Improving the optical efficiency of a waveguide concentrator used with a single-axis tracking system

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Abstract: We propose a method to improve the optical efficiency of a planar concentrator used with a single-axis tracker. The low cost for mass producing the system is kept while the performance is improved.

OCIS codes: (350.6050) Solar energy; (220.1770) Concentrators; (230.7400) Waveguides, slab

1. Introduction

Solar concentration is a well know approach to reduce the cost of solar energy. Planar concentrators have recently been proposed as a new kind of solar concentrators for HCPV [1, 2]. However, they are also usable for low concentration system [3]. This led us to develop a waveguide concentrator for medium concentration that tracks the sun in one-axis. If designed properly, it can be an effective concentrator while keeping the low fabrication cost associated with the initial design.

The major problem associated with this concentrator is the losses coming from the extended surface covered by the coupling prisms. It limits the capacity to increase the length of the waveguide to bring more light to the solar cell. To overcome this problem, the use of a graded index waveguide based on the SELFOC index profile is proposed.

In this paper, a comparison between two planar concentrators is presented. The systems use cylindrical lenses to remove one axis of sun tracking. It is shown that the use of a graded-index waveguide instead of an homogenous waveguide increases the optical efficiency of the system by about 14%. Both systems have been simulated using a mathematical model developed by Karp [1]. The results of these simulations are presented and a discussion on the feasibility of such system follows.

2. Planar concentrator with cylindrical lenses

Sun concentration in one axis reduces the attainable concentration level which becomes the square root of the two axis limit. The advantage of doing so is the elimination of one sun-tracking axis, which can be quite interesting when installation and maintenance costs are taken into account. An illustration of such concentrator is presented on Fig. 1.

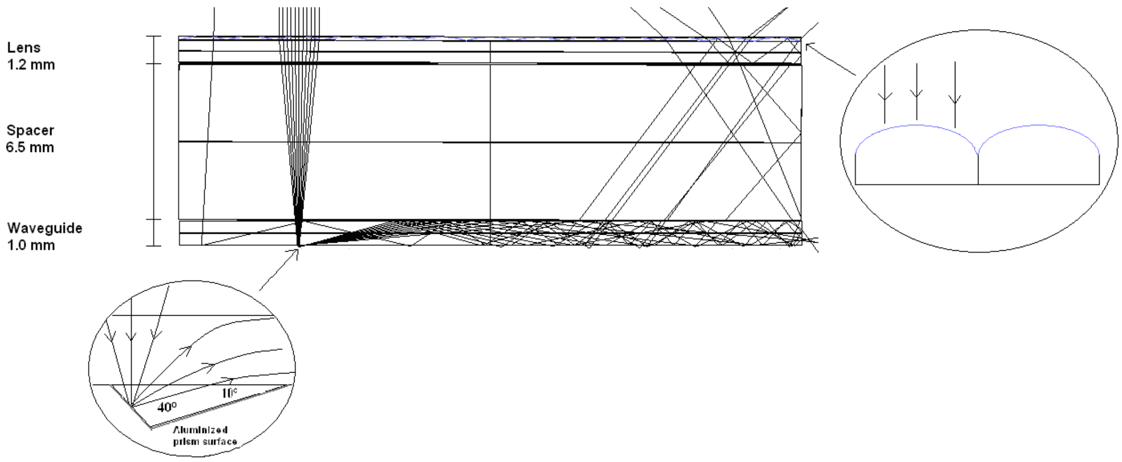

Fig. 1: Lateral view of the planar concentrator with cylindrical lenses

The problem associated with planar concentrators is that the optical efficiency decreases when the length of the waveguide and the associated concentration factor increases.

3. Improving the performance of the system by using a graded-index waveguide

A complete analytical theory of propagation losses in a planar waveguide have been developed by Karp [1]. It has also been adapted to one axis planar concentrators [2]. If we take a look at the rays transmitted by the homogeneous waveguide, it appears that the ones with a small coupling angle will be mostly transmitted to the cell while there will be more losses for the ones with a larger coupling angle. This is illustrated by the numbers in Tab. 1 for rays entering the waveguide at P=18 mm. This difference comes from the length between two backside interactions that is not the same. More interactions will means more chances of striking a second prism and exiting the waveguide.

If we use a waveguide with a graded index profile, the length between two backside interactions is the same for all angles coupled in the system. This length is directly related to the gradient of index inside the waveguide. In this system, the index range was from 1.491 to 1.55. This means that the period of the index profile will be 9 mm, which gives only two interactions during the propagation inside the waveguide. So, there will be more interactions for rays with a small angle compared to the case of a homogenous waveguide. For all other angles, the number of interactions will be lower. The difference between both cases appears in Tab. 1.

Tab. 1: Computed values for rays coupled in two different waveguides.

Angle	Distance between 2 backside interactions		Number of interactions		Optical efficiency	
	Homogeneous	Graded index	Homogeneous	Graded index	Homogeneous	Graded index
°	mm	mm	P = 18	P = 18	C_{lens} = 10	C_{lens} = 10
0.1	1145.91	9	0.02	2	1.00	0.81
2	57.27	9	0.31	2	0.97	0.81
4	28.60	9	0.63	2	0.94	0.81
6	19.03	9	0.95	2	0.91	0.81
8	14.23	9	1.26	2	0.88	0.81
10	11.34	9	1.59	2	0.85	0.81
12	9.41	9	1.91	2	0.82	0.81
14	8.02	9	2.24	2	0.79	0.81
16	6.97	9	2.58	2	0.76	0.81
18	6.16	9	2.92	2	0.73	0.81
20	5.49	9	3.28	2	0.71	0.81
22	4.95	9	3.64	2	0.68	0.81
24	4.49	9	4.01	2	0.66	0.81
26	4.10	9	4.39	2	0.63	0.81
28	3.76	9	4.79	2	0.60	0.81
30	3.46	9	5.20	2	0.58	0.81
32	3.20	9	5.62	2	0.55	0.81
34	2.97	9	6.07	2	0.53	0.81
36	2.75	9	6.54	2	0.50	0.81
38	2.56	9	7.03	2	0.48	0.81
40	2.38	9	7.55	2	0.45	0.81
42	2.22	9	8.10	2	0.43	0.81
44	2.07	9	8.69	2	0.40	0.81
46	1.93	9	9.32	2	0.37	0.81
48	1.80	9	10.00	2	0.35	0.81

Computed values from the analytical expressions show that for coupled angles larger than 12°, the optical efficiency of the system becomes lower for the homogeneous waveguide. It appears that it comes from the number of interactions with the backside surface. Globally, the average optical efficiency of the rays coupled in the system with different angles is higher for the case with the graded-index waveguide. The difference between both situations is about 15% at P=18 mm according to the analytical calculation. This effect will vary depending on the position inside the waveguide. As we move farther from the exit of the waveguide, the difference between the optical efficiency of the different rays coupled at the same point will grow larger.

Simulations with LightTools were conducted to quantify the effect of using a graded-index waveguide on the optical efficiency of the system. The results of these simulations are presented on Fig. 2. It appears that the optical efficiency of the waveguide with a graded-index profile is higher for all lengths. The first point is for L=18 mm and the gap between both curves is smaller at this point. This gap increases and reaches a maximum value between 26 mm and 34 mm. This corresponds to a sweet spot for the development of a planar concentrator with cylindrical lenses, which requires tracking of the sun in only one axis.

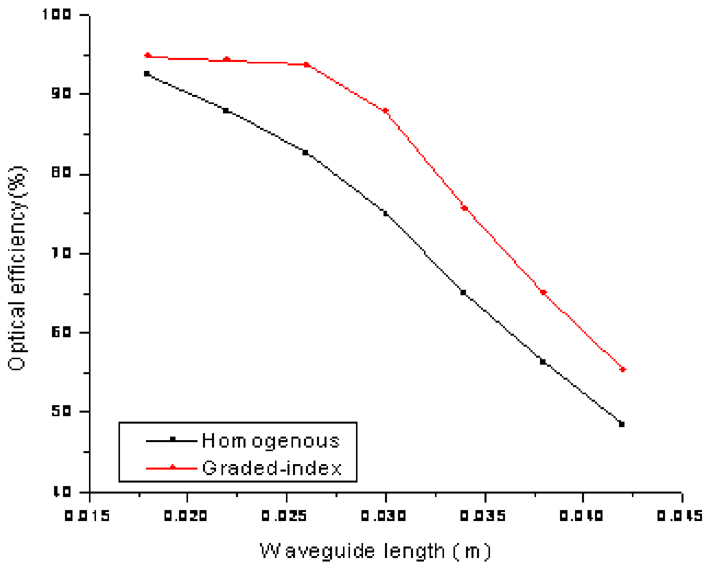

Fig. 2: Optical efficiency of both waveguides for different lengths.

4. Discussion

It appears that there is a theoretical advantage to use a graded-index profile instead of a homogenous index for the waveguide. Doing so with glass might be difficult and costly since only small index modifications are possible. However, with the recent developments in polymer fabrication, plastic is now a prime candidate for such system. There are two methods to produce a plastic having an arbitrary index of refraction.

The first one is based on the addition of an organic-dopant to the polymer matrix. With this method, it is possible to increase the refractive index of PMMA from 1.491 to about 1.585. However, mechanical and optical properties of the polymer are modified by the process. Also, organic-dopant can be expensive compared to the polymer.

Another method is to mix polymers with different refractive indexes. For example, if you use PMMA and PC, you can make plastics with all kind of refractive indexes from 1.491 to 1.585. This promising technique has recently been developed by DARPA to fabricate graded-index plastic lenses. We think this could be applied to fabricate this graded-index waveguide at low cost.

5. References

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