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Spectral radiative property control method based on filling solution

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ABSTRACT

Controlling thermal radiation by tailoring spectral properties of microstructure is a promising method, can be applied in many industrial systems and have been widely researched recently. Among various property tailoring schemes, geometry design of microstructures is a commonly used method. However, the existing radiation property tailoring is limited by adjustability of processed microstructures. In other words, the spectral radiative properties of microscale structures are not possible to change after the gratings are fabricated. In this paper, we propose a method that adjusts the grating spectral properties by means of injecting filling solution, which could modify the thermal radiation in a fabricated microstructure. Therefore, this method overcomes the limitation mentioned above. Both mercury and water are adopted as the filling solution in this study. Aluminum and silver are selected as the grating materials to investigate the generality and limitation of this control method. The rigorous coupled-wave analysis is used to investigate the spectral radiative properties of these filling solution grating structures. A magnetic polaritons mechanism identification method is proposed based on LC circuit model principle. It is found that this control method could be used by different grating materials. Different filling solutions would enable the high absorption peak to move to longer or shorter wavelength band. The results show that the filling solution grating structures are promising for active control of spectral radiative properties.

1. Introduction

Tailoring spectral radiative properties by selecting materials or designing structures of microscale grating is widely researched as a promising method in heat transfer field due to its valuable application in many energy conversion or energy adjustment systems, such as thermophotovoltaic devices [1–3], solar cell [4], optoelectronic devices [5,6], radiation filters [7,8] and photodetector [9]. Through controlling the spectral radiative properties, the performance of devices could be enhanced dramatically. According to different industrial applications, microscale grating structures are designed to meet certain desired radiative properties as wavelength-selective [10], broad absorption/emission peaks [11] or enhanced transmission and emission [12,13]. These radiative properties can be obtained through exciting resonances, which are induced by microscale periodic grating structures via various mechanisms, for instance, surface plasmon polaritons (SPPs) [14,15], surface phonon polariton (SPhP) [16], magnetic polaritons (MPs) [17], cavity resonance [18], Wood's anomaly [19], Fabry–Perot resonance [20], etc. Many researches have been done with regard to the study of properties and microstructure design. Chen and Zhang [21] designed a serial of complex gratings for

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thermophotovoltaic radiators by exciting SPP resonance. Wang et al. [20] reported a detailed experimental study on the spatial and temporal coherence of thermal radiation in asymmetric Fabry–Perot resonance cavities. Chen and Tan [22] demonstrated a systematic and efficient way of profile optimization of two-dimensional periodic nano-structures with wavelength-selective radiative properties. Chen et al. [23] investigated the optical responses of lossy metallic slit arrays at the excitation of MP resonance. Wang and Zhang [16] demonstrated the transmission enhancement with a SiC slit array and coherent thermal emission with a SiC deep grating in the infrared within the phonon absorption band. The results suggested that phonon-mediated magnetic polaritons have promising applications such as filters and selective coherent emitters. Huang et al. [24] provides a kind of modified complex gratings, which is constructed by attaching two sub-micron sized square features symmetrically at walls of the complex gratings, to further tailor the broadband absorptance peaks. All of these researches have shown promising applications of the intentionally designed micro-structures to obtain the desirable radiative properties.

However, the spectral radiation properties of existing proposed micro-structures cannot be regulated after the micro-structures are produced. Namely, in fabricated micro-structures it is hard to realize active control for application systems. Nevertheless, adjusting thermal radiation with the changing environment conditions is a common requirement for some industrial application and energy conversion systems. Therefore, it is a crucial technique to provide an adjustable design to accommodate the changing application environment. In this study, an adjustable, active control method by means of injecting filling solution (FS) is proposed. The new method enables controlling the spectral position of enhanced absorptance peaks excited by magnetic polaritons. Both mercury and water are chosen as filling solutions for the proposed grating structure in this paper. Different effects brought by the two solutions are investigated. As grating structures containing the filling solutions, one-dimensional silver and aluminum gratings are studied in this paper to find common and different functions on spectral radiative property active control.

By means of this design, thermal radiation control can be attained easily via adjusting the filling solution level. The rigorous coupled-wave analysis (RCWA) is employed to calculate the spectral properties of transverse magnetic (TM) wave in the incidence plane, which is perpendicular to the grating grooves. Equivalent LC circuit model is referenced to study the formed mechanism of spectral phenomenon. The capillary effect of filling solutions in micro-channel in this study can be addressed by adding a comb-drive microactuator lid structure. The liquid could be filled in the grooves injected by micropump from the grating bottom through microchannels.

2. Model development and numerical method

2.1. Geometry structure and physical properties

The adjustable grating structure is designed based on traditional simple binary grating by injecting filling solution in grating grooves. The schematic drawing of the cross-sectional view in x–z plane of the new adjustable grating structures is shown in Fig. 1. As it is shown, a lid driven by comb microactuator is added on the surface of filling solution to plug up the groove in order to avoid the superhydrophillicity of liquid in micro-channel. Voltage is added between two microactuator comb structures to direct the lid moving up and down. Comb-drive microactuator, which is a mature technology that has been widely used for many different applications, is driven by electrostatic drive force. It enables high accuracy movement in vertical directions [25]. The material of the lid is selected as magnesium fluoride (MgF_2) considering that its extinction coefficient at infrared wavelength range is close to zero and refractive index is close to one. However, due to the insulation of magnesium fluoride, a film electrode should be coated on one side of the magnesium fluoride comb surface. The filling solution can be filled from the bottom of grating through some microchannels. Filling can be actuated by a micropump. There are several choices of micropump type since design and fabrication of micropump are quite mature now. Membrane pump [26–29] is highly recommended because its operation is independent of liquid properties. The actuation method could be thermal actuation [30], electrostatic actuation [31], shape-memory alloy actuation [32], etc. Microvalve could be installed, depending on the application type of the micropump. Fig. 2 gives the comparison of the spectral property between the grating structures with and without MgF_2 lid that has a lid thickness of 0.1 μm. It can be seen that adding a magnesium fluoride lid brings almost no influence to the spectral radiation property of filling solution grating structure. It should be noted that both micropump actuator and comb-drive microactuator should be placed far away or insulated from the grating structure. Thus, the actuation electromagnetic field would not impact the incident wave magnetic field and the diamagnetism response.

In this paper, two metals, namely silver and aluminum, are chosen to be the grating materials. Mercury and water are filled into the grating groove respectively to investigate

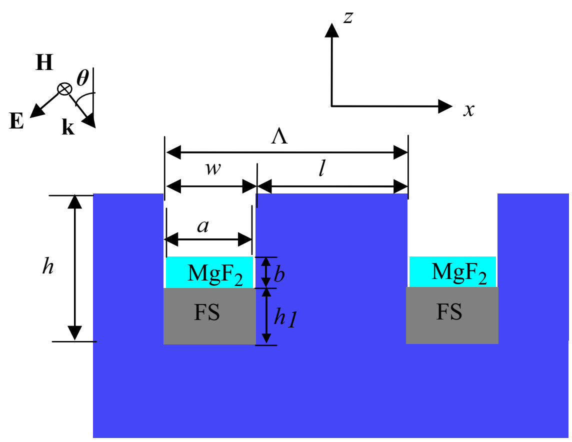

Fig. 1. The schematic drawing of the cross-sectional view in the x–z plane of adjustable grating structure with filling solution and comb-drive microactuator lid structure. FS denotes the filling solutions, which are mercury and water in this study.