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Research on Optimal Design of Thermal Emitter Based on Thermal Photovoltaic Technology

Guangyuran Liao

Department of Applied Mathematics, College of Science, Nanjing Forestry University, Nanjing, China

Abstract: *Improving the thermal conversion efficiency of thermal photovoltaic system to optimize the design of thermal emitter in thermophotovoltaic has attracted worldwide attention in recent years due to the world's major power have devoted great efforts to the exploration of outer space. Based on this background, the focus of this study is to adjust the emission spectrum of the thermal emitter to improve the thermoelectric conversion efficiency of the thermal photovoltaic system. Aiming at the problems of emission spectrum and material characteristics, the model of TMM transfer matrix is established, and the problems of solving thermal radiation emission and calculating emission spectrum in Maxwell equation are solved. Use appendix website: https://refractiveindex.info/, the transmittance of 50 nm thick tungsten at the wavelength of 0.3 ~ 5 μ m is obtained to draw the emission spectrum of tungsten. According to the wavelength analysis of tungsten in the people's Republic of China, it is verified to be within a reasonable range. Aiming at the problems of spectrum and material characteristics of composite structures, a TMM transmission matrix model is established. The coherent light reflection and transmission of multilayer material structure are expressed as the product of matrix. The relationship equation between the properties of multilayer material and its emission spectrum is obtained, and the problem of emission spectrum is solved.*

Keywords: *Emission spectrum, Matrix model, Optimization design*

1. Introduction

With the advance of industrialization in recent years, fossil fuels are increasingly scarce and harmful to the environment. For sustainable development and environmental protection, it is necessary to find clean and viable energy sources. Because of Solar energy's unlimited reserves and universality, it is a hot research topic that solar energy can be utilized efficiently and converted into electric energy at low cost. Since the 21st century, thermophotovoltaic technology allows rovers to carry instruments that work without sunlight. Which uses solar energy, nuclear energy and other heat sources, relying on photovoltaic cells to convert their infrared radiation into electricity. However, due to the limited conversion efficiency of photovoltaic cells converting high-energy photons into electricity, it is necessary to improve the thermal conversion efficiency of thermal photovoltaic system. The thermal conversation efficiency of thermal photovoltaic technology is relay on the ability of photovoltaic cells to convert other heat into electricity.

Firstly, the cells for high-energy photons are required to be in a specific band gap wavelength. The relationship between material properties including refractive index and thickness and emission spectra of monolayer structures is illustrated. Calculate the emission spectra of 50 nm thick tungsten in the range of 0.3 to 5 micron.

In addition, Illustrated the relationship between material properties including refractive index and thickness and emission spectra of multilayered structures. When a composite structure is composed of 50 nm tungsten and 50 nm silicon, the emission spectra of the composite structure in the range of 0.3 to 0.5 microns are calculated.

Finally, using reasonable materials and designing a narrow-band multilayer heat emitter can improve the spectral control rate of the radiator, so that the emission can be concentrated in a very small frequency band. The description includes the number of layers, the material and thickness of each layer, the design parameters of the multilayer structure and its emission spectrum.

2. Thickness and emission spectrum of monolayer structure

There are two small problems in the first question. The first problem is the relationship between the material properties including refractive index and thickness and the emission spectrum of single-layer structure. According to the analysis and research of scholars in recent years, except for a few experimental studies, most experimental studies use the research methods of theoretical analysis and numerical simulation. Among these methods, there are Monte Carlo method [1], double heat flow method [2], gardon method [3,4] and several positive analysis methods, such as reverse ray tracing method [5,6]. According to the study of free conductive electrons in metals under the action of minerals and electromagnetic radiation in Annex I, when the wave falls on the metal surface, two waves will be generated due to the interference of light, which are called transmitted wave (T) and reflected wave (R). This process is also called Fresnel coefficient. In this process, it is not difficult to deduce and calculate the relationship between the emission spectrum of single-layer structure and material properties including refractive index and thickness.

According to the study of the incident angle of the wave on the material surface, it can be concluded that there will be two types of polarization. One is the parallel polarization generated when the electromagnetic field falls from the electromagnetic wave, which is also called p polarization or TM polarization. In the analysis of the subject, Maxwell's four equations 1 are used as the theoretical basis to explain the propagation of electromagnetic wave (EM) in optical medium.

The relevant material properties of 50 nm thick tungsten given in this topic can be derived and calculated using the relationship equation between the obtained emission spectrum and material properties, so as to obtain its emission spectrum in the range of 0.3 to 5 microns.

2.1. Propagation analysis of electromagnetic wave in optical medium

The propagation of electromagnetic wave (EM) in optical medium is explained by Maxwell's four equations 1.

$$\begin{cases} \nabla \cdot \bar{D} = 4\pi\rho \\ \nabla \times \bar{E} = -\frac{1}{c}\frac{\partial \bar{B}}{\partial t} \\ \nabla \times \bar{H} = \frac{1}{c}\frac{\partial \bar{D}}{\partial t} \\ \nabla \cdot \bar{B} = 0 \end{cases} \tag{1}$$

Refractive index in the single-layer structure whose layers in the direction and in X-Y is given.

$$\in_1 = \in_{l(z+d)} \tag{2}$$

In the above formula: D is the period and l is the number of layers. Using Maxwell equations and its boundary conditions, the transverse components of electric field and magnetic field are divided into two types of polarization and TE polarization. The intrinsic impediments is:

$$\eta_l = \frac{k_l}{\omega \in 1 \in 0} \tag{3}$$

According to the conclusion of the above equation, it can be inferred that there is a certain relationship between the thermal radiation intensity of the single-layer structure and the refractive index and extinction coefficient. Because the emission spectrum represents the relationship between the wavelength and the thermal radiation intensity, if the relationship between the wavelength and the refractive index and extinction coefficient can be found, Then the relationship can be obtained by using Maxwell's equations and Fresnel coefficients. According to the data of wavelength, refractive index and extinction coefficient of tungsten given by W - refractive index.csv in Annex V, the relationship between the three can be drawn. First, observe the trend of the chart and make a certain relationship prediction. To facilitate the study, Taking the data when x = y, the image has the trend of diagonal change.

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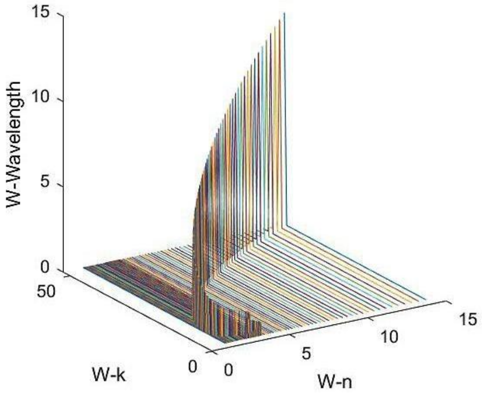

Figure 1: W -n &k & Wavelength

Through the above equation, the following figure can be drawn according to the relationship between extinction coefficient and emission spectrum of tungsten. It can be seen from the figure that when the wavelength is between 0 and 1, the extinction coefficient increases irregularly with the increase of wavelength. When the wavelength is between 1 and 12, the extinction coefficient decreases with the decrease of wavelength, which is a positive correlation.

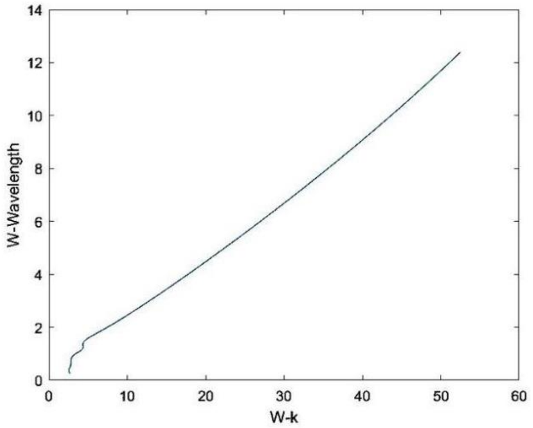

Figure 2: W-k & Wavelength

The relation between refractive index and emission spectrum of tungsten can be drawn according to the material properties of tungsten. According to the figure, when the refractive index is between about 0 and 1, the wavelength is 0. When the refractive index is between about 1 and 4, the wavelength tends to spiral up irregularly. When the refractive index is between 5 and 15, the wavelength of tungsten increases steadily and regularly.

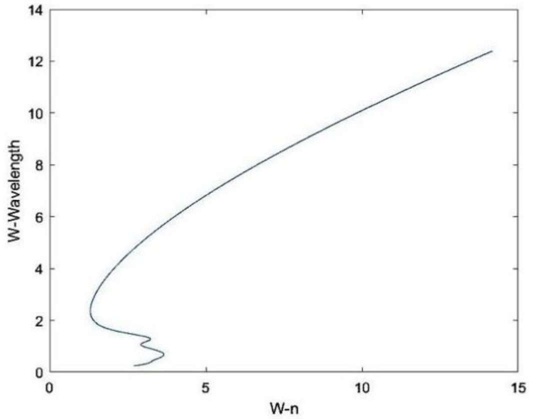

Figure 3: W-n & Wavalength

By using E and H domain conditions and related boundary conditions, the results continue to be obtained in the interface.

$$\begin{bmatrix} E_1 \\ H_1 \end{bmatrix} = M_1 M_2 \ldots MK \ldots M_{l-1} M \begin{bmatrix} E_1 \\ H_1 \end{bmatrix} \tag{4}$$

The matrix of the M_{l-1} lth can be presented as:

$$M_{(l-l)} = \begin{bmatrix} \cos\left(\delta_{(l-1)}\right) & i\gamma_{(l-1)} \sin\left(\delta_{(l-1)}\right) \\ i\gamma^{-1}_{(l-1)} \sin\left(\delta_{(l-1)}\right) & \cos\left(\delta_{(l-1)}\right) \end{bmatrix} \tag{5}$$

The m11, m12, m21 and m22 are the complex numbers. The reflection r and transmittance t are presented:

$$r = \frac{\left(m_{11} + p_s^{-1} m_{12}\right) p_0^{-1} - \left(m_{21} + p_s^{-1} m_{22}\right)}{\left(m_{11} + p_s^{-1} m_{12}\right) p_0^{-1} + \left(m_{21} + p_s^{-1} m_{22}\right)} \tag{6}$$

$$t = \frac{2 p_0^{-1}}{\left(m_{11} + p_s^{-1} m_{12}\right) p_0^{-1} + \left(m_{21} + p_s^{-1} m_{22}\right)} \tag{7}$$

$$z_0 = \sqrt{\frac{\mu_0}{\in_0}} \tag{8}$$

This article can obtain the matrix transfer equation of the whole device through the transition matrix of each layer.

$$\Pi_{k=1}^{l} M_k = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \tag{9}$$

The layer thickness, incident angle and optical constant determine the matrix parameters.

$$\gamma_{(l-1)} = k_{(l-1)} \cdot d_{(l-1)} \cdot \cos\theta_{(l-1)} \tag{10}$$

$$\gamma_{(l-1)} = \begin{cases} \dfrac{\mu_{(l-1)}}{\cos\theta_{(l-1)}} & TE \bmod e \\ \eta_{(l-1)} \cos\theta_{(l-1)} & TE \bmod e \end{cases} \tag{11}$$

Through the calculus and reasoning of the above equation, the spectrum transmission T and reflection R spectrum can be obtained by the above expression:

$$T = \left| m_{11} \right|^2 \tag{12}$$

$$R = \left| \frac{E_r}{E_t} \right|^2 = \left| \frac{m_{21}}{m_{11}} \right|^2 \tag{13}$$

It can be seen from the above expression that the emission spectrum of the single-layer structure is related to the optical thickness of the dielectric layer, the refractive index of the dielectric and the emissivity of the substrate. Among them, the refractive index of the medium has a great influence on the emission intensity of the single-layer structure, which acts together with the optical thickness and other factors. When the wavelength is greater than a certain value, its emission intensity increases with the increase of wavelength, which is positively correlated with the increase of thickness.

2.2. Increasing order of thermal radiation intensity and wavelength

According to the thermal radiation emission spectrum, the thermal radiation intensity is arranged in the order of increasing wavelength. Since the thermal radiation intensity is related to the transmittance of the thin-film structural material of the heat emitter, the higher the transmittance, the higher the thermal radiation intensity. Based on the idea of TMM algorithm, the emission spectrum of tungsten is expressed according to the relationship between wavelength and transmittance. According to the website: https://refractiveindex.info/. Query 50 in turn μ M thick tungsten at 0.3 ~ 5 μ According to the transmittance at M wavelength, the emission spectrum of tungsten is drawn.

The following figure shows the emission spectrum of 50 nm thick tungsten

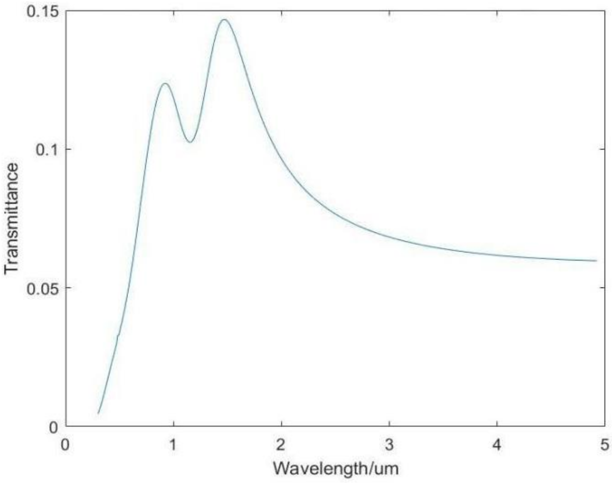

Figure 4: The emission spectrum of a 50-nanometer-thick tungsten

3. Relationship between properties of materials and emission spectra in multilayer structures

According to the research of scholars in recent years, generally speaking, the methods used to study such problems are usually expressed by Fresnel coefficient in 2-2 matrix structure. The elements of the system transmission matrix can be expressed by the complex amplitude reflection coefficient and transmission coefficient R and t of the multilayer structure [1–4]. For materials with one-dimensional inhomogeneity, it is usually necessary to analyze multilayer systems. Ion implanted materials are used as examples of multilayer modeling applications. In particular, the doping distribution is simulated by dividing the injection region into a group of uniform parallel plane sampling layers. The refractive index in each layer is constant, but the refractive index between layers is different, so it represents one-dimensional heterogeneity. Simulation of multilayer heterostructures [7 – 13].

In the second small question of the second question, we need to calculate the emission spectrum of a composite structure in the range of 0.3 to 5 microns. The emission spectrum consists of 50 nm tungsten and 50 nm silicon. In solving this problem, the waveform preparation. characteristics of dielectric charged surface plasmon structures are studied by simple transfer matrix method (TMM) and transfer matrix method (TMM).

3.1. System transfer matrix

For normal incident radiation, the coherent optical reflectivity and transmittance of multilayer structure can be expressed as the product of matrix, that is, the system transfer matrix. The matrix method assumes that the multilayer structure is composed of optically isotropic and uniform layers with plane and plane. The elements of the system transmission matrix can be expressed by the complex amplitude reflection coefficient and transmission coefficient R and t of the multilayer structure [1-4]. for materials with one-dimensional heterogeneity, it is usually necessary to analyze multilayer systems. It is assumed that the refractive index distribution used to simulate the one-dimensional inhomogeneity of the studied sample can be divided into an infinite number of uniform layers. Each layer is represented by its transmission matrix of equation 21 and defined by its thickness D and the square of complex refractive index ˜n or complex dielectric constant c˜ (complex refractive index).

The carrier profile is directly partitioned into $2k\left(\Delta R\right)/\delta x$ homogeneous layers of equal thickness $\delta x\left(=\Delta R/10\right)$ with the carrier concentration N_{cj} in each layer given as

$$N_{cj} = N_{c,\max}\exp\left[\left(-1/2\right)\left[-k\Delta R + j\delta x\right]/R^2\right] \tag{14}$$

In the above expression, NC, Max is the peak value of the concentration curve and j is the layer counter. The convergence test shows that by truncating the Gauss at two standard deviations, the influence of the step in the refractive index curve on the calculated spectrum can be ignored, and the experimental accuracy less than the difference of absolute reflection value is 0.003. The analysis shows that the depth dependence of dielectric function is related to the carrier concentration dependence given as plasma frequency.

$$w_{pj}^2 = \frac{4\pi N_{cj} e^2}{m} \tag{15}$$

The complex dielectric function is calculated for each layer and written in terms of its real and imaginary parts. For the *j* layer this yields.

$$\in'_{cj} = n_j^2 - k_j^2 = \in_\infty - \frac{w_{pj}^2 \in_\infty}{w^2 + \gamma_p^2} \tag{16}$$

Experimental and calculated reflectivity structure of doped $Si - Si\left(70\ keV, 6\times10^{15} As^{+}cm, 0.5h\,annealde\right)$ using incoherent finite substrate correction or semi infinite substrate approximation. Set the thickness to 0.286 μ The non uniformly doped silicon region of M is divided into 80 simulated two half connected Gaussian(R_p= 3800A, ΔR_1= 95A ,ΔR_2= 620A)Sampling layer

$$\in''_{cj} = 2n_j k_j = \frac{\gamma_p w_{pj}^2 \in_\infty}{w\left(w^2 + \gamma_p^2\right)} \tag{17}$$

According to the above equation, the thermal radiation intensity has a certain relationship with the number of layers, thickness and refractive index of the material. According to the thermal radiation medium absorption model, the relationship between the radiation intensity of each layer of material and the material characteristics can be obtained:

$$I_i\left(d,v\right) = I_{i-1}\left(v\right)\exp\left[-\alpha\left(v\right)d\right] \tag{18}$$

Where d is the thickness, v is the wavelength, and I_i is the thermal radiation intensity of the layer

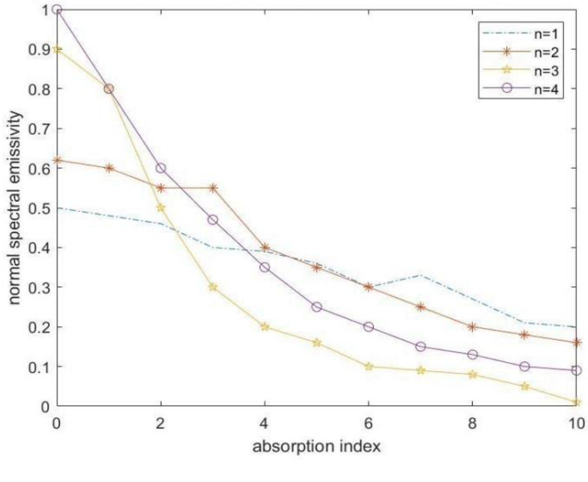

Figure 6: Normal spectral emissivity & absorption index

According to this formula, the material characteristics are analyzed. In terms of thickness: when the wavelength is less than 1, the change of thermal radiation intensity is irregular. When the wavelength is between 1 and 2.5, the thermal radiation intensity increases with the increase of thickness pair. When the wavelength is greater than 2.5, the thermal radiation intensity decreases with the increase of wavelength; In terms of the number of layers: when the wavelength is greater than 0.3 and less than 1.5um, the radiation intensity changes irregularly. When the wavelength is between1.5 and 2.5um, the thermal radiation intensity is the highest when the number of layers is six. When the wavelength is greater than 2.5um, the radiation intensity decreases with the increase of wavelength; In terms of refractive index: the relationship between wavelength and refractive index can be obtained from Figure 3, and the relationship between thermal radiation intensity and refractive index in multilayer structure can be obtained. As shown in the figurebelow:

4. Conclusion

Firstly, the relationship between emission spectrum and material properties in the first problem is explained by Maxwell equations and Fresnel coefficient algorithm. TMM is used to solve the equations explaining the propagation characteristics of electromagnetic waves in optical media, and then the relationship transformation formula of T and R is written according to the transformation of Fresnel formula, and the relationship expression between wavelength (which can be used to represent emission spectrum) and thickness and refractive index is obtained. The multilayer material system is analyzed through the system general transfer matrix: since the coherent light reflection and transmission of the multilayer structure can be easily expressed as the product of the matrix, the complex amplitude reflection coefficient R and transmission coefficient T of the multilayer material structure can be introduced into the parameter elements of the system transfer matrix.

The model established in this paper can be applied to the thermophotovoltaic transmitter as an improvement of its existing design, that is, optimal design. According to the conclusion deduced in the title, our multilayer composite structure can achieve higher thermoelectric conversion efficiency with more reasonable materials. If we further consider the cost of materials and the development of production chain, we can further improve the necessary productivity of society, to reduce production costs, improve production efficiency and expand the application range of heat emitters.

References

[1] Turner W D, Love T J. Directional Emittance of a Two Dimensional Ceramic Coating. AIAA Journal, 1971, 9(9): 1849-1853

[2] Tan H P, Lallemand M. The Absorption Coefficient and Thermal Conductivity. of Molten Potassium N-i trade. Proceedings of the3rd Asian Thermophysical Properties Conference, 1992, 296-302

[3] Garden R. The Emission of Transparent materials. Journal of American. Ceramic Society, 1956, 39(8)

[4] Izard J O. The Emission of Thermal Radiation from Hot Glass (Part 1), Emission of Sheets, Spheres, Cylinders and Tubes. Glass Technology, 1986, 27(1), 376-380

[5] Le Adz V, Lallemand M. Thermal Emittance of Axisymmetric Bodies of. Sem-I Transparent Materials. J. Q. S. R. T., 1992, 47(5): 345- 352

[6] Ji Jiangang, Xia Xinlin, et al. Anisotropic emission characteristics of translucent. body surface. Proceedings of Academic Conference on heat and mass transfer of Chinese society of Engineering Thermophysics, 1995, No. 953121

[7] M. born and E. wolf, principles of optics, Macmillan, New York, 1964, P. two hundred and fifty-four

[8] O.S. day, optical properties of thin films, Dover, New York, 1965, P. sixty-nine

[9] Ye Wenping, light waves in layered media, Willie, New York, 1988, P. one. hundred and two

[10] Z. Knitt, thin film optics, Wiley, London, 1976, P. forty-one

[11] Mehos M, Turchi C, Jorgenson J, et al. On the path to sunshot : advancing concentrating solar power technology, performance, and dispatchability [R].USA:EERE Publication and Product Library, 2016.

[12] IEA. Technology roadmap: solar thermal electricity- 2010 edition [R]. Paris, France: International Energy Agency (IEA), 2010

[13] Graham-Cumming J. The Geek Atlas:128 Places where science & technology come alive [M]. USA: O'Reilly Media, Inc, 2009.

[14] Du, K.; Li, Q; Zhang W; Yang Yong.; Qiu, M. Based on the wavelength and heat distribution of metamaterial absorber, micro bolometer can be selected. IEEE Journal of photonics 2015, 7(3), 1 − 8

[15] Randy, n.i.; Bingham, C.M.; Taylor, T.; Yorkster, N.; Dr. Smith.; Padilla, W.J. design, theory, and measurement of polarization insensitive absorber for terahertz imaging. Physics. minister. B: Condoms. It matters. Physics. 2009, 79 (12), 125104.