Metamaterial and metasurface based emitters for solar thermal photovoltaic applications: analytical review

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ABSTRACT

The motivation behind this paper stemmed from the fact that the world consumes the fast-depleting fossil fuel energy. Before the fossil fuel runs out, new technologies to harvest energy from alternative sources are needed. Sunlight is clean, free and abundant. The market for solar thermal and photovoltaic electricity generation is expanding rapidly. Therefore, an analytical review on the types of emitter for solar thermal photovoltaic (STPV) applications utilizing metamaterials and metasurfaces is presented in this research study. STPV is still important in the development of an emitter technology. STPV classifications based on the types of materials, compositions, dimensions, geometries, and long-term temperature stability are considered. The ability to engineer STPV by controlling one or more of the foregoing physical parameters are useful for researchers. Different types of design and simulation tools are considered. The near future plans are to optimize the efficiency of the emitter and investigate how various layers and different combinations of metamaterials affect such an efficiency by employing a simulation tool such as finite-difference time-domain (FDTD, Lumerical).

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1. INTRODUCTION

About 80% of the world's electric power consumption is supplied by the fast-depleting fossil fuels, simultaneously, the global demand for power consumption continues to increase. Generally speaking, in renewable power generation, solar photovoltaic (PV), which is a clean and green energy type of technology plays a vital role to fulfill the power shortage [1]-[3]. However, the upper most theoretical limit (*detailed balance limit*) of the efficiency of *p-n* junction solar energy converters is still limited by non-radiative recombination mechanism of electron-hole pairs (EHP) at the bandgap energy levels [4]-[7]. Theferore, efficient solar energy harvesting technologies need to be developed. One way of mitigating the global warming and climate change effects is through the development of hybrid solar energy systems [8]-[18]. Hybrid photovoltaic/thermal (PVT) collector systems integration has been investigated in the past decades. A possible hybrid solar/fuel thermophotovoltaic unit has an additional advantage: the fuel-fired part of the hybrid system would permit night-time operations [8], [19]-[23]. Futher, within the metamaterial paradigm, it becomes possible to vary the material designs by engineering “meta-atoms” as constitutive elements for artificial materials using the naturally available materials. As long as the meta-atom sizes remain sufficiently small at the wavelength scale of interest, the macroscopic description of electromagnetic (EM) properties of matter can be applied to metamaterials, which are made of meta-atoms. This is analogous to the case if the aforementioned macroscopic description is applied to naturally occurring materials formed by atoms or molecules [24]-[27].

Thermophotovoltaics (TPV) refers to a thermal to electrical power conversion, which is based on photovoltaic effect. The basic feature of solar (STPV) is based on the principle that a high temperature emitter is employed as an intermediate element that absorbs concentrated solar light and emits thermal radiation energy to the solar cells where the captured thermal radiation energy is converted to electricity. Light, which is collected in the heat source component of TPV system circuit acts as an intermediate agent prior to conversion of heat into electricity. The system consists of three main components: a heat source, an emitter, and a low band gap PV cell as shown in Figure 1. So, different energy sources can be used including radioisotopes [28], chemical fuels [12], and sunlight itself [29]. A two-dimensional schematic diagram of a cylindrical STPV system with a thermal storage material is shown in Figure 2. It is suitable for thermal sources such as wastes, stored heat recovery, and solar energy conversion involving an intermediate thermal energy storage to operate at temperatures near or far above thousands of Kelvins [29]-[32].

There are several advantages in energy conversion scheme including the static and dynamic conversion processes, where the heat conduction is physically separated from the power generation pathway. Also, there is a lack of fundamental temperature gradient across the material [33]-[35]. TPV energy conversion is an example of selective emitter application [19], [36], [37]. A selective emitter is a material that emits optical radiation in a few emission bands rather than in a continuous spectrum like a blackbody or a gray body with constant emittance. In a TPV energy conversion, the selective emitter converts thermal energy to the near infrared radiation at wavelengths where photovoltaic energy conversion is efficient. In a solar thermophotovoltaic system, the solar radiation is absorbed and re-emitted as a thermal radiation before illuminating the PV cells [19], [38]-[42]. For such TPV, the wavelength region of interest is at the interval ~1 μm-3 μm, which is approximately the region of peak emission of the solar radiation. For an emitter heated to a realistic temperature range ~1000 K-2000 K, the peak emission wavelength interval is ~1.449 μm-2.989 μm, which is in agreement with the Wien's displacement law. As such, one of the main requirements of TPV is to have low-bandgap PV cells, with typical bandgaps in the range of ~0.50 eV-0.74 eV or equivalently at a wavelength interval ~1.7 μm-2.3 μm [43].

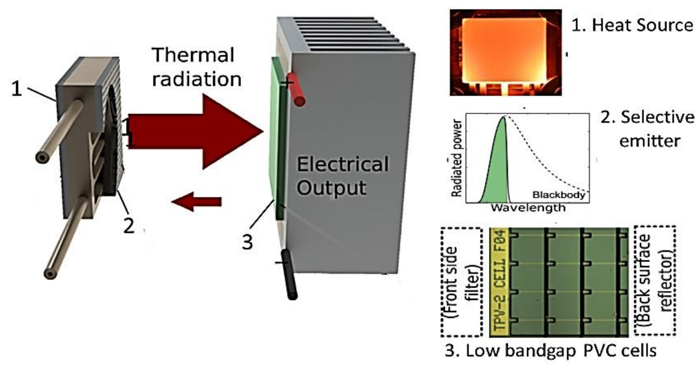

Figure 1. Basic three components of a TPV system: a heat source, an emitter, and a PV cell. 1. heat source: chemical fuel, radio isotope or sun ligt, 2. selective emitter and 3. low bandgap PVC cells [43]

In this review, the authors focus on the study of the development of emitters for solar TPV applications. They are the most suitable types of TPV solar materials for efficient solar TPVs. The identification of emitter based on material type and composition, geometrical structure, dimensions, and long-term high temperature stability for solar TPV applications including factors that determine the emitter's efficiency needs to be investigated further. The fabrications, characterizations, and simulations for nanoscale materials in the field of nanotechnology, especially in nanophotonics are also introduced elsewhere [24], [30], [35]-[37], [44], [45]. Needless to say, the conceptual and technological breakthroughs in the fields of nanophotonics and plasmonics combined with better understanding of the thermodynamics of the photon energy conversion processes have reshaped the landscape of energy conversion schemes and devices [46].

Previously five metrics have been evaluated on the practicality of TPV emitters. In particular, the emitters that are used to demonstrate the TPV prototype system, which have been discussed by Sakakibara *et al.* [43]. Most of the work on TPV emitters has focused on achieving good optical performance, but little consideration has been made associated with implementing emitters in the operation of TPV systems. Meanwhile, reviews on TPV emitters based on numerical optimization simulations have not been carried out.

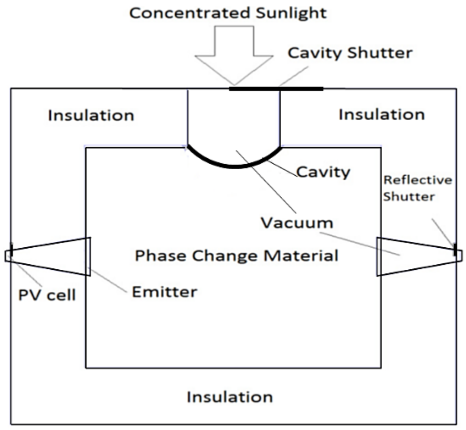

Figure 2. A 2-D schematic diagram of STPV system with thermal storage materials [29]

2. METHOD OF SIMULATED EMITTERS DESIGN DETERMINATION

The scope of our work is focused on a TPV emitter as an important component in the context of high system performance. In particular, we focus on the importance of emitter's practical implementation in TPV systems. A very useful emitter is a selective emitter, which preferentially emits thermal energy in a particular wavelength region. Such a proposed design (shown in Figure 3) is adopted from Boriskina *et al.* [46]. It works based on the power density emission generated from the TPV emitter and is limited by Planck's law for black body emissions only. The other reasons for our choosing are there is a need for integrating several subsystems and there are also difficulties in designing a good emitter type in high-performance TPV systems [34], [47]-[49]. But the challenges are we deal with high temperature selectivity and stability. Therefore, it is critical to further improve not only the theoretical design, but also the experimental fabrication of selective emitters to offer greater high-temperature stability and performance. Also, it is necessary to consider strategies to reduce the need for precise alignment between emitters and receivers [46], [50].

What follows is the coverage of the present review. First, the division of practical TPV emitters is depicted in Table 1. The TPV emmiters are classified into 5 different categories: 1D binary grating, 2D and 3D photonic crystals, multi-layer stacks, and metamaterials. Second, Table 2 (in appendix) depicts a metric-based evaluation of the metamaterial and metasurface based-emitters. Such a metric-based evaluation is based on emitter structures, materials used, method of simulations, and design implementations and results. Our proposed design for a STPV diagram is depicted in Figure 3.

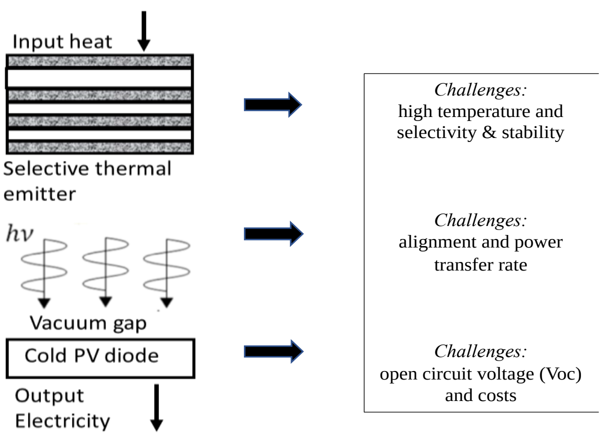

Figure 3. A proposed design of an STPV where a selective thermal emitter is shown. (Adopted from Boriskina *et al*. [46])

Table 1. Implementation of practical TPV emitters that have been investigated through simulations [51]-[70]

No.	Materials	Structures	References
1	Tungsten (W)	1D binary grating: rectangular slits in substrate	[51]
2	Tungsten	1D complex grating	[52]
3	W-SiO_2-W	1D trilayer films grating	[53]
4	Cylindrical air cavities in VO_2	2D photonic crystal (PhC)	[54]
5	Cu, Ag, Au woodpile	3D photonic crystal (PhC)	[55]
6	Chirped mirror on Er-doped Al garnet wafer on dielectric mirror	Multi-layer structures	[56]
7	W in Al_2O_3	2D array of nanowires/metamaterials	[57]
8	W in Al_2O_3	2D array of nanowires/metamaterials	[58]
9	Au (gold) in Al_2O_3	Metamaterial/metasurface	[59]
10	W rectangles on SiO_2 spacer on W	Metamaterial/metasurface	[60]
11	Tungsten as plasmonic material	An integrated solar absorber/narrow-band thermal emitter (SANTE)	[61]
12	Phase-change metamaterials	Two Au layers spaced by $Ge_2Sb_1Te_4$	[62]
13	Metamaterials (EBG and dielectric resonator building blocks)	Metamaterial structures	[63]
14	SiO_2-coated W nanospheres on W with W coating on top	SiO_2-coated W nanospheres on W with W coating on top/Metamaterial	[64]
15	Si squares on Al-doped zinc oxide on Ta	Si squares on Al-doped zinc oxide on Ta/metamaterials	[65]
16	Tantalum (Ta)	2D tantalum (Ta) photonic crystal (PhC)	[66]
17	Silicon (Si)	Silicon-Rod type photonic crystal (PhC)	[67]
18	W/HfO_2 (Tungsten/Hafnia) stacks	W grating over a HfO_2 and a W substrate	[68]
19	Tungsten	1D microstructure tungsten grating (pyramids)	[69]
20	Tungsten/metamaterial	Coupling a flat tungsten surface with guided resonances of a dielectric PhC slab	[70]

3. RESULT AND DISCUSSION OF SIMULATED EMITTERS

An analytical review of how emitters have evolved is depicted in Table 2. A number of researchers have carried out simulations in order to investigate emitters for TPV applications. Sakakibara *et al.* [43] have pointed out five practical metrics that need to comform with: a) optical performance, b) the ability to fabricate in a large area, c) stability to withstand a high temperature for a long period of time, d) ease of integration in a TPV system, and e) cost affordability. The prime objective in the development of an emitter is to attain the best optical performance. Nonetheless, an emitter with the best optical performance may not be necessary the best one for a practical use.

Mo *et al*. [64] indicates that the emitter spectral efficiency, which is 39% higher than those of the other cases is achieveable without the top W cover layer or the W nanospheres. Such an excellent emission selectivity is attributed to the strong photonic interaction within the gaps between the adjacent core-shell nanospheres, tight confined optical fields in both Ω-shaped W-SiO_2-W nanocavities, and bottom nanocavities, which is formed by the W nanospheres and the W substrate. Further, a ~32-% relative enhancement of the TPV system efficiency has beean achieved using selective emitters and reduces to 3.9% with non-ideal selective emitters [65]. This large reduction is due to sub-bandgap losses, off-angular losses, and high-temperature dependence of practical constants. It is our hope that Tables 1 and 2 serve as important resources for researchers.

4. CONCLUSION AND FUTURE WORK

We have reviewed twenty types of materials and emitters from different categories (bulk and naturally occurring selective emitters, 1D, 2D, 3D PhCs, and multi-layer stacks). The present review is an extended version of that of Sakakibara's group research. The review also considers the application of TPV emitters based on different simulation methods and designs. Results and analysis were discussed in the form of thought tables and a proposed design. This framework can be utilized as a useful guide for researchers when conducting simulations and experiments. The reasons are: the framework presents the different types of emitters, varying simulation physical constraints/conditions, and the results of STPV applications. In the future work, the proposed design depicted before will be evaluated and improved aided by simulations using finite-difference time-domain (FDTD) by Lumerical. Simulations will allow us to predict the efficiency of emitters. How the various layers and different combinations of metamaterials and metasurfaces affect the efficiency can be observed through simulation results.

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APPENDIX

Table 2. A compiled list of various types of emitters for TPV applications based on simulations [51]-[70]

No	Types of emitter structure	Materials	Method of Simuations	Design Implementation	Results	Refs
1	Binary grating 1D	W (Tungsten); emittance should be large at wavelengths between 0.6 μm and 2.0 μm at its operating temperature	Hybrid numerical method: the rigorous coupled wave analysis (RCWA) together with a genetic algorithm (GA)	Polarization-insensitive TPV emitter with a simple omnidimensional periodic structure	The peak emittance at the transverse electric and transverse magnetic polarizations was 0.997 and 0.935, respectively	[51]
2	1D complex grating - superposition of two simple binary gratings	The optical constants of tungsten (W) at room temperature from k=0.2 to 4.0 μm	Rigorous coupled-wave analysis (RCWA)	$0^o \leq \theta \leq 20^o$ Polarization, Complex $0^o \leq \theta \leq 90^o$	Wavelength 0.8 – 1.7 mm short period – flat dispersion curve, Long period – band folding and multiple intersections with light lines	[52]
3	1D trilayer films grating	W-SiO_2-W	FDTD simulation with sandwich between two tungsten layers	Inductance–capacitance (LC) circuit model for trilayer grating structure	600 nm – 1900 nm=0.95 (TM waves) 900 nm – 1800 nm=1 (TM waves)	[53]
4	2D photonic crystal	Cylindrical air cavities in VO_2, Photonic crystal SiC, VO_2	FDTD simulation	Emitter temperatures vary between 1300 K, 1400 K, and 1500 K	Effective power density: 2.32 – 6.36 W/cm^2 radiation efficiency: 41.57, 48.20, 54.11 % TPV efficiency: 8.44, 10.45, 12.37 %	[54]
5	3D photonic crystal	Cu-Ag-Au woodpile	A hybrid optimization method	Emitter and power efficiencies in excess of 90% at 1200 K	LL – Photonic crystal : Cu 51 % emitter efficiency, 76.9 % power efficiency Au : 66.7 % , 86.9 % Ag : 55.6 % , 82.9 %	[55]
6	Multi-layer structures	Chirped mirror on Er-doped Al garnet wafer on dielectric mirror	Stanford Stratified Structure Solver (S4) + coupled wave analysis & scattering matix algorithm	A rare-earth-based ceramic thermal emitter without cold-side filters	Emitter temperature of 1573 K and TPV efficiencies of 34%	[56]
7	2D array of nanowires embedded in material	W in Al_2O_3 (Metamaterial)	Epsilon-near-zero and near-pole metamaterials	The angular nature, spectral position, and width of the thermal emission and optical absorption	High temperature (emitter 1500 K) thermal engineering applications of metamaterials and efficiency 41%	[57]
8	Tungsten nanowire arrays embedded in Al_2O_3	W in Al_2O_3	Effective medium theory and anisotropic thin-film optics	Two hyperbolic metamaterials (HMMs)	The power output from a semi-infinite TPV cell is improved by 2.15 times with the nanowire HMM emitter	[58]
9	Metamaterial/Metasurface	Au (gold) in Al_2O_3	Finite element method (FEM)	Metamaterial thermal emitters based on gold nanowire cavities on a gold substrate	Polarization-insensitive and have nearly omnidirectional emission angles, T_e=940 K	[59]
10	2D periodic array of tungsten	W rectangles on SiO_2 spacer on W	Rigorous coupled-wave analysis (RCWA)	2-D grating/thin-film nano-structure	Wavelength-selective and polarization-insensitive TPV emitter	[60]
11	Metasurfaces	Tungsten as plasmonic material	A large-area, nanoimprint-patterned film of plasmonic structures	an integrated solar absorber/narrow-band thermal emitter (SANTE)	An efficiency as high as 41% for T_e=2300 K	[61]

Table 2. A compiled list of various types of emitters for TPV applications based on simulations [51]-[70] (continue)

No	Types of emitter structure	Materials	Method of Simuations	Design Implementation	Results	Refs
12	Phase-change-metamaterials (PCMMs)	Two Au layers spaced by $Ge_2Sb_1Te_4$	FDTD simulation within the 3D EM Explorer Studio software	Polarization-independent tunable absorbing metamaterial (MM) in the mid-infrared wavelength regime	10% tuning of the absorbance peak can be obtained by switching the PCM (phase-change material) between its amorphous and crystalline states	[62]
13	Directional emitters based on metamaterial structures	Metamaterial structures (EBG and dielectric resonator building blocks)	Genetic Algorithm (GA) optimization technique	Metamaterial structures based on EBG surface and a dielectric resonator array for use as near-IR emitters with custom angle selectivity	Metamaterial coatings can be effectively synthesized by a GA to achieve custom angle-selective emitters (8-fold and 4-fold mirrored symmetry)	[63]
14	Tungsten (W) spherical core-shell nanostructure	SiO_2-coated W nanospheres on a W substrate and a thin W layer deposited on top	Numerical optimization	Silicon dioxide (SiO_2)-coated W nanospheres periodically distributed on a W substrate and a thin W layer deposited on top	Spectral efficiency of 39% (0.39) > those of other cases without the top W cover layer of the W nanospheres	[64]
15	Si squares on Al-doped zinc oxide on Ta	Si squares on Al-doped zinc oxide on Ta	Simultaneous control of angular and spectral properties of thermal emitters on the efficiencies of TPV systems	Angular and spectral selective thermal emitter based on waveguide perfect absorption phenomena in epsilon-near-zero thin-films	Expected relative enhancement of the TPV system efficiency ~ 32% using selective emitters, but reduces to 3.9% with non-ideal selective emitters	[65]
16	2D tantalum (Ta) photonic crystals (PhCs)	Tantalum (Ta) Photonic Crystals (PhCs)	High- fidelity axisymmetric thermal-electrical hybrid model thermal coupling	Emitter ~1400 K, tandem filter (10%), irradiation flux of ~ 130 kW/m^2	Absorber-to-electrical STPV efficiency can be improved up to ~ 16% by eliminationg optical and electrical non-idealities in the PV cell	[66]
17	Silicon-rod type photonic crystal (Si- PhC)	Silicon (Si)	Silicon rods as thermal emitter with a relatively narrow emission spectrum and PV cells	Emitter at 1338 K, bandgap corresponding wavelength of 1.76 μm	Output power=0.368 W/cm^2, actual system efficiency=11.2 % (ratio of output power to ingoing heat flux)	[67]
18	Gratings based on tungsten/hafnia (W/HfO_2) stacks	W/HfO_2 (tungsten/hafnia) stacks	A W grating over a HfO_2 spacer layer and a W substrate analyzed over a range of geometries	Shallow gratings and deep gratings	Both surface plasmon polaritons (spp) and magnetic polaritons (mp) play a crucial role in shaping the emittance for TM radiation	[68]
19	One-dimensional microstructure tungsten grating (pyramids)	Tungsten (W)	Rigorous coupled-wave analysis (RWCA)	Emitter temperature about 1900 K, cut off wavelength about 2.2 μm	Grating period=0.5 μm, filling ratio=0.8, grating height, h=0.2 μm, λ_{opt}=0.5-1.8 μm, no need for a filter > more complex structures	[69]
20	Metamaterial (Tungsten PhC)	Coupling between tungsten and PhC slab	Numerically demonstration of narrowband thermal emission with unity emissivity peak	Tungsten surface is separated from the PhC slab by a vacuum gap	Emits a strongly photon light near an energy of 0.6 eV (typical range of standard TPV operation system)	[70]

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