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Photo-receiving device for conversion of energy and data transmitted via atmospheric laser channel

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Received July 11, 2022
Revised July 11, 2022
Accepted August 8, 2022

A power-communicating photo-receiving device for an autonomous laser communication unit has been designed to receive energy from powerful laser radiation and convert it into electricity, as well as to simultaneously registration of information high-frequency optical signals.

Keywords: wireless power transmission, laser beam, photo-receiving device, photovoltaic cell, high-speed photodiode.

DOI: 10.21883/TPL.2022.10.54786.19302

Wireless data transmission via atmospheric optical communication channels has been demonstrated long ago by, e.g., ZAO „Mostkom" (Ryazan) and OOO NPK „Katarsis" (St. Petersburg). The concept of wireless power transmission by laser radiation via an open channel with its subsequent photovoltaic conversion at an end device has also been implemented (see [1–4]). For example, the laser system developed by PowerLight powered an Ericsson 5 G cell site that was not connected to any other source of power supply. Simultaneous power and data transmission by laser radiation via an open channel in space within the external dimensions of a spacecraft was used for transforming the reflecting surface of a space antenna [5].

In the present study, we outline the concept of a system for power and data reception and transmission over distances up to several kilometers via a single atmospheric optical channel. An analytical examination of various versions of design of such a system was performed, and the feasibility of utilization of different optical spectral ranges in the visible and infrared regions was analyzed with consideration for the atmospheric transparency windows, invisibility to the human eye, availability of commercially produced radiation sources with sufficient power parameters and photovoltaic converters, their spectral and spatial matching, and the probable influence of „power" radiation on the infrared signal receiver. It was decided that power and data should be transmitted at different wavelengths and that „power" radiation should have a shorter wavelength than the „data" one. This approach was chosen in consideration, among other things, of the factor of divergence of optical rays. When high-power optical radiation (e.g., laser radiation) is transmitted over long distances, its ray tends to diverge and form a circle of a considerable diameter at a receiver (even if collimating optics is used). Thus, one is forced to use a large-area dense receiving array of large photovoltaic converters or an optical system for radiation concentration onto relatively small photoconverters. However, the design of a photoreceiving system becomes more complicated in the latter case, since forced heat removal from a photoreceiver of concentrated radiation needs to be implemented. In the former (more preferable) case, large photoconverters in a receiving array are ill-suited to serve as receivers of high-frequency-modulated „data" radiation, since their speed performance is poor (due to high capacity). Therefore, an independent photoreceiver should be provided for „data" radiation. Owing to the „data" ray divergence, high-frequency-modulated radiation needs to be collected from a large aperture and concentrated onto a high-speed photodiode with a small photosensitive area, which is characterized by a low electric capacity. A fitting design solution for a compact photoreceiving device for „power" and „data" radiation transmitted via a common spatial atmospheric channel is the positioning of an optical concentration system for „data" radiation behind (along the direction of propagation of rays) a photoreceiving array for „power" radiation, which should be transparent at the „data" radiation wavelength. This condition may be satisfied if the band gap of the primary semiconductor material of the „power" radiation photoconverter is larger than the band gap of the semiconductor material of the high-frequency photodiode and the wavelength of „power" radiation is shorter than the wavelength of the „data" one.

Relying on this approach, we constructed a compact photoreceiving device for simultaneous reception of power and data transmitted via an open laser atmospheric channel. The key design criteria for this device were simplicity, low cost, and ready availability of components, which is required for civil application. Functioning full-scale models of power-communicating photoreceiving devices were designed and fabricated as a result (Fig. 1, a). Their performance efficiency was examined experimentally, and the values of key operating parameters were determined. The obtained data verified the feasibility of their practical application in laser communication systems, including for the purposes of

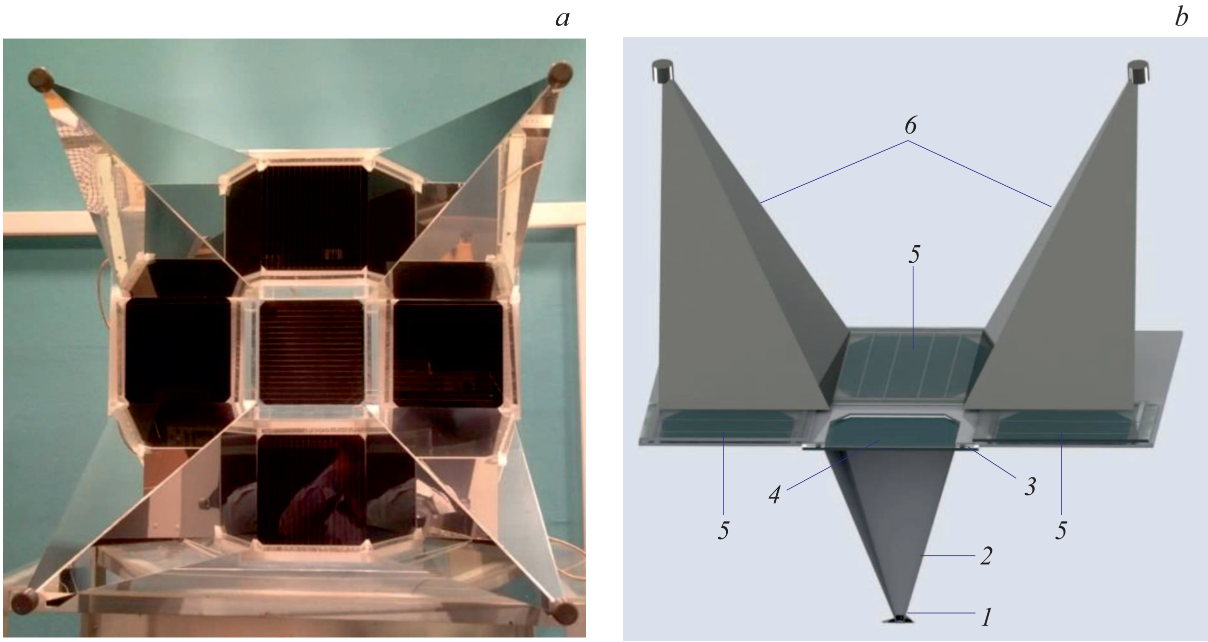

Figure 1. *a* — Photographic image of a model of the power-communicating photoreceiving device viewed from the front. *b* — Cross section of a 3D model of the power-communicating photoreceiving device. *1* — InGaAs PIN photodiode, *2* — hollow focusing cone, *3* — Fresnel lens, *4* — silicon photovoltaic converter with bifacial sensitivity that is transparent for optical data-transmitting radiation, *5* — silicon photovoltaic converters (four in total), and *6* — mirror reflectors (eight reflecting faces in total).

power supply of active equipment at remote communication stations with no access to grid electricity (e.g., located on moving objects).

The constructed photoreceiving device (Fig. 1, *b*) features five photovoltaic converters (PVCs) 157×157 mm in size based on a silicon HJT structure, which lie in one plane and form a photoreceiving array for conversion of „power" radiation, and is fitted with a single high-speed photodiode based on a lattice-matched InGaAs PIN semiconductor structure with its maximum photosensitivity at $1.55\,\mu$m, which is used to detect „data" radiation and is positioned at the focal point of a concentrator that is constructed from a hollow focusing cone with a reflective inner surface and a focusing Fresnel lens positioned in the plane of the wide cone edge. Four PVCs are arranged in the shape of a cross around the central PVC. A specialized grid structure of the back contact of the central PVC and the use of a transparent laminating film in its design ensure bifacial sensitivity of this PVC and its transparency for „data" radiation with a wavelength around $1.55\,\mu$m. The high-speed photodiode with the concentrator are positioned in axial alignment behind the central photovoltaic converter. A light filter, which is meant to enhance the signal-to-noise ratio in data reception by suppressing external parasitic radiation transmitted through the silicon PVC structure within its spectral transparency window, is mounted on the optical axis between the PVC and the high-speed photodiode. A NIR01-1550/3-25 single-band interference light filter with a transmittance above 90% within the 1548.5−1551.5 nm spectral range may be used for this purpose. The edges of four peripheral PVCs are aligned with the corresponding edges of eight mirror faces reflecting „power" laser radiation, which enters the external regions between peripheral PVCs, onto the surfaces of these PVCs. With axially symmetric incidence of a „power" radiation ray with a centrally symmetric (e.g., Gaussian) distribution on the photoreceiving array within the spectral absorption region of silicon, the total incident radiation power at each peripheral PVC may get close to the power for the central PVC owing to reflection of additional radiation from mirror faces. This was verified in model calculations of the distribution of radiation intensity incident on the PVC surface with reflections taken into account (Fig. 2). Radiation with a planar front and Gaussian intensity distribution $I(x, y)$ incident normally on the photoreceiving array is characterized in the model by the following formula:

$$I(x, y) = k\left[\exp\left(-0.5(x^2/c_x^2 + y^2/c_y^2)\right)\right]/(2\pi c_x c_y), \quad (1)$$

where $k = 4.75$, $c_x = 0.868$, and $c_y = c_x$. It is assumed that the maximum intensity corresponds to unity.

It is also assumed that the PVC edge length is unity, the angle between the photoreceiving array surface and a mirror aluminum face is $\pi/3$, the coefficient of power reflection from a mirror aluminum face is 0.9, and the fraction of radiation intensity unreflected from the silicon PVC surface is 0.7 under normal incidence and 0.65 under oblique incidence. With these assumptions factored in, the total radiation powers available for photovoltaic conversion in each of the five PVCs agree closely. This redistribution of incident „power" radiation due to reflection leads to

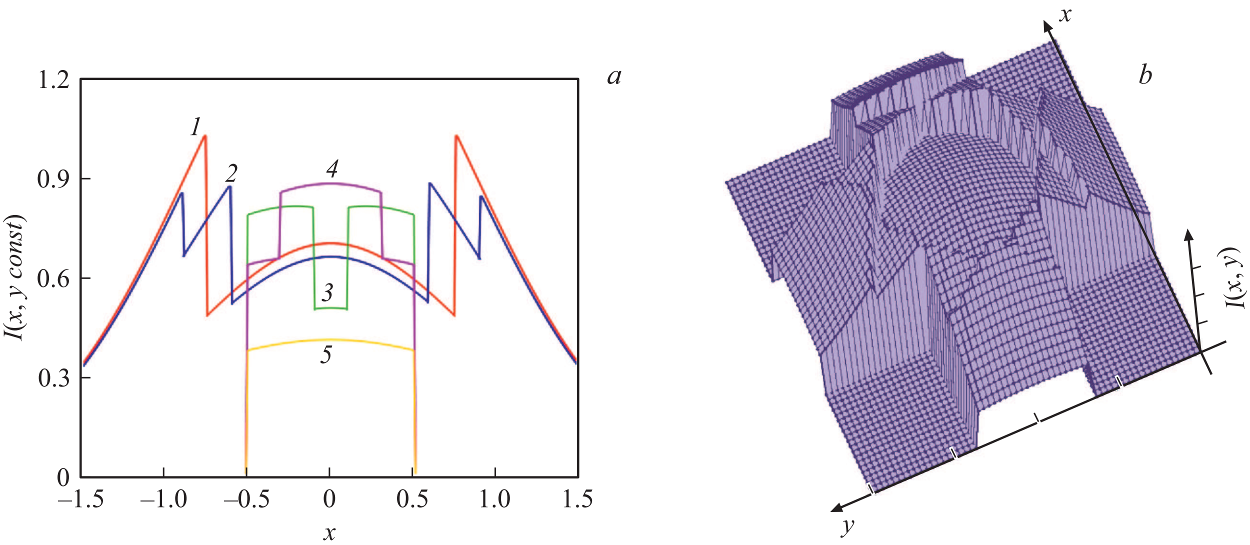

Figure 2. *a* — Model distribution of the radiation intensity at the photoreceiving array surface along its symmetry axis drawn through the centers of three PVCs (*1*) and along a line shifted by 0.3 (*2*), 0.7 (*3*), 0.9 (*4*), and 1.4 units (*5*) parallel to the symmetry axis toward the array edge within the array plane. *b* — 3D image of the radiation intensity distribution near the surface of the photoreceiving array with five PVCs.

partial equalization of the photocurrents of all PVCs in the device, provides an opportunity to connect them in series with almost no enhancement of resistive losses, simplifies their wiring, and has a positive effect on the efficiency of the photoreceiving array. „Power“ laser radiation used for conversion in the photoreceiving device should have a wavelength within the $0.6-1.06\,\mu$m spectral range; if we take the requirement of invisibility to the human eye and the positioning of atmospheric transparency windows into account, the admissible range shrinks to the intervals of $0.85-0.9$ and $0.95-1.06\,\mu$m. The wavelength of high-frequency-modulated „data“ radiation should fall within the $1.3-1.6\,\mu$m range.

The key operating parameters of the constructed photoreceiving device are as follows:

— generated electric power: up to 80 W;

— cut-off frequency of the data receiver: up to 600 MHz;

— dimensions $(L \times W \times H) : 570 \times 614 \times 600$ mm.

In the daytime, the photoreceiving device may generate additional electric power by converting solar radiation. In order to examine this possibility experimentally, the photoreceiving device was mounted on a tracker of a solar tracking system, and the generated power was measured throughout the solar day using a specialized monitoring system for solar cells. The power value at the operating point of the maximum power was determined. The total intensity of solar radiation incident on the solar tracking surface and the direct solar radiation intensity were recorded simultaneously by the monitoring system. This is important for analyzing the power yield of the photoreceiving device in view of the presence of reflecting faces, which channel additional direct solar radiation to PVCs, in its design. The results of these measurements are shown in Fig. 3, *a*. The power generation of five PVCs is generally consistent with the specified PVC efficiency, but is somewhat lower than expected. This is attributable, first, to the use of a smooth frontal surface of the PVC glass (instead of a faceted one), which reduces the total radiation intensity reaching the silicon structure surface, and, second, to the nonuniformity of distribution of the total radiation intensity over the photoreceiving array surface: owing to reflections from mirror faces, each peripheral PVC receives a higher total power than the central PVC, and this differs from the quasi-uniform distribution corresponding to the incidence of a Gaussian beam (i.e., the conversion geometry for which the design of the photoreceiving device with reflectors was optimized). With the radiation power incident on the central PVC being lower than the power corresponding to peripheral converters, this PVC generates a weaker photocurrent and limits the total current, since the PVCs in the photoreceiving device are connected in series. This leads to a reduction in the efficiency of conversion of radiation with an initially uniform distribution (e.g., solar radiation). A comparative analysis of the transmission spectrum of the silicon PVC and the photosensitivity spectrum of the high-speed photodiode, which are shown in Fig. 3, *b* and exhibit a marked overlap, confirms that the data photodiode needs to be protected from solar radiation with, e.g., a light filter. The complexity of the PVC transmission spectrum with two apparent minima is attributable to the use of a multilayer PVC design that incorporates, in addition to the multilayer silicon HJT structure itself, a carrier refined glass on the one side of this structure and a transparent laminating film, which produces the transmission minima at 1212 and 1413 nm, on the other side. Reflections of transmitted radiation off

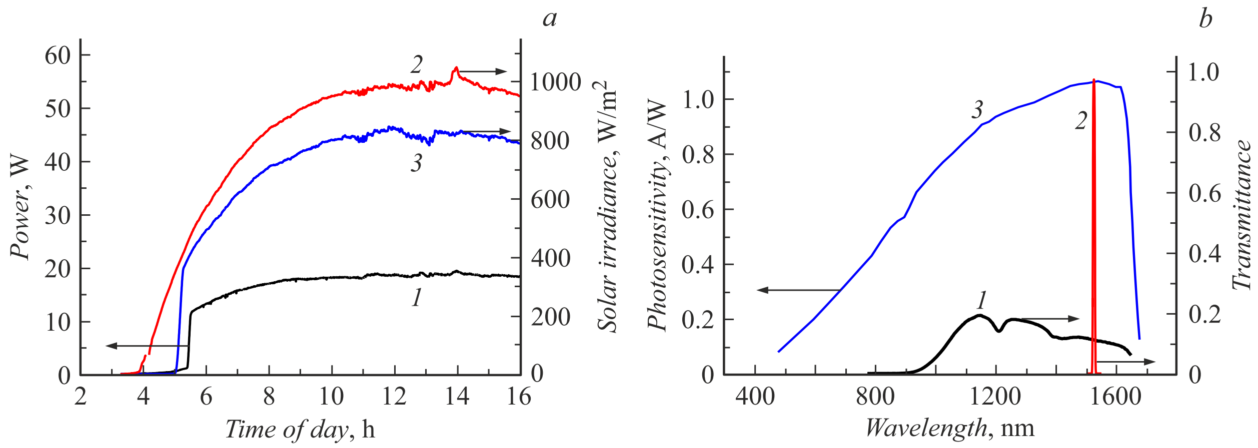

Figure 3. *a* — Generation of additional electric power due to the conversion of solar radiation by the photoreceiving device within a solar day (*1*), total solar radiation intensity incident on the solar-tracking surface (*2*), and intensity of direct solar radiation (*3*). *b* — Transmission spectra of the PVC (*1*) and the interference light filter (*2*) and photosensitivity spectrum of the high-speed photodiode (*3*) plotted on a common spectral scale.

multiple structure interfaces and its scattering off the slightly corrugated external surface of the laminating film are the factors that explain why the PVC transmission values in the region of spectral transparency of the converter are relatively low.

Thus, a power-communicating photoreceiving device capable of receiving high-power laser radiation and converting it into electric power with simultaneous detection of high-frequency optical data signals was constructed in the present study. This device may find application, e.g., in the field of remote control of sensors and equipment of distant stop valve stations at gas transmission pipelines, in optical communication networks in mountainous areas with certain network nodes having no access to grid electricity, and in establishing communication links between a large power-equipped spacecraft and microsatellites with weak onboard power supplies.

Acknowledgments

The authors wish to thank E.I. Terukov, M.Z. Shvarts, and V.S. Kalinovskii for their help in conducting the research.

Conflict of interest

The authors declare that they have no conflict of interest.

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