Spectrally Controlled Thermal Radiation
Based on Surface Microstructures for
High-Efficiency Solar Thermophotovoltaic system

Asaka Kohiyama*, Makoto Shimizu, Hiroaki Kobayashi, Fumitada Iguchi, Hiroo Yugami

Abstract
Thermophotovoltaic (TPV) system is expected to generate electrical power from various heat sources. One of the key devices of TPV system is spectrally control thermal emitters. The performance is not sufficient to achieve high efficient TPV systems. In this study, we developed new type spectral selective emitters with closed-end surface microcavity array. The simulated spectral thermal radiation band width is only 70nm and Q-value=26.4. This Q-value is 5 times larger than the conventional open-end microcavity emitters. The design of Solar-TPV system which is driven by concentrated solar energy using refractory metal emitters with multi-layer coating. The estimated system efficiency and electric power density using the experimentally obtained spectral property of the selective emitters is 16.6% and 2.9W/cm², respectively.

Keywords: STPV ; Spectrally Selective Emitter ; Microcavity Effect

1. Introduction
Thermophotovoltaic (TPV) systems generate electricity from thermal radiation as shown in Fig. 1. This system has some advantages compared with conventional photovoltaic (PV) systems. A TPV system is generally composed of three main components, namely, a heat source, an emitter, and PV cells. Thermal radiation from an emitter heated at high-temperature is converted into electricity with PV cells. To obtain high-efficiency, the emitter temperature is required 1000 K or more, since radiation energy is proportional to fourth power of temperature. At such temperatures, thermal radiation shows a peak in the near infrared (NIR) region (~3.0 μm) according to Planck’s law. Therefore narrow bandgap PV cells are often used in TPV systems, since they can convert photons with longer wavelengths by comparison to conventional Si PV cells.

TPV systems have been studied by many groups. The basic concept of TPV generation was first suggested in Massachusetts Institute of Technology in 1950s [1, 2]. In the early 90’s, a great interest on TPV technology was happened. In particularly, relevant results were gained with GaSb cells developed at Boeing [3] and InGaAs cells developed at NREL [4]. The NASA InGaAs TPV cells obtained electrical power densities and current densities slightly above 0.2 W/cm² and 1 W/cm² respectively. Further experiments conducted by Essential Research Inc. [5] with InGaAs MIM devices and SiC emitters show a power density of 0.82-0.9 W/cm² for emitter temperature of approximately

* Corresponding author. Tel.: +81-22-795-6925; fax: +81-22-795-6923.
E-mail address: a_kohiyama@energy.mech.tohoku.ac.jp.
1230 °C. By using GaSb cells for a 16.6 W solar power imprinting the aperture window, the measured electric output power was 0.38W [ ]. This represents overall efficiency around 2.3%, without considering the concentrator losses.

Considering the previous study, TPV systems still show low efficiency. To improve the system efficiency, it is effective to control spectrum of the emitter. Up to now, various researches on the spectrally selective emitter for TPV systems have been studied by several groups [ , ]. However, the control of thermal radiation is still insufficient to improve the TPV system efficiency drastically.

The purpose of this study is to obtain high-efficient TPV systems by improving spectrally selective of emitters. We investigate two types of the emitters. One is to control broad-band thermal radiation into quasi-monochromatic thermal radiation. It has been theoretically known that quite high efficiency can be obtained by monochromatic light [ ]. The other one is refractory metal emitters with multi-layer coating which is expected to have spectral with sharp cutoff property.

In this study, we mainly researched two topics. One is design of a new emitter which has quasi-monochromatic radiation. The other is design of a TPV system using fabricated multi-layer emitter. The design of emitters is conducted using numerical simulation based on Rigorous Coupled-Wave Analysis (RCWA) [ ]. The multi-layer emitters are fabricated based on tungsten (W) and Yttria-Stabilized Zirconia (YSZ). The configuration of TPV system using multi-layer emitters is designed for Solar-TPV system which is driven by concentrated solar energy.

2. Improvement of TPV efficiency with quasi-monochromatic thermal radiation

Major losses in a GaSb PV cell, which is a typical for TPV systems, are schematically illustrated in Fig. . The blue line is internal quantum efficiency ($\gamma$) of a GaSb PV cell. The black line and the red line are broadband thermal radiation and quasi-monochromatic radiation, respectively. The quasi-monochromatic radiation is assumed by Lorentz function. The one of the losses is attributed to transmittance loss for photons with energy lower than the bandgap ($E_g$). Another loss is attributed to the energy content of photons above the bandgap is wasted surplus re-emitted as heat or light. This is the second loss.
By irradiating quasi-monochromatic radiation of which energy is close to bandgap of a PV cell, both the transmittance and heat losses are suppressed in this condition. Green et al. reported that by irradiating monochromatic light of 1.064 µm into Si PV cell by means of Nd-YAG laser, the conversion efficiency reached 45.1%, even though the efficiency of the Si cell is shown 23.0% under AM1.5 solar irradiance.

To evaluate the narrowing effect of thermal radiation spectrum quantitatively, we calculated conversion efficiency by assuming the spectral emissivity which have a peak with various Q-value defined by Lorentz function shown in Fig. 3(a). The Q-value is defined by Eq. (1).

\[ Q_v = \frac{\omega_0}{\omega_1 - \omega_2} \] (1)

where \( \omega_0 \) is frequency at the peak center, \( \omega_1 \) and \( \omega_2 \) are frequencies at half maximum of the peak (\( \omega_1 > \omega_2 \)).

To evaluate the conversion efficiency between emissive power from selective emitters and electrical power from PV cells, the following equation is defined.

\[
\chi = \frac{\int_0^\infty I_{emitter}(\lambda) \cdot \gamma_f(\lambda) \cdot \frac{E_g}{E_{photon}(\lambda)} d\lambda}{\int_0^\infty I_{emitter}(\lambda)d\lambda} \] (2.)

\[ I_{emitter} = \epsilon_{\lambda} E^B(\lambda, T) \] (3.)

where \( I_{emitter} \) is spectral emissive power from the emitter, which is described by Eq.(3). \( \epsilon_{\lambda} \) is the spectral emissivity and \( E^B \) is spectral emissivity from black body. \( \gamma_f \) is internal quantum efficiency of a GaSb cell. \( E_g \) is bandgap energy of a GaSb cell, and \( E_{photon} \) is energy of the photon as described by

\[ E_{photon} = h \nu = h \frac{c}{\lambda} \] (4.)

where \( h \) is Planck’s constant, \( \nu \) is frequency and \( c \) is the speed of light. In the Eq. (2), the denominator shows the total emissive power and the numerator shows potentially convertible energy where the two losses are considered. In this calculation, we assumed the same temperature for emitters with different Q-value.

The calculated conversion efficiency is improved at two temperatures range with increasing the Q-value shown in Fig. 3(b). The conversion efficiency attains more than 0.5 at Q=15 when the temperature is 1735K.

Since the achieving temperature of emitters is limited by the total emissive power, the quasi-monochromatic thermal emitter can reach higher temperature than broadband emitters. For example, the total emissive power of the emitter with Q=22 at 1735 K is the same as that of the emitter with Q=1 at 1100K. TPV system equipped with quasi-monochromatic thermal emitters has very high advantages due to high conversion efficiency and high achieving temperature.
3. Design of quasi-monochromatic thermal emitter

Two-dimensional microcavity on metal surface shows a spectrally selective thermal radiation originated from confined effect of electromagnetic wave called microcavity-effect as reported by Maruyama et al.\cite{Maruyama}. All researches on microcavity-effect have been conducted by open-end microcavity systems. In such case, it is revealed from the numerical simulation by RCWA shown in Fig. 4 (a) that the confined effect on electromagnetic field in open-end microcavity is not perfect due to the open-end correction effect. Consequently, a spectral emissivity peak contributed to open-end microcavity is broadened and shows weak enhancement as shown the black line in Fig. 5. In order to obtain quasi-monochromatic thermal radiation, we have to design the microcavity with high Q-value. Considering analogy of laser cavity system, the top of the microcavity is covered by semi-transparent metal film. We found from the numerical simulation that ultra-thin Au film (<10nm) is the most suitable in the point of view of Q-value. Figure 4 (b) shows the electric field distribution at the peak wavelength (1.85μm). Highly confined electric field in the closed-end microcavity is clearly observed in this figure. The intensity of the localized electric field on the closed-end microcavity is almost two times larger than that of the open-end microcavity. The confined effect is improved by ultra-thin Au top layer. The red solid line in Fig. 5 shows that the closed-end microcavity which has high peak intensity with narrow-band width, which is resulted from improvement of confined effect by ultra-thin Au thin film. The full-width at maximum-half (FWMH) is approximately 70 nm, which correspond Q-value is 26.4. This Q-value is 5 times larger than that of the conventional open-end microcavity.

These simulation results clearly show the high spectral selectivity on closed-end microcavity systems. The fabrication process of closed-end microcavity is under developing in our laboratory.

![Fig. The half size cross sectional view of electric field distribution (a) the microcavity with open-end and (b) the microcavity covered by semi-transparent metal film](image)

![Fig. The simulation result of the closed-end microcavity comparing to open-end microcavity.](image)
4. System design of high-efficiency Solar-TPV system using multi-layer selective emitters

Spectrally selective thermal radiation has been obtained by interference effect of multi-layer coating on metal or semiconductor substrates. We fabricated spectral selective emitters with multi-layer coating using YSZ film and W substrate, since YSZ has high melting point and high refractive index, and YSZ keeps fluorite crystal structure from ambient temperature up to 2000K in contrast with non-doped zirconia. The YSZ film is fabricated by pulsed laser deposition (PLD) method using an ArF excimer laser. During the deposition, the substrates were kept at 500 °C and the chamber pressure is fixed to 0.33Pa with argon gas. The clear cutoff of emissivity at the bandgap of PV cells is a key property for selective emitter. Using RCWA simulation, we have designed the thickness of YSZ on W substrates in order to tune the cutoff wavelength to the bandgap of GaSb PV cell. Figure 6 shows the spectral emittance of W coated single YSZ layer (thickness = 116nm). The emittance is estimated for reflectance spectra at room temperature by using Kirchhoff’s law. Their reflectance property was measured by Fourier transform infrared spectroscopy (FT-IR). The bandgap of GaSb PV cell is located at 1.67μm obtained spectrum shows sharp cutoff at the wavelength range.

![Fig. The reflectance of the emitter with multi-layer coating](image)

We designed a Solar-TPV system using the emitter. To avoid a heat loss from radiative heat loss from absorber/emitter surfaces, we adopt a planner type integrated selective absorber/emitter system shown in Fig. 7. In addition, the thermal radiation loss from absorber/emitter can be reduced by the Molybdenum (Mo) radiation shield. To suppress a heat conduction loss from Mo radiation shield, we use ceramic screw to hold Mo radiation shield. Furthermore, to reduce convection heat loss, the system is evacuated. The system efficiency is evaluated by following formulae. Required solar concentration is estimated from Eq. (4) in which the absorber/emitter temperature is assumed at 1500 K.

\[
C \int_0^\infty \varepsilon_{\text{absorber}}(\lambda) \cdot I_{\lambda, \text{Solar}}(\lambda) \, d\lambda = \int_0^\infty (\varepsilon_{\text{absorber}}(\lambda) + \varepsilon_{\text{emitter}}(\lambda)) \cdot I_{\lambda, 1500K}(\lambda) \, d\lambda
\]

(5.)

where \(C\) is concentration ratio, \(\varepsilon_{\text{absorber}}\) is spectral absorptance, \(\varepsilon_{\text{emitter}}\) is spectral emittance, \(I_{\lambda, \text{Solar}}\) is solar irradiance (AM1.5) and \(I_{\lambda, 1500K}\) is spectral emissive power at 1500K.

The converted electric power from emitter irradiance at 1500 K is given by;

\[
E_{\text{output}} = F \int_0^\infty \gamma_{\lambda}(\lambda) \cdot \varepsilon_{\text{emitter}}(\lambda) \cdot I_{\lambda, 1500K}(\lambda) \, d\lambda
\]

(6.)
where $F$ is view factor. In this system, it is set to 0.1. $\chi$ is the external quantum efficiency of a GaSb cell. By using the result from above equations, the system efficiency is given by:

$$\eta = \frac{E_{\text{output}}}{C \int_{\lambda} I_{\text{solar}}(\lambda) d\lambda}$$  \hspace{1cm} (7.)

It is estimated from the calculation that the concentration ratio is 175 sun is needed to obtain 1500K. In this condition, the expected electric power density is 2.9 W/cm$^2$. If whole emissive power from the emitters is received by PV cells, the estimated system efficiency is about 16.6%.

5. Conclusion

In this study, we mainly researched two topics; the design of the quasi-monochromatic thermal emitter based on microcavity effect and the design of the configuration of Solar-TPV system using multi-layer emitter based on W and YSZ. The estimated conversion efficiency of the TPV system is enlarged as decreasing the width of the peak because two main losses in the conversion process are minimized. The numerical simulations based on RCWA method indicate that the emissivity of open-end cavity shows a high narrow-band peaks attributed to confined mode of the microcavity. We evaluate the system efficiency considering the emitter temperature using the multi-layer emitter. It is expected that the system efficiency is about 16.6% if whole emissive power from the emitters is received by PV cells. This study will contribute to improve efficiency of a TPV system.

Acknowledgement

A part of this study is supported by JST, ALCA (Advanced Low Carbon Technology Research and Development Program).
References


