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Characterization of photonic bands in metal photonic crystal slabs

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ABSTRACT

By rotating metal photonic crystal (PC) slab around ΓK and ΓM lattice directions, transmission spectra were measured to study photonic bands in such metal PC with a triangular lattice. We found that the photonic band diagram for the ΓM lattice direction is different from that for the ΓK direction. Approximate formulas of angular-dependent resonant frequencies are derived to quantitatively analysis the dispersion of metal PC. Furthermore, experimental results for the dominant resonances of (−1, 0) (ΓM) and (0,−1) (ΓK) confirm the accurate of formulas. All these results can be used to analyze and design devices based on metal PC.

1. Introduction

Photonic crystal (PC) slabs, which often refer to two dimensional PC with finite thickness, have been widely concerned due to their potential to control the propagation of electromagnetic waves [1]. In terahertz (THz) range, as the fabrication of PC is much more convenient than that at optical frequencies, increasing interest in the use of PC has been seen for many applications. Lots of research focused on the transmission properties for out-of-plane propagations through silicon PC due to the low loss property of silicon in THz range. From the angular variation of the transmission spectra, the photonic band structure for the guided resonances can be found, which can benefit to the development of photonic devices [2–5]. Compared with the silicon PC, the metal PC slabs (also called metal holes array, MHA) show the unique characteristics in the microwave and THz range due to their influence on the electric field of electromagnetic wave. Extraordinary transmission phenomenon has been sufficiently studied through such metal PC slabs which can be applied to filters and sensors [6–8]. One can find systematic introduction of metal PC (or MHA) in some review articles [9,10]. More recently, the dispersion curves of spoof surface plasmons (SPs) and photonic band structures in metal PC are discussed in microwave and THz range for the propose of extraordinary transmission [11–13]. However, they all focused on the metal PC slabs with a square lattice. Interestingly, such dispersion characteristics of SPs for long range and short range in a triangular array of holes have been studied in visible region and the photonic bands have been clearly found by the angle-resolved spectra [14]. In this paper, we use the method proposed in Ref. [3] to analysis the THz photonic band diagrams for the ΓM and ΓK directions in metal PC with a triangular lattice and verify the dominant dispersions by rotating the sample with ΓM and ΓK directions. Analytic formulas of resonant frequencies for two lattice directions are derived based on the momentum conservation theory. Compared with metal PC slabs with a square lattice, the band structure for the ΓM direction is different from that for the ΓK direction. The dominant resonant frequencies experimentally observed show good agreement with results from formulas. Our results should inspire further interest in the development of metal photonic devices.

2. Experimental results and discussion

The proposed metal PC consisted of a triangular array of circle air holes in an aluminum plate with the parameters of t=0.25 mm, d=0.7 mm, and p=1.13 mm, as shown in Fig. 1(a). To study photonic band, we employ an out-of-plane illumination scheme (Fig. 1(b)), which is similar to the experimental setup of the silicon PC [3,4]. The ΓM and ΓK directions are also shown in Fig. 1(b). The metal PC has geometry with size of 50 mm in order to provide sufficient periodical extension and nearly infinite boundary condition [15].

The transmission measurement was carried out using a terahertz time domain spectroscopy (THz-TDS) system [15–17]. A collimated THz wave, which was radiated from the emitter of a photoconductive antenna pumped by a 100-fs 800 nm laser

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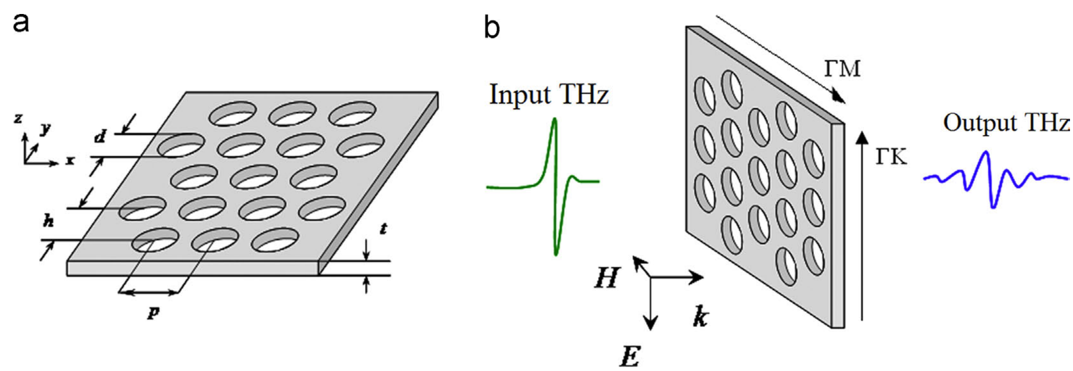

Fig. 1. (a) Overview of the metal PC slab. The crystal parameters of this sample are $d=700$ μm, $p=1.13$ mm and $t=250$ μm. (b) Schematic of the experimental arrangement. At the incident angle θ corresponding to the normal of the slab, the in-plane component of the wave vector of the incident THz wave is along the ΓM or ΓK directions of triangular lattice.

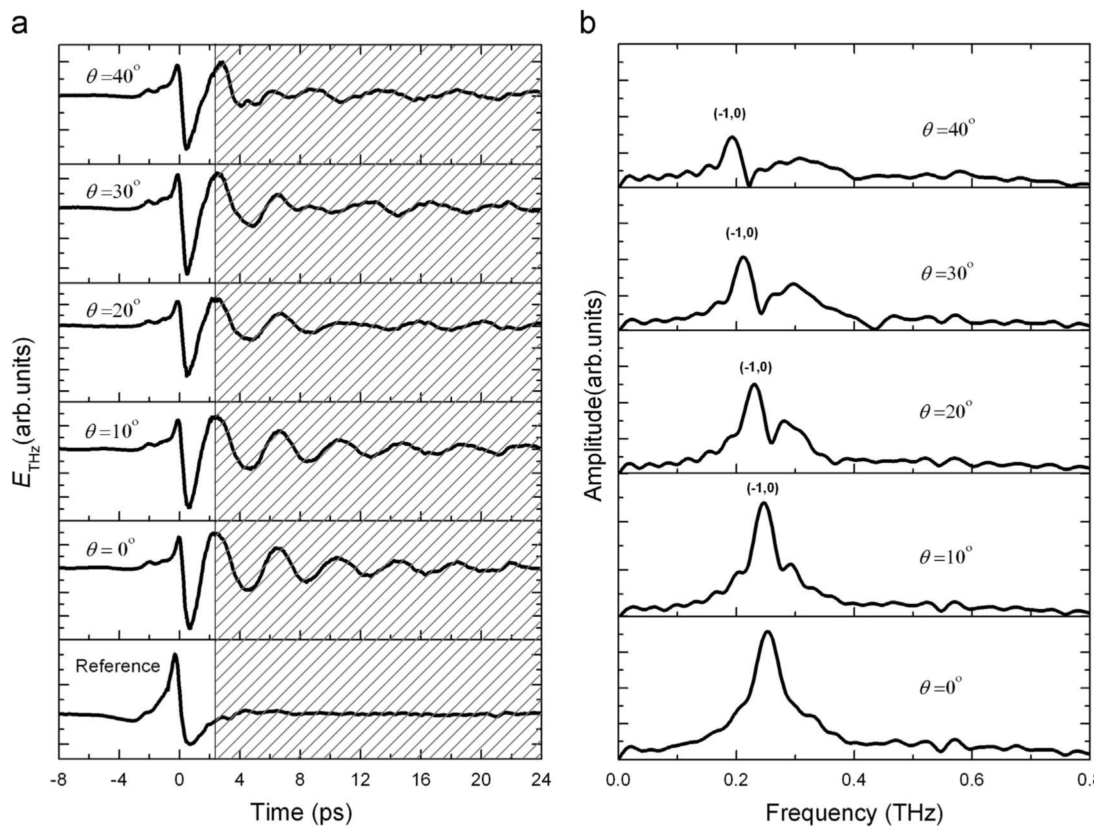

Fig. 2. (a) The incident THz wave form and THz wave forms transmitted through the metal PC along the ΓM direction. (b) Corresponding Fourier-transformed spectra in the time range after 2.5 ps.

pulse, was irradiated on the sample. By changing the time delay between the pumping and probe pulses, the wave form of the electric field of the transmitted THz wave could be measured. The sample with triangular arrays has two lattice directions: ΓM and ΓK (see Fig. 1(b)). *p*-polarized THz pulses were incident at the angle θ relative to the surface normal of the slab. The THz spot size is larger than the lattice constant of the metal PC, so many holes could be illuminated. A reference measurement was taken when there was no sample present, which we referred to as an air signal.

We measured the time domain waveforms of the metal PC at normal angle ($\theta=0^\circ$ in Fig. 2(a)) and found that each wave form has an initial fast pulse and a long decaying tail. Since SP resonances are modes that are not confined inside the metal PC slab, they decay out of the slab with various lifetimes. To evaluate the frequency of such oscillation components, we made Fourier transformations of the waves form in the range after 2.5 ps, where the oscillation component appeared ($\theta=0^\circ$ in Fig. 2(b)). The transmission peak at normal angle is observed at 0.26 THz. Then, we also experimentally studied the effects of the angle of incidence on the transmitted time-domain waveforms in ΓK (Fig. 2(a)) and ΓM (Fig. 3(a)) directions. When the incident angle θ becomes finite, after 2.5 ps the oscillation components are weak with the increase of the incident angle in ΓK and ΓM directions. This seems to be a consequence of lack of symmetry along the incident direction. Their transmission spectra are illuminated in Figs. 2(b)