

ON THE USE OF OPTICAL WAVEGUIDES IN HYBRID PHOTOVOLTAIC SOLAR THERMAL ENERGY CONVERTERS

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ABSTRACT

We analyze a variety of optical filtering technologies and find that fiber and rod waveguides provide some thermal distribution advantages as well as useful filtering capabilities for solar energy applications. We define photovoltaic and hybrid improvement factors which characterize the utility of optical filters for solar energy applications. Comparison of two types of optical fiber filtered concentrators is then facilitated by this metric.

1. INTRODUCTION

Two of the most promising means of cost effectively producing electricity from solar energy are: solar thermal driven electrical generators; and concentrated photovoltaic (CPV) systems. In this paper we describe means of enhancing the performance of either of these leading technologies. A primary objective of the proposed hybrid is to increase the electrical output of photovoltaic (PV) systems via optical filtering and concentration of the incident sunlight in a way that simultaneously transfers virtually all of the unconverted energy into a solar thermal system with exceptional efficiency. Therein the out-of-band infrared (IR) and ultraviolet (UV) spectral components that would ordinarily cause heating and/or damage of the PV, in a conventional CPV system, are removed from the light *before* impinging upon the PV; thereby permitting higher levels of concentration. A variety of filtering technologies have been analyzed [1] including: the use of chromatic aberration (in a lens, prism, etc.); multilayer dielectric filters; optical fiber; and optical rod waveguides. We find that optical waveguides and optical fiber offer some useful filtering qualities which also provide some thermal distribution advantages. As a filter, a waveguide provides additional opportunities because the filter response evolves as a function of the length of the guide – thus this shape can be optimized for the application (e.g., for the particular PV and

thermal loop to be employed). The thermal advantages are several. For example, fiber can efficiently couple heat to almost any solar thermal technology due to its great flexibility in configuration (fibers could snake out away from the collection bundle into the coolant; wrap around the coils of absorption chillers, etc.). Moreover, they hold the potential for heat transfer efficiencies that could approach 100% simply by making them longer (as low loss, low cost, options exist).

The calculated power transfer results stand on their own, as useful information. To go further with this, it is useful to assess their impact on system performance with simple models, therein defining PV and overall system improvement factors that characterize the merit of the filtering and thermal distribution technology. The problem of extrapolating actual system performance from power levels within any frequency band is a complex subject of its own as there are many factors to include. However, we can define simple models and performance measures that represent performance limits, approachable when some of the many real-world factors become negligible. Alternatively, we can also take the performance measures as simply a means of concisely characterizing the quality of the filter as applied to the solar energy application: providing a tool for researchers and designers in making choices among filtering technologies.

We formulate lower bounds on improvement factors by neglecting various beneficial effects. For example, the reduction of the amount of out-of-band UV and IR that would otherwise impinge upon a PV reduces the heat going into it, which reduces its temperature (per its specific heat) which increases the PV

efficiency (per “0.5%/degree C”). But such a model would be complicated by the need to deal with temperature on an absolute scale, resulting in complications of ambient, wind, etc., in attempting to extrapolate actual system performance. Moreover, this effect is negligible (hence not included herein) compared to the fact that removing the sources of heat allows operation at higher levels of concentration.

Instead, we prefer a model [2] that does not hinge upon the *absolute* value of any parameter and relies solely upon a *ratio* of heat as follows. If we reduce the amount of heat going into the PV by some factor (say 1/2) then we could increase the amount of concentration by one over that factor (say double the light gathered by the collection optics) and still provide, roughly, the same operating environment. This neglects the effect of ohmic losses in the PV that would increase as we increase its output power at higher levels of concentration – but it does define a simple model with improvement factors that could be realized in the limit that these other effects are negligible. We also neglect the fact that the photovoltaic efficiency itself actually increases with increased concentration (as long as its temperature remains constant). In that sense these improvement factors provide lower bounds on what could be achieved. Alternatively, these photovoltaic improvement factors, PVI, can be interpreted as performance *measures* (not *predictors*) which simply characterize the utility of an optical filter when applied to the solar energy application.

2. OPTICAL FIBER FILTERING CONCENTRATORS

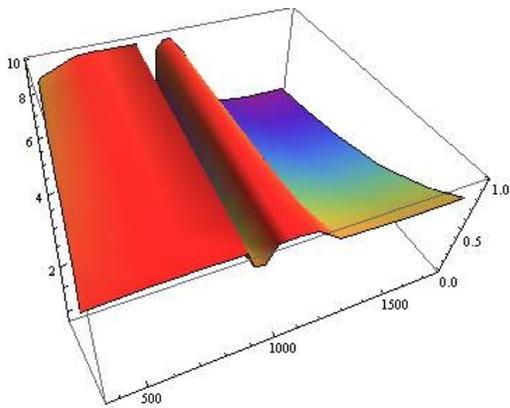


Fig.1: Spectral response of UV fused silica fiber for fiber lengths from 1 to 10 meters

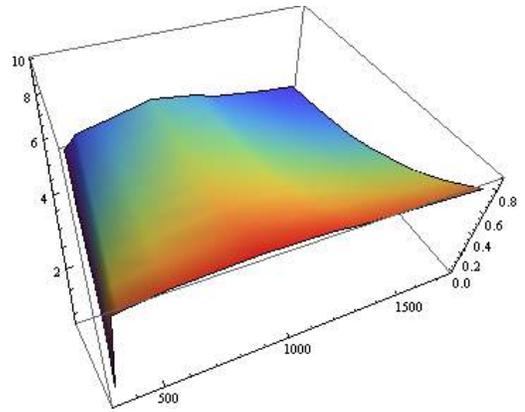


Fig.2: Spectral response of borosilicate fiber for fiber lengths from 1 to 10 meters

Figures 1 and 2 depict how the spectral response of the fiber/filter evolves as a function of the distance down the waveguide. For UV fused silica we see in figure 1 high transmission over silicon’s responsivity range of 400-1125 nm (except for an unfortunate absorption near 950 nm). Also, the attenuation of the IR rapidly becomes appreciable and we see the onset of some useful filtering in the UV as well. The fact that these shaping effects are improving, while maintaining good in-band transmission, suggests that we might expect some improvement factors at moderately increased concentration levels. The evolution of borosilicate’s response in figure 2 is from one that is relatively flat, to one that is more sharply peaked at 860 nm (fortunately close to silicon’s peak responsivity of 910 nm). The in-band losses can be mitigated by whatever level of increased concentration, C, is permitted. Yet, even if we could neglect the costs of C (in larger collection optics costs, increased thermal stresses, etc.) it still would not be clear as to which shapes are optimal. To determine that (and to determine the associated value of C) we turn to our metrics.

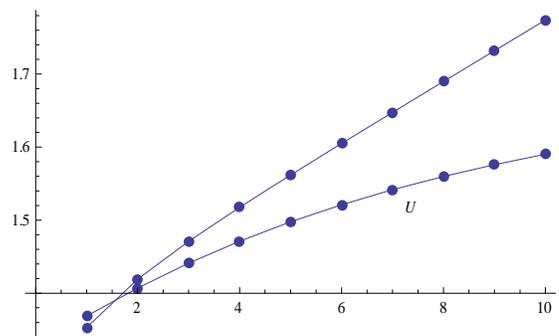


Fig.3: PVI lower bounds for the two fibers vs length

Borosilicate is providing a larger lower-bound PVI at fixed length, z , in figure 3 for $z > 1.5$. However, it is accomplishing this via larger values of C : 6.9 as opposed to only 1.8 for UV fused silica at $z=10$ (which increases the cost of the collection optics). When C is the fixed constraint (instead of a fixed length of fiber) we find that UV fused silica fiber provides superior PVIs: achieving a PVI of 2 at $C=3.2$, which requires $C=17.4$ for borosilicate. These metrics are tools for larger-scale optimizations that would have to include other facts such as: one square meter Fresnel lenses are commercially available for ~150\$; and UV fused silica comes at a cost/m of roughly 100 times that of borosilicate fiber, etc. Moreover, increased levels of C could require a fused fiber bundle input head (rather than high temperature epoxies) which is an expensive proposition. To translate these PVIs into similar cost/kW improvement factors, a water-based rod waveguide might provide an attractive alternative [3] to fiber.

3. OPTICAL ROD WAVEGUIDE

Of course there are many ways to filter incident light in a solar energy converter. One could utilize for example the chromatic aberration of the primary collection optics. Therein the frequency dependence of the index of refraction causes a frequency dependence of the focal length of the lens (or mirror) so that an aperture can collect some wavelengths while shadowing, hence attenuating others. The spectral response of such a (collection optics) filter is analyzed herein. Similarly, the chromatic aberration of the waveguide material (herein we focus on water in a rod waveguide) forms a filter. In practice both of these (collection optics and waveguide) will function as low-pass filters; thus chromatic aberration by itself is shown to yield limited improvement factors for the solar energy application. However, when used in conjunction with the high-pass filtering effects of the absorptive properties of the media, we find that chromatic aberration can significantly enhance the performance of the absorptive filter.

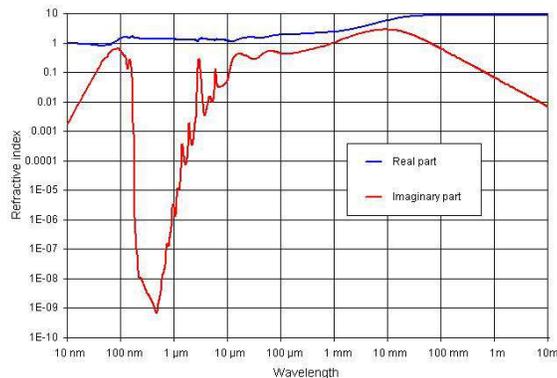


Fig. 2: Spectral dependence of the real and imaginary parts of the refractive index of liquid water (from [4])

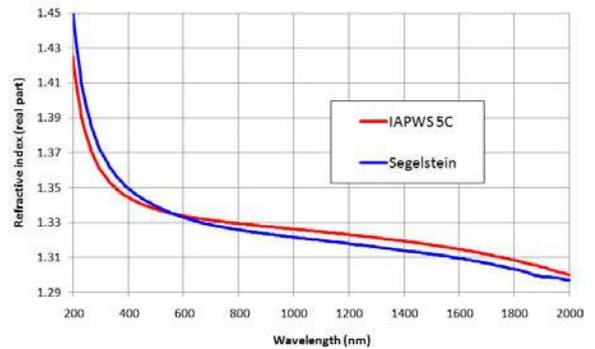


Fig. 5: Spectral dependence of the real part of the refractive index of liquid water (from [4])

Figure 4 presents the spectral dependence of the real and imaginary parts of the refractive index of liquid water, which determine the chromatic aberration and the absorption of the material, respectively. This data [4] was measured at room temperature (30 degrees C) but the temperature dependence is almost negligible as long as the water doesn't make a phase-change (i.e, remains liquid, not steam, nor ice). The chromatic aberration of the waveguide material can be analyzed in a manner similar to that outlined above for the collection optics. The absorptive filtering properties of the waveguide material can be analyzed akin to our analysis of fiber (after converting the imaginary part of the refractive index into dB/km of loss).

Since the dependence of the index of refraction over most of the solar bandwidth is monotonic in wavelength, as shown in figure 5, with a sharp decrease in the UV and a more gradual decline in the IR (as is also the case for fused-silica and quartz collection optics) the focal length decreases in the UV and flattens out to a constant in the IR. Thus, in the case of if the distance between the lens and the aperture (which could be a waveguide input head) is set to the focal length corresponding to the peak wavelength of the responsivity of the PV; then wavelengths shorter (more blue) than that are focused in front of the aperture and wavelengths longer (more red) than that are relatively unaffected and thus focused near the plane of the aperture. It turns out that for the collection optics, the choice of placing the aperture at the focal length of the peak responsivity wavelength of silicon (900nm) is not optimal, and results in a PVI of less than 1. The absorption of the out-of-band spectral components, which allows for a higher optical concentration level to achieve the same PV operating conditions, does not compensate for the loss of the in-band energy that would have undergone

PV conversion. However, if we chose to locate the aperture at the focal point for 600nm (instead of 900nm) then we can enhance the performance of this system with this type of filter, resulting in a PVI of 1.12. Similarly, the material chromatic aberration of the waveguide can lead to a PVI of 1.30.

The absorptive filtering properties of water are useful in the IR (beyond the 1125nm cutoff of silicon's responsivity) but it passes an unfortunate amount of UV (at wavelengths below the 400nm cutoff of silicon). Thus the PVI from the absorptive filtering, by itself, would be limited to 1.6, for any water-rod waveguide length. However, if we use the UV attenuation (high-pass filtering) effects of chromatic aberration in conjunction with the absorptive properties of the media, we find that can achieve a PVI of 2.03. Since the incremental cost is minimal, this technology might lead to a means of accomplishing the DOE's goal of reducing the cost/kW of photovoltaics by a factor of 2.

4. FREQUENCY CONVERSION POTENTIAL

We note in passing that optical fiber and rod waveguides also might provide a viable technology for frequency conversion of the IR and UV into the response range of the photovoltaic (rather than simply absorbing them and conducting the resulting heat into the thermal loop). This frequency conversion can be achieved via nonlinear optical processes and/or processes similar to the pumping of an optical amplifier or laser. Photonic crystal fiber, PCF, and other micro-structured fiber components [5] have enormous bandwidth and high power handling capabilities – sufficient for many solar energy applications. Moreover, fluorescent materials in thin-films have demonstrated recent improvements in up-conversion [6]. A wide variety of nonlinear optical processes could be employed; and one class of embodiments would employ resonators to enhance the net efficiency of the frequency conversion process [7]. Therein, even if the single-pass conversion in a nonlinear material (such as a fiber) might be small (e.g., say 4%); close to 100% conversion could still be achieved by putting the nonlinear material (e.g., fiber) in a resonator (e.g., a fiber ring resonator) because the field *inside* the resonator is larger by a factor of $1/(1-r)$ where r ; the

reflectivity of the resonator mirrors (or input/output couplers) can be made very close to 1.

The improvement resulting from frequency conversion depends on the PV used. For example, with silicon the ideal (perfectly cooled, no ohmic losses, no reflection, etc.) responsivity efficiency limit of 26% (note, responsivity is in units of electrical-amps per optical-watt, in contrast to the dimensionless quantum efficiency) could be increased to an effective limit of 40%; whereas Indium Gallium Arsenide's ideal limit of 19% could be increased to 60%. Thus, frequency conversion might also be employed to go beyond the simple filtering aspects analyzed above.

5. REFERENCES

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