BROAD BAND RUGATE FILTERS FOR HIGH PERFORMANCE SOLAR ELECTRIC CONCENTRATORS

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ABSTRACT

This paper presents the results of recent studies involving broadband Rugate filters for use in a high efficiency Photovoltaic Cavity Converter (PVCC) being developed by UI^2. PVCC's success in the achievement of a conversion efficiency of ~50% depends on the optical performance of Rugate filters that are deposited on the solar cells lining the interior of PVCC's cavity. The underlying principle behind PVCC's high performance is the optimal utilization of the solar spectrum based upon a novel spectral splitting process induced by the Rugate filters, and the use of single-junction cells with different but congruent energy bandgaps. Although narrowband Rugate filters found many applications in the past, there is no experience with broadband applications. Analytical modeling conducted under this project shows that it is possible to design high quality broadband Rugate filters with satisfactory reflectance (99%) and transmittance (99%). Results obtained for a four-bandgap system consisting of GaInP, GaAs, GaInAs and GaInAsP are reported here.

INTRODUCTION

Under a separate NREL project, UI^2 is developing a Dish/PVCC concentrator system consisting of a first stage parabolic concentrator, a second stage non-imaging flux booster, and a spherical cavity collecting the highly focused light. Figure 1 illustrates a complete system based on a dish with circular facets. The trapped light inside the cavity is converted to electricity using a multiplicity of single junction III-V cell groups lining the interior surface of the cavity. Each cell group is characterized by a specific energy bandgap and spectral response. Individual cells in a given group have a Rugate filter overlay that has conjugate reflectance/transmittance characteristics matching the spectral response of the cell underneath. During their "random walk" inside the cavity, photons of conjugate frequencies are transmitted into the respective cells, whereas the other photons are reflected (Figure 2). This selective transmission and reflection of photons in an ongoing recycling process represents a new form of the spectral splitting concept that has been studied earlier by others in order to achieve higher efficiencies. The underlying principle behind PVCC's predicted high performance is the optimal utilization of the solar spectrum as is in the case of multi-junction (MJ) cells. Although the basic idea of a multi-band gap cell system is common to both technologies, PVCC is dramatically different. As can be seen from Figure 3, PVCC replaces the vertical, 3D architecture of MJ cells consisting of monolithic or stacked sub-cells with a lateral, 2D array of single junction cells. The result is an increased degree of freedom in the choice of semiconductor materials and the elimination of electronic, structural, thermal and optical difficulties that MJ technology faces when the number of sub-cells is four or more and the flux concentration exceeds 500 suns.

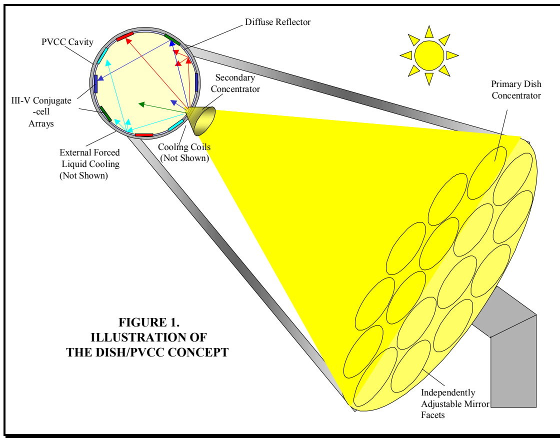
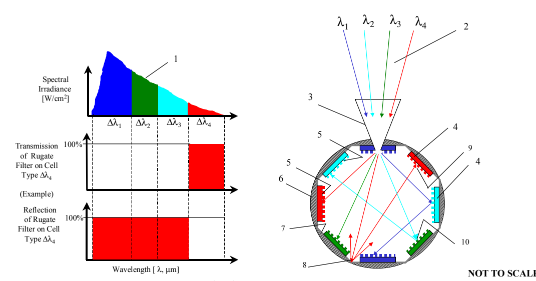
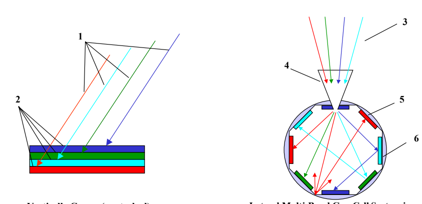


FIGURE 1. ILLUSTRATION OF THE DISH/PVCC CONCEPT



1 - Solar Flux (AM1.5) Divided in Four Spectral Bands ($\Delta\lambda_1$, $\Delta\lambda 2$, etc.)
2 - Pre-focused Solar Flux Represented by Four Photons (λ_1, λ_2, etc.)
3 - Bezier Optimized Secondary Concentrator
4 - Single-junction Cells with Spectral Responses Matching Bands ($\Delta\lambda_1$, $\Delta\lambda 2$, etc.)
5 – Rugate Filters with Band Matching Reflective and Transmitive Characteristics
6 – Spherical Light Trapping Cavity
7- High Reflectivity Lining on Cavity Walls (Diffuse)
8- Diffusely Reflected λ_4 Photons from Cavity Wall
9- A λ_4 Photon Entering a Matching $\Delta\lambda_4$ Cell
10- A λ_2 Photon is Rejected by a $\Delta\lambda_3$ Cell

FIGURE 2. PRINCIPLES OF SPECTRAL SPLITTING BY SELECTIVE REFLECTION AND TRANSMISSION INSIDE THE PVCC



Vertically Grown (or stacked) Conventional Multi-junction Cell

Lateral Multi-Band Gap Cell System in a Light Confining Cavity

1 – Photons representing different frequency bands of the solar spectrum
2 – III-V semi-conductor layers (sub-cells) with conjugate energy band gaps
3 – Pre-focused solar spectrum with full spectral content
4 – Secondary stage concentrator (high flux injector)
5 – Light confining cavity with diffuse reflecting interior walls
6 – Individual single-junction solar cells with conjugate energy band gaps and and matching broad-band Rugate filters

FIGURE 3. PRICIPLES OF SPECTRAL SPLITTTING PV CAVITY CONVERTER (PVCC) AND A CONVENTIONAL MULTIJUNCTION CELL WITH VERTICAL ARCHITECHTURE

RUGATE FILTERS: AN ENABLING TOOL FOR PVCC

Although Rugate filters have found several powerful optical applications in the military, they are relatively unknown in the solar energy community. The theory of Rugate filters, particularly that of narrow band systems, is well understood [1]. The challenge of this specific project is, however, to explore the feasibility of broadband Rugate filters. For the sake of clarity, UI^2 will now provide a brief description of Rugate systems.

In principle, a Rugate filter is an interference coating based on a refractive index that varies continuously (not in discrete steps) in the direction perpendicular to the film plane. When the refractive index varies periodically and within two extreme values, it is possible to design a rejection filter with high reflectance (~ 99%) in the middle, and high transmission (~ 99%) on either side of the rejection band. They can be designed to eliminate side-lobes, higher harmonics, and other significant parasitic losses. Thus, Rugate filters are ideal for PVCC because they significantly minimize losses during the spectral splitting process.

In general, Rugate filters are refractory silicon oxynitride alloys obtained by chemical vapor deposition of silane, ammonia, and nitrogen as source gases. The resulting graded index Rugate filter layers are insensitive to UV and humidity. The material can survive exposure to sub-zero temperatures as well as high temperatures over 200C. Up to 250C, the spectral characteristics move toward longer wavelengths by a few nm. This shift is reversible when the temperature decreases. Above 250C, a permanent shift can take place the first time the filters are brought above that threshold.

ANALYTICAL MODELING RESULTS AND DISCUSSION

Figure 4 shows the AM 1.5 solar spectrum and the Rugate filter frequency bands for InGaP(1.86eV), GaAs(1.42eV), InGaAsP(1.10eV) and InGaAs((0.74eV). In this limited space, only the reflectance/transmittance profile for GaAs filter is shown in Figure 5 as a typical example. This particular Rugate filter reflects all wavelengths from 350nm to 610nm and from 870nm to 1800nm, and transmits wavelengths from 610nm to 870nm. In both cases, i.e., average reflection and transmission, the optical performance is about 99%. The results for other frequency bands are also very similar. In all cases, the average transmission and reflection profiles are symmetrical, and the up-ramp and down-ramp slopes are very steep. This particular feature supports operation with minimum photon leaks (cross-talk) from one frequency band into another.

CONCLUSIONS

Results obtained under this project so far have demonstrated that, in principle, it is possible to design broadband Rugate filters that meet the stringent requirements of the PVCC application. In a parallel study also supported by NREL, UI^2 has developed an optical model of the PVCC cavity to predict the Photon Utilization Factor (PUF) in a cavity where the interior wall of the cavity is 75% covered with the III-V cells selected for this project. (PUF is defined as the probability that a photon entering the cavity will be detected and converted by a conjugate cell.) This model assumes that each individual cell is covered with a matching Rugate filter as depicted in Figure 2. As a result of an optimization study, a PUF of 0.9 was obtained. Given this PUF for the cavity under consideration, UI^2 then calculated that a multi-bandgap array consisting of InGaP(1.86eV), GaAs(1.42eV), InGaAsP(1.10eV), and InGaAs (0.74eV) could achieve a collective photo-conversion efficiency of 48.3%.

At this point, it is important to note that the actual fabrication of broadband Rugate filters still remains a challenge yet to be overcome. The anticipated concerns with regard to deposition time (cost) and material problems associated with the unusual film thickness required will be the subject of further studies under this program.

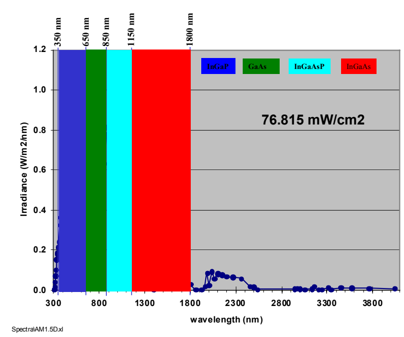


FIGURE 4. AIR MASS 1.5 SOLAR SPECTRUM AND RUGATE FILTER FREQUENCY BANDS MATCHING THE III-V CELLS

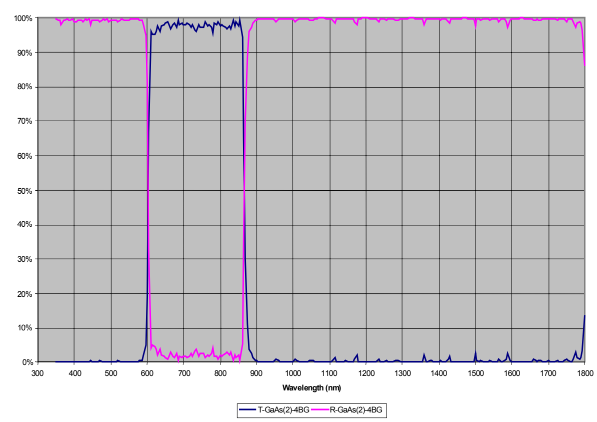


FIGURE 5. BROADBAND RUGATE FILTER FOR GaAs

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1. Bertrand Bovard, “Rugate Filter Theory: An Overview”, Appl. Opt. **32**, 5427-5442 (1993).