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# Optical switching realized in three-dimensional unusual surface-plasmon-induced photonic crystals composed of plasma-coated spheres

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ABSTRACT

In this paper, the dispersive properties and switching state of three-dimensional (3D) photonic crystals (PCs) with face-centered-cubic lattices, which are composed of core anisotropic dielectric (tellurium) spheres surrounded by non-magnetized plasma shells inserted in the air, are theoretically investigated in detail based on a modified plane wave expansion method. The equations for calculating the band structures for such 3D PCs are deduced. Our analyses show that the proposed double-shell structures can produce the complete photonic band gaps (PBGs) which can work as the optical switching by manipulating the radius of core dielectric sphere and the plasma frequency. However, the switching state of PCs cannot be tuned by the thickness of the plasma shell and plasma collision frequency as the radius of the core dielectric sphere is certain. Numerical simulations also demonstrate that a flatbands region, and the stop band gaps (SBGs) in the (1 0 0) and (1 1 1) directions which are above the flatbands region can be achieved. The SBGs in the (1 0 0) and (1 1 1) directions can also be tuned by the parameters as mentioned above. There is also a threshold value for the thickness of plasma shell, which makes the band structures of such 3D PCs with double-shell structures to be similar to those obtained from the same PCs containing the pure plasma spheres. In this condition, the dielectric function of inserted core sphere will not affect the band structures. It means that the PBGs can be achieved by replacing the pure plasma spheres with such double-shell structures to make fabrication possible and save the material in the realization. It is also noted that the flatbands region is determined by the existence of surface plasmon modes, and the upper edge of flatbands region does not depend on the topology of lattice. The proposed 3D PCs with double-shell structures offer a novel way to realize the tunable optical switching.



## 1. Introduction

From the time the concept of photonic crystals (PCs) was first proposed by Yablonovitch [1] and John [2], researchers have shown great interest in PCs. During the last two decades, the properties of PCs have been investigated extensively by both experimental and theoretical approaches. The photonic band gaps (PBGs) of PCs can be obtained in some frequency regions, which originate from the interface of Bragg scattering [3]. In the PBGs, any polarizations of electromagnetic (EM) waves cannot propagate through PCs along any direction. This unique feature makes PCs be looked as a promising candidate to build many important optical devices, such as defect-mode PCs lasers [4], absorber [5], all-optical adder [6], filter [7], omnidirectional reflector [8] and waveguide [9]. Recently, the plasma is introduced into the PCs to realize the tunable PBGs, which can overcome the drawbacks of the conventional dielectric PCs, such as being highly sensitive to the lattices and randomness. In nature, the plasma can be looked as a kind of metamaterial [10], and also is a good candidate to form the tunable PCs. Compared to the conventional dielectric, the plasma not only is a kind of frequency-dependent material [11,12] but also the physical properties can be modulated by many external parameters such as the electric field, the magnetic field and the electron temperature [11,12]. Thus, the plasma photonic crystals (PPCs) have become a new research focus since the time it was first proposed by Hojo and Mase [13] in 2004. Compared to

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the conventional dielectric PCs, many interesting properties can be found in the PPCs [14–16]. Thus, the PPCs have been obtained with an ever-increasing interest in experiment and theory. The properties of the one- and two-dimensional (2D) PPCs have been investigated in detail, as reported by Prasad et al. [17], Qi et al. [18] and Zhang et al. [7]. The properties of PBGs and defect modes for the PPCs are investigated by the finite difference time domain (FDTD) and transfer the matrix methods (TMM). The results showed that the plasma density and the external magnetic field are key points to manipulate the PBGs and defect modes of PPCs. According to those principles, the tunable filter [19,20] and omnidirectional reflector [21,22] can be easily realized. In the recent years, the special PPCs have also attracted people's attention, in which the magnetic material or metal is introduced, such as mentioned in the reports by Hamidi et al. [23], Mehdian et al. [24] and Fu et al. [25]. However, Zhang et al. [26] and Qi et al. [27] formed a new kind of PPCs, which are only realized by arranging the plasma periodically by the external magnetic field, and they found that the dispersive properties can be tuned by the external magnetic field. Guo [28] studied negative refraction in the 1D and 2D PPCs as the plasma collision frequency is ignored. In the experiment, great works have been done by the Sakai research group [29–31]; they verified and observed the PBGs of PPCs in millimeter range and the abnormal refraction around the plasma frequency. Fan et al. [32] and Dong et al. [33] used a dielectric barrier discharge with two liquid electrodes to obtain a tunable 1D and 2D PPCs, respectively.

Furthermore, the 1D and 2D PCs structures may not be very well in accordance with the real applications and the 3D PCs structure may be closer to the actual situation. Compared to the 1D and 2D cases, the complete PBGs can only be obtained in the 3D PCs. Thus, our research group pays attention on the dispersive properties of 3D PPCs [34–40]. From those research results, we can also know that if the 3D PPCs are with high symmetry, such as face-centered-cubic (fcc) lattices [34–40], simple-cubic (sc) lattices [34–40], and body-centered-cubic (bcc) lattices [34–40], the complete PBGs can be hardly achieved. Especially, the 3D PPCs with fcc lattices as the dielectric spheres inserted in the air cannot produce the complete PBGs [39,40]. To solve this problem, the anisotropic dielectric can be introduced into the 3D PPCs [39,40]. According to the results in our published work [35], the dispersive properties of stop band gaps (SBGs) in the (1 0 0) and (1 1 1) directions and PBGs of 3D PPCs with fcc lattices are investigated. If we want to tune the switching gaps of 3D PPCs, the dielectric constant of background must be large enough, and the inserted spheres must be pure. Unfortunately, technological difficulties can be found in fabricating such 3D PPCs with high symmetry. In order to realize the tunable all-optical switching in 3D PPCs with low background dielectric constant, we can use double-shell structures to construct 3D PPCs as mentioned by Chan et al. [41] and Aryal et al. [42]. On the other hand, the relationships between the surface plasmon modes and lattices of PPCs are also not investigated in the 3D case.

As mentioned above, the aims of this paper are to investigate the optical properties and switching state of 3D PPCs with fcc lattices, that are composed of the core tellurium (Te) spheres surrounded by non-magnetized plasma shells inserted in the air based on a modified plane wave expansion (PWE) method, and the unusual properties of surface plasmon modes are also investigated. A Drude-like model is used to describe the effective dielectric function of the non-magnetized plasma, and the plasma collision frequency is also considered. This paper is organized as follows. The equations for calculating the band structures are deduced in Section 2. In Section 3, the influences of the radius of core dielectric sphere, the thickness of plasma shell, and the plasma frequency on the optical properties and the switching state of such 3D PPCs are investigated. The unusual properties of surface plasmon modes have also been discussed in this section. Finally, conclusions are given in Section 4. An $e^{-j\omega t}$ time-dependence is implicit throughout the paper, with $t$ being the time and $j=\sqrt{-1}$. We also consider $c$ as the speed of light in vacuum.

## 2. Theoretical model and numerical method

The first irreducible Brillouin zone and schematic structure of the 3D non-magnetized PPCs with fcc lattices can be found in Fig. 1. As shown in Fig. 1, a symmetric set of primitive vectors for the fcc lattice is $\mathbf{a}_1=(0.5a,\ 0.5a,\ 0)$, $\mathbf{a}_2=(0,\ 0.5a,\ 0.5a)$, and $\mathbf{a}_3=(0.5a,\ 0,\ 0.5a)$. The reciprocal lattice vector basis can be defined as $\mathbf{b}_1=(2\pi/a,\ 2\pi/a,\ -2\pi/a)$, $\mathbf{b}_2=(-2\pi/a,\ 2\pi/a,\ 2\pi/a)$, and $\mathbf{b}_3=(2\pi/a,\ -2\pi/a,\ 2\pi/a)$. The high symmetry points have the coordinates $\Gamma=(0,\ 0,\ 0)$, $X=(2\pi/a,\ 0,\ 0)$, $W=(2\pi/a,\ \pi/a,\ 0)$, $K=(1.5\pi/a,\ 1.5\pi/a,\ 0)$, $L=(\pi/a,\ \pi/a,\ \pi/a)$, and $U=(2\pi/a,\ 0.5\pi/a,\ 0.5\pi/a)$. The (1 0 0) and (1 1 1) directions can be described by the points $L$, $\Gamma$ and $X$. We assume that the dielectric background, the dielectric core spheres and the plasma shells are isotropic and homogeneous, and the relative dielectric functions are $\varepsilon_b$, $\varepsilon_a$ and $\varepsilon_p$, correspondingly. As shown in Fig. 1(b), we consider the radius of the shell, the radius of the core sphere and the lattice constant to be $R_2$, $R_1$ and $a$, respectively. In the following numerical calculations, the non-magnetized plasma is assumed to be frequency-dependent, and $\varepsilon_p$ can be written as [12]

$$\varepsilon_p(\omega)=1-\frac{{\omega_p}^2}{\omega(\omega+j\nu_c)} \tag{1}$$

where $\omega_p$ and $\nu_c$ are the plasma frequency and the plasma collision frequency, respectively. Plasma frequency $\omega_p=(e^2n_e/\varepsilon_0 m)^{1/2}$ where

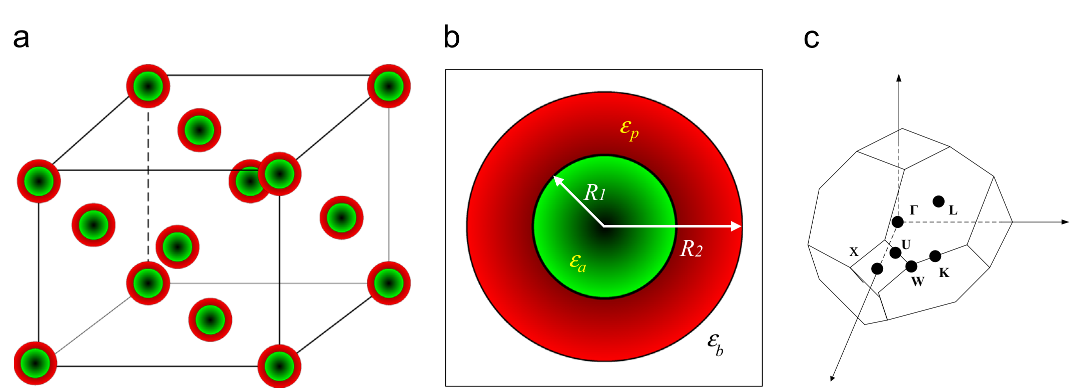


**Fig. 1.** (Color online) (a) Schematic structure of such 3D PPCs. (b) Illustration of a unit cell of such 3D PPCs. (c) The first irreducible Brillouin zone showing symmetry point used for obtaining the PBG.