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A high-irradiance solar furnace for photovoltaic characterization and nanomaterial synthesis

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ABSTRACT

A high-irradiance solar furnace geared toward (a) elucidating the distinctive physics of concentrator photovoltaics and (b) driving high-temperature reactors for the generation of novel nanostructures is described, with a target irradiance up to 12 W/mm^2. The opto-mechanical design permits real-sun flash illumination at a millisecond time scale so that solar cells can be characterized with only insubstantial increases in cell temperature even at irradiance levels of thousands of suns.

1. Introduction and basic optical design

High solar irradiance provides a distinctive probe for subtle and sometimes unanticipated characteristics of ultraefficient (usually multi-junction) photovoltaic (PV) cells [1,2], as well as a tool for producing nanostructures, whose synthesis requires high-temperature and strongly non-equilibrium environments [3–8]. Conducting experiments under controlled indoor conditions is markedly facilitated by a solar furnace: an optical system that reflects sunlight into the laboratory and concentrates it typically to irradiance levels from thousands to tens of thousands of suns [3–5,9–12] (1 sun ≡ 1 mW/mm^2).

Recent studies in these areas were performed using solar minidish concentrators [1,2,6–8] with power delivery through optical fibers of large numerical aperture (NA)—high NA being fundamentally mandated for attaining high concentration [13]. These optics were limited by (a) relatively low power levels (less than 8 W) and hence were fully applicable only to ultrasmall targets, and (b) the diverging nature of emission from the tip of a high-NA fiber not being amenable to the insertion of a temporal control between the fiber and the target without a significant dilution of absorber power density.

Hence the motivation for the higher-power, higher-concentration, converging solar furnace illustrated in Fig. 1. A dual-axis tracking flat heliostat reflects sunlight into the laboratory, where a flat mirror (with a hole at its center) tilted at 45° redirects the light upward to a 526 mm-diameter paraboloidal dish of $NA = 0.40$, whose focal plane is just below the tilted mirror. Venetian blind slats were used to reduce the solar intensity while preserving its angular distribution.

Experiments at irradiance levels up to 4.5 W/mm^2 were conducted at the paraboloid's focal spot (*vide infra*). Irradiance values up to 12 W/mm^2 were realized by introducing a terminal concentrator comprising a tapered glass kaleidoscope (based on total internal reflection) with its entry positioned in the paraboloid's focal plane and its exit in optical contact with the solar cell via optical gel. This design provides a converging high-concentration system with a sizable gap between the optic and the absorber (or kaleidoscope entry) that permits the insertion of elements for moderating delivered flux without incurring power density dilution or jeopardizing the absorber.

The spirit of the optical design—by itself unremarkable—is of being at the service of experiments that uniquely necessitate high irradiance, combined with the ability to control the time and spatial dependence of delivered solar power.

2. Optical measurements

At a normal beam irradiation of 0.90 mW/mm^2, a solar power of 150 W was measured (with a spectrum-neutral pyrometer) in the paraboloid's focal plane, corresponding to a solar furnace optical efficiency of 0.77 (with a peak flux density of 4.5 ± 0.25 W/mm^2). By analyzing the digital image of the focal spot on a diffusing target (using MatLab's image toolbox), the flux map could then be ascertained (Fig. 1) as approximately Gaussian, with a standard deviation of 3 mm.

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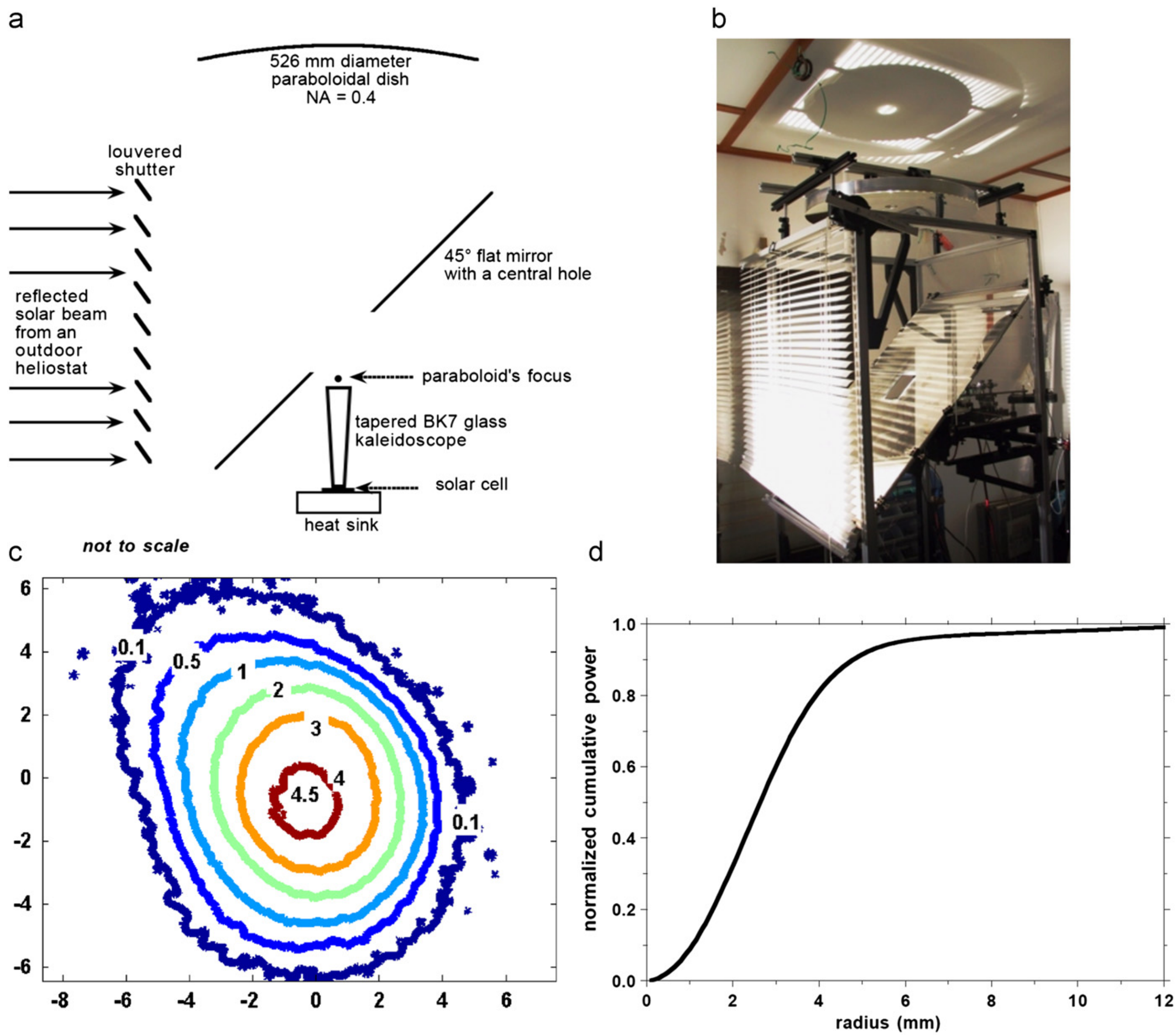

Fig. 1. Solar furnace: (a) schematic, (b) side photograph and (c) flux map in the paraboloid's focal plane. The abscissa and ordinate are in mm and the iso-irradiance contours are in W/mm^2. (d) Normalized cumulative power.

Because of (a) the interest in experiments at irradiance values well above 4500 suns, (b) the inhomogeneity of the target flux map (Fig. 1) and (c) the fact that photovoltaic performance can vary with flux distribution, solar cell experiments included a tapered kaleidoscope terminal concentrator (BK7 glass, square cross section, 50 mm height, 7.5 mm entry width and 2.5 mm exit width that exceeded the solar cell diameter of 1.3 mm, *vide infra*) that also served as a flux homogenizer. Computer ray-tracing confirmed a high degree of target flux uniformity. (The kaleidoscope was not used in the nanomaterial experiments described in Section 5, where flux uniformity appears to be far less important.) Radiative power delivery from the kaleidoscope was assessed via solar cell measurements that exploit the proportionality of short-circuit current to irradiance (described in Section 4).

The silvered mirrors and kaleidoscope preserved a delivered spectrum close to ambient beam radiation (aside from the ultraviolet attenuation of silver—Fig. 2)—particularly germane for the characterization of spectrally sensitive multi-junction solar cells (and slightly mitigated by their low spectral response in the ultraviolet [14]).

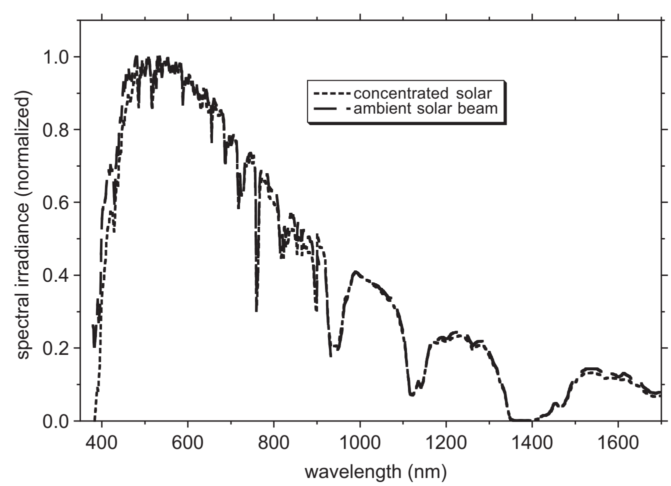

Fig. 2. Measured solar spectral irradiance of ambient beam radiation and concentrated sunlight from the paraboloid's focal spot (at the kaleidoscope exit). Each curve is normalized to its own maximum value.