TECHNIQUE
PHOTOVOLTAÏQUE

Phillip Graviss

LPRL: Laboratoire de Physique et du Rayonnement de la Lumière

2 and 3D opto-photovoltaic systems

Double-pane photovoltaics and solar towers

LPRL has developed proprietary enabling technologies in the field of photovoltaics. Special material compositions and system configurations combine wavelength-shifting effects and waveguide effects to optimize the quality and quantity of direct and diffuse sun light before it reaches solar cells. Sample applications include photovoltaic double-pane and photovoltaic solar towers. It is anticipated that these next-generation luminescent solar concentrators in the form of glass-based, building-integrated photovoltaics will play an important role in accelerating the shift towards renewable electricity.

The latest evolution in the development of photovoltaics is their integration into buildings, termed building-integrated photovoltaics (BIPV). In this paradigm, various architectural elements become bi- or multifunctional, such as load-bearing structures, lighting, thermal and acoustic insulation, electrical elements, etc. In this context glass can play a pivotal role as an "intelligent" multifunctional material. The primary consideration in the fabrication of such glass is that it be transparent to wavelengths that can be efficiently converted by photocells [11].

This article presents several technologies developed and patented by the Laboratoire de Physique du Rayonnement et de la Lumière (LRPL). This technology combines specific doping of organic or inorganic glass with novel architectural arrangements to increase the photovoltaic conversion efficiency. Glass is thus promoted from a simple encapsulation material to a vital photovoltaic component.

THE LIGHT CASCADE PRINCIPLE

Consider a host material doped with organic or inorganic optically active substances (OAS), in the form of either solution or dispersion. By exploiting the optical activity of these dopants, the light cascade (LC) principle makes it possible to convert a significant portion of the incident electromagnetic spectrum into wavelength bands that are most efficiently absorbed by photocells.

This transfer of energy is based on the absorption of incident energy at a wavelength λ_1 followed by re-emission at λ_2. Applying this basic conversion step sequentially leads to a cascade effect that shifts the incident wavelength to the desired wavelength ln that is then added to the incident energy within this desired wavelength band for which the photocell is most efficient. For $\lambda_1 < \lambda_n$, this energy transfer process corresponds to Stokes shifted fluorescence. It is also possible to create anti-Stokes systems in which several photons are absorbed prior to re-emission at a higher energy ($\lambda_1 > \lambda_n$). This concept of spectrally adapting the incident energy before it arrives at the photocells was patented by the LPRL in 1974 [1], following which we rapidly extended the idea to light-concentrating systems and to multi-molecular systems with diverse geometries [2]. Similar concepts have been developed, notably by Pr. Adolf Goetzberger et al., who founded the first European solar institute, and was honored as inventor of the year in 2009.

PRIMARY CONSEQUENCES

Applied to photovoltaics, the light cascade principle optimizes the light-matter interaction by shifting a maximum amount of the Sun's incident energy into the wavelength band of maximum conversion efficiency for the photocell. At 365 and 440 nm the conversion efficiency of photocells is only 25% to 50% of the maximum efficiency, so higher frequency photons are more likely to be transformed into thermal energy, which serves only to heat the photocells, which in turn further diminishes the conversion efficiency. Above 10 °C, losses due to thermalized photons are on the order of 1% per +15 °C. Thus, it is clearly advantageous to shift energy from these high-frequency photons λ_i (365 to 440 nm) to a wavelength band λ_ε for optimum photocell conversion efficiency (800 to 900 nm), which can be done by exploiting a Stokes shift.

IMPLEMENTATION OF LIGHT CASCADE SYSTEM

As a host material we use polymethylemetacrylate (PMMA) which is a material well-known in the aerospace industry for its mechanical and optical qualities and in the nuclear power industry for its stable physical-chemical properties. In the nuclear power industry PMMA is used in scintillation devices, for which it is doped by optically active molecules (OAMs). Typical OAMs are cyclic aromatic hydrocarbons, for which the number ϕ of aromatic rings determines the absorption and Stokes-shifted emission wavelengths.

The OAMs are chosen so that the emission band of one corresponds to the absorption band of the next, so that the net result is a shift from an incident wavelength to a desired final wavelength. Using these concepts, we have fabricated light cascade modules for which the PMMA emission spectrum corresponds to the wavelength band of peak photocell conversion efficiency (red and near infrared).

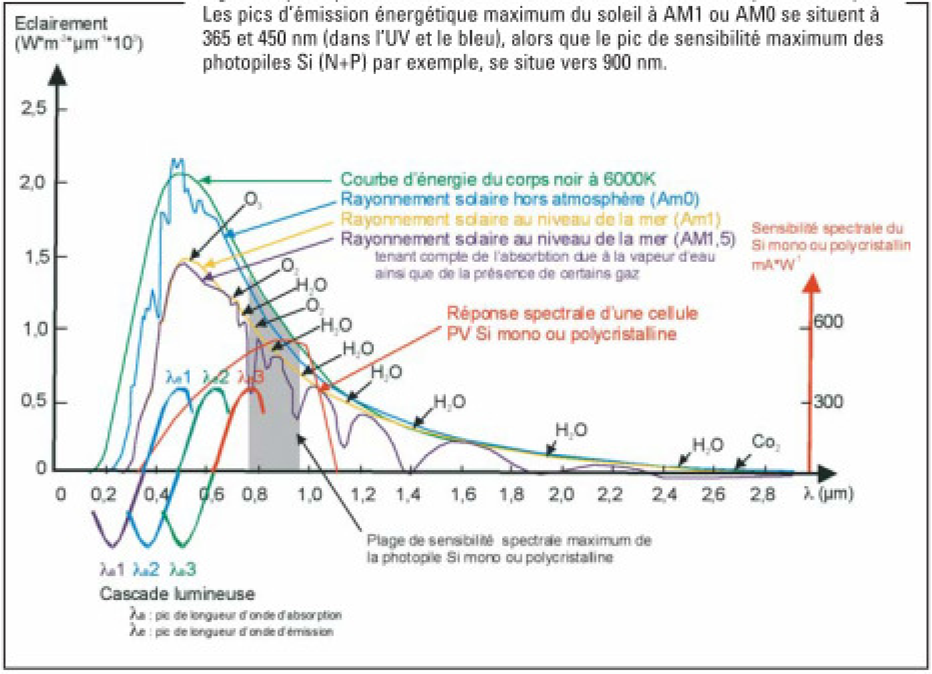
The conversion efficiency of these light cascade materials depends on the intrinsic characteristics of the host material (e.g., PMMA) and of the OAMs doped into the host. These latter must be added in concentrations inversely proportional to their molecular weight to avoid self-quenching effects. The optimization of these and other parameters have been the object of extended research efforts by LPRL.

SYNERGY

Once the problem of heating by thermalization of photons is overcome by shifting UV and 440 nm light toward shifting UV and 440 nm light toward the red and near infrared, several effects combine:

- The frequency shift of the supra-visible photons toward the absorption band of the photocells leads to the creation of a larger number of carriers. This effect also eliminates the "hot-spot" phenomenon.
- For initial trials, homogeneous host matrices were used to optimize the conversion efficiency (see Fig. 2). In this design, the photocell cover is fabricated from sequential layers of doped PMMA, with each layer targeting the conversion of a specific wavelength band. Compared with theory, however, this architecture results in a 50% loss per layer, so heterogeneous host matrices were used instead (the theoretical justification for this is given in the next section). In fact, using single layers doped with a complementary blend of OAMs is more effective and much simpler than using multiple homogeneous layers. For single heterogeneous layers, thermodynamic or ray-tracing

Figure 1 : principe de fonctionnement d'une cascade lumineuse photovoltaïque. Les pics d'émission énergétique maximum du soleil à AM1 ou AM0 se situent à 365 et 450 nm (dans l'UV et le bleu), alors que le pic de sensibilité maximum des photopiles Si (N+P) par exemple, se situe vers 900 nm.



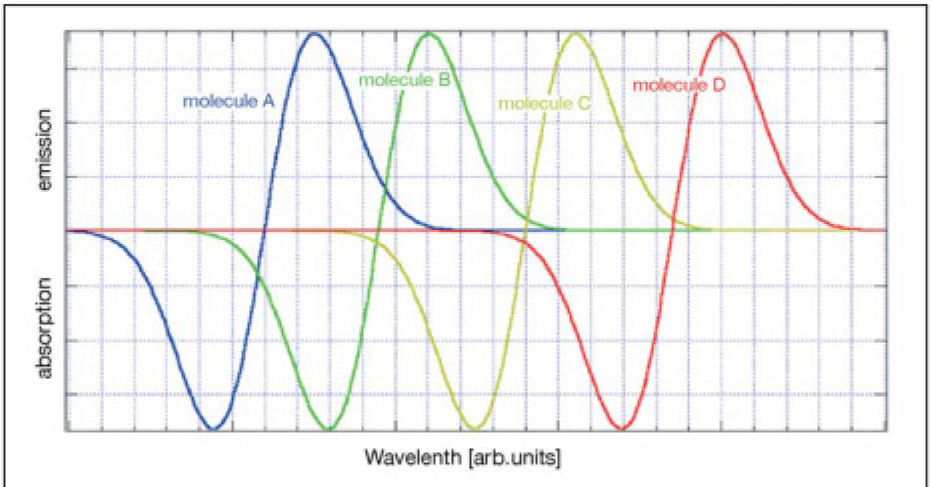


Figure 2 : interaction des MOA (molécules optiquement actives) dans une cascade lumineuse. Les spectres d'émission des unes correspondent aux spectres d'absorption des autres pour obtenir un décalage de fréquence dans la bande de longueur d'onde déterminée.

models can give a quantitative understanding of the problem.

- Although the frequency shift is the primary function of the light-cascade material, the technique also leads to more efficient capture of diffuse radiation that does not come in a direct path from the Sun, thus further increasing photocell performance.

ADAPTING THE SOLAR SPECTRUM TO THE SPECTRAL RESPONSE OF Si OR POLYCRYSTALLINE SOLAR CELLS

It is thus advantageous to concentrate the incident spectrum into the photocell's absorption band to maximize the photocurrent. The useful solar spectrum is defined by its overlap with the absorption spectrum of the photocell, which is typically optimum near 700 to 800 nm.

Therefore the useful portion of the solar spectrum can be enlarged by shifting the UV part of the solar spectrum toward these red wavelengths. LPRL has developed light cascade technology permitting the transformation of high-frequency photons (250 to 600 nm) to low-frequency photons (600 to 700 nm), which has been used for commercial applications in France and in the USA. These solar cells, fabricated from organically-doped PMMA, achieve 25% improvements in photocurrent.

A PHOTON'S ROUTE THROUGH A LIGHT CASCADE MATERIAL

Research by the LPRL has demonstrated frequency shifts in passive materials, which forms the basis of the light cascade technology. This technology is accompanied by other opto-electronic phenomena that, under certain conditions, contribute to further improving photocurrent. For example, the re-emission of light at wavelengths $\lambda_1, \lambda_2, \ldots, \lambda_n$ over 4π steradian and the wave-guiding action of the host matrix layer leads to an improved conversion of the albedo throughout the entire spectrum addressed by the light cascade material.

Among other things, this allows photons that would not be directly incident on the encapsulated photocell to be captured, converted, and ultimately to generate photocurrent. In addition, in certain designs, secondary, monochromatic light can be concentrated within the host matrix by waveguiding principles and delivered to a slice of a photocell, with the final intensity at the photocell being larger than the initial, orthogonal intensity at the given wavelength.

This capacity to efficiently collect light incident far from normal means that light cascade photocell systems do not need to be equipped with solar tracking systems.

ACTIVE OPTICAL ENCAPSULATION AND PHOTON/OAM INTERACTION

The matrix materials for light cascade elements are characterized by high transmission in the visible and the infrared. The OAMs are chosen so that the emission spectrum of one overlaps the absorption spectrum of another, which permits by sequential absorption and re-emission the shifting of a significant part of the solar spectrum into the wavelength band of interest (e.g., 250 to 800 nm).

Consider radiation of a given wavelength λ_{i-1} that is within the absorption band of an OAM$_i$, and that is

a) Eclairage ville de Venice, Floride
Montage et raccordement électrique des panneaux photovoltaïques à CL

b) Signalétique publicitaire à détection de passage
Highway, Etats-Unis, Floride

c) Radio Balises Militaires
Signalisation discrète de terrains Aéronautique

Figure 3 : exemples d'applications réalisés avec le procédé CL Opto PV 2D

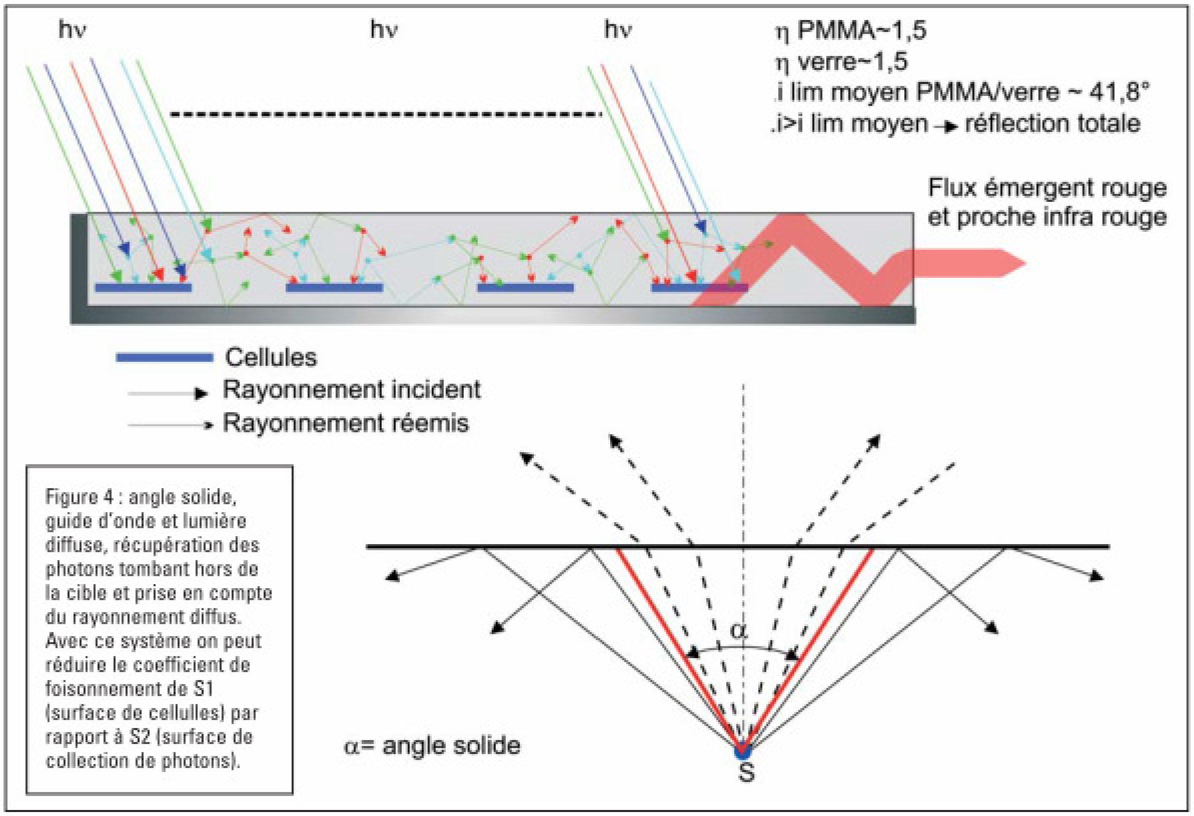


Figure 4 : angle solide, guide d'onde et lumière diffuse, récupération des photons tombant hors de la cible et prise en compte du rayonnement diffus. Avec ce système on peut réduire le coefficient de foisonnement de S1 (surface de cellulles) par rapport à S2 (surface de collection de photons).

within the absorption band of an OAM$_i$, and that is absorbed. The photons that excite OAM$_i$ via absorption are thereby eliminated from the incident radiation field, and OAM$_i$ is promoted to an unstable, higher-energy electronic state. OAM$_i$ remains photo-excited on the order of 10^{-15} to 10^{-9} s (fs to ns), during which time it relaxes toward the ground state via several pathways, one of which is radiative emission (e.g., Stokes shifted fluorescence).

The photons emitted by this process correspond to the absorption spectrum of OAM $_{i+1}$, chosen because its absorption spectrum corresponds to the emission spectrum of OAM$_i$. Thus, one OAM can absorb either the incident solar radiation directly, or can absorb secondary radiation that originates from an OAM one step above it in the light cascade process. This sequence of steps constitutes the light cascade process.

SIGNIFICANT GAINS IN PHOTOVOLTAIC EFFICIENCY

One of the first applications of the light cascade concept is to tune the solar spectrum to match the spectral response of photocells. The light cascade material can be integrated into the photocell encapsulation design, or can be applied in film form over glass.

POLYMETHYLMETHACRYLATE (PMMA)

The light cascade effect has been successfully achieved from the viewpoint of both conversion efficiency and photostability by doping PMMA with OAMs. Solar panels fabricated using this technology have a life time of over 10 years, and satisfy the standard NFC 57100 and the American standards set by the US Department of Energy and the Jet

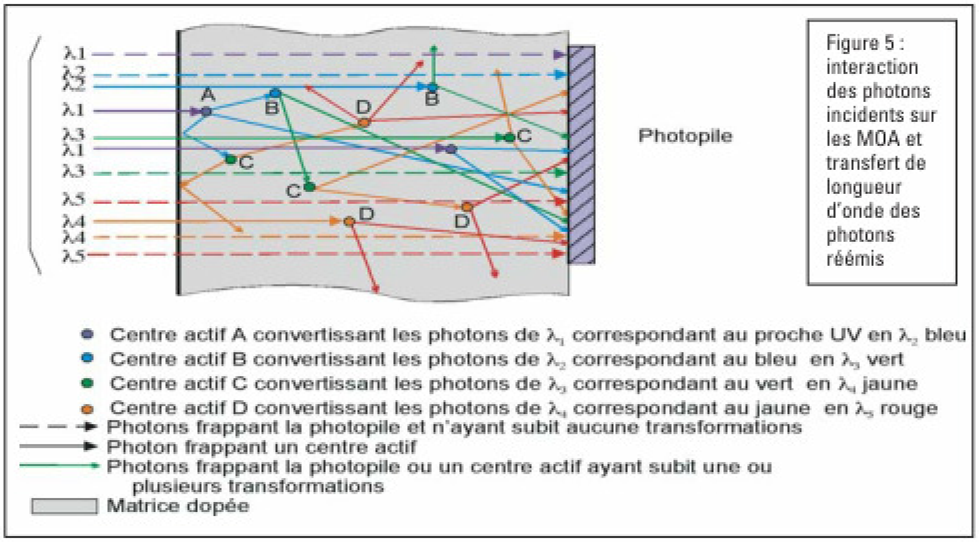


Figure 5 : interaction des photons incidents sur les MOA et transfert de longueur d'onde des photons réémis

Propulsion Laboratory. These solar panels have conversion efficiencies 20% to 40% greater than conventional panels, depending on the meteorological conditions, for panels with an active area that is 75% of the total surface area. The light cascade solar panels are particularly efficient under diffuse lighting conditions (i.e., cloudy days), which makes them attractive for use in regions with limited direct sunlight.

LC TECHNOLOGY APPLIED TO GLASS

The LPRL and its collaborators have adapted the light cascade technology for use on glass products. Figure 7 presents several items that associate glasses with the light cascade technology.

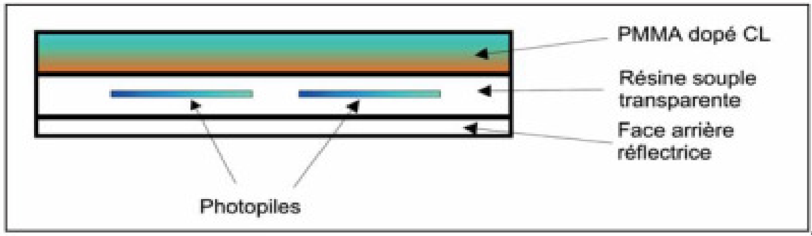


Figure 6 : vue en coupe de la structure d'un module réalisé selon notre procédé.

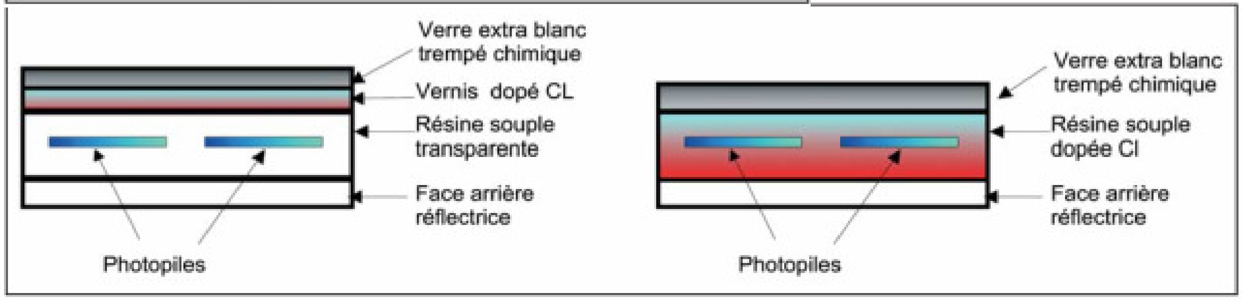


Figure 7

EXTENDING THE USE OF LC TECHNOLOGY

The LPRL has worked with several glass varnishes for photovoltaic applications. Another solution for existing glass supports consists of applying the light cascade material by spray or lacquer. The LPRL is currently studying the integration of light cascade material by spray or lacquer. The LPRL is currently studying the integration of light cascade materials into systems with specific optical functions, notably dichroic filters. Associating such systems to photovoltaics results in even greater conversion efficiencies per unit active area of the solar cell.

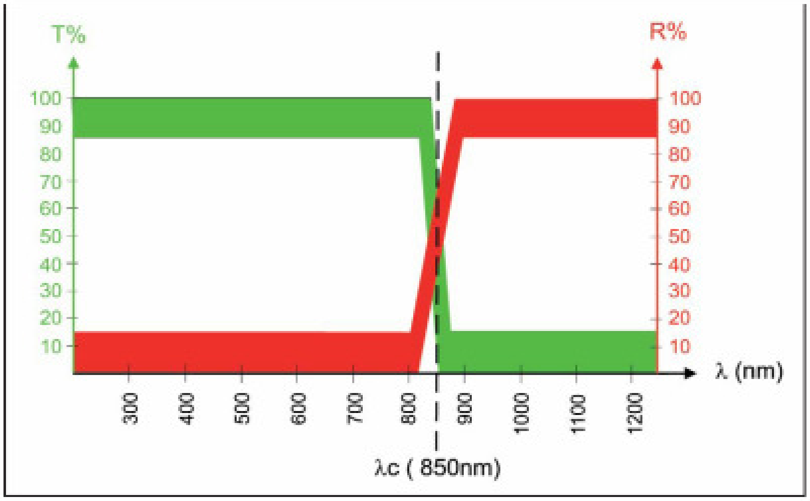


Figure 8 : réponse spectrale d'un verre dichroïque destiné à une CL photovoltaïque

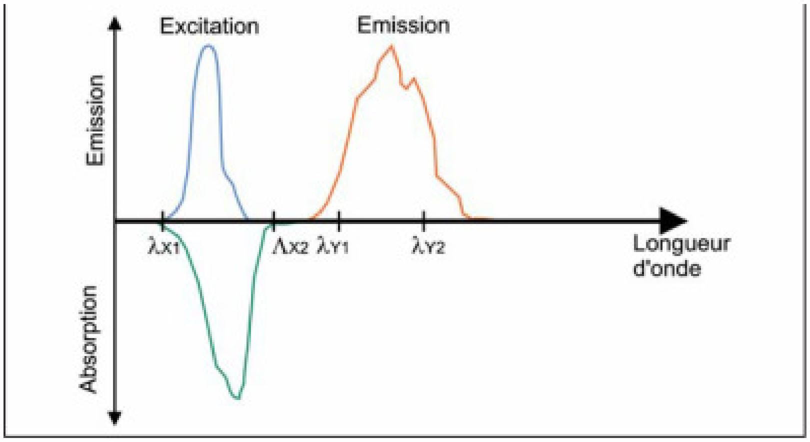


Figure 9 : spectre d'absorption/émission d'une CL

FREQUENCY-SHIFTING ELECTROMAGNETIC CONCENTRATOR

Operating principles

A frequency-shifting electromagnetic concentrator (FSEC) is based on the simultaneous use of light cascade technology with a dichroic system. Imagine a light cascade system characterized by the absorption/emission spectra shown in Fig. 9.

The optical structure is shown in Fig. 11(b), and consists of a sandwich with a dichroic filter as the top layer, followed by a sheet of light cascade material, with the back layer being an efficient reflector. The transmission and reflection of the dichroic filter is given in Fig. 11(a).

The incident radiation of wavelength λ_{x1} to λ_{x2} that is transmitted by the dichroic filter is absorbed by the light cascade material and is re-emitted over 4π steradian in the wavelength range λ_{y1} to λ_{y2}. Due to the backside reflector and the dichroic filter, this radiation is effectively trapped in the light cascade material and can only exit via the optical exits (i.e., the sides of the light cascade layer).

Principle and measurement results

We use an optical fiber to connect the output of the light cascade layer in the FSEC to an SFH 350 photodetector (the experimental details are given elsewhere). Figure 14 shows the results obtained from the various structures discussed above. Under the given excitation, the FSEC yields a gain between 5 and 11 times that of untreated material.

Guided by these results, we have developed new, economical architectures with even higher conversion efficiencies. In particular, we describe below a three-dimensional (3D) solar cell that incorporates these concepts.

Clean technologies, and particularly solar energy, constitute a rapidly expanding sector of the economy. In this context, new optical and dimensional approaches to photovoltaics to concentrate energy without the need for active cooling nor solar tracking are welcome, and are even promoted by several companies including Covalent Solar (USA) and Prism Solar (USA) who use prisms and holograms, and Cool Earth Solar (Australia) that uses inflated spheroids.

OPTO PV 3D: DOUBLE-PANE PHOTOVOLTAIC GENERATORS

Figures 15 and 16 show various structural concepts for 3D double-pane photovoltaics of standard configurations or of glass and aluminum for use in the construction industry.

PHOTOVOLTAIC TOWERS

Figures 17, 18 and 19 show examples OPTO PV 3D systems that

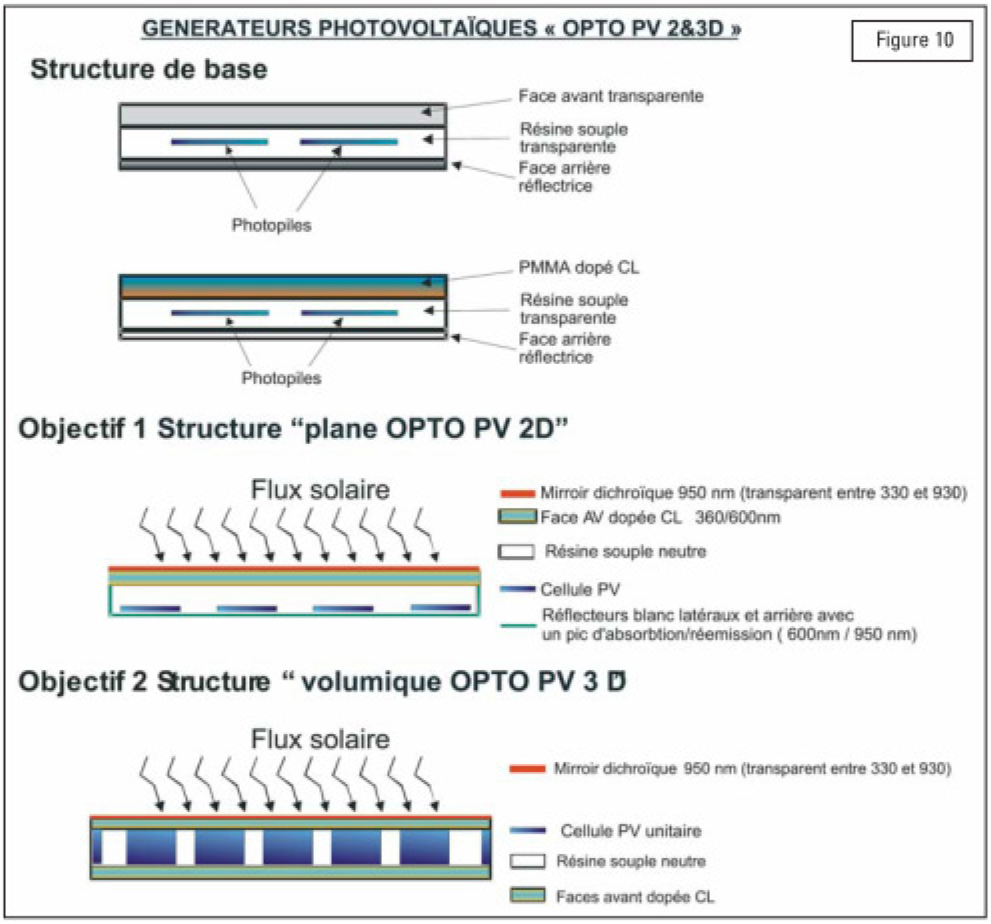


Figure 10

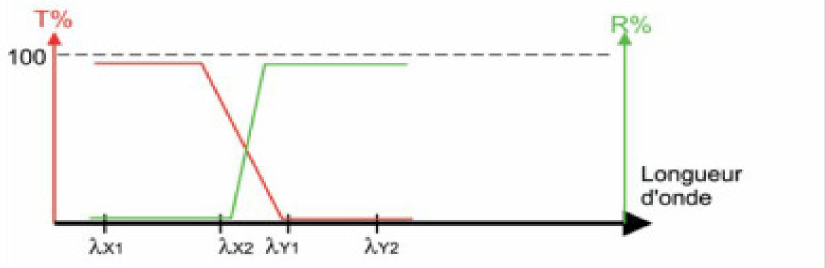


Figure 11a : Spectre de R% et T% du filtre dichroïque

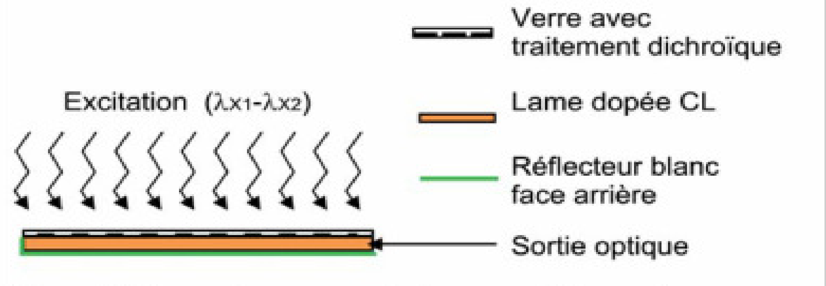
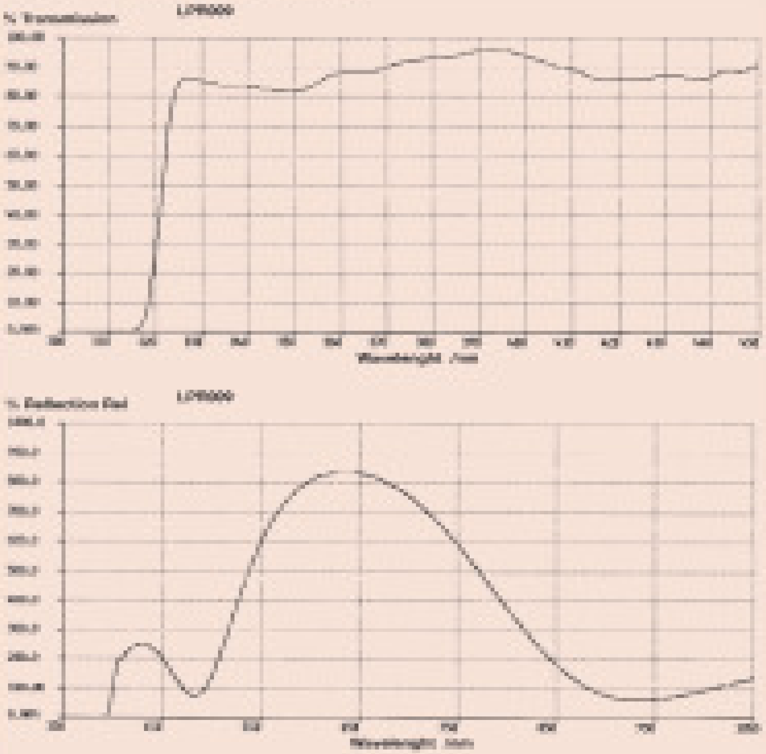


Figure 11b : Structure du concentrateur à changement de fréquence

Démonstrateur de laboratoire, un concentrateur électromagnétique à changement de fréquence avec une cascade lumineuse à base d'oxyde d'yttrium dopé europium. Les courbes de la figure ci-dessous nous donnent les spectres de transmission et de réflexion du filtre dichroïque LPRL009.



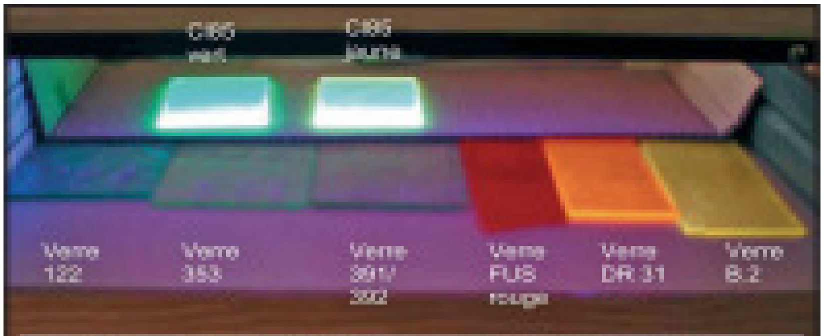


Figure 13 : Photographie sous éclairement 365nm des différents échantillons CL/dichroïques ayant servis aux mesures (ref. lab 1298 LPRL)

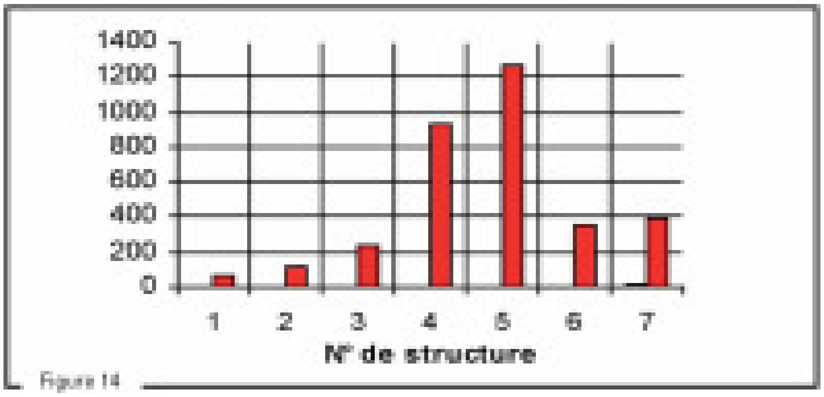


Figure 14

use the dichroic filters combined with the light cascade technology in 3D structures. These structures accomplish the following functions:

- Shift the input light frequency by the light cascade effect combined with waveguiding in the sheets;
- Trap photons inside the structure with the dichroic reflectors;
- Reflect the UV/visible radiation with a reflector on the south-facing surface;
- Converts the photon flux into dc current with Si photocells;

The OPTO PV 3D architecture creates a volumetric structure where the actual photocells are placed in 3D parallelepiped enclosures with dichroic light cascade material combined with a low-pass filter tuned to the spectral response of Si comprising the walls of the structure. It is possible to stack these blocks to create even more efficient solar cells, even to attain a doubling of the conversion efficiency with respect to conventional Si solar cells.

PV OPTO PV 3D generators and different volumetric architectures

Figure 20 presents several solar cell modules using various 3D volumetric architectures, where the walls consists of light cascade material with an outer surface consisting of a dichroic or low-pass (in wavelength) filters. The cutoff wavelength of these depends on the type of photocells and OAMs used, but is generally between 650 and 900 nm.

In this type of structure, the various steps involved in generating power are partitioned between the different optical elements: light cascade, dichroic filter, reflector, photovoltaic cell, and encapsulation. This can be achieved as well by incorporating photocells directly into the light cascade host material and treating the exterior surface to obtain the desired optical properties.

The 3D architecture gives the greatest degree of liberty in managing the various power generating functions. In such a way, we can increase the energy produced per unit volume or per unit area (depending on the geometry used). Figure 22 shows a schematic of a “solar tower”, which is composed of several volumetric solar cell modules. This geometry increases the power generated without increasing the installation’s footprint.

CONCLUSION

These developments in 2 and 3D OPTO photovoltaics represent the future of photovoltaics, where the encapsulation material and architecture plays a vital technical and economic role, on a par with the photocells themselves. The technology is already available, making the emblematic “solar tower” a concrete possibility.

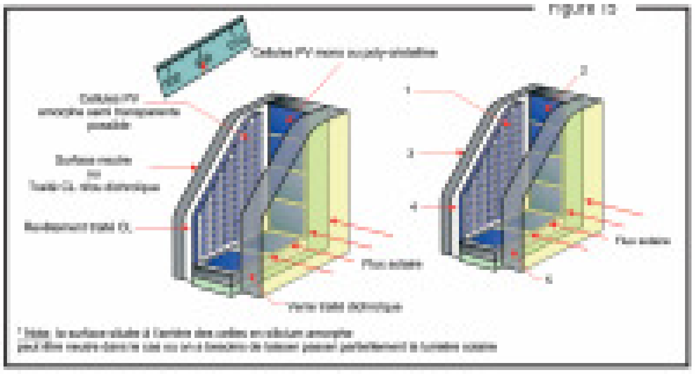


Figure 15

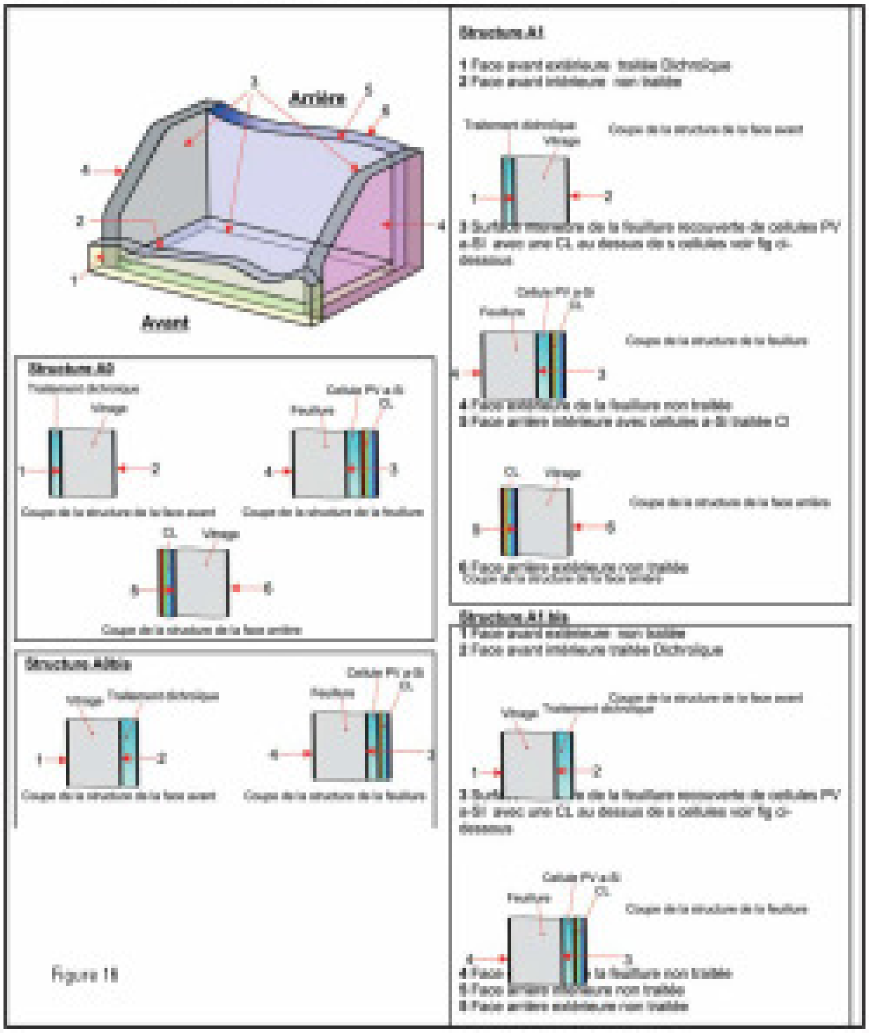


Figure 16

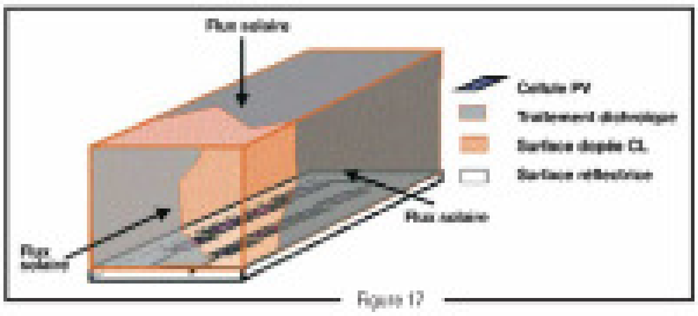


Figure 17

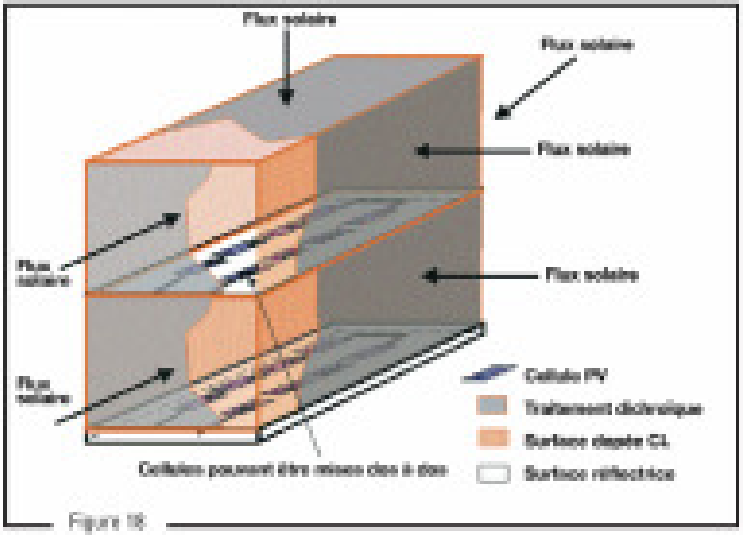


Figure 18

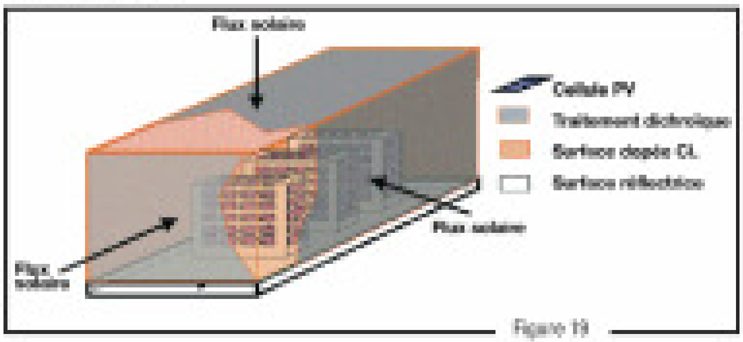


Figure 19

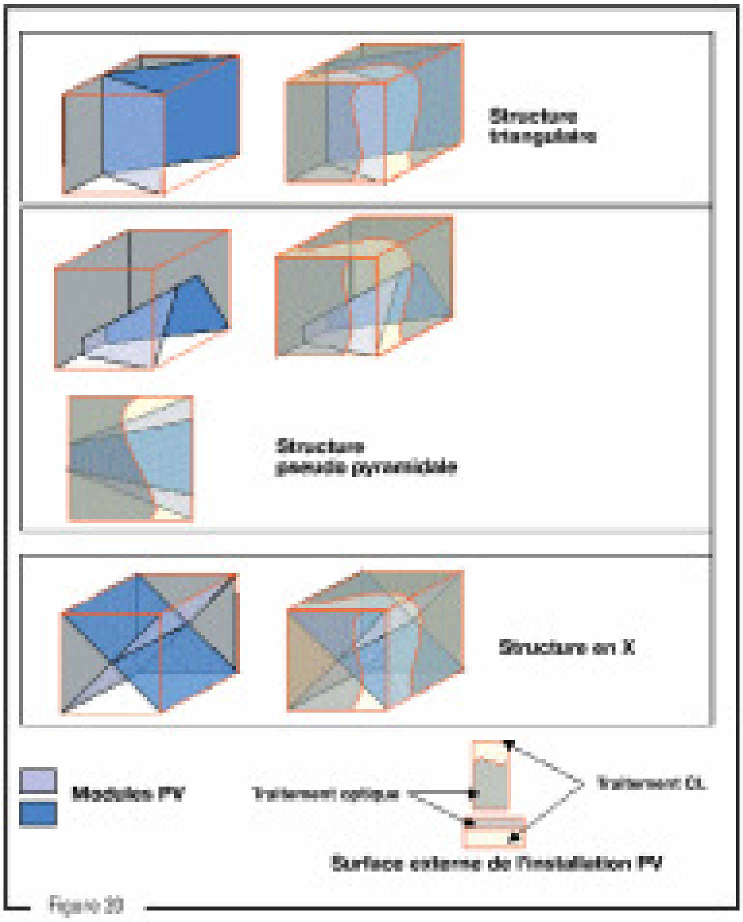


Figure 20

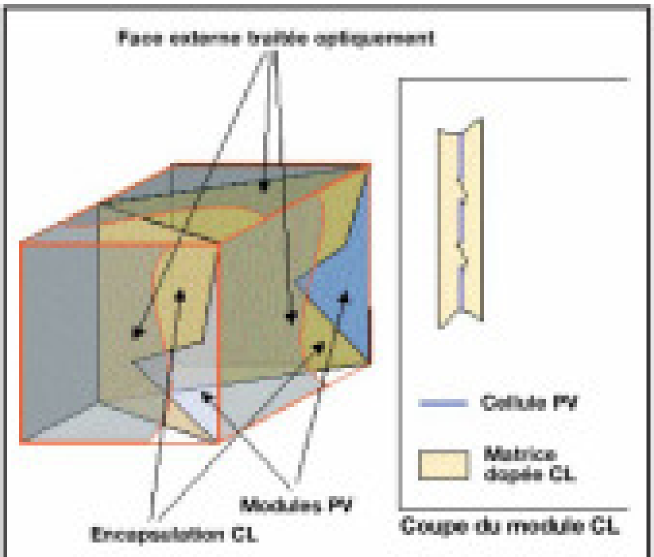


Figure 21 : La structure en V simple est présentée pour plus de lisibilité mais les autres structures peuvent aussi adopter la dissociation de la fonction CL et la fonction traitement optique

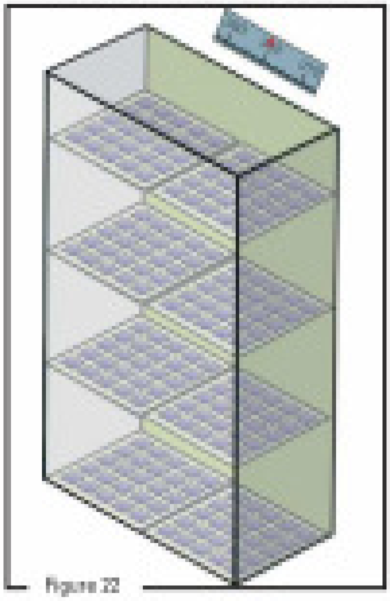


Figure 22

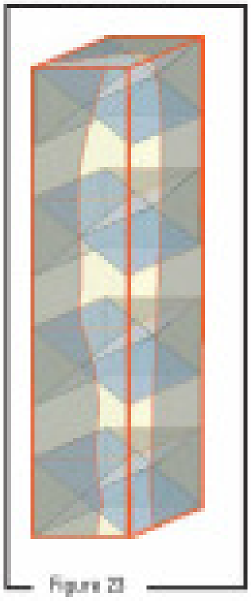


Figure 23

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