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Achieving multi-order nearly perfect absorption based on phase resonance in a compound metallic grating

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ABSTRACT

In this study, a free-standing subwavelength metallic grating with grooves on its output surface is shown to have suppressed transmission and reflection simultaneously at different incident wavelengths both for normal incidence and oblique incidence, resulting in multi-order nearly perfect absorption. This extraordinary absorption originates from the phase resonance of this compound grating together with the contribution of the cavity modes (CMs) resonance in the grating slits. The CMs resonance gives rise to the suppressed reflection, and the phase resonance not only reinforces this suppression effect, but also blocks the transmission completely. Compared with the conventional perfect absorbers, this perfect absorber has obvious advantages, such as simple single layer structure, single material composition, can be achieved at multiple frequencies and wide angular range.

1. Introduction

Perfect absorbers which act as a new kind of functional material can be used in many applications such as plasmonic sensors [1], solar cells [2], photodectors [3], thermal emitters [4], thermal imaging [5], energy harvesting [6] etc. It is well known that one of the basic methods to enhance the absorption is to bring about electromagnetic resonances. Light-matter interactions in a metallic structure patterned at the subwavelength scale give rise to various resonances. For example, the conventional metamaterial perfect absorbers are achieved by simultaneously stimulating electric and magnetic resonances in a structured metallic layer to obtain the matched impedance to the free space and then blocking the transmission by using another thick metallic layer [7–10]. These two layers are separated by a kind of dielectric. Thus, the basic configuration of the metamaterial perfect absorber comprises at least three layers. Actually, for the convenience of fabrication and integration this three layer configuration can be simplified to a single layer. For example, even in a single layer metallic grating, there can be as many as four kinds of resonance mechanisms: horizontal surface Plasmons (HSPs) excited on the top and bottom boundaries of the gratings [11,12], cavity modes (CMs) resonance occurring in the grating slits [11,12], Wood–Rayleigh (WR) anomalies that occur when one of the diffraction orders grazes the grating surface [13], phase resonance caused by the interference between different cavities (slits or grooves) in compound gratings [14–19]. Through selectively combining and utilizing some of these resonances, transmission and reflection can be controlled separately just like those in the metamaterial absorbers. For example, when the CMs resonance coupled with surface plasmon polaritons (SPPs) is excited, most of the incident energy can be directed through the grating structure, resulting in the famous extraordinary optical transmission (EOT) phenomenon [20,21]. Simultaneously, the reflection is minimized and in some circumstance, it can be decreased to near zero. On the other hand, the enhanced transmission of the EOT can also be suppressed effectively by using the phase resonance [15,22]. If the phase resonance occurs on the output surface, especially for the π phase resonance, i.e., the phases at the exits of the adjacent cavities are opposite to each other, the transmission will be completely suppressed by destructive interference [22]. At the same time, it leads to an enhanced resonance and field distribution inside the grating structure which forces more incident energy to enter the grating slits. Consequently, the reflection can be further decreased. If the CMs resonance and the π phase resonance are excited in a same grating structure, the reflection and transmission will be both suppressed. Thus, the incident energy will be confined in this structure and be absorbed eventually. Inspired by this idea, we design a free standing metallic grating with grooves on its output surface. By using two different resonance mechanisms, perfect absorption is obtained. Not only that, this perfect absorption phenomenon can be obtained at multiple frequencies. It is more

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convenient than fabricating and arranging artificial meta-cells with different sizes in the conventional multi-band metamaterial absorbers [23,24]. In addition, this multi-order perfect absorption can also be obtained at oblique incidence.

2. Structure design and simulated results

Fig. 1(A) shows the proposed grating structure and the incident configuration, where D, H and W_1 indicate the period, thickness and slit width of the grating, respectively. For illustration of the incident configuration, a part of this structure is not shown. The blue part represents the single grating material sliver. In order to stimulate the phase resonance on the output surface, a groove is carved on this side at each center of the sliver strips. The depth and width of the groove are denoted by h and W_2, respectively. Cartesian co-ordinates are adopted in this figure and the xz plane is set as the incident plane. A TM polarized plane wave (the magnetic component is perpendicular to the incident plane and the electric component is parallel to the incident plane) is incident upon this structure at an incident angle of θ (the red arrow shows the incident direction). We perform the simulation based on the Finite Difference Time Domain (FDTD) method by using a commercial software Lumerical FDTD Solutions. In simulation, we suppose that the structure is infinite in the y direction; therefore, 2D simulation is performed. The calculated region is truncated by using perfectly matched layers in the z direction. As for the x direction, periodic boundary conditions and Bloch boundary conditions are used under normal and oblique incidence, respectively. The permittivity of sliver is obtained from Ref. [25].

Fig. 1(B) shows the simulated spectra under normal incidence for both our proposed grating structure and a conventional grating (the same dimensions but without grooves), where the parameters are taken to be $D=0.8$ μm, $H=3.507$ μm, $W_1=0.1$ μm, $W_2=0.3$ μm and $h=1.93$ μm. The red and black curves correspond to our new grating structure and the conventional grating, respectively. One can see that there are two kinds of resonant absorption peaks alternatively distributed in the absorption spectrum of the new grating, one is higher almost up to 100%, the other is lower not larger than 50%. All these absorption peaks appear at the EOTs' resonant frequencies of the conventional grating. The higher absorptions appear at the odd orders while the lower absorptions locate at the even orders. The transmission, reflection and the absorption of the even orders (lower absorption peaks) are all almost the same as those of the conventional grating, as if there were no grooves on the output surface. In contrast, for the odd orders (higher absorption peaks) where there should be high transmission peaks, the transmission peaks are suppressed

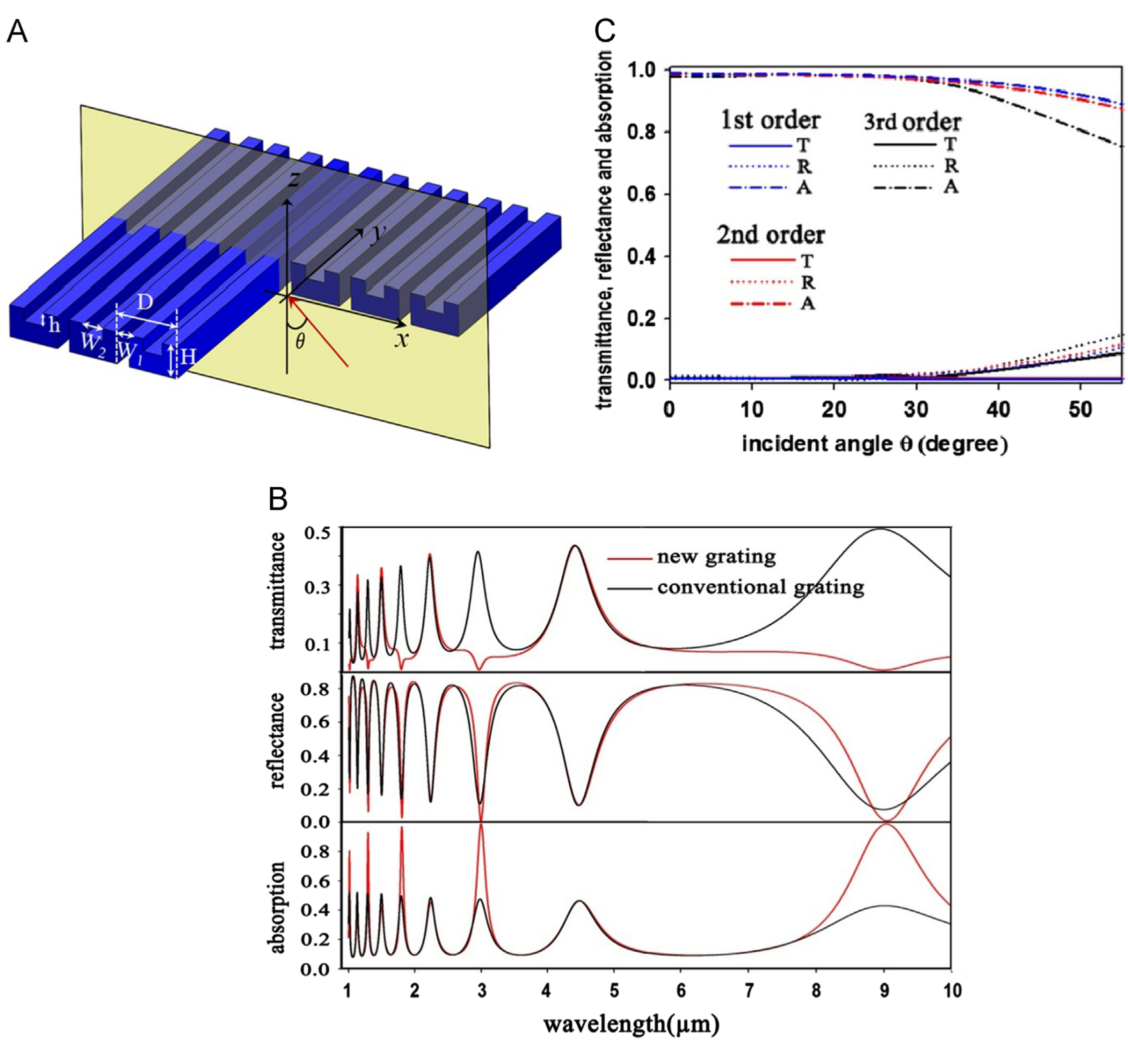

Fig. 1. (A) Schematic of the proposed metallic grating structure and the incident configuration. (B) Transmission, reflection and absorption spectra both for the proposed grating (red lines) and the conventional grating (black lines) at normal incidence, where $D=0.8$ μm, $H=3.507$ μm, $W_1=0.1$ μm, $W_2=0.3$ μm and $h=1.93$ μm. (C) Transmittance, reflectance and absorption of the first three near-perfect orders ($\lambda=9.0$ μm, 3.0 μm, 1.8 μm) varying with the incident angle θ. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)