GRIN planar waveguide concentrator used with a single axis tracker

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Abstract: It is generally accepted that small to medium level concentrators could be used as cost-competitive replacements for tracked solar panels. The objective is to design a system that can reach a good level of sun concentration with only one sun-tracking axis and is cheap to fabricate. As the most critical parameter for all concentrator designs, optical efficiency needed improvement to reduce the cost of power produced by our system. By using a graded-index planar waveguide with an index profile similar to SELFOC fiber, the ray's path can be controlled. Also, the concentrator can be fabricated in a single block, which reduces Fresnel reflections. Overall, the optical efficiency can be improved by as much as 33% compared to the same system made with a homogeneous waveguide. Furthermore, the ability to cost-effectively fabricate the concentrator by molding can be preserved, making it possible to reduce the cost of the solar power produced.

OCIS codes: (350.6050) Solar energy; (220.1770) Concentrators; (230.7400) Waveguides, slab; (160.5470) Polymers; (230.3120) Integrated optics devices.

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1. Introduction

The use of concentrated photovoltaics (CPV) is an interesting technology to reduce the cost associated with solar power. By concentrating sunlight with a cheap optical system, a smaller surface of expensive cells can be used to produce more power. High concentration values require a precise solar tracker, as stated by the conservation of etendue [1, 2]. Another option is to use lower concentration levels to relax the tolerance on the tracking system.

Planar waveguide concentrators have been proposed as an efficient CPV system [3–5]. They make a more compact system than a lens system with the same concentration factor. Compared to a stepped-thickness waveguide, a planar waveguide offers a larger attainable concentration factor since the modal volume stays constant when the length is increased [3]. However, the stepped-thickness waveguide is designed to maximize the optical efficiency [6, 7]. In the case of planar system, an adapted version for a lower concentration value has also been proposed to remove tracking during the day [8]. For single or dual-axis sun tracking, the optical efficiency of the system is directly related to the length of the waveguide.

Single-axis tracking planar waveguide concentrators using cylindrical lenses offer great promise for the replacement of traditional solar panels [9, 10]. However, the optical efficiency of the system must be increased to reduce the cost ratio of solar power produced in $/W. The light losses in planar waveguide concentrators come from the coupling prisms which are much larger than the ones required for dual axis tracking. Consequently, the light losses during propagation in the waveguide are higher due to the interaction of the light rays with the subsequent coupling prisms. When the rays hit the other coupling structure, they are decoupled from the waveguide.

To increase the optical efficiency of the single-axis tracking planar waveguide concentrator, we must reduce the interactions between the light rays and the backside surface of the waveguide containing the coupling prisms. To achieve this, we were inspired by the technology used in graded-index optical fibers. In such systems, all rays coupled with different angles propagate the same length along the fiber axis before being re-imaged. In our case, the rays are coupled in the waveguide by the prism. The sun is then re-imaged periodically along the backside surface of the waveguide. The GRIN planar waveguide parameters can be adjusted to avoid the light rays hitting a second coupling prism. The propagation losses into the waveguide will be minimised. To our knowledge, this is not something that has been previously considered to increase the efficiency of cylindrical planar concentrators.

Another aspect that reduces the optical efficiency of planar concentrators is the number of optical interfaces needed to keep rays propagating by total internal reflection (TIR). Anti-reflection coatings could be used but this increases the cost of the system. By keeping rays coupled in the waveguide without TIR on one surface, the use of a graded-index waveguide permits elimination of two air-material interfaces, which means that the lens and the waveguide can be built within a single piece.

Also, to keep the GRIN planar waveguide cost-competitive compared to traditional systems, plastic instead of glass must be used since it offers the possibility of molding and reduces cost in mass production.

A major drawback from using polymers to fabricate a graded-index optical system comes from the limited number of available refractive indexes. For example, at 587.6 nm, polymethyl methacrylate (PMMA) and polycarbonate (PC) have an index of 1.491 and 1.585 respectively. Both materials are widely used due to their high transmission in both the visible and near IR spectra.

To address this concern, two methods have been proposed that could be used to modify the refractive index of a polymer to fabricate a graded-index waveguide. The first method is to mix an organic dopant with the polymer matrix to modify its refractive index [11, 12]. The second method is to mix two polymers together, a technique which has been developed by DARPA during the last few years [13, 14]. With these techniques, it is possible to fabricate a graded-index planar concentrator made with polymer.

This paper proposes a low-cost concentrator alternative to the traditional one-axis tracked solar panels using graded index polymer waveguides. The second section presents a comparison between a step index planar waveguide concentrator and a graded-index planar concentrator both used with cylindrical micro-lens arrays. Section 3 shows simulation results using raytracing software (LightTools) to compare the performances of both systems. Finally, a discussion about the method for manufacturing a low-cost graded-index planar waveguide made of polymer is presented.

2. Step-index waveguide versus graded-index waveguide

An efficient way to eliminate one axis of tracking is to use cylindrical lenses. The cylindrical lenses are used to couple light into the planar waveguide. This geometry has already been studied by the authors in the case of seasonal tracking [8]. A brief review of the homogeneous waveguide is first presented and then compared to the new design using a graded-index waveguide.

2.1 Homogeneous planar waveguide

The analytic model of the planar concentrator with cylindrical lenses has already been presented in a previous paper [8]. A brief synthesis of this concentrator based on the use of cylindrical lenses to couple light in the waveguide is presented here. Equations (1)–(3) were defined by Karp to calculate the optical efficiency of the waveguide concentrator. They can also be applied to a one-axis planar concentrator. The major difference is the lens concentration parameter $C_{cylind.\ lens}$ that will be much lower in that case. In Eq. (1), the efficiency of light coupling is calculated for an angle Φ at a point P along the waveguide. The absorption in the material and the reflection coefficient of the coupling prism is then taken into account in Eq. (2). Finally, the optical efficiency of the complete concentrator is calculated by integrating over all angles coupled and over all points P along the waveguide. This is done in Eq. (3).

$$\eta_{decouple}(P,\Phi) = (1 - \frac{1}{C_{cylind.\,lens}})^{P\tan\Phi / 2H} \tag{1}$$

$$\eta_{position}(P,\Phi) = R \times \eta_{decouple} \times \exp(-\alpha P / \cos\Phi) \tag{2}$$

$$\eta_{total} = \frac{\sum_{P} \int_{0}^{\Phi_{max}} \eta_{position}(P,\Phi)}{(L-r) / 2r} \tag{3}$$

In these equations, R is the reflection coefficient of the metalized coupling prism, α is the waveguide material attenuation coefficient, H is the waveguide thickness, L is the waveguide length, P is the position inside the waveguide (the distance to the exit surface) and 2r is the pitch of the cylindrical lens. The parameters used in the calculation of the optical efficiency of the system are illustrated in Fig. 1.

It is shown in Fig. 1 how the homogeneous waveguide concentrates light. An array of cylindrical lenses is placed over the waveguide. A coupling prism is placed at the focal point of each lens to couple sunlight in the waveguide. Light travels along the waveguide and exits by the side. The geometrical concentration factor is the ratio between the length L and the thickness H.

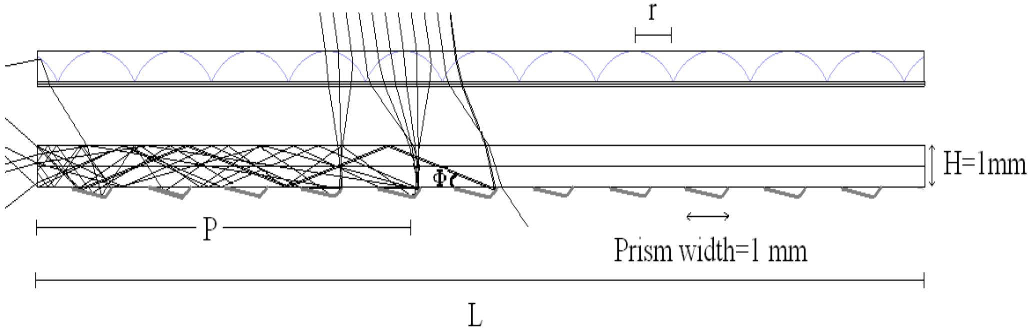

Fig. 1. Lateral view of the waveguide with the parameters used in Eqs. (1)–(3).

All the parameters are calculated for different waveguide coupling angles Φ and positions P. The coupling angle Φ is integrated over all angles propagating in the waveguide. The lower limit for integration is 0 while the upper limit is Φ_{max}, as calculated with Eq. (4) using the same parameters as previously defined. Here, θ is the half angular extension of the sun (± 0.26°) and n is the waveguide refractive index. The f/# is the ratio between the focal length and the diameter of the cylindrical lens.

$$\Phi_{\max} = 2\left[\theta + \arctan\left(\frac{1}{2n\, f/\#}\right)\right] \quad (4)$$

There is an important point about Eq. (1) that needs to be looked at. It is the dependence of the optical efficiency on the angle Φ for rays coupled in the waveguide. This angle will affect the distance between two backside interactions $2H/\tan\Phi$. So, rays coupled with a larger angle will interact more with this backside surface, which will increase the probability of escaping the waveguide by striking a second coupling prism during propagation.

2.2 Graded-index planar waveguide

Instead, if we use a graded-index waveguide, the length of propagation without a second interaction with the backside surface is modified. In the case where a parabolic index profile is chosen, it becomes the same for all coupled angles Φ in the waveguide [15]. This corresponds to the period F of the graded-index waveguide. The difference between both systems is illustrated in Fig. 2. The number of interactions with the backside surface is diminished for high angles closer to the guiding limit. It is then possible to choose the positioning of the coupling prisms to eliminate losses.

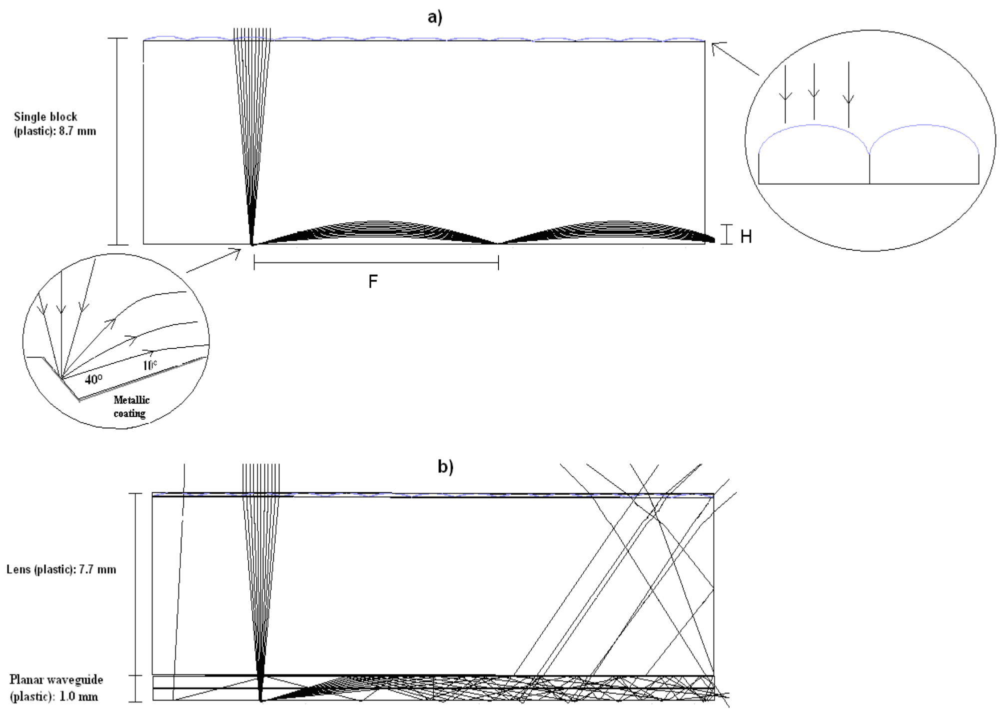

Fig. 2. Rays' paths inside the waveguide for both systems. a) Graded-index waveguide and b) Homogeneous waveguide.

In Fig. 3, we take a look at all the angles that propagate in the two types of waveguides. It appears that each type of waveguide has an advantage for certain angles. The number of interactions, which is directly linked to the optical efficiency, is calculated for all angles that can be guided in the waveguide from point P = 18 mm. With a thickness H of 1 mm and an index range of 1.491 to 1.55, the period F for the waveguide is 9 mm. It means that after being coupled in the waveguide by a reflecting prism at P = 18 mm, the rays strike two times the backside surface before exiting the system.

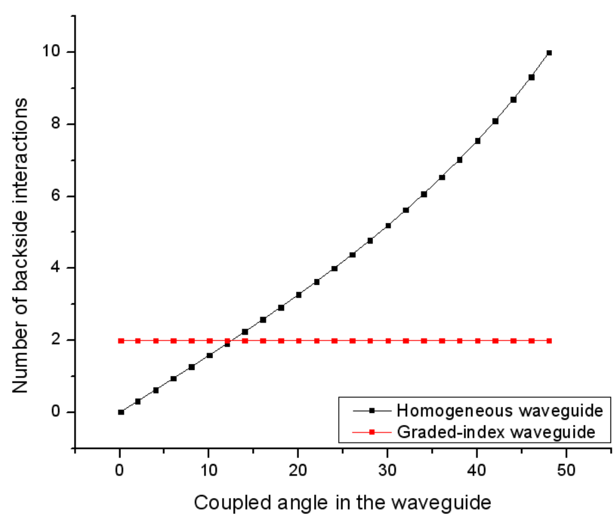

Fig. 3. Number of backside interactions for different angles coupled in the waveguide at position P = 18 mm.

#202346 - $15.00 USD Received 2 Dec 2013; revised 10 Jan 2014; accepted 13 Jan 2014; published 23 Jan 2014

It is apparent that a homogenous waveguide will transmit rays having a small coupling angle with a better optical efficiency. There is a quasi-linear decrease of the optical efficiency since rays having a higher coupling angle will propagate with more interactions with the backside surface containing the coupling prisms.

However, with a graded-index waveguide, all angles are re-focused at the same point farther along the waveguide. The number of backside surface interactions is thus increased for low angles and is reduced for large angles coupled in the waveguide. On average, the optical efficiency of a bundle of rays with different angles coupled in the waveguide at point P = 18 mm is increased by about 15%. This improvement of the optical efficiency will vary depending on the point taken along the waveguide. It will increase as we move farther from the exit surface.

3. Simulation of the system

To validate the improvement of the optical efficiency coming from the graded-index planar waveguide, the system has been modeled in LightTools.

The index is chosen in a range from 1.491 to 1.55, which means lenses with f/3.19 in air are needed to have all rays guided in the waveguide. A refractive index of 1.491 corresponds to pure PMMA. The propagation of the rays is not the same in a graded index waveguide as it is in a waveguide with a homogenous index. The difference is illustrated in Fig. 2. Between both systems, the only modification is the index of the waveguide. The lenses are the same and the coupling prisms have the same size.

In Fig. 2(a), it can be seen that the use of a graded-index waveguide eliminates the need for an air space between the lens and the waveguide. This comes from the fact that rays do not propagate by TIR on the surface opposed to the coupling prisms. As so, the system can be made of a single block without alignment procedure, which is an interesting aspect for cost reduction in the fabrication process. It also eliminates some air-material interfaces across the light path, which reduces Fresnel reflections and increases the optical efficiency.

The index profile, which is the mathematical relation between the refractive index and the position on the z axis, is presented in Eq. (5). The z axis is parallel to the thickness of the waveguide with z = 0 at the bottom interface. The total thickness of the waveguide is 1 mm (Zmax). The index profile in Eq. (5) should ideally be a hyperbolic secant to eliminate dispersion of the image point along the waveguide. However, a parabolic profile is a good approximation of the ideal index profile.

$$n(z) = n_0 - n_0 \frac{A}{2} z^2 \tag{5}$$

The value of parameter A is dictated by the lens. It must be adjusted depending on the f/# of the lens used to couple light in the waveguide. In the system that has been simulated in LightTools, the f/# of the lens in air is 3.19. It gives a value of 0.042 for parameter A. Since the coupling prisms do not produce a perfectly conical bundle of rays in the waveguide, we chose to use a value of 0.04 for the parameter A to optimize the optical efficiency of the system. The parabolic index profile inside the waveguide for the system that has been simulated in LightTools is presented in Fig. 4.

#202346 - $15.00 USD Received 2 Dec 2013; revised 10 Jan 2014; accepted 13 Jan 2014; published 23 Jan 2014

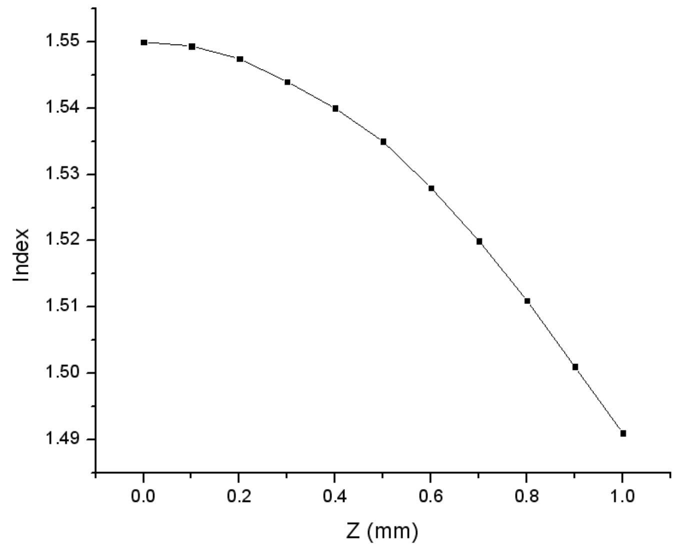

Fig. 4. Variation of the index along the z axis.

The refractive index gradient will re-image the sun periodically along the waveguide. The distance between two images is the period F of the gradient. With the parameter A chosen for this system, the value of period F is 9 mm. So, rays coupled at point P = 18 mm would strike the back surface two times before exiting the concentrator. We want to choose the position of the coupling prisms so that that rays will strike them only for coupling in the waveguide.

Both systems presented in Fig. 2 were simulated in LightTools to evaluate their optical efficiency at two moments of the year. The cylindrical lens eliminates the seasonal tracking since the sun moves in the axis parallel to the lens. The concentrator entrance face is tilted at an angle corresponding to the latitude. So, the sun is directly over the concentrator on March 21st and on September 21st. There is an angle of ± 23.4° on June 21st and on December 21st. This geometry is illustrated in Fig. 5. The system is optimized to produce a light output as constant as possible throughout the year. The light from the lens stays focused on the coupling prisms even when the sun is off-axis.

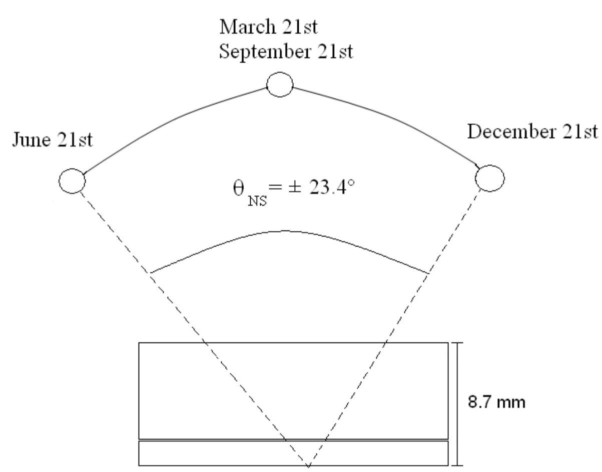

Fig. 5. Position of the sun versus the concentrator at different moments during the year.

Simulations of the performances of the concentrator with a homogenous waveguide and with a graded-index waveguide were then carried out for March 21st and for June 21st. The

#202346 - $15.00 USD Received 2 Dec 2013; revised 10 Jan 2014; accepted 13 Jan 2014; published 23 Jan 2014

results for both systems include losses associated with the reflection coefficient of the metalized prism structure and the absorption coefficient in the material. With the symmetry of the system, there is no need to look at other points during the year. The results of the simulations are presented in Table 1.

Table 1. Comparison of the optical efficiency for the same planar concentrators using f/3.19 lens in air. The only modification between both systems is the homogenous waveguide that is replaced by a graded-index waveguide (n = 1.491-1.55). An anti-reflection coating is used on the lens surface but Fresnel reflections are taken into account at other interfaces.

	Graded-index waveguide	Homogenous waveguide
March 21st - 18 mm	96.4%	86.0%
June 21st – 18 mm	88.5%	79.0%
March 21st – 26 mm	95.3%	76.0%
June 21st – 26 mm	84.8%	66.7%
March 21st – 30 mm	92.1%	71.0%
June 21st – 30 mm	83.4%	61.0%
March 21st – 34 mm	84.8%	66.1%
June 21st – 34 mm	79.3%	56.0%

It is clear that the optical efficiency of the system drops faster with the increasing length of the waveguide when using the homogenous material. The shorter waveguides give similar results if we do not consider the increase in the optical efficiency coming from the elimination of the Fresnel reflections. Effectively, there are two more air-material interfaces in the light path in the case of a homogeneous waveguide. They come from the air space between the lens and the waveguide needed to have TIR. This corresponds to a drop of about 8% in the optical efficiency. When increasing the length of the waveguide, the gap between both systems increases. This can be related to Fig. 2, where the number of backside surface interactions of rays coupled in the waveguide increases for the homogenous waveguide versus the graded-index waveguide. For a short waveguide, the number of interactions will not be a problem since the small portion of angles that present higher losses will not be enough to significantly degrade the overall optical efficiency of the system. When the length increases, the number of interactions will follow the same trend. As mentioned in Eq. (1), there is an exponential decrease of the optical efficiency versus the number of backside interactions.

A similar simulation has been performed to confirm these results. Here, the optical efficiency of the planar concentrator using a graded-index waveguide is calculated for a system with one-axis sun tracking and the sun directly over the concentrator. This corresponds to results for March 21st of Table 1. The data takes into account the reflection coefficient of the metalized prism and the absorption in the material. The results are presented in Fig. 6. It appears that the optical efficiency stays around 94% for systems with lengths under 26 mm. For the period F of 9 mm, this corresponds to the maximum length for the waveguide just before rays interact with the backside surface for a fourth time. If we increase the length of the waveguide to 27 mm, rays coupled by the farthest lens will then fall on the prism closest to the exit. A certain part of these rays will be lost and the optical efficiency of the system will be reduced. Since the waveguide length is increased by steps of 4 mm corresponding to two cylindrical lenses, there is a faster drop in the optical efficiency at the first point after L = 26 mm. This explains why the peak for the concentration factor is reached at L = 30 mm.

Since the optical efficiency stays constant from 18 mm to 26 mm, the concentration factor increases rapidly. For a 30 mm waveguide, the optical efficiency diminishes to about 89%. It corresponds to the maximum concentration factor attained with an f/3.19 optical system, which is (26.8 ± 0.2)x. If we further increase the length of the waveguide, the optical efficiency of the concentrator starts to fall rapidly. For a 44 mm waveguide, the optical

#202346 - $15.00 USD Received 2 Dec 2013; revised 10 Jan 2014; accepted 13 Jan 2014; published 23 Jan 2014

efficiency of the concentrator is only about 54%, which corresponds to a concentration factor (23.7 ± 0.2)x.

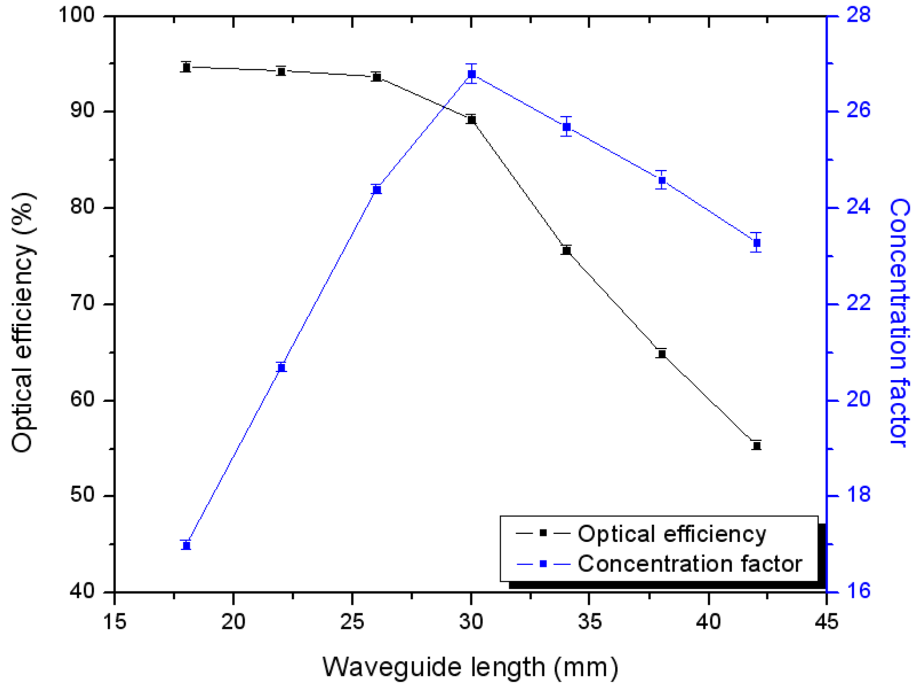

Fig. 6. Optical efficiency and related concentration factor for the graded-index waveguide concentrator tested in LightTools.

4. Fabrication of the waveguide

As discussed in the introduction, to be competitive, the new graded-index planar waveguide concentrator must be efficient and must be fabricated using a low-cost process. According to this goal, both lenses and waveguide must be manufactured using polymer. The advantage of using polymer to fabricate the waveguide is the capacity to mold the system, which is a low-cost solution for mass production.

A problem with the use of polymers could be that absorption and scattering is important in these materials compared to glass. In this work, it was not possible to consider the specific value of scattering or absorption for a graded-index polymer waveguide since no number has been published to our knowledge. However, to get a loss of 1% over a 5 cm path inside the waveguide, the attenuation coefficient would need to be $\alpha = 2.0\text{x}10^{-3}\text{cm}^{-1}$, which is about an order of magnitude superior to the value $\alpha = 1.43\text{x}10^{-4}\text{cm}^{-1}$ obtained 24 years ago by Koike & al. for a graded-index polymer fiber [16]. Still, 1% attenuation would be considered negligible for a solar concentrator. So, we do not consider attenuation or scattering as significant factors in this design.

To support our suggested graded-index waveguide we have developed a laboratory graded index polymer. It is possible to modify the refractive index of PMMA by adding an electron-rich organic dopant [11, 12]. In such case, the use of benzoquinolin gives the possibility of attaining a large increase in the refractive index. The index of pure PMMA is 1.491 and by adding 50% W/W of benzoquinolin, we can obtain an index of 1.59. As shown in Fig. 7, the relation between refractive index and concentration of benzoquinolin is linear. This is in agreement with results from literature [11, 12]. One problem with benzoquinolin is that it is an expensive dopant to use in commercial production. It is then a good idea to reduce the

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refractive index variation in the waveguide. Also, the dopant can modify the absorption spectrum of the polymer.

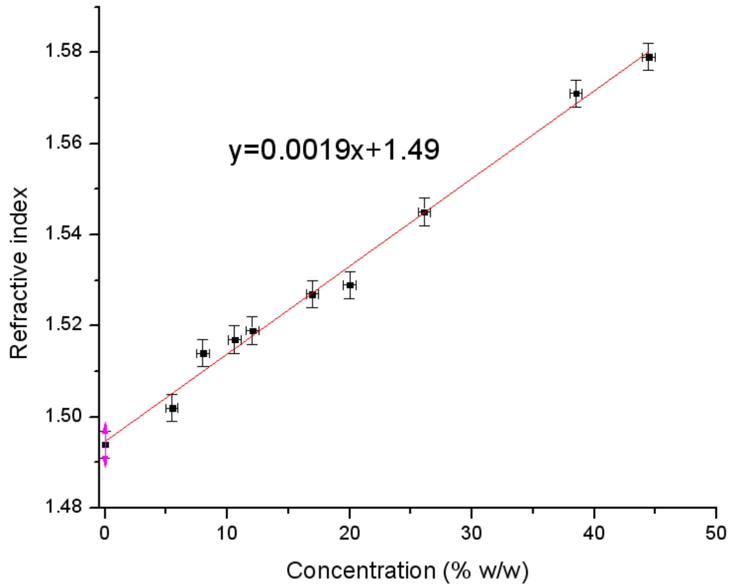

Fig. 7. Refractive index modification of PMMA by the addition of benzoquinolin in the polymer matrix.

With the addition of benzoquinolin to the PMMA matrix, there is a plasticising effect that can be observed. This is another reason why the highest refractive index used in this system is limited to 1.55. It will still be possible to use evaporated aluminum to cover the coupling prisms with a reflecting surface without melting the plastic. Also, since the system is built to collect sunlight, it must be able to face higher temperatures without melting.

More recently, a new method has been developed at Case Western Reserve University to fabricate a gradient index lens that could be used to produce the waveguide [13, 14]. The process is illustrated in Fig. 8. This method uses two polymers with different indexes that are laminated to create a sheet with a new refractive index. The index of the mixture is related to the proportion of each polymer that is added. For the fabrication of the planar waveguide concentrator presented in this paper, two polymers like PC and PMMA could be used. This would give a range of refractive index from 1.491 to 1.585, which would fit the requirement for the design presented in this paper.

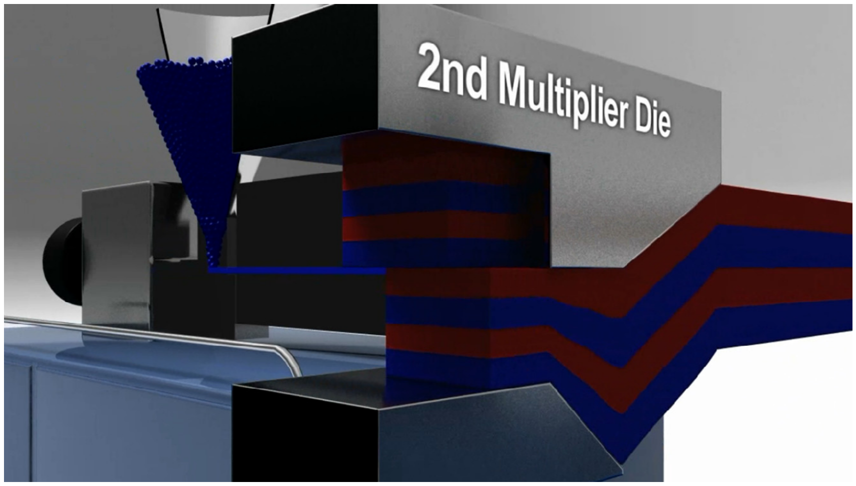

Fig. 8. Technique developed by DARPA to fabricate GRIN lens made with polymer [17].

5. Conclusion

The use of a graded-index waveguide in a planar concentrator has been presented in this paper. The objective was to design a one-axis tracking concentration system that has a good optical efficiency while being cost-competitive to fabricate. For this reason, polymer was chosen as the perfect material since molding is suited to mass production of components. One-axis tracking is a good trade-off between the poor annual energy collection of static systems and the high cost of precise dual-axis tracking.

Simulations with LightTools were done to validate the improvement. It was shown that the use of an index gradient in a range from 1.491 for pure PMMA to 1.55 can increases the optical efficiency of the system by as much as 33% compared to a homogenous polymer waveguide with an index of 1.52. A part of the improvement comes from the elimination of the Fresnel reflections along the rays' path. This possibility to fabricate the concentrator in a single block is also an interesting aspect of this design from a mechanical point of view.

To fabricate the graded-index waveguide with polymer, there are two methods that can be used. We think that the new technique developed by DARPA to produce GRIN lenses has the potential to make this concentrator design really cost-competitive.

Compared to a homogeneous waveguide, the graded-index waveguide attains a higher optical efficiency for the same length. This corresponds to a higher concentration factor for the graded-index concentrator. This is done at the expense of more complex manufacturing. However, with the recent progress in gradient-index manufacturing, we think that this difference will slowly disappear.

The planar waveguide concentrator proposed in this paper is a new alternative to more traditional one-axis tracked solar panels. It shows great potential for commercial and industrial scale solar fields. Experimentation under real conditions will allow verifying the accuracy of the simulations and the commercial viability of the system.

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