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Spectral radiative properties of a nickel porous microstructure and magnetic polariton resonance for light trapping

Y.B. Liu, R. Jin, J. Qiu *, L.H. Liu *

School of Energy Science and Engineering, Harbin Institute of Technology, Harbin 150001, China

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ABSTRACT

In this work, we investigated theoretically the spectral radiative properties of a nickel porous microstructure, including wavelength-selective transmission, reflection, and absorption. The structure can be described briefly like that the arrays of uniformly sized spherical pores are ordered closely inside the structure and nickel is filled in the whole void spaces between the pores. The finite-difference time-domain (FDTD) method for electromagnetics was used to calculate the spectral radiative properties of the nickel porous microstructure. It is found that the absorption spectra of the nickel porous microstructure will generate two peaks within the wavelength range of 0.2–2.0 μm at normal incidence of light. Furthermore, the value, position and shape of the absorption peaks have tightly coupled relationships with the pore diameter, the filling height of nickel, the incident angle and polarization of light. Then magnetic polariton (MP) resonance can be observed clearly in the obtained results of this work, which is the crucial mechanism to elucidate for the power absorption enhancement. Additionally, it is revealed that the power absorption predominantly focuses on the top surface of the structure, especially on the region near the orifice. In practical application, we can enhance the efficiency of power absorption in the target wavelength by modulating the pore size, the filling height of nickel, the incident angle and polarization of light, which has great potential in many fields such as thermophotovoltaic (TPV) systems and impact energy absorption applications.

1. Introduction

The materials with porous structures have tremendous applications because of their superior physical natures of high strength, low density, and large specific surface area [1]. Historically, metallic periodical structures were developed for wavelength-selective light absorption [2]. Coupled with the resonance enhancement mechanisms such as surface plasmon polariton (SPP), magnetic polariton (MP), or cavity resonance [3–5], the periodical metallic porous microstructures will have great potential in energy conversion devices [6], thermophotovoltaic (TPV) systems [7], and impact energy absorption applications [8]. These applications usually require high-temperature materials such as Nickel, and highly desire for improving the performances in energy absorption and conversion which are related to the spectral radiative properties of the structures in these applications. Hence, studying the spectral radiative properties of the periodical metallic porous microstructures will be essential for the development of these fields.

In the past few years, the spectral radiative properties of the porous structures including cellular metallic foams and inverse opals have been studied by many researchers [9–17]. Clyne et al. [9] made a brief analysis to present how heat transfer takes place in porous materials of various types and the emphasis was on materials able to withstand extremes of temperature, gas pressure and irradiation. Tseng et al. [10] used the Mie scattering theory to analyze how the properties of foam material such as its density and mean cell size affect the radiative properties of silicon carbide (SiC) foams. And the spectral extinction coefficients of SiC foams which are measured experimentally are found to agree well with the theoretical prediction at 1000 K. Contento et al. [11] proposed a theoretical approach to develop a new radiative heat transfer model based on the tetrakaidecahedron representation of open cell metal foams proposed by Lord Kelvin and evaluated the radiative conductivity of foams by means of proposed model. Antenucci et al. [12] developed the electro-deposition of copper on aluminum open-cell foams substrates to enhance the thermal and mechanical properties of these cellular materials. Besides, the analytical models were proposed to predict the quantity and the quality characteristics of the coating. In our previous work [13], we also provided a validation result about the thermal radiation properties

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* Corresponding authors. Tel.: +86 451 86412138.
E-mail addresses: qiujun@hit.edu.cn (J. Qiu), lhliu@hit.edu.cn (L.H. Liu).

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Nomenclature

a	area of the monitor plane
A	absorptance
d	pore diameter
$\boldsymbol{E}$	electric field vector
h	filling height
$\boldsymbol{H}$	magnetic field vector
$\boldsymbol{J}$	current density
$\boldsymbol{k}$	wave vector
m	natural member
n	refractive index
$\hat{n}$	complex refractive index
P-polarization	parallel polarization
p	power
R	reflectance
$\boldsymbol{S}$	Poynting vector
S-polarization	vertical polarization
T	transmittance
w	absorption or dissipation density
X, Y, or Z	X, Y, or Z axis in the Cartesian coordinate system

Greek symbols

ε	permittivity or dielectric function
ε_0	permittivity of vacuum
ε_r	relative permittivity
ε''	imaginary part of ε
σ	electrical conductivity
σ'	real part of σ
σ''	imaginary part of σ
λ	wavelength
ω	angular frequency
μ	permeability
θ	incidence angle
η	volume fraction of nickel
Ψ	polarization angle
Φ	azimuthal angle

Superscripts

$*$	complex conjugate

Subscripts

Inc.	incidence
r	reflective monitor plane
t	transmitted monitor plane
eff	effective index
avg	average index
$\bar{h}kl$	Miller index of crystal face

of subwavelength aluminum foam structures and found that the cavity resonances can enhance the absorption coefficient of the incident wave energy. Martin et al. [14] reported on the fabrication and characterization of tungsten inverse opals for the visible and near-infrared spectral region and investigated experimentally the crucial influence of the strong absorption in this spectral region by means of a gradient deposition technique. Arpin et al. [15] used a template directed electrodeposition method to fabricate tungsten inverse opal photonic crystals which were conformally coated with hafnia or alumina via atomic layer deposition. And they found that this surface passivation layer increased the thermal stability of the tungsten microarchitectures by limiting surface diffusion. Braun et al. [16] fabricated a high-quality Ni inverse opals by an electrochemical approach, which can control completely sample thickness, surface topography and structural openness. They also made some experiments to discuss the reflectivity of the Ni inverse opals at the wavelength range of 1.5–5.5 μm. Yeng et al. [17] fabricated a two-dimensional tungsten photonic crystal which consists of an array of cylindrical cavities. The emittance of the structure at different high temperatures has been studied and experimentally obtained thermal emissivity spectrum is shown to match well with numerical simulations.

So far, current researches on the porous array microstructures mostly stay in the preparation stage, while the comprehensive studies of their spectral radiative properties are still demanded. In this work, we investigated theoretically the spectral radiative properties of a nickel porous microstructure by the finite-difference time-domain (FDTD) method for electromagnetics. The material is chosen as Nickel, because it has the advantage of the temperature stability, and ease of electrochemical processing. The structure contains the arrays of uniformly sized spherical pores which are ordered closely inside the structure and the whole void spaces between the pores fill up with nickel. Moreover, the spectral radiative properties of the nickel porous microstructure have been studied when the pore diameter, the filling height of nickel, the incident light and polarization of light change. Finally we explored the energy absorption distribution and the mechanism of absorption enhancement of the nickel porous microstructure. As specific target applications, the work can be applied to TPV emitters studied by Chen et al. [18] and Park et al. [19].

2. Geometry model and theoretical function

2.1. Geometry model

As can be seen in Fig. 1(c), the nickel porous microstructure considered in this work contains the arrays of uniformly sized spherical pores which are ordered closely inside the structure and the whole void spaces between the pores fill up with nickel. The optical constants of nickel come from Ref. [20]. If we characterize the concentration of nickel by filling coefficient ξ which can be defined as the surface fraction of nickel in the monolayer, the minimum filling coefficient $\xi = 0.0931$ will be gotten. It's worth noting that the nickel porous microstructure can be fabricated by some mature methods which are similar to the preparation methods of inverse opals. Among these methods, the colloidal crystal-templating approach has been used to prepare three-dimensionally ordered porous materials [21,22]. The procedure of the colloidal crystal-templating approach can be briefly represented in the Fig. 1(a)–(c). Firstly, monodisperse spherical particles depend on the natural tendency to self-assemble into a close-packed arrangement [23], which will be regarded as a template as shown in Fig. 1(a). Secondly, utilizing a precursor capable of solidification fills the voids of the template [24], as shown in Fig. 1(b). Finally, removing the template yields a porous structure with a close-packed arrangement of air spheres [24], as shown in Fig. 1(c). d and h represent the cavity diameter and filling height, respectively. Fig. 1(d) plots the plane of incidence and polarization. The wavevector $\boldsymbol{k}_{\mathbf{inc}}$ represents the propagation direction of the incident radiation at an incidence angle θ, azimuthal angle Φ, and polarization angle Ψ. The angle between $\boldsymbol{k}_{\mathbf{inc}}$ and the surface normal of the structure denotes the incidence angle θ. The polarization angle Ψ is defined as the angle between the