HIGHLY EFFICIENT COLLECTION OPTICAL SYSTEMS FOR PROVIDING LIGHT DETECTORS SUCH AS PHOTODETECTORS AND THE LIKE WITH HEMISPHERICAL FIELDS OF VIEW

The present application is a file wrapper continuation of parent application Ser. No. 951,089, filed Sep. 25, 1992 now abandoned.

The present invention relates to photodiode or other light-detection collection optics, being concerned primarily, though not exclusively, with substantially hemispherical fields of view (FOV) and in an important application, to use with spectrophotometric light integrating spheres and the like. The term "light" is used herein to connote both invisible and invisable electromagnetic radiation.

BACKGROUND

A lens is an image-forming optical device which collects and concentrates light flux density. Lens systems can produce excellent image quality but have limited light concentration power. In considering the theoretical limits of concentration, optical physicists have developed a class of optical devices that would have very large aberrations if used in image-forming systems but do exhibit very high light concentration power.

Two such non-imaging light concentrator devices are the Compound Parabolic Concentrator (CPC) and the Compound Elliptical Concentrator (CED). "Compound" implies the cone is rotated about an axis other than its natural axis.

The CPC is intended to collect and concentrate light from a distant point source. The design of a 3D CPC is such that radiation enters a larger aperture within a specific incident angle and is concentrated to a smaller aperture, leaving in a hemispherical distribution. It is the most common concentrator often used in solar energy systems, having been first proposed as an attachment to the photomultiplier detectors used in Cerenkov radiation counters employed in particle physics as described, for example, in Hinterberger, H. and R. Winston, "EFFICIENT LIGHT COUPLER FOR THRESHOLD CERENKOV COUNTER". *Rev. Sci. Inst.*, 37, 1094–1095. Other early applications involved concentration onto photodetectors used in infrared astronomy as explained in B HARPER, D. A., R. J. HILDEBRAND, ET AL, "HEAT TRAP: AN OPTIMIZED FAR INFRARED FILED OPTICS SYSTEM", APPLIED OPTICS, 15, 53–60 (1976).

Recently, it has been proposed that the CPC cone concentrator could be used to control the FOV of photodetectors in instruments designed for measuring the diffuse reflectance of surfaces, as in SNAIL, K. A. , "REFLECTOMETER DESIGN USING NONIMAGING OPTICS", *APPLIED OPTICS*, 26, 24, 5326–5332 (1987). The cone is inverted so that the incident light would enter hemispherically through the smaller aperture impinging upon a photodetector positioned at the larger aperture. An additional advantage is that the CPC can be designed to control the incident angle for rays striking the photodetector.

Turning to the CEC, such is optimized to collect and concentrate light from a nearby extended source. The radiation emanating from within the boundaries of the source are accepted by the large aperture of the CEC to be concentrated onto the smaller aperture.

Recently CED's have been used with the photodetectors of integrating spheres, as set forth in LANG, M. C. AND K. D. MASTERSON, "COMPOUND ELLIPSOID CONCENTRATOR BAFFLED INTEGRATING SPHERE", *J. OPT. SOC. AM.*, 70, 1564A (1980); TARDY, M. L., "FLUX CONCENTRATORS IN INTEGRATING SPEHERE EXPERIMENTS: POTENTIAL FOR INCREASED DETECTOR SIGNAL", *APPLIED OPTICS*, 24, 22, 3914–3916 (1985); and SNAIL, K. A., SNAIL AND K. F. CARR, "OPTICAL DESIGN OF AN INTEGRATING SPHERE FOURIER TRANSFORM SPECTROPHOTOMETER (FTS) EMMISSOMETER," *PROCEEDINGS SPIE*, 64B, 234–250 (1986). The major application has involved infrared detectors mounted within liquid nitrogen dewars. The dewar inherently spaces the detector element at some distance from the inner sphere wall, reducing the flux density incident on the detector. The introduction of a CEC between the sphere port opening and detector element virtually negates the spacing losses. The CEC also better defines the detector's FOV on the opposing section of sphere surface.

Most detectors, however, exhibit non-uniform responsivity across their sensitive area. In situations where uniform responsivity is necessary, detector attachments are required. The most common attachments are diffusers. These include flat pieces of translucent opal glasses and plastics or perhaps even an integrating sphere with a specific entrance aperture. Applications include solar irradiance measurements on the earth's surface by pyronometers or spectroradiometers.

The major problem associated with diffusers is their drastic attenuation of incident light by absorption and scattering. These losses can generally be tolerated with "visible" light because of high source energies and very high detector signal-to-noise ratios (SNR). However, in the infrared where source energies are several factors lower and detector SNR is many magnitudes lower, any loss in signal cannot be tolerated.

One special case applies to using a photodetector with an integrating sphere used to measure the diffuse reflectance of surfaces over wide spectral ranges. The integrating sphere is intended to redistribute the spatial distribution of reflected flux. This simplifies the technique compared to directly measuring an otherwise complex flux distribution. A correct average of the incident flux is obtained if the photodetector signal is a true average of the flux redistribution within the integrating sphere. This is best accomplished by a photodetector which receives light equally from over the entire sphere surface. In this condition it can be stated that the photodetector features a hemispherical FOV.

Each type of concentrator (CPC and CEC) used independently as an attachment to integrating sphere detectors, moreover, has serious drawbacks.

The CEC effectively concentrates the flux density from the sphere port onto the photodetector, but its FOV is not hemispherical and, therefore, does not properly average the spatial distribution of flux inside the sphere.

The inverted CPC can approach the hemispherical FOV but its inverted configuration cannot concentrate the flux density. One may counter this by using a large area photodetector to fill the large aperture of the CPC. This, however, inherently increases the detector generated noise (especially for IR detectors). Therefore, an increase in signal is offset by no improvement in the SNR.

Underlying the present invention, on the other hand, is the discovery that CPC and CEC concentrators may be synergistically combined not only to obviate the disadvantages of each, but to produce highly novel results. With the two concentrators used in a special way in tandem, the inverted CPC may be coupled directly to the sphere port opening to receive rays from over the subtended hemisphere. The CEC is then used to concentrate the flux at the larger aperture onto a small area photodetector. Smaller IR photodetectors can