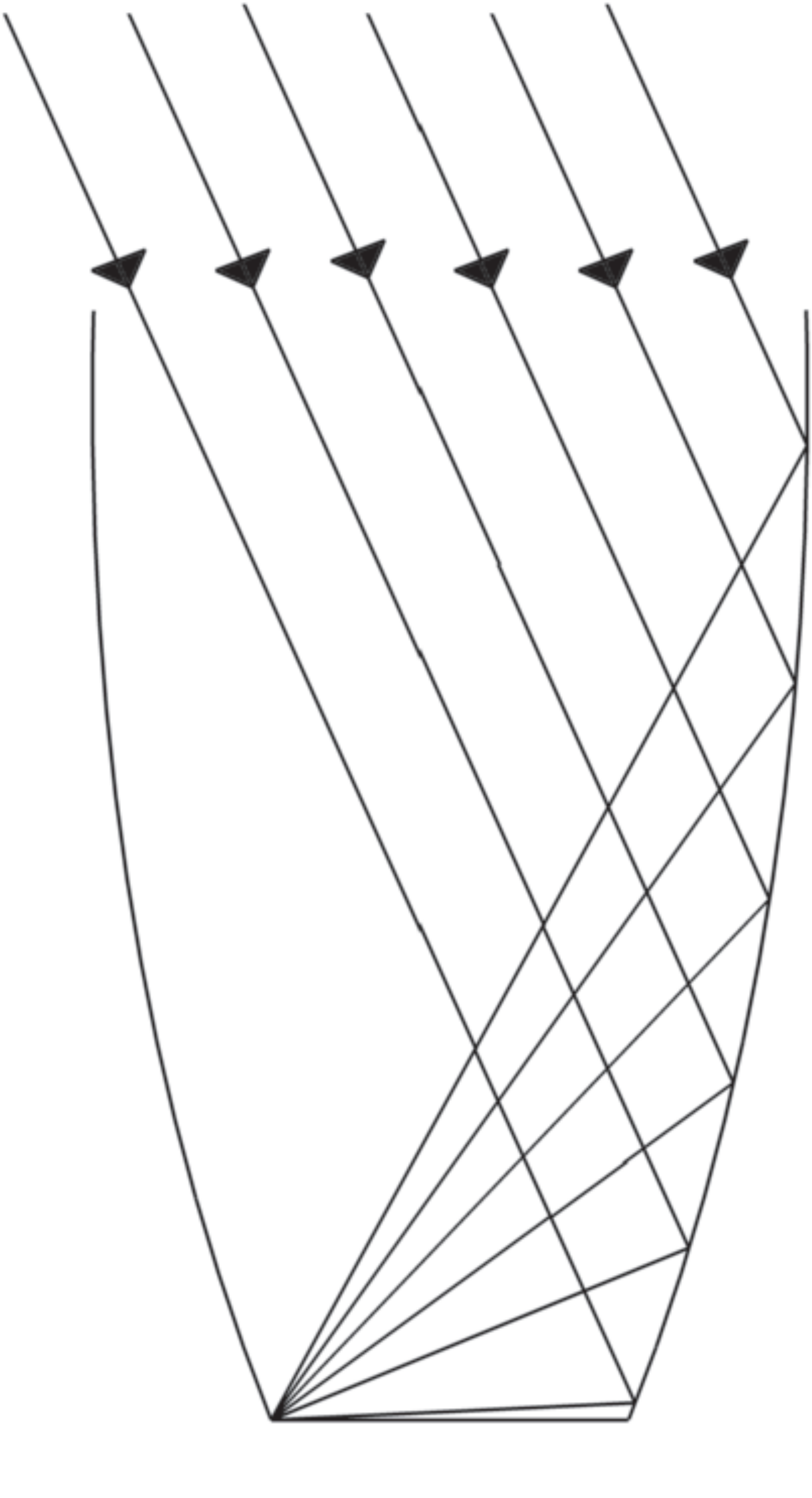

Figure 4 Sea Shell concentrator
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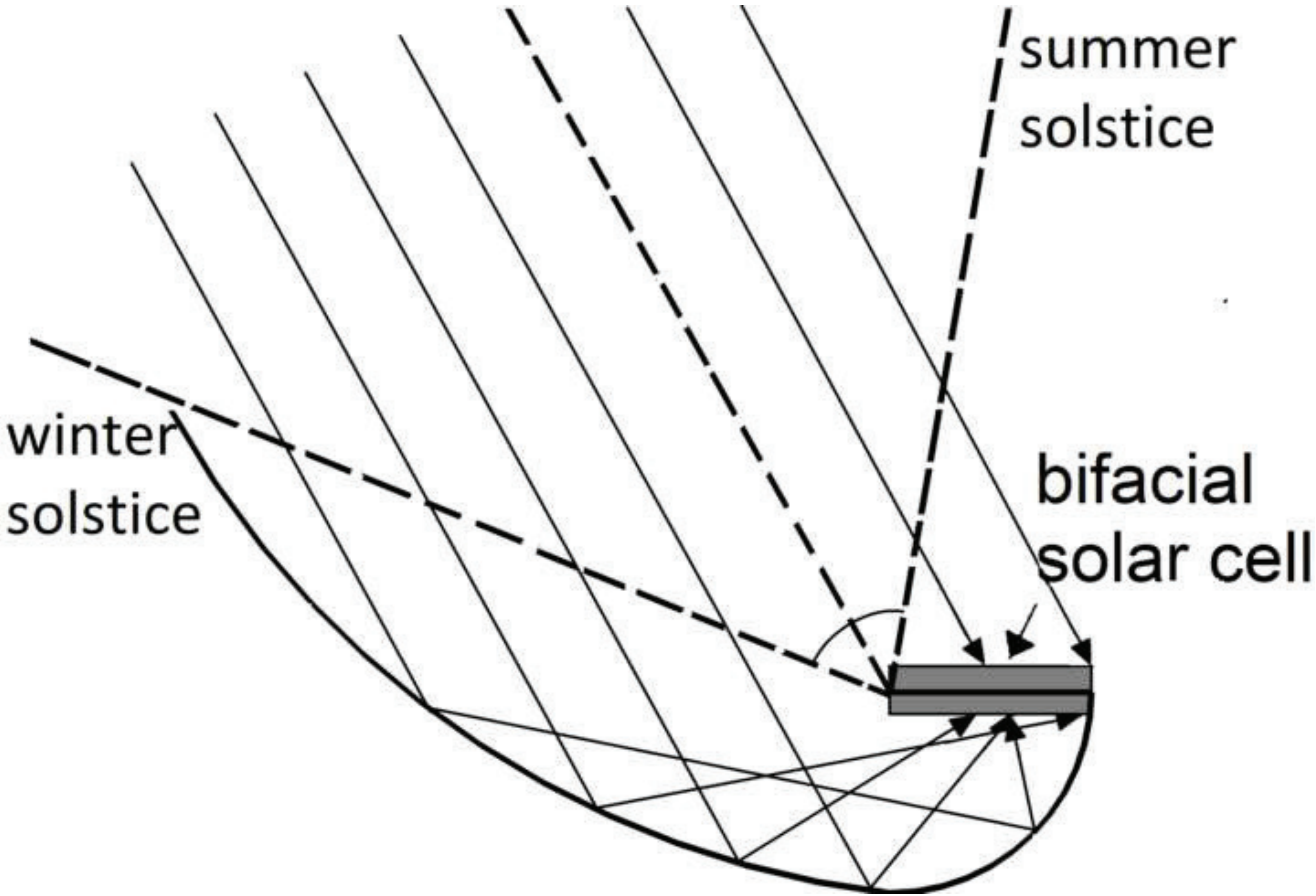

Figure 5 Hyperboloid concentrator

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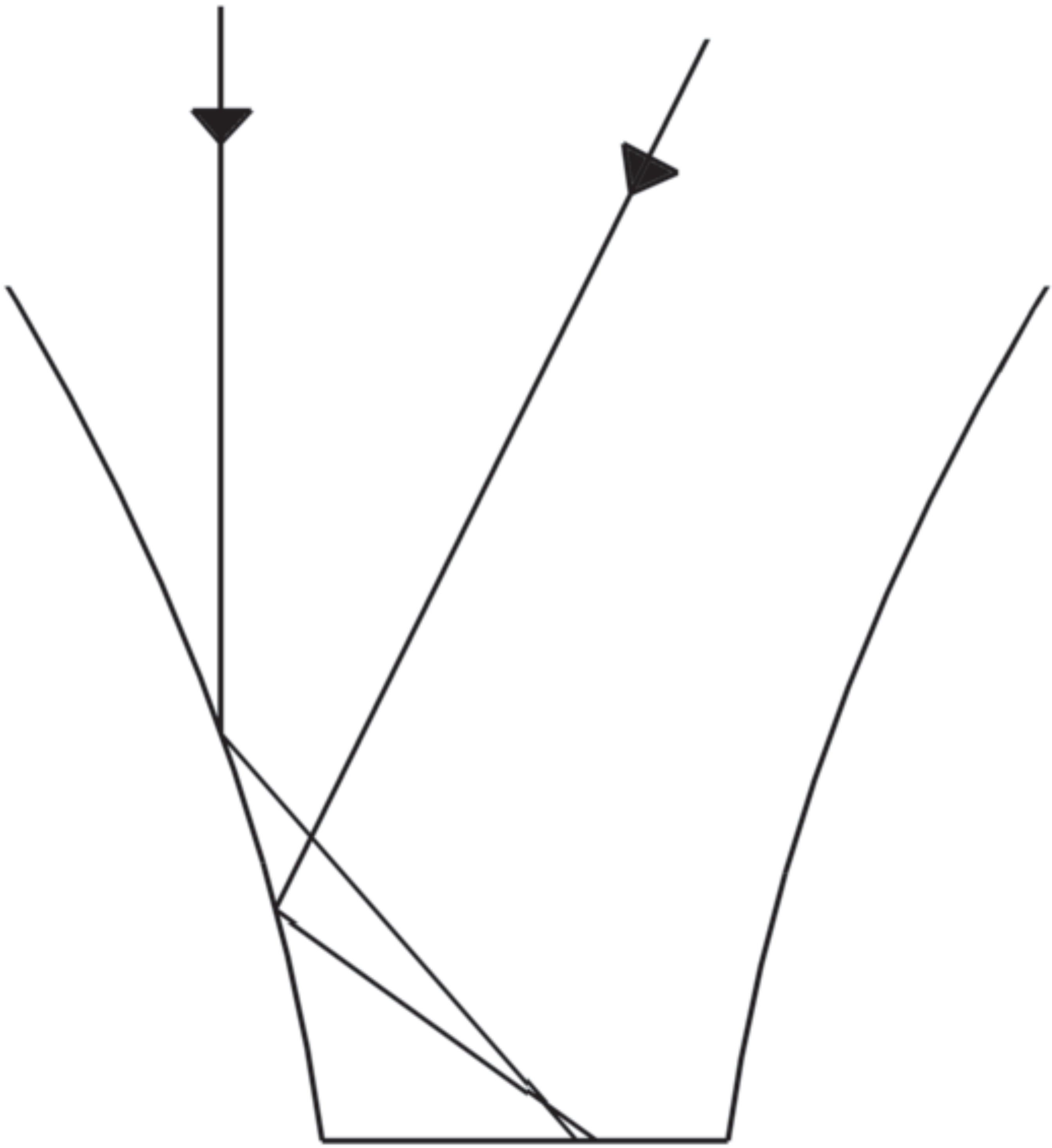

Figure 6 Cone concentrator
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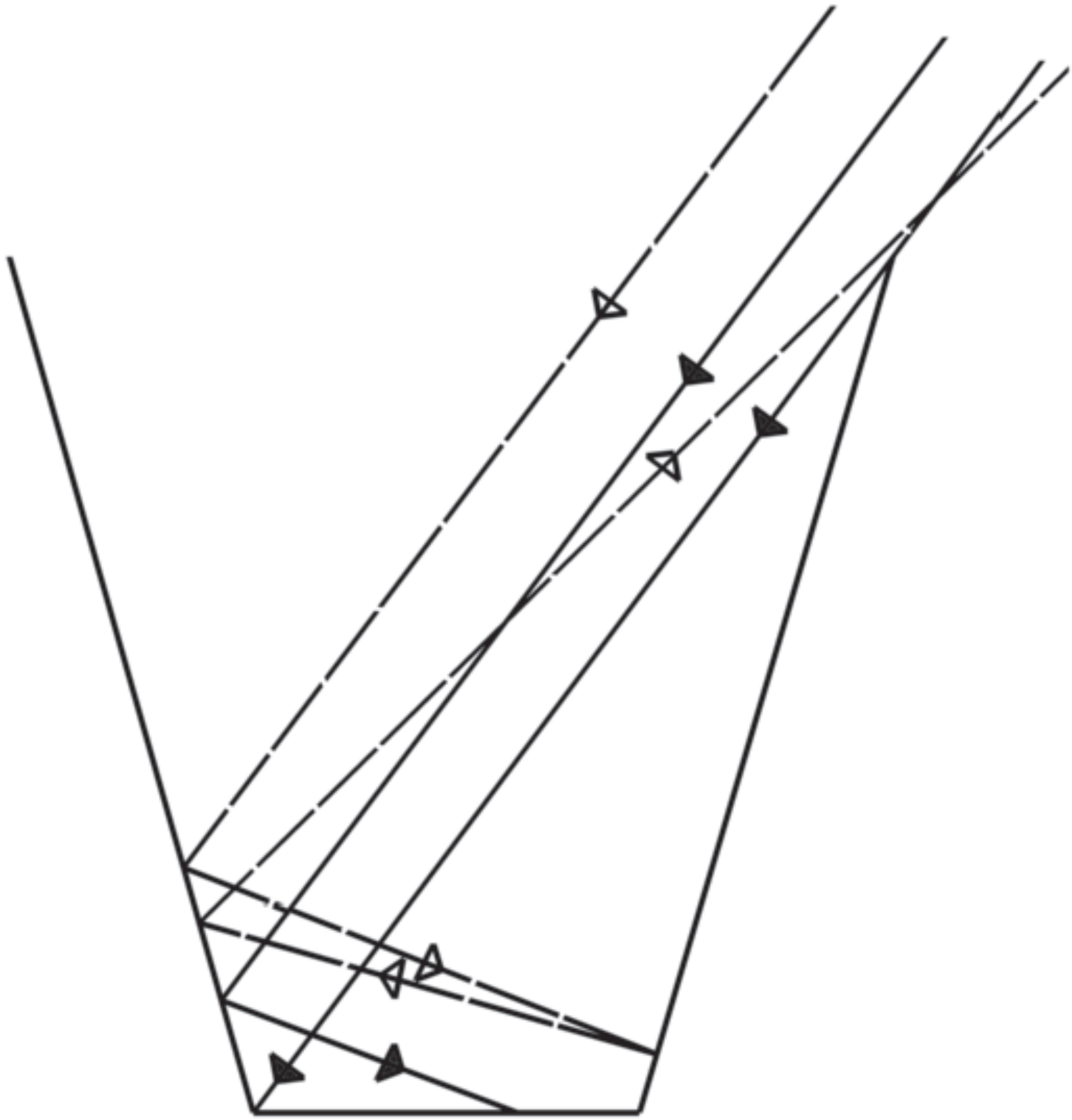

Figure 7 Fresnel Concentrator (redrawn from [46])
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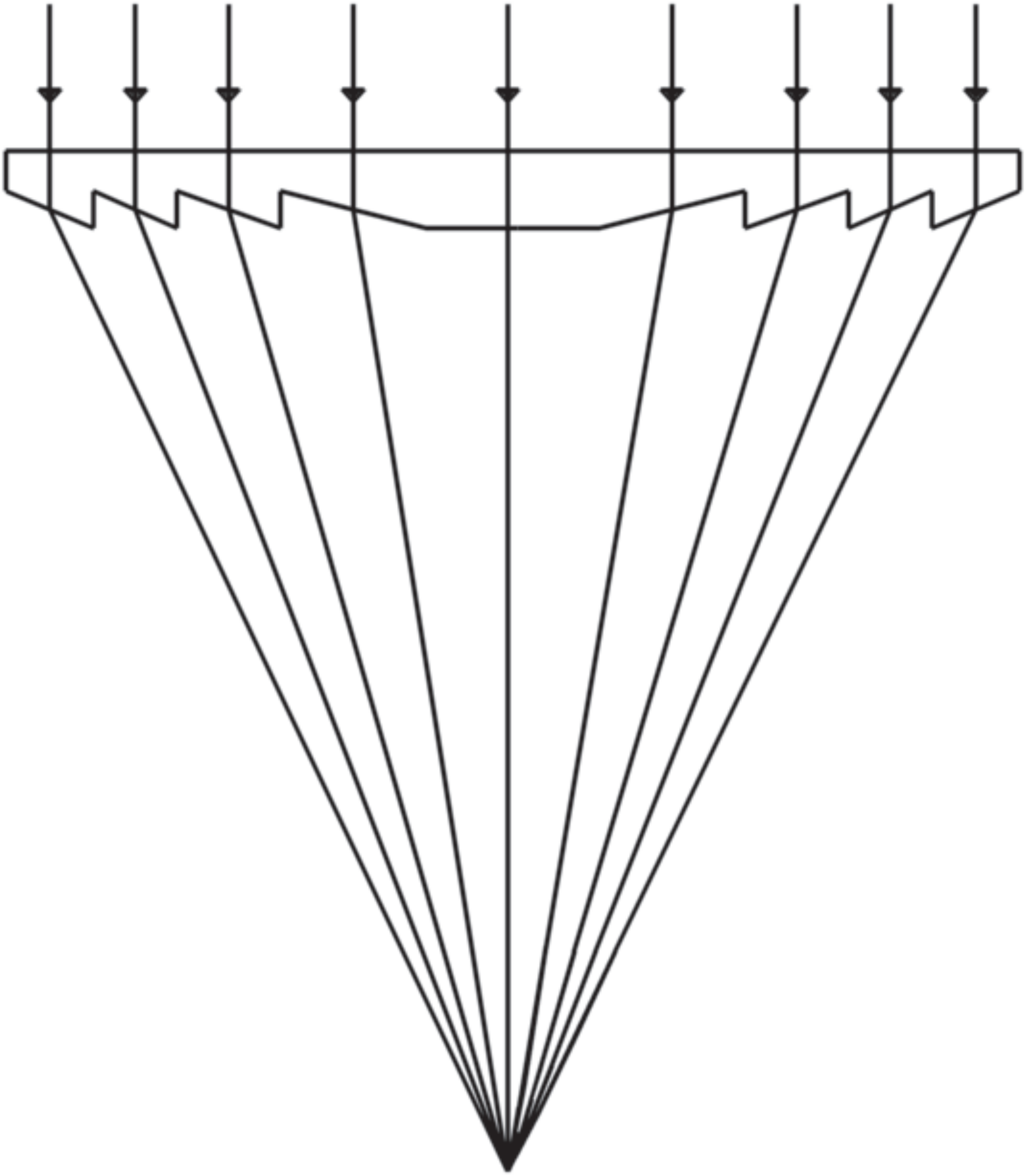

Figure 8 Flat high concentration nonimaging concentrator of the
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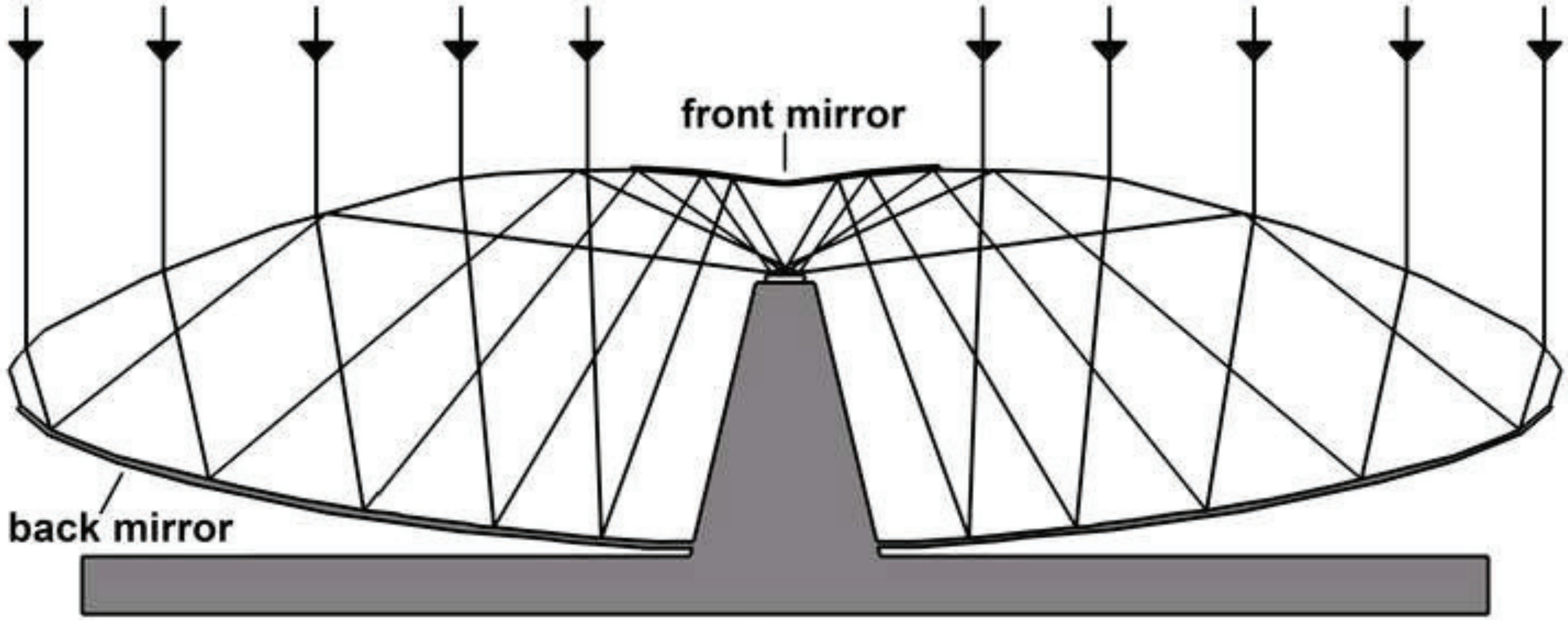

Figure 9 Dielectric totally internally reflecting concentrator

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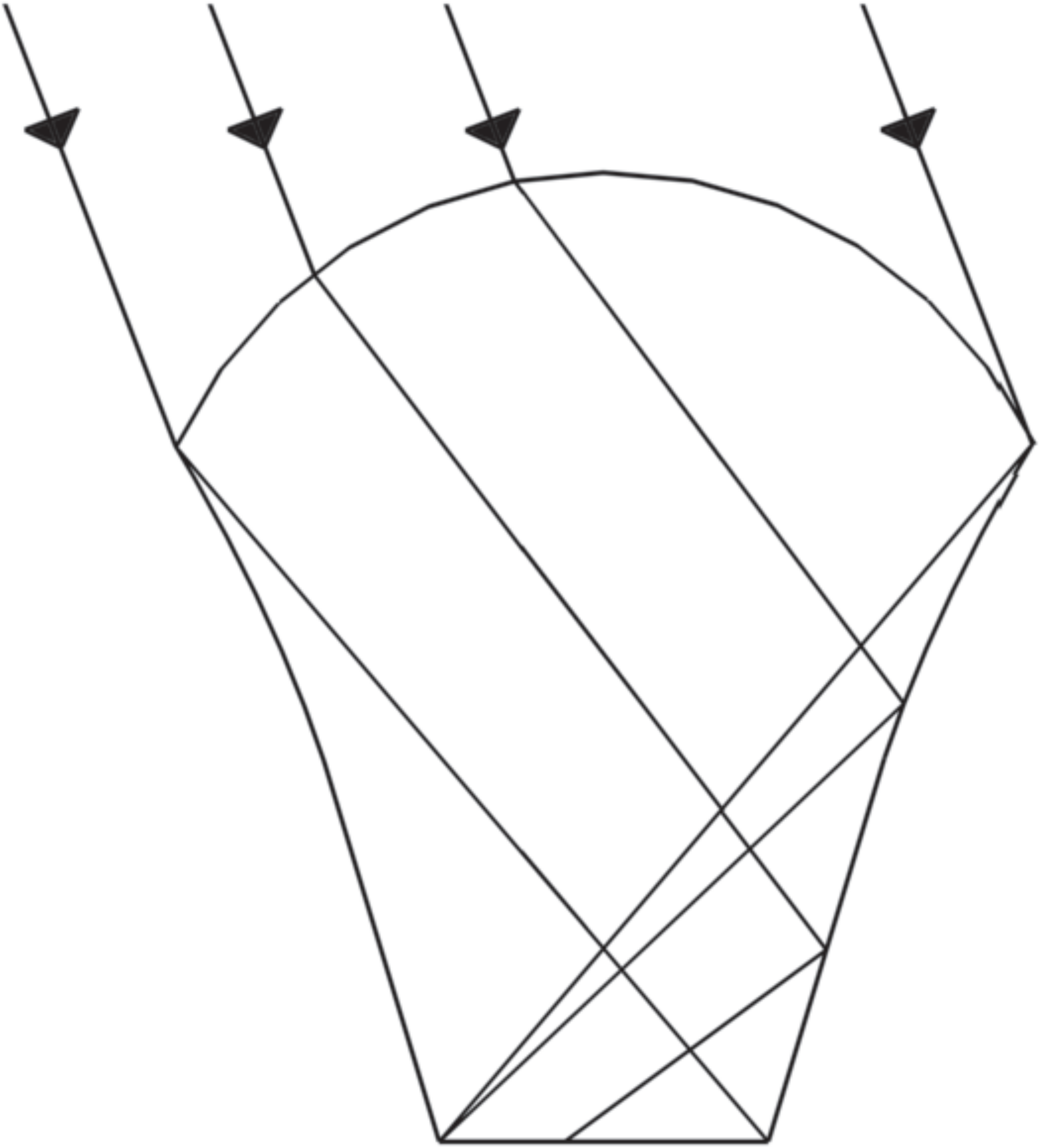

Figure 10 Wedge prism concentrator

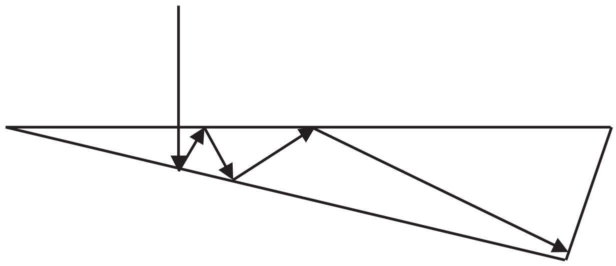

Figure 11 Luminescent concentrator

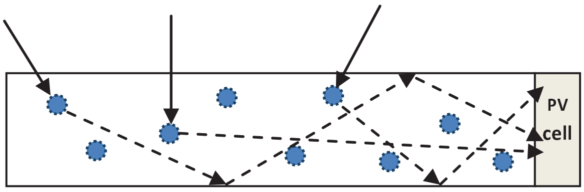

Figure 12 Truncated dielectric asymmetric compound parabolic con

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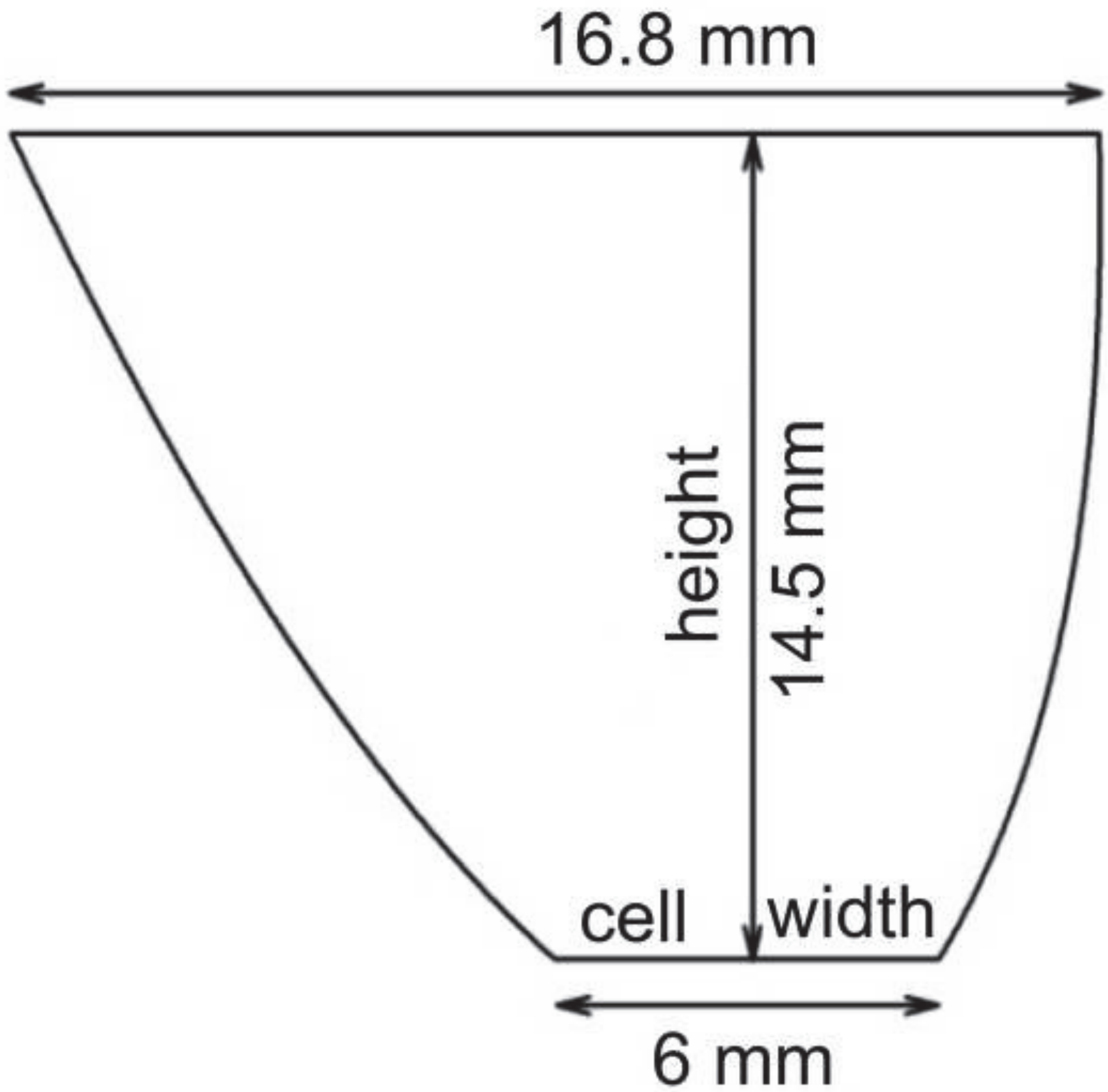

Figure 13 3D crossed compound parabolic concentrator
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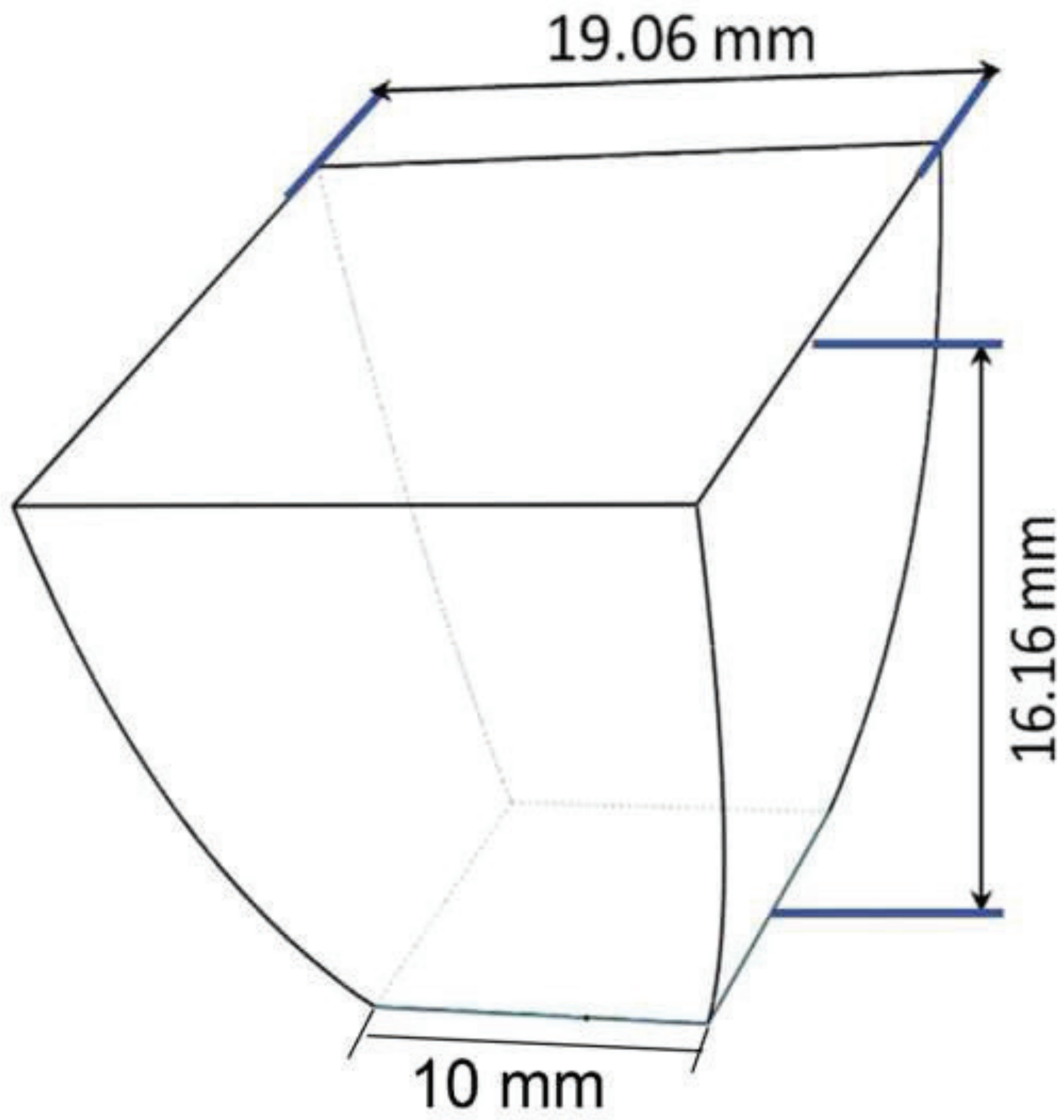

Figure 14 Square elliptical hyperboloid
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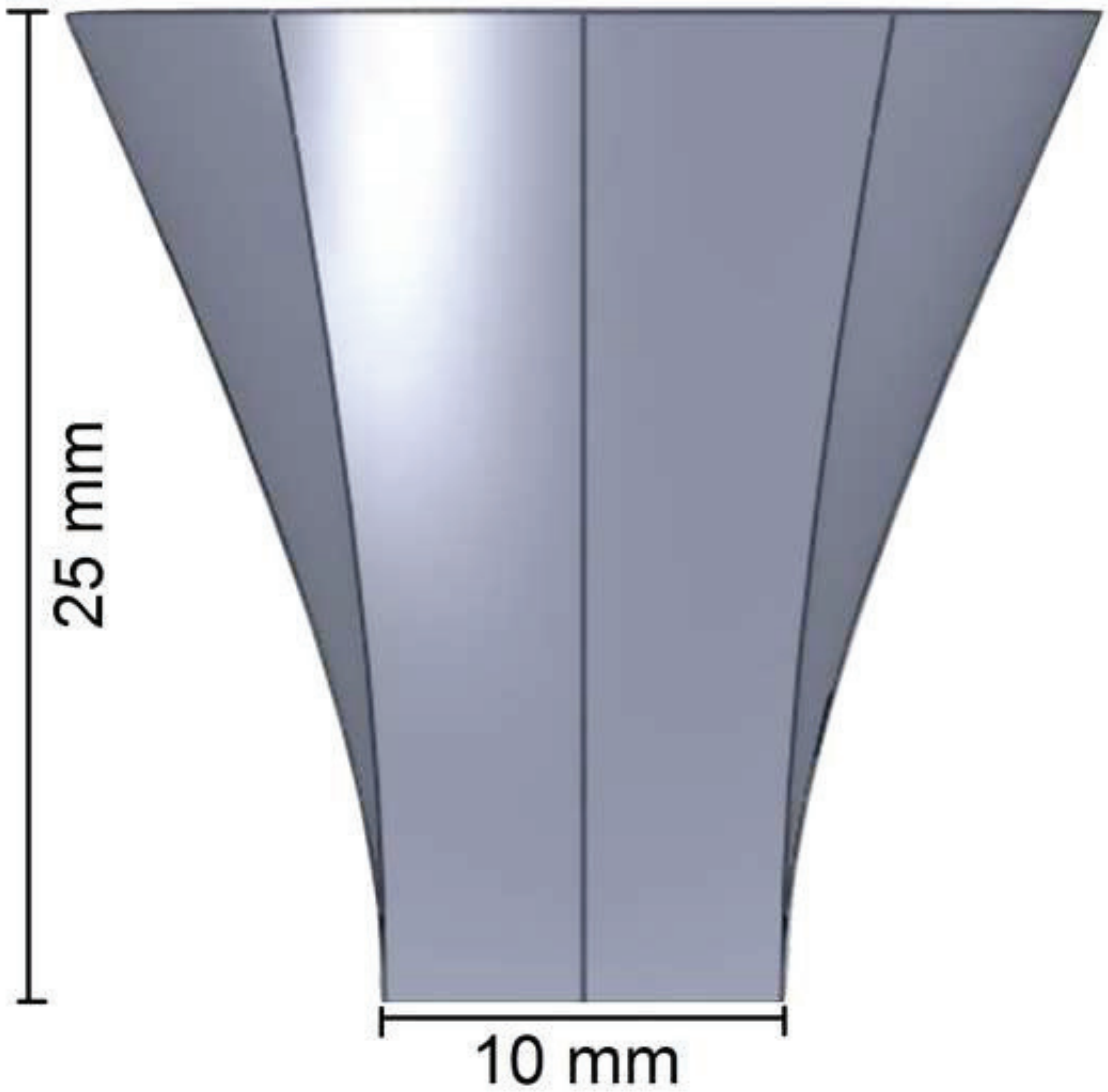

Figure 15 Novel lens walled compound parabolic concentrator
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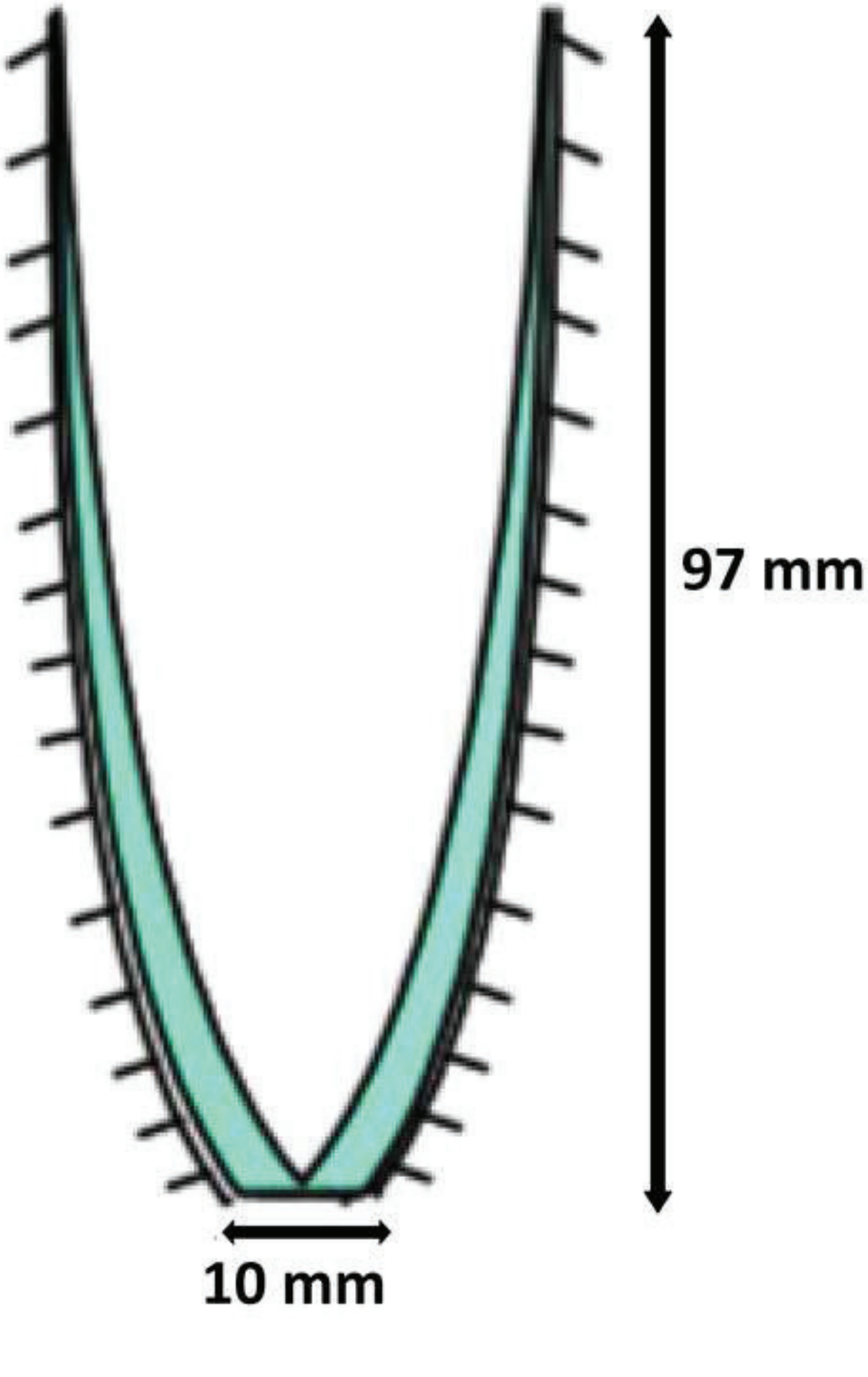

Figure 16 Rotationally asymmetrical dielectric totally internall
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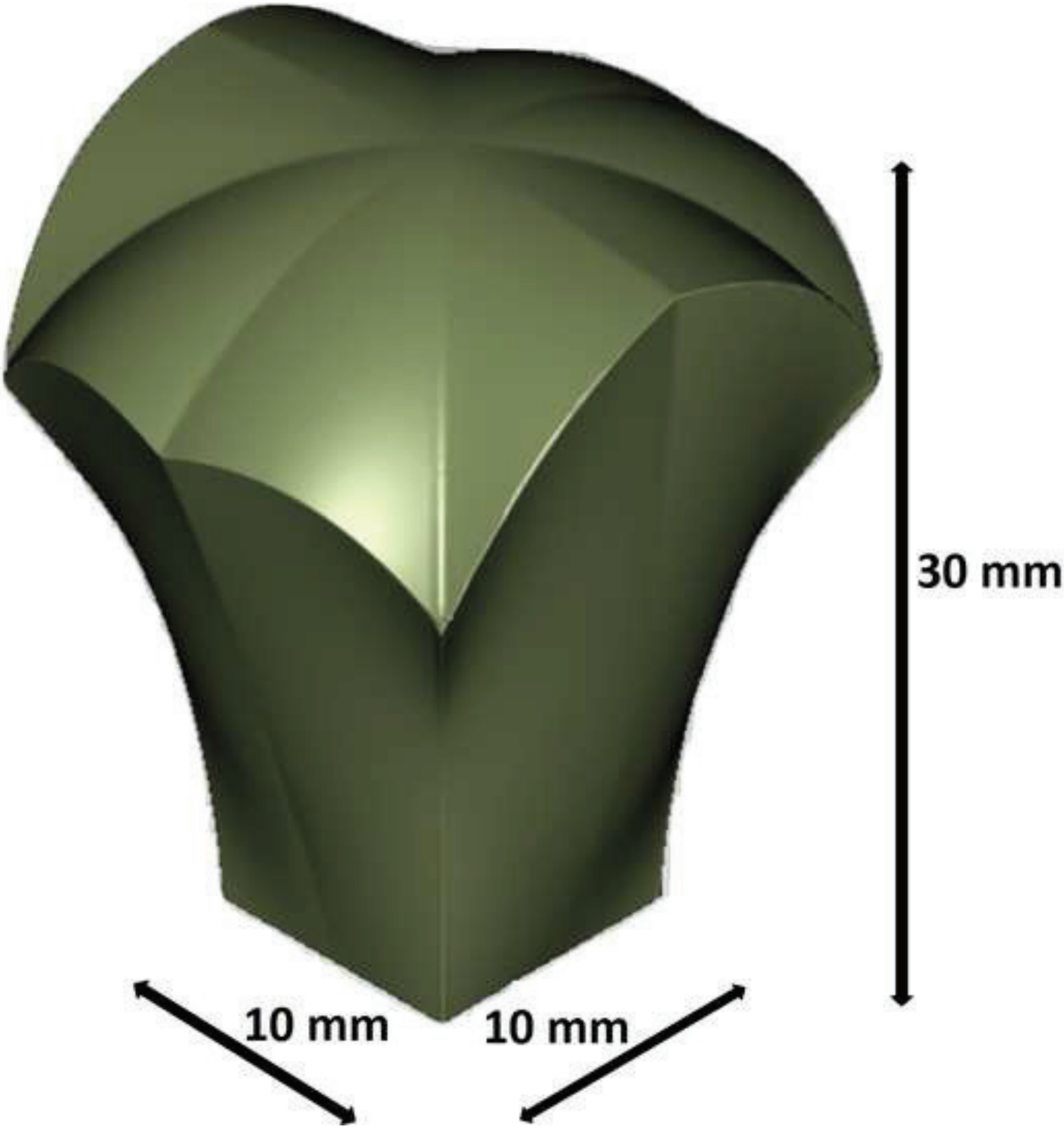

Figure 17 Rotationally asymmetrical compound parabolic concentra
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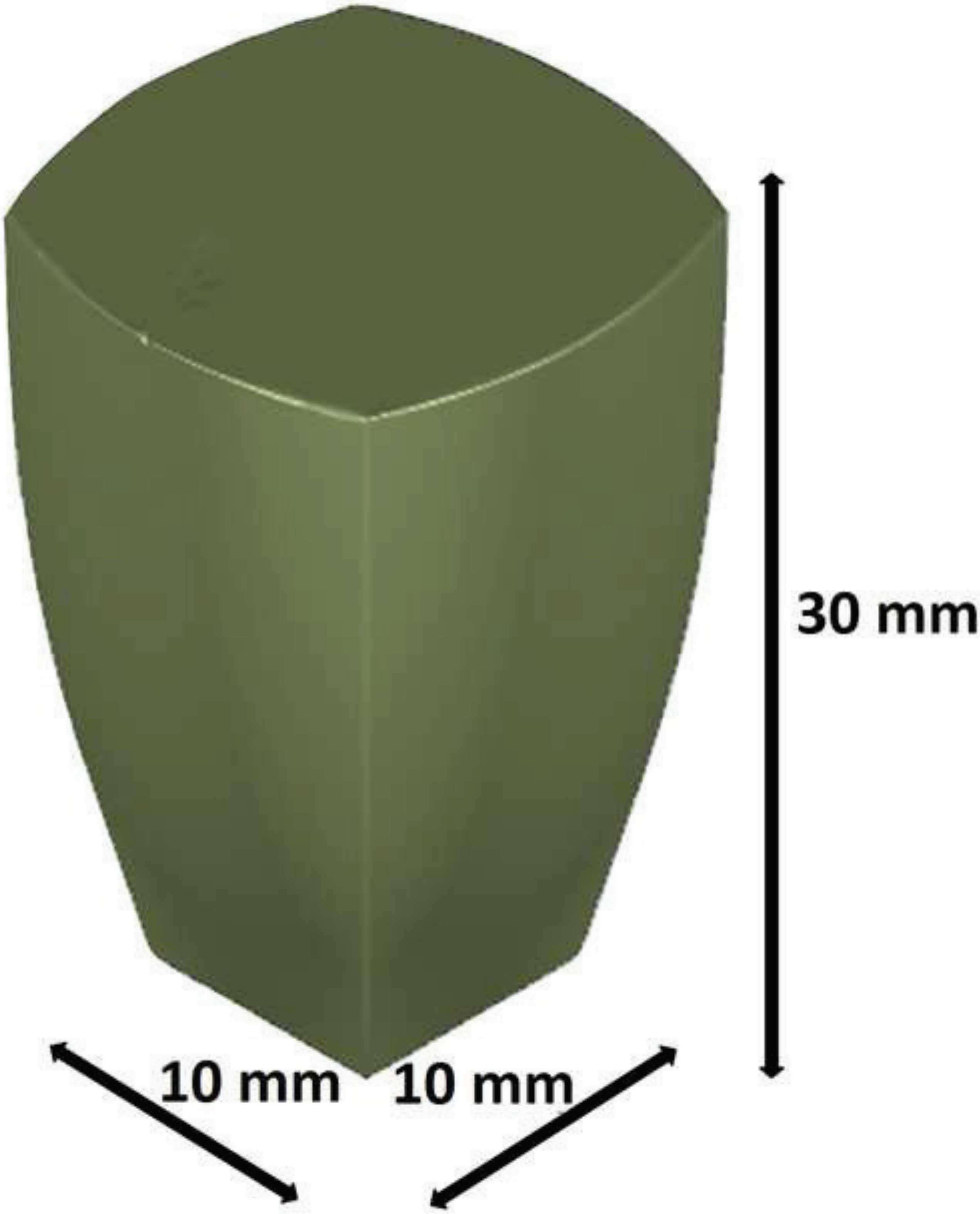

Figure 18 Refractive static 3D lens
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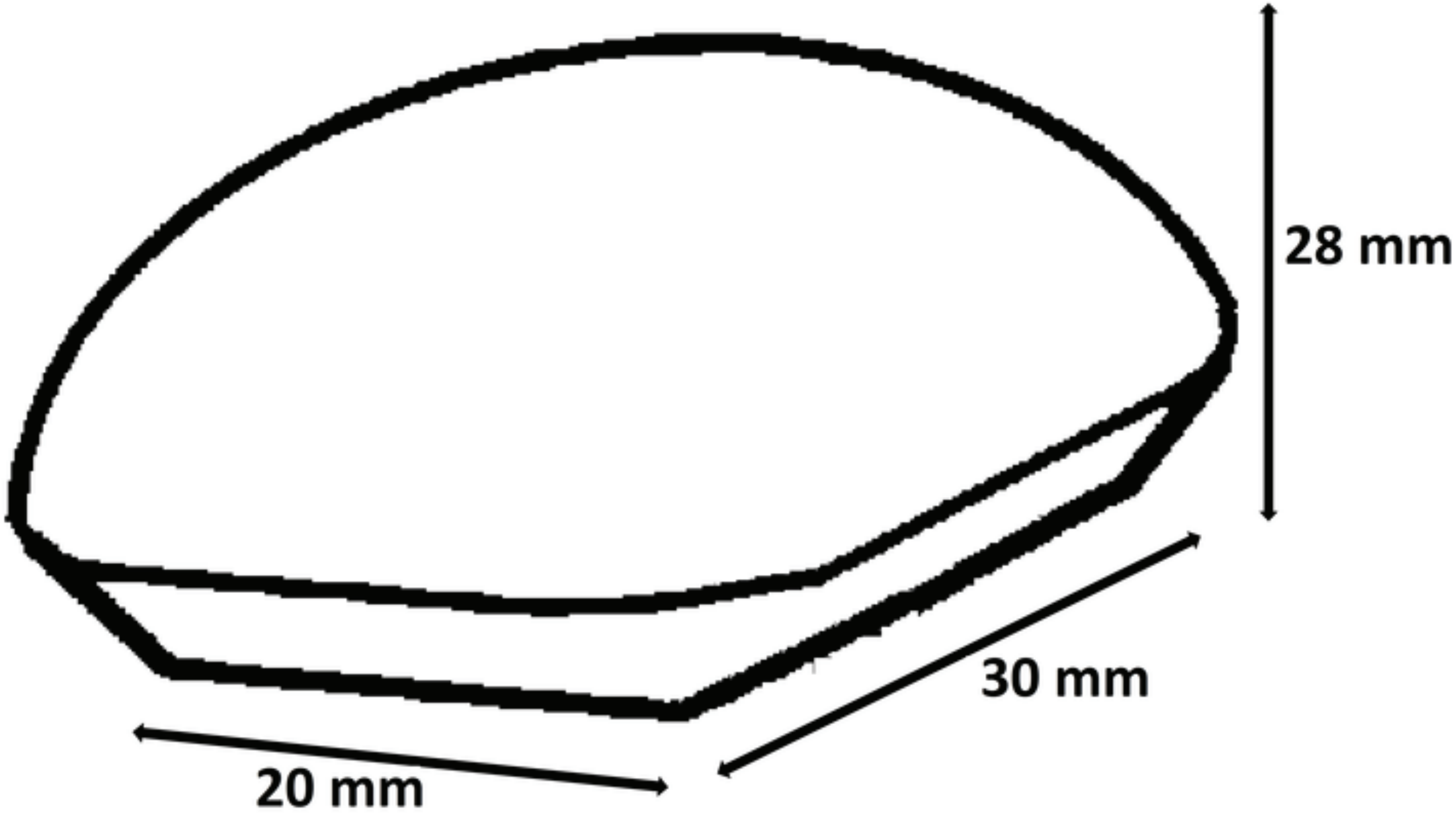

Table 1 Current price range of solar lamps [18-25]

Light intensity	Price (USD)
Up to 25 lumens	5 – 10
Up to 50 lumens	20 – 25
Up to 100 lumens	30 – 50

Table 2 Comparison of rechargeable batteries most commonly used

	Life time (years)	Life time (cycles)	Cost (USD/Wh)	Self-discharge per month (%)	Recycling	Toxicity
NiMH	1 - 3	500 - 1000	0.3	15 - 30	Nickel	Low
NiCd	1 - 2	300 - 1000	0.3	15 - 20	Cadmium, Ferronickel	Highly toxic
$LiCoO_2$	3 - 5	500 - 1200	0.35	2 - 10	Cobalt	None
$LiFePO_4$	5 - 10	500 - 2000	0.35	2 - 10	None	None

Table 3 Essential requirements of a solar PV concentrator design

Low complexity	-	equal acceptance angle and concentration ratio on all vertical planes parallel to the axis of symmetry
	-	sufficiently large acceptance angle[a] to enable full battery charge without manual adjustment
Low cost	-	suitability of the design for concentrator array moulding[1] to keep manufacturing cost low
	-	minimum concentrator volume to save material and minimise cost
	-	sufficiently high concentration ratio to offset PV material cost
Portability	-	minimum weight of the optic to minimise overall weight
	-	compact design to ease distribution and storage of the devices in remote areas

[a] *Since on average solar lights take 5 - 10 hours to charge, halving the charging time by increasing the charging current would result in an approximate 4 hours charge. This again requires a minimum acceptance angle of 60° to enable full charge without adjustment. However, a larger acceptance angle gives longer collection hours*.

[1] An array of concentrators produced in a single mould

Table 4 Comparison of static nonimaging concentrators and their

Concentrator designs	Geometrical concentration ratio	Maximal optical efficiency (%)	Half-acceptance angles (°)	Height[1] (mm)	Joint moulding	Similar acceptance angle on all vertical planes	Ref
2D designs							
DiACPC-55	2.80	83	0 / 55	24.2	Yes	No	[111]
Truncated sym. CPC	2.96	> 90	0 / 36.4	29.4	NA	No	[94]
Truncated asym. CPC	2.46	> 90	0 / 37	17.7	NA	No	[94]
3D designs							
Refractive 3D CCPC	3.61	73	± 40	16.16	Yes	Yes	[62]
SEH	4.00	40	± 60	10	Yes	No	[62]
Lens walled CPC with air gap	4.00	90	± 28	96	NA	Yes	[100]
RADTIRC	4.91	95	± 30 / ± 40	30	No	Yes	[110]
RACPC	3.67	93	± 43	30	Yes	Yes	[102]
3D refractive conc.	2.30	86	± 30 / ± 45	14	Yes	No	[104]
Aspheric lens	4.00	47	± 40	4	Yes	Yes	[105]

[1] Height calculated for ACPC, Lens walled CPC and 3D refractive conc. for a 10 mm wide absorber

*Highlights

Static nonimaging solar PV concentrators are most suitable for portable solar systems

Reduction in photovoltaic material and battery charging time

Potential reduction in overall cost and environmental impact

Need for novel concentrator designs for portable solar systems