CIGS PV Power Enhancement from Photonic Crystal Fiber Concentrators

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ABSTRACT

The use of optical waveguides as solar energy concentrating filters permits higher levels of concentration in concentrated photovoltaic systems. Photonic crystal fiber (PCF) permits exciting new results in this field. Owing to the fact that the guidance mechanism in a PCF is a transverse resonance (set up by a pattern of air holes) rather that total-internal-reflection, the electric field can be predominantly confined to air instead of glass. This results in many new properties – one being minimization of Rayleigh scattering in the visible, which opens up new possibilities for solar energy applications. We demonstrate that the output power of a CIGS photovoltaic can be tripled by increasing the concentration level by a factor of 16 through the use of a PCF concentrating filter.

Keywords: solar energy, photovoltaics, concentrators

1 INTRODUCTION

Two of the most promising means of reducing the cost per kilowatt of photovoltaic (PV) systems are: 1) to reduce the cost – which includes recent progress made in thin-film (e.g., CdTe, CIGS) and polymer PVs; and/or 2) to increase the power – which includes progress in CPV (concentrated PV) systems and multiple-bandgap PVs. CPV systems however are also arguably targeted at cost reduction since they utilize the fact that the collection optics is less expensive than the PV material. For example, plastic is certainly cheaper than silicon so why not just collect a large amount of solar energy in an inexpensive Fresnel lens and focus it onto a relatively efficient silicon PV? The inherent problem is that we are also concentrating the out-of-band ultraviolet (UV) and infrared (IR) spectral components, that aren't converted into electricity, and merely increase the temperature of the PV causing its efficiency to plummet. The conventional CPV approach is to use a broader-band (multiple-bandgap) PV to reduce the out-of-band components; and/or heat-sinks to reduce the temperature of the PV, but these increase the system cost. Alternatively some type of optical filtering can be inserted between the collection optics and the PV – thereby reducing the sources of heat from the light itself *before* it impinges upon the PV. A wide variety of optical filtering technologies have been analyzed including: the use of chromatic aberration (in a lens, prism, etc.); multilayer dielectric filters; optical fiber; and optical rod waveguides. We have found [1] that optical waveguides (including optical fiber) offer useful filtering qualities as well as many thermal distribution advantages. As a filter, a waveguide holds an advantage due to the fact that the filter response evolves as a function of the length of the guide – thus this shape can be readily optimized for the particular PV involved. The thermal advantages include the fact that a waveguide can efficiently couple heat to virtually any solar thermal technology due to its great flexibility in configuration (e.g., individual fibers could rapidly spread away from the hot spot at a fiber bundle input head into a coolant; wrap around the coils of an absorption chiller, etc.). Moreover, the heat transfer efficiencies can be increased to virtually any level, simply by making the waveguides longer.

This mitigation of the heat sources via optical waveguide filtering concentrators permits higher levels of concentration, thereby increasing the PV output power while also enhancing the cost advantages of collection optics vs PV area. The calculation of the evolution of the transmission spectra of the waveguide as a function of the length of the guide is straight-forward in principle. Prediction of PV system performance however is a complicated subject of its own when one incorporates the plethora of real-world factors. This can be greatly simplified however by considering bounds on system performance. To assess the utility of a filter on a PV a lower-bound photovoltaic improvement (PVI) model has been formulated [2] and experimentally confirmed in borosilicate fiber and water-based optical rod waveguides for the case of silicon PVs. The model is based on a ratio of heats as follows. If a filter reduces the sources of heat by say a factor of two, then we ought to be able to double the level of concentration and still maintain roughly the same operating temperature. The PVI is the PV output at that filtered and increased level of concentration, normalized to its unfiltered response. A PVI of 2 at an increased level of concentration, C, of 3 for example would imply that we can double the output power by tripling the concentration level (because we can do so without increasing the out-of-band spectral components as these are reduced by the filter). Alternatively we can take the PVI model as a simple metric: a performance measure, rather than a performance predictor – which provides a means of comparing the performance of various filters when applied to the solar energy application. The theory also provides information on the requisite increased level of concentration permitted by the filtering and the possible increase in collection optics costs must be considered, as well as the waveguide costs, in order to translate the PVI power enhancements into cost/kW reductions.

2 PHOTONIC CRYSTAL FIBERS

Recently [3], [4] photonic crystal fibers (PCFs) have achieved very low loss in the visible and near-IR range of the spectrum (where the most efficient and cost effective PVs have an appreciable responsivity). In addition to creating new ultra-broadband transmission windows for the telecommunications industry this opens up new possibilities for the use of fiber as a power distribution network for solar energy [5]. If these also have an appropriate spectral shape they could also serve as highly efficient waveguide filtered concentrators for the enhancement of PV output power, as described above. Rather that total-internal-reflection, the guidance mechanism in a PCF is a transverse resonance (a pattern of air holes throughout the fiber works like a Bragg grating in the transverse direction). Thus the electric field can be predominantly confined to air instead of glass. This results in the minimization of Rayleigh scattering in the UV and absorption in the IR, which opens up new transmission windows while maintaining excellent performance in the existing telecom bands [6]. PCFs also offer unprecedented amounts of dispersion control, which is essential for the transmission of information. The resulting explosion in bandwidth offered by PCFs is well suited to meet the unending exponential increase in the need for the capacity to haul information, thus the telecommunications industry will inevitably drive down the costs of PCFs (independent of the solar energy applications).

3 PCFS AS FILTERING SOLAR ENERGY CONCENTRATORS

A wide variety of PCFs exist, some of which have a transmission spectra well suited to PVs of reasonable cost and efficiency. Figure 1 depicts the spectral response of such a PCF (where the y axis is the length of fiber in meters, the x axis is the wavelength in nanometers, and the transmission contours range from 90% in red to 10% in violet). This visible range PCF [7] should be well matched to the responsivity of silcon (which is appreciable from roughly 400nm to 1125nm) or CIGS (roughly 300nm to 1200nm). Herein we show results for CIGS PVs, which are similar to silicon, but as thin film devices they are flexible and are expected to maintain a cost-effective edge since they can be manufactured in a roll-to-roll process.

In figure 2 we display the resulting PVI (y axis) and requisite increased concentration level C (x axis) for lengths z from 1 to 10 meters, for a CIGS PV filterd by the visible range PCF of figure 1. Thus, with 10 meters of this PCF we can obtain a lower-bound PVI of 3.12 by increasing the concentration level of the collection optics to C = 15.77. This impresive result stems from the PCF's transmission spectra being well centered within the resposivity of the PV.

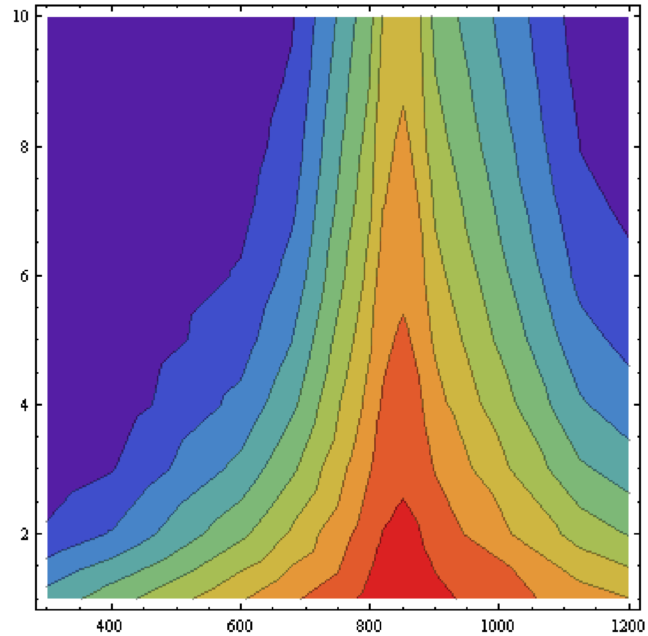

Figure 1: Transmission spectra of a visible range PCF.

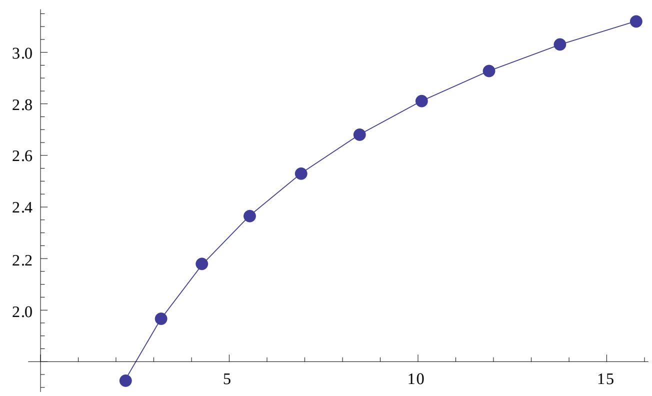

Figure 2: PVI versus C for the PCF of figure 1.

Many PCFs are designed for ultra-wide-band transmission and for those to be used in the concentrator applications we might need to supplement the system with a short-pass filter in order to reduce the out-of-band IR components. The transmission spectra of a hollow core PCF (with a kagome lattice) which is intended to provide new transmission windows for telecommunication applications (between 400nm and 1000nm) while maintaining excellent performance in the existing telecom bands [6] (centered at 1310nm and 1550nm) is presented in figure 3. If we used this entire spectrum as a waveguide filter concentrator for CIGS PVs (which don't have any appreciable responsivity

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past 1200nm) then we might anticipate that this filter lets in too much of the undesired IR.

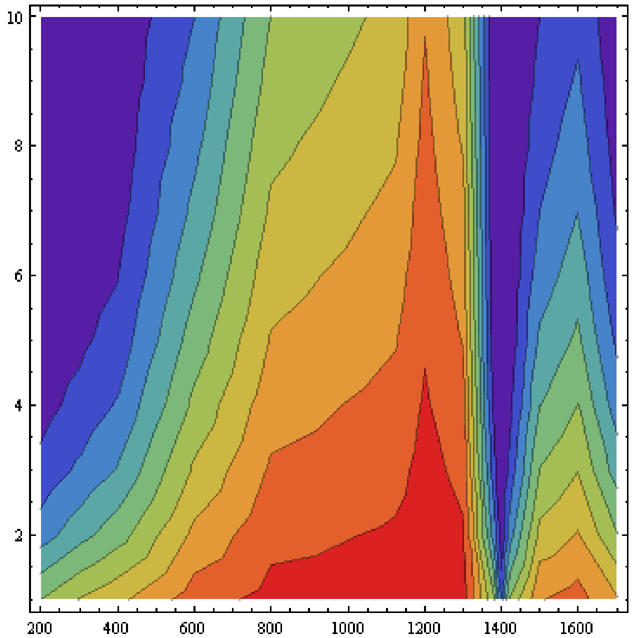

Figure 3: Transmission spectra of a kagome lattice PCF.

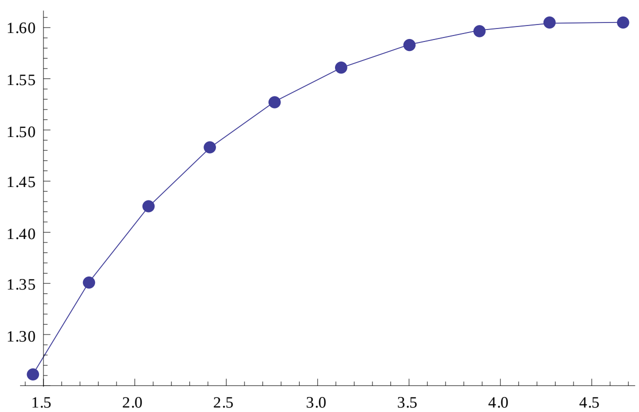

Figure 4: PVI versus C for the PCF of figure 3.

Indeed, as depicted in figure 4, we get diminished results relative to those of figure 2 in which the filter was better matched to the photovoltaic. Note also that the curve has flattened out indicating that making the fiber longer isn't going to help much. The relatively low values of C also indicate that we aren't able to filter out the out-of-band components to permit the increased levels of C that could lead to more significant improvements.

If one were to actually use a PCF in solar energy applications, that is instead intended for telecommunication applications, then it would be more likely that this would be in a shared network for the simultaneous transmission of power and information [5]. In this case one would want to deploy ultra-broadband WDM couplers to isolate the two applications. Such enormous bandwidths are currently unavailable in commercial couplers Recently however, microstructured couplers [8] using tapered fiber have been demonstrated the extraordinarily broad bandwidths that would facilitate the realization of such a shared network. In figure 5 we presesnt the spectra of the PCF of figure 3 after filtering it with a sharp short-pass filter at 1200nm to model the effects of such a coupler.

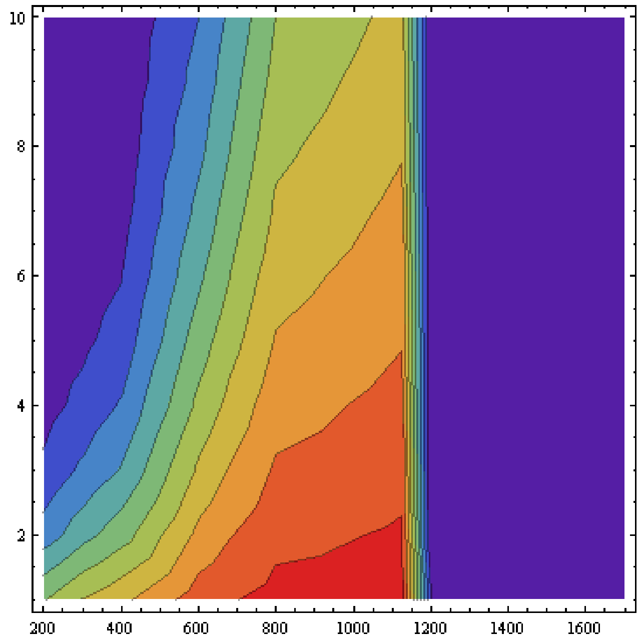

Figure 5: Transmission spectra of a filtered PCF.

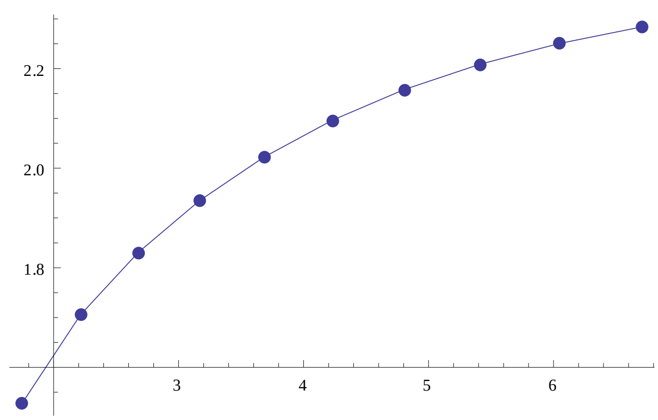

Figure 6: PVI versus C for the PCF of figure 5.

Figure 6 displays the corresponding PVI curve. The fact that it has not flattened out indicates that performance can be further enhanced by utilizing longer lengths. Taking the accomplishment of a PVI = 2 as a benchmark, this is a good result. Particularly since that benchmark can be achieved with a modest increase in concentration level.

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