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A Review on Measurement of Spectral Directional Emissivity of Microstructured Surfaces in Infrared Wavelength Range

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Abstract—**A survey of researches in the field of spectral directional emissivity measurements of microstructured surfaces by using direct and indirect radiometric methods in infrared wavelength range is presented. Nowadays, new concepts of periodic surface microstructures with geometrical dimensions of the same order of magnitude as the thermal radiation wavelengths are becoming one of the attractive methods for controlling spectral radiative properties of a surface like emissivity and reflectivity. Since the resonance effect between the periodic microstructures and the electromagnetic field has become one of the most promising ways to vary optical or radiative properties of the radiating surfaces artificially, in this review paper emphasis is given to the measurement of directional spectral emissivity of microstructured surfaces. A review of many systems is presented that are capable of measuring the spectral directional emissivities of solid surfaces at moderate temperatures. An overview of experimental setups is provided including the reference sources of radiation, the sample clamping and heating, detection systems, methods for the determination of surface temperature and procedures for emissivity evaluation. The paper is focused on methods of finding the emissivity of microstructures. Selected experimental data in the form of graph are presented for various microstructured surfaces.**

Keywords — **Directional spectral emissivity, Micro-structured surface, Reference source, Radiometric method, FTIR-Spectrometry, Validation, Resonance effect, Infrared wavelength**

1. Introduction

ENERGY transfer through radiation is one of the most fundamental and pervasive processes in the universe. It plays an important role in the operation of many natural and man- made systems on our earth. Radiative heat transfer in the earth's atmosphere determines the temperature on the surface of our planet and ensures the possibility of life here. In this scientific age, the knowledge of the thermal radiation is also very essential in satellite and other space systems because of the absence of convective heat transfer due to the vacuum in space. Space systems are exposed to both solar radiation and near-zero Kelvin blackbody radiation of deep space so that they must face severe radiant heating and cooling conditions. Radiative thermal energy transfer is also of great importance in terrestrial energy systems such as fossil-fuel-fired utility boilers and thermal- as well as solar photo voltaic energy systems [1,2].

For the sake of simplicity, in engineering science it is often found that the radiative energy transfer is described with the help of hemispherical and over total range of wavelength integrated quantities of radiative surface properties. However, for the detailed description of radiative energy transfer spectral and directional quantities of radiative surface properties are necessary. For example, the entropy content of a radiation energy flux depends on its spectral and directional distribution [3]. Hence the aim of this review work is to present and discuss the experimental results about directional spectral emissivity of technical surfaces especially micro-structured surfaces and about different systems which are used for the determination of the emissivity of such surfaces.

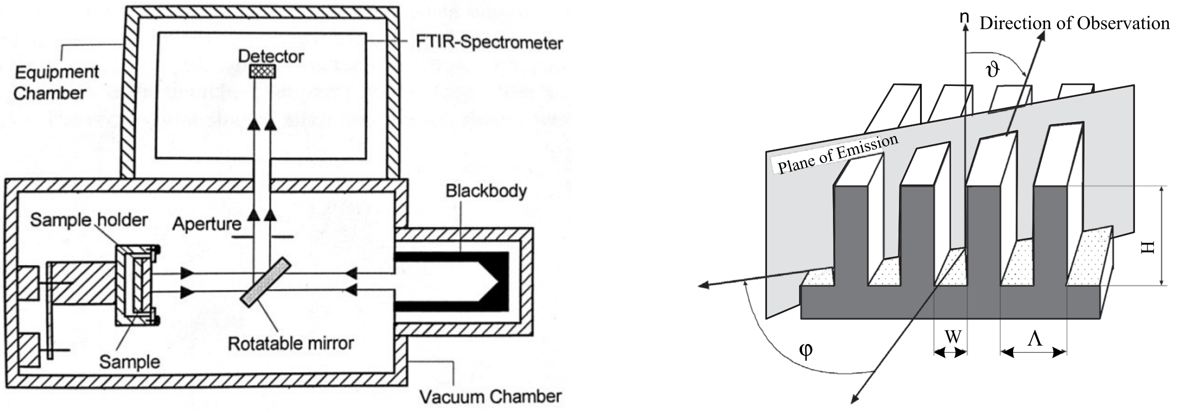
Recently, spectral control of thermal radiation has been focused on as an application of micromachining techniques. This method is expected to be applicable in various thermal systems since electromagnetic interactions at a micro-structured surface are receiving considerable attention. Till now, several authors have demonstrated spectral control of the emissivity by means of periodic microstructures and some of the most recent works will be presented in this work.

Many systems are reviewed that are capable of measuring the directional spectral emissivities of solid surfaces especially microstructures at moderate temperatures. The directional distribution is presented for polar angles between 0° and 70° and for azimuth angles between 0° and 90°. In most of the works a FTIR (Fourier Transform Infrared)-spectrometer or radiometer are used to measure the radiation intensity in the infra-red wavelength range between 2.5 µm and 24 µm. Experimental results are presented for various periodic micro structured surfaces.

2. Experimental device and procedure

Directional spectral emissivity measurement methods utilize different experimental devices. These reflect the requirements such as the material of the samples and range of surface temperatures and are based on the technical equipment available in the laboratory (detection system, vacuum, or controlled atmosphere). Experimental setups consist of radiation sources (one or more), reference sources of radiation and the analyzed sample, a system of sample clamping and heating, a system of sample surface temperature determination, a detection system (FTIR-spectrometer), and additional optical components. The components include mirrors to define the optical path of collected radiation, apertures to define the analyzed area on the sample surface, or various optical windows and lenses.

The reference source of radiation (black body), analyzed sample, and detection system can be in different relative positions. Figure 1 (a) shows the most frequently used arrangement where the radiation sources are in opposition [2,4,5]. There is a rotary mirror (with a stepper motor) acting as a switch to alternatively collect the radiation from both sources through one optical path between the two sources.



(a) (b)

Fig. 1. (a) Experimental device for the measurement of the directional spectral emissivity of microstructured sample

(b) Schematic diagram of the microstructured sample with different physical parameters

The detection of weak infrared radiation emitted by a sample is possible with the help of Fourier transform infrared (FTIR) spectrometry because of its high sensitivity. But there is a poor signal to noise ratio due to the large background radiation. This low signal to noise ratio is one reason why the great potential of infrared emission spectroscopy has not yet been fully exploited. Few results have been reported in the literature; however, many of the published papers on emission spectroscopy demonstrate that this sampling technique is a powerful tool for studying emission spectra of technical surfaces [5]. The effect of geometrical conditions like smoothness, irregular surface roughness, coatings, the periodic surface microstructures as shown in figure 1 (b) were studied by many researchers by using this device with FTIR-spectrometer.

2.1. *Principle Of Measurement*

Emissivity is a measure of the thermal emission capability of a surface. It is defined as the fraction of energy being emitted from a real surface relative to that emitted by a blackbody surface at the exact same temperature. A blackbody is a material which is a perfect emitter of radiative heat energy. Since maximum absorption implies maximum emission, it emits all energy that it absorbs. Therefore, its emissivity is taken as unity. The radiation of a real object is always less than the blackbody radiation at the same temperature. To describe the difference between the real object and blackbody, emissivity (ε) is defined as the ratio of the real object emissive power to the blackbody emissive power at the same temperature.

The emissivity can depend on factors such as the body temperature, the particular wavelength being considered for the emitted energy, and the angle at which the energy is being emitted. The consideration of the emission from a surface into all solid angles and wavelengths leads to the definition of four dimensionless quantities: spectral directional emissivity, hemispherical spectral emissivity, directional total emissivity and hemispherical total emissivity. Among them the basic quantity is the directional spectral emissivity which can be directly determined experimentally. The other three quantities can be derived from it [4]. The directional spectral emissivity is defined as the ratio of the emissive ability of the real surface in terms of the directional and the wavelength distribution to that of a black body at the same temperature, mathematically it can be expressed as

$$\varepsilon'_{\lambda}(\lambda,\vartheta,\varphi,T)=\frac{L_{\lambda}(\lambda,\vartheta,\varphi,T)}{L_{\lambda b}(\lambda,T)} \qquad (2.1)$$

where $L_{\lambda}(\lambda,\vartheta,\varphi,T)$ is the directional spectral intensity of the real surface and $L_{\lambda b}(\lambda,T)$ is the blackbody directional spectral intensity at the same temperature, direction and wavelength.

With the indirect method the directional spectral emissivity is determined by measuring the directional spectral reflectivity first and then using the Kirchhoff's law of radiation which states that the sum of the directional spectral emissivity, reflectivity, and transmissivity of a sample is unity. This can be also expressed as

$$\varepsilon'_{\lambda}(\lambda,\vartheta,\varphi,T)=1-\rho'_{\lambda}(\lambda,\vartheta,\varphi,T)-\tau'_{\lambda}(\lambda,\vartheta,\varphi,T) \quad (2.2)$$

where $\varepsilon'_{\lambda}(\lambda,\vartheta,\varphi,T)$ is the directional spectral emissivity, $\rho'_{\lambda}(\lambda,\vartheta,\varphi,T)$ is the directional spectral reflectivity and $\tau'_{\lambda}(\lambda,\vartheta,\varphi,T)$ is the directional spectral transmissivity. For the thermal radiation from an opaque sample the directional spectral transmissivity can be taken as zero. Then the equation (2.2) becomes

$$\varepsilon'_{\lambda}(\lambda,\vartheta,\varphi,T)=1-\rho'_{\lambda}(\lambda,\vartheta,\varphi,T) \quad (2.3)$$

Equation (2.3) shows that the directional spectral emissivity of a sample can be determined if the directional spectral reflectivity of the sample is known.

2.2. Determination Of Sample Surface Temperature

The emissivity measurement is based on the comparison of the radiation fluxes from the sample surface and the blackbody radiator at the same temperature. These radiation fluxes depend on the fourth power of the temperature as per Stefan - Boltzmann law. This means a small error in the temperature measurement of the sample surface may introduce a large error in the heat flux and consequently in the measurement of the emissivity of the sample surface. Hence, the accurate determination of the surface temperature is important for an accurate measurement of the radiation properties like emissivity of surfaces.

The surface temperature of the analyzed sample can be determined in several ways depending on the desired range of surface temperatures, the selected heating method, the arrangement of laboratory apparatus, and the analyzed material. Contact and noncontact surface temperature measurement methods or mathematical models are used. The contact methods are characterized by a direct contact of the temperature sensor e.g. resistance thermometers or thermocouples with the analyzed sample [2,4,6,7,8]. However, it is not suitable to place a contact sensor directly on the sample surface, because of the radiation exchange between the contact sensor and the detector which may introduce errors in the measurement of radiative properties of the sample surface. The determination of the surface temperature is rather based on the local energy balance for the sample [6,9]. The noncontact surface temperature measurement methods are based on the detection of the thermal radiation of the sample. The sensors such as bichromate pyroreflectometers [6,10], monochromate and multichromate pyrometers [6,7,11,12], and infrared thermocameras [4,8] are applied.

3. LITERATURE REVIEW

This section contains a literature review on the researches of optical properties such as emissivity and reflectivity of microstructured surfaces of electrical good conductors, semiconductors, insulators and coatings. The review covers two aspects: methods for measurements of the optical properties and geometrical conditions of the investigated microstructured surfaces with dimensions in the order of the wavelength of radiation. The methods for measurements of the optical properties can mainly be divided into two groups: direct and indirect radiometric techniques of measurement. In the indirect method first the reflectivity of the sample surface is measured and then the emissivity of the sample is calculated by using the relation that the sum of the spectral reflectivity and emissivity of the opaque surface is unity [13]. The other is the direct method of measuring emissivity of the sample surface.

Hesketh et al. [14,15,16,17] extensively reported the directional and polarized spectral emissivity from one-dimensional heavily doped lamellar silicon surfaces with rectangular microstructure geometries. Selective thermal emission by electromagnetic standing waves was observed in microgrooves with repeat distances and depths of the grooves varied from 10 µm to 22 µm and from 0.7 µm to 44 µm, respectively. The measurements were carried out at temperatures of 300 °C and 400 °C and the experimental results were compared with data calculated by a geometric optics model. This research on the emission properties was extended by Wang and Zemel [18,19,20] to the case where the silicon is a dielectric material. Several theoretical models, for example Bloch-wave, coupled-mode, effective medium and waveguide methods were examined.

Cohn et al. [21] systematically studied modal reflection from micro-contoured nickel surfaces with one-dimensional sinusoidal and triangular profiles, and for chrome and doped silicon samples with rectangular profiles. The experimental results were compared with rigorous calculations based on the electromagnetic theory and extinction theory [22,23,24]. Good agreement was observed between the experimental findings and the theoretical predictions qualitatively and quantitatively. Polarized directional spectral reflectivity and emissivity of a silicon carbide (SiC) with one dimensional grating was studied experimentally and theoretically by Gall et al. [25] in the wavelength region between 10 µm and 11.5 µm. It was shown that the existence of peaks of the emitted monochromatic radiation in particular angular directions implies that the thermally excited field is partially coherent along the interface due to surface waves.

Tang and Buckious [26] reported detailed results on reflection from two dimensional metallic square grooved surfaces with repeat distances and surface heights ranging from 10 µm to 30 µm and from 1.6 µm to 20 µm, respectively. The detailed feature of thermal emissivity from microstructured surfaces was demonstrated experimentally as well as analytically. The possibility of controlling spectral reflectivity and thereby spectral emissivity from periodic microstructured metallic surfaces was shown, although the incident wavelength is restricted to the mid infrared range (2 µm 12 µm). A simulation study of selective emission from the tungsten surface with periodic microstructures was presented by Heinzel et al. [1,27,28] using the coupled wave theory. It was demonstrated that thermal radiation from microstructured tungsten surfaces can be utilized for fabricating thermo-photovoltaic selective emitters.

Sai et al. [29,30,31] investigated the resonance effect between the emissive fields and two-dimensional periodic microstructured metal surfaces in the near infrared region as high temperature applications e.g. thermophotovoltaic generation of electricity). Numerical calculations based on rigorous coupled wave analysis were also performed to obtain the optimum configuration of surface microstructures with rectangular and hexagonal cavities. It was confirmed that the surface microstructure can be applied to the control of the spectral emission from high temperature resistive materials made of a single crystal.

For the infrared wavelength region between 3 µm and 25 µm, Maruyama et al. [32] performed measurements of polarized directional emission spectra, which reveal that the thermal emission from a two-dimensional microcavity shows an isotropic and random polarization character. It was found that the surface microcavity structure made on low-emissivity material surface is very efficient to control the thermal radiation and the dominant peaks of the emission spectra can be explained by a simple cavity resonator model. Puscasu et al. [33] demonstrated an enhancement of the emitted radiation from frequency selective surfaces consisting of aluminium patches on silicon substrates in the infrared wavelength region from 3 µm to 15 µm. By using the near field coherence properties of thermal sources [34,35], Greffet at al. [36] made theoretical calculations and experimental measurements which demonstrate that it is indeed possible to build an infrared antenna by properly designing a microstructure on a polar material such as glass, silicon carbide (SiC), and semi-conductors. A modification of the Greenhouse effect of glass by changing the absorption of the glass with the microstructured surface is possible. Instead of being reflective, the glass will be more absorptive and the heat isolation with the Greenhouse effect will be improved to some extent.

Within the visible spectral range, Zou et al. [37] investigated the effects of two-dimensional etched holes on the optical properties of micromachined polycrystalline silicon reflective surfaces (mirrors). It was found that when the dimension of etched holes increases, an increasing portion of the incident power will be diffracted and transmitted due to etched holes, leading to decreasing reflectivity of surface micromachined mirrors. Similarly, Jaecklin et al. [38] studied mechanical and optical properties of surface micromachined mirrors in single crystalline silicon, polycrystalline silicon and aluminium. Foley [39] presented recent technological advances in the field of replicated, microstructured plastic optics and their applications in display optics. It was noted that new processes such as high precision molding, new materials such as high temperature thermoplastics, and new optical elements such as moth - eye antireflective micro-structure and one piece imaging screens provide optical designers and systems engineers with new degrees of freedom and flexibility in display applications.

Lin et al. [40,41] demonstrated spectral control of emissivity by means of periodic microstructures on three-dimensional photonic crystals. It was shown that the absence of electromagnetic modes in a certain wavelength range suppresses the thermal emission, while in the pass bands high thermal emission is observed.

Labuhn and Kabelac [2] analyzed a photovoltaic cell from a thermodynamic view point. Special attention was given to the entropy balance equation and the entropy fluxes of the incoming and outgoing radiations. The spectral directional emissivity and the spectral directional degree of polarization of a glass-coated silicon cell which are needed to calculate the radiation energy and entropy fluxes, were measured. The fluxes and the conversion efficiency were calculated for different optical data sets.

Koirala [4] presented a measurement system which allows the measurement of the directional spectral emissivity of technical solid surfaces with different geometries and coatings. With the developed system it was possible to measure the emissivity at sample surface temperature up to 250°C at polar angles from 0° to 70° and azimuthal angles from 0° to 90° for wavelength between 4 µm and 25 µm. The comparison of smooth silicon surfaces with the microstructured silicon surfaces showed the possibility to influence the radiation characteristic of a surface with microstructures. It was found that the microstructure can increase the total hemispherical emissivity and it made possible to adjust emissivity maxima for a specific wavelength and a specific solid angle.

Maloney et al. [42] measured infrared transmittance and hemispherical directional reflectance data from 2.5 µm to 25 µm of microstructured silicon surfaces and spectral emissivity was calculated for this wavelength range. Hemispherical total emissivity was calculated for the samples and found to be 0.84 before a measurement induced annealing and 0.65 after the measurement for the sulfur doped sample.

A system was developed by Feng et al. [43,44] to measure the normal spectral emissivity of microstructured silicon manufactured by femtosecond laser for the middle infrared wavelengths at temperature range 100°C to 400°C. Emissivity was enhanced over the entire wavelength range as compared to that of plane (flat) silicon. The minimum emissivity at a temperature of 100°C is more than 0.96 for a sample with different spike heights. Although the average emissivity is less than that of Nextel-Velvet 811-21 coating, it can be used stably at more wide temperature ranges.

Ibos et al. [45] investigated several materials (conducting materials or dielectrics) for the determination of the directional emissivity of materials with consideration of the influence of surface roughness. The experimental method used for the determination of the directional emissivity is based on the use of a periodic excitation and the recording of the surface temperature variations of the sample using infrared thermography. Several consecutive measurements are performed for emission angles varying from 0° to 85°. The experimental device developed is simple compared to existing devices but the variation of directional emissivity is limited to the spectral bandwidth of the camera used.

Guo et al. [46] measured the directional spectral emissivity of silicon carbide (SiC) at high temperatures up to 1400 K. Also a new kind of water-cooled surface of the sample heating unit is designed to reduce the error by reducing the thermal radiation from surface of the heating unit so that measurement accuracy is improved. An electro-controlling rotating stage is adopted, and measuring angle is up to 60°. Although only plane silicon carbide surface was investigated in this work, this experimental set up could be used for the measurement of the directional spectral emissivity of the microstructured surfaces.

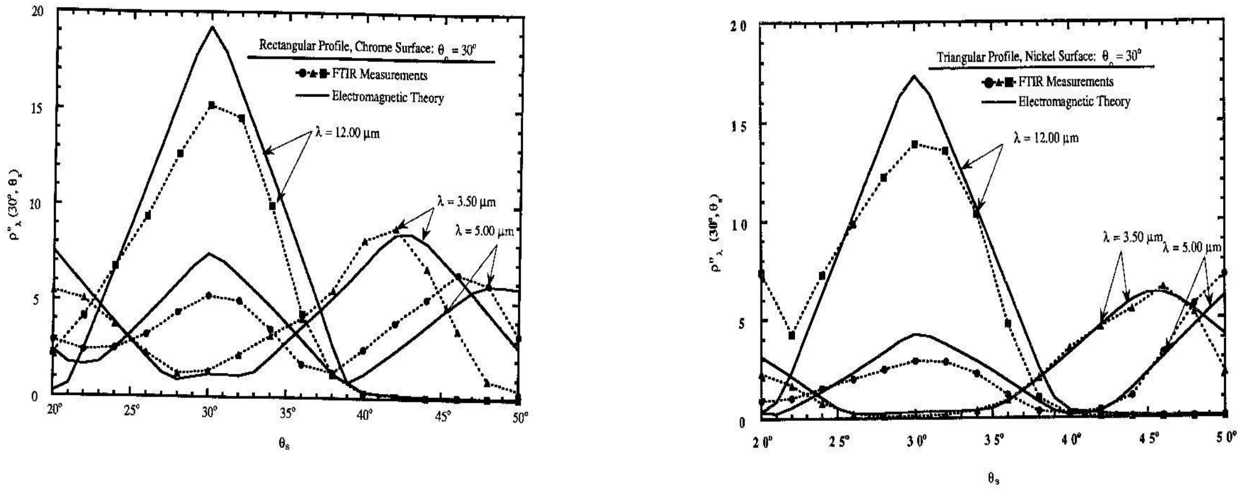
Thus, the analysis of optical properties of surfaces with microstructures is still a difficult problem. Yet, despite the large amount of works in this field, it is worth mentioning that most of the reported works deal with the study of the reflectivity. Although there is a simple relation between emissivity and reflectivity of an opaque material given by Kirchhoff's law, there is still a lack of detailed analysis of the emission processes in the framework of electromagnetic theory.

4. RESULTS AND DISCUSSION

From the literature survey it is found that different authors have achieved different results for the measurement of directional spectral emissivity of micro structured surfaces by using different methods. Here below some selected results which are more emphasized will be presented and discussed.

In order to validate directional spectral emissivity results obtained in the most of the works, the spectral emissivity of black body (e.g. a black paint so called Nextel - Velvet Coating 811-21 on a metal surface) is measured at different emission angles. Its directional spectral emissivity values at different temperatures have been investigated experimentally by different authors [4,47,48] in detail. Since its emissivity is very close to unity, many authors have taken it as reference material for validation of the results of the emissivity measurements.

Cohn et al. [21] systematically measured the directional spectral reflectivity of the microstructured chrome surfaces with one dimensional rectangular profiles. The experimental results were compared with rigorous calculations based on the electromagnetic theory. Good agreement was observed between the experimental findings and the theoretical predictions qualitatively and quantitatively as shown in figure 2 (a) and (b). It is seen that the existence of peaks of the emitted monochromatic radiation in particular angular directions.

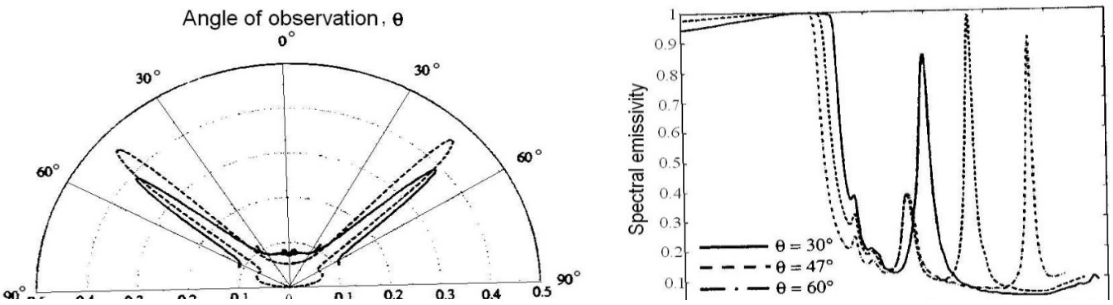


(a) (b)

Fig. 2. Comparison between electromagnetic theory and experimental results as a function of scattering angle (θ_S) and incident wavelength for (a) chrome surface with a rectangular profile and (b) nickel surface with a triangular profile.

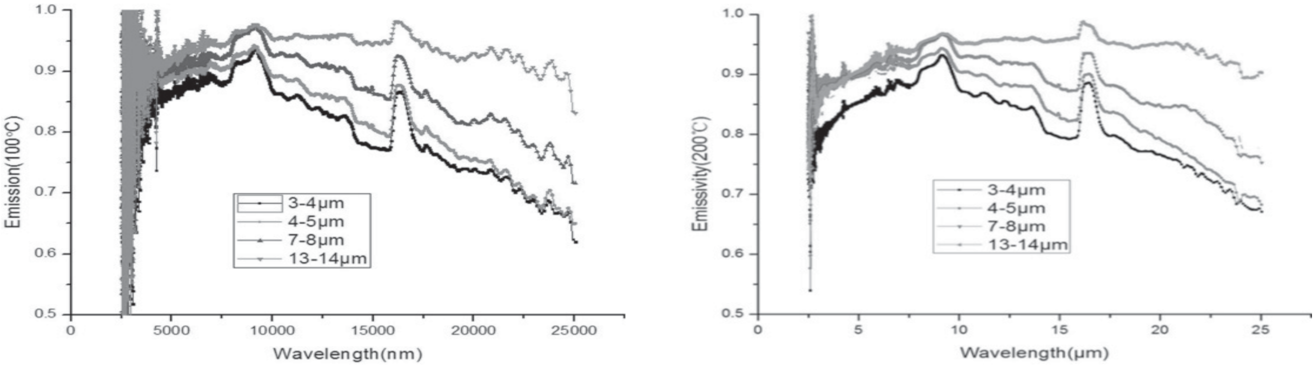
Greffet at al. [36] made theoretical calculations and experimental measurements which demonstrate that it is indeed possible to build an infrared antenna by properly designing a microstructure, for example on a silicon carbide (SiC) as given in figures 3 (a) and (b). It was observed that thermal emission of radiation by silicon carbide surface may be controlled in order to produce new types of infrared sources. This shows that a modification of the Greenhouse effect of glass by changing the absorption of the glass with the microstructured surface is possible. Instead of being reflective, the glass will be more absorptive and the heat isolation with the green house effect will be improved to some extent.

The normal spectral emissivity of microstructured silicon was measured by Feng et al. [43] for the middle infrared wavelength at surface temperature from 100°C to 200°C as presented in figures 4 (a) and (b) respectively. Emissivity was enhanced over the entire wavelength range as compared to that of plane (flat) silicon. The minimum emissivities at surface temperatures of 100°C and 200°C are more than 0.9 in both cases for a sample with different spike heights.



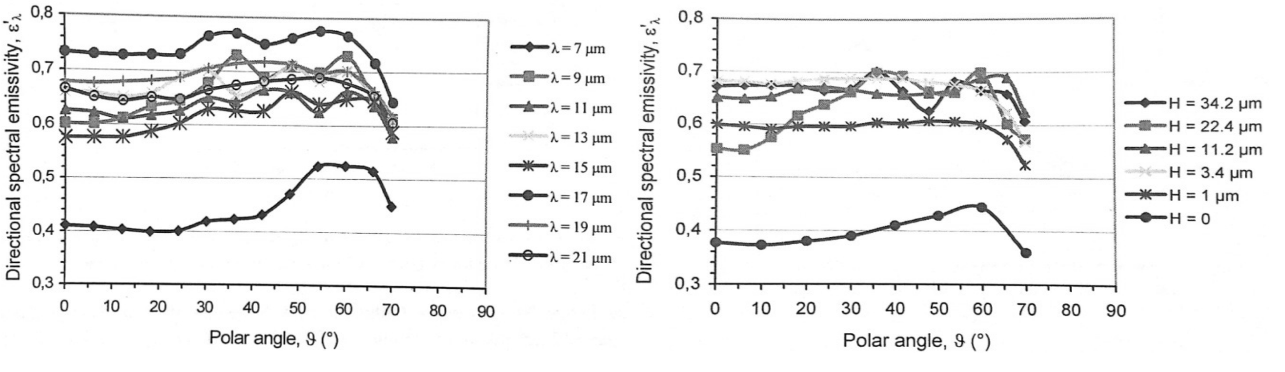
(a) (b)

Fig. 3. (a) Emissivity of a silicon carbide (SiC) grating for the wavelength, λ = 11.36 μm where solid curve was obtained from experimental data and dash curve was obtained from theoretical calculation (b) Theoretical spectral emissivity for different angles of observation (θ) for a silicon carbide (SiC) grating with period, Δ = 6.25 μm, height, H = 0.285 μm.



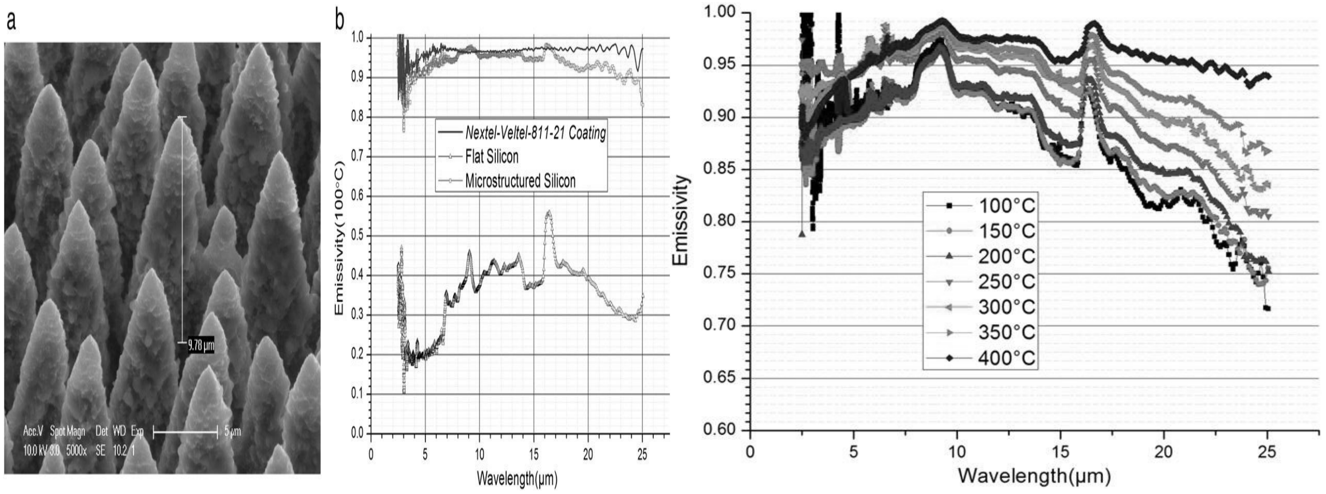
(a) (b)

Fig. 4. Normal spectral emissivity of silicon for different spike heights at temperature (a) 100°C and (b) 200°C.



(a) (b)

Fig. 5. Directional spectral emissivity of a microgrooved undoped silicon surface measured at an azimuthal angle, φ = 0° for (a) groove depth, *H* = 34.2 μm with different wavelengths, λ (*T* = 200 °C) and (b) wavelength, λ = 14 μm with different groove depths, *H* (*T* = 200 °C).



(a) (b)

Figure 6. (a) Normal spectral emissivity of microstructured silicon at different source temperatures. (b) Enhanced normal spectral emissivity versus wavelength (T = 100 °C).

The directional spectral emissivity of the micro-structured undoped silicon surface at a surface temperature of 200°C was measured by Koirala [4] at the azimuthal angle 0° for the groove depth 34.2 µm with the wavelength of radiation as parameters as shown in figure 5 (a) and for the wavelength 14 µm with the different groove depths as shown in figure 5 (b). Several pronounced emissive peaks are observed for wavelengths from 9 µm to 17 µm. A few features and some broad maxima are seen at shorter and longer wavelengths. The spacing between emission maxima increases as the wavelength increases.

The normal spectral emissivity of microstructured silicon manufactured by femtosecond laser irradiation was measured for the wavelength range 2.5 µm to 25 µm in the works of Feng et al. [43,44]. Greatly enhanced emissivity compared to that of flat silicon was observed over the entire wavelength range. For a sample with 13–14 µm high spikes, the emissivity at a temperature of 100°C is approximately 0.96. The emissivity decreases slightly in the wavelength region above 8 µm, but remains higher than 0.9 over most of the measured wavelength range as shown in figure 6 (a). Although the average emissivity is less than that of Nextel-Velvet-811-21 coating (see figure 6 (b)), it can be used stably at more wide temperatures from 100°C to 400°C. These results show the possibility of microstructured silicon to be used as a flat blackbody source or silicon-based pyroelectric and microbolometer devices.

5. CONCLUSION

A review on the different measurement systems presented in this paper which allow the direct or indirect measurements of the directional spectral emissivity of technical solid surfaces with different geometries and coatings, especially of microstructures. The experimental results and discussion are focused on the microstructured surfaces. It is found that there are different methods and systems to measure the directional spectral emissivity at moderate surface temperatures of a sample for polar angles from 0° to 70° and azimuthal angles from 0° to 90°. With the optics and detectors used good results were achieved for infrared wavelength range between 2.5 µm and 25 µm.

The comparison of emissivity of smooth (plane) surfaces with that of the microstructured surfaces shows the possibility to influence the radiation characteristic of a surface with the microstructures. The microstructure can increase the total hemispherical emissivity. It seems possible to adjust emissivity maxima for a specific wavelength and a specific solid angle.

Despite the wide range of previous researches in the field of the measurement of the directional spectral emissivity of microstructured surfaces, there are still many researches to do regarding new systems of measurement, for example for the different heating and clamping methods of samples, for more accurate surface temperature measurement techniques or in the development of solutions for commercially manufactured measuring instruments.

Detailed features of directional spectral emissivity from microstructured surfaces were demonstrated by many researchers experimentally as well as analytically. The possibility of controlling spectral reflectivity and thereby spectral emissivity from periodic microstructured metallic surfaces were presented for the wavelength of infrared ranges. The results from the periodic micromachined surfaces indicate that there are methods for the prediction of the emission properties, but none of the models yields a complete solution.

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