The Luminescent Solar Concentrator: An Illuminating Solution for Solar Energy

by Dennis Meredith

THE TIME might be only a decade or so away, and you find yourself driving along a typical country road, with fields stretching away on both sides. Abruptly, however, you come upon a very atypical sight. Spread out in a multi-acre array is a series of large sheets of orange or green plastic, basking in the sunlight. Each sheet is bordered in silicon solar cells, with wires leading away into a network of power lines. These strange contraptions are harvesting electricity from the sun, using a combination of photovoltaic cells and a solar concentrator with seemingly magical properties. Such a scenario is a real possibility because of the work of a group of Caltech researchers.

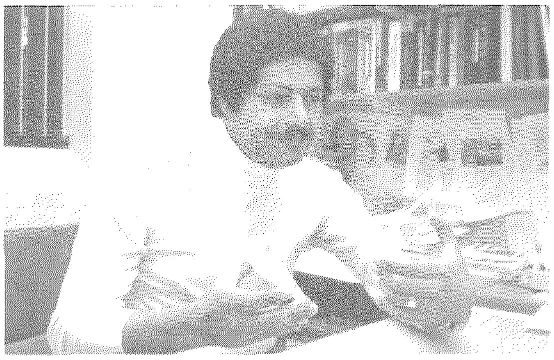
When illuminated with solar radiation, a sheet of the plastic glows brightly at the edges, not only concentrating sunlight but also altering its spectrum, transforming short-wavelength radiation into those longer wavelengths most efficiently used by photovoltaic cells. First conceived by Ahmed Zewail, professor of chemical physics, and his colleagues, these energy-cascade devices have developed rapidly, and now the scientists are highly optimistic that such concentrators will contribute significantly to the development of solar power.

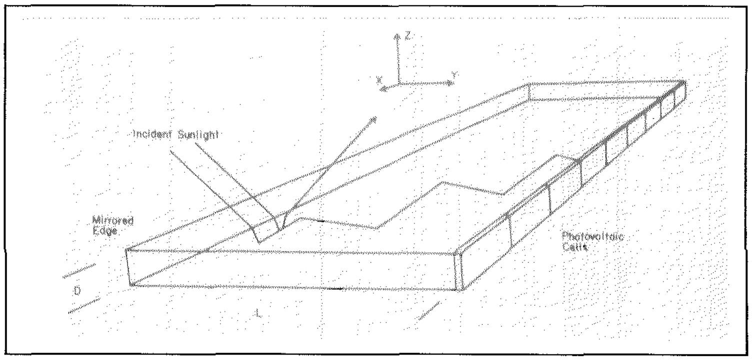
Even though solar energy has long been hailed as a clean, virtually unlimited energy source, the technological problems of generating electricity from sunlight cheaply have been considerable. Photovoltaic silicon cells, the most promising way of generating solar electricity efficiently, remain expensive compared to conventional methods of generating electricity. Reducing the cost of photovoltaic cells is one way to attack the problem. Another is to develop light concentrators that would increase the flux of sunlight impinging on the solar cell, so that fewer cells would be needed per watt of output.

When research on solar concentrators began at Caltech, the most widely studied devices were either Fresnel lenses or parabolic reflectors that focused solar radiation on photovoltaic cells. While these systems do effectively concentrate light, they have two drawbacks that designers have yet to overcome. First, they also focus heat on the cells, creating temperature increases that could reduce the cells' efficiency and lifetime. And second, to be effective, they must follow the sun, which requires expensive motorized tracking systems.

In 1977, however, Zewail, Terry Cole, who was then a Fairchild Scholar at Caltech, and graduate student Barry A. Swartz published a paper in the *Journal of Optics Letters* describing a new type of energy-cascade concentrator that promised to reduce the cost of silicon in solar electricity systems and to alleviate the tracking problem. It consisted basically of several dyes impregnated into a flat sheet of inexpensive Plexiglas. These laser dyes — so called because they are usually used as the lasing medium in chemical dye lasers — capture the sunlight as their molecules assume an excited state. They subsequently re-radiate this light at longer wavelengths. The dyes are matched so that radiation emitted by one kind of dye is at a wavelength ideal for being absorbed by another, producing a cascade in which short-wavelength solar radiation is funneled to longer wavelengths more usable by solar cells.

Because of total internal reflection, light entering a sheet of concentrator or re-emitted by the dyes tends to be trapped, creating a greenhouse effect as suggested by the Jet Propulsion Laboratory's John J. Lambe, who is also a lecturer in applied physics at Caltech. As a result of this "light-pipe" trapping, which is well known in physics, light emerges mainly at the edges of the Plexiglas as an extremely bright orange or green radiation, depending upon the dyes used. If a thin strip of solar cells is attached to these edges, the result is to greatly enhance the power that can be produced by a given area of solar cells. Such concentrators typically increase the solar flux on a





Ahmed Zewail (left) holds two samples of luminescent solar concentrator material, whose Plexiglas edges glow brightly. The concentrators (right) work by capturing incident sunlight, which reflects internally to the edges, where it is transformed into electricity by photovoltaic cells. In addition, laser dyes impregnated in the Plexiglas change the wavelength of the light, making it more suitable for use by the cells.

photovoltaic cell by four or five times that of a cell that has merely been pointed at the sun.

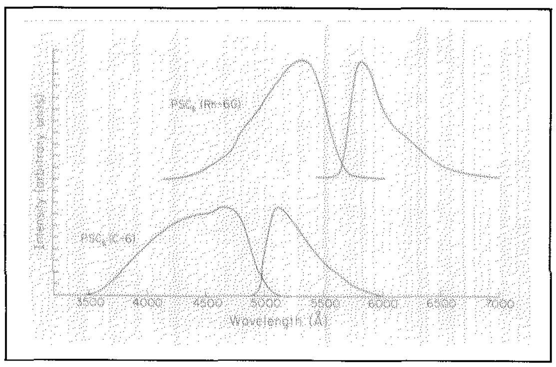
The idea was simple yet powerful, and in early experiments it showed significant promise. Because the concentrator diffused the sun's heat, it did not greatly increase the temperature of the solar cells. And because light could enter the plate at a wide range of angles and still be concentrated, expensive tracking systems were not necessary. The concentrators also worked well in diffused light, as might occur on a cloudy or hazy day. Nevertheless, if the devices were ever to be useful, their geometry, physics, and chemistry would have to be understood in detail. So, since publishing that first paper, Zewail and his group have made steady progress in optimizing the efficiency of the devices, which they have dubbed Luminescent Solar Concentrators, or LSCs. The physics behind the optimization of LSC efficiencies was published in two detailed papers in *Applied Optics* last year by Zewail, Cole (who is now at JPL and also a senior research associate in chemistry and chemical engineering at Caltech), and graduate student John S. Batchelder.

One important aspect of their work has been to understand how the geometry of LSCs governs their effectiveness as light concentrators. The trapping of light within the plastic depends basically on the principle that light entering a material with a higher index of refraction tends to be reflected internally if it enters at greater than what is called "the critical angle." In the case of a flat sheet of plastic, the critical angle can be rotated to make a "critical cone." Light rays emitted within this cone will escape, while light outside will be internally reflected, as shown above right. This internally reflected light eventually reaches the edge of the sheet through a series of internal reflections.

Of course, in the case of an LSC, the dye molecules within the plastic absorb a considerable amount of the light, subsequently re-radiating it. Because of this geometry of reflection, theoretically, the greater the ratio of plate area to edge area, the greater the amount of light concentration. Thus, the scientists could theoretically enhance solar energy concentration more and more by simply making the plate larger and larger. Unfortunately, this simple theory does not tell the whole story, and the scientists quickly found that the physics of the dye molecules would not allow the plates to be made arbitrarily large.

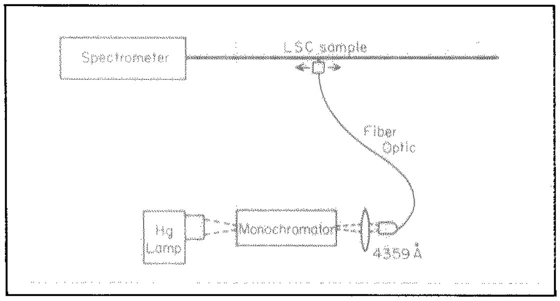
The light robber within the plate is called self-absorption, and it arises from the nature of the absorption and emission of light by the organic dyes. The basic phenomenon that allows these dyes to alter the wavelength of captured light is called the "Stokes shift," which means that when a dye absorbs light and then re-emits it, the emission is shifted to a longer wavelength by a certain amount. The figure below shows the difference in the curves.

If this Stokes shift is large enough, the re-emitted light is at a wavelength far from the absorption wavelengths of the dye. Under these circumstances, the emitted light would simply reflect to the edge of the concentrator, where it could be captured by the solar cells. Since laser dyes typically have high quantum efficiencies, re-emitting about 90 percent of the energy fed into them, the LSCs should be highly efficient in transporting light to the edge. However, in the dyes used in the early solar concentrators — Rhodamine-6G and Coumarin 6 — there is an overlap between the absorption and emission spectra of the dyes. Thus, there is a chance that emitted light will be reabsorbed before reaching the edge, and this likelihood increases as the con-



The absorption and emission spectra for two laser dyes used in the concentrators show that the dyes capture light at shorter wavelengths (left curves) and emit it at longer wavelengths (right curves). By combining certain dyes, concentrators can be made to "cascade" light into wavelengths most usable by solar cells.

To measure how light changes in spectrum and intensity as it travels through the concentrator, a long rod of the plastic is excited by light from a mercury lamp fed through an optical fiber. By moving the fiber along the rod, the distance light must travel to the spectrometer can be changed, and the effects on emerging light studied.



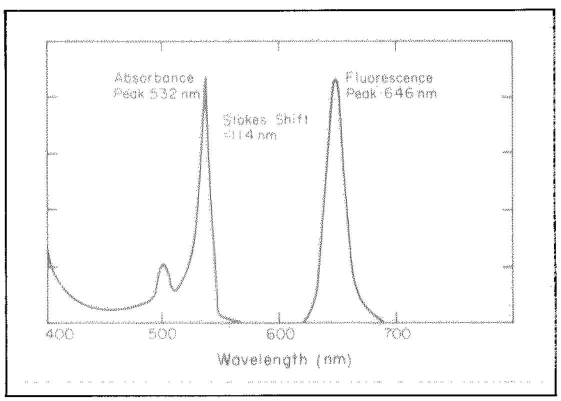
centrator is made larger. In taking this reabsorption into account, the scientists must limit the size of the concentrators.

To study this phenomenon, Zewail's group developed a number of basic methods of measuring self-absorption. For example, in order to measure the progress of light through LSC material, Batchelder performed an experiment in which a spot of light was used to excite a point along a rod of LSC material. In this experiment, the spectrum of light emerging from the end of the rod is measured. As the spot of light is moved along the rod (shown above) away from the end, the spectrum changes because the light has undergone more absorptions and re-emissions as its path length increases.

Besides self-absorption due to overlaps in absorption and emission spectra, other less important sources are scattering and absorption by the Plexiglas, reflection at the interface between the edge and the solar cell, and variations in output due to changes in solar radiation. All of these sources can be minimized by careful engineering. For example, methods have been developed for attaching solar cells to the edges of LSCs using adhesives with indices of refraction that reduce reflection.

The most important solution to the problem of self-absorption, however, is to find dye molecules whose Stokes shift is large enough that the spectrum of emitted radiation overlaps very little with the absorption spectrum. In fact, the researchers have recently done just that. Caltech undergraduate Lynne Hannah — working with Zewail, and Cole and Amy Gupta at JPL — has discovered that a porphyrin molecule and some other similar derivatives (below, left), when incorporated into a solar concentrator, display a Stokes shift that greatly reduces self-absorption. These types of molecules are widely employed in nature as energy trappers — chlorophyll is the most important example — so Zewail believes that such molecules offer considerable promise.

A promising new dye for solar concentrators is revealed in this set of absorption and emission spectra for a porphyrin molecule now being tested. Since the two spectra do not overlap, the dyes will not reabsorb emitted light, and the transformation of wavelengths in the solar concentrators can be much more efficient.



The degradation of dyes when exposed to the rigors of sun and weather is perhaps the most critical problem facing the developers of LSCs. By using a special weathering chamber at JPL, the scientists have been able to accelerate the aging of Rhodamine and Coumarin LSCs by exposing them to ultraviolet radiation, heat, and humidity. They found that heat and light seriously degraded the dyes, so that a typical LSC might have a useful lifetime of only about a year. Even though LSCs are quite cheap, a lifetime approaching a decade would be required to make them truly economical, say the scientists.

Zewail and his colleagues are attacking the longevity problems in a number of ways. For example, they are developing LSCs in which the dyes, rather than being simply dissolved in the plastic polymer, are chemically linked to the polymer molecules. This step could greatly enhance stability of the dyes.

The researchers are also studying alternative forms of the solar concentrator which might offer longer lifetimes and higher efficiencies. They have, for instance, developed a liquid LSC in which the dye is circulated between two sheets of glass, one mirrored and one transparent. The dyes last far longer in such systems, and in fact can be easily replaced. Also, some important dyes in solutions show a larger Stokes shift than when embedded in a solid. The scientists also believe that a number of simple construction steps might help alleviate the degradation problem. Covering each LSC with glass to reduce ultraviolet radiation is one such example. And though the system development has concentrated on the LSCs themselves so far, the scientists expect significant increases in efficiency once they begin designing photovoltaic cells specifically to match LSC properties.

Clearly, much work remains to be done on the LSCs, but the Caltech researchers now have a thorough understanding of the factors governing the efficiency of the devices. This understanding, together with the wealth of ideas they have on improving the LSCs, brings closer the day when fields throughout the world will be adorned with gaily colored, and quite useful, sheets of electricity-producing plastic. □