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LINE-FOCUS OPTICS FOR MULTIJUNCTION CELLS IN SPACE POWER ARRAYS

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ABSTRACT

Since 1986, ENTECH has been developing light-weight, high-performance Fresnel lens optics for space photovoltaic concentrator systems. This development work has been technically and financially supported by NASA-Lewis, SDIO, BMDO, Boeing, JX Crystals, and AEC-ABLE. A fully functional experimental mini-dome Fresnel lens concentrator array was onboard the PASP Plus mission launched in August 1994 [1, 2]. This array, assembled by Boeing using mechanically stacked multijunction (MSMJ) cells, confirmed the high-performance and low-radiation-degradation characteristics predicted for the refractive concentrator approach. Since PASP Plus, ENTECH has developed a line-focus Fresnel lens offering much improved manufacturability, cost, and sun-pointing error tolerance. This paper presents the latest line-focus optical designs customized for use with MSMJ cells and with monolithic multijunction (MMJ) cells.

INTRODUCTION

Fig. 1 shows the key elements of a line-focus concentrator array for space power applications. An arched glass/silicone Fresnel lens focuses incident photons onto a photovoltaic receiver containing high-efficiency multijunction cells. The tandem cells can be either mechanically stacked multijunction (MSMJ) devices or monolithic multijunction (MMJ) devices. Optional secondary optics (not shown) can be employed to boost the achievable concentration ratio and to provide radiation shielding of the cells [3, 4]. Waste heat is rejected from the receiver via radiation from a composite or aluminum panel.

A continuous, high-throughput production process has been developed for manufacturing the silicone lens from space-qualified material (Dow Corning 93-500). The 220-micron-thick Fresnel lens material is produced and delivered on 150-meter-long rolls. An 80-micron thick ceria-doped microsheet superstrate is laminated to the silicone lens to provide structural support and ultraviolet radiation protection for the lens. For typical space missions, the primary lens provides 90% optical efficiency at 10X concentration with a sun-pointing error tolerance of ± 2 degrees about the critical axis. Thus, even without secondary optics, the concentrator reduces the required cell area per watt of array power by a full order of magnitude compared to one-sun arrays. Compared to one-sun arrays, the concentrator array multiplies the cell vendors' manufacturing capacity by 10X (in watts/year equivalent), reduces cell shielding mass penalty by 90%, and minimizes cell cost per watt. Because of these advantages, the concentrator array enables the early orbital application of advanced MSMJ and MMJ cells. The preferred adaptations of the line-focus optics for MSMJ and MMJ cells are described separately below.

LINE-FOCUS OPTICS FOR MSMJ CELLS

The most efficient MSMJ cell is the GaAs/GaSb tandem device developed by Lew Fraas, formerly of Boeing, and now of JX Crystals. Fig. 2 shows recent measured efficiencies of the top cell, bottom cell, and total tandem cell for JX Crystals GaAs/GaSb MSMJ cell, all as a function of concentration [5]. To reach the peak efficiency of more than 26%, an overall concentration ratio of 25X or more is needed. Thus, a pure line-focus array without secondary optics will not work optimally with this MSMJ cell. To overcome this concentration limitation, a solid silicone compound parabolic concentrator (CPC) has been developed, as shown in Fig. 3. This secondary optical element provides a 1.5X boost in concentration due to its lateral walls, and a 2.0X boost due to its longitudinal walls, both of which rely on total internal reflection (TIR) at the silicone/vacuum interfaces. For a typical application, the thickness of the secondary is 0.5 cm, providing a good level of particulate radiation protection for the underlying tandem cell. Later this year, about 150 secondary optical elements will be produced, applied to JX Crystals MSMJ cells, and tested.

LINE-FOCUS OPTICS FOR MMJ CELLS

The most efficient MMJ cell is the GaInP/GaAs tandem device developed by Olson et al. of the National Renewable Energy Lab (NREL), and now being produced by Applied Solar Energy Corporation (ASEC) and Spectrolab. Fig. 4 summarizes the chromatic aberration (CA) problem inherent in the use of refractive optical concentrators with this MMJ cell, a subject which has been previously investigated by others [6, 7]. The two curves in this figure result from the convolution of the AM0 spectral irradiance (photon flux vs. wavelength), the dispersion curve of the silicone lens material (refractive index vs. wavelength), and the spectral responses of the top and bottom junctions (quantum efficiency vs. wavelength for each). Note that the top junction current is produced by shorter wavelength photons which are refracted by the silicone lens material over the refractive index range of 1.407 to 1.430. Note that the bottom junction current is produced by longer wavelength photons which are refracted by the silicone lens material over the refractive index range of 1.403 to 1.414. The current-weighted average difference in refractive index for the photons generating current in the two junctions is 0.01. Thus, each prism in the Fresnel lens refracts the top junction photons much more strongly than the bottom junction photons, thereby producing the two junction currents at different lateral positions across the solar cell. The lateral current separation distance is least for prisms near the centerline of the lens, and greatest for prisms near the outer edges of the lens, since this distance depends on the total ray refraction angle as well as the index of refraction difference. In the MMJ cell, the current flows in series through both the top and bottom junctions. Thus, a lateral mismatch in top/bottom junction currents requires a lateral current flow between the junctions to complete the series circuit. This lateral current flow involves a power loss due to the relatively high resistance in the lateral layers between the junctions [8].

To accurately analyze this CA problem, the ray trace model described in Fig. 5 has been used. This analysis has also led to a simple solution to the CA problem, namely a color-mixing lens design. In the color-mixing lens, all even-numbered prisms are configured to a normal “red-edge” design, which has been used for many years for single-junction cells. The red-edge approach places infrared photons from the rim of the solar disk at the outer edge of the cell active width when the largest sun-pointing error is present. This red-edge approach maximizes full spectrum photon collection by ensuring that the longer wavelength photons are all collected, and by providing the widest possible target area for the shorter wavelength photons, which are more strongly refracted toward the opposite edge of the cell. In contrast, all of the odd-numbered prisms in the color-mixing lens are configured to a “red-shifted” design. Compared to their neighboring prisms on either side, these red-shifted prisms refract incident photons by an amount equivalent to an increase in refractive index of 0.01, the color-mixing stroke shown in Fig. 4. Thus, each odd-numbered prism places the center of the bottom junction current generation distribution on top of the center of the top junction current distribution for the preceding even-numbered prism. This approach is analogous to painting a wall with two spray cans, one red and one blue. If the cans are taped together and the buttons pushed simultaneously, a red spot and a blue spot will be formed with the spot separation corresponding to the distance (L) between the centers of the cans. If the cans are then moved laterally by this same distance or stroke (L), and the buttons are pushed simultaneously again, there will be three spots: a red one, a purple one (mixed), and a blue one. If this shifting process is repeated over and over several hundred times (corresponding to several hundred prisms in each half of the Fresnel lens), about half of the red paint will be well mixed with about half of the blue paint in the purple spot in the center. The other half of each color paint will be unmixed. While far from perfect, this simple approach provides significant current mixing, as shown by the two photocurrent profiles of Fig. 6 and Fig. 7, for a color-mixing and a simple red-edge lens, respectively. A sophisticated CA cell model has recently been developed to accurately calculate the power loss due to CA [8]. This new model provides the results shown in Fig. 8, for both the color-mixing and red-edge lens designs. Note that the CA power loss varies non-linearly with the lateral sheet resistance of the conductive layers between the junctions in the MMJ cell structure. (NREL recently measured about 260 ohms/square for the sheet resistance between the junctions of production MMJ cells [8].) The CA power loss is much lower for the color-mixing lens because the top/bottom junction currents are more closely matched, and lateral current flow is thereby reduced.

Production lenses of the color-mixing design will be manufactured later this year, for use in the 2.6 kW SCARLET 2 concentrator array [9]. This second-generation concentrator array is being developed for BMDO and NASA, by a team of organizations led by AEC-ABLE.

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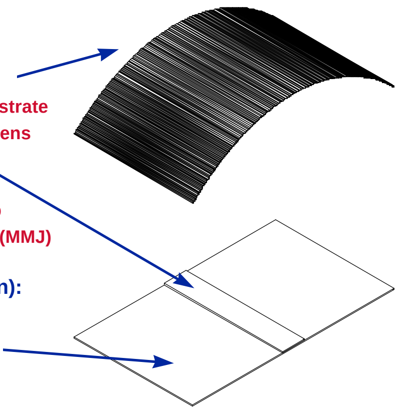
Fig. 1 -Line-Focus Concentrator for Space Power



- **Arched Linear Fresnel Lens:**
  - 80 micron Ceria Glass Superstrate
  - 220 micron 93-500 Silicone Lens
- **Photovoltaic Receiver:**
  - Mechanically Stacked Multi-Junction (MSMJ) GaAs/GaSb
  - _or_ Monolithic Multi-Junction (MMJ) GaInP/GaAs
- **Secondary Optics (Not Shown):**
  - Optional Silicone CPC(s)
- **Radiator Panel for Cooling:**
  - Carbon Composite
  - _or_ Aluminum

Fig. 2 - MSMJ Cell Performance vs. Concentration

The Problem: > 25X Concentration Needed for Optimal Cell Performance

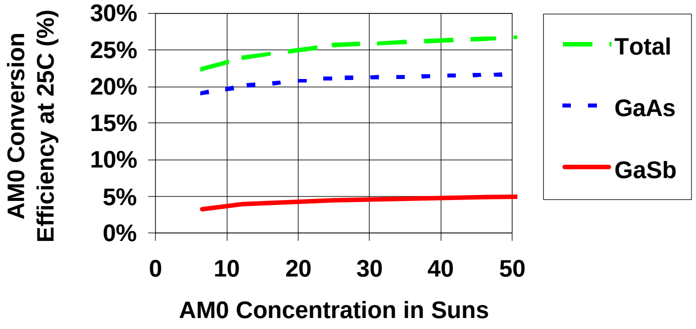
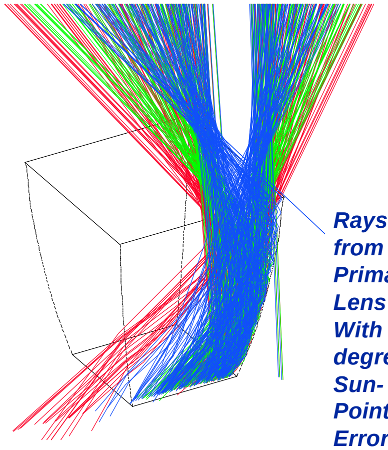


Fig. 3 - Optical Secondary for MSMJ Cell

Solid Silicone Secondary with 4 Curved Walls (TIR CPC's) Provides a 3X Boost to the 10X Primary Lens Concentration for 30X Overall Concentration



Rays from Primary Lens With 2 degree Sun-Pointing Errors

Fig. 4 - Color-Mixing Lens Modeling and Design Method

GaInP/GaAs MMJ Cell

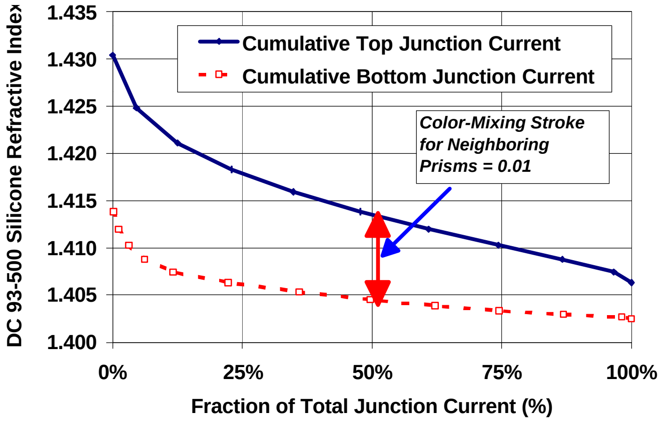


Fig. 5 - Ray Trace for Color-Mixing Silicone Lens

- Transmittance-Optimized, Symmetrical-Refraction Lens
- Different Color Rays Represent Different Wavelengths
- Model Includes AM0 Spectrum, Lens Optical Properties, and Junction QE Curves for GaInP/GaAs MMJ Cell
- Alternating Prisms Are Red-Edge Design and Red-Shifted Design, with Color-Mixing Stroke of 0.01 Refractive Index Units for Neighboring Prisms

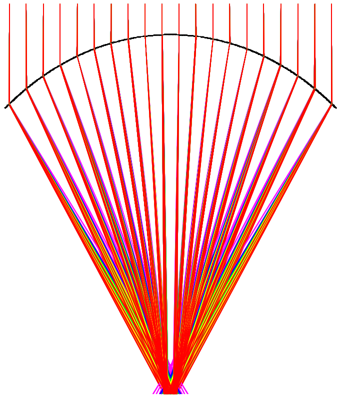


Fig. 6 - Red-Edge Lens:
Photocurrent Profiles for Both Junctions of MMJ Cell

GaInP/GaAs MMJ Cell

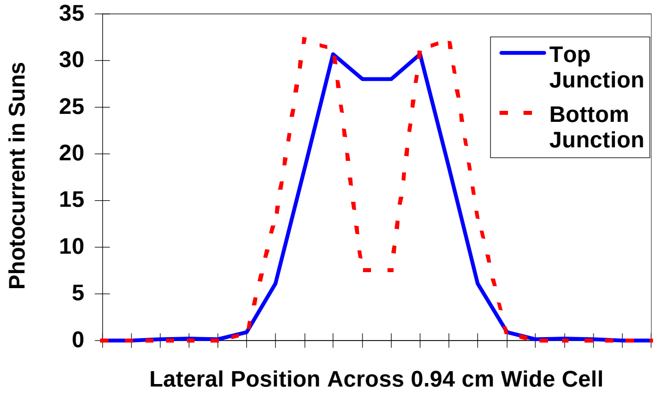


Fig. 7 - Color-Mixing Lens:
Photocurrent Profiles for Both Junctions of MMJ Cell

GaInP/GaAs MMJ Cell

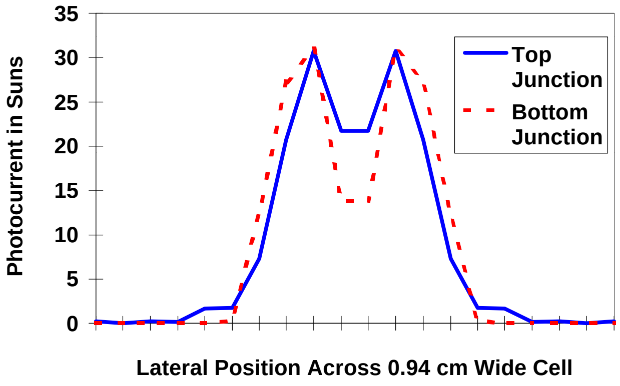


Fig. 8 - Red-Edge Lens vs. Color-Mixing Lens:
MMJ Cell Chromatic Aberration Power Loss