BROADBAND EMITTER BASED ON MULTILAYER METASURFACE FOR ELECTROMAGNETIC ENERGY HARVESTING

Simret Sisay Alemu

A Thesis Submitted to Department of Applied Physics
School of Applied Natural Science
Presented in Partial Fulfillment of the Requirement of Master of Science degree in Applied physics (Condensed Matter Physics)

Office of Graduate Studies
Adama Science and Technology University

June 2024G.C

Adama, Ethiopia

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APPROVAL PAGE

I/we, the advisors of the thesis entitled “Broadband Emitter Based on Multilayer Metasurface for Electromagnetic Energy Harvesting” and developed by Simret Sisay, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Advisor Signature Date

Dr. Fekadu Tolessa ________ ________________

We, the undersigned, members of the Board of Examiners of the thesis by SimretSisay have read and evaluated the thesis entitled “Broadband Emitter Based on Multilayer Metasurface for Electromagnetic Energy Harvesting” and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for Presented in Partial Fulfillment of the Requirement of Master of Science degree in Applied physics (condensed Matter Physics)

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Finally, approval and acceptance of the thesis is contingent upon submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC).

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Declaration

I hereby declare that this Master Thesis entitled “Broadband Emitter Based on Multilayer Metasurface for Electromagnetic Energy Harvesting” 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

Name of the student	Signature	Date
Simret Sisay	______________	_______________

Recommendation of Advisor

I advisor of this thesis, here by certify that I have closely advised the student while developing this proposal and read the draft thesis proposal entitled “Broadband Emitter Based on Multilayer Metasurface for Electromagnetic Energy Harvesting” prepared under my guidance Simret Sisay. Therefore, I recommend the submission of the thesis to the department for further review and evaluation

Advisor	Signature	Date
Dr. Fekadu Tolessa	____________	____________

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Contents

List of figures

List of table

Abstract

Anthropogenic activities typically leak waste heat into the environment in an unnecessary manner without any kind of planned strategy. As a result, both urban heat islands and global warming steadily get worse over time. Thermophotovoltaic (TPV) systems have the potential to be used in order to collect waste heat and recover energy in order to address this worldwide problem by producing more electrical energy. This study offers a comprehensive analysis of emitters created using multilayer systems and metamaterials as viable options for TPV cells. The benefits and limitations of Furthermore, this study evaluates and analyzes the emitters' performance in relation to metal, dielectric, and height variations. A thorough analysis and discussion of the structural design's contribution to the improvement of emitter efficiency is also provided. The review's highlighted insights will help focus more attention on creating TPV systems with higher emitter efficiencies in the future. Generally speaking, spectral efficiency rises with temperature, indicating that emitters operating at low temperatures are essential for increasing TPV efficiency. In particular, selective emitters suppress out-of-band radiations to increase efficiency. Overall, a selective metamaterial emitter with a high average emittance over the needed wavelength was conceived and implemented in this work.

1. Introduction

1.1 Background of the study

Energy and the environment pose significant challenges to the sustainability of our planet and modern civilization. Because of the harmful impact of fossil fuel combustion on our environment, fossil fuels constitute the primary source of global energy consumption. However, they are nonrenewable resources that will decline over time owing to indiscriminate mining. Panayiotou calculated that European companies generated 370.41 TWh of waste heat per year in 2017. This large volume of waste heat output has sparked global concern about the environmental impact, as well as a search for more efficient waste heat usage in sectors. As a result, there is an urgent need to investigate alternate methods for improving waste heat recycling and energy conversion efficiency in order to reduce reliance on fossil fuels (V. Stelmakh, 2017).

Thermal photovoltaic (TPV) systems convert thermal energy directly into electricity and show promise in waste heat recovery, solar energy collecting, and space applications. A TPV system is environmentally benign and consists of two major components: an emitter that emits radiation after collecting thermal energy from various heating sources, and a TPV cell, which generates electricity by absorbing incident photons from the emitter.

A TPV system converts thermal radiation from a variety of heat sources, including fuel combustion, industrial waste heat, concentrated sun, and nuclear energy, into electricity. In this context, a thermophotovoltaic (TPV) system looks to be a viable option for meeting these requirements. Furthermore, the ability to convert multiple heat energy sources such as solar, nuclear, chemical combustion, and waste heat into high electrical power density broadens the range of TPV applications, from micro-scale to large-scale TPV generation. (V. Rinnerbauer, 2012). Fraas projected a worldwide potential of 3.1 GW power generation utilizing TPV system in steel sector (>1373 K).(Gamel, 2021)

TPV energy conversion is the most efficient solid-state thermal-to-electric energy converter, with a record efficiency of approximately 30% at heat source temperatures above 1000°C. (Datas. A, 2021) In fact, it is the most efficient small-scale heat engine. Spectral control tactics performed on the emitter and/or photovoltaic cell, such as back surface, reflectors, or front-side filters, together with a good selection of semiconductor bandgap energy, are the fundamental design features that permit obtaining such high conversion efficiency. (O.Nielsen, 2003)

High band gap energies combined with excellent photon recycling leads to the highest theoretical conversion efficiencies at the expenses of very low output power density.(Cheng, 2021) When optical losses are considered the optimal semiconductor band gap energy shifts to lower values. Moreover, low band gap energies are required to maximize the output power density at the expenses of reducing the maximum attainable conversion efficiency. Low band gap semiconductors also bring undesirable practical limitations, mostly regarding the large amount of non-radiative recombination losses.(W.chan, 2013)

Thus, a trade-off exists between power density and conversion efficiency that mostly drives selection of semiconductor band gap energy. The fulfillment of such a trade-off is heavily reliant on specific applications. Closed-TPV systems (those in which the heat source is enclosed within the system, such as radioisotope-TPV) tend to require maximization of TPV efficiency, whereas open-TPV systems (those in which the heat source is external to the system, such as solar-TPV) typically require maximization of TPV power density to compensate for heat losses through the heat inlet aperture. In any case, all current conventional TPV devices require very high temperatures, near or beyond 1000°C, to achieve decent output power densities of one W/cm2 or more.(Rashid)

Novel TPV approaches strive to overcome such trade-offs and limits while also reducing some of the major design constraints. For example, NF-TPV, thermophotonics, and LTPV all seek to improve output power density at lower emitter temperatures. Furthermore, thermophotonics enables the use of larger TPV cell semiconductor band gaps.Wolf, 2018. TIPVs provide increased power density and lower ohmic and shadowing losses, which are especially useful when combined with NF-TPV devices. None of these concepts has yet achieved a high level of technological readiness. However, improvement has been rapid in recent years, particularly with NF-TPV devices. These advancements, together with current uses of TPV in ultrahigh temperature energy storage, are driving a fresh interest in TPV energy conversion. (Datas.A, 2021)

A TPV system operates at a lower radiator heating temperature for a longer period of time than a solar photovoltaic system. According to Sakakibara (2019), a thermopane vacuum system comprises four primary components: a filter that synchronizes the emission spectrum with the TPV cell, a radiator that translates thermal energy into an emission spectrum, and a TPV cell itself that transforms photon radiation into electrical energy. To improve overall performance, a thorough investigation of every part of the TPV system has been carried out. Specifically, the fundamental element that enhances the overall performance of the TPV system is the TPV cell, which directly transforms photon radiation into electricity. (Gamel, 2021)

Figure 1 shows the TPV system, which includes a generator, a radiator, a filter and an array of TPV cells. The generator produces power from various heating sources (P_{source}) to the radiator with certain heat loss ($P_{source,\ loss}$). Next, the radiator generates the radiant power ($P_{radiant}$) to the TPV cells via the filter. The filter then narrows the emission band from the radiator. The filtered radiated energy from the radiator should exceed the band gap of TPV cells with the bandgap power (P_{gap}), whereas losses ($P_{gap,loss}$) are induced by the photons with lower energy than the bandgap of TPV cells. These photons are recuperated to the radiator ($P_{recuperate}$) to conserve heat and reduce P_{source} at the required radiator temperature. The output power (P_{out}) at TPV cells measured through the optical-to-electrical signal conversion process.

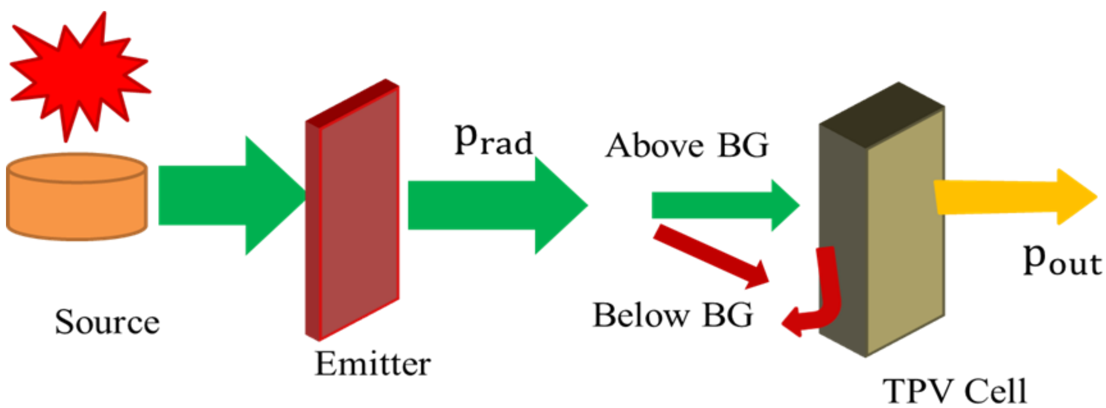

Fig.1 schematic diagram of an overall TPV system

Because a TPV system may retain and subsequently convert energy in sub-band gap photons, unlike a solar cell, its efficiency is characterized differently from that of a solar cell. This is due to the TPV cell's high view factor to the emitter in the scenarios where it is intended to be used. In contrast to solar cells and the sun, below band gap photons are reflected back to the emitter by the TPV cell. (V.Rinnerbauer, 2012) By reflecting unconverted photons, the energy of the below-band gap light preserved through reabsorption by the emitter. The reflected and subsequently reabsorbed light helps to keep the emitter hot, thereby minimizing the energy input required to heat the emitter. In general, the efficiency(η_{TPV}) of a TPV is given by the ratio of P_{out} and P_{inc} then reducing $P_{ref,}$.

In this experssion, $P_{out}$is the electric power generated by the TPV cell (that is, $P_{out}=V_{oc}I_{sc}FF$), where V_{oc} is the open circuit voltage, I_{sc} is the short-circuit current and FF is the fill factor of the current–voltage (IV) curve. The total heat absorbed and generated in the cell is denoted by Q_c, which is made up of the heat generated by parasitic absorption in the semiconductor or metal reflector, thermalization losses due to excess incident photon energy, Joule heating losses due to current flow and non-radiative recombination losses. The net energy received by the cell is equivalent to $P_{out}+Q_c$ and can also be expressed as $P_{inc}-P_{ref}$, where P_{inc} is the incident energy and P_{ref} is the reflected energy. Based on equation, to increase TPV efficiency, one must increase the power output Pout and/or reduce the amount of heat absorbed and generated in the cell (Q_c). The efficiency, η_{TPV}, is the metric we use here because it is the conventional and generalizable metric used to describe the performance of a cell–emitter pair independent of other system-level characteristics. System-specific losses can cause a whole system with TPVs to be less efficient than ηTPV. However, in the case of TEGS or a large-scale combustion-based energy generation, these system-level losses can become insignificant.(W.chan, 2013)

1.2 Statement of the problem

A relatively new technology that produces clean energy by burning fossil fuels, recycling trash, and harnessing solar energy is called thermophotovoltaic (TPV) (Babiker, Samah G., et al., 2014). With the use of an emitter, it can be changed from thermal emission to electricity before being converted. The TPV emitter is essential to power generation and conversion efficiency. The choice of material and emitter design can regulate the conversion efficiency and power generation. Temperature resistance and the way in which their cutoff wavelengths align with the TPV cell are essential considerations in the design of the emitter for TPV system efficiency. While emitters are made of a variety of materials, metamaterials are more selective due to a tiny repeating pattern that allows them to manipulate electromagnetic radiation in novel ways. Thus, by utilizing metamaterial emitter maximizes the TPV system's power generation and conversion efficiency. More clean energy that improves quality of life is produced when waste is minimized during the production and conversion of electricity, fossil fuels are burned, and solar energy is perfectly recycled. We are therefore here to accomplish.

Significance of the study

The emission spectrum below the band gap energy is made up of needless absorption and emission, which inevitably raises the cell's temperature and lowers conversion efficiency. Higher TPV cell efficiencies could be the outcome of such spectrum structuring. Increased power generation and conversion efficiency result in high electric power that may be put to a variety of uses. Overall, this work will advance our understanding of how to design metamaterial emitters for TPV systems in the future.

1.4 Objective

1.4.1 General objective

The main objective of work to study numerically Broadband multilayer metasurface emitter for energy harvesting.

1.4.2 Specific objective

The specific objectives are:

- ✓ To enhance broadband emitter in selective wavelength
- ✓ To improve spectral efficiency of TPV
- ✓ To increase the overall efficiency of the TPV

2. Review Literature

A thermophotovoltaic (TPV) system is made up of three main parts: a low band gap photovoltaic (PV) cell, an emitter, and a heat source. The system uses light as an intermediary to convert heat into energy. The heat source heats the emitter to a high temperature (≥1000 K), which releases thermal radiation that the PV cell absorbs and transforms into electricity. The physical separation of the pathways for heat conduction and electricity generation, the quiet and static conversion process, and the absence of basic temperature differences between materials are some benefits of this energy conversion strategy. (V.Rinnerbauer, 2012)

Furthermore, a variety of heat sources can be employed, primarily falling into three categories: concentrated and absorbed sunlight, chemical fuel, and radioactive decay of isotopes. Planck's law is the single fundamental constraint on the radiated power density from the TPV emitter for blackbody emission. (Sakakibara, practical emitters for thermophotovoltaics , 2019) The scope of our review is the TPV emitter, which we consider the critical component towards high system performance and specifically on its practical implementation in TPV systems.(O.Nielsen, 2003) Any material that has reached a high temperature is the emitter. An emitter that selectively emits within a given wavelength range is especially helpful. There isn't a one method for creating emitters; instead, there are numerous varieties that may require various material combinations and geometric arrangements. In this review, we explore emitters that have been used in system demonstrations of TPV prototypes, and we offer five metrics to assess the practicality of TPV emitters. The majority of TPV emitter research has been on attaining strong optical performance; however, the difficulties of integrating and managing the emitter within a TPV system have received less attention.(V.Rinnerbauer, 2012)

Components of TPV Systems

Systems that transform thermal energy into electrical energy are known as TPV systems. These technologies provide an alternative to the way that electricity is currently produced. Among the primary parts of this system are filters, photovoltaic cells, heat source, and selective emitter. *(Xu Yet al.*2014*)*

The sun and other heat sources like fuels and combustion engines can both be employed as heat sources in TPV systems. In TPV systems, photons are obtained through the heat source. The filter sends back the selective emitter by reflecting back the non-energized radiation, while the selective emitter is employed to boost the efficiency of the system. Photon energy from the emitter is converted into electrical energy by photovoltaic cells. Devices that use TPV capture electromagnetic radiation and transform it into 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.(GauravSahu,et al2020)

The main components of a TPV system are the heat source, thermal emitter, and TPV cells. The heat source is a source of photons, such as solar or waste heat energies, that the thermal emitter can transform into thermal radiation. ATPV cell uses this thermal radiation to produce electricity. *(Woolf et.al, 2018)*

The heat source

The heat source, which comprises of sunlight, radioactive isotopes (β-photons), and flame combustion, is the essential and basic part of the TPV device. The selective emitter, filter, and cell are all passed through by the heat energy coming from the heat source. *(.Xu Yet al.*2014*)*

Photo voltaic cells

Photons from the emitter are absorbed by photovoltaic cells, which then transform them into electrical or heat energy. The use of low band gap materials is required in order to absorb as many photons as feasible. (*Xu Yet al. (*2014*)*

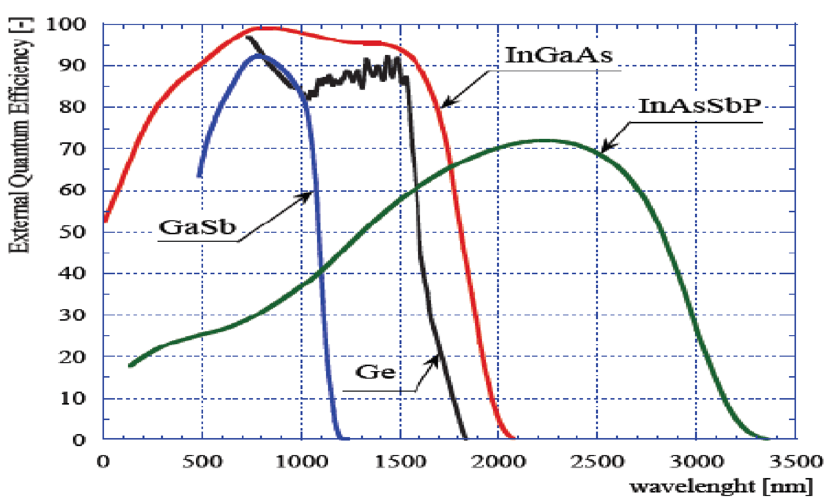

Figure 2: EQE for different TPV cells with respect to wavelength

Low bandgap 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 al2014)

Emitter

Any material that has been heated to a high temperature can be an emitter. An emitter that selectively emits within a given wavelength range is especially helpful. The system's purpose is to boost its efficiency. (DurischWet al2008)

Re-emitting radiation in a range of frequencies just above the PV cell's band gap is the emitter's primary objective. Usually, thermal emitters run at very high temperatures. This means that materials with high melting points, such tungsten and tantalum, must be used to make the emitter. Any material that has been heated to a high temperature can be an emitter. An emitter that selectively emits within a given wavelength range is especially helpful. The system's purpose is to boost its efficiency. (GauravSahu,et al2020)

Selective emitters are more popular as modern TPV system components as they only emit a narrow range of wavelengths, resulting in higher conversion efficiencies (Vanderveldeet al2017*)*. A body that emits all of its radiation within a specific wavelength range that closely matches the wavelength of the receiver band gap is known as a selective emitter. An emitter can be made in a variety of ways; each type requires a unique collection of materials as well as a distinct physical design. Furthermore, the main goal of emitter development is optical performance; an emitter with the best optical performance is not always the ideal emitter for real-world applications. Several authors focused on this kind of emitters and proposed genuine solutions based on 1D photonic crystal*(*Kassakiann*J*.et al2005*)* single-defect photonic crystals *(*Abdallah P.et al2007*)*or random multilayer structures. *(*Mulet J.P et al2004*)*

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 Yet al.*2014*).*Material used for the emitter are Rare earth materials, Photonic crystals, Metamaterial.

Classification of TPV emitters

Before examining the practicality of TPV emitters, we first categorize emitters in the literature as follows: i) utilized in system demonstrations of TPV prototypes ii) manufactured and optical performance tested; iii) optical performance simulated.

Optical performance

An emitter with strong optical performance suppresses out-of-band photons and preferentially emits in-band photons from all angles. The emission of photons as a function of angle and photon energy, specifically in two regimes for the latter—in-band photons with energy higher than the PV cell bandgap and out-of-band photons with energy lower—is referred to as optical performance. The techniques that allow for preferential in-band emission are referred to as spectral control. While some spectrum control schemes are intended for narrow-band emission, others are intended for broadband emission.

In the latter instance, photons are released with energy that are marginally higher than the PV cell bandgap. Broadband emitters generally produce an increased output electrical power density, whereas narrow-band emitters have the ability to enhance the TPV conversion efficiency. Since an emitter radiates photons over a wide range of angles, angular control, which is typically an implicit aspect of spectrum control, aims to ensure spectral control over all angles (polar and azimuthal, ϴ and φ). This is particularly significant because, in accordance with Lambert's law, the majority of thermal radiation is abnormal.

For TPV, the wavelength regions of interest are around 1-3 µm, approximately the regions of peak emission. For an emitter heated to realistic temperatures of 1000-1500 K, the peak emission wavelengths are 1.9-2.9 µm, as according to Wien's displacement law. As such, one of the main requirements of TPV is to have low-band gap PV cells, with typical band gaps in the range of about 0.50-0.74 eV or 1.7-2.3 µm. Although a PV 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 PV cell, they overheat the PV cell and reduce the PV 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 6 emitters, there are actually two main approaches of spectral control.(Burgt, 2020) The first is to enhance in-band and suppress out-of-band emission via selective emitters.

The second method involves using cold side filters or reflectors (CSFR) in front of (front side filter) or behind (back surface reflector) the PV cell to reflect out-of-band photons back to the emitter, also known as photon recycling. Combining the two methods is also an option; for instance, one might theoretically have a selective emitter together with a filter or reflector, or even all three. View factor and absorption losses plague an emitter with a CSFR, despite its superior performance over a blackbody or greybody (comparatively higher temperature and reduced PV cell efficiency decline). Photons are lost in the finite gap between the emitter and the filter/reflector in view factor loss, which is a feature of systems with diffuse emitters, and absorbed at any.(Bethke, 2018)

Selective emitters, in contrast, reduce out-of-band emission in comparison to in-band emission. For out-of-band photons, this lowers view factor and absorption losses; but, for in-band photons, both losses—especially view factor losses—remain significant. But just because an emitter has reached a high temperature doesn't mean it's better than others; temperatures above 1500 K are difficult to reach, the input power needed to heat an emitter can vary greatly, and it's not always clear whether a particular emitter can maintain high optical performance at high temperatures for extended periods of time. The question of stability at high temperatures is covered later on as a different metric. Because having high output electrical power is the ultimate goal of the system, one sub-metric is the in-band radiated power density which enabled by maximizing the in-band power density that is emitted and can be converted.(Malyshev.V, 1979)

Scalability to large areas

Increasing the emitter area (its macroscopic external dimensions) is one method to raise the absolute emitted power because the fundamental restriction for emitters is on the power radiated per unit area. When putting this into practice, it's crucial to take the following into account: 1) The substrates need to be offered in big sizes. 2) The fabrication techniques need to make it quite easy to work with large-area samples.

For example, for 1, the single-crystalline substrates of tungsten and tantalum are typically available in small diameters 1-1.5 cm (area ~3 - 7 cm^2), while naturally selective emitters made of rare earth metals can be on the order of tens of cm2. Scalability and cost can be impacted by the total complexity of the fabrication process, which includes the number of processes and the intricacy of each individual phase. But rather than being appropriate for scale manufacturing, many of the fabrication methods employed in publications would be more appropriate for proof-of-concept demonstrations. (Aguas, 2015)

Long-term high-temperature stability

The TPV emitter must sustain its optical performance at high temperatures for extended periods of time, either continuously or over multiple thermal cycles. However, at high temperatures the kinetic energy of atoms increases and atoms diffuse more easily, leading to a number of potential thermodynamic effects:

First Sharp edges and features may become more rounded. Also, It is possible for there to be a phase change (the emitter melting, for example), along with morphological and visual alterations. This is also possible for phases that are crystalline. But it's crucial to remember that a material's melting point is lower at the nanoscale than it is at the bulk.

Grain sizes in polycrystalline materials are not limited by size. But this can also stabilize the material, which is why some substrates, like polycrystalline tantalum, need to be annealed before they can be used. Moreover, single-crystal or large-grain substrates can be used. There could be chemical deterioration, leading to the production of tantalum carbide and tungsten oxides. This may need the emitter to function in a vacuum or in an inert atmosphere, necessitating unique packaging and complicating the integration of the TPV system. The chemical deterioration of 2D and 3D tantalum and tungsten photonic crystals can be lessened by covering the surface with a protective layer of hafnium dioxide (HfO2), which ranges in thickness from 20 to 40 nm. HfO2 has been found to be more thermally resilient than Al2O3 in a comparison of the two materials in 3D photonic crystals; nevertheless, Al2O3 is less expensive and has been used to shield a Meta surface emitter.

The longest reported studies we know of are 300 hours each for an erbium-doped yttrium aluminum garnet (Er-YAG) crystal used in a solar TPV system and a 2D photonic crystal made of tantalum-tungsten alloy and capped with 20-40 nm HfO_2 used in an radioisotope TPV prototype. The former cracked and darkened after 300 hours in the sun, although the authors attribute it potentially to a water leak. The 2D photonic crystal showed little to no degradation in optical performance after annealing for 300 hours at 1000 ◦C (1273 K) and 1 hour at 1200 ◦C (1473 K).

The only other emitters we know of that were used in both system demonstrations and some high-temperature stability experiments include a Yb_2O_3 foam ceramic, a 2D photonic crystal made of polycrystalline tantalum and coated with 20-40 nm HfO_2, and a multilayer stack made of tungsten and HfO_2. The foam ceramic was robust under 200 thermal cycles, the 2D tantalum photonic crystal showed no visible degradation after 144 hours at 900 ◦C (1173 K) and 1 hour at 1000 ◦C

(1273 K), and the multilayer stack showed little to no degradation after at least hour at 1423 K in vacuum.(Malyshev.V, 1979)

Ease of integration within the TPV system

When 1) placing the emitter and heat source physically close together for thermal contact and 2) packaging the system for operation in a vacuum or inert gas environment, the emitter's design choices may pose a number of hurdles to its integration inside the TPV system. Sometimes the heat source and emitter are made of the same material, like platinum or silicon carbide, or the emitter is fabricated directly onto the heat source. An example of this would be the deposition of tantalum or silicon dioxide onto a micro combustor, or the creation of an absorber/emitter combination for solar TPV.

In other situations, it could be necessary to mill and weld the emitter onto the heat source—a tiny combustor, for example—after cutting it to the proper size. A solid-state substrate, foil, or sputtered coating can be used. The mechanical characteristics of the emitter material become important, particularly in the last scenario. Three distinct substrates, for instance, have been investigated in the creation of 2D photonic crystal emitters. These consist of tantalum-tungsten alloy, polycrystalline tantalum, and single-crystal tantalum. Polycrystalline tantalum is more compliant and easier to machine and weld than tungsten, but it is softer than tungsten and requires a thicker layer to attain the same mechanical stability. Tungsten is brittle and difficult to machine and weld.(Stelmakh, 2013)

Tantalum-tungsten alloy combines tantalum's easier machining and welding capabilities with the superior thermomechanical properties of tungsten. Concerns about the stability of high temperatures also apply: using the heat source and emitter at high temperatures can cause the emitter or heat source to break or delaminate. Furthermore, in order to stop chemical degradation processes like oxidation and heat losses via convective heat transfer processes, the emitter frequently needs to be in a vacuum or inert gas environment. We compared the prototype TPV system demonstrations and noted whether the emitter was constructed onto the heat source or in addition to it, as well as whether the system operated in an inert atmosphere or under vacuum.(Malyshev.V, 1979)

Cost

The price of raw materials, fabrication, and system integration all affect the total cost of producing emitters. Specifically, a lot of emitters use materials that are relatively uncommon, such hafnium and rare earth metals. If there are more processing stages or complex fabrication procedures, the cost of fabrication may go up.(Malyshev.V, 1979)

At-a-glance evaluation of emitters used in prototype system demonstrations

Broadly, there are five types of emitters that have been implemented in prototype system demonstrations

1. Bulk emitters

(a) **Grey body emitters**: - such as silicon and silicon carbide are frequently able to be produced onto or with the heat source, are generally affordable, and are simple to fabricate in large regions. Nevertheless, because of their strong out-of-band and in-band emissions, they are frequently used in conjunction with cold side filters.

(b) **Metals with or without ARC**: - may be cheaply and easily made in big spaces. The metal's optical characteristics determine the emission; the ARC layer's usual function is to increase emittance in a narrow band around the band gap.

2. Naturally selective emitters

Rare earth metals, particularly erbium and ytterbium, have been used mainly in its construction. Large-scale fabrication and excellent temperature stability are features of them, particularly when high-temperature ceramics are doped. Nevertheless, naturally selective emitters have a narrow-band, untunable emission wavelength range, which may result in low in-band emitted power density.

3. 1D photonic crystals

Known by another name, dielectric mirrors are made up of alternating layers of materials whose indices of refraction contrast greatly. This structure's interference effects produce a reflection bandwidth that is reasonably wide and can be utilized to reduce a material's high natural emittance for a certain wavelength range. Although they can be directly constructed onto a heat source, they are often not formed of high-temperature materials and are difficult and expensive to fabricate at large areas. Instead, they have several interfaces. Outside of the suppression region, they might exhibit large levels of out-of-band emission.

4. 2D photonic crystals

For TPV, a 2D array of features with feature sizes roughly equal to the wavelength of interest is usually placed on top of or within a substrate, like air cavities or cylindrical posts. In photonic crystals with air cavities, the emission of wavelengths below a cutoff (approximately half a wavelength corresponds to the cavity diameter) is enhanced by each cavity acting as a waveguide. The substrate—a high-temperature material—largely determines whether an emitter can be made affordably with a big surface and integrated with the heat source.

5. The multilayer stacks

They are distinct from 1D photonic crystals in that their layer thicknesses are not cyclical. The combination absorber/emitters for solar TPV in this review are made of alternating layers of dielectric and metal with different thicknesses. Sometimes subwavelength, the layer thicknesses are tuned to provide for both emission and absorption in the broadband range. The ability to construct vast areas depends on the sizes of the metal that are available, even though the optical performance is strong and the fabrication costs are probably inexpensive. Despite the use of high temperature materials, there are several interfaces, and it is unknown whether high temperature stability will last over time. (Maremi, 2018)

Efficiency

The ratio of the emitter's total energy emitted to the energy that is appropriate for the PV device (above Eg) is known as the emitter efficiency (E). It is possible to engineer the thermal emitter element to maximize the radiation spectrum that is beneficial. *(David et.al, 2014)*

Equation describes the efficiency with which a TPV system converts radiated heat to electrical power.

$$\eta_{TPV} = \eta_{SP}\eta_{PV} = \frac{P_{out}}{P_{rad}} \qquad (1)$$

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

$$\eta_{SP} = \frac{\int_0^{\lambda_c} E(\lambda)\varepsilon(\lambda)d\lambda}{\int_0^{\infty} E(\lambda)\varepsilon(\lambda)d\lambda}, \qquad (2)$$

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 metamaterial* (Maremi et al. 2018)

In the past, many metamaterial emitters were created to boost the TPV system's effectiveness. By absorbing the incident thermal energy with a wavelength selective absorber and emitting it with a thermal emitter—which emits photons at a specific wavelength that matches the highest quantum efficiencies (QE) of a particular photovoltaic (PV) cell—the TPV system can effectively convert thermal energy from any kind of heat source into electricity.

For the investigation, a metal–dielectric–metal (MDM)–structured metasurface is used to create a high-efficiency emitter. Traditionally, MDM metasurfaces were made to operate at ambient temperature. As a result, noble metals are typically used to create MDM metasurfaces. But recent studies successfully demonstrated MDM metasurfaces for high temperature *applications (B.J.*et al2016*).* Tungsten (W) is a promising material for high-temperature applications due to its high melting point.

3. Material and Method

This part included a discussion of the study's methodology and procedure. COMSOL Multiphysics is a numerical program used in the design of multilayer systems. We will employ numerical analysis in this study; COMSOL Multiphysics software is used to do numerical analysis. Through the verification and optimization of devices and processes, multiphysics simulation software helps engineering, industrial, and scientific research firms manage physics-based modeling. Users of the platform can design unique modeling processes and make data transmission between various models—such as fluid flow, heat transfer, electromagnetic, structural mechanics, and others—easier.

In addition to offering geometric modeling capabilities including surfaces, curves, solids, and Boolean operations, COMSOL Multiphysics also specifies the steps to take in order to gather data for editing and parametric research. Numerous features are available with the solution, including virtual operations, the import of CAD data, pre-defined physical interfaces, automated and manual networking, and 2D and 3D modeling, among others. Researchers may view simulation data using interactive visuals, charts, and figures, and export results in text, DAT, CSV, and Excel forms thanks to its visualization and post-processing facilities. Additionally, researchers can create unique modeling programs and distribute them to production departments, test labs, process operators, and clients.

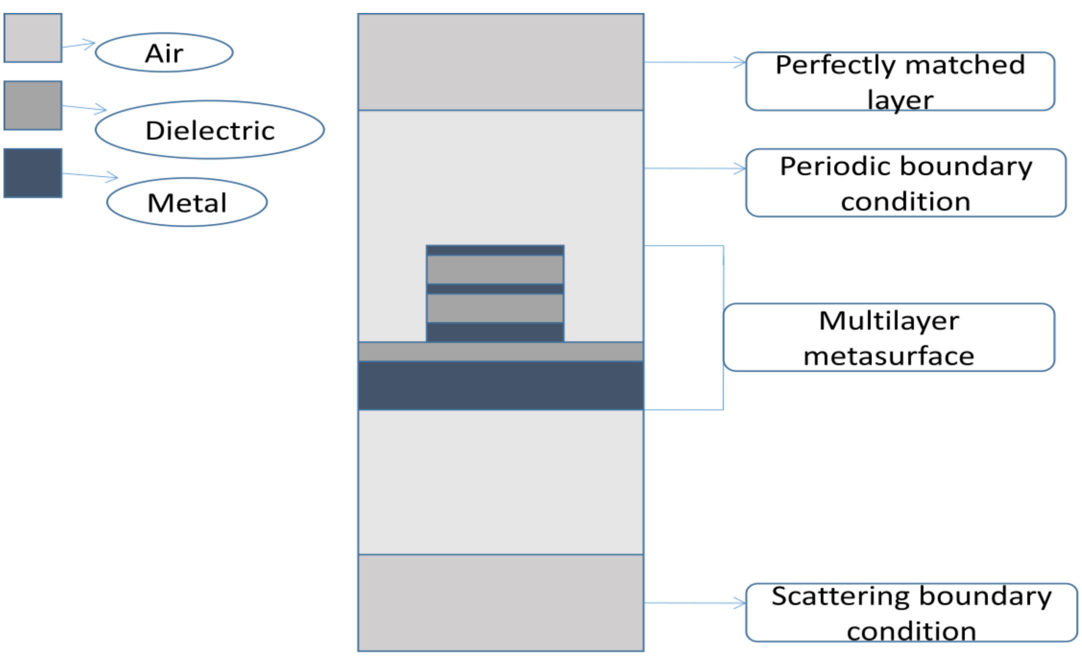

Figure 3: Design of emitter with a multilayer structure

Utilizing COMSOL Multiphysics software, the multilayer emitter was constructed utilizing aluminum nitrate and tungsten, as depicted in figure 3. The dimension of 3D space was chosen for the workspace. The electric and magnetic fields for our system, where the wavelength was similar to or significantly smaller than the device under study, were computed using the optics interface. The response of the model to harmonic excitation for one or more wavelengths was calculated using the Wavelength Domain research. It is used to calculate the transmission and reflection of a structure vs wavelength in electromagnetic wave propagation through the proposed structure.

The design parameters are w (width of unit cell), h1 (top Tungsten height), h2 (dielectric thickness), h3 (ground Tungsten thickness). The Multilayer designed starts with W and ends with W, in other word it consists metal-dielectric-metal (M-D-M) structure. The multilayer was subjected to numerical simulation in an effort to reduce calculation time. With the aid of COMSOL Multiphysics, a three-dimensional electromagnetic wave and the wavelength domain investigation were carried out. To reduce reflection, exactly matching layers were assigned along the z-axis or at the top and bottom of the computational domains throughout the numerical analysis. In order to take into consideration oblique incidence and an infinite flat surface on the emitter, the periodic boundary condition was additionally established at the left and right borders.

Through the working wavelength, the electromagnetic waves or incident light on the emitter are seen as being perpendicular to the x-y plane. The software's default material list was used to obtain the refractive index (optical characteristics) of the metallic sheet and the dielectric spacer.

4. Result and Discussion

The metamaterial emitter used in this work was numerically designed with varying parameters, including unit cell width, W film thickness, and dielectric thickness. In this study, the unit cell width (w) and film thickness (W) are fixed, while other parameters are optimized. Based on the intended structure, the efficiency of several metals and dielectrics was compared. The most obvious ways to control the metamaterial's effective permittivity and permeability are through design geometry and arrangement.

Current induction in the metallic periodic structure of metamaterial causes it to interact with impinging electromagnetic waves. The periodic unit cell arrangement and the geometry of metamaterials were the source of the electromagnetic property since the wave of the magnetic component travels perpendicular to the plane of pattern. The electromagnetic characteristics can be altered by altering the width, height, and thickness of the dielectric and the metal.

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4.1. **Effect of height of metal (h1)**

This optimized result is obtained from multilayer metasurface build from the metal Tungsten and the dielectric Aluminum Nitrate. We optimized the data by changing the parameter which is the height of the metal varies with the range of 0.01µm< h1< 0.17µm. But for that of the dielectric the height remains constant which is h1=0.02µm. We have obtained the highest efficiency when h1=0.17µm and the lowest one in this context h1=0. 09µm.Furthermore, the average emissivity becomes 0.8681.

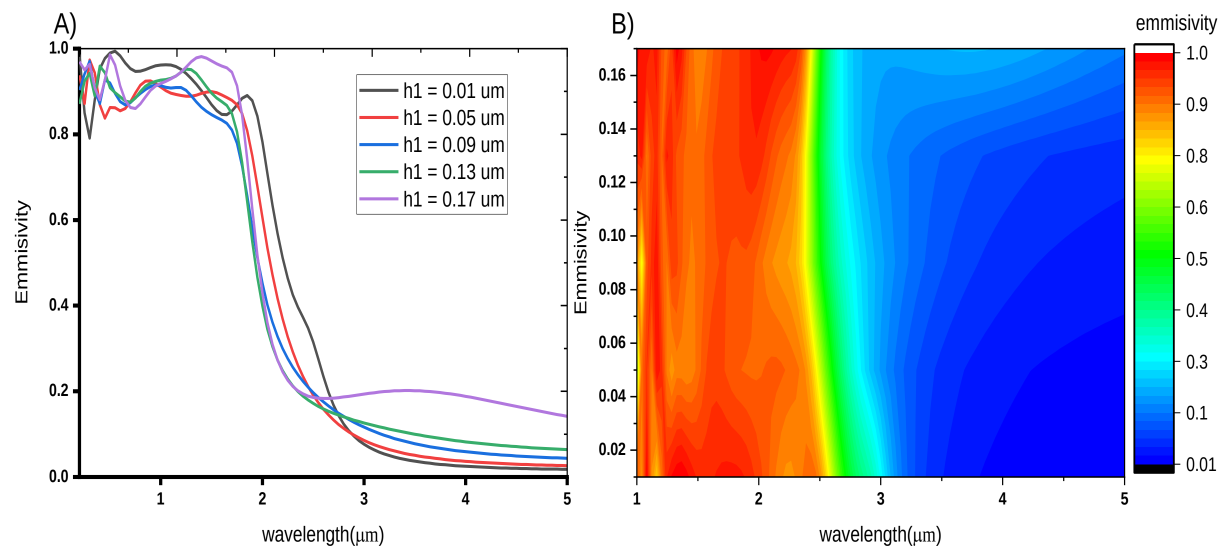

Fig 4: - Result obtained from designing the multilayer using the metal W, and the dielectric AlN and the height of the metal ranging from 0.01µm< h1< 0.17µm.

4.2. **Effect of thickness of dielectric(h2)**

An MM emitter's dielectric thickness, or the spaces between metalized patches, is a key factor in determining the device's resonance frequency. The induced fields will alter even further when two metal surfaces are adjacent to one another because of capacitance. As the distance between the metal regions changes, the capacitance and, consequently, the resonant frequency will also change.

From simulation we demonstrate that the resonance frequency occurs because of MP shift to lower wave length and resonance frequency occur because of SPP shift to larger wave length when the dielectric thickness is increase. As illustrated on the figure 15 below, the emissivity of the designed Multilayer metamaterial emitter depends on the thickness of the dielectric layer. When h2 increases from 0.02µm to 0.14µm the emissivity slightly changed. The broad band and high emission obtained at h_2 =0.06µm. Furthermore, the average emissivity becomes 0.815131.

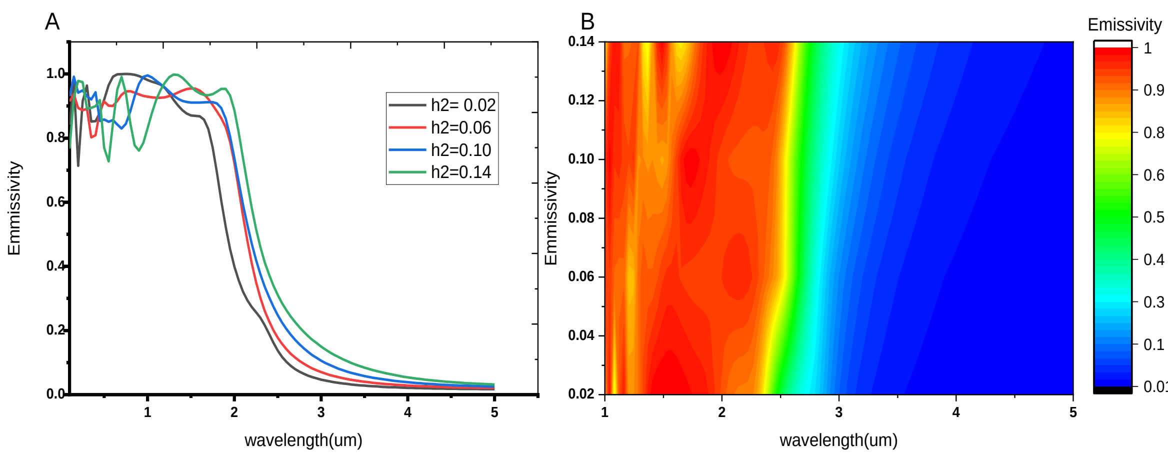

Fig 5:- Result obtained from designing the multilayer using the metal W, and the dielectric AlN and the height of the dielectric ranging from 0.02µm < h2 <0.14µm.

4.3. **Effect of Polar Angle on Emissivity**

The character of angular emissivity of TPV emitter is important due to polarization angles of electromagnetic waves. 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 ($\theta = 0^0$ø = 0°). However, the outcomes imply that azimuthal angles and polarizations have no effect on the intended metamaterial emitter. This illustrates the symmetry of the suggested emitter, indicating the independence of polarization. At all angles, the emissivity spectra were nearly identical, although at θ = 450, minor distinctions could be seen. It was possible to obtain wide angle spectrum emissivity of multisurface metamaterial emitter by excitation of diverse physical process.

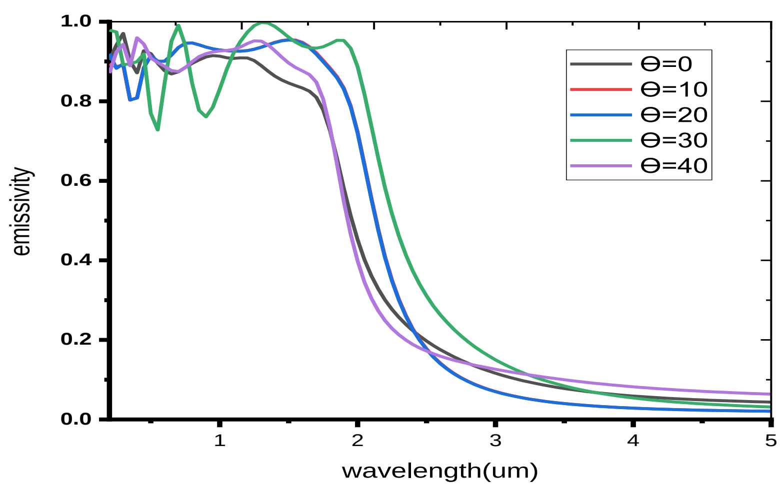

Fig 6: Result obtained from designing the multilayer using the metal W, and the dielectric AlN and the theta ranging from 0 < Θ < 30.

4.4. Effect of Azimuthal Angle on Emissivity

The character of angular emissivity of TPV emitter is important due to polarization angles of electromagnetic waves. Nonetheless, the results suggest that the designed metamaterial emitter is independent of azimuthal angle. This explains that the proposed emitter is symmetric, which means that the polarization is independent which means similar for TM (magnet transverse) and TE (electric transverse). The simulation result is demonstrated that as the incident angle increased from 0° to 60°, the emittance curve did not change. This result shows that the emitter is suitable for plane waves with a wide range of incident angles.

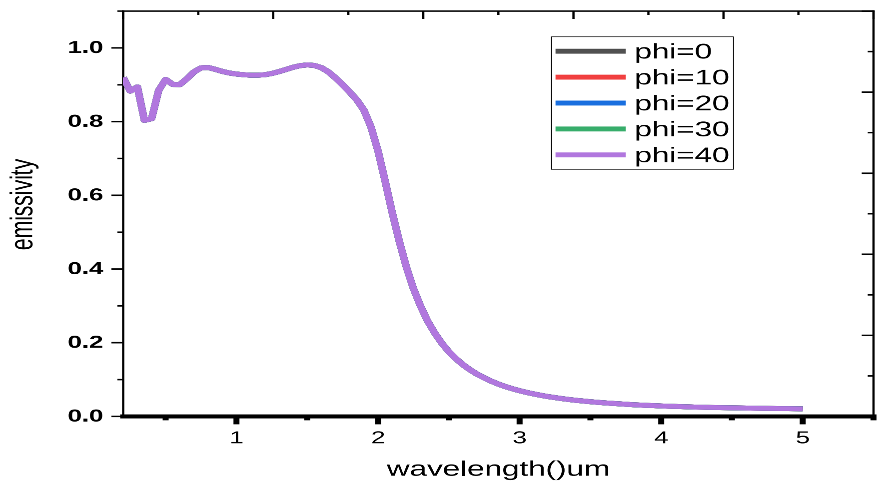

Fig 7: Result obtained from designing the multilayer using the metal W, and the dielectric AlN and the phi ranging from 0 < ϴ< 60.

4.5. **Distribution energy flow**

The metal-dielectric-metal (M-D-M) structure of the metamaterial design we show in this work allows us to generate resonances at various wavelengths because of the MPs, SPP, CMP, high intrinsic loss of platinum, and other factors. This physical absorption mechanism is combined to give our metamaterial its increased broad band emissivity. The design of a multilayer selective metamaterial emitter was selected to provide broadband emissivity irrespective of polarization.

The distribution of the normalized energy flow at wavelengths of 0.5µm, 1.6µm, and 3µm has depicted in the figure 8below respectively. The energy and energy density carried by a travelling electromagnetic wave in space is related to electric and magnetic field. Pointing 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 Pointing vector, Re is real, **E** is electric field and **H*** is complex conjugate of magnetic field.

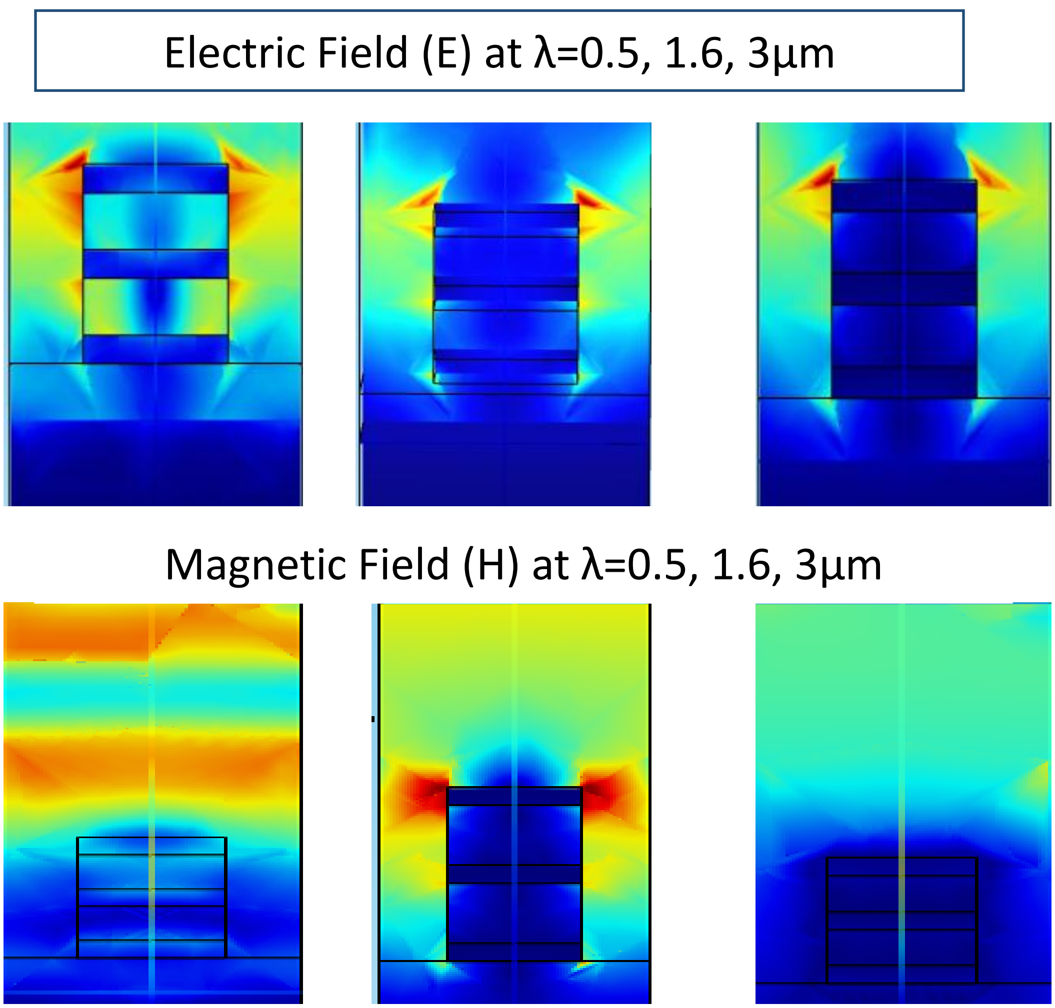

Fig 8:- The distribution of the normalized energy flow at wavelengths of 0.5µm, 1.6µm, and 3µmwithin Multilayer designed metamaterial emitter.

4.6. **Effect of Di-electrics on Emissivity**

As illustrated on the figure, the emissivity of the designed Multilayer metamaterial emitter does not depend on the types of the dielectric. When dielectric changed from Aluminum nitride to silicon dioxide the emissivity moreover is the same it doesn't show that much of difference. Therefore, we can use both dielectrics with a small parameter change in this design.

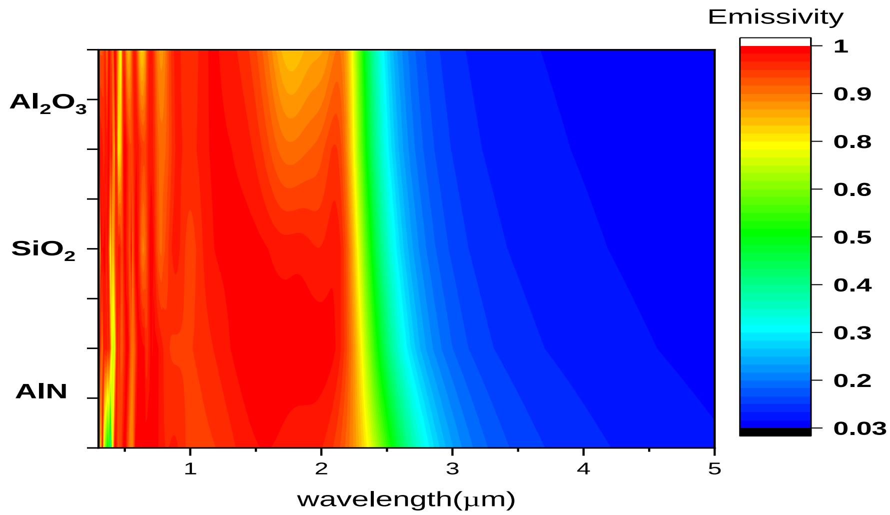

Figure 9: The emissivity of the designed metamaterial dependent on different di-electric

4.7. **Effect of Metals on Emissivity**

From figures below Tantalum based emitter work doesn't have the cutoff wavelength we expected for the cell with 2.1μm but this work was designed for low temperature emitters which is Tungsten based emitter (W-AlN-W). Tungsten based emitters was selected.

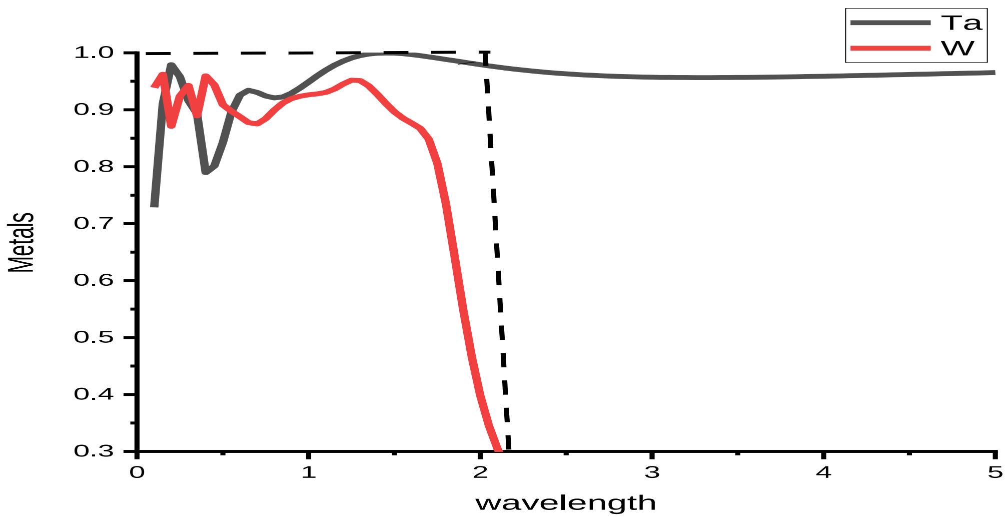

Figure 10: The designed metamaterial emitter emissivity by different metals, And the graph shows when we use Ta as a metal and AlN as dielectric.

4.8. **Comparison of the spectral irradiance of black body with the proposed selective emitter at different temperature**

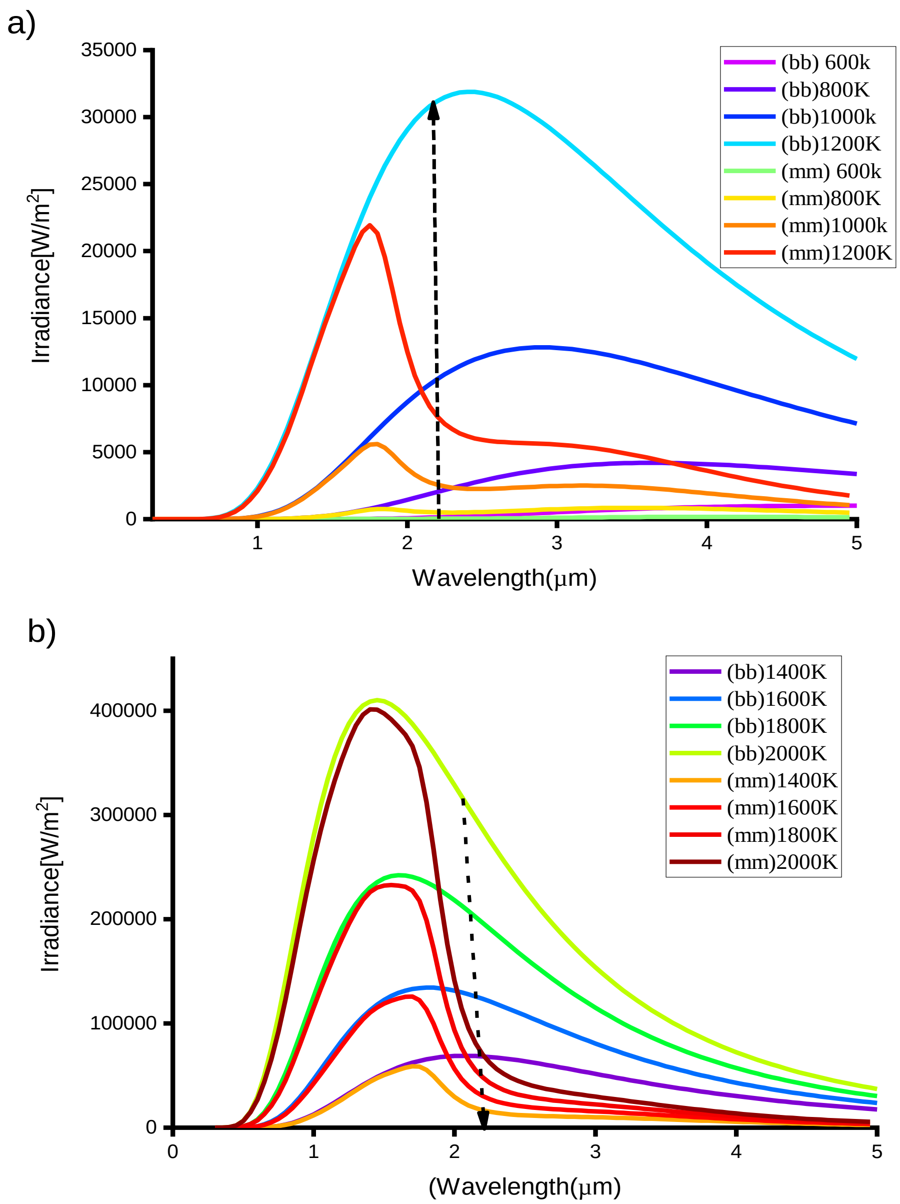

Fig 11: Comparison of the spectral irradiance of black body with the designed selective emitter at different temperature, with indicating BB and MM comparisons at the same temperature.

As illustrated in figure 11 above when I compare the suggested emitter with blackbody in terms of spectral emissivity at different temperature, the Multilayer i have designed exhibit selective emission above band gap.

The vertical line on each graph indicates cutoff wavelength of InGaAs which is 2.1µm. In contrast to, black body above this line the spectra of suggested MM decreased dramatically, this shows us the selectivity of the emitter.

4.9. **Performance of designed metamaterial emitter**

The emissivity spectra of the proposed Multilayer metamaterial emitter, wherein the shaded area shows the EQE of InGaAs (2.1µm).

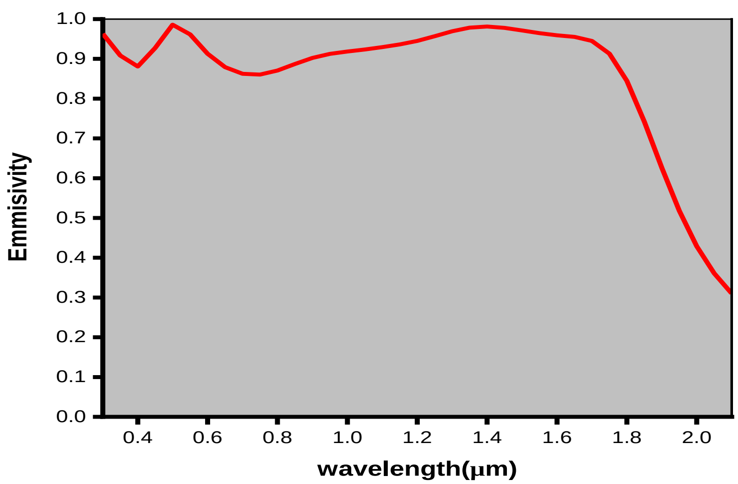

Figure 12: the emissivity spectra of the designed metamaterial emitter with the shaded area are external quantum efficiency of InGaAs.

From the figure12 be clearly seen that, we obtained a near perfect broadband emitter below the cut-off wavelength of InGaAs, which dramatically decreased after the cut-off wavelength of 2.1µm. 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, our result reveals that our emitter emits high convertible photons. 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 Multilayer metamaterial that offers better spectral efficiency performance in a TPV system.

The spectral efficiency of emitter at different temperature which calculated according to equation (8) above can be given in the table below.

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 (1).

Where the spectral efficiency of the emitter is ηsp, ηpv is the efficiency of the photovoltaic cell, $Pout$ is the maximum output power, and $Prad$ is the total radiant power from an emitter. Spectral efficiency ηsp is defined by Equation 1) (Ghanekar et al., 2016).

$$E(\lambda) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{\lambda k_b T}-1}}. \qquad (3)$$

*Where c is the cut-off wavelength, **E** (λ) is emission spectrum of a blackbody, **ε(λ)** 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.*

To compare the spectral irradiance of the planned selective emitter and the black body, we extend our investigation of the optimized Multilayer selective metamaterial emitter with a black body at various temperatures. Spectral efficiency can be calculated using Equation (2) And E (λ) can be calculated by using equation (3).

When the selective emitter has low emissivity above the cut-off wavelength and excellent emissivity below it, the maximum efficiency is reached. The spectrum irradiance of the black body and the selective emitter metamaterial at temperatures ranging from 600 K to 2000 K are contrasted in Figure 11. The spectral efficiency improved with temperature, indicating that the emission peak moved to a lower wavelength. This suggested that the emission spectrum peak was above the band gap region.

Table1: spectral efficiency of designed emitter calculated at different temperature

Temperature(K)	Spectral efficiency
600	3.6%
800	16.77%
1000	35.66%
1200	52.66%
1400	65.20%
1600	73.92%
1800	79.98%
2000	84.27%

5. CONCLUSION AND RECOMMENDATION

Conclusion

This work proposed and statistically investigated a metamaterial selective emitter for TPV use. Polarization and azimuthal angle independent selective emission were demonstrated by the metamaterial. We gave 2.1μm as the cut-off wavelength for InGaAs some thought. In order to attain perfect broadband emissivity above the band gap energy, geometric characteristics such as breadth and the height of the metals and dielectrics were researched and improved. The suggested metamaterial improved the TPV system's efficiency. When the TPV cell absorbed 100% of the photons that were radiated, efficiency was also increased. After optimizing the geometric parameters, the suggested metamaterial emitter demonstrated a wide-angle average emissivity of above 70% of the wavelengths at 2.1μm and an increased near perfect broadband. This outcome helped to improve the TPV's performance.

Recommendation

The rapid increase in energy consumption has an effect on non-renewable energy sources, which is why renewable energy options are being considered. The development of energy conversion efficiency is a major problem for the globe today with the use of renewable energy sources. In relation to this TPV system, it is a leading contender. A TPV system appears to be a good option for absorbing, recovering, and converting waste thermal energy into electrical power. Every element in the thermoelectric power system, such as the thermal emitter, TPV generator, and TPV cells, is essential and can be designed to improve the heat-to-electricity ratio.

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