THERMOPHOTOVOLTAIC EMITTER BASED ON FREE LITHOGRAPHY THIN FILM NANO STRUCTURE METAMATERIALS

Muktar Osman Husein

A Thesis Submitted to the Department of Applied Physics,

School of Applied Natural Science

Presented in Partial Fulfillment of the Requirement of Master of Science Degree in Applied physics (Material Physics)

Office of Graduate Studies

Adama Science and Technology University

June, 2022
Adama, Ethiopia

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Declaration

I hereby declare that this Master Thesis entitled "Thermophotovoltaic emitter based on free lithography thin film Nano structure metamaterials" 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

Muktar Osman	_______________	________________
Name of the student	Signature	Date

Recommendation

We, the advisors of this thesis, hereby certify that we have read the revised version of the thesis entitled "Thermo photo voltaic emitter based on free lithography thin film Nano structure metamaterials" prepared under our guidance by Muktar Osman submitted in partial fulfillment of the requirements for the degree of Master's of Science in Applied Physics (Material physics). Therefore, we recommend the submission of revised version of the thesis to the department following the applicable procedures.

Dr. Fekadu Tolessa	____________________	________________
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Dr. Gashaw Beyene	____________________	________________
Co-advisor	Signature	Date

Approval Page

We, the advisors of the thesis entitled "Thermophotovoltaic emitter based on free lithography thin film Nano structure metamaterials" and developed by Muktar Osman, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Dr. Fekadu Tolessa	__________________	__________________
Major Advisor	Signature	Date
Dr. Gashaw Beyene	__________________	__________________
Co-advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis Muktar Osman have read and evaluated the thesis entitled "Thermophotovoltaic emitter based on free lithography thin film Nano structure metamaterials" 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 Applied Physics (Material physics).

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LIST OF ACRONOMY

TPV-Thermophotovoltaic	EBL-Electron Beam Lithography
2D- Two dimension3 D- Three dimension	NSL-Nano sphere Lithography
RIE-Reactive Ion etching	µm-micro meter -electron volt
Phcs –Photonic crystal	XRL-X-ray Lithography
MDM- metal dielectric –metal	HCP-hexagonal-closed-packed
CCM-Colloidal crystal mask	QE-Quantum efficiency
MIM-Metal-Insulator-Metal	Eg Energy band gap
FDTD- Finite- difference-time-domain	MP-magnetic poloritan
SEM-Scanning electron microscope	EM-Electromagnet
STPV-solar Thermo photo voltaic	AR- antireflection
BB -Black body	EQE External quantum efficiency
LSP Localized surface plasmon polariton	MM Metamaterial
MP Magnetic polariton	TPV Thermo photovoltaic
PV Photovoltaic	
SPP Surface plasmon polariton	λ c Cut-off wavelength

Abstract

The present study has focused on designing and enhancing the efficiency of Thermophotovoltaic emitter by free lithography method. The all selective band and wide angle emissivity below cut-off wavelength were obtained. The metamaterial nano-hole was designed from Titanium and Aluminum oxide by using COMSOL Multiphysics software. To get broadband emission, the geometric parameter such as the radius, thickness of dielectric and width of unit cell were optimized, while parameters such as the thickness of nano hole and ground Titanium thickness were fixed in this study. The numerical simulation results showed that the proposed emitter had an average emissivity of 0.964 within the targeted wavelength of 3μm. We obtained high emissivity because of excitation physical mechanism of absorption like Surface Plasmon polariton and magnetic polariton, unlike blackbody the designed nano -hole metamaterial emitter emit only selective wavelength of radiation. Moreover, the designed nano -hole metamaterial emitter obtained *64.53%, 71.74%, 75.47%, 77.61%, 78.96%, 79.87%, 80.51%, 80.99% and 81.36%with InAsSbP cell of 3μm or 0.41eV band gap at 600 K, 800 K, 1000 K, 1200 K, 1400 K, 1600 K, 1800 K , 2000 K and 2200 K respectively. In general as temperature increases from 600 K to 2200 K the spectral efficiency increase In general at high temperature TPV efficiency was high as spectral efficiency at 2200 K is 81.36% and at 1000 K is 75.47%. This result showed us the TPV system requires high temperature to enhance efficiency*.

Keywords; Thermophotovoltaic (TPV), free lithography, Spectral efficiency, Metamaterial (MTM)

CHAPTER-1

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. Thermophotovoltaic (TPV) systems convert thermal energy directly into electricity and hold promise in waste heat recovery, solar energy harvesting, and space applications. ATPV system is environmentally-friendly and requires two key components. The PV cell is responsible for converting the thermal radiation from the emitter into electricity. TPV cells and it converts thermal radiation directly in to electrical power with the aid of photovoltaic (PV) effect .The TPV systems have been considered a promising way of recycling waste heat, harvesting solar energy, and space applications *(B. Zhao et al, 2013).*

TTPV devices collect electromagnetic energy and transform it to electrical energy (Palfinger et al., 2003).The role of the thermal radiator is to convert solar or waste heat to thermal radiation, from which a PV cell generates electricity using the photovoltaic effect; however, the conversion of electromagnetic energy to electrical power happens only when the photon energy is higher than the energy band gap of the PV cell.

If the TPV emitter has high emissivity within the targeted wavelength region and low emissivity above cut-off wavelength, the PV cell can effectively operate to generate electrical power with relatively low thermal loss. 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 of materials such; as metals and plastics. In order to further improve the utilization of solar power, a large number of studies have been carried out. One idea is to fabricate multi-junction PV cells with multiple semiconductor materials to match the solar spectrum, broadening the effective spectral width by splicing multiple band gap materials *(*Maremi et al. 2018).

An ideal TPV emitter should have unity emissivity through the spectra range from ultraviolet to near-infrared. The zero emissivity in the mid-infrared is highly recommended for minimizing the heat loss from self-emission. The TPV cells are quiet, pollution-free, and portable with low-maintenance cost. Therefore, the conversion efficiency can be greatly enhanced where the theoretical maximum efficiency for solar TPV devices is equal to 85.4% of the efficiency (Abdel-Latif et al 2021).

The metamaterial selective emitters have some advantages over traditional emitters. For example, luminescent bands of rare earth oxides have been used for selective emission, but the realization of the perfect emissivity is limited by the lack of such materials. Photonic crystals are considered as another candidate for selective emitters in energy conversion system. However the emitters usually do not have very high emittance because of their nonresonant nature with metamaterial selective emitter, the loss caused by non-adequate photon energies and radiative recombination can be avoided *(Maowen et.al, 2013).*

Nanofabrication is the design and manufacture of devices with dimensions measured in nanometers. One nanometer is 10^{-9} meter, or a millionth of a millimeter. The processes and methods of nanofabrication include the formation of micro/nano-structures with minimal dimensions. It also provides precise control over material composition and allows multi-functional devices with unique characteristics less than 10 nm scale. In the past two decades, several nano-manufacturing techniques have been developed which address high expectations relating to nano-technology. Nanofabrication can be categorized into two main categories ; Bottom-up and Top-down nanofabrication.

Bottom-up nanofabrication

The top-down nanofabrication techniques, a process that starts from a smaller piece and subsequently uses finer and finer tools for creating correspondingly larger structures Various lithography techniques are known as top-down processes. These techniques are used to produce Nano scale structures in various applications in the microelectronics industries (NSL) (Cloots et al 2013).

Top-down nanofabrication

a process that starts from a large piece and subsequently uses finer and finer tools for creating correspondingly smaller structures. These approaches use larger (macroscopic) initial structures, which can be externally-controlled in the processing of nanostructures few methods of a bottom-up process are explained Sol-gel, Colloidal, Electro deposition, Solution phase reductions

1.2 Statement of the problem

Thermo photovoltaic systems convert thermal energy directly into electricity and hold promise with heat recovery. Before converting it to electricity it can be change to thermal emission by using emitter. Emitter of TPV is playing crucial role in conversion efficiency and power generation (Maremi et al. 2018).

To increase the emissivity of emitter selective emitters are important metamaterials meta materials are fabricated by different fabrication techniques, photo lithography, electron beam lithography (EBL), deep UV lithography, reactive ion etching (RIE) and Nano sphere lithography (NSL) or free lithography most fabrication techniques are expensive and time consuming, but free lithography is inexpensive techniques (Cloots et al2013).This is why we were interested to select free lithography to design high spectral efficient selective metamaterial emitter for high temperature energy harvesting. Therefore, the study was guided by the following questions.

1. How to design metamaterial using free lithography methods?

2. How to enhance high efficiency via selective emitter?

3. What is the role of metamaterial emitter in thermophotovoltaic system?

4. Which fabrication technique is easier?

1.3 Objective of the study

1.3.1 General objective

The general objective of this work is to study numerically high spectral efficiency and high temperature energy harvesting metamaterial emitter to improve Thermophotovoltaic Performance.

1.3.2 Specific Objectives

The specific objectives are:

- To increase emissivity near to unity below cut-off wave length of 3µm And reduce the emissivity near to zero above cut-off wave length of 3µm.
- To enhance high spectral efficiency of designed metamaterial emitter
- Parameter optimization to improve spectral efficiency.

1.4 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 at 3µm were enhanced and photons above 3µm had been suppressed. To obtain a high-efficiency emitter, a metal-dielectric–metal (MDM)-structured metasurface is employed for the studies Conventional MDM metasurfaces were designed for room temperature applications. Therefore MDM metasurfaces are usually fabricated with noble metals. But recent studies successfully demonstrated MDM metasurfaces for high temperature applications. Tungsten (W) is a promising material for high temperature applications because it has a high melting point previously different metamaterial emitter is fabricated to increase the efficiency of TPV system. Most fabrication techniques expensive and time consuming, but free lithography is inexpensive method In general, this work will contribute to the knowledge for future development metamaterial emitter of TPV system.

CHAPTER-2

2 Review Literature

2.1 Thermophotovoltaic (TPV)

Renewable and nonrenewable resources are energy sources that human society uses to function on a daily basis. The difference between these two types of resources is that renewable resources can naturally replenish themselves while nonrenewable resources cannot. This means that nonrenewable resources are limited in supply and cannot be used sustainably. There are four major types of nonrenewable resources: oil, natural gas, coal, and nuclear energy. 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, 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 (Gaurav Sahu, et al 2020).

The heat source brings the emitter to high temperature ($\geq$1000 K), causing the emitter to emit thermal radiation, which is absorbed and converted to electricity by the PV cell. Thermo photovoltaic is absorbing the incident thermal energy with a wavelength selective absorber and emitting that energy with a thermal emitter. The thermal-to-electricity conversion of TPV is depending on the photocurrent generation by those photons having energy beyond the electronic band gap. 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 *(*Wang XJ et al. 2009).

2.2 Components of TPV Systems

TPV systems are systems that convert thermal energy into electrical energy. These systems are an alternative to current electrical energy production. *(Xu Y et al.* 2014*)*.In TPV systems, the sun can be used as a heat source as well as other heat sources such as combustion systems and fuels. The heat source is used to obtain photons in TPV systems. While the selective emitter is used to increase the system efficiency, the filter sends back the selective emitter by reflecting back the non-energized radiation. Photovoltaic cells convert photon energy from the emitter into electricity energy. Thermophotovoltaic (TPV) devices harvest electromagnetic energy and convert it to electrical energy *(Woolf et.al, 2018).*

In order to design and optimize a TPV system, an understanding of the main components of a TPV device and how they interact is needed (Gaurav Sahu, et al 2020). Heat source, selective emitter and PV cells are the fundamental parts of a TPV system. The heat source is the source of photons such as solar or waste heat energies which can be converted by the selective emitter into thermal radiation, from which a TPV cell generates electricity using the thermal radiation from selective emitter *(Woolf et.al, 2018).*

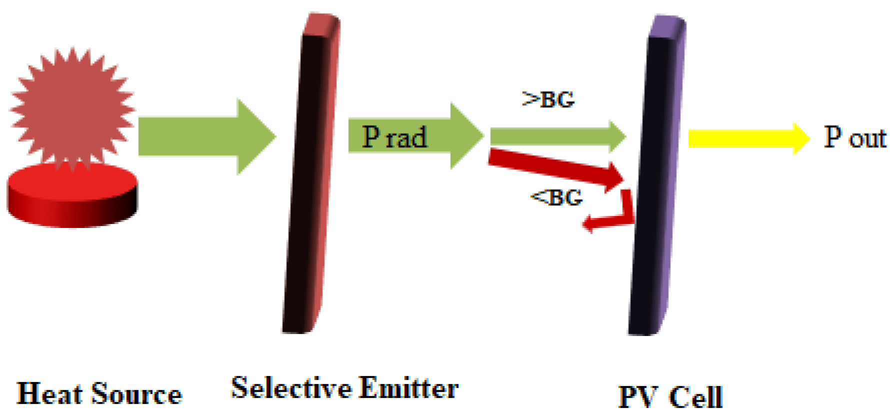


Figure 1: Basic schematic diagram of a TPV system.

2.2.1 The heat source

The heat source is the basic and fundamental components of TPV device. These sources include sunlight, radioactive isotopes (*β*-photons) and flaming combustion. The heat energy from the heat source passes through the selective emitter and cell *(.Xu Y et al.* 2014*).*

2.2.2 Photo voltaic cells

Photovoltaic cells absorb photons from the emitter and convert them into electrical energy. The necessity of absorbing as many photons as possible obligates the use of materials with low band gap *Xu Y et al. (*2014*).*Low band gap PV cells are one critical component to achieve the highest conversion efficiency in TPV systems. Each semiconductor has unique band gap energy, determined by its crystalline structure. Ternary and quaternary compounds as InGaAs and InAsSbP are the ones showing the lowest Eg and, therefore, being the ideal candidates for TPV systems *(*Claudio F. et al 2014).

2.2.3 Emitter

Emitter is any material that is heated up to a high temperature particularly, useful emitter is a selective emitter, which preferentially emits in a specific wavelength region. The system is used to increase system efficiency (Durisch. W et al 2008). Thermal emitters typically operate at high temperatures for this reason; the emitter must be made of high melting point materials, such as tungsten, tantalum Gaurav Sahu, et al (2020). Selective emitters are more popular as modern TPV system components as they only emit a narrow range of wavelengths, resulting in higher conversion efficiencies (Vandervelde et al 2017*).*

Selective emitter is a body that emits all its radiation in a narrow wavelength range well matched to the receiver band gap wavelength. 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. Several authors focused on this kind of emitters and proposed genuine solutions based on 1D photonic crystal *(*Kassakiann *J.* et al 2005*)* or random multilayer structures (Mulet J.P et al 2004). Others proposed solutions based on 2D and 3D nanostructure materials (Kassakiann *J.* et al (2005).Selective emitters radiate photons in a specific wavelength band that is spectrally matched to PV cells and increase the efficiency of the system(*Xu Y et al.* 2014).

2.3 Material used for the emitter

Most of work on TPV emitters has focused on achieving good optical performance, but there has been little consideration of the challenges associated with implementing the emitter in and operating a TPV system. The emitter is constructed from materials such as polycrystalline, rare earth materials, photonic crystals and metamaterials.

2.3.1 Rare earth materials

Rare-earth-based emitters have naturally selective emission that can be matched to available PV cell technologies. For instance, erbium oxide and ytterbium oxide can be fabricated either in a mantle structure, coated on a foam ceramic or on $MoSi_2$ substrates and can be used as thermal emitters whose selective radiation band matches well with Si and Ge PV cell band gaps (*B.J.* et al 2016).

Emitters Rare earth based SE are a common subject of study as rare earths present unique optical properties due to some radiative transitions between energy levels. These materials also present very high melting points and high temperature stability. The first rare earth SE was polycrystalline in structure. Rare earth oxide emitters resulting in much lower spectral emittance outside the emission bands. As an example, an Yb_2O_3 emitter heated at 1700 K presents a sharp emission peak centered at (1.27eV) with 0.85 emissivity. Another compound as Er_2O_3, presents a selective emission peak at (0.8eV) with 0.82 emissivity (Gaurav Sahu, et al 2020).

2.3.2 Photonic crystals (PhCs)

PhCs is another type of selective solar absorber. PhCs are characterized by a photonic band gap, a selected range of wavelengths that are strongly reflected. Combined with suitable absorber, this can give rise to selective solar absorption. The absorption cutoff can be tuned by adjusting the dimensions of the periodic structure, and thus shifting the photonic band gap. Furthermore, PhCs can also enhance absorption via quality factor *(B.J.* et al 2016*)*. Photonic crystals (PhCs) offer a more engineer able option of selective emitter than what is available naturally. A photonic crystal is an array of multiple materials that repeats in one, two or three dimensions the dimensions of repetition determine how many planes of photonic response will be induced while the size of the repeated geometries will change what wavelength is affected *(*Hao. Y. et al 2017*)*.

2.3.3 Metamaterial

Metamaterials (MTM) are the artificial materials which have exotic properties of electromagnetic which does not show in natural material. MTM are also called artificially composite material. It is a wonderful discovery of modern science that has been able to attract researchers (Gaurav Sahu, et al 2020). In recent decades, scientists have spent a lot of time and effort in researching new materials and physical phenomena in order to cater to modern life. There are many new artificial materials that have been found to replace the earlier natural materials, which have brought significant benefits in various areas of life.

MTM are among those new materials that are made up of the arrangement of metal structures on the surface of dielectric substrates. Therefore, the physical properties of MTM depend on their structures more than the component that makes up them. In fact, materials with negative permittivity and permeability were first studied in 1968 by Veselago, who termed this material with left-hand (LH) media, which is formed by triad's of vectors: electric field, magnetic field, and phase propagation (Wang. L. et al 2018*)*.

In designing MTM s, we carefully engineer a periodic array of unit cells to create an artificially structured composite material. MTMs free us from the constraints of naturally occurring materials and allow for full control over light flow through the design of artificial materials. 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 (Maremi et al. 2018).

2.4 Properties of MTM

Many definitions are suggested about electromagnetic MTMs, all of which can give us an understanding of electromagnetic MTM as follows. Electromagnetic MTMs are artificial material that are created by arranging homogeneous metal structures and having unusual properties that natural materials are not available. The arrangement of atoms can be in an orderly or chaotic manner, the purpose of which is to create the desired macro characteristics for the MTM (Wang. L. et al 2018*)*

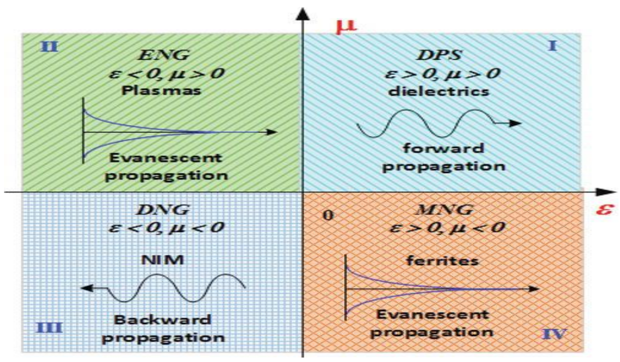


Figure 2: The classification of electromagnetic MTMs based on signs of the ε and μ.

In the quadrant I, both parameters ε and μ are positive, and are called Double Positive (DPS) or right-handed medium (RHM). These materials can be found in nature, such as dielectric materials, in which the electromagnetic waves can propagate. In the quadrant II, the parameters are $\varepsilon < 0$—negative, and $\mu > 0$—positive and such material is called as epsilon negative (ENG) medium, and is represented by plasma. In the quadrant III, parameters $\varepsilon < 0$—negative, and $\mu < 0$—negative, this region is called double-negative (DNG) or left-handed medium (LHM), and such material could not be found in nature. The quadrant IV $\varepsilon > 0$—positive, and $\mu < 0$—negative, and such material is called μ—negative (MNG), represented by ferrite materials. Such medium has below plasma frequency. Most waves can propagate in two mediums, namely: at region I and III. Non-propagating evanescent waves are found in regions II and IV (Sailing He1 et al 2018*)*

2.5 Types of Metamaterials

I. Electromagnetic Metamaterials

Electromagnetic MTM (EM) is having the composition of traces and particles in a dielectric matrix; this EM MTM s has a zero or negative refractive index. Applications like beam stereos, antenna radomes, modulators, lenses, microwave couplers and band-pass filters are widely using these materials. The single-negative MTM s defines electromagnetic MTMs which have either negative permeability or negative permittivity, but not both (Gaurav Sahu, et al 2020).

II. Photonic Metamaterials

These types of MTM deal with design of optical frequencies using photonic MTM. Photonic MTM has zero indexes of refraction, and this MTM is the current research area in the field of optics. A Photonic MTM is an artificially fabricated, sub wavelength, periodic structure, designed to interact with optical frequencies. The sub-wavelength period distinguishes the photonic MTM from photonic band gap structures (Gaurav Sahu, et al 2020).

III. Acoustic Metamaterials

Two or three distinct materials with different mass densities and bulk modulus are made up of acoustic MTM; these types of MTM s have negative effective mass densities and bulk modulus. These are the MTM s produced artificially to steer, regulate and monitor sound waves in liquid, for solids, for gases. It is possible to specifically control any kind of sound waves by manipulating the bulk modulus and density of mass.

Acoustic MTM s: Negative Refraction, Imaging, Lensing and Cloaking

IV. Mechanical Metamaterials

Mechanical MTM s is the artificial composite MTM which is consisting of different types of mechanical properties; MTM is having negative Poisson’s ratio, negative elastic modulus, zero shear modulus and frictional properties. This is made up of material with inclusion of secondary materials or a controlled pored structure *(M. A et.al, 2010).*

Kirchhoff law of thermal radiation

Kirchhoff's law is generally considered to be the first amongst the laws governing thermal emission. Kirchhoff's law can take on several formulations, which stem from the equivalence between the coefficients of emission, and absorption at thermal. Kirchhoff's law of thermal radiation states that "For an arbitrary body emitting and absorbing thermal radiation in thermodynamic equilibrium, the emissivity is equal to the absorptivity". The absorptivity and emissivity based on Kirchhoff's law with the assumption of no transmittance as follows (U ber das Verha ltnis zwischen,1978).

$$\varepsilon(\lambda) = \alpha(\lambda) = 1 - \rho(\lambda) \qquad (1)$$

where ε is emissivity, α absorptivity, ρ is reflectivity and λ are wavelength.

Efficiency

The Emitter Efficiency (E) is defined as the ratio between the emitter's radiated energy which is suitable for the PV device (above Eg) to the total energy radiated by the emitter. The thermal emitter element can be engineered to maximize the useful" radiation spectrum *(David et.al, 2014).* The efficiency of a TPV system to convert radiated heat to electrical power is given by Equation

$$\eta_{TPV} = \eta_{SP}\eta_{PV} = \frac{P_{out}}{P_{rad}} \qquad (2)$$

Where η_{SP} the spectra efficiency of the emitter, 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 η_{SP} is defined by Equation

$$\eta_{SP} = \frac{\int_0^{\lambda_c} E(\lambda)\varepsilon(\lambda)d\lambda}{\int_0^{\infty} E(\lambda)\varepsilon(\lambda)d\lambda}, \qquad (3)$$

Where, λ_c is the cut-off wavelength, $E(\lambda)$ is emission spectrum of a blackbody, and $\varepsilon(\lambda)$ is spectral emissivity of the proposed selective emitter MTM (Maremi et al. 2018).

Previously different MTM emitter is fabricated to increase the efficiency of TPV system**.** The TPV system can efficiently convert thermal energy from any kind of heat source into electricity by absorbing the incident thermal energy with a wavelength selective absorber and emitting that energy with a thermal emitter, which emits photons in a certain wavelength that matches the highest quantum efficiencies (QE) of a specific photovoltaic (PV) cell. To obtain a high-efficiency emitter, a metal–dielectric–metal (MDM) structured metasurface is employed for the study*(B.J.* et al 2016*).*

The TPV emitter is numerically analyzed using finite difference time domain method via Lumerical software package (Lumerical Solution). The emissivity properties are studied over spectra range from UV to mid-infrared. To maximize the emissivity over the studied wavelength range, the geometrical parameters are tuned thoroughly. In addition, the effect of oblique incidence at different polarizations is introduced. The suggested TPV emitter achieves a spectral efficiency of 74% and 95% at 1000 K and 2000 K over a wide range of incident angles from 0 to 65° for both polarizations. This is due to the coupling between the surface Plasmon polar ton, magnetic Polariton and intrinsic loss of the tungsten material.

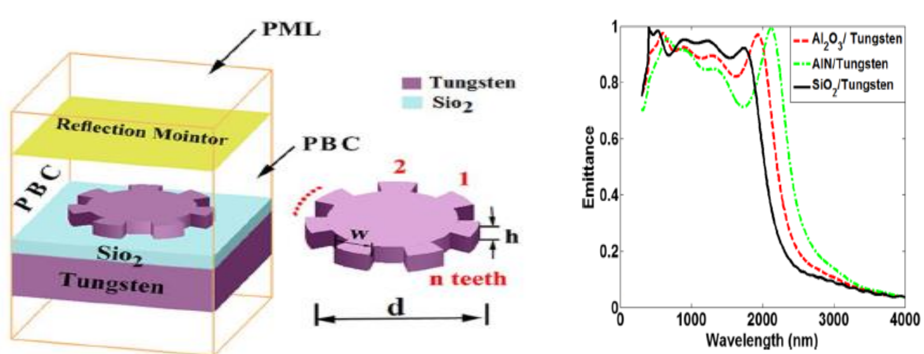


Figure 3: Unit cell of the reported wavelength-selective 2D cylindrical gear grating based TPV emitter and The Emittance spectra of the 2D gear based TPV emitter using Tungsten/different dielectric materials

Proposed design has 2D tungsten cylindrical gear grating with a number of teeth *n* = 7 and width w of 47 nm. Additionally, the gear unit has a diameter d of 280 nm with height h of 60 nm. The cylindrical gear array with periodicity of Λ = 400 nm is placed over a silicon dioxide (SiO2) spacer with a thickness t of 60 nm. The dialectic layer covers a tungsten (W) metallic layer with a thickness of 200 nm. The optical constants of the tungsten and SiO2 are taken form Palik Lumerical Solutions. The tungsten is chosen due to its good corrosion resistance in the visible light region with high melting point *(*Abdel-Latif et al 2021).

2.6 Nano fabrication

The processes and methods of nanofabrication include the formation of micro/nano-structures with minimal dimensions. It also provides precise control over material composition and allows multi-functional devices with unique characteristics less than 10 nm scaleIn the past two decades, several Nano-manufacturing techniques have been developed which address high expectations relating to Nano-technology. Nano fabrication can be categorized into two main categories Bottom-up and Top-down nanofabrication (Jeong et al 2021)

2.6.1 Bottom-up Nano-fabrication

The ultimate objective of bottom-up techniques is self-organizing integrated processes and tools This approach has the potential to generate practical multi component highly functional devices by regulating the integration of atoms and molecules, without wasting or removing portions of the final structure. The most appealing properties of bottom-up nanofabrication are that no pricy instruments are usually needed to fabricate structures at Nano scale and can easily fabricated in large quantities (Jeong et al 2021).

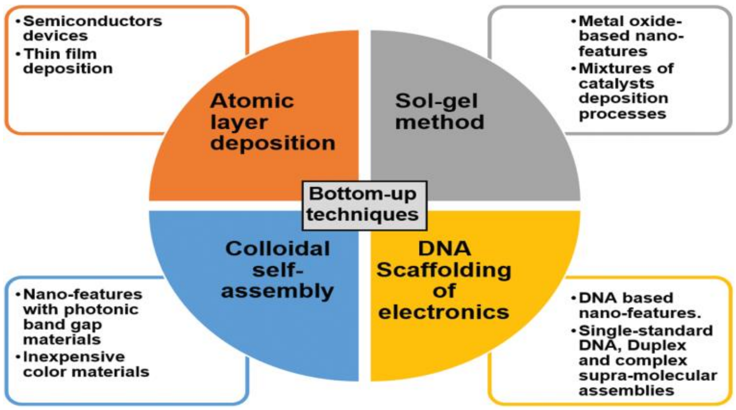


Figure 4: Characterization of bottom-up approaches for the fabrication of optical devices

2.6.2 Top-down Nano-fabrication

Various lithography techniques are known as top-down processes. These techniques are used to produce Nano scale structures in various applications in the microelectronics industries. Top-down manufacturing techniques generally based on dimensional material reduction by external factors (Jeong et al 2021)

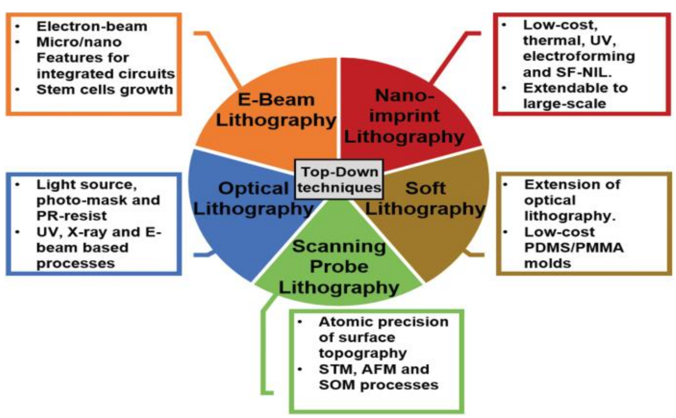


Figure 5: Characterization of Top-down approaches and their working principals for optical device fabrication**.**

E-Beam Lithography

Electron beam lithography (EBL)] is known as the ideal technique for product design and also the best technique for the processing of stamps that further used in Nano-imprint lithography.

The processing of the EBL technique is based on direct patterning on the layer of resist by using the electron beam (Jeong et al 2021).

Scanning Probe Lithography

Scanning probe lithography (SPL) is also a direct imprinting technique that allows control at the molecular level and mapping of atomic precision of the surface topography. SPL works at atmospheric conditions, a single step, and has non-aquatic processes. Various techniques may be used for the development of Nano scale patterns such as scanning-tunneling microscopy (STM) atomic-force-microscopy (AFM) and scanning-optical-microscopy (SOM) respectively. A common mechanism, based on scanning prop, is usually used in these techniques to create changes above the surface of the material (Jeong et al 2021)

Optical Lithography

Optical lithography or photolithography is based upon three fundamental steps (a) light source (b) photo-mask, and (c) photo resist (PR) material respectively.There are two types of PR materials: negative PR [and positive PR. After exposure to a light source, the positive PR becomes more soluble while the negative PR becomes less soluble. The mask patterns are transferred to the PR through the exposure process (Jeong et al 2021).

Soft Lithography

A complementary expansion of photolithography is known as Soft lithography. Conventional photolithography has been developed for semiconductor applications in the microelectronics industry. The photolithography method primarily focused on the tuning of PR materials and soft lithography expands the potential of photolithography techniques in different ways. Soft lithography is generally used for elastomers (soft) materials such as polymers, organic materials, and gels (Jeong et al 2021)

Nano imprint Lithography

Nano imprint lithography (NIL) is also a top-down nanofabrication technology uses a variety of approaches with a common goal relative to other technologies. NIL is used to produce patterns of higher resolutions that are restricted by light or beam dispersion in standard lithographic techniques. NIL technology also offers an effective and low-cost replication of Nano- patterning over to 10 nm scale and considered as a dominant approach for the fabrication of semiconductors and also overcome the limitation of optical lithography NIL can be classified into three categories(a) Thermal (b) UV and (c) Electroforming imprinting Technology(Jeong et al 2021)

Nano sphere lithography (free lithography)

Most lithography techniques are expensive and time consuming to solve this problem Nano sphere lithography (free lithography) is the best techniques. Nano sphere lithography (NSL) is a promising in expensive fabrication tool for producing regular and homogenous arrays of Nano particles with different sizes. This method combines the advantages of both top-down and bottom-up approaches (Wang. et al 2018). The process in NSL comprises three steps: (i) dispensing a colloidal suspension on a flat substrate to self-assemble into a hexagonal close packed array of Nano spheres; (ii) depositing materials on the substrate using the self-assembled layer as a pattern transfer mask; (iii) stripping the Nano sphere mask in an appropriate solvent. (Stepwise Nano sphere lithography: an alternate way of fabricating nanostructures (Lenert, *A.* et al 2020).Nano sphere lithography is an easily implemented, low cost and versatile technique that uses a single layer (monolayer) or double layer (bilayer) array of hexagonally close-packed spheres with a diameter of less than a micron . (William. A, 2005)

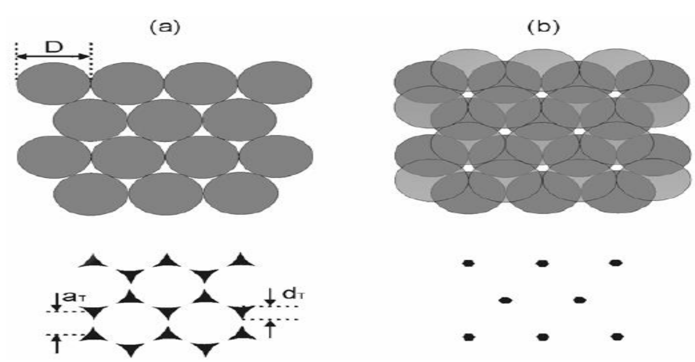


Figure 6: Schematic representation of a hexagonally close-packed Nano sphere array and the resulting nanoparticle array formed from a monolayer (a) and a bilayer (b).

Two-dimensional hexagonal close packing to three dimensional structures for broader applications such as photonics and artificial spin ice was fabricated by (Lenert, *A*. et al 2020). to create matrices of novel two- and three-dimensional nanostructures. Different sets of nanostructures are placed at desired locations through step-by-step deposition during thermal evaporation onto a substrate surface Experimental and Simulation and he got the result as follows

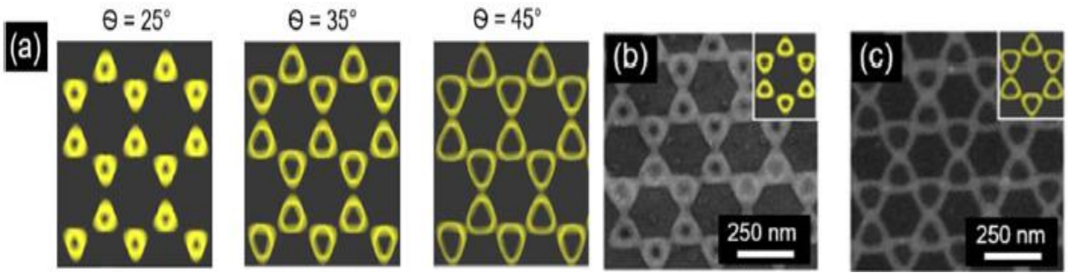


Figure 7 :(a) shows the simulation results of the nanostructure formed as β is changed continuously for various deposition angles θ.

The simulation results show that both the internal and external diameters of the ring increase as the deposition angle increases. For θ=25° to 35°, the Nano rings remain unconnected as stand-alone rings. However, when θ reaches 45°, the rings begin to join adjacent rings to form interconnected structures. Figure 7 (b) shows the SEM images of experimental results of small diameter Nano rings fabricated at θ=35° while figure 7 (c) shows the large diameter interconnected Nano rings fabricated at angle θ=45°. There is a slight discrepancy between the simulation and experimental values at which the rings form interconnected structures. This is because the simulation assumes parallel rays impinging the mask whereas there is a finite distance between the source and the mask experimentally (Lenert, *A*. et al 2020).

CHAPTER-3

3 Materials and Methods

The materials and method used in this study were discussed in this section. Nano-hole is designed by using numerical software called COMSOL Multiphysics and the physical mechanism of absorption was explained extensively. Materials likes, Titanium (1943 K), Platinum (2041.4 K). Tungsten (3695 K) .Aluminum Oxide (2345 K), Aluminum Nitride (2473 K), Silicon dioxide (1973 K) and Titanium dioxide (1853 K) were used in this study

3.1 Numerical Analysis (COMSOL Multiphysics)

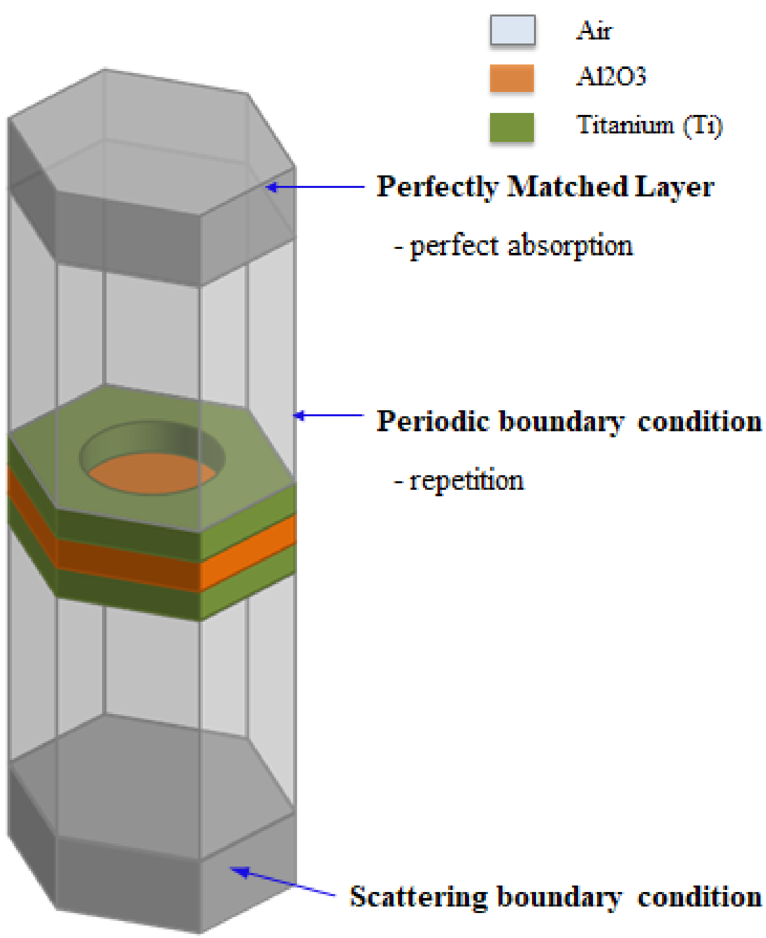


Figure 8: schematic showing a unit cell of MTM using COMSOL MultiPhysics software.

Figure 8 show that the design of MTM 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-hole MM emitter was designed from Titanium and aluminum oxide by using COMSOL Multiphysics software as shown on the figure 8. By the following steps COMSOL Multiphysics software was opened.

1) Double click on Comsol icon → File → New → ModelWizard → 3D → Radio frequency → Electromagnetic Waves,frequency domain → Add → Study Frequency domain → Done

2)Define the set parameters that used to design geometry

3)Add perfect match layer the top and bottom of the computational domain to minimize reflection from defintion tool bar

4)Add material from material tool bar and from physics

3D space dimension was selected for working environment. The optics interface had been used in order to compute electric and magnetic fields for my system, where the wavelength was comparable to or much smaller than the studied device. The Wavelength Domain study was 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 Titanium height), h_2 (dielectric thickness), h_3 (ground Titanium thickness), r (radius of Nano-hole). Melting point of Ti and Al_2O_3 are 1943 K and 2345K respectively.

The Nano-hole we designed starts with Ti and ends with Ti, in other word it consists metal-dielectric-metal (M-D-M) structure. Numerical simulation was conducted on the single unit cell as shown in the figure 10, 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 thin film (Ti) 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 ports were 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 11below. We assume that no transmittance occurred, as the back of the reflector was made by Ti. Thus, we can calculate the reflection coefficient based on the S-parameter of S11; S11 meant the signal ratio between the incident wave and the reflected wave. Consequently, we can calculate reflectivity as:

$$\rho=1-|\Gamma|^2=1-|S_{11}|^2 \quad (4)$$

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:

$$\varepsilon(\lambda) = \alpha(\lambda) = 1 - \rho(\lambda) \quad (5)$$

Where ε is emissivity, α absorptivity, ρ is reflectivity and λ are wavelength.

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:

Port and Scattering parameters

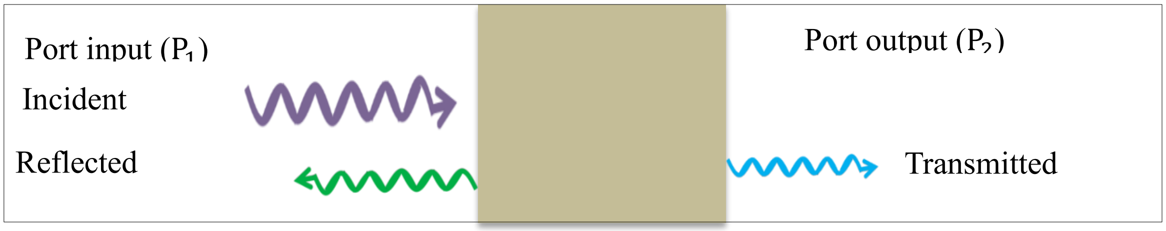


Figure 9: Showing port and scattering parameters.

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), transmitted wave (b_2) .The impedance of material can be calculated from S-parameter as

$$\boldsymbol{z} = \pm\sqrt{\frac{(1+s11)^2-s21^2}{(1-s11)^2-s21^2}}\,S21 \quad \ldots\ldots\ldots(6)$$

Where, $\boldsymbol{z}$ is impedance of material

S_{11} reflected signal port 1 $(\frac{b1}{a1})$

S_{21} transmitted signal port 2 $(\frac{b2}{a1})$.

$z \cong \pm\sqrt{\frac{(1+s11)^2}{(1-s11)^2}}$. S_{21} goes to zero is controlled by the ground

$z = \sqrt{\frac{\mu eff}{\varepsilon eff}} \cong 1$. When S11 goes to zero it is called impedance match

$\mu eff = nZ$, effective permeability, $\varepsilon eff = n/Z$ effective permittivity and n are refraction index.

3.2 Physical Mechanism of absorption

There are several physical mechanisms 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 Polari ton 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.

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 Polari ton 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 Ti or the upper layer Ti there is a net flow of electric current in the dielectric layer which resulted induced magnetic field. This is known as excitation of magnetic Polari ton. MP can powerfully localize electromagnetic energy in the dielectric layer of the designed metamaterial. In our work this physical absorption mechanism and fabrication steps where highly considered.

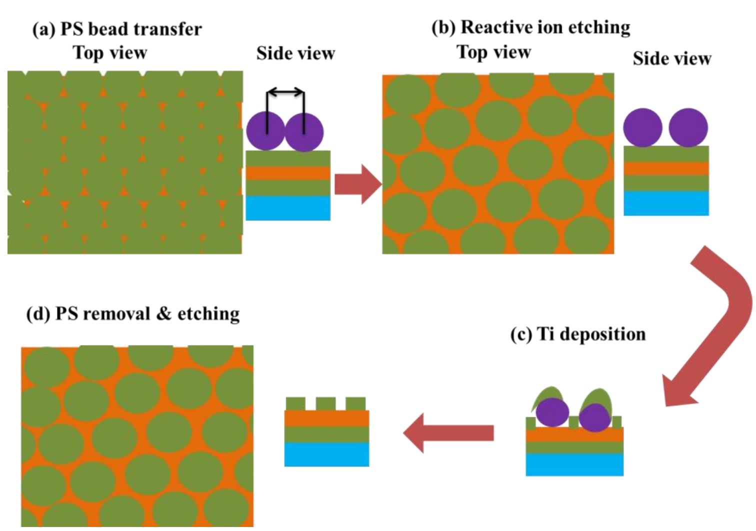


Figure 10: proposed fabrication steps

CHAPTER-4

4 Result and Discussion

In this work MTM emitter was Numerical designed with different parameters, width of the unit cell (w), Radius of hole(r), Ti film thickness (h_3), height of hole (h_1) and thickness of dielectric (h_2) , height of hole (h_1), Ti film thickness (h_3) are fixed in this study and other parameters where optimized. The MTM emitter designed has a three-layer structure as demonstrated in Figure 11 underneath. The top most layers are composed of a Titanium array arranged in a hexagonal lattice. Ti has been used for low temperature applications due to a low melting temperature (1943 K) of Titanium 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 Ti and Al_2O_3 with height h_1 of hole, a radius r. A thin film of Al_2O_3, thickness h_2, is designed on top of a Ti film of thickness h_3.

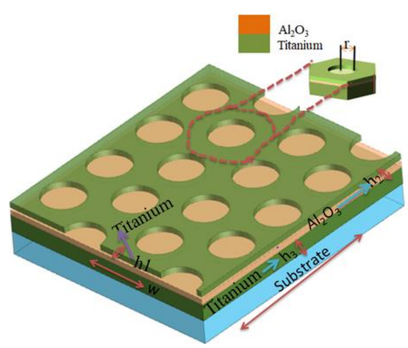


Figure 11: The schematic unit cells of the proposed MTM nano-hole emitter with h_1 (nano-hole height), h_2 (dielectric thickness), h_3 (Titanium thickness), w (width of the unit cell)

To prevent incoming light transmission, Al_2O_3 is used as a spacer layer with a thickness of h_2. Ti was chosen as the perfect reflector with a thickness of h_3. COMSOL Multiphysics generated an electromagnetic wave with a frequency of 300 THz from the in port to our constructed MTM emitter, as illustrated in figure 11. The results below were achieved after a lot of trial and error. The effect of varying parameters on the emissivity of the planned MTM emitter was discussed in the following subtopics. Furthermore, the polar impact angle on emissivity, a comparison of the emitter emissivity with different dielectric and metal and also comparison to a BB emitter. Finally, the results of this investigation were compared to those of previous studies.

4.1 Effect of Radius (r) of Nano-hole

To control effective permittivity and permeability of MTM geometry and arrangement of the design are the most noticeable. MTM interact with impinging electromagnetic wave due to current induction in the metallic periodic structure. To explain the perfect broadband absorption, we analyzed the electromagnetic field around the Nano-hole emitter. Several excitation mechanisms occurred with resonance frequencies such as MPs, SPP and high intrinsic loss of Titanium due to design is featured as Metal-Dielectric- Metal structure. Combining these resonances increased broadband emissivity.

Figure 12 showed that the dependence of emissivity of the designed MTM emitter on r. As can be seen, when radius r, increases from 150 nm to 350 nm, emissivity increases and become broad band at r equal to 250 nm with consideration of cut-off wavelength. Our result revealed that when w = 600 nm, h_2 = 170 nm r = 250 nm perfect broad band and emission with consideration of cut-off wavelength was achieved. When r was 250 nm, three major peaks were observed, those were, 1400, 2400 and 3000 nm with amplitude of 0.995411, 0.98616 and 0.964107 respectively. Which caused by excitation of magnetic polariton in the dielectric between two Ti layer and surface plasmon polariton that was created between Ti (metals) and dielectric Al_2O_3 or air.

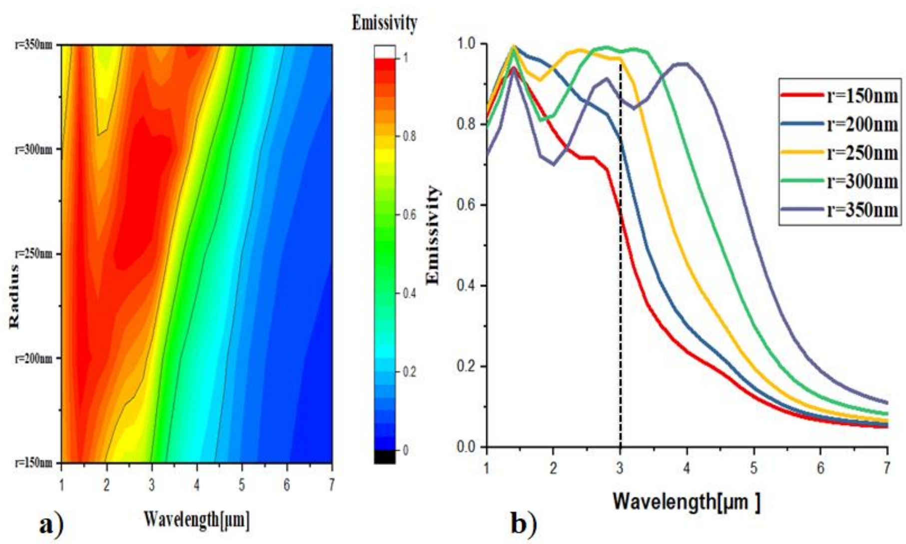


Figure 12: Schematic of the proposed MTM emitter emissivity dependence on r varies from150 nm to 350 nm with, h_1= 290 nm, h_3 = 200 nm.

4.2 Effect of Width (w) of the Unit Cell

Figure 13 showed that the dependence of emissivity of the designed MTM emitter on w. As can be seen, when width of the unit cell increases from 400 nm to 700 nm, emissivity increases and become broad band at w equal to 600 nm with consideration of cut-off wavelength. My result revealed that when w = 600nm, h_2 = 170 nm r = 250 nm perfect broad band and emission with consideration of cut-off wavelength was achieved.

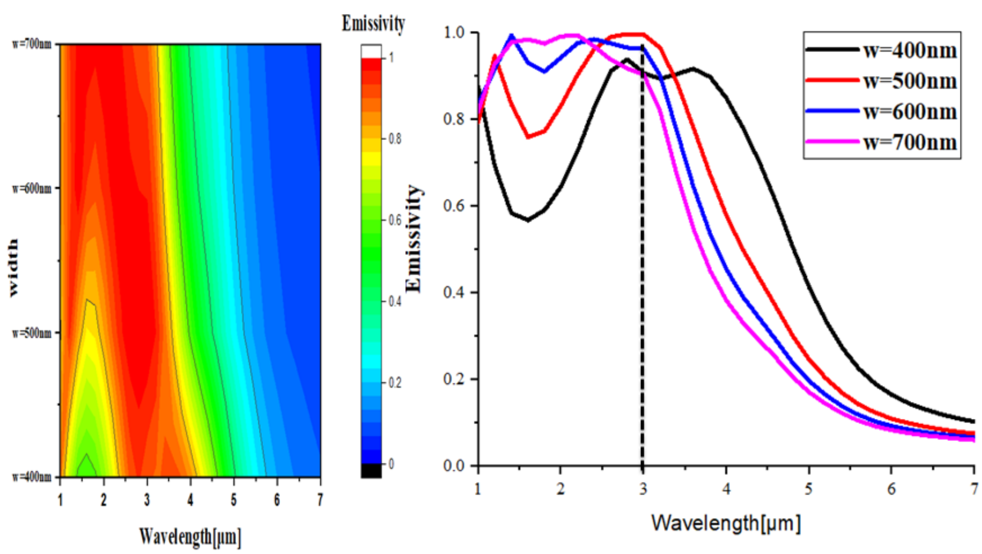


Figure 13: Schematic of the proposed MTM emitter emissivity dependence on w varies from 400 nm to 700 nm with, h_1= 290 nm, h_3 = 200 nm.

4.3 Effect of Thickness of Dielectric (h_2)

The gaps between metalized areas (dielectric thickness) on an MTM emitter are crucial in defining the devices resonant frequency. Two metal areas close to one other will induce capacitance, causing the induced fields to change even more. The capacitance and hence the resonant frequency will fluctuate when the distance between the metal areas is increased or decreased. From simulation we demonstrate that the resonance frequency occurs because of MP shift to lower wavelength and resonance frequency occur because of SPP shift to larger wave length when the dielectric thickness is increased.

As illustrated on the figure 14 below, the emissivity of the designed Nano-hole MTM emitter depends on the thickness of the dielectric layer. When h_2 increases from 80 nm to 170 nm the emissivity slightly increases. One can see from the figure that, when h_2= 170 nm three major peaks were observed those were, 1400, 2400 and 3000 nm with amplitude of 0.995411, 0.98616 and 0.964107 respectively. Which caused by excitation of magnetic polariton at the interface between dielectric and two Ti layer.

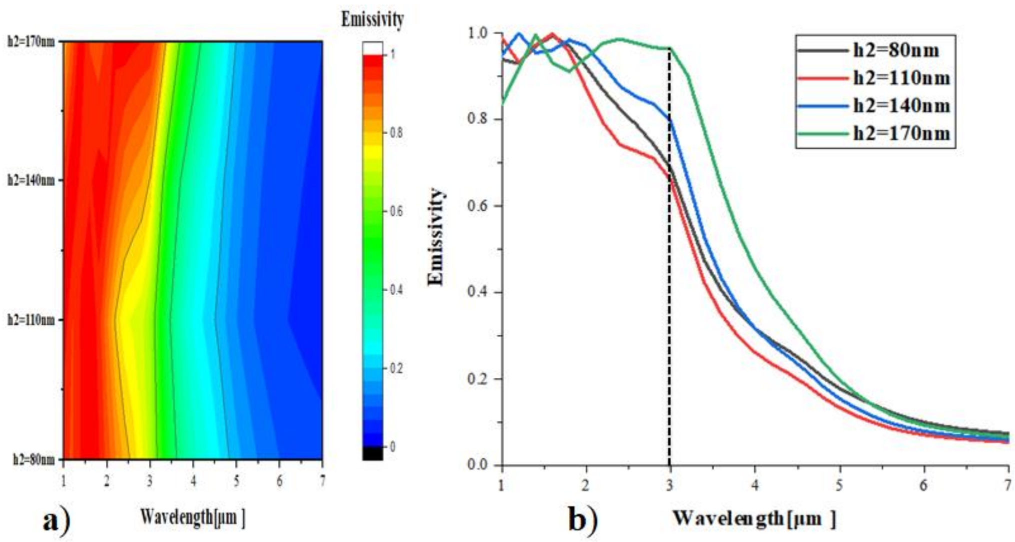


Figure 14: The dependence of emissivity of the proposed MTM emitter on thickness of dielectric (h_2).

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. Figure 15 depicts the effect of polarizations angles on spectral emissivity of the proposed selective MTM emitter with optimized geometric parameter w= 600 nm, h_2=170 nm and r=250 nm. Figure 15 showed 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-hole MTM emitter. The average emissivity of we designed emitter at polar angle $\theta= 0^0$ was above 96.4% at the wavelength of 3μm, but decreased dramatically beyond the cut-off wavelength.

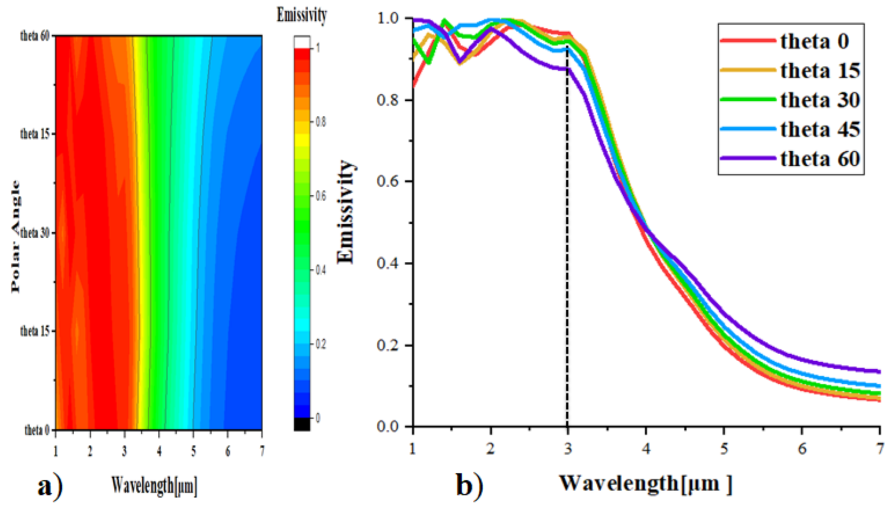


Figure 15: The emissivity of the proposed MTM at different angular emissivity

4.5 Effect of Azimuthal Angle on Emissivity

The character of angular emissivity of TPV emitter is important due to polarization and azimuthal angles of electromagnetic waves. Figure 16 depicts the effect of azimuthal angles on spectral emissivity of the proposed selective MTM emitter with optimized geometric parameter w=600nm, h_2=170 nm and r=250 nm. Nonetheless, the results suggest that the designed MTM emitter is independent of azimuthal angle. The simulation result was demonstrated that as the incident angle increased from 0° to 60°, the emittance curve did not change considerably.

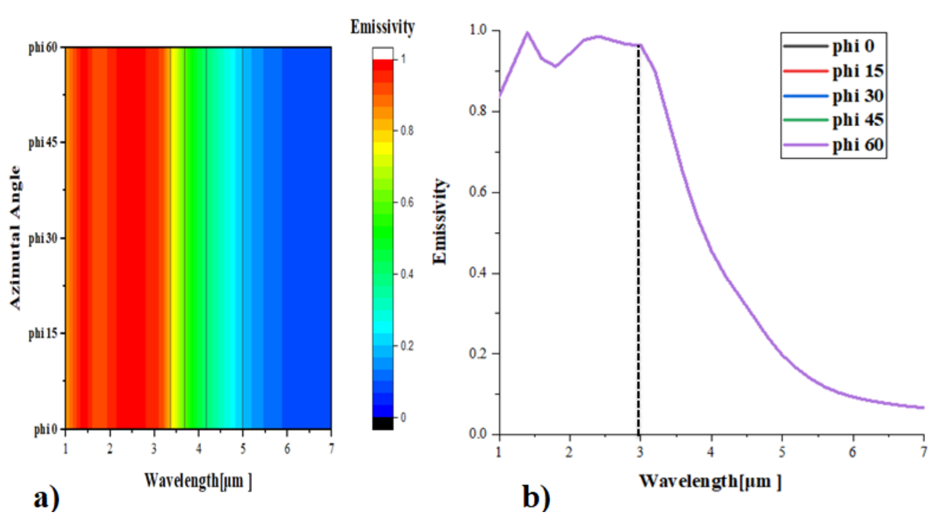


Figure 16: The emissivity of the proposed MTM at different azimuthal emissivity

4.6 Distribution of Energy Flow

The MTM 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, and high intrinsic loss of Titanium and so on. The enhanced broad band emissivity of our MTM was due to the combined resonance of SPPs and MP. A nano-hole selective MTM emitter design was chosen for polarization-independent broadband emissivity. The distribution of the normalized energy flow at wavelengths of 1.4 μm, 2.4 μm, and 7 μm, was depicted in the **figure 17 (a, b and c)** below respectively. The energy and energy density carried by a travelling electromagnetic wave in space was 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 point, **E** is electric field and **H*** is complex conjugate of magnetic field

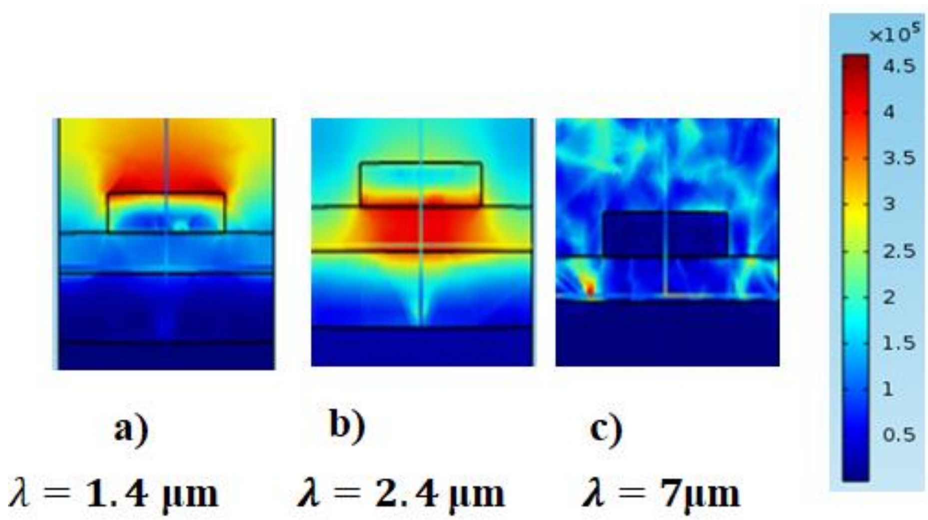


Figure 17: The distribution of energy flow (Pointing vector) at wavelengths of, a) 1.4 μm, b) 2.4 μm and c) 7 μm within Nano-hole designed MTM emitter

4.7 Performance of Designed MTM Emitter

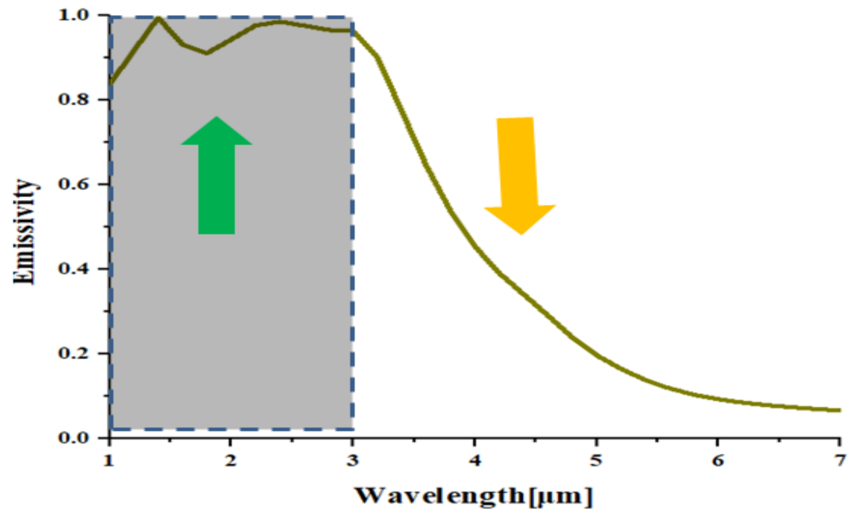


Figure 18: the emissivity spectra of the proposed MTM emitter with the shaded area are external quantum efficiency of InAsSbP.

The emissivity spectra of the proposed Nano-hole MTM emitter, where in the shaded area shows the EQE *(Alcañiz et al., 2019)* of InAsSbP (3µm).

From the figure 19 below be clearly seen that, I obtained a near perfect broadband emitter below the cut-off wavelength of InAsSbP, which dramatically decreased after the cut-off wavelength of 3µm (see figure 19).In principle radiation energy below the band gap was considered as waste energy, while low radiation energy above band gap was mandatory (convertible) energy; this is due to the existence of a band gap in the PV cell. Consequently, my result reveals that my emitter emits high convertible photons. The graph depicts a nearly perfect broad band emissivity of wavelength at 3000 nm, at that point and above from that point it dramatically falls. The average spectral emissivity at a wavelength on 3µm for band gap of InAsSbP PV cell was about 96.4%, showing the performance characteristics of the designed nano-hole emitter to be high.

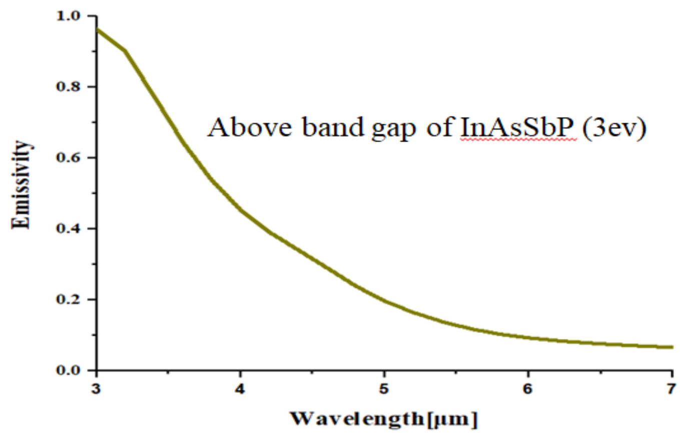


Figure 19: The emissivity spectra of proposed Nano-hole MTM emitter above cut-off wavelength of InAsSbP (3 µm), with MTM parameter w = 600 nm, h_1 = 290 nm, h_2 = 170 nm, h_3 =200, r = 250 nm.

As illustrated on figure 19 above cut-off wave length or below band gap of InAsSbP the designed MTM emitter emit very small photons, in other word out of band photons where suppressed. The emittance above 3µm decreased dramatically. 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 was given by Equation (7)

$$\eta_{tpv} = \eta_{pv}\eta_{sp} = \frac{Pout}{Prad} \quad \text{.............} \quad (7)$$

Where, the spectral efficiency of the emitter is ηsp, ηpv is the efficiency of the photovoltaic cell, $Pout$ is the maximum output power, and $Prad$ was the total radiant power from an emitter. Spectral efficiency ηs is defined by Equation (7) (Ghanekar et al., 2016).

$$\eta_{SP} = \frac{\int_0^{\lambda c} E(\lambda)\varepsilon(\lambda)d\lambda}{\int_0^{\infty} E(\lambda)\varepsilon(\lambda)d\lambda}, \quad \text{.............} \quad (8)$$

$$E(\lambda) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{\lambda k_b T}-1}}. \quad \text{.............} \quad (9)$$

where, *c* is the cut-off wavelength, **E** (**λ**) is emission spectrum of a blackbody, **ε** (**λ**) is spectral emissivity of the presented selective MTM emitter, h is planks constant, c is speed of light, Kb is Boltzmann constant and T is temperature. 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 22(a-d) shows a comparison of the spectral irradiance of the black body with the selective emitter MTM at temperatures from 1000 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 = 290 nm, h_2 = 170 nm, h_3 = 200 nm, r= 250 nm and w = 600 nm of Nano-hole and achieved high emissivity of TPV emitter

4.8 Effect of Di-electric on Emissivity

As illustrated on the figure 20, the emissivity of the designed Nano-hole MTM emitter depends on the types of the dielectric. When dielectric changed from Titanium dioxide to Silicon dioxide the emissivity slightly increases and change to the lower wavelength.

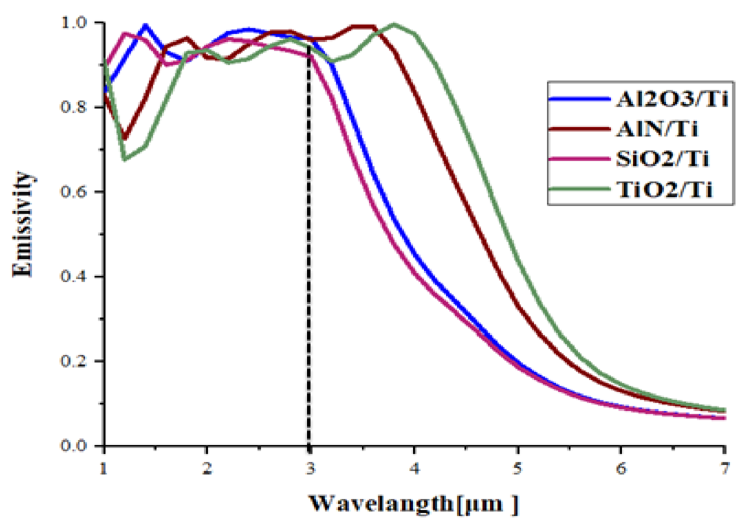


Figure 20: The emissivity of the proposed MTM dependent on different di-electric

As we see from figure 20 above four dielectric where compared as we go from TiO_2 to Al_2O_3 the emitter emissivity increase below cut-off wavelength (3um) and dramatically decrease above cut-off wavelength (3um).therefore this work was depended on Al_2O_3 (2345K).

4.9 Effect of Metals on Emissivity

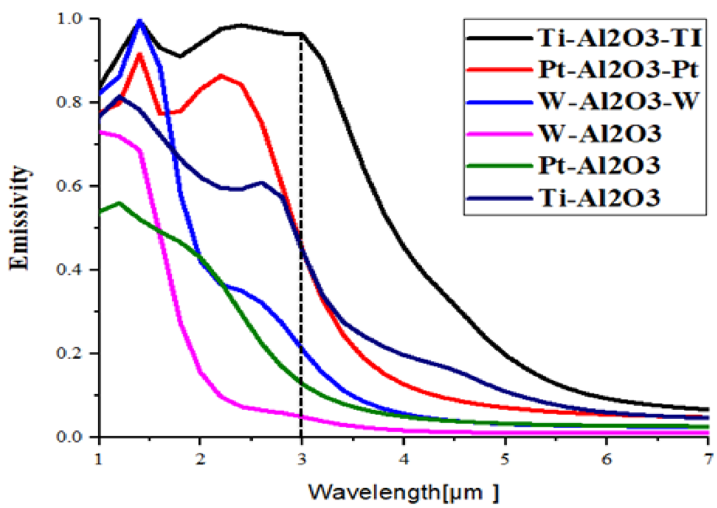
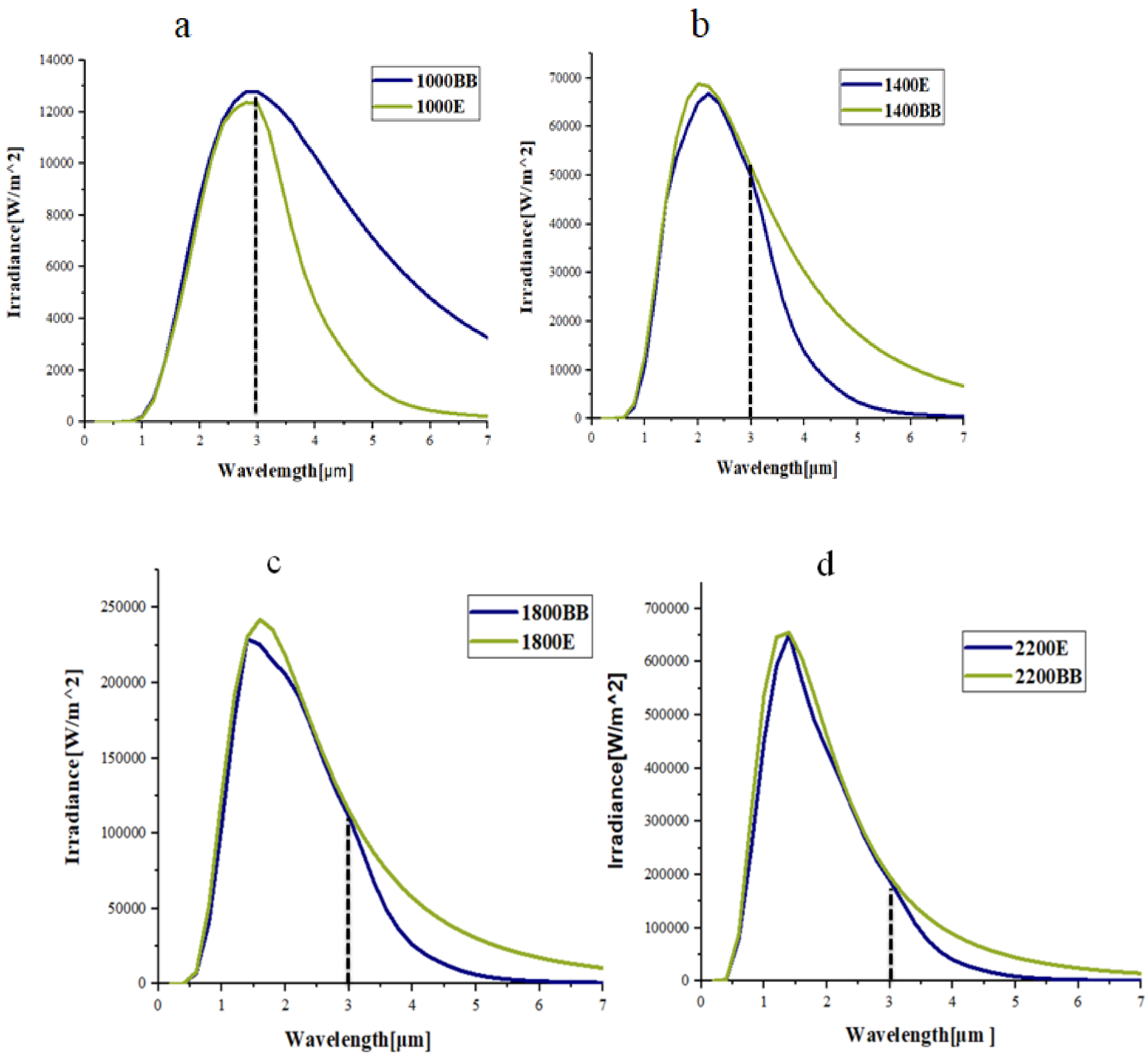


Figure 21: Schematic of the proposed MTM emitter emissivity with parameters of w=600nm, h_1= 290 nm, h_2 = 140 nm, h_3 = 200 nm and r=240nm by different metals.

From figures above Tungsten based emitter was work for high temperature stable elements but this work was proposed for low temperature emitters therefore Titanium based emitter (Ti-Al_2O_3-Ti) was selected As we see from figure 23 above three metals with metal-dielectric-metal(M-D-M)and two with only metal-dielectric(M-D)(flat) where compared: from those M-D-M which was(Ti-Al_2O_3-Ti) had the most appropriate results As we discussed above this work was depending on low melting temperature elements figure 21 above showed that Titanium with $Al_2O_3$the emitter emissivity increase below cut-of wavelength (3um) and dramatically decrease above cut-off wavelength (3um).therefore this work was depended on (Ti-Al_2O_3-Ti) MTM s

4.10 Comparison of the Spectral Irradiance of Black body with the proposed Selective Emitter at different Temperature



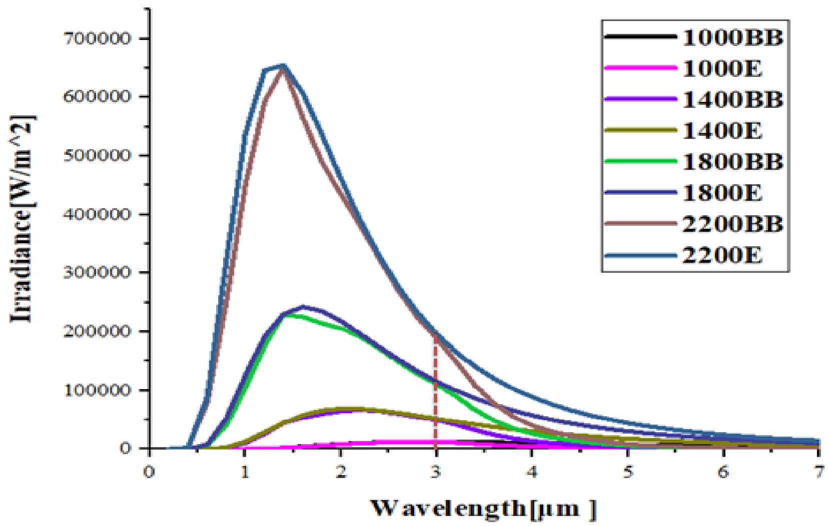


Figure 22: Comparison of the spectral irradiance of black body with the proposed selective emitter at different temperature, with (a–d) indicating BB and MM comparisons at the same temperature

For each graph, while the last one sketches illustrate irradiance versus wavelength for both materials at different temperature on the same graph. As illustrated in figure 24 above when we compare the suggested emitter with blackbody in terms of spectral emissivity at different temperature, the Nano hole we have designed exhibit selective emission above band gap. The vertical line on each graph indicates cutoff wavelength of InAsSbP which is 3µm. In contrast to, black body above this line the spectra of suggested MM decreased dramatically, this shows us the selectivity of the emitter. The blue shaded area on the graph (a-d) was the emissivity of the designed emitter. The spectral efficiency of emitter at different temperature which calculated according to equation (8) above can be given in the table below.

Table1: spectral efficiency of designed emitter calculated at different temperature

Temperature (K)	Spectral efficiency
600	64.53%
800	71.74%
1000	75.47%
1200	77.61%
1400	78.96%
1600	79.87%
1800	80.51%
2000	80.99%
2200	81.36%

4.11 The Emissivity of the proposed MTM Compared with other Work

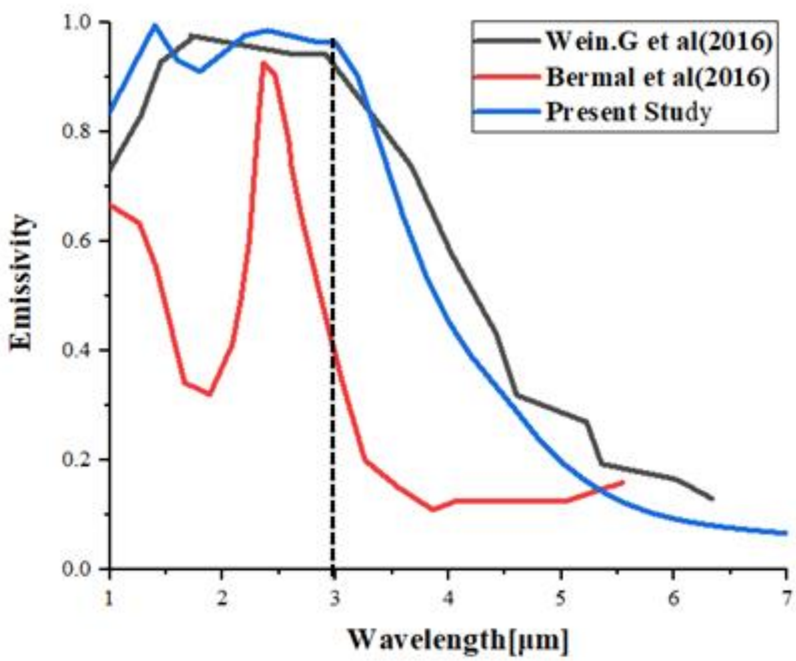


Figure 23: The emissivity spectra of proposed Nano-hole MTM emitter compared with other

Table2: comparison between the designed emitter and other emitters at room temperature.

Reference	Materials		Emissivity	Wavelength
	Metals	Dielectrics		
Binghong et al (2022)	Tantalum	SiO_2	88%	3500nm
Bermel et al(2016)	Tungsten	Al_2O_3	80%	3000nm
This study	Titanium	Al_2O_3	95%	3000nm

Figure 24 shows a comparison of the proposed Nano-hole MTM s spectral efficiency with the spectral efficiency of blackbody and Bermel et al 2016 1000K and 1200K.

The green histogram shows the designed selective emitters spectral efficiency, whereas the blue histogram represents black body and the red histogram represents Bermel et al 2016 The red and black histogram in the picture depicting spectral efficiency of the blackbody on 3µm and MTM emitter up to 3µm respectively whereas green histogram shows the spectral efficiency of designed MTM within 3µm cutoff wavelength. As shows in the figure the black bodies are converts 4.1% and 13.87% of radiated energies at 1000K and 1200K respectively and Bermel et al (2016) 66.4% and 70.12% of radiated energy by the similar temperature respectively. However, the designed emitter is convert about 75.47 %and 77.61% of the radiated at 1000K and 1200K respectively this results shows that high radiated energy where convertible by designed Nano-hole emitter

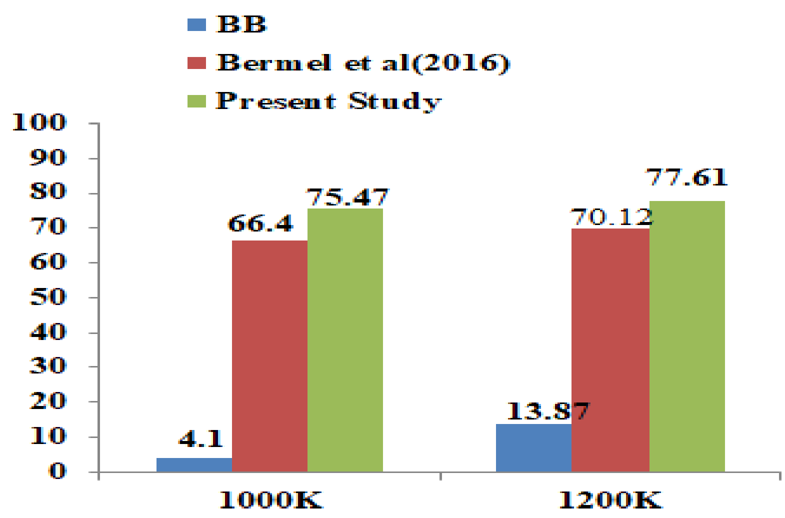


Figure 24: Comparison of the proposed Nano-hole MTM s spectral efficiency with the efficiency of blackbody and Bermel et.al at 1000K and 1200K

CHAPTER-5

5 Conclusion and Recommendation

5.1 Conclusion

In this work, MTM selective emitter for TPV application was proposed and numerically analyzed the MTM showed polarization and azimuthal angle independent selective emission. In this thesis, we have considered InAsSbP with energy band gap of 0.41eV and a cut-off wavelength of 3 µm. Geometric parameters such as radius, thickness of dielectric, and the width of the unit cell (w) were studied and optimized to achieve perfect broadband emissivity above the band gap energy. The proposed MTM increased the efficiency of the TPV system. Efficiency was also enhanced when all radiated photons were absorbed by the TPV cell. The proposed MTM emitter exhibited an enhanced near perfect broadband and a wide-angle average emissivity of above 96.4% of the wavelengths of 3µm on optimization of the geometric parameters. This result contributed to the enhancement of the TPV performance. Additionally, the spectral efficiency of the designed Nano-hole emitter we had obtained was 64.53%, 71.74%, 75.47%, 77.61%, 78.96%, 79.87%, 80.51%, 80.99% and 81.36% with InAsSbP cell of 3 µm or 0.41eV band gap at 600 K, 800 K, 1000 K, 1200 K, 1400 K, 1600 K, 1800 K , 2000 K and 2200 K respectively. In general as temperature increases from 600 K to 2200 K the spectral efficiency increase In general at high temperature TPV efficiency was high as spectral efficiency at 2200 K is 81.36% and at 1000 K is 75.47%.

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.

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