DESIGN OF METAMATERIAL FOR HIGH THERMOPHOTOVOLTAIC EMITTER

Gurmu Alemu Gobena

A Thesis Submitted to the Department of Applied Physics

School of Applied Natural Science

Presented in Partial Fulfillment of the Requirements for the Degree of Masters of Science in Material Physics

Office of Graduate Studies

Adama Science and Technology University

July, 2021

Adama, Ethiopia

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Advisor: Fekadu Tolessa (Ph.D.)

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Approval Page

I/we, the advisors of the thesis entitled "DESIGN OF METAMATERIAL FOR HIGH THERMOPHOTOVOLTAIC EMITTER" and developed by Gurmu Alemu, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

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We, the undersigned, members of the Board of Examiners of the thesis by Gurmu Alemu have read and evaluated the thesis entitled "DESIGN OF METAMATERIAL FOR HIGH THERMOPHOTOVOLTAIC EMITTER" and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Material physics

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I hereby declare that this Master Thesis entitled "DESIGN OF METAMATERIAL FOR HIGH THERMOPHOTOVOLTAIC EMITTER" is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation

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Recommendation

I/we, the advisor(s) of this thesis, hereby certify that I/we have read the revised version of the thesis entitled "DESIGN OF METAMATERIAL FOR HIGH THERMOPHOTO-VOLTAIC EMITTER" prepared under my/our guidance by Gurmu Alemu submitted in partial fulfillment of the requirements for the degree of Mater's of Science in material physics. Therefore, I/we recommend the submission of revised version of the thesis to the department following the applicable procedures.

Dr. Fikadu Tolessa ______________________ _______________

Major Advisor Signature Date

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LIST OF ACRONYMS

BB……………………………Black body

CMP…………………………Coupled magnetic polariton

E_g……………………………..Energy band gap

EQE…………………………...External quantum efficiency

LSPP…………………………Localized surface plasmon polariton

MM……………………………Metamaterial

MP…………………………….Magnetic polariton

TPV…………………………...Thermophotovoltaic

PV……………………………..Photovoltaic

SPP……………………………Surface plasmon polariton

SPV…………………………....Solar thermophotovoltaic

λ_c……………………………….Cut-off wavelength

ABSTRACT

In this work thermophotovoltaic emitter designed of metamaterial were presented. The broad band and wide angle emissivity above cut-off wavelength were obtained. The metamaterial nano-cone was designed from tungsten and aluminum oxide by using COMSOL Multiphysics software. To get broadband emission, the geometric parameter optimization of the bottom radius, thickness of dielectric, and the width of the unit cell were conducted, while parameters such as nano-cone height, top radius of nano-cone and ground tungsten thickness were fixed in this study. The numerical simulation results showed that the proposed emitter had an average emissivity of 0.975 within the targeted wavelength, which ranged from 0.5 µm to 1.8 µm. The obtained high emissivity is because of excitation of different physical mechanism of absorption. Unlike black body the designed nano-cone metamaterial emitter emit only selective wavelength of radiation. Moreover, the designed nano-cone metamaterial emitter obtained 3.79%, 8.4%, 15.49%, 24.9%, 36.6%, 50.3%, 64.6%, 80% spectral efficiency of with GaSb band gap of 0.74 ev or 1.8 µm wavelength at 900 K, 1000 K, 1100 K, 1200 K, 1300 K, 1400 K, 1500 K and 1600 K respectively. In general as temperature increases the spectral efficiency also increases, this shows the emitter working at high temperature play a vital role in enhancing TPV efficiency. Particularly, selective emitter maximize efficiency by suppressing the out band radiations. Over all, in this paper selective metamaterial emitter were designed and this designed metamaterial emitter has high average emittance over required wavelength.

1. INTRODUCTION

1.1 Back ground of the study

The substantial opposition to sustain our earth and modern life are energy and Environment. Because of the negative impact of fossil fuel combustion on our surroundings, the exploration for inexhaustible and immaculate energy becomes mandatory. The solar energy has a specific consideration due its tremendous amount of clean energy (Abdelatif et al., 2021). Transforming waste heat and solar energies into electricity is a best way of energy-harvesting technology due to an ample quantity, ubiquitous, and nature-friendly properties of these energy sources (Nelson, 2003). Thermophotovoltaic (TPV) devices collect electromagnetic energy and transform it to electrical energy (Palfinger et al., 2003). A heat source, a thermal radiator, and TPV cells are the essential parts of a TPV system.

The purpose of the thermal radiator is to convert solar or waste heat energies into thermal radiation, from which a TPV cell produces electricity using the photovoltaic effect (Jin and Lee, 2016). However, the conversion of electromagnetic energy to electrical power takes place only when the photon energy is greater than the energy band gap of the TPV cell. Because of this, the selective emitter should be a perfect broadband and wide-angle emissivity below the cut-off wavelength of the TPV cell. Whether the TPV emitter has high emissivity within the targeted wavelength region or low emissivity above cut-off wavelength, the TPV cell can helpfully operate to produce electrical power with comparatively low thermal loss (Jin and Lee, 2016; Guazzoni and Mattews, 2004; Burger et al., 2020).

Metamaterial emitter can be designed to different symmetries for application of TPV. A 2D pyramidal metamaterial-based nano-structure has been designed as a wavelength selective TPV emitter. It has been demonstrated that this emitter was wavelength selective, polarization-insensitive, and direction-insensitive in emittance. The mechanisms supporting the emittance close to 1.0 in the wavelength range of 0.3-2.0 μm was elucidated in the proposed structure (Ghanekar & Zheng, 2016).

2D trilayer grating with a tungsten/silica/tungsten (W/SiO2/W) structure on a tungsten substrate as a TPV emitter has been designed. A broadband high emittance with an average spectral emittance of 0.953 between 600 and 1800 nm has been obtained for both transverse magnetic and transverse electric polarized waves. The study demonstrates that the emitter has good wavelength selectivity and polarization insensitivity in a wide geometric and angular range (Gong et al., 2020).

Similarly, metamaterial thermal emitters based on gold nanowire cavities on a gold substrate has been designed to achieve a narrow band emission spectrum with the emission peak located slightly above the band gap of TPV cells, in order to improve the overall efficiency of TPV systems. Narrow band emitter is emitter which emits photons with energy slightly above band gap or photons with wavelength slightly below cut-off wavelength. From Simulation results it is showed that the designed metamaterial emitters have been polarization-insensitive and have nearly Omni-directional emission angles (Lin &Fleming, 2003).

As we try to see so far, TPV emitters can be created in 1D (Burger et al., 2020), 2D (Huo & Zhao. 2018), as grating and 3D (Durisch & Bitnar,2010) photonic crystals, or from artificial optical materials known as metamaterial. A metamaterial is any material engineered to have a property that is not found in naturally occurring materials. They are made from assemblies of multiple repeating patterns at small scales, containing elements fashioned from composite materials such as metals and plastics. Metamaterial emitters are conventionally designed with different symmetry structures such as disks, squares, crosses, pyramids, nanowires, cones, and nano-particles to improve TPV performance attained by perfect emissivity below the cut-off wavelength of PV cell. Correspondingly, the nano-sized cone has been studied for different applications because of low reflection from top and high absorption at bottom. However, there has been less consideration of a nano-sized cone for TPV emitters. For this reason, it is important to design the nano-sized cone emitter with consideration to cut-off wavelength to maximize energy conversion efficiency.

In this work, we designed an emitter from metamaterial to increase a perfect broad band and wide-angle emission within the energy band gap of GaSb (cut-off wavelength of 1.8 μm to increase the spectral efficiency of the TPV emitter). Based on numerical simulation, we optimized a nano-cone structure on the basis of designed metamaterial parameters such as width, bottom radius and thickness of dielectric. Near perfect and wide-angle emissivity were obtained at the target wavelength (visible and near-IR), which matched with the GaSb cut-off wavelength at 1.8 μm.

1.2 Statement of the problem

Energy can be converted by different technologies to the required form. The transformation of energy from one form to the forms needed by human is called energy conversion. TPV system is one of these energy conversion technologies where heat is converted in to electricity. As reported in different papers, this energy conversion technology has a problem of low conversion efficiency. One of the problems of low conversion efficiency originates from the spectral mismatch between emitter and TPV cell (Ghanekar & Zheng, 2016: Gong et al., 2020: Lin &Fleming, 2003). Sub-band gap photons that increase the heat of TPV cell are a result of this problem. Application of metamaterial for absorbing electromagnetic radiation initiates researcher to the field of TPV. Designing emitter from metamaterial increase average emissivity by reducing the emission of inband photons.

1.3 Significance of the study

A relevant aspect of TPV system is the design of emitter, which has to suppress the thermal emission of sub-band gap photons as they cannot be converted to electrical output and simultaneously enhance thermal emission just above the cell band gap. In the same manner, in this study we investigated the emitter that the photons it emits with wavelength range between 0.5 μm to 1.8 μm were enhanced and photons above 1.8 μm had been suppressed. One fundamental requirement for an emitter is a robust optical response and thermal or structural stability of the emitter which has to withstand high temperatures. The material we have used to design our emitter has high melting point as the result, it have the ability to resist and operate at high temperature.

The use of a selective emitter in contrast to direct application of the electromagnetic radiation emanating from a source is beneficial for several reasons. One way to raise the fractional radiative power beyond the band gap is to exploit selective emitters that ideally emit photons over a broad spectrum at above band gap energies. In fact, one would like to prevent sub-band gap photons from entering the photovoltaic cell so as to prevent unnecessary absorption that invariably leads to raising the temperature of the cell and thus reducing its conversion efficiency. Additionally, tailoring down the excessively energetic part of the spectrum to a range of energies only slightly above the band gap of the cell will reduce the thermalization losses and hence further increase the cell conversion efficiency. Such spectral shaping (if properly achieved) could result in higher TPV cell efficiencies.

Another way to increase the fraction of photons with energies above the band gap energy of the TPV cell is to avail lower band gap TPV cells such as GaSb (which has a band gap energy of 0.72 ev). The thermal selective emitter modifies the emission spectrum of the heat source to match the absorption spectrum of the solar cell. A TPV exploiting the emitter designed in this study will operate in waste heat recovery and also for energy scavenging in thermal power plant. In general, this work will contribute to the knowledge for future development metamaterial emitter of TPV system.

1.4 Objective

1.4.1 General objective

The main objective of this work was design of metamaterial for high photon emission of thermophotovoltaic emitter that match band gap of GaSb TPV cell. Designs of emitter that emit in band photons or convertible photons and out band photons or suppress inconvertible photons were our prime aim.

1.4.2 Specific objective

The specific objectives were:

- to obtain selective wavelength emitter
- to obtain high emission above band gap

- to decrease out band photons
- to get wide angle emission

1.5 Scope of the study

Energy is the power we use for transportation, for heat and light in our homes and for the manufacture of all kinds of products. There are two sources of energy: renewable and nonrenewable energy. A non-renewable resource is a natural resource that cannot be readily replaced by natural means at a quick enough pace to keep up with consumption. An example is carbon-based fossil fuel. The original organic matter, with the aid of heat and pressure, becomes a fuel such as oil or gas. Renewable energy is energy that is collected from renewable resources, which are naturally replenished on a human timescale, including carbon neutral sources like sun light, wind, rain, tides, waves, PV, SPV, TPV, and geothermal heat. Solar energy is derived by capturing radiant energy from sunlight and converting it into heat and electricity. TPV is one of power generating technologies that convert thermal energy into electrical energy. This system uses heat source, emitter and TPV cell converter to achieve power generation and efficiency. The energy emitted from emitter can be entire light spectrum or specific range of wavelength such as UV to near infrared which can be optimized for absorption. In this study we concentrate on the designing of selective emitter based on MM.

2. LITERATURE REVIEW

2.1 Thermophotovoltaic (TPV)

Renewable energy is energy that is collected from renewable resources, which are naturally replenished on a human timescale, including carbon neutral sources like sunlight, wind, rain, tides, waves, PV, STPV, TPV and geothermal heat. Renewable energy often provides energy in four important areas: electricity generation, air and water heating/cooling, transportation, and rural (off-grid) energy services.

The photovoltaic (PV) system collects and transforms solar energy into electricity with structured semiconductor materials. However, PV cells hurted from high cost and low absorption. Accordingly, light confining approach is required to intensify the absorption of the PV active materials (Abdel-Latif & Obayya, 2021). The low absorption of PV system arises from a sort of reason. The primarily and essential reason is the direct contact between photon from the source and PV cell. This allows both photons, (i.e., photons below band gap and above band gap) to enter the cell and causes thermalization loss which is enemy of the system. Secondly photovoltaic system uses photon as input from solar system or sun. Consequently, during cloudy day, night and rainy day the system is hurted from scarcity of photon. In general it is season and time dependent system.

Solar thermophotovoltaic (STPV) system is a system that converts solar energy from sun into electricity. In contrast to photovoltaic system STPV system has three key parts are: heat source, thermal radiator and SPV cell. The radiation from the source is absorbed by thermal radiator and thermal radiator emits photons that hit STPV cell, from which electron hole pair are produced. Most society's lives in rural area use this system for different purposes. For instance, for light, for charging mobile phone and so on. Even if, this system is modern, structured and systematic than photovoltaic system, it has its own drawback. It uses photon from the sun, in absent of sunlight the system doesn't function. This all problems lead peoples to search for new energy conversion system and they come up with the modern and new technology called thermophotovoltaic system.

TPV is one type of renewable energy that converts heat energy in to electric energy by means of photo electric effect (Tang & Fraas, 2019). The idea of TPV was born in the mid- 1950s when Henry Kolm of MIT's Lincoln Laboratories was queried by the US defense department whether he could devise a method to generate electricity from heat (Song &Luo, 2016). A TPV system converts heat to electricity using heat as an intermediary and consists of (at least) three components: a heat source, an emitter, and a TPV cell with energy band gap (Coutts, 1997). The heat source brings the emitter to high temperature (≥1000 K), causing the emitter to emit thermal radiation, which is absorbed and converted to electricity by the TPV cell (Córdova et al., 2018). Some advantages of this energy conversion scheme include the static and quiet conversion process, the physically separated paths of heat conduction and electricity generation, and the lack of fundamental temperature gradients across materials. In addition, several heat sources can be used, of which there are three major kinds: radioisotope decay, chemical fuel, and sunlight that is concentrated and absorbed (Rinnerbauer et al., 2014). TPV systems are indistinguishable to PV systems other than that they transform heat (infrared light) to electricity on the contrary focusing more on the visible wavelengths (Cui et al., 2014). The emitter even if it is a natural material or a metamaterial (MM), in a TPV system absorbs heat via conduction, convection, radiation and emits waves (Bitnar, 2003). Moreover, we discuss the components of TPV system extensively in the subsequent topic

2.1.1 Components of TPV system

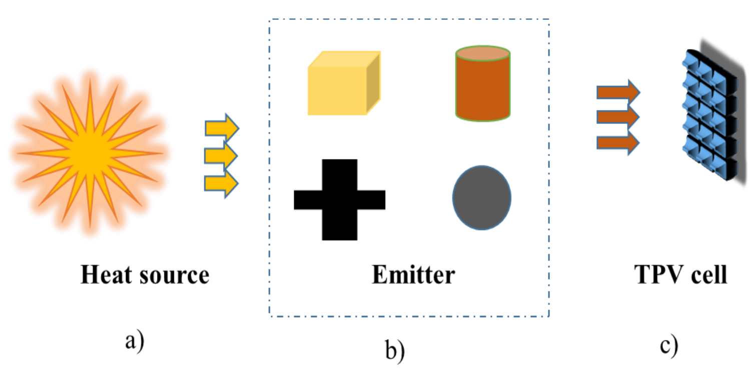


Figure 1 Basic components of TPV system a) Heat source b) Emitter (Inset can be square, circle, cross, cylinder etc.) c) TPV cell

2.1.1.1 Heat Source

As illustrated (on the figure 1 a), heat source is the basic and fundamental components of TPV device, that serves the system by feeding or generating heat. Furthermore it brings the emitter of TPV device to high temperature. TPV system uses a variety of heat sources, such as; combustion, radiative isotope decay, chemical fuel sun, and so on.

2.1.1.2 Emitter

Emitter is any material that is heated up to a high temperature (see figure 1 b above). A particularly useful emitter is a selective emitter, which preferentially emits in a specific wavelength region; figure 1b depicts this type of emitter. There is no one way to make an emitter; there are many types of emitters each of them involve a different geometric configuration and a separate set of materials. Additionally the primary aim to develop an emitter is for its optical performance, the emitter with the best optical performance is not necessarily the best emitter for practical implementation. Because of this, the following five practical metrics have been mentioned: optical performance, ability to scale to large areas, long-term high-temperature stability, ease of integration within the TPV system, and cost.

An emitter with good optical performance has, at all angles, preferential emission of in band photons and suppression of out-of-band photons. Optical performance refers to the emission of photons as a function of both angle and photon energy, in particular, in two regimes for the latter, in-band photons that have energy higher than the TPV cell band gap and out-of-band photons that have energy lower than band gap of TPV cell. Spectral control refers to the methods that enable preferential in-band emission. Some designs of spectral control are designed for broadband emission while others for narrow-band emission (the ideal cases which are shown in Fig. 2, for broad band). In the latter case, the emitted photons have energies slightly above the PV cell band gap. Typically, broadband emitters yield higher output electrical power density while narrow-band emitters can increase the TPV conversion efficiency (Jin & Lee, 2016).

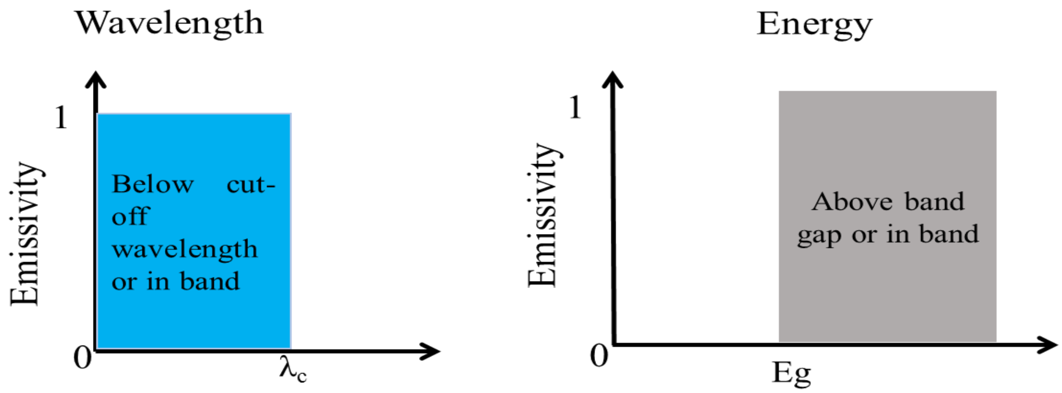


Figure 2An ideal emitter with broadband emission, where any in-band photons are preferentially emitted.

Although a TPV cell can generate electricity only from in-band photons, a real emitter emits both in-band and out-of-band photons at any given angle. This leads to the following problems: (a) if out-of-band photons reach the TPV cell, they overheat the TPV cell and reduce the TPV cell efficiency and (b) when out-of-band photons are emitted and not recovered, this leads to both reduced heat-to-radiation efficiency and emitter temperature.

While we have initially defined good optical performance as that achieved by designing selective emitters, there are actually two main approaches of spectral control. The first is to enhance in-band and suppress out-of-band emission via selective emitters. The second is to reflect out-of-band photons back to the emitter, or photon recycling, via cold side filters or reflectors (CSFR) in front of (front side filter) or behind the TPV cell (back surface reflector). It is also possible to combine both approaches, for example, to have a selective emitter and a filter or reflector, or even all three in theory.

On the other hand, selective emitters suppress out-of-band emission relative to in-band emission. This reduces view factor and absorption losses for out-of-band photons, although both losses, especially view factor losses, remain significant for in-band photons. For the approach of selective emitters, the objective is to search or design a TPV emitter that emits mostly in-band photons and little to no out-of-band photons. Emitters can be designed from polycrystalline silicon carbide (SiC), rare earth oxides such as;

ytterbium oxide (Yb_2O_3) and erbium oxide (Er_2O_3), photonic crystal and metamaterial (Jin & Lee, 2016). We will discuss these and other emitters one by one in the subsequent subtopics.

1. Rare Earth-Based Emitters

Rare earths oxides (REOs) exhibit selective emissivity over narrow bandwidths in the infrared region and predictably have been investigated extensively for TPV applications. In the lanthanides, the localized 4f electrons do not provide to the ceramic bonding system. Because of this, various lanthanides shows very similar chemical properties. The electronic excitations within the f-orbitals are the main cause of several intriguing optical properties. As the result, lanthanides exhibit thermal emission that all in all is similar to that of gaseous materials, i.e., the spectral distributions are included of sharp lines corresponding to atomic-like transitions.

Between rare earth oxides, ytterbium (Yb_2O_3) is particularly fitted to match with silicon photocells. It has one main peak of emissivity at about 1.27 ev (960 nm). Ytterbia can be functioned at quite high temperatures owing to its very high melting point of about 2400 ℃. Moreover, unlike metallic selective emitters such as tungsten, Ytterbia can be operated in oxygen consisting atmosphere or in contact with a combustion flame. Besides to Ytterbia, erbium oxide (erbia; Er_2O_3) has also been interesting to match with low band gap photocells such as GaSb (with band gap energy of 0.72 ev) or Ge (with a band gap energy of 0.66 ev). Its emission peaks at 0.805 ev (1540 nm) and has a quite high melting point of about 2400℃, just as that of ytterbia.

2. Transition Element (TE)-Based Emitters

TPV emitters designed from Co or Ni-doped refractory oxides such as Al_2O_3 and MgO exhibit moderate spectral selectivity in the NIR (Daneshvar & Kherani, 2015; Teofilo&Ermer, 2008).Between the transition elements, tungsten (W) is peculiarly relevant to spectrally match with GaSb photocells which have a bandgap of 0.72 eV (corresponding to a wavelength of 1.8 μm). The interband absorption/emission frequency of tungsten matched closely with the bandgap of GaSb.Another advantage of tungsten is its very low evaporation rate at high temperatures typical in TPV systems. The main disadvantages are strong angle dependence of the surface plasmon resonance (SPR) frequencies, which results in highly angle-dependent emission spectra, and poor structural stability at high temperatures due to surface diffusion.

3. Photonic Crystals (PhCs)

Photonic crystals (PhCs), which are periodic structures designed by modulating the refractive index in one, two or three dimensions, invite us a promising method to engineer emissivity in applications such as TPV emitters. By designing appropriate photonic crystals one can engineer photonic bandgap intervals (where photonic density of states and emissivity are zero) so as to obtain emitters that match the absorption of given photocells, and thus achieve higher spectral efficiencies that are required for the realization of efficient TPV devices. However, complete band gaps can only be achieved by 3D photonic crystals, while in PhCs with incomplete band gaps photons with certain energies cannot propagate only in limited directions or polarizations.Advances in metamaterial designs for TPV promise the development of robust emitters (Teofilo&Ermer, 2008).

4. Metamaterial

Metamaterials are artificially created structures where we design the unit cell length to our own specifications. In designing metamaterials, we carefully engineer a periodic array of unit cells to create an artificially structured composite material. These unit cells can be made up of constituent elements with periodicities ranging from tens of nanometers to millimeters depending on the target operating frequency and thus are much larger than the atomic or molecular scale features that are common in natural materials.

Natural materials are made up of individual atoms and molecules separated by distances on the order of angstroms. When visible light interacts with natural materials, standard processes such as reflection, absorption, and transmission follow expected behavior, as the wavelength of visible light is several times larger than the constituent atoms and molecules. At an elementary level, reflection, absorption, and transmission are determined by the characteristic length of the unit cell of the atom (Bermel et al., 2010)

2.1.1.3 Thermophotovoltaic Cell

It has been contended that one of the main challenges on way to commercialization of TPV technology is the development of inexpensive photocells which are appropriate for implementation in TPV systems. In this section, prior to begin the discussion of the particular TPV cells which have been developed for operation in TPV systems, we first discuss some of the general specifications which ideally are needed for a TPV cell to be appropriate for implementation in TPV (Song et al., 2016).

i. **Correspondence of Photocell Bandgap and Selective Emitter Emissivity**

Un complicated calculation, using Wien's displacement law of black body radiation, demonstrates the peak of radiation for a black body radiator at 1800 K is located at about 1610 nm, while solar radiation (which resembles the radiation from a blackbody at about 5800 K) peaks at about 525 nm. From this uncomplicated comparison it is of course that typical photocells such as Si, with a bandgap of about 1120 nm, can only be suitable for application in TPV systems, if they are combined with peculiarly designed selective emitters which would yield a radiation spectrum that is noticeably shifted compared to that of a black body radiator at the same temperature.

As we talk over so far, fabrication of robust emitters with enhanced optical characteristics can be absolutely complicated and expensive. Hence, another method to increase the ratio of photons with energies above the bandgap of TPV photocells is to make use of lower bandgap photocells such as GaSb or InGaAsSb. Particularly, for a given emitter with known emissivity function ε (λ), the external quantum efficiency (EQE) of photovoltaic cells must be as high as possible, especially over the range of energies where the emissivity is high. Mathematically, the spectral overlap between the emitter Radiation and the EQE of photocells may be quantified by $\int EQE(\lambda).\ \varepsilon(\lambda)d\lambda$, which for a given ε (λ), should ideally be as high as possible. As an example, when using Yb_2O_3 emitters which have the highest emissivity between 1.05 eV and 1.55 eV (Pendharker et al., 2016) theoretically we need photocells which have the highest external quantum efficiency over this specific range of photon energies (Ferrari,& Melino,2014).

ii. Minimal Reflectance over the Range of Photon where the Emissivity is Highest

Besides to need the highest possible EQE over the range of energies where the emissivity is the highest, TPV photocell should have minimum reflectance over this range of photon energies. As we talk over in the coming subsection, this may be reached by means of applying antireflection coatings on and physical texturing of the cell's front surface.

iii. Optimized Substrate Configuration for Effective Cooling of TPV cells

In TPV structures necessary cooling of TPV cells is important so as to avoid a decrease in cell efficiency. As the result, a substrate with high thermal conductivity is mandatory.Through the utilization of specific ceramics such as AlN that would fulfil the requirement of high thermal conductivity and low electrical conductivity, one can survive the cell from high heat.TPV systems may need additional enhancement of passivation quality so as to decrease the bulk and surface recombination effects and thereby reduce the loss of photo generated carriers given the high current density in TPV cells (Omair et al., 2019; Alcañiz et al., 2019).In the subsequent we will discuss a variety of TPV cell.

1. Silicon TPV Cell

Silicon (Si) with a bandgap energy of about 1.1 eV can be suitable for application in TPV systems only if combined with designed selective emitters showing well-matched radiation. The merit of Si photocells is their quite inexpensive cost compared with low bandgap cells such as GaSb, and also their commercial availability in large quantities. Furthermore, in contrast to GaSb or CIGS cells, silicon is a non-toxic material. This is an essential factor, as in TPV systems the cells are usually closely located to the burner emitter system and one needs to assure that no toxic materials will be emitted, if the cells are heated up to high temperatures in the event of a malfunction of the cooling system (Alcañiz et al., 2019).

2. GaSb TPV cell

GaSb cells with comparatively low bandgap energy of 0.72 eV and the ability to operate under elevated irradiation densities are appropriate for use in TPV systems. Invented in 1989, GaSb cells were obviously one of the main reasons for the renewed interest in TPV technology since the early 90's. GaSb photocells are fabricated either by a zinc vapor diffusion technology or by epitaxial techniques such as liquid phase epitaxy (LPE) or metal–organic vapor phase epitaxy (MOVPE). Demerits of GaSb cells are their toxicity as well as very high cost (Woolf et al., 2018).

3. III–V TPV cells

III–V TPV converters which have been innovated for application in TPV include InGaAsSb, AlGaAsSb, InAsSb, InGaSb, InGaAs and InAsSbP (Nguyen-Huu et al., 2016; Deng et al., 2014; Omair et al., 2019). Efficiencies comparable to those of GaSb cells can be achieved.

4. Copper indium gallium diselenide (Cu(In,Ga) Se2 or CIGS)

Copper indium gallium diselenide (Cu (In, Ga) Se_2 or CIGS) photocells are another potentially attractive class of PV converters for use in TPV systems. CIGS bandgap can be adjusted between 1.0 eV (pure CIS without Ga) and 1.7 eV depending on the Ga content of the material.CIGS can match well with Yb_2O_3 emission spectrum.

5. Germanium (Ge)

Germanium (Ge) with a bandgap energy of 0.66 eV is some other PV material which has been scrutinized for application in TPV technology (Ghaneka et al., 2019; Ren, 2008). A simple calculation shows that the 0.66 eVbandgap energy of germanium match with the radiation maximum of a blackbody radiator at 1540 K. Thereby, Ge can be appropriate for application in TPV devices, where the emitter temperature is conventionally less than 1800 K. Also, when matched with Er_2O_3 emission, Ge TPV cells yield spectral efficiencies much higher than the spectral efficiency which would be obtained by matching a Si photocell with Yb_2O_3 emission. Nonetheless, the efficiency of Ge cells is generally much lower than that of Si and GaSb TPV photocells. Economically, Ge cells are basically more expensive than Si cells, but still much cheaper than III–V low bandgap cells such as GaSb and GaInAsSb.

2.1.1.4 TPV Filter

In the absence of ideal emitters, that emit photons only in a narrow band of energies slightly above the bandgap of given photocells, one may utilize selective filters to reflect sub-bandgap radiation back to the emitter. Some of these photons are absorbed by the emitter and reradiated with energies above the photocell bandgap energy, hence increasing the spectral efficiency of the TPV device. Optical filters may also be used to reflect some of the excessively energetic photons back to the emitter to reduce the thermalization losses in photocells and hence to further increase the overall efficiency of the TPV system. Similar photon recycling features may also be created by back-reflectors or other built-in optical components to increase the global efficiency of a TPV system.

The so-called rugate filters are optical interference filters with a continuously varying refractive index which changes periodically in the direction perpendicular to the filter plane. It has been claimed that appropriately designed rugate filters may be used as selective filters in TPV systems with close-to-ideal optical performance, i.e., close to 100% transmissivity of only a narrow spectral band of radiation above the photocell bandgap (Tong et al., 2015). Nonetheless, due to their complex fabrication process, rugate filters are quite expensive and their application has not received much attention.

2.2 Application of Thermophotovoltaic

TPVs promise efficient and economically viable power systems for both military and commercial applications. Compared to traditional non-renewable energy sources, burner TPV have little pollution emissions to environment and are virtually silent. Solar TPVs are a source of emission-free renewable energy. TPVs can be more efficient than PV systems owing to recycling of unabsorbed photons. However, losses at each energy conversion step lower efficiency. When TPVs are used with a burner source, they provide on-demand energy. As a result, energy storage may not be needed. In addition, owing to the PV’s proximity to the radiative source, TPVs can generate current densities 300 times that of conventional PVs.

2.2.1 Man-Portable Power

Battlefield dynamics require portable power. Conventional diesel generators are too heavy for use in the field. Scalability allows TPVs to be smaller and lighter than conventional generators. Also, TPVs have few emissions and are silent. In early 2001, JX Crystals delivered a TPV based battery charger to the Army that produced an output of 230 W with propane. This prototype utilized an SiC emitter operating at 1250 °C and GaSb photocells and was approximately 0.5 m tall (Ferguson &Dogan, 2001). To increase efficiency, narrowband emitters must be realized and the temperature of the burner must be raised. Further thermal management steps, such as water cooling or coolant boiling, must be implemented. Although many successful proof-of-concept prototypes were demonstrated, no portable TPV power sources have reached troop testing or battlefield implementation.

2.2.2 Spacecraft

For space travel power generation systems must provide consistent and reliable power without large amounts of fuel. As a result, solar and radioisotope fuels (extremely high power density and long lifetime) are ideal sources of energy. TPVs have been proposed for each. In the case of solar energy, orbital spacecraft may be better locations for the large and potentially cumbersome concentrators required for practical TPVs. However, because of weight considerations and inefficiencies associated with the somewhat more complicated design of TPVs, conventional PVs will almost surely be more effective for these applications (Wang & Zhang, 2011;Mitrofanov et al., 2014; Wilt et al., 2007).

2.2.3 Off-grid generators

Many homes are located in remote regions not connected to the power grid. Where available, power line extensions can be impractical. TPVs can provide a continuous supply of power in off-grid homes. Traditional PVs on the other hand, would not provide sufficient power during the winter months and nighttime, while TPVs can utilize alternative fuels to augment solar-only production.The greatest advantage for TPV generators is cogeneration of heat and power. In cold climates, it can function as both a heater or stove and a power generator. JX Crystals developed a prototype TPV heating stove and generator. It burns natural gas and uses a SiC source emitter operating at 1250 °C and GaSb photocell to output 25,000 BTU/hr simultaneously generating 100 W. However, costs must be significantly reduced to render it commercially viable (Tang et al., 2019).

2.2.4 Recreational vehicle

TPVs have been proposed for use in recreational vehicles. With the advent of hybrid and other electrically powered vehicles, power generators with electrical outputs have become more interesting. In particular the versatility of TPVs for fuel choice and the ability to use multiple fuel sources makes them interesting as a wider variety of fuels are being with better sustainability are emerging. The silent operation of TPVs allow the generation of electricity when and where the use of noisy conventional generators is not allowed (i.e. during "quiet hours" in national park campgrounds), and do not disturb others. However, the emitter temperatures required for practical efficiencies make TPVs on this scale unlikely (Song et al., 2016).

3. METHOD AND MECHANISM

The methodology and mechanism used in this study were discussedin this section. Nano-cone (conical frustum or truncated cone) is designed by using numerical software called COMSOL Multiphysics and the physical mechanism of absorption will be explained extensively.

3.1 Numerical Analysis (COMSOL Multiphysics)

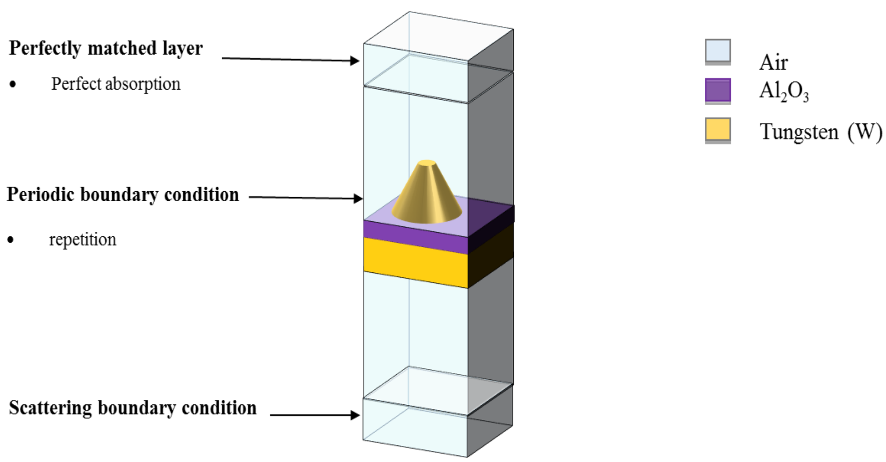


Figure 3 Design of metamaterial emitter with one unit cell for COMSOL Multiphysics simulation with perfectly matched layers from top and bottom, periodic boundary condition from left and right, scattering boundary condition, and two ports one from top (source) and other from bottom.

The nano-cone MM emitter is designed from tungsten and aluminum oxide by using COMSOL Multiphysics software as shown on the figure 3. 3D space dimension is selected for working environment. The optics interface has been used in order to compute electric and magnetic fields for our system, where the wavelength is comparable to or much smaller than the studied device. EMWFD interface is selected to solve for time-harmonic electromagnetic field distributions. The Wavelength Domain study is used to compute the response of model subjected to harmonic excitation for one or several wavelengths. In electromagnetic wave propagation through the designed structure, it is used to compute a structure's transmission and reflection versus wavelength.

The design parameters are w (width of unit cell), h_1 (top tungsten height), h_2 (dielectric thickness), h_3 (ground tungsten thickness), r_1 (bottom radius of nano-cone), r_2 (top radius of nano-cone). Optical material properties of air n = 1, W (Rakik et al. (1998)), and Al_2O_3 (Pastrnak (e) et al. (1966)). Melting point of W and Al_2O_3 are 3695 K and 2345 K respectively. The nano-cone we designed starts with W and ends with W, in other word it consists metal-dielectric-metal structure.

Numerical simulation was conducted on the single unit cell as shown in the figure 3, with the intention of decrease computational time. A three-dimensional electro-magnetic wave and the wavelength domain study were performed using COMSOL Multiphysics software. During the numerical analysis, perfectly matched layer were assigned on the top and bottom of the computational domains or along z-axis to minimize reflection. The periodic boundary condition was also set at both the right and left boundaries to account for an infinite flat surface on the emitter and also for oblique incidence. The electromagnetic waves or incident light on the emitter is considered to be perpendicular to the x-y plane through the working wavelength. The refractive index (optical properties) of the metallic film (W) and the dielectric spacer (Al_2O_3) was taken from the default material list of the software.

In the course of the numerical analysis, two portswere considered. The first port was known as the in-port, which produced electromagnetic waves, and the second port was called the out-port. From the simulation results, the Scattering parameters (S-parameters), were gathered, they discussed more comprehensively on figure 4 below. We assume that no transmittance occurred, as the back of the reflector was made by W. Thus, we can calculate the reflection coefficient based on the S-parameter of S_{11}; S_{11} meant the signal ratio between the incident wave and the reflected wave. Consequently, we can calculate reflectivity as:

$$\rho = 1 - |\Gamma|^2 = 1 - |S_{11}|^2 \qquad (1)$$

Where,ρ and Γ are reflectivity and reflection coefficient, respectively. In addition, we also derive the absorptivity and emissivity based on Kirchhoff’s law which states that the emissivity of an object is equal to its absorptivity for a given frequency, polarization, and direction, with the assumption of no transmittance as follows:

$$\mathcal{E}(\lambda) = \alpha(\lambda) = 1 - \rho(\lambda) \qquad (2)$$

Finally, we evaluate the emissivity based on absorptivity from the simulation results. There are number of considerations that should be taken into account when building a COMSOL model. In particular, symmetry should be used as often as possible as this will significantly reduce the simulation run time. The following guidelines are an attempt to outline some basic considerations for building the types of suggested geometry: Model wizard, 3D, Optics, Wave optics, EMWFD, Add, Study, Wavelength domain, Done.

Port and Scattering parameters

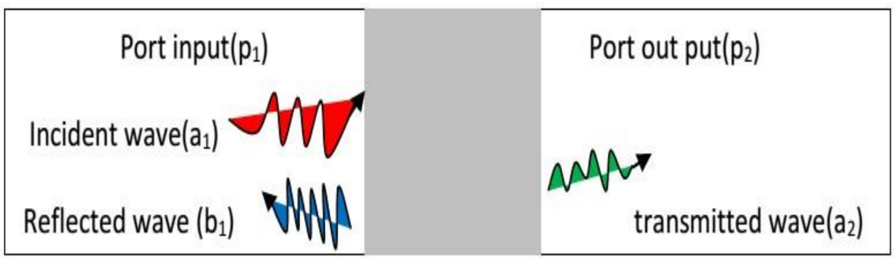


Figure 4 Showing port and scattering parameters. Port input (p_1) the left hand side, port output (p_2) the right hand side. Incident wave (a_1) and reflected wave (b_1) in p_1, transmitted wave (a_2) in p_2

S – Parameter

S_{11} reflected signal port 1 $\left(\frac{b_1}{a_1}\right)$

S_{21} transmitted signal port 2 $\left(\frac{b_2}{a_1}\right)$

$z = \pm\sqrt{\frac{(1+S_{11})^2 - {S_{21}}^2}{(1-S_{11})^2 - {S_{21}}^2}}$ S_{21} goes to zero is controlled by the ground

$z = \pm\sqrt{\frac{(1+S_{11})^2}{(1-S_{11})^2}}$ When s_{21} goes to zero it is called impedance match

$\mu_{eff} = nz$ $\varepsilon_{eff} = \frac{n}{z}$ $z = \sqrt{\frac{\mu_{eff}}{\varepsilon_{eff}}}$ where n is refraction index

3.2 Physical Mechanism of absorption

There are several physical mechanism that can augment the absorption or emission of radiation. In this section we discuss a number of these technique considered in the suggested emitter.

Surface Plasmon polariton (SPP): Surface plasmon polariton are one of excitation mechanism that formed between two interfaces when the two medium have opposite electric permittivity (i.e. when one medium has positive and the other has negative permittivity). In this study SPP is created between the interface of metal and dielectric (W-Al_2O_3). There is an exponentially decrease in amplitude perpendicular to the normal and propagation in parallel with the interface. SPPs are perfect imaging because Plasmon remains stationary. Metals are usually known to be perfect reflectors but when they are structured on a scale of the wavelength, light reflection fades away and enhanced absorption occurs with a sharp spectrum much narrower than that of a blackbody due to excitation of resonant modes confined in the sub wavelength metallic cavities or excitation of surface plasmon polariton (SPPs) on the corrugated metal surfaces (Tong et al., 2015).

Magnetic polariton (MP): Magnetic polariton are one of excitations mechanism that created in the dielectric layer of the metamaterial because of impedance match. Due to the existence of free charge on the ground layer W or the upper layer W there is a net flow of electric current in the dielectric layer which resulted in induced magnetic field. This is known as excitation of magnetic polariton. MP can powerfully localize electromagnetic energy in the dielectric layer of the designed metamaterial. In our work this physical absorption mechanism was highly considered.

4. RESULT AND DISCUSSION

The metamaterial emitter designed has a three-layer structure as demonstrated in Figure 5 underneath. The top most layer is composed of a tungsten array arranged in a square lattice with a periodicity of *P*. W has been used for high temperature applications due to a high melting temperature (3695 K). Al_2O_3, also, has adequate melting temperature (2345` K) and, especially, good oxidation resistance (Woolf et al., 2018). A unit cell has a layer, designed from W and Al_2O_3 with height h_1 of top cone, a periodic distance P, a top radius r_2 and a bottom radius r_1. A thin film of Al_2O_3, thickness h_2, is designed on top of a W film of thickness h_3, which acts as a perfect reflector.

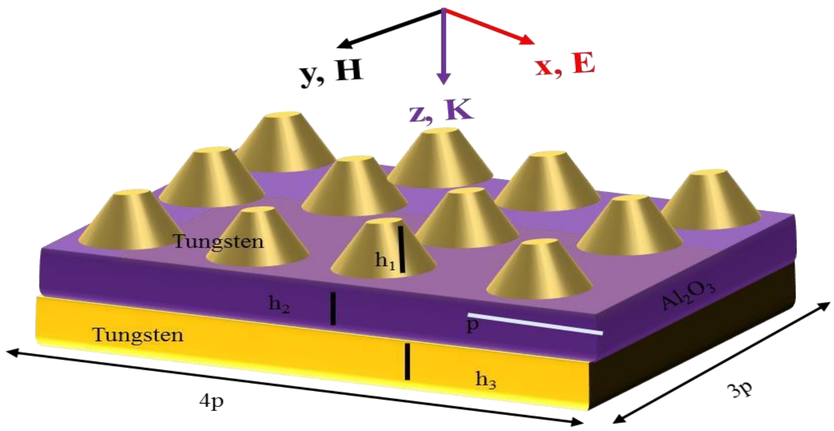


Figure 5 The schematic unit cells of proposed metamaterial nano-cone emitter with h_1 (nano-cone height), h_2 (dielectric thickness), h_3(tungsten thickness), w (width of the unit cell) and p (period of unit cell).

The top radius of the nano-cone is 50 nm, height of nano-cone is 100 nm and thickness of W film is 320 nm, these parameters were fixed in this study. In contrast width of the unit cell, bottom radius and thickness of dielectric layer are variables. Al_2O_3, is introduced as the spacer layer with thickness h_2. W, as substrate with a thickness of $h_3$was selected to prevent transmission of the incident light. Electromagnetic wavewas released, with frequency of 300 THz from the in port to our designed MM emitter by COMSOL Multiphysics as shown on figure 3. Through a lot of optimization and trial the below resultwere obtained. In the next sub topics the effect of variable parameters on the emissivity of the designed MM emitterwere discussed. Additionally, the effect of polar angle on emissivity and comparison with BB emitter were discussed. Finally, comparison between result of this study and different former papers were done.

4.1 Effect of width of the unit cell (w) on spectral emissivity of the emitter

The impact of width of the unit cell (w) on the spectral emissivity of a selective emitter is shown on figure 6. It may be seen from the figure that when w was 300 nm (blue dashed line) the peak is located at wavelength 2280 nm. As the width increase from 300 nm to 600 nm the emissivity peak change toward shorter wave length and it is broad band (500 nm – 1800 nm) accordingly. This result suggested that the width of the unit cell influences and maximizes the emissivity. In addition, w has strong effect on magnetic polariton peak around 860 nm. The widest and most near perfect broad band emissivity occurred when w = 600 nm (red dotted color), h_2=130 nm, r_1=150 nm.

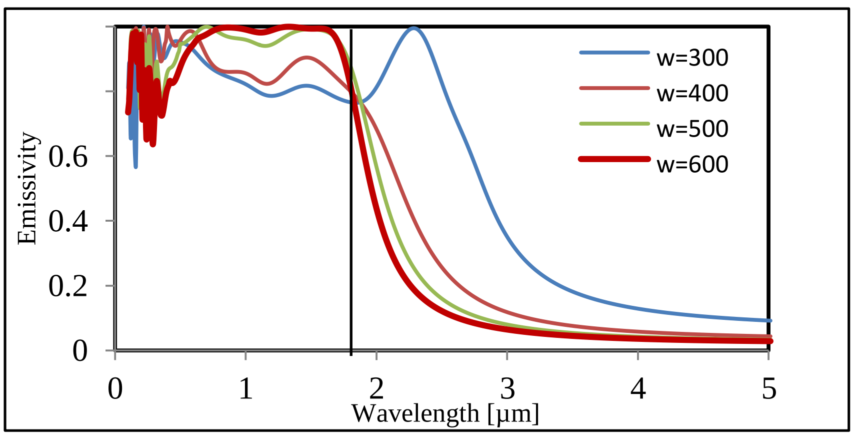


Figure 6 Effect of width of nano-cone unit cell on spectral emissivity of the proposed emitter with dimensions of w = 600 nm, h_1=100 nm, h_2 = 130 nm, h_3 = 320 nm, r_1 = 150 nm, r_2 = 50 nm.

The broadband perfect absorption can be credited to localized surface plasmonic resonance (LSPR), excited by the continuous diameter evolution from the apex to the base of the Nano cone, and the gap Plasmon's excited among the Nano cones, as well as in the spacer layer at longer wavelengths. Particularly, the coupling of the resonances is essentially behind the broadening of the absorption spectrum (Gu et al., 2015).

To explain the perfect broadband absorption, we analyzed the electromagnetic field around the nano-cone emitter. The results show that the absorber is not only correctly coupling to the incident electric field and magnetic field, but also can trap the input power into specific positions of the devices and absorb it, besides insensitivity to the polarized angle and incident angle (Pfiester et al., 2017). Moreover, the simulation demonstrates that the emitter achieves strong absorptions of 99.6983 % near 860nm.Several excitation mechanisms occurred with resonance frequencies; here, we considered magnetic polariton. This excitation method can powerfully localize the electromagnetic energy in the dielectric (Al_2O_3) layer, which was inserted between the first W layer and the ground film layer, as well as between two consecutive metal (W) layers (metal-dielectric-metal or W-Al_2O_3-W). Due to the existence of free charge on the thin film W surfaces of the ground layer, the first W layer, or between two sub-layers in the nano-cone, there was a net flow of oscillating electric currents, which resulted in induced magnetic fields. This mechanism was known as the excitation of magnetic polariton (MPs). The simultaneous collaboration of magnetic polariton (MP) resonances at a targeted wavelength created a near perfect broadband emissivity (Wang,H.,&Wang,L, 2013).

The property of electromagnetic in a metamaterial originated from the arrangement of the periodic unit cell and its geometry. The properties electromagnetic can be controlled by varying the parameters of the W and Al_2O_3 (Ferrari et al., 2014). The metamaterial design we present in this study has contained a metal-dielectric-metal structure (M-D-M), through which we can achieve resonances at different wavelengths due to the MPs, SPP, CMP, high intrinsic loss of tungsten and so on. For instance, at λ = 140 nm, 180 nm, 200 nm there is excitation of localized surface plasmon with amplitude of 0.9783, 0.9347, 0.974 respectively. Moreover SPP excited at λ = 160 nm with amplitude of 0.983. Additionally, at λ = 860 nm magnetic polariton is excited with amplitude of 0.996983. The enhanced broad band emissivity of our metamaterial is due to the combined resonance of these physical absorption mechanism. A nano-cone selective metamaterial emitter design was chosen for polarization-independent broadband emissivity.

The distribution of the normalized energy flow at wavelengths of 0.6 µm, 1.8 µm, and 5 µm, has depicted in the figure 7(a, b and c) below respectively. The energy and energy density carried by a travelling electromagnetic wave in space is related to electric and magnetic field. Poynting vector is the amount of energy flowing through a given unit area in the perpendicular direction to the incident energy per unit of time. Mathematically (S = Re (**E** x **H***)/2) (Ghanekar et al., 2016), where S is Poynting vector, Re is real, **E** is electric field and **H*** is complex conjugate of magnetic field. We recognized that the pointing vector field was fitted with the magnitude of emissivity, as showed in Figure 7. Our results revealed that, weak-energy density distribution at low emission and high-energy density distribution at high emission.

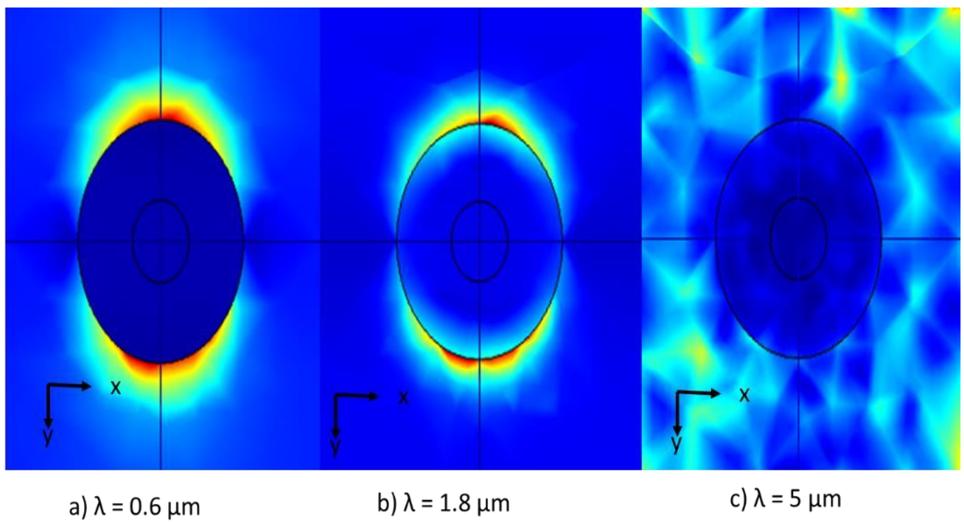


Figure 7 The distribution of energy flow (Poynting vector) at wavelengths of, a) 0.6 µm, b)1.8 µm and c) 5 µm within nano-cone designed metamaterial emitter: The results show that high spectral emissivity is close relation with high energy density distribution:(a) ε(0.6) = 0.993,(b) ε(1.8) = 0.823, (c)ε(λ) = 0.028 respectively.

4.2 Effect of bottom radius of nano-cone (r_1)

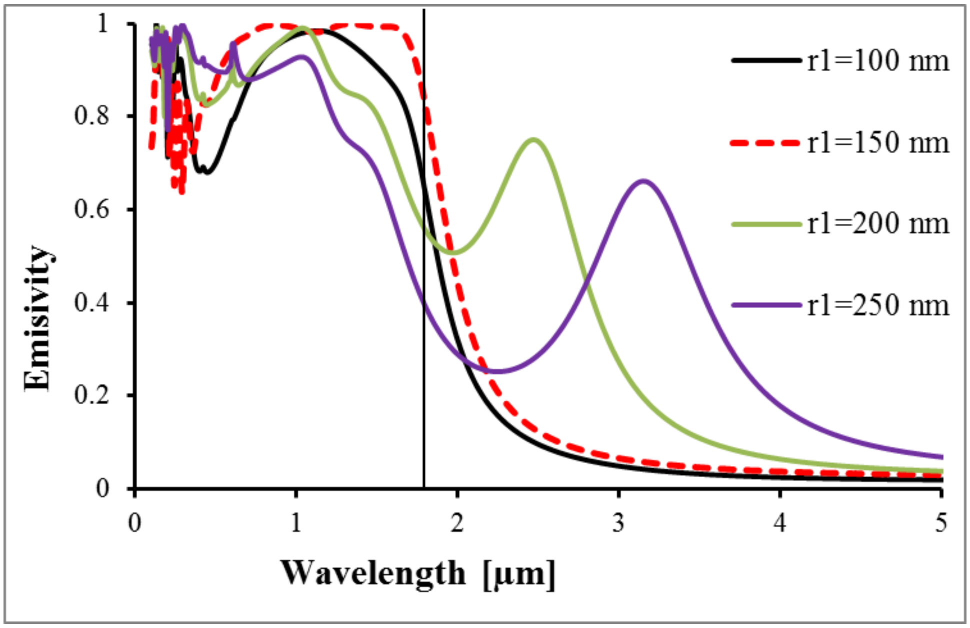


Figure 8 Schematic of the proposed metamaterial emitter emissivity dependence on $r_1$varies from 100 nm to 250 nm with 50 nm interval and w = 600 nm, h_1= 100 nm, h_2 = 130 nm, h_3 = 320 nm, r_2 = 50 nm.

Figure 8 showed that the dependence of emissivity of the designed metamaterial emitter on r_1. As can be seen, when radius r_1, increases from 100 nm to 150 nm, emissivity increases and become broad band at r_1 equal to 150 nm with consideration of cut-off wavelength. But as r_1 increases from 150 nm to 250 nm the emissivity start to decrease. Our result revealed that when w = 600 nm, h_2 = 130 nm r_1 = 150 nm perfect broad band and emission with consideration of cut-off wavelength was achieved. When r_1 was 150 nm, three major peaks were observed which caused by excitation of magnetic polariton in the dielectric between two W layer. The peaks are 860, 1330 and 1570 nm with amplitude of 0.996983, 0.999277 and 0.993662 respectively. At shorter wave length the peak seen can be formed because of excitation of SPP at the interface between metal and dielectric. These are located around 140, 160 and 200 nm with amplitude of 0.978324, 0.983176 and 0.974078 respectively.

4.3 Effect of thickness of dielectric (h_2)

As illustrated on the figure 9, the emissivity of the designed nano-cone metamaterial emitter depends on the thickness of the dielectric layer. When h_2 increases from 50 nm to 170 nm the emissivity slightly increases and change to the lower wavelength. The broad band and high emission obtained at h_2 = 130 nm. Furthermore, the average emissivity over 0.5 µm to 1.8 µm was 0.975. One can see from the figure that, when h_2= 130 nm there are three major peaks. These peaks correspond to wavelength 860, 1330 and 1570 nm with amplitude 0.996983, 0.999277 and 0.993662 respectively. These peaks were formed because of magnetic polariton. There is also high peak around λ = 140, 160 and 200 nm with amplitude of 0.978324, 0.983176, and 0.974078 respectively. These two peak are formed due to excitation of SPP.

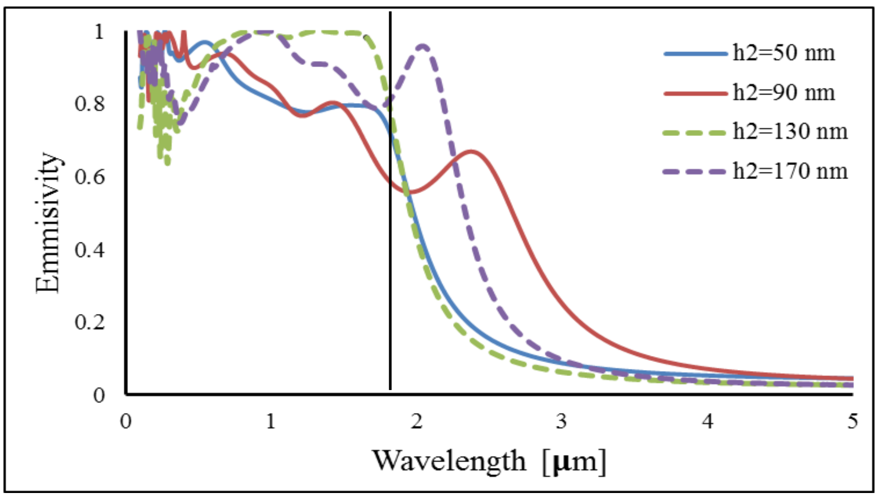


Figure 9 The dependence of emissivity of the proposed metamaterial emitter on thickness of dielectric (h_2). When h_2 varies from 50 nm to 170 nm, with other metamaterial parameters value w = 600 nm, h_1 =100 nm, h_3 = 320 nm, r_1 = 150 nm, r_2 = 50 nm.

4.4 Effect of polar angle on emissivity

The character of angular emissivity of TPV emitter is important due to polarization angles of electromagnetic waves (Teofilo et al., 2006). In our work we studied the effect of polarizations and azimuthal angles on spectral emissivity of the proposed selective metamaterial emitter at a normal polar angle ($\theta = 0^0$,$\o = 0°$). Nonetheless, the results suggest that the designed metamaterial emitter is independent of polarizations and azimuthal angles. This depicts that the proposed emitter is symmetric (nano-cone), which means that the polarization is independent. Figure 10showed optimized emissivity spectra, as the angular emissivity varied from 0^0 to 60^0 in 15^0 steps. The emissivity spectra at all angles were almost similar, but at $\theta = 60^0$, some differences were distinguished. Excitation of different physical mechanism was responsible for obtained wide angle spectral emissivity of nano cone metamaterial emitter. The average emissivity of our designed emitter at polar angle $\theta = 60^0$ was above 87.3% in the wavelength range of 0.16 μm to 1.8 μm, but decreased dramatically beyond the cut-off wavelength. These emission spectra of the presented emitter were well matched with the external quantum efficiency (EQE) of GaSb.

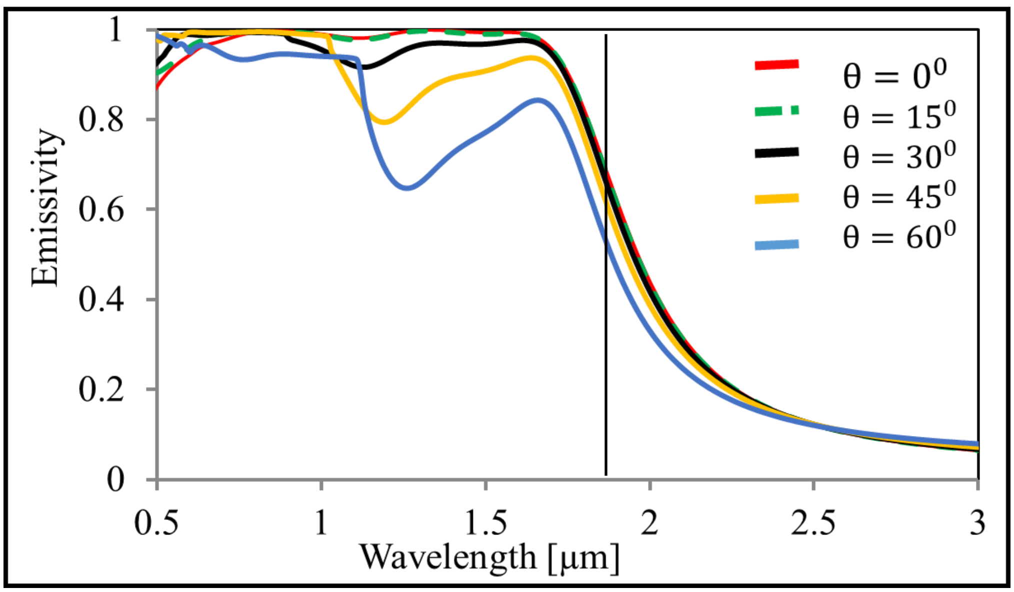


Figure 10. The emissivity of the proposed metamaterial at different angular emissivity, with dimensions of w=600 nm, h_1=100 nm, h_2=130 nm, h_3=320 nm, r_1=150 nm, r2=50 nm

4.5 Performance of designed metamaterial emitter

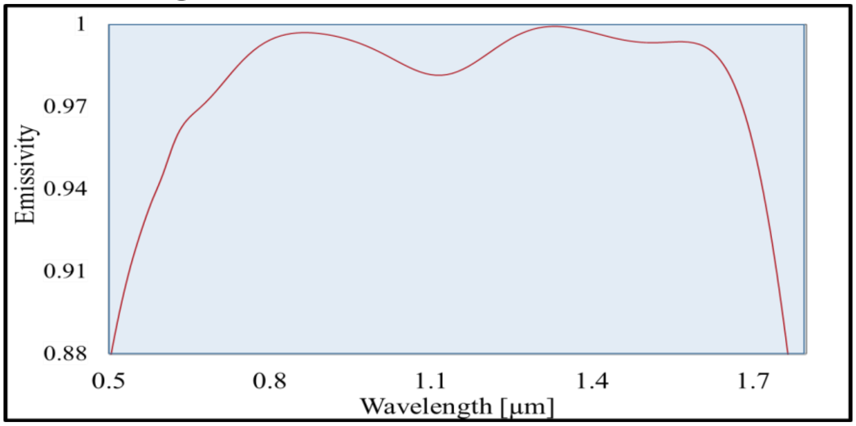


Figure 11 The emissivity spectra of the proposed metamaterial emitter with the shaded area is external quantum efficiency of GaSb.

The emissivity spectra of the proposed nano-cone metamaterial emitter, wherein the shaded area shows the EQE (Alcañiz et al., 2019) of GaSb (1.8 µm).From the figure one can be clearly seen that, we obtained a near perfect broadband emitter below the cut-off wavelength of GaSb, which dramatically decreased after the cut-off wavelength of 1.8 µm (see figure 12 below). In principle radiation energy below the band gap was considered as waste energy, while low radiation energy above bandgap was mandatory (convertible) energy, this is due to the existence of a band gap in the PV cell. Consequently, our result reveals that our emitter emit high convertible photons.

The graph depicts a nearly perfect broad band emissivity of wavelength less than 1800 nm, at that point and above from that point it dramatically falls.The average spectral emissivity at a wavelength range of 0.5 µm to 1.8 µm for band gap of GaSb PV cell was about 97.5%, showing the performance characteristics of the designed nano-cone emitter to be high. Thus, our optimized metamaterial emitter had a high performance. High emissivity above band gap of TPV cell, and low emissivity below band gap of TPV cells are the factors that needs attention when designing an emitter, mainly to increase the performance of a TPV system. In this study, we designed a nano-cone metamaterial that offers better spectral efficiency performance in a TPV system. In this study, we designed a nano-cone metamaterial that offers better spectral efficiency performance in a TPV system.

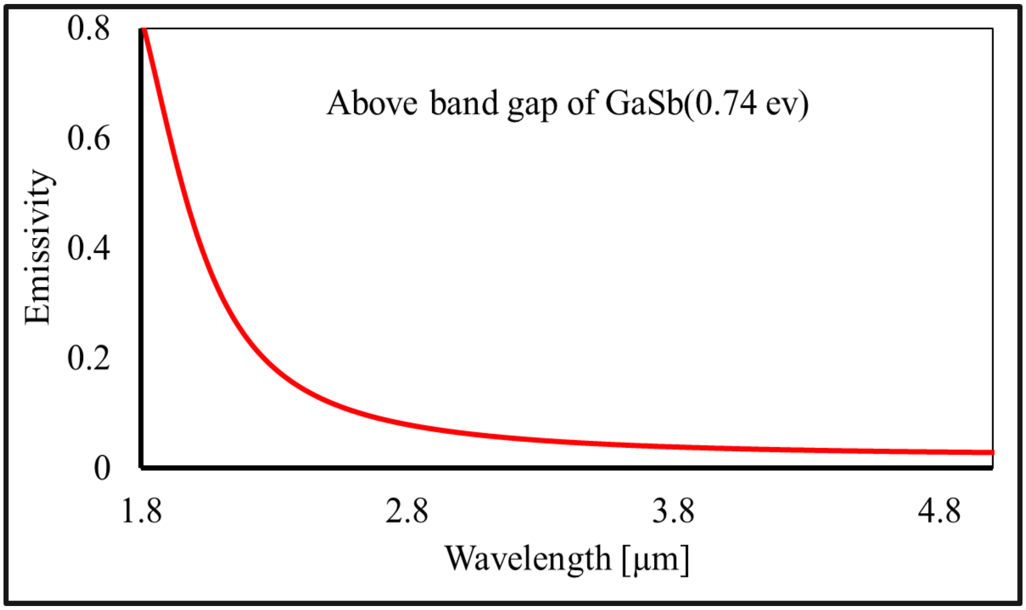


Figure 12 The emissivity spectra of proposed nano-cone metamaterial emitter above cut-off wavelength of GaSb (1.8 µm), with metamaterial parameter w = 600 nm, h_1 = 100 nm, h_2 = 130 nm, h_3 =320, r_1 = 150 nm, r_2 = 50 nm.

As illustrated on figure 12, above cut-off wave length or below band gap of GaSb, the designed metamaterial emitter emit very small photons, in other word out of band photons are suppressed. The emittance above 1.8 µm decreased dramatically and the average emissivity above this point is less than 0.05.

In order to evaluate the efficiency of an optimized emitter for a TPV cell, we have to analyze the efficiency of the TPV system. Mathematically the efficiency of a TPV system to convert radiated heat to electrical power is given by Equation (3) (Alcañiz et al., 2019):

$$\eta = \eta_{sp} \, . \, \eta_{pv} = {}^{P_{out}}/{P_{rad}} \qquad (3)$$

Where the spectral efficiency of the emitter is η_{sp}, η_{pv} is the efficiency of the photovoltaic cell, P_{out} is the maximum output power, and P_{rad} is the total radiant power from an emitter.

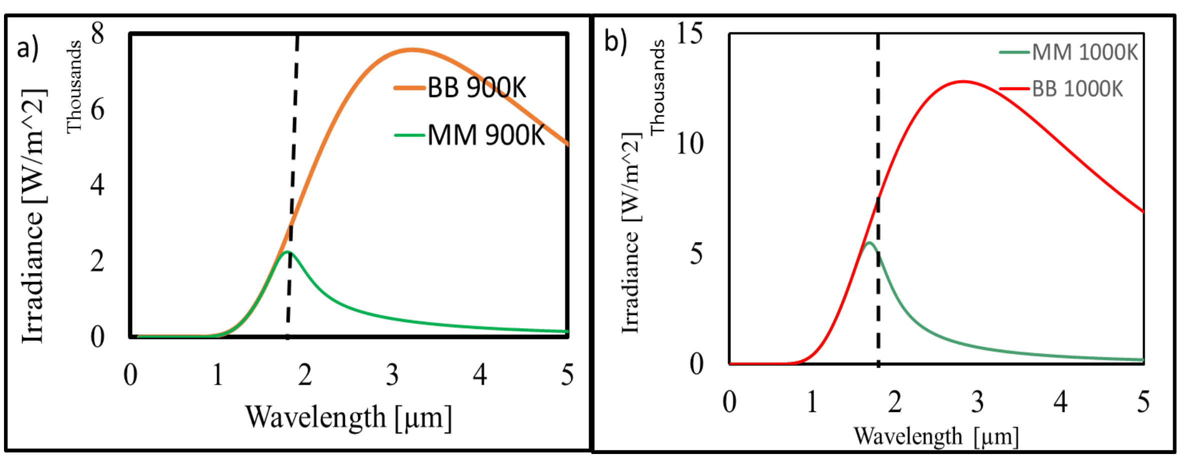
Spectral efficiency $\eta_{sp}$is defined by Equation (4) (Ghanekar et al., 2016; Pendharker et al., 2017):

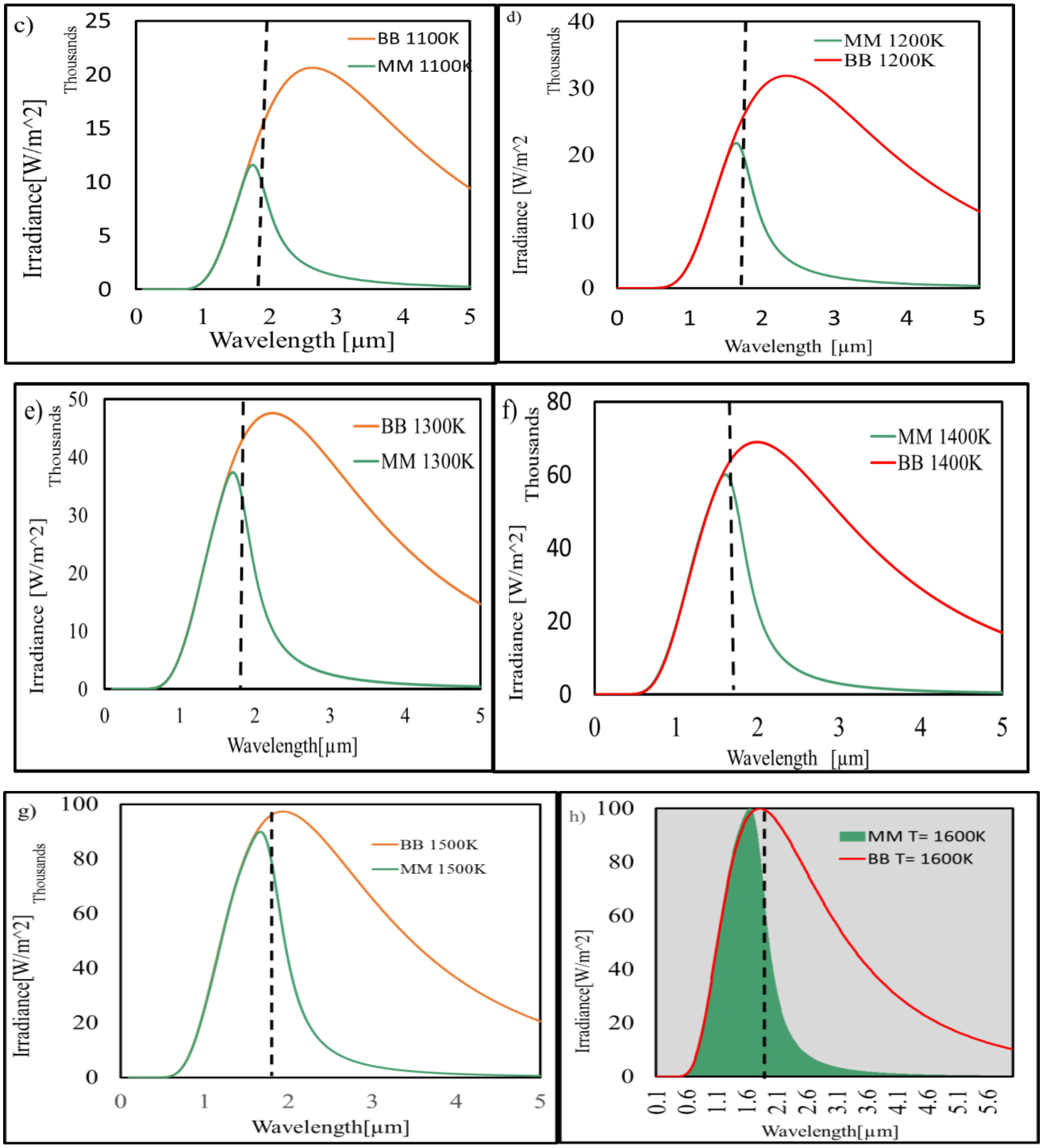
$$\eta_{sp} = \int_0^{\lambda_c} \frac{E(\lambda)\varepsilon(\lambda)d\lambda}{E(\lambda)\varepsilon(\lambda)d\lambda} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

$$E(\lambda) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{\lambda k_b T}-1}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

Where λ_c is the cut-off wavelength, **E(**$\boldsymbol{\lambda}$**)** is emission spectrum of a blackbody, $\boldsymbol{\varepsilon(\lambda)}$ is spectral emissivity of the presented selective metamaterial emitter, h is planks constant, c is speed of light, Kb is Boltzmann constant and T is temperature.

We broaden our study of the optimized nano-cone selective metamaterial emitter with a black body at different temperatures to compare spectral irradiance of both the designed selective emitter and the black body. Spectral efficiency can be calculated using Equation (4) AndE(λ) can be calculated by using equation (5). The best efficiency is achieved when the selective emitter has perfect emissivity below the cut-off wavelength and low emissivity above the cut-off wavelength. Figure 13(a-m) shows a comparison of the spectral irradiance of the black body with the selective emitter metamaterial at temperatures from 900 K to 2200 K. As the temperature increased, the spectral efficiency also increased; this indicate that the emission peak shifted to a lower wavelength as the temperature rose, which showed that the emission spectrum peak was above the band gap region. The optimized design of the emitter had h_1 = 100 nm, h_2 = 130 nm, h_3 = 320 nm, r_1 = 150 nm, r_2 = 50 nm and w = 600 nm of nano-cone and achieved high emissivity of TPV emitter.





c)
Thousands
Irradiance[W/m^2]
BB 1100K
MM 1100K
Wavelength [µm]
d)
Thousands
Irradiance [W/m^2
MM 1200K
BB 1200K
Wavelength [µm]
e)
Thousands
Irradiance [W/m^2]
BB 1300K
MM 1300K
Wavelength[µm]
f)
Thousands
Irradiance [W/m^2]
MM 1400K
BB 1400K
Wavelength [µm]
g)
Thousands
Irradiance[W/m^2]
BB 1500K
MM 1500K
Wavelength[µm]
h)
Irradiance[W/m^2]
MM T= 1600K
BB T= 1600K
Wavelength[µm]

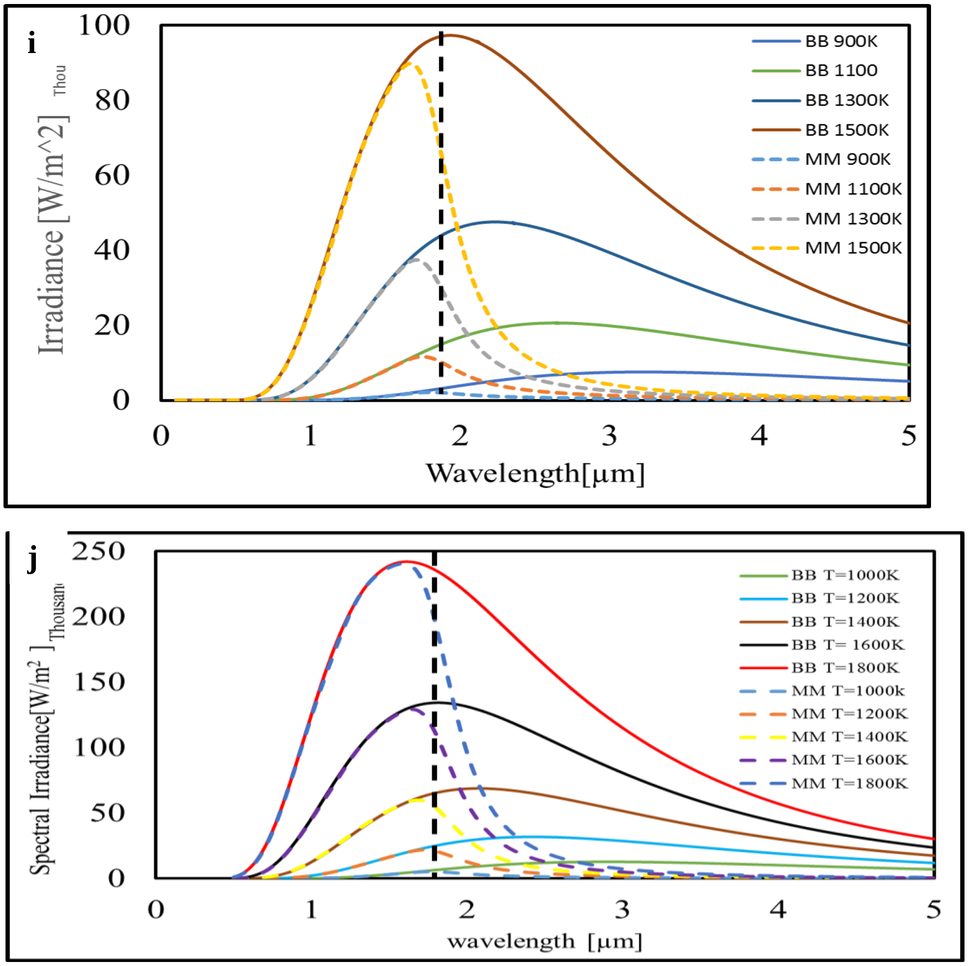


Figure 13 Comparison of the spectral irradiance of black body with the proposed selective emitter at different temperature, with (a–k) indicating BB and MM comparisons at the same temperature for each graph, while the last two sketch illustrate irradiance versus wavelength for both materials at different temperature on the same graph.

As illustrated in figure 13 above when we compare the suggested emitter with blackbody in terms of spectral emissivity at different temperature, the nano-cone we have designed exhibit selective emission above band gap. The vertical line on each graph indicates cutoff wavelength of GaSb which is 1.8 µm. In contrast to, black body above this line the spectra of suggested MM decreased dramatically, this shows us the selectivity of the emitter. The green shaded area on the graph h, i, j, and k are the emissivity of the designed emitter. The spectral efficiency of emitter at different temperature which calculated according to equation (4) above can be given in the table below.

Table 1 spectral efficiency of designed emitter calculated at different temperature

Temperature (K)	Spectral efficiency
900	3.8 %
1000	8.4 %
1100	15.5 %
1200	24.9 %
1300	36.6 %
1400	50.3 %
1500	64.6 %
1600	80 %

Table 2 depicts a comparison between the state-of-the-art metamaterial emitters and the proposed design in terms of used materials, and obtained emissivity. It may be seen that the achieved emissivity range is larger than those reported in the above table. Further, high emissivity of 0.975 is achieved over the studied wavelength range. Emitter with cylindrical geared geometry from tungsten and aluminum oxide has been designed(Jiang et al., 2019). Wang and Zhang (2012), design emitter from tungsten and SiO_2 in circular geometry. Song et al. (2015), has also design emitter in square geometry from Tungsten and Al_2O_3. Their emissivity and range of wavelength they absorb were given in the tabular form below.

Table 2 comparison between the designed emitter and other emitters at room temperature.

Reference	Materials		Emissivity
	Metals	Dielectric	
Jiang et al. (2019)	Tungsten	Al_2O_3	0.91 (500–2400 nm)
Wang and Zhang (2012)	Tungsten	SiO_2	0.8 (620–1980 nm)
Song et al. (2015)	Tungsten	SiO2	0.95 (600–1900 nm)
This study	Tungsten	Al_2O_3	0.975(500-1800 nm)

5. CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

In this work, we proposed and numerically analyzed metamaterial selective emitter for TPV applications. The metamaterial showed polarization and azimuthal angle independent selective emission. We considered GaSb with energy band gap of 0.74 eV and a cut-off wavelength of 1.8 µm. Geometric parameters such as the bottom and top radius of the nano-cone, width of nano-cone were studied and optimized to achieve perfect broadband emissivity above the band gap energy. The proposed metamaterial increased the efficiency of the TPV system. Efficiency was also enhanced when all radiated photons were absorbed by the TPV cell. The proposed metamaterial emitter exhibited an enhanced near perfect broadband and a wide-angle average emissivity of above 97.5% between the wavelengths of 0.5 µm to 1.8 µm on optimization of the geometric parameters. This result contributed to the enhancement of the TPV performance. Additionally, the spectral efficiency of the designed nano-cone emitter we had obtained was 3.79 %, 8.4 %, 15.49 %, 24.9 %, 36.6 %, 50.3 %, 64.6 %, 80 % with GaSb cell of 1.8 µm or 0.74 eV band gap at 900 K, 1000K, 1100K, 1200K, 1300K, 1400K, 1500K and 1600K respectively. In general at high temperature TPV efficiency was high as spectral efficiency at 900K is 3.79% and at 1600K is 80 %. This result showed us the TPV system requires high temperature to enhance efficiency.

5.2 RECOMMENDATION

Quick exhaustion of fossil fuels owing to the increasing necessity for energy has resulted in a global alarm to advance energy conversion efficiency. Up to now, the energy conversion of typical fossil fuel power generation plants remains relatively low and a large amount of energy is wasted in the form of heat, leading to global warming issues. Reusing and recovering even a small portion of energy sufferers could provide a huge impact on energy saving and reduce the dependence on fossil fuels. TPV system seems to be a potential candidate to capture, recover, and convert waste heat energy into useful electricity. Each component in the TPV system including TPV generator, thermal emitter, and TPV cells is vital and can be engineered to achieve a better heat-to-electricity conversion efficiency. All of these components should be designed properly to obtain high efficiency, particularly I recommend that, emitter of TPV requires a further study. From our work as temperature increases the efficiency of TPV also increases. To exploit materials at high temperature, temperature and thermal resistant materials will need the further study.

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