Development of One-Dimensional Photonic Selective Emitters for Energy Harvesting Applications

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Abstract

The small wavelength utilizable range used for determining the optimum performance of photovoltaic and rectenna devices, compared to the broad band spectrum of solar or other heat sources, limits the energy conversion efficiency of such technologies. A selective emitter, with an emissivity profile that matches the receiver's characteristic bandwidth, can be used to improve the overall efficiency of such energy harvesting devices. This paper compares simulated and experimental results of the design and fabrication of a selective emitter that can be used in the 8-12 micrometer frequency range. The matrix transform method is used to calculate the radiative properties of one dimensional metal-dielectric photonic structures. By using genetic algorithm as a powerful optimization tool, the simulated design characteristics of such structure are adjusted to minimize the mean square deviation of the actual spectral emissivity from the target emissivity profile. Specifically, this paper presents and compares results of the simulated design and fabrication of selective emitters composed of alternating layers of $\text{Al}_2\text{O}_3\text{-SiO}_2$ or $\text{Al}_2\text{O}_3\text{-SiC}$ on an aluminum substrate. The output radiation of these selective emitters could be used as the input radiation to high efficiency rectenna devices.

Keywords: Selective emitter, Photonic structure, Rectenna, Thermo-photovoltaic

1. Introduction

The vast amount of radiative thermal energy available from solar radiation and terrestrial thermal sources like industrial process heat has made the energy harvesting technologies a hot topic of research. Since natural thermal sources usually emit electromagnetic (EM) radiation in a wide frequency range and are usually located far from the receiver their power densities are generally low. Currently, photovoltaic cells are the most common devices for converting solar energy into electricity. The working principle of a photovoltaic cell is well known based on the photovoltaic effect [1]. The efficiency of photovoltaic cells can be calculated according to the Shockley-Queisser model [2] that limits (bandgap limitation) the maximum attainable energy conversion efficiency (e.g. 30% for crystalline silicon cells under solar radiation [3]).

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This inherent limitation on the efficiency of photovoltaic cells is the main motive to develop alternative EM energy conversion technologies. Recently, thermo-photovoltaic and rectenna systems have attracted attention for harvesting solar energy (see Figure 1). A thermo-photovoltaic system uses the radiation from a heat source to produce electricity in the same way as a solar photovoltaic cell. The heat source in a thermo-photovoltaic system has a lower temperature than solar radiation (i.e. up to 1500 °C for a typical flame) which could be tuned to have its peak emittance just above the band gap energy of the photovoltaic cell. A theoretical efficiency of about 85% has been estimated for a thermo-photovoltaic system that uses concentrated solar energy to heat the emitter [4]. Rectenna is another EM harvesting technology consisting of two main components: an antenna that collects the incident EM waves and a rectifier (diode) that converts the alternating voltage induced at the terminals of the antenna into direct current [5].

The concept of converting solar radiation directly to electricity using a rectenna device was introduced by Bailey [6], in 1972. However, it is still a challenge to rectify electric field at the high frequencies of solar radiation. Therefore, Stefanakos et al. [7] proposed to absorb the solar radiation first by a thermal absorber and re-emit as infrared radiation with lower frequencies that can be rectified by tunnel diodes. Efficiency limits of nano-antennas to capture EM waves and efficiency bounds of converting captured waves to electricity by rectifiers are presented by Vandenbosch and Ma [8,9]. It has been demonstrated that rectennas can reach efficiencies as high as 80% in converting EM energy into electricity [10]. The thermodynamic aspects of energy conversion via either rectennas or thermo-photovoltaics calculating exergy of partially coherent radiation is described by Wijewardane and Goswami [11].

Figure 1: Schematic of the operation principle of two different technologies used to harvest EM energy: (a) thermo-photovoltaic and (b) rectenna

In order to reach high energy conversion efficiencies by thermo-photovoltaic or rectenna technologies, the incident EM waves and the receiver characteristics must be matched. One approach to ensure high efficiency, when using broadband radiation from a heat source, is to send back the photons with energy lower than the receiver's characteristic bandgap back to the emitter. Although, this can be achieved using different methods like: reflective filters and back surface reflectors, the more effective approach is to use a selective emitter that emits in the wavelength range matched with the receiver's characteristic bandwidth.

The term selective emitter is used for structures with thermal emissivity close to blackbody emission at a desirable narrow spectral band and suppressed emissivity at other wavelengths. The desired selective emission profile can be achieved in various ways, such as:

- Intrinsic selective emissivity of materials like rare earth oxides.
- Control the emissivity of the structure, by tailoring the surface roughness with a characteristic length corresponding to the target wavelength.
- Plasmonic emitters, where collective oscillation of electrons in segments of a conductor at the interface of a dielectric and a metal is used to manipulate the emissivity of the structure.
- Photonic structures, where periodic structures of materials with different dielectric functions are employed to produce the selective emissivity by interference of waves reflected from the boundaries.

Considerable amount of research has been conducted in the use of the intrinsic selective emissivity of rare earth oxides like Er_2O_3 and Yb_2O_3 and their mixtures with other materials to achieve selective emissivity for thermo-photovoltaic systems [12,13]. However, the emissivity profile of such emitters cannot be modified precisely as desired and their use is limited by the availability of the materials. The radiative properties of a structure could also be modified by tailoring its surface roughness [14], but such emitters do not have high enough emissivity and sharp bands and therefore have limited performance. Applying paints and coatings on the surface are other approaches that have been used to modify the radiative properties of the structure [15]. In recent years, remarkable advancements have been made in developing selective emitters using nanofabricated structures [16]. Photonic and plasmonic structures have been demonstrated theoretically and experimentally for application in building radiative cooling [17,18], excess heat dissipation for concentrating solar power plants [19], thermo-photovoltaics [20–24], solar thermo-photovoltaics [25,26] and rectennas [27].

Snail [28] analyzed the spectral selectivity of a metal substrate covered with a thin layer of an absorbing film. He concluded that it is possible to reach a high degree of selectivity by the proper selection of the covering material and its thickness. Wong et al.

[29] showed that the radiative properties of a multilayer thin film structure can be altered by changing the film thickness when the thickness of the layers is on the same order of magnitude as the emitted or incident radiation. Furthermore Hu et al. studied the effect of one dimensional (1-D) periodic multilayer stack of dielectric materials on blackbody radiation [30]. They used the transfer matrix method in order to calculate the radiative properties of multilayer dielectric stacks. Liu et al. [16] demonstrated the technique for obtaining selective emissivity for small and large bandwidths using thin metallic fragments on top of a metallic mirror separated by a thin dielectric layer. Their design consisted of a periodic array of cross shaped metallic segments in the outer layer. In their design, by changing the length of arms and arrangement of the crosses the emissivity of the structure could be tuned. Drevillon and Ben-Abdallah [31] presented a numerical procedure to design a coherent thermal emitter using the principles of optics. They used an objective function based on the discrepancy of emissivity and reflectivity of the emitter and the target emissivity and reflectivity over the desirable range of the spectrum. Nefzaoui et al. [3] used a similar procedure to design 1-D photonic selective emitters suitable for thermo-photovoltaic cells. Two and four layer structures with alternating layers of lossy materials (i.e. noble metals and heavily doped semiconductors) and dielectrics were suggested to reach the desirable characteristics.

It has been demonstrated that a 1-D photonic structure is an effective way to achieve the desired radiative properties in high efficiency electromagnetic energy harvesting devices. Such a structure is sufficiently simple to be considered for industrial manufacturing and can be tuned to obtain the desired radiative properties. However, the problem is to find the composition of the layers, number of layers and thickness of each layer in order to reach the desirable radiative profile. At least $2N$ parameters should be determined for a structure with N layers: layer material and its thickness.

This paper focuses on presenting a comprehensive procedure to design 1-D photonic selective emitters. The transfer matrix method is used to determine the emissivity profile of the emitter over the desired spectrum. The objective function is selected as the mean square deviation of the emissivity profile of the emitter from the target emissivity, which is selected according to the characteristics of the receiver. By using a stochastic optimization method (i.e. genetic algorithm), the design parameters are altered to minimize the objective function. In the last part of the paper a number of designed multilayer structures suitable for application in rectenna systems are presented to demonstrate the application of the design method. Furthermore, one of the structures is fabricated and characterized.

2. Modeling and analysis

A schematic of a 1-D photonic structure is shown in Figure 2. Such a structure consists of a multilayer stack of thin films on top of a supporting substrate. Each layer is

identified by its complex refractive index $\bar{n}_\lambda = n_\lambda + ik_\lambda$. The real part n_λ represents the refractive index, and the imaginary part k_λ is the extinction index, both being wavelength dependent. However, in order to simplify the notations, wavelength dependence of the refraction index is dropped throughout the equations in this paper. It is worth mentioning that the spectral emissivity of a surface specifies radiation emitted from the surface as compared with the radiation emitted from the blackbody at the same temperature, as

$$\epsilon_\lambda(T, \theta) = \frac{I_\lambda(T, \theta)}{I_{\lambda b}(T)} \quad (1)$$

Where ϵ is the directional spectral emissivity of the surface, I is the directional emitted spectral intensity, T is the absolute temperature, and subscripts b and λ represent the blackbody and wavelength, respectively. The spectral intensity for a blackbody is calculated from the Plank's distribution function, as:

$$I_{\lambda b}(T) = \frac{2hc_0^2}{\lambda^5 [\exp(hc_0/\lambda k_b T) - 1]} \quad (2)$$

Where h and k_b are the universal Plank and Boltzmann constants, respectively, and c_0 is the speed of light in vacuum. Furthermore, the radiative power density emitted by the emitter in a specific wavelength range (Δw) can be found by integrating the emitter's spectral emission over the wavelength range, as:

$$E_{\Delta w} = \int_{\lambda_l}^{\lambda_u} \epsilon_\lambda(T, \theta) I_{\lambda b}(T) d\lambda. \quad (3)$$

Where λ_u and λ_l are the upper and lower bounds of the wavelength range of interest. One of the common quantitative parameters used when comparing selective emitters in a given wavelength range, is the emitter efficiency or radiant conversion efficiency [4,32]. Such efficiency is defined as the ratio between the radiative power emitted in the specific wavelength range (Δw) and the total radiant power emitted by the emitter, expressed as:

$$\eta_e = \frac{E_{\Delta w}}{E_{\text{tot}}} = \frac{\int_{\lambda_l}^{\lambda_u} \epsilon_\lambda(T, \theta) I_{\lambda b}(T) d\lambda}{\int_0^\infty \epsilon_\lambda(T, \theta) I_{\lambda b}(T) d\lambda} \quad (4)$$

In the following sections the calculation procedure used for finding the emissivity of the structure is presented. In addition, the objective function and optimization procedure to find the desirable spectral emissivity profile of an emitter are discussed.

Figure 2: Schematic of a 1-D photonic structure

2.1. Physical model

There are two different methods available when calculating the radiative properties of a film: the wave optics method (for thin films) and the geometric optics method (for thick films) [33]. Wave optics is based on the superposition of amplitudes of electromagnetic fields and accounts for the interference phenomenon. On the other hand, geometric optics is based on the superposition of intensities and excludes interference effects. These two methods usually yield different results when applied to the same structure. In order to decide which method should be used in each case, the coherence length of the wave was introduced [34], as:

$$l_c = 0.15 \frac{hc}{k_b T} \quad (5)$$

Where c is the speed of light, with the rest of the symbols defined in equation (2). When the thickness of a layer is less than l_c it is considered thin, otherwise it is considered thick. The same film can appear thin or thick depending on the radiation field incident or emitted from it. However, Hu et al. [30] showed that, for a multilayer structure, even when the thickness of the layer is larger than the coherence length, wave optics predicts the properties of the structure more closely. In addition, Macleod [35] has indicated that films on a substrate can be treated thin as long as the substrate supporting the layers can be considered thick. Hence, wave optics is selected as the modeling technique for calculating the radiative properties of 1-D photonic structures. The standard method for calculating thin film structures radiative properties based on wave optics is the transfer

matrix method, which has been used by numerous researchers [3,29–31,33]. The transfer matrix for each layer is given by:

$$M_j = \begin{bmatrix} \cos \delta_j & \frac{i}{Y_j} \sin \delta_j \\ iY_j \sin \delta_j & \cos \delta_j \end{bmatrix} \quad (6)$$

With

$$\delta_j = \frac{2\pi \bar{n}_j d_j \cos \theta_j}{\lambda} \quad (7)$$

$$Y_{j,TE} = y \bar{n}_j \cos \theta_j \text{ for s polarization} \quad (8)$$

$$Y_{j,TM} = y \bar{n}_j / \cos \theta_j \text{ for p polarization} \quad (9)$$

Here, λ is the wavelength of the EM wave, $\bar{n}$ is the refractive index of the layer, d is the thickness of the corresponding layer, θ is the angle of incidence, y is the optical admittance and Y is the optical admittance for oblique incidence. Subscript j represents the j th layer as shown in Figure 2, and subscripts TM and TE represent the transverse magnetic and transverse electric fields, respectively. Overall transfer matrix M of a multilayer structure is defined as the product of the transfer matrices of each layer and is expressed as:

$$M = \prod_{j=1}^m M_j = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \quad (10)$$

Knowing the overall transfer matrix of the multilayer, the characteristic matrix of the assembly is calculated from:

$$\begin{bmatrix} B \\ C \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \begin{bmatrix} 1 \\ \eta_s \end{bmatrix} \quad (11)$$

Where the subscript s represents the substrate. Finally, for a multilayer structure on top of the substrate s the emissivity (ϵ) and reflectivity (ρ) can be calculated from:

$$\epsilon = \frac{4Y_0 \text{Re}(BC^* - Y_s)}{(Y_0 B + C)(Y_0 B + C)^*} \quad (12)$$

$$\rho = \left(\frac{Y_0 B - C}{Y_0 B + C} \right) \left(\frac{Y_0 B - C}{Y_0 B + C} \right)^* \quad (13)$$

Where Y has been defined earlier, Re represents the real part of a complex number, the subscript 0 denotes the material adjacent to the first layer, and superscript $*$ depicts the complex conjugate. More details on the transfer matrix theory and its applications can be found in Born and Wolf [34].

For simplicity, it is assumed that the structure consists of homogenous and isotropic layers with no surface roughness, smooth, and perfect interfaces between layers. Furthermore, because the emitter and receiver are usually located adjacent to each other in thermo-photovoltaic and rectenna devices and to reduce the required calculations, only the case of normal incidence radiation is considered.

2.2. Objective function

The target spectral radiative properties can be defined as the spectral emissivity $\epsilon_T(\lambda)$ of the structure. In order to solve the problem, the number of layers and composition and thickness of each layer have to be found. In general, no multilayer structure can reach the exact target spectral radiative features. Therefore, it is only possible to find a design of a multilayer structure with radiative properties relatively close to the target features.

In order to reduce the number of variables and make the conversion of the optimization process in reasonable calculation steps, a design comprising of only two alternating materials is proposed in various references [3,31,36]. Now, by fixing the number of layers and refractive indices in each step, the emissivity of the structure depends only on the thickness of layers. By defining a thickness vector D , with the coordinates as each layer physical thickness the optimization procedure can be considered in the m (total number of layers) dimensional parametric space, that is.

$$D = [d_1, d_2, \dots, d_m] \quad (14)$$

Hereafter, the optimization problem is reduced to finding the vector D , resulting radiative characteristics $\epsilon(D, \lambda)$ of the structure as close as possible to the target spectral radiative property $\epsilon_T(\lambda)$. A wavelength grid is considered over the wavelength range, with a total number of grid points equal to L . The points of the spectrum grid are denoted as $\lambda_1, \lambda_2, \dots, \lambda_L$. In order to estimate the deviation of the actual emissivity from the target emissivity, a weighted mean square deviation is calculated as:

$$F(D) = \frac{1}{L} \sum_{j=1}^L \left[\frac{\epsilon(D, \lambda_j) - \epsilon_T(\lambda_j)}{\Delta \epsilon_j} \right]^2 \quad (15)$$

Here $\Delta \epsilon_j$ values are the design tolerances, with the rest of the symbols defined previously. If all the tolerances are set to 0.01, $F^{1/2}$ would represent the mean square deviation of the actual spectral emissivity from the target spectral emissivity. Setting the design objective function equal to $F^{1/2}$ makes it possible to use a numerical optimization scheme to optimize the design by minimizing the objective function.

Special care must be given when choosing the wavelength grid where the design targets are specified. Too sparse wavelength grid may cause the loss of key features of

the target radiative features or even prevent the optimization process from convergence. On the other hand, a too dense grid may slow down the optimization process. The following equation is a useful criterion to estimate the number of wavelength grid points L :

$$L = \frac{20D_{Tot}(\lambda_u - \lambda_l)}{\lambda_u \lambda_l} \quad (16)$$

Where D_{Tot} is the total optical thickness of the design, λ_u and λ_l are the upper and lower bounds of the spectrum region of interest. More details on the selection of the wavelength grid points can be found in reference [37].

2.3. Optimization process

Due to the large number of local minima of the objective function, numerical solution of the optimization problem is formidable and selection of an effective optimization scheme is vital to solve the problem. Almost all optimization methods tend to converge to a local minimum, for this reason finding the global minimum becomes extremely difficult when the number of local minima is large. One of the most popular optimization schemes for solving such a problem is the Genetic Algorithm (GA). GA is a stochastic optimization method that does not require a specific starting point and uses a population of candidate solutions to find the global minimum. As long as the diversity is preserved in the population the chance of trapping in a local minimum is very low [38]. Thus, the GA optimization scheme is proposed here to solve the problem of finding the optimum thickness vector, D , for each case with a known number of layers.

The GA is a member of optimization methods from a larger class of optimization schemes called evolutionary algorithms, which follow the process of natural evolution to find the global minimum of a function [39]. The first population set is generated randomly and the objective function (usually called fitness function) is calculated for each member of the population. The best candidates are selected as the parents. The crossover, which is a genetic operator, is applied to parents and a new set of population is produced. The crossover operator generates two children structures from two parent structures with a combination of features of each parent. In order to improve the algorithm performance another operator is applied to the children's generation called mutation. Mutation prevents the conversion towards a local minimum. The best candidates are selected at the end of each generation and the procedure is repeated. Figure 3 shows the flow chart of the optimization algorithm and the main genetic operations.

Figure 3: Flowchart of the optimization algorithm and main operators

2.4. Model validation

The results obtained from the presented design procedure are compared with results in the literature to validate both the physical model and the optimization method. Snail [28] analyzed the spectral reflectivity of a metallic substrate covered with a thin absorbing film to use in a solar thermal receiver. Figure 4 shows the spectral reflectivity profiles for two different films on an Aluminum substrate presented by Snail and results obtained by the physical model presented in section 2.1. Coating 1 has a refractive index $\bar{n}_1=1.2+ i 0.5$ and thickness of $0.333 \mu\text{m}$ and Coating 2 has a refractive index $\bar{n}_2=2.6+ i 0.56$ and thickness of $0.115 \mu\text{m}$. Furthermore, to validate the GA optimization procedure the results obtained are compared by one of the designs presented by Tikhonravov et al. [36]. They presented an antireflection translucent multilayer structure made of 40 alternating layers of dielectrics for the spectral region between 400 and 1200 nm. Only two dielectric materials were used with $\bar{n}_1=2.35$ and $\bar{n}_2=1.45$. Figure 5 compares the

reflectance of the translucent structure profile presented by Tikhonravov et al. [36] and the results from the GA optimization method discussed in section 2.3. As it is evident this design procedure is able to produce results with high accuracy for photonic structures.

Figure 4: Validating the transfer matrix model by comparing the data from Snail [28]

Figure 5: Validating the optimization method by comparing the data from Tikhonravov et al. [36]

3. Results

This section presents results of the design of thin layer structures used for the development of a selective emitter whose output radiation frequency spectrum is centered at ~30 THz (~10 μm). The selective emitter thermal energy can be provided by solar or any other type of heat source. One of the main problems of using rectennas for harvesting solar energy is their inability to rectify frequencies in the optical range (~ 400 THZ). Tunnel diodes have been proposed to be used for rectification at lower frequencies (~30 THz), because of their fast switching speeds [40]. Under this scenario, solar energy can be absorbed by one side of a metal plate and lower frequency radiation emitted from the opposite side via a selectively emitting surface.

3.1. Designed structures (numerical results)

The procedure described in section 2 is applied to design a selective emitter comprised of a metallic substrate with a dielectric multilayer deposited on it. Thin layers of Al_2O_3 on a metallic substrate have been demonstrated previously emitting selectively at wavelengths between 8 μm to 14 μm [41]. Also, the dielectric functions of SiO_2 and SiC have resonances at about 10 μm . SiO_2 has a sharp resonance at 9.5 μm and SiC has an extinction coefficient peak at 12.5 μm . Therefore, alternating layers of Al_2O_3 and SiC or SiO_2 on an aluminum substrate are selected to produce the desirable emission profile. For all materials, refractive index properties are extracted from tabulated values [42] and the refractive index of air is assumed to be $n_0=1$. Furthermore, it is assumed that the refractive indices remain constant over the temperature range of the present investigation (i.e. from room temperature to 300°C). Figure 6 shows the target spectral emissivity and the emissivity of an Aluminum substrate.

Figure 6: Comparison between the Aluminum substrate spectral normal emissivity and target spectral normal emissivity (numerical results)

Figure 7 to Figure 9 show the spectral emissivity at normal incidence of optimum designs of $\text{Al}_2\text{O}_3\text{-SiO}_2$ structures with two, four and six thin film layers. As it is depicted in Figure 7, the two-layer structure produces the desired selective emissivity profile centered at $9.5\ \mu\text{m}$, however, the peak emissivity is around 0.2, which is not high enough. The four-layer structure emissivity profile peak reaches 0.9 at $9.5\ \mu\text{m}$, which is high enough to be considered as the selective emitter in a rectenna device (Figure 8). The six-layer structure also exhibits an emissivity peak close to 0.9 at around $9.5\ \mu\text{m}$ and at the same time has a wider emissivity profile compared to the four-layer structure (Figure 9). Structures made of alternating layers of Al_2O_3 and SiC also produce a favorable emissivity profile, but with less emitter efficiency compared to $\text{Al}_2\text{O}_3\text{-SiO}_2$ multilayer stacks. Figure 10 and Figure 11 show the spectral emissivity profiles of two-layer and four-layer selective emitter structures of $\text{Al}_2\text{O}_3\text{-SiC}$ on the Aluminum substrate. Although for the $\text{Al}_2\text{O}_3\text{-SiC}$ structures the emissivity peak is observed at around $10.2\ \mu\text{m}$, the emissivity is not suppressed strongly at shorter wavelengths.

Figure 7: Spectral normal emissivity of an Al₂O₃-SiO₂ photonic structure with 2 layers of coating (numerical results).

Figure 8: Spectral emissivity of an Al₂O₃-SiO₂ photonic structure with 4 layers of coating (numerical results).

Figure 9: Spectral normal emissivity of an Al₂O₃-SiO₂ photonic structure with 6 layers of coating (numerical results)

Figure 10: Spectral normal emissivity of an Al_2O_3 -SiC photonic structure with 2 layers of coating (numerical results)

Figure 11: Spectral normal emissivity of an Al_2O_3 -SiC photonic structure with 4 layers of coating (numerical results)

For all cases the GA optimization algorithm populations were composed of 200 members. The optimization process was continued for 100 generations or until the fitness function reached a plateau. The total multilayer thickness upper bound was set to 10 μm . Figure 12 shows the variations of the best fitness function and the mean fitness function for each generation with the generation number for the six-layer Al_2O_3 - SiO_2 photonic structure. The optimization algorithm was terminated after 84 generations as the fitness function reached a plateau. The large population size guarantees the conversion of the algorithm very close to the global minimum of the objective function in the first few generations. The rest of the generations fine tuned the results.

Figure 12: variations of the best fitness function and the mean fitness function for the 4 layer structure.

Figure 13 depicts the spectral distribution of normal emissive power at 100 $^{\circ}\text{C}$ of a blackbody and of a two, four and six layer structure selective emitters made of Al_2O_3 - SiO_2 alternating layers. As it is apparent, the emissive power peaks are at the desirable spectral region and are suppressed at undesired wavelengths. Figure 14 shows the same characteristics for structures made of two and four alternating layers of Al_2O_3 and SiC . The two-layer structure of Al_2O_3 - SiO_2 shows the highest emitter efficiency but its emissive power is very small compared to the four and six layer structures. It is worth mentioning that the emissive power profile would have a similar distribution at higher surface temperatures if the temperature range is limited (up to 300 $^{\circ}\text{C}$).

Table 1 presents the total emissive power density for a 1 μm bandwidth centered at the emissivity peak (i.e. 9.5 μm) of Al_2O_3 - SiO_2 photonic selective emitters at various surface temperatures. For the structures composed of Al_2O_3 - SiC thin layers the emissivity peak is located at 10.2 μm , therefore, the bandwidth region is from 9.7 μm to 10.7 μm (Table

2). As expected, $\text{Al}_2\text{O}_3\text{-SiC}$ structures resulted in a lower emitter efficiency (less than 0.22) as compared to $\text{Al}_2\text{O}_3\text{-SiO}_2$ structures (up to 0.84). The emitter efficiency is not a standalone indicator, the emissive power of the emitter must also be high enough at the target bandwidth to guarantee efficient total energy conversion. The six-layer structure of $\text{Al}_2\text{O}_3\text{-SiO}_2$ has an emissive power of almost 9 times higher at the target bandwidth when compared to the two-layer structure, in spite of its lower emitter efficiency. As expected, an increase in the surface temperature increases the emissive power of the emitter. But the efficiency of the emitter may increase ($\text{Al}_2\text{O}_3\text{-SiO}_2$ case) or decrease ($\text{Al}_2\text{O}_3\text{-SiC}$ case) depending on the spectral emissivity profile.

It is shown by Tikhonravov et al. [36] that undesired emissions can be further suppressed by increasing the number of interference surfaces (i.e. a structure with more layers).

Table 1: Emissive power density emitted at wavelengths between 9 μm and 10 μm and emitter efficiency for $\text{Al}_2\text{O}_3\text{-SiO}_2$ selective emitters designed for application in a rectenna system

Temperature [°C]	2 layer structure		4 layer structure		6 layer structure	
	$E_{\Delta w}$ [W/m ²]	η_e	$E_{\Delta w}$ [W/m ²]	η_e	$E_{\Delta w}$ [W/m ²]	η_e
50	0.38	0.79	2.29	0.62	3.47	0.48
100	0.73	0.82	4.67	0.69	6.57	0.52
200	1.79	0.84	11.34	0.73	15.90	0.57
300	3.25	0.84	20.55	0.74	28.74	0.59

Table 2: Emissive power density emitted at wavelengths from 9.7 μm and 10.7 μm and emitter efficiency of $\text{Al}_2\text{O}_3\text{-SiC}$ selective emitters designed for application in a rectenna systems.

Temperature [°C]	2 layer structure		4 layer structure	
	$E_{\Delta w}$ [W/m ²]	η_e	$E_{\Delta w}$ [W/m ²]	η_e
50	8.19	0.15	12.38	0.22
100	14.95	0.16	22.47	0.22
200	34.55	0.15	51.53	0.21
300	60.69	0.14	90.10	0.20

Figure 13: Spectral normal emissive power profile of Al_2O_3 - SiO_2 selective emitters compared to the blackbody emission at 100°C (numerical results).

Figure 14: Spectral normal emissive power profile of Al_2O_3 - SiC selective emitters compared to the blackbody emission at 100°C (numerical results).

Lower emission outside the target bandwidth from Al_2O_3 - SiO_2 structures result in more efficient selective emitter designs for rectenna applications.

3.2. Fabrication and characterization (experimental results)

In order to verify the effectiveness of the design procedure, an Al_2O_3 - SiO_2 selective emitter structure was fabricated and characterized. For thin film applications the common technique of deposition of Al_2O_3 , SiC and SiO_2 is electron beam evaporation.

Al_2O_3 and SiO_2 can also be deposited by reactive or RF sputtering and SiC can be deposited by ion beam sputtering [37]. The experimental selective emitter was deposited using electron beam evaporation on top of a $500\text{ }\mu\text{m}$ thick, 100 mm diameter silicon wafer. A 200 nm layer of aluminum was first deposited, followed by four alternating layers of Al_2O_3 and SiO_2 at the thicknesses shown in Fig 8. Due to oxygen depletion in the film, Al_2O_3 was evaporated in a partial pressure of oxygen. The experimentally measured absorptivity (emissivity) spectra of the selective emitter via Fourier-transform infrared (FTIR) spectroscopy with an un-polarized incident light beam are shown in Figure 15. Although there is a selective emissivity peak observed in the emissivity profile of the emitter, its peak is not high enough and differs from the simulation results. Further investigation with a scanning electron microscope (SEM) has shown that there was a problem in the fabrication process and the second layer of the structure that should have a thickness of more than 10 nm was fabricated with a less than 6 nm thickness. With such small thickness, the uniform layer of Al_2O_3 between two layers of SiO_2 was not formed completely and the two thicker layers merged into one thick layer of SiO_2 . The resemblance between the measured emissivity profiles of the fabricated selective emitter (Fig. 15) and the two-layer structure presented in Fig. 7 verifies this interpretation.

Figure 15: Normal emissivity profile of the fabricated selective emitter measured by FTIR, and its SEM image (experimental results).

4. Conclusions

In this work, the procedure for the design and optimization of selective emitters that can be used in electromagnetic energy harvesting devices is demonstrated. One-dimensional photonic structures composed of an Aluminum substrate and alternating layers of Al_2O_3 and SiO_2 or SiC were simulated for this application for demonstration of their applicability to rectenna energy systems. It was shown that the emitter efficiency is not a stand-alone benchmark in comparing different designs. Other indicators, such as emissive power density, must also be considered when choosing the optimum design. Fabrication techniques for thin film multilayer structures are well known and have been applied successfully in the past for the development of optical instruments. Therefore, photonic selective emitters can be produced by current technology. However, a more detailed investigation is required taking into account the temperature dependency of the material properties, effects of imperfect interfaces and inhomogeneous layers as well as structural durability at elevated temperatures.

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Nomenclature

EM	Electromagnetic	<u>Subscripts</u>	
1-D	One dimensional	λ	Wavelength [m]
h	Planks constant= 6.623×10^{-34} [J.s]	b	Blackbody
D	Thickness vector	Δw	Wavelength range
T	Temperature [K]	u	Upper limit
I	Radiative intensity [$W/m^2 \cdot \mu m \cdot sr$]	l	Lower limit
k_b	Boltzmann constant= 1.381×10^{-23} [J/K]	tot	Total
c	Speed of light [m/s]	e	Emitter
c_0	Speed of light in vacuum = 2.998×10^8 [m/s]	TM	Transverse magnetic
E	Emissive power [$W/m^2 \cdot \mu m$]	TE	Transverse electric
L	Number of grid points	t	Target
l_c	Characteristic length [m]	<u>Greek notations</u>	
$\bar{n}$	Complex refractive index	θ	Angle of incidence [Rad]
n	Refractive index	η	Emitter efficiency
k	Extinction index	ϵ	Emissivity
y	Normal optical admittance	ρ	Reflectivity
d	Physical thickness	$\Delta \epsilon_j$	Design tolerance
M	Transfer matrix	Υ	Oblique admittance

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