

# Tandem Ce:YAG fluorescent solar concentrator

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## ABSTRACT

The purpose of this work is to investigate the performance of a new design concept for a tandem Ce:YAG fluorescent solar concentrator. In this design, elements of Ce:YAG arranged in a hexagonal pattern within a waveguide absorb high energy photons and emit them at an energy optimized for edge-mounted III–V solar cells with a bandgap higher than silicon's bandgap. A silicon solar cell is located below the waveguide to absorb light transmitted or re-emitted through the concentrator. We first determined the optical properties of single crystal Ce:YAG. These results yielded a peak excitation at 470 nm with an absorption coefficient of  $25.8 \text{ cm}^{-1}$ , a peak emission at 530 nm with an absorption coefficient of  $1.57 \text{ cm}^{-1}$ ; and an internal quantum efficiency of 80.0%. Our experimental analysis using powder Ce:YAG yields a waveguide optical efficiency of 33% for the design excluding focusing lenses and 54% with lenses. There are some sources of error that were addressed by using single crystal Ce:YAG instead of powder.

The projected overall FSC efficiency is 15.4% for a tandem fluorescent design using GaP edge-mounted solar cells and a silicon solar cell below the waveguide. This efficiency increases to 19.9% for InGaP edge-mounted cells instead of GaP cells. In both cases single crystal Ce:YAG is assumed.

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## 1. Introduction

Recent developments in materials not available 2 or 3 decades ago, such as near infrared (NIR) semiconducting organic dyes, and quantum dots (QDs) have regenerated interest in fluorescent solar concentrators (FSCs). FSCs initially pioneered in the 1970's as an alternative technology to lower the cost of solar cells promised to (i) reduce solar cell active area, and (ii) optimize incorporation into buildings therefore offsetting installation costs. In most FSCs, light is absorbed by a fluorescent material<sup>1</sup> (FM) embedded in a transparent sheet, and is emitted at a different energy range from the absorbed range. Fluorescence is then waveguided to the solar cells at the edges of the sheet [1–5].

Fluorescent concentrators still have not been commercialized mainly due to their low efficiencies. There are several loss mechanisms that contribute to low efficiencies, which will be explained in greater detail in subsequent sections. The efficiency range for these concentrators depends on the solar cell and the performance of the waveguide itself. Efficiencies are however, typically low as shown in Table 1 [1].

The optical efficiency is dependent on a number of energy loss processes which are illustrated in Fig. 1.

For electrical power to be generated, incident light (1) in Fig. 1 needs to excite fluorescent centers in the waveguide shown at (2). The fluorescence (3) must be transmitted to the edge-mounted solar cells (5). Energy loss may occur due to optical absorption or scattering (4). Losses can also occur through escape cone fractions shown in (8), from the upper or lower surfaces [1,4,6].

We can model the performance of a FSC using the following expression,

$$\eta_{opt} = (1 - R) \cdot P_{TIR} \cdot \eta_{abs} \cdot \eta_{QY} \cdot \eta_{Stokes} \cdot \eta_{TIR} \cdot (1 - \eta_{self}), \quad (1)$$

where  $\eta_{opt}$  represents the system's efficiency. Light can be externally reflected, resulting in reflectivity,  $R$ , as shown in (6).  $P_{TIR}$  is the probability of internal reflection, and  $\eta_{abs}$  is the absorption efficiency of the FM as indicated in (7). The number of photons emitted with respect to the number of absorbed photons is determined by the material's quantum yield,  $\eta_{QY}$ . In addition, the difference in energy level between the absorbed vs emitted energy is determined by the material's Stokes Shift,  $\eta_{Stokes}$ , which is represented by (3). Finally,  $\eta_{TIR}$  accounts for imperfections and scattering and  $\eta_{self}$  is the reabsorption probability, as indicated in (9) [1,4,6].

To improve the overall efficiency of the concentrator, research has mainly been focused on investigating specific fluorescent materials such as semiconducting organic dyes, rare earth materials and quantum dots. Organic dyes such as Rhodamines and Coumarins

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<sup>1</sup> FSC – Fluorescent Solar Concentrator.

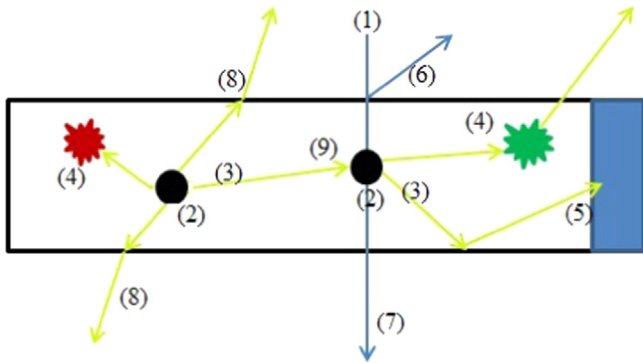
FM Fluorescent material.

SS – Stokes shift.

Ce:YAG – Cerium doped yttrium aluminum garnet.

**Table 1**  
Reported efficiencies for FSCs [1].

Fluorophore	Cell Type (# of Edges)	FSC Size (cm)	Efficiency (%)
CdSe/CdS QD	Si (1)	5.0 × 5.0 × 0.3	2.1
Coumarin, Rhodamine	Si (1)	140 × 140 × 3.0	3.2
CdSe/CdS QD	GaAs (1)	140 × 140 × 3.0	4.5
Red 305/CSR040	GaAs (4)	5.0 × 5.0 × 0.5	7.1



**Fig. 1.** Loss Mechanisms in a continuous sheet of fluorescent material. (1) Incident photons. (2) Fluorescent centers. (3) Fluorescence. (4) Light lost to absorption or scattering in the waveguide. (5) Solar cell. (6) Incident light externally reflected from the top surface. (7) Light transparent to fluorescent material, i.e. does not get absorbed. (8) Escape cone fraction. (9) Reabsorption of fluorescence [6].

achieved high quantum yields and suitable Stokes shift (to minimize reabsorption losses), respectively. However, they proved to be unstable when subjected to high energy photons. Rare earths, on the other hand, have good photostability and large Stokes shifts, but low absorption efficiencies. High concentrations of these ions are therefore required which leads to high costs and increased reabsorption losses. The main advantage of quantum dots (InP, ZnS and CdSe) is that they have a tuneable bandgap. Decreasing their diameter increases their bandgap, but results in blue shifted absorption and emission spectra. In recent years, some research has been targeted towards implementing a different geometry to the traditional rectangular prism, such as cylinder and hollow multi-cylinder designs [1,3,6–10].

## 2. Approach

### 2.1. Materials and design concept

Since semiconductors currently used in single junction solar cells have a limited absorption energy range, an opportunity exists to take advantage of fluorescence to maximize the absorption range of the solar spectrum when combined with the absorption range of the solar cell. In this work, we propose a novel tandem solar cell system designed around the waveguide. The tandem solar cells further optimize the utilization of the solar spectrum by incorporating solar cells with at least two distinct semiconductor bandgaps to enhance the overall efficiency. We anticipate a cost structure well below a conventional single crystal tandem solar cell cost structure, since lattice matched tandem solar cells involve materials and manufacturing costs that are high, and therefore not practical for widespread terrestrial deployment.

The focus of this research is to explore the optical properties of cerium doped yttrium aluminum garnet (Ce:YAG) as a FM first. We wish to improve the optical transport of fluorescence to the edge-

**Table 2**  
Ideal properties of fluorescent material for a solar cell with a bandgap of  $E_{g1}$ , and the properties that Ce:YAG satisfies [11–16].

Desired property	Ce:YAG
Absorb all photons $E \geq E_g$ and emit at $E \approx E_g$	Absorbs 465 nm $\geq \lambda$ , emission peak at $\lambda = 550$ nm
Exhibit minimal reabsorption losses	Stokes shift = 85 nm
Has quantum efficiency close to 100%	Close to unity
Be environmentally stable for at least 20 years	Proven to be highly stable in LEDs
Be produced at low costs	Economical for LEDs but costly in large sheets

coupled solar cells having a first bandgap of  $E_{g1}$ , matched to the spectrum of Ce:YAG's emission energy. The second aspect of this work is to propose the use of a second photovoltaic cell with  $E_{g2}$  smaller than  $E_{g1}$ , located at the back of the concentrator.

The overall efficiency of the concentrator is dependent largely on the inherent properties of the FM. For a solar cell with bandgap  $E_{g1}$ , the fluorescent material's ideal properties are outlined in Table 2, and the properties that Ce:YAG as the FM satisfies are indicated as well.

A new waveguide structure was designed to address light reabsorption issues normally associated with fluorescent materials in a typical concentrator design, to maximize the amount of light that gets waveguided to the edges as shown in Fig. 2.

This design incorporates a spatially patterned Ce:YAG array comprising of Ce:YAG embedded in the lower face of a 3 mm acrylic plate. These Ce:YAG elements are located at a distance equivalent to the focal length of a lens sheet (obtained from Fresnel Technology), which is placed in close proximity such that each lens is aligned with one Ce:YAG element. This lens sheet is used to permit strong sunlight coupling to the Ce:YAG elements. The lower face of the 3 mm acrylic sheet is then bonded to a second 6 mm thick acrylic sheet to increase the thickness of the concentrator and to improve the waveguiding efficiency.

### 2.2. Methods

#### 2.2.1. Fabrication techniques

Both a single crystal YAG:Ce waveguide as well as a the new waveguide structure of Fig. 2 were fabricated. The single crystal Ce:YAG fluorescent material with a cerium doping level of 0.180 mol% ((Ce<sub>0.06</sub>:Y<sub>0.94</sub>)<sub>3</sub>Al<sub>5</sub>O<sub>12</sub>) was obtained from Scientific Materials Corporation. To obtain an optical finish, this single crystal was polished down to a dimension of 9.3 × 9.2 × 2.1 mm using polishing cloths saturated with colloidal alumina. This piece was analyzed to determine the optical properties of Ce:YAG with a 0.180 mol% doping level.

For the waveguide structure of Fig. 2 it proved to be difficult to polish single crystals of Ce:YAG of dimension 0.5 mm × 0.5 mm × 0.5 mm to an optical finish. A slow curing adhesive was required to hold small single crystalline pieces of Ce:YAG onto a polishing sample holder. Also, this adhesive needed to be stronger than the force applied during polishing, so that Ce:YAG does not detach from the polishing sample holder. Two problems arising from using this kind of bond is that when polishing one side is completed, the sample holder needs to be submerged in a strong agent to dissolve the adhesive. This resulted in the tiny crystals being lost in the solution, or residual bonding agent on the crystal which could only be removed by grinding the area using a coarser grit paper. Since the area being polished on each Ce:YAG element is very small (approximately 0.25 mm<sup>2</sup>), a weaker force can be applied during polishing, therefore allowing a much weaker bonding agent to be used. In this case, it nevertheless takes an impractical amount of time to polish all sides to an optical finish.

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