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Control of thermal radiative properties using two-dimensional complex gratings

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ABSTRACT

The present work theoretically investigates the electromagnetic resonance modes on two-dimensional (2-D) complex gratings consisting of a metallic grating, a dielectric film, and a metal substrate. We treat a complex grating as geometrical combination of two square grating elements with different sizes in a single unit cell. In order to identify various resonance modes, such as surface plasmon and magnetic resonance (or magnetic polariton) existing in gratings, the finite-difference time-domain method is employed in solving Maxwell's equation. Differently from 2-D simple grating structures, we observe the diverse magnetic polariton modes associated with each grating elements in a single unit cell. Furthermore, if two different grating elements are merged together, magnetic polariton will be branched out into multiple modes. These characteristics of 2-D complex grating will be desirable for achieving broad-band absorption, which is critical for energy harvesting applications.

1. Introduction

Tailoring radiative properties using subwavelength-sized structures are crucial for various applications, such as thermophotovoltaic device, mid-infrared photodetector, plasmonic sensor, solar cell, solar thermal absorber, and radiation filter [1–5]. Common ways to control radiative properties using engineered nanostructures are employing a one-dimensional (1-D) or a two-dimensional (2-D) simple grating. Wang and Zhang [6] proposed a 1-D tungsten simple grating for thermophotovoltaic device. A 2-D tungsten grating/thin-film nanostructure was also designed as a thermophotovoltaic emitter, whose emittance value is close to the unity within the visible and the near-infrared spectral region but is nearly insensitive to the incidence and azimuthal angle [7]. Several studies have also focused on investigating the electromagnetic resonance phenomena in 1-D or 2-D grooved structures. Wang et al. [8] showed the excitation of surface phonon polariton using photonic crystal made by silicon carbide. Lee et al. [9] showed that an 1-D metallic grating atop an opaque metallic substrate with a dielectric spacer can support the surface plasmon polariton (SPP) and magnetic resonance. The magnetic resonance exists between the metallic strips and the film and is often called as magnetic polariton (MP) [6,9–11]. The key underlying mechanism of the MP is the coupling of the incident wave with the anti-parallel displacement current on the metallic strips separated by a dielectric spacer [12]. Later, Zhang et al. [13] verified the SPP, MP, and cavity resonance modes caused by a 2-D simple grating structure and compared resonance characteristics between 1-D and 2-D metallic gratings.

Recently, more complicated structures, such as nanowire, nanorod, nano-pillar, and nano-hole array, have been considered for enhancing the emission or absorption efficiency in broader spectral range [14,15]. Lundgren et al. [16] designed silicon-branched nanowire forest for the solar energy absorption. The trapezoid array structure was also considered for the broadband and polarization-independent light absorption [17]. Due to difficulties in fabrication of aforementioned structures as well as in prediction of their performance using a rigorous computational method, relatively simpler grating structures were also proposed for achieving the dual-band or multi-band absorption. For example, Wang and Wang [18] considered the 2-D double-sized metamaterial that consists of two different-sized gratings within one period. They showed that the structure can have a broadband absorption within the visible and the near-infrared spectral region. Bouchon et al. [19] proposed four different-sized 2-D simple gratings exhibiting four magnetic resonance peaks that are insensitive to the incidence and azimuthal angle. Chen and Zhang [20] verified multiple surface plasmon branches from the 1-D complex grating made by heavily doped silicon. Except for those studies, structures made by nichrome [21], multi-cross type grating [22], a sawtooth

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Nomenclature

C	capacitance (F)
c_0	speed of light in vacuum (2.997×10^8 m/s)
d_f	dielectric film thickness (m)
d_g	grating thickness (m)
k	magnitude of the wavevector (m^{-1})
L	inductance (H)
t	time (s)
w_l	width of the large grating element (m)
w_o	width of the overlapped grating region (m)
w_s	width of the small grating element (m)
Z	impedance (Ω)

Greek Symbol

ϵ	dielectric function
Λ	grating period (m)
θ	incidence angle (°)
ν	wavenumber (cm^{-1})
ϕ	azimuthal angle (°)
ω	angular frequency (rad/s)

anisotropic metamaterial slab [23], and multi-sized nano-antennas [24] were also investigated.

As briefly summarized above, the common way of achieving the dual-band or multi-band absorption is to employ two or multiple grating elements (or segments) in a single unit cell (i.e., complex grating) and to utilize the resonance mode associated with each grating element at different wavelengths. There also exist few studies about the hybridization of magnetic polaritons observed from the vertically stacked metal-oxide-metal elements in multilayer structures [25–27]. However, little has been done on how MP modes are branched out especially when horizontally arranged grating elements of a complex grating begin to be merged. Therefore, the present work aims to systemically investigate the electromagnetic resonance modes on 2-D complex gratings in which different-sized grating elements are horizontally arranged in a single unit cell. In order to identify various resonance modes, including the surface plasmon and the magnetic polariton existing in such complex grating structures, the finite-difference time-domain (FDTD) method is employed in solving Maxwells equation. The coupling mechanism of MP modes of a complex grating when horizontally arranged grating elements are merged is elucidated by the equivalent inductor–capacitor circuit model as well as the local field distribution.

2. Theoretical modeling

Fig. 1 depicts one unit cell of the proposed 2-D complex grating structures. Geometric parameters defining a complex grating are period (Λ), width of large and small grating elements (w_l and w_s, respectively), and thickness of the grating (d_g) and the dielectric film (d_f). In the calculation, we set geometric parameters: $\Lambda = 1000$ nm, $w_l = 600$ nm, $w_s = 300$ nm, $d_g = 40$ nm, and $d_f = 40$ nm. The gratings and substrate are made of gold. SiO_2 is used as a dielectric spacer. For comparison, we consider the four types of grating structures as follows. The first type is the simple grating (SG) that has just one large grating element w_l within one unit cell. The second type is the complex grating I (CGI) that consists of separated large and small grating elements, w_l and w_s, respectively. The separation distance between the large and small grating elements is $w_h = 50$ nm in both x- and y-directions. The third type is complex grating II (CGII) that also has large and small grating elements, but they are overlapped by $w_o = 250$ nm in both x- and y-directions; that is, the length of remaining portion of the small grating element is 50 nm. The last type is complex grating III (CGIII) that has large and small grating elements overlapped by $w_o = 50$ nm (i.e., the remaining portion of the small grating element is 250 nm).

A linearly polarized electromagnetic wave is incident from a free space to the complex grating at normal incidence. The transverse magnetic (TM) polarization is defined when the magnetic field oscillates perpendicularly to the x-z plane (refer to Fig. 1). The freely available FDTD package MEEP [28] is used to calculate the spectral reflectance as well as the local field distribution with uniform meshes of 5 nm along the x-, y-, and z-directions. The numerical convergence of FDTD method is examined by varying the mesh size from 2.5 nm, 5 nm, and 8 nm, confirming that 5-nm mesh is sufficient to assure the convergence. In making an array structure, periodic boundary condition is applied in the x- and y-directions, and perfectly matched layer with 200-nm thickness (i.e., greater than 10 times of the Yee grid size) is embedded along the z-direction for the numerical stability [29]. In order

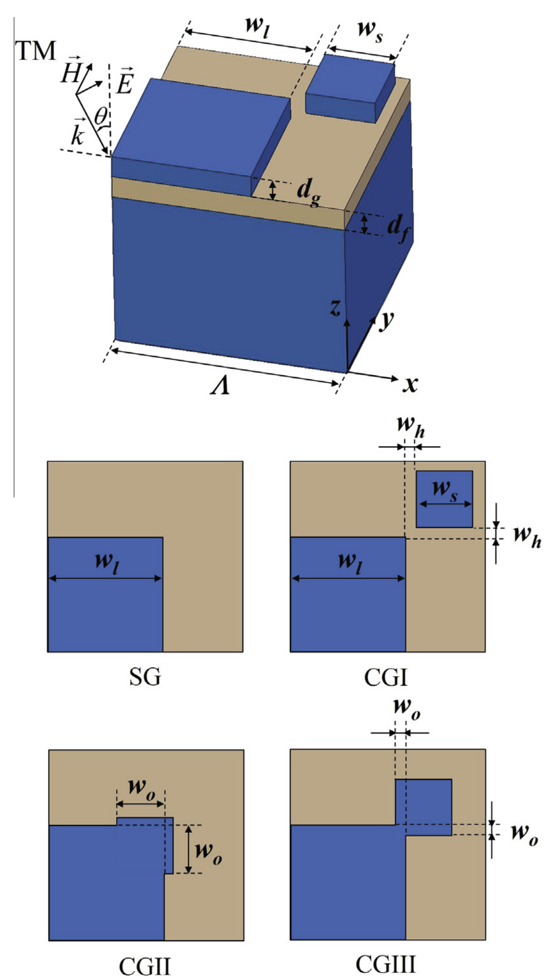

Fig. 1. Schematic of one unit cell of CGI and top view of four types of grating structures.