Second International Conference on Computational Methods for Thermal Problems
THERMACOMP2011, September 5-7, 2011, Dalian, China
X.K.Li, N.Massarotti and P.Nithiarasu (Eds.)

MICRO/NANO SCALE RADIATIVE HEAT TRANSFER

Xuan Yimin
School of energy and power engineering, Nanjing University of Science & Technology, 210094,
ymxuan@mail.njust.edu.cn

ABSTRACT

The mechanism of the radiative heat transfer in micro/nano scale structures is different from that of the traditional one, and the “near-field effects” are needed to be considered. Several examples of calculation model are introduced here to describe the radiative properties of the structured surface with the characteristic length smaller than the incident wavelength.

Key Words: *Micro/Nano structure, FDTD, Near-field radiative theory.*

1. INTRODUCTION

As a basic way of energy transfer, thermal radiation exists commonly in nature. In the area of engineering technology such as the energy, power, aerospace, optoelectronics, military technology, optical technology, mechanical and electrical systems, the thermal radiation plays an important role. Since the 1920s, research of the basic theory and application of thermal radiation has been made considerable progress, and has become very active in the field of thermal science.

The process of radiation heat transfer is generally divided into emission, absorption, scattering and transmission. When the characteristic length of the object involved in the thermal radiation heat transfer is much larger than the wavelength of thermal radiation, the radiant energy transfer process can be simulated using the methods of ray-tracing or geometrical optics approximately. These problems are named as "far-field radiative heat transfer problem". When the characteristic length of the object is close to or smaller than the wavelength, the wave characteristics ignored in traditional radiation heat transfer equation stand out, and the effect of the surface properties of the object on radiation heat transfer process is more obvious, i.e., the "near field" significantly affects the whole process of energy radiation. Such problems are called as "near-field radiative heat transfer problem."

Microscale radiation effects don’t only show on micro-structured surface, when the distance between two objects is close to or smaller than the wavelengths of radiation, the radiation transfer process between the objects also shows strong microscale effect. For the enhanced near-field radiation effects, the traditional theory of radiation heat transfer could not be analyzed and resolved.

In this paper, based on the FDTD method and near-field radiative theory, several examples of calculation model are introduced to describe the radiative properties of the micro/nano structured surface. In addition, near-field radiative theory is used to study the mechanism of near field effect between magnetic and non-magnetic materials.

2. FDTD METHOD AND NEAR-FIELD RADIATIVE THEORY

FDTD method is a direct time-domain method for solving Maxwell differential equations. The basic idea of FDTD method is: Using the Yee cell as discrete units, the Maxwell's equations are converted to a set of central difference equations to solve in each Yee unit cell. Based on the results of the solution of Maxwell's equations, it is needed to analysis the energy penetrating into the system in a certain time, and its reflection, transmission and absorption in different directions, then to obtain the spectral properties of the thermal radiation.

The near-field radiative theory is a direct method to deal the radiative heat transfer in microscale, in which the magnitude of the heat flux is directly achieved. It is mainly assumed that the thermal radiation is due to the fluctuating electromagnetic field result from the fluctuating electric and magnetic current sources in the medium. By combination of the stochastic Maxwell's equations and the correlation functions between these sources given by fluctuation-dissipation theorem (FDT), the heat flux described by the time-averaged Poynting vector is achieved.

3. EXAMPLES

3.1 Structure color of tropical Morpho butterflies

Structure color of tropical Morpho butterflies is one of very hot topics. It is commonly accepted that their brilliant and iridescent color is principally due to optical interference. The calculation models based on morpho's microstructure is presented here, and characteristics of structure color from such ridge microstructures were simulated by using the FDTD method in order to explore the color mechanism of the butterfly. Explorations were offered to explain structure color of Morpho butterflies according to our simulations. Our analysis meets with other's experiment results very well, and which shows our method is very feasible to investigate the structure color of morpho butterflies.

3.2 One-dimensional Si/SiO$_2$ photonic crystals for thermophotovoltaic filter

The one-dimensional PC filter for the spectral control of photons in order to maximize the conversion efficiency and power density of a TPV system is shown in Fig 1. The filter structure has been designed as 4 periods and 8 layers (4 pairs) by using SiO$_2$ and Si material pair, and the thicknesses of SiO$_2$ and Si layer have been determined to be equal to 0.204 and 0.194 μm in the first period and 0.408 and 0.176 μm in the other three periods. The physical vapor deposition (PVD) process has successfully been used to fabricate the filter. The normal transmittance performance of the filter has been measured with two spectrophotometers within the spectral range from 0.7 to 3.3 μm. It shows that the reflectivity of the filter is over 92% in the wavelength range 1.8—3.3 μm and the averaged transmissivity reaches 90% in the wavelength range 0.9—1.8 μm. The theoretical prediction has also given the identical results. The estimated spectral efficiency of the TPV increases with the emitter temperature. For example, the spectral efficiency of the TPV system with such a filter reaches 53%. The temperature-withstanding experiment has indicated that the fabricated 8-layer matching one-dimensional Si/SiO2 PC filter can normally work at the temperature environment below 600.

FIGURE 1. Sample of one-dimensional PC Si/SiO$_2$

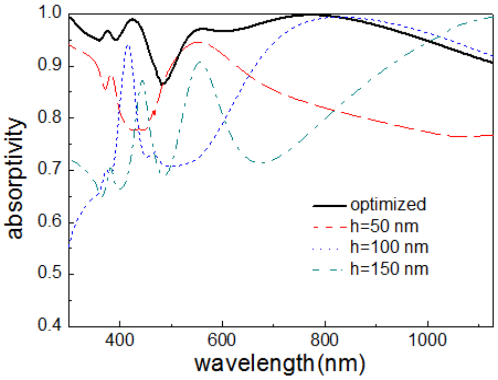

FIGURE 2. Absorptance of the assembly grating structure compared with the monotone structure surfaces

3.3 Absorption enhancement of solar cells with an assembly grating structure

Figure 2 illustrates the spectral absorptance of the assembly structure of the gratings. For the purpose of comparison, the surface absorptance of three conventional monotone grating structures is included. It is clear that the absorptance spectrum of the assembly grating structure is much higher than those of the three conventional ones, especially in the visible spectrum. It is found that the absorptance of the assembly structure surface is greater than 0.85 throughout the wave-band, which is also higher than those of the nanostructured surface [1, 2]. Such an absorption property of the assembly structure is beneficial for improving the conversion efficiency of solar cells.

3.4 Spectral properties of multilayer hole arrays

The spectral properties of the symmetric metal-insulator-metal hole arrays consisting of an air or MgF_2 core layer sandwiched between two silver layers with rectangular hole arrays have been investigated using FDTD Sin-Cos method. Numerical investigation has revealed that the structural parameters and the physical parameters of the dielectric core layer affect the optical properties of the structure. The absorption and EOT peaks in absorptance and transmittance spectra are mainly attributed to the internal- and external-SPPs excited in metal-dielectric multilayer system. Compared with other SPPs modes, the external-SPPs (1, 0) mode has a greater contribution to the strong absorption and EOT phenomena. From the spectra maps, an important feature can be found that the absorptance can reach more than 90% if the internal- and external-SPPs are simultaneously excited. By selecting the suitable structural parameters, the metal-insulator-metal film hole arrays structure can reach a higher EOT peak than single metallic 2DHAs. Therefore, these features can be applied to design the novel optical-electronic devices.

3.5 Spectral properties of 2D Ag micro-cavity arrays and the application in narrow-band emitter

To investigate spectral properties of structured silver surface with periodic rectangular hollow cavities. Numerical computation is conducted to obtain spectral distribution of surface absorptance with different structural parameters using the finite-difference time-domain (FDTD) method. By means of numerical examples, the effects of structural parameters, incident angle and azimuthal angle on the spectral features of the structured surface are discussed. It is found that the structured surface shows the characteristics of the peak absorption in the vicinity of resonant wavelength of rectangular cavity. For some special structure parameters, the peak absorptance of the incident plane wave can reach as high as above 80% due to the excitation of microcavity effect. The optimal narrow-band absorption can be achieved by the rational design of the structural parameters of rectangular cavity. The directional dependence of spectral absorptance is also analyzed and the results reveal that the absorption peak positions are incident-angle-independent. The results show that the microscaled rectangular cavities fabricated on the low-emissivity silver surface are very efficient for selective improvement of the radiative features, which provides guidance for the design of narrow-band infrared thermal emitters.

3.6 The near field radiative heat transfer between magnetic and non-magnetic materials

So far, most investigations of near field radiative heat transfer were restricted to the assumption of nonmagnetic substances. From these researches, it was clear that excitation of surface waves in TM polarization would enhance the near-field radiative heat transfer and made it monochromatic [3]. With the development of the metamaterials, the surface waves in TE polarization might be excited. In order to discuss the effect of the excitation of surface waves in TE polarization on the near-field radiative heat transfer, we developed the theory of near-field radiative heat transfer to deal with near-field radiative heat transfer for layered magnetic media (involving metamaterials). According to the theory, we calculated the near-field radiative heat transfer between two semi-infinite bodies (made by identical nonmagnetic/magnetic materials) separated by different vacuum gap, as shown in Fig.3. It should be pointed that except the relative permeability is 1, the other conditions is same as that for magnetic materials.

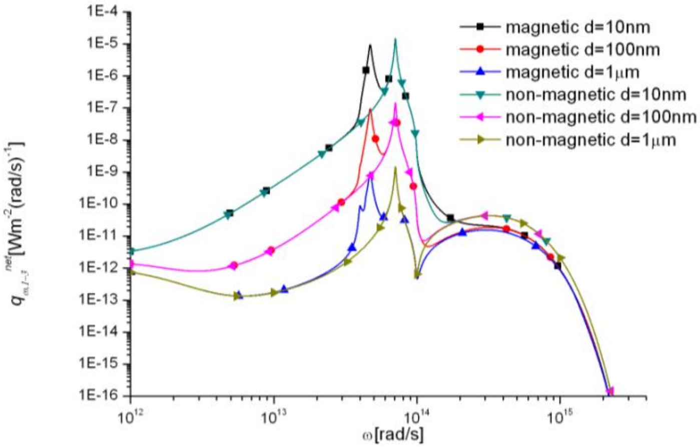

FIGURE 3. Spectral rediative energy flux between magnetic and non-magnetic materials at different air-space distance

As shown in Fig. 8, the different behaviors for the radiative heat transfer were observed for magnetic and nonmagnetic materials. Although there exists a peak $\omega = 7.0705\times10^{13}$ rad/s for both magnetic and non-magnetic media due to the effect excitation of surface waves in TM polarization, there is an additional peak around $\omega = 4.7134\times10^{13}$ rad/s due to the effect of excitation of surface waves in TE polarization for the magnetic media as the dispersion relation for surface polaritons in TE polarization could be satisfied, which will further enhance the heat transfer between the two bodies. By comparison of the contributions of TE and TM waves to the heat flux, it might be found that the main difference between the magnetic and nonmagnetic materials is that the surface wave would be excited in TE polarization, resulting the enhancement of the contributions of TE waves to the heat flux and little effect on the contributions of TM waves to it.

4. CONCLUSIONS

In this paper, the investigations, in which "near-field effects" are considered adequately, are carried out by solving Maxwell equations directly. The results show great influence of the near-field effects on heat radiation of the micro/nano-structured surface. By adjusting micro/nano-scale structure, the radiative heat transfer can be enhanced/suppressed greatly. Therefore, the mechanism of the radiative heat transfer in micro/nano scale structures can provide a good guidance in the control of heat radiation.

Acknowledgements This work is sponsored by the National Natural Science Foundation of China (Grant No. 50936002).

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