THERMOPHOTOVOLTAIC CONVERTERS WITH SOLAR POWERED HIGH TEMPERATURE EMITTERS

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ABSTRACT: Results of a solar thermophotovoltaic (STPV) system study are reported. Suntrackers, sunlight concentrators and STPV modules were designed, fabricated and tested at indoor and outdoor conditions. Developed sunlight concentrators of refractive- and reflective-types with secondary quartz meniscus lenses ensured the high concentration ratio exceeding 7000x, which is necessary for achieving the high efficiency of the concentrator-emitter system owing to trap escaping radiation. Several types of STPV modules have been developed and tested under concentrated sunlight. Temperature as high as 2000 K was obtained in a 12 mm dia and 15 mm length tungsten/tantalum emitters in vacuum, illuminated by concentrated sunlight. Photocurrent density of 4.5 A/cm^2 was registered in a photoreceiver based on 1 x 1 cm^2 GaSb cells under a solar powered tungsten emitter. Cell efficiency as high as 19% has been measured in this STPV system with solar powered tungsten emitter heated to ~ 2000 K. ETA = 27% was estimated for the tungsten emitter spectrum cut-off at $\lambda > 1820$ nm. Analysis of various parameters, influencing the performance of the developed STPV systems is presented. The ways for the STPV system efficiency increase up to 30% and higher are considered: - improvement of the emitter radiation selectivity and application of selective filters for better matching the spectra of emitter radiation and cell photoresponse; - application of the cells with a back-surface reflector for recycling the sub-bandgap photons; - development of the low-bandgap tandem TPV cells for better utilisation of the radiation spectra.
Keywords: Thermophotovoltaics, Concentrators, III-V Semiconductors

1 INTRODUTION

In the solar thermophotovoltaic (STPV) system, solar radiation is absorbed and reemitted as a thermal radiation before illumination of PV cells. Conventional solar PV systems are strongly determined by the sunlight spectrum and by the fact that there is no back connection between a PV cell and the Sun. In STPV systems, the optimization may imply a choice of the emitter spectrum and a possibility to return the unused part of radiation from the receiver back to the emitter surface supplying it by an "additional" power. STPV system allows to utilize selective filters/mirrors and sub-bandgap photon reflection to the emitter, which ensures efficiency increase. The more so, as photons emitted by the TPV cells due to radiative recombination are utilized, the emitter absorbs also these photons using their energy. Owing to this effect, TPV cells would operate in the conditions, where the generated voltage is higher than in the case of solar PV, when there is no trapping the emitted photons due to radiative recombination. In solar-powered TPV systems, high-temperature (~ 2000K) emitter in a vacuum bulb can be used with a good enough "quality" of radiation. Like in a concentrator photovoltaics, the thermophotovoltaic conversion of concentrated sunlight is promising for the decrease of the solar electricity cost in comparison with non-concentrated photovoltaics owing to reduction of the PV cell area proportionally to an increase of the output electrical power density from the PV cells in high-concentrator STPV systems. The hybrid system with PV conversion (or lighting) for visible part of sunlight and with TPV conversion for the infrared part of solar spectrum can be also created ensuring the increase of BOS efficiency. The possible hybrid solar/fuel thermophotovoltaic unit have the additional advantage: fuel-fired part of the hybrid system would permit operation during the night.

There are the following key problems arising at optimization of a STPV systems: providing the high sunlight concentration; tailoring the emission spectrum of the photon emitter; filtering the radiation to utilize photon recycling process and to reduce the thermal impact on the photocells; tandem cell design allowing to increase PV conversion efficiency of radiation from the emitter. These problems may be interconnected. For instance, selective filter may be deposited directly on the photocell surface reflecting long-wavelength radiation back to the emitter. The role of such a filter may play a photocell itself, if there is a mirror on its back surface, which reflects the sub-bandgap photons, nonabsorbed in the PV cell material.

Theoretical [1-7] and experimental studies [8-14] show an opportunity to achieve a high efficiency in STPV systems. For ideal system elements, maximal theoretical efficiency were found to be about 85%, that is identical to the efficiency of unlimited stack of tandem cells. Expected in practice efficiencies of STPV converters are 30-35%.

2 EVALUATION OF STPV SYSTEM EFFICIENCY

One of the possible solar TPV systems shown in Fig. 1 consists of a sunlight concentrator (Fresnel lens and secondary lens), emitter and photoreceiver of cylindrical shapes.

In general, STPV efficiency depends on the PV conversion efficiency and the emitter efficiency. Emitter efficiency can be defined as a ratio of the part of radiation, which can be utilized for TPV conversion, to the total energy irradiated by the emitter. It increases with the decrease of the incident light aperture of the absorber and, thus, emitter efficiency increases with increasing the sunlight concentration ratio.

The following factors have been taken into account at estimation of the real STPV system efficiency. Direct sunlight (850 W/m^2) is collected by the concentrator

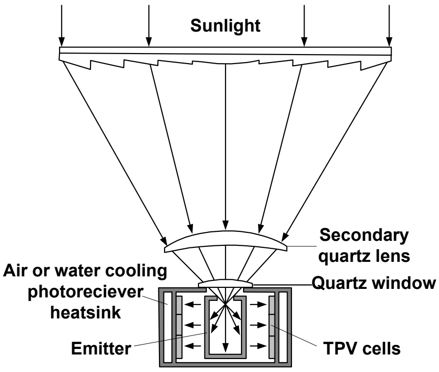

Figure 1: Concept of solar TPV systems with Fresnel lens as a primary concentrator.

system with overall efficiency of 90%. Emitter is a black-body. Part of emitter radiation, determined by emitter efficiency falls on PV cells. The emitter radiation is scattered by elements of the inner construction (these losses are accepted equal to 10%) falls on photocells, which occupy 90% of the whole irradiated surface (view factor is 90%). Radiation with photon energies $h\nu < Eg$ returns from PV cells to the emitter with the return efficiency $RE = 90\%$. The radiation with $h\nu > Eg$ is absorbed in the semiconductor and generates electron-hole pairs. Recombination losses have the lowest value limited by radiative recombination. No ohmic losses in the cells are assumed. The cell operating temperature is equal to 50ºC.

As is seen from Fig. 2, the efficiency maximum of 33% takes place at emitter temperatures of about 2000K in the cells made of materials with bandgaps in the range of 0.7-0.9 eV. This range is higher in comparison with the optimal bandgap range of 0.4-0.5 eV in the TPV systems with lower efficiency of sub-bandgap photon recirculation ($RE < 50\%$) and at lower emitter temperature[15-17]. It means that GaSb and InGaAs/InP widly used for fabrication of TPV cells [15-23] are the optimal materials for STPV systems with high return efficiency and high emitter temperature (~ 2000 K).

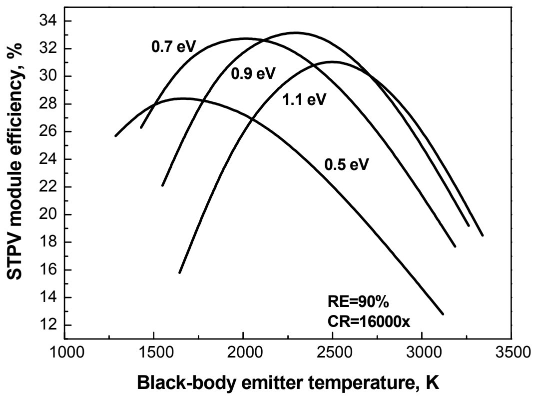

Figure 2: Calculated STPV converter efficiency as a function of emitter temperature for the different bandgaps of TPV cell materials from 0.5 eV to 1.1 eV.

As is seen from Fig. 3, efficiency of STPV converter based on GaSb ($Eg = 0.72$ eV) increases with concentration ratio increase. The drop in the efficiency with lowering down temperature is explained by the decrease of the conversion efficiency of the GaSb PV cell, owing to the worse matching the PV cell photoresponse spectrum to radiation spectra at lower emitter temperature. The drop in efficiency at high temperatures is associated mainly with the rise of losses of radiation, which leaves the absorber through the absorber aperture (i.e. owing to decrease in emitter efficiency). For these reasons, with increasing sunlight concentration ratio, an efficiency increase from 18% at 1000x to 33% at 16000x takes place, when the emitter temperature of efficiency maximum increases from 1400 K at 1000x to 2000 K at 16000x.

This efficiency evaluation shows the necessity to design STPV systems with high sunlight concentration ratio and high emitter temperatures of 1800-2000 K.

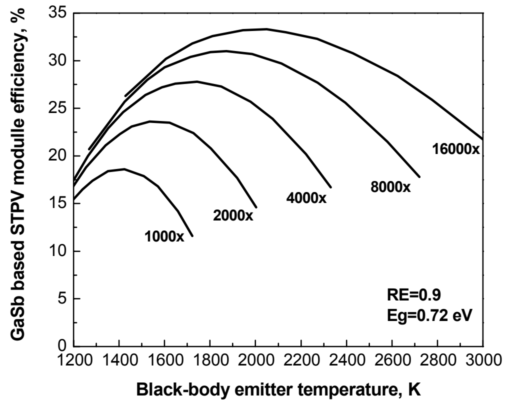

Figure 3: Calculated GaSb based STPV converter efficiency versus black-body emitter temperature at various solar concentration ratios from 1000x to 16000x.

3 SUN TRACKER DESIGN FOR STPV SYSTEMS

High accuracy of tracking to the sun is a specific feature of the high-concentration PV and STPV methods. Another very important requirement for these systems is low cost of suntrackers. The tracker prototypes have been designed and built for designated capacities up to 5 kWp [24]. They had been installed at the Ioffe Institute (St.Petersburg), at Fraunhofer ISE (Freiburg) and at NREL (Golden).

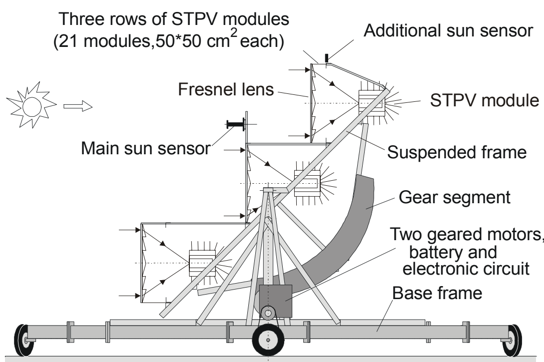

Figure 4: Schematic of the 1kWp solar tracker equiped with STPV modules.

Recently an improved 1 kWp tracker was designed and built in the Ioffe Institute. Tracker consists of two main moving parts (see Fig. 4,5): a base platform moving around the virtual vertical axis by means of three wheels, and a suspended one moving around horizontal axis. The suspended platform is a frame where STPV modules should be installed as three steps of a stair. Position of the suspended frame can vary in the range of ±45° symmetrically about a horizontal plane.

The base frame is driven by one of three wheels moving in a large radius with respect to a circle (see photograph in Fig. 5). At normal tracking the motor is switched on periodically, after each 5-8 seconds. Similar operation takes place for the vertical channel. For vertical driving there are two cogwheels and two gear segments, situated symmetrically on two sides of the suspended frame. Such a design allows reducing free movements of the frames under wind conditions and simplifying the tracker structure. For operation during cold periods with blanket of snow, the tracker is supplied with special caps on the wheels. Also, these caps will protect rubber covers of the wheels against direct sunrays.

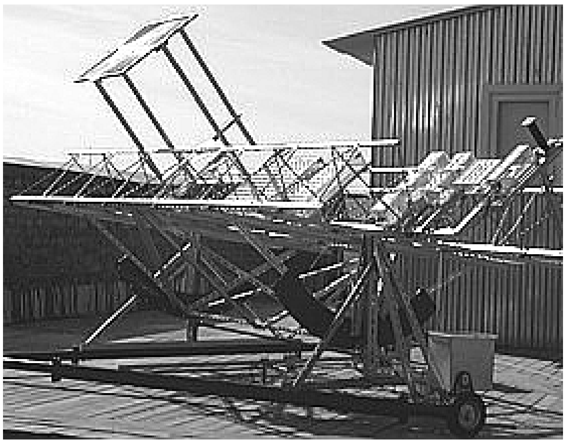

Figure 5: Sun tracker with STPV (on the left) and PV concentrator modules (on the right side) based on Fresnel lens concentrators installed at the Ioffe Institute.

The tracker is equipped with main (accurate) sensor and additional one, both equipped with tandem III-V solar cells and operating as a part of a close-loop system. Main sensor can align the tracker with the sun within 0.05 degree of arc accuracy with acceptance angles of ±70°. Additional sensor makes wider the "East/West" turning angle (up to 270°). Both sensors are mounted on the suspended frame together with STPV modules. An advantage of the developed sensors is the protection from the illumination level changes caused by light reflections from various objects and by presence of clouds. For this, the main sensor includes two sub-channels in both horizontal and vertical channels. Differential signals are generated in correspondence with misalignments of the tracker to the sun in azimuth and elevation. Simplicity and consumption of current as low as 45 microamperes from a rechargeable 12V-battery in stand-by regime are the positive features of the developed electronic board. Overall power consumption for tracking including West-East returns was estimated to be no more than 0.2% of installed power.

4 DESIGN AND PERFORMANCES OF SUNLIGHT CONCENTRATORS FOR STPV SYSTEMS

Two-stage sunlight concentrators with pseudo-parabolic mirrors and Fresnel lens were fabricated as a first stage of the concentrator systems. Quartz meniscus lenses with diameter of 7 cm were used as a secondaries to increase the concentration ratio in 1.7-2 times. The secondary lenses have antireflection coatings for the spectral range of 400-2000 nm.

The sunlight concentrator shown in Fig. 6 is a combination of a four-segment pseudo-parabolic compound mirror and a secondary meniscus lens installed close to the entrance window of the STPV module. This two-stage concentrator ensures the sunlight concentration ratio of about 6000x, i.e. 90% of input sunlight comes to the 10 mm aperture emitter.

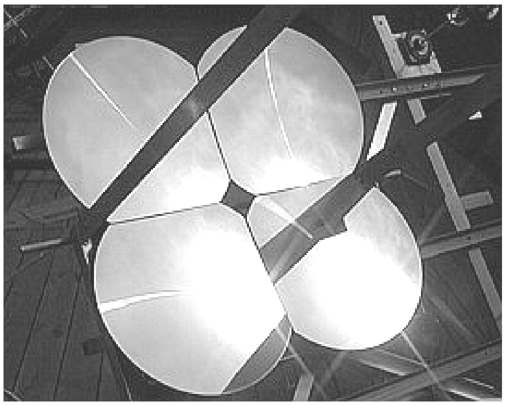

Figure 6: Four-segment pseudo-parabolic mirror ($0.45\ m^2$ in area, 0.75 m focal length) made of four brass spherical dish mirrors (with aluminium reflection layer protected by HfO_2 layer) installed on the sun tracker.

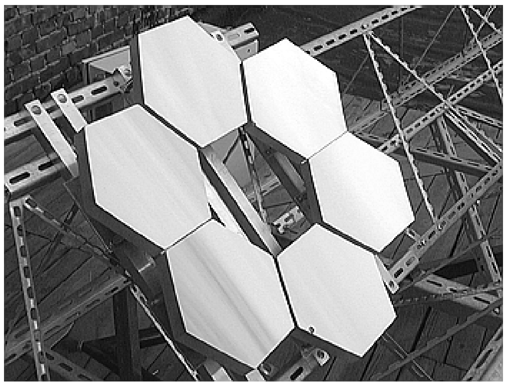

Figure 7: Facet-type pseudo-parabolic mirror ($0.2\ m^2$) made of glass (with Al-reflection layer protected by SiO_2 as a first stage of concentrator system, installed on the sun tracker.

The sunlight concentrator shown in Fig. 7 consists of a 6-segment facet-type pseudo-parabolic mirror (aperture area of $0.2\ m^2$ and focal length of 0.75 m) and a secondary quartz meniscus lens. Owing to high quality of the fabricated facet mirrors the concentration ratio of more than 7000x is ensured by this two-stage concentrator.

The refractive-type sunlight concentrator shown in Fig. 8 consists of a Fresnel lens (0.36 m^2 in area and 0.75 m focal length) and a secondary quartz meniscus lens. 90% of concentrated sunlight is collected in the spot with diameter of 10 mm. Concentration ratio of 4000x is ensured by this concentrator, the main advantage of which is its low cost. However, the material (PMMA) of the Fresnel lens is characterized by poor outdoor stability. Recently, a new technology for Fresnel lenses of composite structure was developed at the Ioffe Institute [25]: the microprisms are formed from the transparent silicone rubber contacting with the front silicate glass sheet as a protective superstrate. The developed formation process allows fabricating the lens of total area of 0.6 m x 0.6 m. Such a type of Fresnel lenses ensures much better environmental stability owing to the use of high stable silicate glass, protecting the Fresnel lens made of silicone rubber, which is also characterized by high stability under the action of outdoor conditions. These of Fresnel lenses are very promising for fabrication of concentrator PV modules [25] and have a perspectives for use in low cost STPV systems.

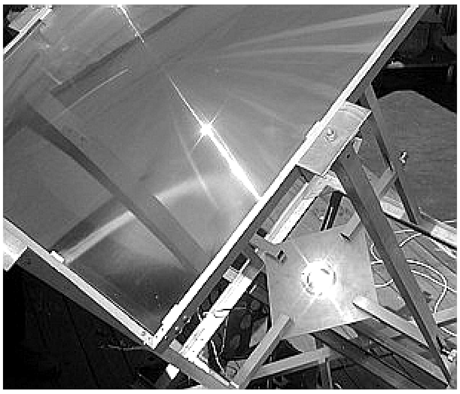

Figure 8: Two-stage refractive concentrator based on a Fresnel lens (primary) and a quartz meniscus lens (secondary).

5 HIGH-POWER SIMULATOR OF CONCENTRATED SUNLIGHT FOR INDOOR TESTING OF SOLAR TPV CONVERTERS

Taking into account that outdoor testing of STPV modules is possible in St.Petersburg during the summer months only, it is very important to have the possibility of indoor characterization of the developed devices. Simulator of concentrated sunlight (SCS) has been developed for indoor testing of TPV converters under high intensive (more than 500 W/cm^2) illumination of the emitter. SCS (Fig, 9,a) consists of a power supply block (1), a remote control block (2) and a radiating element (3). The illuminator consists of an elliptical dish mirror with diameter of 0.6 m, a lamp ignition device (5) and a xenon lamp (4). The optical scheme of the furnace is shown in Fig. 9,b. The lamp is installed vertically. The control block is intended for the ignition pulse voltage supply (30 kV, 0.5 MHz) and for a smooth regulation of the lamp power. The simulator design provides a possibility to sustain automatically a designated lamp mode by fixing a feedback and by delivery of a signal from the object tested to the control block. The discharge illumination spot of the lamp is located in the first focus of the mirror. In the second focus (at the distance of 1 m) there appears an increased image of the discharge spot cross section.

The simulator is characterized by the following performance: input electrical power of the lamp is up to 10 kW at continuous mode operation; lamp efficiency is 55%; optical system efficiency is 35%; the optical power up to 2 kW is collected in the focal spot. Distribution of the radiation over the spectrum ranges is as follows: 0.2 kW in the UV region, 0.7 kW in the visible region and 1.1 kW in the IR region. The use of the secondary meniscus quarts lens allows achieving the optical power density up to 1 kW/cm^2, that is equivalent to > 10000 suns.

At a loss of a part of the energy for thermal conductivity of a tested specimen placed in the focus of the described simulator, the temperature exceeding 1700°C was achieved in the tungsten/tantalum emitters placed in vacuum.

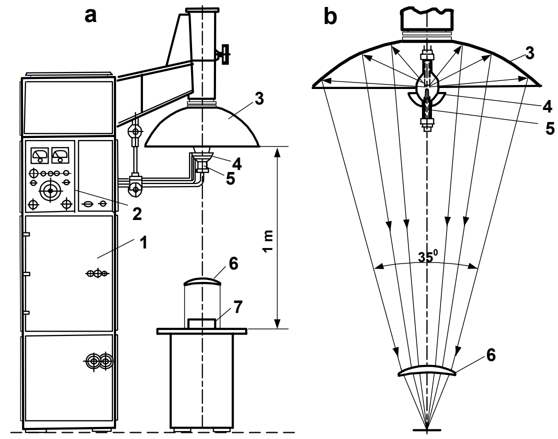

Figure 9: Simulator of high intensive solar illumination with a xenon lamp (a), optical scheme of illuminator (b): 1 – power supply block; 2 – remote control block; 3 – dish elliptical mirror; 4 – backside reflector; 5 – xenon lamp; 6 – secondary quartz lens; 7 – STPV module on the table providing the motion of the module in three dimensions.

6 SOLAR TPV MODULE DESIGNS AND EXPERIMANTAL RESULTS

The TPV parts of the modules (Fig. 10) include a cylinder-shaped tungsten emitters, embedded in a vacuum chamber or in argon. For several experiments, tantalum emitters were used instead of tungsten ones, because of easier tantalum treatment. Vacuum chambers with quartz windows for sunlight entrance were used to prevent the emitters from the oxidation. STPV modules of conical and cylindrical shapes have been developed. In the conical system (Fig.10, a and Fig. 11), thermal radiation is reflected to PV cells by an Au coated cone-shaped mirror, and the PV cells are mounted on a flat basement. In the cylindrical system (Fig.10, b and Fig. 12,13), PV cells surround the emitter, being mounted on the inner side of a cooled cylindrical base (Fig.13). Both modules were tested outdoors under direct sun illumination. Average direct sun irradiation was measured to be 850 W/m^2. Emitter temperature was registered by both a pyrometer and a W-Re thermocouple. Temperatures in the range of 1700-2000 K were obtained, depending on emitter size and material.

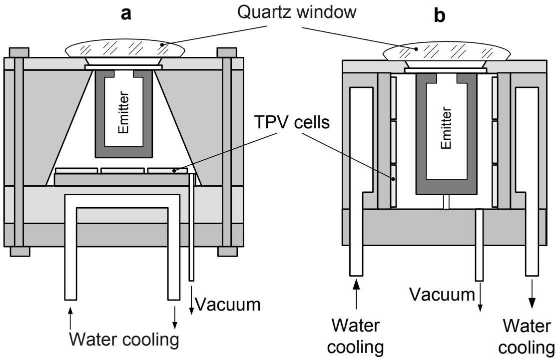

Figure 10: Schematic drawings of the developed conical (a) and cylindrical (b) STPV modules.

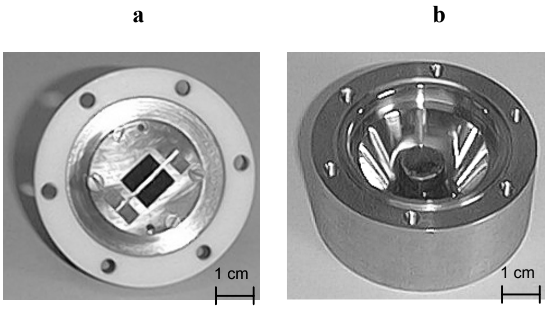

Figure 11: STPV module with a flat PV receiver (a) and a tungsten emitter surrounded by a conical reflector (b).

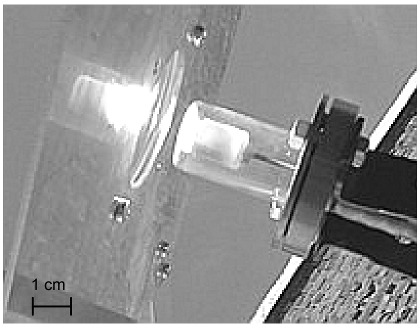

Figure 12: Solar powered tantalum (12 mm dia) emitter at 1800 K inside the bulb (filled up with argon) in the focal spot of a Fresnel lens with a secondary meniscus lens.

GaSb TPV cells were fabricated with the use of the Zn-diffusion and LPE technologies. In the first experiments the cells were mounted in parallel on heatsink made of copper (Fig. 13,b). To ensure the series connection of the cells, the heatsink substrate with high thermal conductivity must be an electrical insulator [18,20]. For fabrication of photoreceivers, we have selected BeO ceramics, which has electrical resistivity of more than 10^{14} Ωcm with the best thermal conductivity of 250 W/mK. The thermal expansion coefficient of BeO ceramics is $6{\cdot}10^{-6}$ 1/K being close to that of GaSb in the temperature range of 20-150ºC. Contact composition Mo/Ni/Au to the BeO substrate allowed to solve the problem of adhesion of GaSb cells to ceramics.

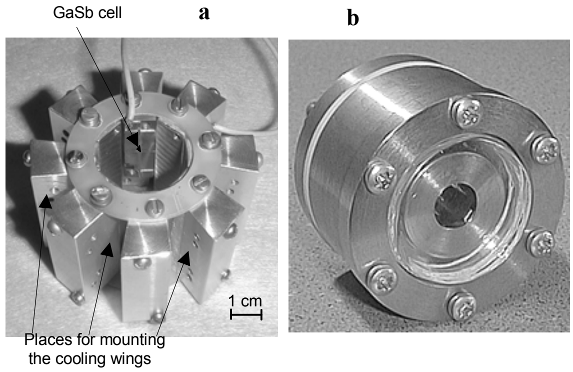

Figure 13: a – PV receivers of cylindrical shape with forced air-cooled GaSb cells (air-cooling wings are not shown); b – conical TPV module with water-cooled photoreceiver.

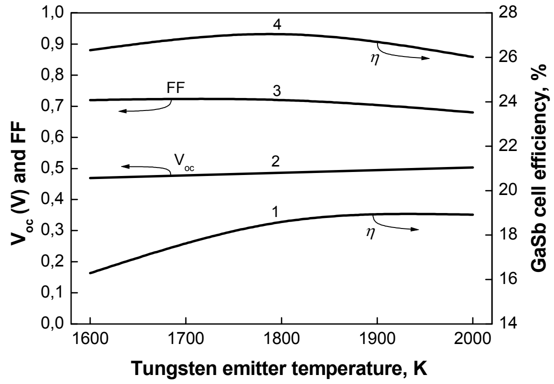

Figure 14: Open circuit voltage (V_{OC}, curve 2), fill factor (FF, curve 3) and efficiency (curves 1,4) of GaSb TPV cell as a function of tungsten emitter temperature. Efficiency was estimated under the following radiation conditions: under the full radiation spectra (curve 1) and under spectra cut-off at $\lambda > 1820$ nm (curve 4).

The photocurrent density $J_{SC} = 4.5$ A/cm^2, open circuit voltage $V_{OC} = 0.49$ V and fill factor FF = 0.68 have been measured in GaSb cell in the conical module under the solar powered emitter heated to the temperature of about 2000 K. The cell efficiency of 19% under illumination by tungsten emitter heated up to 1900-2000 K had been derived from experimentally measured PV parameters (Fig. 14). Cell efficiency as high as 27% was estimated for the spectrum cut-off at $\lambda > 1820$ nm (conditions of 100% return efficiency for sub-bandgap photons).

7 CONCLUSIONS

The following approaches can ensure the efficiency increase in STPV systems.

One of the main common features of thermophotovoltaics and solar photovoltaics is that in both systems the energy source is characterized by a wide spectrum. It means that the most effective approach to improvement of the solar system efficiency, which is the multijunction approach, may be applied to improvement of the TPV system efficiency. Theoretical efficiencies of dual-junction TPV cells based on narrow bandgap semiconductors exceed 45% in STPV systems with high-temperature emitters and at high enough return efficiency of 90%. Sub-bandgap photons can be returned to the emitter by inserting a broadband metallic mirror on the PV cell backside. Maximum reflectance of 80% was measured in GaSb cells with such backside mirror. Another way to return unused energy to the emitter is to insert a selective filter between the emitter and the cells.

The overall efficiency of a real STPV system can be also increased by the use of the selective emitters. Tungsten is a slightly selective material with emissivity increasing in the visible spectrum range. However, more selective materials are preferable [26-28]. For instance, 2D- or 3D-texturized tungsten may lead to the increase in emissivity in a desired wavelength region (say, 1.5-1.7 μm). All these approaches together should ensure the STPV system efficiency increase up to 30% and higher.

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