Performance analysis of solar thermophotovoltaic conversion enhanced by selective metamaterial absorbers and emitters

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ABSTRACT

By converting broadband sunlight into narrowband thermal radiation matched to the bandgap of thermophotovoltaic (TPV) cells, solar thermophotovoltaic (STPV) systems could potentially reach a high conversion efficiency far exceeding the Shockley-Queisser limit. However, actual STPV systems exhibit much lower efficiency due to non-idealities in solar absorbers, thermal emitters and TPV cells. In this work, the STPV system with selective metamaterial solar absorber and emitter is investigated, whose conversion efficiency is between 8% and 10% with concentration factor varying between 20 and 200. This conversion efficiency is remarkably enhanced compared with the conversion efficiency of less than 2.5% for the STPV system employing black absorbers and emitters. The sidewall emission losses from the absorber-emitter module and the non-unity view factor between the thermal emitter and TPV cell will diminish the performance of the STPV system, which are also quantitatively discussed in this work. Furthermore, the non-planar STPV systems with larger emitter-absorber area ratios are investigated, whose conversion efficiency can reach up to 12.6% under 200 suns when the emitter is four times as large as the absorber.

Keywords: Solar energy; thermophotovoltaic; metamaterial; selective absorption and emission; efficiency analysis.

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1. INTRODUCTION

Energy conversion by single-junction solar cells is constrained by the Shockley-Queisser limit [1], which limits the utilization of clean and abundant solar energy. Two of the main factors leading to this limitation are: photons with energy below the bandgap of solar cells cannot generate electron-hole pairs; photons with energy higher than the bandgap can at most generate one electron-hole pair in most cases, which results in the waste of excess energy above the bandgap. On the other hand, by converting broadband solar radiation into narrowband thermal emission with an intermediate absorber-emitter module, solar thermophotovoltaic (STPV) systems can potentially reach a much higher efficiency of 85% [2, 3]. In spite of the potentially high conversion efficiency, actual STPV devices exhibit much lower efficiency mainly due to the non-ideal spectral selectivity of solar absorbers and thermal emitters, in addition to other imperfections such as energy losses, the non-unity view factor between TPV emitter and cell, as well as low efficiency of TPV cells.

Recently, STPV systems have been studied both theoretically and experimentally, seeking for approaches to enhance the conversion efficiency. By modifying the radiative properties of the absorber-emitter module, energy conversion of STPV systems can be remarkably enhanced by a better match between the thermal radiation from the emitter and the bandgap of TPV cells. Nam *et al.* theoretically predicted a conversion efficiency up to 10% for an STPV device with tantalum (Ta) photonic crystals as absorber and emitter [4], while Lenert *et al.* experimentally demonstrated an efficiency of 3.2% for the STPV system consist of a carbon nanotube array as the solar absorber and 1D photonic crystals as the selective emitter [5]. The experimental conversion efficiency is further increased to 3.74% with 2D Ta photonic crystals as

the absorber and emitter [6], while a STPV device with further optimized Ta photonic crystals as the absorber and emitter whose measured efficiency exceeds 10% is reported [7].

Besides photonic crystals [8-11], selective absorption/emission for the absorber-emitter module can also be obtained with multilayer cavities [12-15], nanowire [16-18] and nanoparticle based structures [19, 20]. Recently, film-coupled metamaterials with selective radiative properties have been investigated. These metamaterials are usually in metal-dielectric-metal configurations, with different nanostructures on the top including 1D [21, 22] and 2D convex gratings [23, 24], concave gratings [25, 26], trapezoid gratings [27], pyramid [28], disk [29, 30] and crossbar arrays [31, 32]. Through the excitation of plasmonic resonances such as surface plasmon polariton (SPP) [33-35] and magnetic polariton (MP) [21, 36-38], spectrally selective radiative properties can be obtained in these metamaterials. Note that, the radiative properties can easily be modified by tuning the geometric parameters of the film-coupled structures, making it feasible to adjust the cutoff wavelengths of the absorber and emitter to fit with the applications in different STPV systems.

Previously, a broadband selective solar absorber [24, 39] and a TPV emitter made of film-coupled metamaterials [23] have been successfully designed, both of which exhibit high absorptance/emittance in the visible and near-infrared region and low emittance in the mid-infrared with angular-insensitive and polarization-independent behaviors. In this work, the metamaterial based selective absorber and TPV emitter are incorporated into an STPV system, whose conversion efficiency is analyzed systematically. In order to show the performance improvement of the STPV system utilizing metamaterials as the absorber and emitter, its photon-to-electricity conversion efficiency is compared with the STPV system employing a blackbody as the absorber and emitter. Further discussions are made on the effects of non-ideal factors such

as the energy loss through sidewall emission of the absorber-emitter module, as well as the non-unity view factor between the TPV emitter and cell. In order to further optimize the STPV system and improve the conversion efficiency, the effects of different emitter-absorber area ratios are also explored.

2. THEORETICAL BACKGROUND

Figure 1 shows the energy flow in an STPV system: the incident solar radiation is converted into heat by the solar absorber, with part of the energy dissipated through reflection and thermal re-emission; then the heated emitter generates thermal radiation towards the TPV cell, which generates electricity. Note that the temperature of the absorber and emitter is associated with their radiative properties and the incident solar flux. Neglecting the temperature difference between the absorber and emitter (i.e., $T_{\text{abs}} = T_{\text{emit}}$) as well as the conduction and convection losses, the energy balance at steady state for the absorber-emitter module yields:

$$A_{\text{abs}}(q_{\text{in}} - q_{\text{ref}} - q_{\text{re-emit}} - q_{\text{abs,side}}) = A_{\text{emit}}(q_{\text{E-PV}} + q_{\text{envi}}) \quad (1)$$

where A_{abs} and A_{emit} are respectively the top surface area of the solar absorber and the bottom surface area of the TPV emitter. q_{in} is the incident solar radiative heat flux, q_{ref} is the reflected solar radiative flux from the absorber, and $q_{\text{re-emit}}$ is the heat flux through thermal re-emission from the solar absorber surface. $q_{\text{abs,side}} = \sigma \varepsilon_{\text{abs,side}} (T_{\text{abs}}^4 - T_{\text{bg}}^4) A_{\text{abs,side}} / A_{\text{abs}}$ represents the thermal emission loss from the sidewall of the solar absorber normalized to the absorber's top surface area, where σ is the Stefan-Boltzmann constant, $\varepsilon_{\text{abs,side}}$ is the emittance of the absorber sidewall, and $A_{\text{abs,side}}$ is the sidewall surface area for the absorber. On the other hand, q_{envi} represents the radiative energy flux from the TPV emitter to the environment (from top, bottom and sidewall

surfaces) normalized to its bottom surface area, and $q_{\text{E-PV}}$ is the radiative heat flux from the emitter to the TPV cell. Assuming that the radiative properties for the absorber and emitter are independent of direction (i.e., diffuse surfaces), q_{ref} , $q_{\text{re-emit}}$, $q_{\text{E-PV}}$, and q_{envi} can be respectively calculated by:

$$q_{\text{ref}} = \int_{0.3\mu\text{m}}^{4\mu\text{m}} [1 - \alpha_{\text{abs}}(\lambda)] G_{\text{AM1.5}}(\lambda) d\lambda \quad (2)$$

$$q_{\text{re-emit}} = \int_{1\mu\text{m}}^{20\mu\text{m}} \varepsilon_{\text{abs}}(\lambda) [E_{\text{bb}}(\lambda, T_{\text{abs}}) - E_{\text{bb}}(\lambda, T_{\text{bg}})] d\lambda \quad (3)$$

$$q_{\text{E-PV}} = \int_{1\mu\text{m}}^{20\mu\text{m}} q_{\lambda, \text{E-PV}} d\lambda = \int_{1\mu\text{m}}^{20\mu\text{m}} \frac{[E_{\text{bb}}(\lambda, T_{\text{emit}}) - E_{\text{bb}}(\lambda, T_{\text{cell}})]}{R_{\text{emit, cell}}} d\lambda \quad (4)$$

$$q_{\text{envi}} = q_{\text{emit, bottom}} + q_{\text{emit, side}} + q_{\text{emit, top}} \quad (5)$$

In Eqs. (2-4), $\alpha_{\text{abs}}(\lambda)$ and $\varepsilon_{\text{abs}}(\lambda)$ are respectively the spectral absorptance and emittance of the absorber which are identical according to Kirchhoff's law, $G_{\text{AM1.5}}$ represents the solar radiative heat flux at air mass 1.5 (AM1.5) [40], $E_{\text{bb}}(\lambda, T)$ is the spectral blackbody emissive power at the temperature of T , T_{abs} is the absorber temperature, T_{bg} is the background temperature (considered as 20 °C), T_{emit} is temperature of the emitter, and T_{cell} is the cell temperature (considered as 20

°C). $R_{\text{emit, cell}} = \frac{1 - \varepsilon_{\text{emit}}(\lambda)}{\varepsilon_{\text{emit}}(\lambda)} + \frac{1}{F} + \frac{1 - \varepsilon_{\text{cell}}(\lambda)}{\varepsilon_{\text{cell}}(\lambda)}$ is the radiative resistance between the TPV emitter

and cell, where $\varepsilon_{\text{emit}}(\lambda)$ is the spectral emittance of the emitter, $\varepsilon_{\text{cell}}$ is the emittance of the InGaAsSb TPV cell, and F is the view factor between the TPV emitter and cell. Assuming that the emitter and TPV cell are both square-shaped with the same length of L and separated by a distance d , the view factor F can be calculated as [41]:

$$F = \frac{1}{\pi r^2} \left(\ln \frac{x^4}{1+2r^2} + 4ry \right) \quad (6)$$

where $r = L/d$, $x = \sqrt{1+r^2}$, and $y = x \tan^{-1}\left(\frac{r}{x}\right) - \tan^{-1}(r)$.

In Eq. 5, q_{envi} which represents the energy flux lost to the environment consists of three modes. The first term $q_{\text{emit,bottom}} = \int_{1\mu\text{m}}^{20\mu\text{m}} (E_{\text{bb}}(\lambda, T_{\text{emit}}) - E_{\text{bb}}(\lambda, T_{\text{bg}})) d\lambda / R_{\text{emit,bottom}}$ is the radiative heat flux from the TPV emitter to the environment due to the non-unity view factor between the emitter and cell. $R_{\text{emit,bottom}} = \frac{1 - \varepsilon_{\text{emit}}(\lambda)}{\varepsilon_{\text{emit}}(\lambda)} + \frac{1}{1-F}$ represents the radiative resistance between the TPV emitter and background environment from the bottom side of the TPV emitter. The second term $q_{\text{emit,side}} = \sigma \varepsilon_{\text{emit,side}} (T_{\text{emit}}^4 - T_{\text{bg}}^4) A_{\text{emit,side}} / A_{\text{emit}}$ is the radiative heat flux through the sidewall of the emitter normalized to the bottom surface area of the emitter, in which $\varepsilon_{\text{emit,side}}$ and $A_{\text{emit,side}}$ are respectively the emittance and surface area of the emitter sidewall. The third term $q_{\text{emit,top}} = \sigma \varepsilon_{\text{emit,top}} (T_{\text{emit}}^4 - T_{\text{bg}}^4) A_{\text{emit,top}} / A_{\text{emit}}$ accounts for the radiative heat flux from the top of the TPV emitter while the absorber area is smaller than the emitter area. $\varepsilon_{\text{emit,top}}$ is the thermal emittance for the top surface of the TPV emitter, and $A_{\text{emit,top}}$ is the area for the top surface of the emitter which is not covered by the absorber. Note that the integration range for the thermal radiative power is from 1 μm to 20 μm in wavelength due to the limited data for the radiative properties of the absorber and emitter, while the considered spectral range contains 98.5% of the thermal radiative energy for a blackbody at temperature of 1000 K. On the other hand, the spectral integration for solar radiation is from 0.3 μm to 4 μm in wavelength due to the limited AM1.5 data, which covers around 96% of solar energy.

The total solar-to-electricity conversion efficiency for an STPV system is obtained by dividing the generated electrical power density by the total incident solar flux, which can be decomposed into three sub-efficiencies by:

$$\eta_{\text{TPV}} = \eta_{\text{abs}} \cdot \eta_{\text{emit}} \cdot \eta_{\text{cell}} \quad (7)$$

In Eq. 7, $\eta_{\text{abs}} = (q_{\text{in}} - q_{\text{ref}} - q_{\text{re-emit}} - q_{\text{abs,side}}) / q_{\text{in}}$ is the absorber efficiency, which is defined as the ratio of the energy flux converted to heat by the absorber divided by the total incident solar radiative heat flux. $\eta_{\text{emit}} = q_{\text{E-PV, E} \geq E_g} / (q_{\text{E-PV}} + q_{\text{envi}})$ is the emitter efficiency defined as the percentage of useful thermal radiative energy from the emitter which is collected by the TPV cell, where $q_{\text{E-PV, E} \geq E_g}$ represents the radiative heat flux collected by the TPV cell with photon energy above its bandgap. $\eta_{\text{cell}} = P_e / q_{\text{E-PV, E} \geq E_g}$ is the TPV cell efficiency characterized as the ratio of the generated electricity power density divided by the useful radiative heat flux collected by the TPV cell, where P_e is the electricity power density generated by the TPV cell.

The TPV cell employed in this work is made of InGaAsSb with a bandgap of 0.54 eV (equivalently 2.3 μm in wavelength) [42]. The generated power density P_e can be calculated by:

$$P_e = V_{\text{oc}} I_{\text{sc}} FF \quad (8)$$

where V_{oc} and FF are respectively the open-circuit voltage and filling factor of the TPV cell obtained from Ref. [42]. I_{sc} is the short-circuit density calculated by:

$$I_{\text{sc}} = \int_{1\mu\text{m}}^{2.3\mu\text{m}} \frac{e\lambda}{hc} \eta_i(\lambda) q_{\lambda, \text{E-PV}} d\lambda \quad (9)$$

where e is the elementary electric charge, $\eta_i(\lambda)$ is the internal quantum efficiency (IQE) of the TPV cell [42], h is Planck's constant, c is the speed of light in vacuum, and $q_{\lambda, \text{E-PV}}$ is the spectral

radiative heat flux between the TPV emitter and cell which can be obtained from Eq. 4. Note that the integration range is from 1 μm to 2.3 μm , which covers the wavelength range in which the TPV cell has non-zero quantum efficiency.

3. RESULTS AND DISCUSSION

3.1. Efficiency Analysis for STPV systems with Ideal Selective Absorbers and TPV Emitters

3.1.1. Spectral absorptance/emittance of ideal selective solar absorbers and TPV emitters. Figure 2(a) shows the spectral distribution of solar radiative heat flux at AM 1.5, as well as the thermal radiative heat flux from a blackbody at different temperatures. It can be observed that at the temperature of 400 $^{\circ}\text{C}$, the intensity of thermal emission is comparable to the incident solar radiation. It is also found that most of the energy from solar radiation is distributed in visible and near infrared regime, while most of the energy from thermal emission is in the mid-infrared range according to Wien's displacement law. In order to maximize the efficiency of solar absorbers, it is crucially important to increase the absorbed solar radiation and reduce the energy loss from thermal re-emission, which can be realized by modifying the radiative properties of the solar absorbers. Figure 2(b) shows the absorptance for an ideal absorber, which exhibits unity absorptance below cutoff wavelength $\lambda_{\text{c,abs}}$ to maximize the absorbed solar radiation, and zero emittance beyond cutoff wavelength to minimize the thermal re-emission. Note that, the efficiency of an ideal absorber is a function of $\lambda_{\text{c,abs}}$, and the optimal $\lambda_{\text{c,abs}}$ varies with changed incident solar concentrations.

The emittance for an ideal TPV emitter is plotted in Fig. 2(c), which is unity in the wavelength range between $\lambda_{\text{c,emit}}^{\text{s}}$ and $\lambda_{\text{c,emit}}^{\text{l}}$, and zero outside this spectral regime. The purpose for this narrowband emitter is to avoid the wasted photons below the bandgap, which cannot

generate electron-hole pairs, as well as to reduce the wasted excess energy above the bandgap. Since the value of $\lambda_{c,emit}^1$ is fixed at 2.3 μm which is the band edge of the InGaAsSb cell, the value of $\lambda_{c,emit}^s$ determines the performance of the TPV emitter. Similar to $\lambda_{c,abs}$, the value of $\lambda_{c,emit}^s$ needs to be optimized to maximize the STPV conversion efficiency. A great amount of the excess photon energy above bandgap of the TPV cell will be wasted if $\lambda_{c,emit}^s$ is too small (i.e., broad emission band), while the temperature of the absorber will dramatically increase if $\lambda_{c,emit}^s$ is too close to $\lambda_{c,emit}^1$ (with a narrow emission band), which will in turn increase the thermal re-emission loss and diminish the performance of the solar absorber.

3.1.2. Efficiency analysis for STPV systems with ideal absorbers/emitters under 50 suns.

In order to investigate the effect of $\lambda_{c,abs}$ and $\lambda_{c,emit}^s$ on the performance of the STPV system, parameter sweeps are performed for $\lambda_{c,abs}$ and $\lambda_{c,emit}^s$ with a fixed concentration factor of 50. Note that in the analysis here, the energy loss due to sidewall emission from the absorber-emitter module ($q_{abs,side}$ and $q_{emit,side}$) is neglected, as well as the energy loss due to non-unity view factor between the TPV emitter and cell ($q_{emit,bottom}$). These non-ideal factors will be discussed later. Also, the STPV systems with the same absorber and emitter area are discussed first, while the non-planar configuration with a smaller absorber and bigger emitter will be considered in section 3.2.4.

The absorber/emitter temperature is plotted as a function of cutoff wavelengths in Fig. 3(a), in which brighter color represents higher temperature. Note that the absorber temperature is obtained by analyzing the energy balance defined in Eq. 1, and it is strongly correlated with the

concentration factor for the incident solar radiation. It can be observed that as $\lambda_{c,emit}^s$ increases, the absorber temperature increases up to higher than 1600 K. This is because the emission band becomes narrower as $\lambda_{c,emit}^s$ increases, which will increase the absorber/emitter temperature due to weaker heat dissipation from the emitter. Note that in practice, the absorber temperature is limited by the melting point of the materials used for the absorber and emitter.

Figure 3(b) shows the absorber efficiency as a function of $\lambda_{c,abs}$ and $\lambda_{c,emit}^s$. It can be found that the absorber efficiency is maximized when $\lambda_{c,abs}$ is around 1.2 μm , in which case most incident solar radiation can be absorbed and little energy is dissipated through thermal radiation. It can also be observed that the absorber efficiency decreases as $\lambda_{c,emit}^s$ increases, which is the result of an increased absorber temperature caused by the narrower emission band. It is easy to understand that the absorber efficiency will drop when the thermal re-emission loss increases due to raised absorber temperature. Note that the emitter efficiency is 100% regardless of the values of $\lambda_{c,abs}$ and $\lambda_{c,emit}^s$, which is because the emittance for an ideal emitter is zero below the bandgap of TPV cell. Therefore, without considering the radiative energy lost to the environment through the sidewall and bottom surface of the emitter, the fraction of useful photon energy above the bandgap of TPV cell is always 100%.

Figure 3(c) shows the TPV cell efficiency as a function of cutoff wavelengths. It can be observed that the cell efficiency increases as $\lambda_{c,emit}^s$ increases (i.e. narrower emission band). This is because photons with energy higher than the bandgap of TPV cell can at most generate one electron-hole pair in most cases, and the excess energy exceeding the bandgap is wasted. Therefore, in order to maximize the TPV cell efficiency, it is ideal to have an emitter with an extremely narrow emission band right above the bandgap of the TPV cell. However, this will

increase the absorber temperature and diminish the performance of the STPV absorber as indicated in Fig. 3(b). Therefore, there exists a trade-off between the absorber efficiency and TPV cell efficiency associated with the width of the emitter's emission band. After all, it is the total efficiency for the STPV system that matters. Figure 3(d) plots the total conversion efficiency for the STPV system as a function of $\lambda_{c,abs}$ and $\lambda_{c,emit}^s$. It can be found that the maximum total efficiency of 20% occurs when $\lambda_{c,abs}$ and $\lambda_{c,emit}^s$ are respectively around 1.1 μm and 1.5 μm . Note that these optimal cutoff wavelengths are only valid under 50 suns, and they will vary with different concentration factors.

The performance of the STPV system with ideal absorbers and emitters is further investigated under varied incident solar concentration factors. Note that the cutoff wavelengths of ideal absorber and emitter are optimized to achieve maximum total conversion efficiency for a given concentration factor. Figure 4(a) shows the absorber temperature as a function of the incident concentration factor, which shows that the absorber temperature increases from 1230 K to 1700 K when the concentration factor increases from 20 to 200. Figure 4(b) plots the absorber, emitter, cell and total efficiency as a function of the absorber temperature. It can be observed that the absorber efficiency decreases with increased absorber temperature. This is because when the absorber temperature increases, the peak for thermal radiative intensity will shift to shorter wavelengths (Wien's displacement law), where the emittance for the absorber is high. Therefore, the radiation loss becomes stronger which leads to a lower absorber efficiency. The emitter efficiency is 100% as the emittance is zero below the bandgap of TPV cell for ideal emitters, with the assumption that the energy losses from sidewall and non-unity emitter-cell view factor are neglected. The cell efficiency decreases with increased emitter temperature, which will be discussed in detail later. In sum, the total efficiency for the STPV system with ideal surfaces

decreases from 22.6% to 11.1% when the absorber temperature increases from 1230 K to 1700 K.

3.2. Film-coupled 2D tungsten grating metamaterials as selective absorber/emitter

3.2.1. Radiative properties of film-coupled metamaterial selective absorber/emitter. In the previous section, the performance of the STPV systems with ideal absorbers and emitters is investigated. However, in actual STPV systems, the absorber and emitter have neither ideal cutoff wavelengths nor perfect (unity or zero) spectral absorptance/emittance. Here, we consider to employ film-coupled metamaterial absorbers and emitters, whose radiative properties exhibit strongly spectral selectivity and diffuse behaviors from our previous theoretical [23, 24] and experimental studies [39] to enhance the STPV performance. Figure 5(a) depicts the schematic for the metamaterial absorber and emitter, which are film-coupled structures with tungsten grating and substrate separated by a SiO_2 spacer. The geometric parameters are different for the absorber and emitter with different cutoff wavelengths. The absorber has single sized grating on the top (i.e., $w_1 = w_2 = 0.2 \mu\text{m}$), with grating period $\Lambda/2 = 0.4 \mu\text{m}$, grating height $h' = 100 \text{ nm}$, and spacer thickness $t = 60 \text{ nm}$. On the other hand, the emitter is made of double sized grating with $w_1 = 0.3 \mu\text{m}$, $w_2 = 0.4 \mu\text{m}$, $\Lambda = 1.6 \mu\text{m}$, $h' = 200 \text{ nm}$, and spacer thickness $t = 60 \text{ nm}$. Note that the radiative properties for the metamaterial absorber and emitter are highly dependent on the geometric parameters and can be tuned for different applications.

The spectral normal absorptance/emittance obtained from finite-difference time-domain (FDTD) simulations for the metamaterial absorber and emitter is plotted in Fig. 5(b), with the wavelength in logarithm scale. It can be observed that the metamaterial absorber exhibits high absorptance from 0.3 to 1.5 μm , and low emittance beyond 1.5 μm . On the other hand, the

emitter has a high emittance between 0.8 and 2.2 μm , and low emittance down to 4% in the mid-infrared. The spectral selectivity of the radiative properties of metamaterial absorber and emitter is due to the phenomenon of Wood's Anomaly, as well as the excitation of surface plasmon polariton (SPP) and magnetic polariton (MP), which have been thoroughly studied in Ref. [24]. Note that even though the cutoff wavelengths for the solar absorber and TPV emitter can be tuned by changing the geometric parameters, the tunability is still limited and the radiative properties for the actual absorber and emitter cannot be modified to be exactly the same as ideal ones. Though the spectral-normal radiative properties are shown here, our previous studies have demonstrated the diffuse-like behaviors of these film-coupled metamaterials [23, 24, 39].

3.2.2. Efficiency for the STPV system with metamaterial selective absorbers/emitters.

With the radiative properties obtained for the metamaterial absorber and emitter, the performance of the STPV system utilizing metamaterial absorber and emitter can be analyzed. Figure 6(a) shows the absorber/emitter temperature under different solar concentrations, for the STPV systems with ideal, metamaterial and black surfaces as absorber and emitter. It is observed that for the STPV system with metamaterial surfaces, the absorber temperature increases from around 1000 K to 1500 K when concentration factor ranges from 20 to 200. Through comparison, it is found that the absorber temperature for the STPV system with ideal surfaces is the highest, while the STPV system with black surfaces exhibits the lowest absorber temperature. This is because the total emittance for an ideal emitter is very low due to its narrow emission band, which leads to a higher absorber/emitter temperature due to a weaker heat dissipation through thermal radiation from the emitter. On the contrary, since the total emittance for the black emitter is as high as unity, the temperature of black absorber/emitter will be the lowest.

Figure 6(b) shows the absorber efficiency as a function of concentration factor for STPV

systems with ideal, metamaterial and black absorber/emitter. It is observed that for the STPV system with metamaterial surfaces, the absorber efficiency drops from 58% to 53% when concentration factor varies from 20 to 200. The decreased absorber efficiency with increased concentration factor is mainly because the peak of thermal radiative intensity shifts to shorter wavelength when the absorber temperature is increased with higher concentration factors. Therefore, the total thermal emittance for the solar absorber will be higher as its spectral emittance is higher in shorter wavelengths, which leads to a higher thermal re-emission loss and a lower absorber efficiency. The same trend is also observed for the STPV system with ideal surfaces, whose absorber efficiency is about 20% higher than the STPV system with metamaterial surfaces. On the other hand, the absorber efficiency of the STPV system with black surfaces barely changes with concentration factor, as the total emittance for the black absorber remains as unity regardless of its temperature. As a result of spectral selectivity, the STPV system with metamaterial surfaces exhibits an absorber efficiency which is at least 10% higher than that with black surfaces.

Figure 6(c) shows the emitter efficiency as a function of the concentration factor. As explained previously, the emitter efficiency remains as 100% for STPV systems with ideal emitter. On the other hand, the emitter efficiencies for STPV systems with metamaterial and black emitters are below 100% due to the wasted emission below the bandgap of TPV cell. It is observed that the emitter efficiency increases from 58% to 80% for the STPV system with metamaterial surfaces, as the concentration factor increases from 20 to 200. This is because the emitter temperature increases with increased incident solar concentration, which shifts the peak for radiative intensity to shorter wavelength and decreases the percentage of emitted photons with energy below the bandgap of the TPV cell. By comparison, the STPV system with black

emitter exhibits much poorer emitter efficiency due to its non-selective thermal emittance, and a large amount of energy is wasted on photons with energy below the bandgap of the TPV cell.

Figure 6(d) indicates the cell efficiency for the STPV systems with different absorber/emitter surfaces under varied solar concentration. It can be observed that the cell efficiency of the STPV system with ideal surfaces decreases with increased incident solar concentration, while the STPV system with black surfaces exhibits opposite trend. On the other hand, the trend for cell efficiency of the STPV system with metamaterial absorber and emitter is not monotonic, which increases first but starts to decrease at concentration factor around 40. The different trends originate from different absorber/emitter temperatures for the three STPV systems. The cell efficiency reaches maximum when most photons emitted from the emitter have photon energy right above the cell bandgap, in which case little energy is wasted on photons with energy either lower or much higher than the bandgap of the TPV cell. For the STPV system with metamaterial surfaces, the cell efficiency reaches maximum with a concentration factor of around 40, which corresponds to an emitter temperature of 1200 K. Based on Wien's displacement law, the peak for thermal radiative intensity is at $2.4\ \mu\text{m}$ with temperature of 1200 K, which is close to the bandgap of the TPV cell. Therefore, the maximum cell efficiency is obtained with a concentration factor of around 40 for the STPV system with metamaterial surfaces, when most of the photon energy is right above the bandgap of TPV cell. On the other hand, the emitter temperature is higher for the STPV system with ideal surfaces, and the emitter temperature reaches 1200 K at a concentration factor smaller than 20. Therefore, the peak of radiative intensity is shifting away from the bandgap to shorter wavelengths when the concentration factor increases from 20 to 200. As a result, the cell efficiency decreases with increased solar concentration. In contrast, for the STPV system with black surfaces which

exhibits a lower emitter temperature, the peak for thermal radiative intensity is shifting towards the bandgap of TPV cell from longer wavelength when the concentration factor increases from 20 to 200. Therefore, the cell efficiency increases with increased solar concentration for the STPV system with black surfaces.

Figure 6(e) shows the total efficiency for the STPV systems with ideal, metamaterial and black surfaces. It can be observed that the total conversion efficiency for the STPV system with metamaterial absorber and emitter varies from 8% to 10% with different solar concentrations, which is greatly enhanced compared with the efficiency of less than 2.5% for the STPV system with black absorber and emitter. However, it is still lower than the STPV system with ideal absorber and emitter, which varies from 11% to 23% with different incident solar concentrations.

3.2.3 Effects of energy loss due to sidewall emission and non-unity view factor. The discussions in previous sections consider the ideal cases that there are no energy losses through sidewall emission from the absorber ($q_{\text{abs,side}} = 0$) and emitter ($q_{\text{emit,side}} = 0$), and that the view factor between the TPV emitter and cell is unity ($q_{\text{emit,bottom}} = 0$). However, these two non-ideal factors have to be considered in practical applications. Figure 7(a) shows the total conversion efficiency with different ratios of t_{wall}/L for the STPV system with metamaterial absorber and emitter. Note that t_{wall} is the total sidewall thickness for the absorber-emitter module which will affect both the $q_{\text{abs,side}}$ and $q_{\text{emit,side}}$, while L is the length for the STPV absorber and emitter ($L_{\text{abs}} = L_{\text{emit}} = L$). The emittance of the sidewall for both the absorber and emitter is taken as 0.05 (the sidewall is assumed to be diffuse and gray) considering that the sidewall is covered by weakly emitting materials (metal). Due to the energy loss through sidewall emission, the STPV system shows diminished performance with thicker sidewall, with a maximum total efficiency of 10.1%,

9.7%, 8.4% and 7.1% when the t_{wall}/L ratio is respectively 0, 0.1, 0.5 and 1. Figure 7(b) shows the effect of the distance d between the TPV emitter and cell, in which the d/L ratio affects $q_{\text{emit,bottom}}$ by changing the view factor between the TPV emitter and cell. It can be found that the maximum total efficiency for the STPV system decreases from 10.1% to 2.2% when the value of the d/L ratio is increased from 0 to 1, indicating a substantial energy loss due to a decreased view factor between the TPV emitter and cell. As a conclusion, it is crucial to fabricated ultrathin solar absorber and TPV emitter, as well as to keep a small distance between the TPV emitter and cell for a large view factor.

3.2.4. Effect of emitter-absorber area ratio. Previous sections analyzed the efficiency of STPV systems with simple planar layout (i.e. same emitter and absorber surface areas), while a different emitter-absorber area ratio ($A_{\text{emit}}/A_{\text{abs}}$) with the solar radiation concentrated to a smaller absorber would also affect the photon transport and power generation. Note that when the absorber and emitter have different surface areas, the $q_{\text{emit,top}}$ in Eq. 5 will not be zero, which is different from the STPV system with planar layout. The emittance for the top surface of the emitter is considered as 0.05, which is the same as the sidewall. Figure 8(a) shows the absorber/emitter temperature for the metamaterial based STPV system with different $A_{\text{emit}}/A_{\text{abs}}$ ratios. Note that in this case the sidewall emission loss is neglected, and the view factor between the TPV emitter and cell is considered as 1. It can be found that a larger $A_{\text{emit}}/A_{\text{abs}}$ ratio results in a lower absorber temperature. This is because with a larger $A_{\text{emit}}/A_{\text{abs}}$ ratio, the absorber-emitter module is absorbing less solar radiation and emitting more thermal radiation, which leads to a lower absorber temperature.

Figure 8(b) shows the absorber efficiency for the metamaterial based STPV system with different $A_{\text{emit}}/A_{\text{abs}}$ ratios. It can be observed that the absorber efficiency increases from around

55% to 85% as the $A_{\text{emit}}/A_{\text{abs}}$ ratio varies from 1 to 8. This is because the energy loss through thermal self-emission is greatly reduced when the absorber temperature is decreased with a larger $A_{\text{emit}}/A_{\text{abs}}$ ratio.

Figure 8(c) plots the emitter efficiency with different $A_{\text{emit}}/A_{\text{abs}}$ ratios. In contrary to the effect of $A_{\text{emit}}/A_{\text{abs}}$ ratio on the absorber efficiency, the emitter efficiency decreases with increased $A_{\text{emit}}/A_{\text{abs}}$ ratio. This is caused by two main reasons: 1. There will be more radiative energy loss from the top of the emitter when the $A_{\text{emit}}/A_{\text{abs}}$ ratio becomes larger; 2. When the emitter temperature decreases with larger $A_{\text{emit}}/A_{\text{abs}}$ ratio, the emitter will radiate more photons with energy below the bandgap of the TPV cell, which leads to a lower percentage of useful photon energy (i.e. emitter efficiency).

Figure 8(d) shows that the cell efficiency is not substantially different with varied $A_{\text{emit}}/A_{\text{abs}}$ ratio. It can be also observed that the cell efficiency reaches maximum at lower concentration factor for smaller $A_{\text{emit}}/A_{\text{abs}}$ ratios, while the maximum cell efficiency is acquired at higher concentration factor for larger $A_{\text{emit}}/A_{\text{abs}}$ ratios. This is also related with different emitter temperature when the $A_{\text{emit}}/A_{\text{abs}}$ ratio is varied. As discussed in section 3.2.2, the cell efficiency reaches maximum when the emitter temperature is around 1200 K. For STPV systems with larger $A_{\text{emit}}/A_{\text{abs}}$ ratios, the emitter temperature is lower and reaches 1200 K at higher concentration factors; while for STPV systems with smaller $A_{\text{emit}}/A_{\text{abs}}$ ratios, the emitter temperature is higher and reaches 1200 K at lower concentration factors. Therefore, the maximum cell efficiency for the STPV systems with larger $A_{\text{emit}}/A_{\text{abs}}$ ratios reaches maximum at a higher concentration.

As discussed in this section, the $A_{\text{emit}}/A_{\text{abs}}$ ratio has different effects on the absorber, emitter and cell efficiency of the STPV system. Therefore, the total efficiency for the STPV

system will not simply increase or decrease with increased $A_{\text{emit}}/A_{\text{abs}}$ ratio. Instead, an optimized $A_{\text{emit}}/A_{\text{abs}}$ ratio exists for maximum total efficiency. Figure 8(e) shows that the STPV systems with $A_{\text{emit}}/A_{\text{abs}}$ ratios of 2 or 4 exhibit maximum total efficiency for most concentration factors. The total system efficiency can reach a maximum of 12.6% under 200 suns with an $A_{\text{emit}}/A_{\text{abs}}$ ratio of 4. Although a larger $A_{\text{emit}}/A_{\text{abs}}$ ratio leads to a higher system efficiency at most incident concentration factors, a smaller absorber area will lead to a decreased total power output density from the TPV cell due to the decreased power input onto a smaller absorber area. Figure 8(f) shows the output power density from the TPV cell for different $A_{\text{emit}}/A_{\text{abs}}$ ratios, which indicates that a larger $A_{\text{emit}}/A_{\text{abs}}$ ratio achieves a higher system efficiency at the cost of a lower output power density.

4. CONCLUSION

This work investigates an STPV system employing film-coupled metamaterial as the solar absorber and TPV emitter, whose conversion efficiency ranges from 8% to 10% with concentration factor varying between 20 and 200. Due to the spectral selectivity of metamaterials, the conversion efficiency of the STPV system with metamaterial absorber/emitter is remarkably enhanced when compared with the efficiency of the STPV system with black absorber and emitter (< 2.5%). Furthermore, the effects of sidewall emission loss and non-ideal view factor between the TPV emitter and cell are also investigated, and the diminished performance of the STPV system due to these two non-ideal factors is quantitatively discussed. Moreover, the STPV system with emitter-absorber area ratio larger than 1 is also studied, and it is demonstrated that the total conversion efficiency can be further enhanced with larger emitter-absorber area ratios. It is found that the STPV system with an emitter-absorber area ratio of 4 can further reach to a total

conversion efficiency of 12.6% under 200 suns. This work will facilitate the development of high-efficiency STPV systems with novel metamaterials for solar energy conversion.

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NOMENCLATURE

A	area, m ²
c	speed of light in vacuum, m/s
d	distance between TPV emitter and cell, m
E	Emissive heat flux, W/m ²
e	elementary charge, C
F	view factor
FF	filling factor for TPV cells
G	solar radiative heat flux, W/m ²
h	Planck's constant, J·s
h'	grating height, m
L	length, m
I_{sc}	short circuit current density, A/m ²
P_e	generated electric power density from TPV cell, W/m ²
q	radiative heat flux, W/m ²
R	radiative resistance between surfaces
r	L/d
T	temperature, K
t	thickness, m
V_{oc}	open circuit voltage, V
w	width of grating, m
x	$\sqrt{1+r^2}$

$$y = x \arctan \frac{r}{x} - \arctan r$$

Greek Symbols

α	absorptance
ε	emittance
η	conversion efficiency
η_i	internal quantum efficiency
Λ	grating period, m
λ	wavelength, m
λ_c	cutoff wavelength, m
σ	Stefan-Boltzmann constant, W/(m ² ·K ⁴)

Subscripts

1, 2	grating 1 or grating 2
AM1.5	air mass 1.5
abs	absorber
bb	blackbody
bg	environmental background
bottom	bottom side
cell	TPV cell
envi	environment
E-PV	from emitter to TPV cell
$E \geq E_g$	with photon energy above bandgap of TPV cell
emit	emitter
in	incident
re-emit	from thermal re-emission
ref	reflected
side	sidewall of absorber and emitter
TPV	TPV system
top	top side
wall	sidewall of absorber/emitter

Superscripts

l	longer cutoff wavelength
s	shorter cutoff wavelength

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FIGURE CAPTIONS:

- Fig. 1 The schematic and energy flow for an STPV system.
- Fig. 2 (a) Spectral distribution for radiative heat flux of solar and thermal radiation; (b) Spectral absorptance for an ideal solar absorber; (c) Spectral emittance for an ideal TPV emitter.
- Fig. 3 (a) Absorber temperature; (b) Absorber efficiency; (c) Cell efficiency; and (d) Total efficiency for the STPV system with varied cutoff wavelengths for absorber and emitter under 50 suns.
- Fig. 4 (a) Absorber/emitter temperature in an STPV system with ideal absorber and emitter; (b) Conversion efficiency as a function of absorber temperature in an STPV system with ideal absorber and emitter.
- Fig. 5 (a) Structure schematic for the metamaterial selective absorber and emitter; (b) Spectral **normal** absorptance/emittance for the metamaterial absorber and emitter.
- Fig. 6 (a) Absorber temperature; (b) Absorber efficiency; (c) Emitter efficiency; (d) Cell efficiency; and (e) Total efficiency for the STPV systems with metamaterial, ideal and black absorber/emitter.
- Fig. 7 (a) Effects of sidewall emission loss; (b) Effects of non-unity view factor between the TPV emitter and cell on the conversion efficiency of the STPV system.
- Fig. 8 (a) Absorber temperature; (b) Absorber efficiency; (c) Emitter efficiency; (d) Cell efficiency; (e) Total efficiency; and (f) **Output power density from the TPV cell** for the STPV system with metamaterial absorber and emitter with different emitter-absorber area ratios.

Wang et al, Fig. 1

Wang et al, Fig. 2

Wang et al, Fig. 3

Wang et al, Fig. 4

(a)

(b)

Wang et al, Fig. 5

Wang et al, Fig. 6

Wang et al, Fig. 7

Wang et al, Fig. 8