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A completely open cavity realized with photonic crystal wedges*

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Abstract: A completely open cavity, which is formed by three 60-degree wedges of a photonic crystal with negative effective index, is introduced. Such a realizable design for a completely open cavity (i.e., without any reflective wall in the radial direction) is the first of its kind ever been reported. Due to the negative effective refraction index of the photonic crystal and the high transmission at the photonic crystal/air interfaces, a closed path with zero optical path is formed for the resonance. The present open cavity is very suitable for use as a biosensor as it has large air wedges into which a liquid measurand can flow easily.

Key words: Completely open cavity, Photonic crystal, Negative refraction index, Left-handed, Resonator
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A left-handed (LH) material (also called a negative refraction index material) exhibiting a negative refraction index due to simultaneously negative permeability and permittivity, was first introduced by Veselago in 1967 (Veselago, 1968). Negative refraction has recently attracted much attention in the physics and electrical community engineering due to its potential impacts and applications (Shelby *et al.*, 2001; Pendry, 2000). Negative refraction can also be achieved in some negative refraction photonic crystals (PCs). Negative refraction occurs in two distinct types of PCs: (1) PCs having negative effective refractive index n_{eff} near the center of the Brillouin-zone (Notomi, 2000). For this type, the dot product of the Poynting vector and wave vector is negative (like in LH material), and consequently it may have behavior similar to that of LH material (e.g. focusing slab-lens satisfying Snell's law (Pendry, 2000)); (2) PCs with convex equal frequency contours (EFCs) at a corner of the Brillouin-zone (Luo *et al.*, 2002). For this type, the dot product of Poynting vector and wave vector is positive, and n_{eff} cannot be deduced.

Open cavity (Notomi, 2000), which relies on the concept of negative refraction index, is another amazing property of an LH material. The open cavity first suggested by Notomi consists of four alternating rectangular blocks of two materials with opposite refractive indices (Notomi, 2000). A simple ray-trace analysis can show that there exist many closed ray paths (with zero value of the optical path) running across the four interfaces and thus a kind of an open cavity with no surrounding reflective wall is formed. The idea of open cavity is based on the cancellation of the optical path (defined as the integration of the refractive index over the ray path) and is straightforward. Since a homogeneous LH material at an optical wavelength has not been experimentally realized yet and a PC with negative refraction at an optical frequency is comparatively much easier to fabricate, one may expect the realization (at least numerical simulation) of an open cavity with a PC of negative refraction of LH behavior (type (1)). However, this has not been achieved since Notomi introduced the idea of open cavity (Notomi, 2000). In the present Letter

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we report for the first time an open cavity realized with a negative refraction PC.

In the design of our open cavity, we use the same negative refraction 2D PC considered by Notomi (2000), i.e., a triangular lattice of air holes (of radius 0.4a; a is the lattice constant) in GaAs background (with n=3.6). For E-polarization (with the electric field along the z-direction), the equal-frequency surface is almost circular (indicating that the PC can be considered as an isotropic medium and n_{eff} can be well defined at these frequencies) at the second band in a frequency window ranging from 0.29(c/a) to 0.34(c/a) (Fig.1). Furthermore, EFS for a higher frequency has a smaller radius. This indicates that the Poynting vector (group velocity) is in the opposite direction of the wave vector and thus the negative refraction has of LH behavior. In particular, n_{eff} is around –1 at frequency f=0.3(c/a). It was shown in our previous work (Ruan *et al.*, 2005) that the reflection is large (i.e., small transmission) for any incident angle at an interface normal to the Γ-K direction and the reflection is small for virtually all incident angles when the interface is normal to the Γ-M direction. Therefore, the open cavity sketched by Notomi would not work due to the large reflection at the air-PC interfaces (if one tries to reduce the reflection at one air-PC interface of a rectangular block by aligning the normal of this interface with the Γ-M direction, the reflection would be large at the other air-PC interface of the rectangular block).

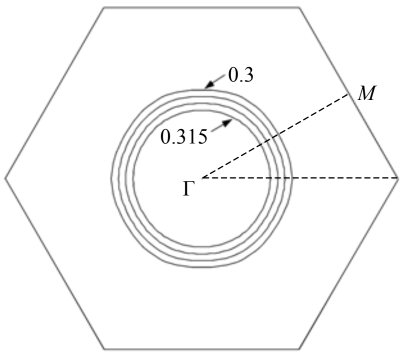

Fig.1 Equal frequency contours for the second band (E-polarization) of the 2D photonic crystal of negative refraction. The numbers mark the frequencies in unit of (c/a)

Fig.2 shows the novel design of our open-cavity consisting of three 60-degree wedges of negative refraction PC and three 60-degree wedges of air (in-between). The whole structure is designed in such a way that all the air-PC interfaces are normal to the Γ-M direction (to reduce the reflection at the air-PC interfaces). The simple ray-trace sketch for a close optical path in the inset of Fig.2 shows how such an open cavity may work (if the reflection at the interfaces is small). Fig.3 shows the spectral response (indicating the quality factor) and the resonant mode of the present open cavity [calculated with the finite difference time domain (FDTD) method (Taflove, 2000)]. The modal profile remains virtually the same when the total number of rows of air holes increases.

The present open cavity can be used as a biosensor. A small change of the refractive index of the measurand (filling the 3 air wedges) due to e.g. immobilized bio-molecules will cause a shift in the resonant wavelength (Fig.4), which can be measured by e.g. a wavemeter. Unlike a conventional PC cavity, the present open cavity has large air wedges into which a liquid measurand can flow easily (this makes the present open cavity more suitable for biosensing applications).

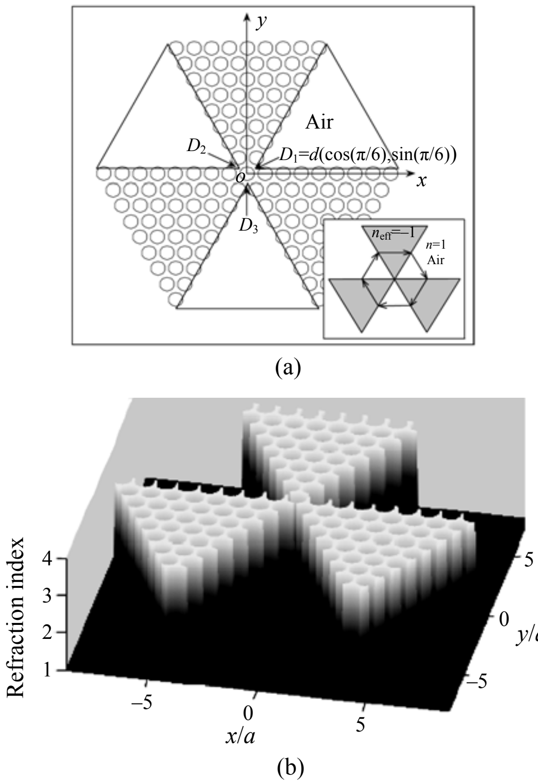

Fig.2 (a) The proposed open cavity formed by three 60-degree wedges of PC of negative refraction. The inset shows a ray-trace analysis for a closed optical path of the open cavity; (b) A 3D picture of the open-cavity

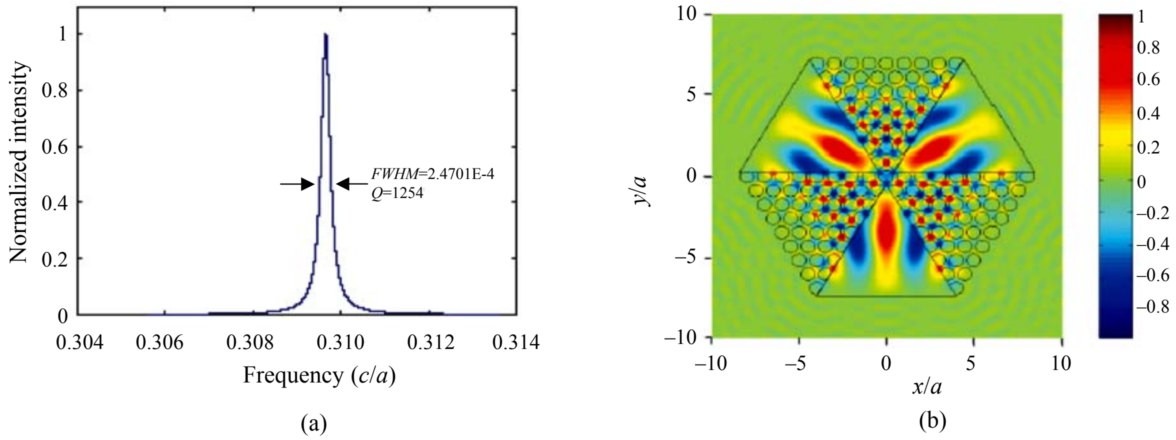

Fig.3 (a) The spectral response of the open-cavity; (b) The intensity distribution of the modal profile for the open-cavity at resonant frequency *f*=0.309657(*c/a*). Each PC wedge contains 9 rows of air holes

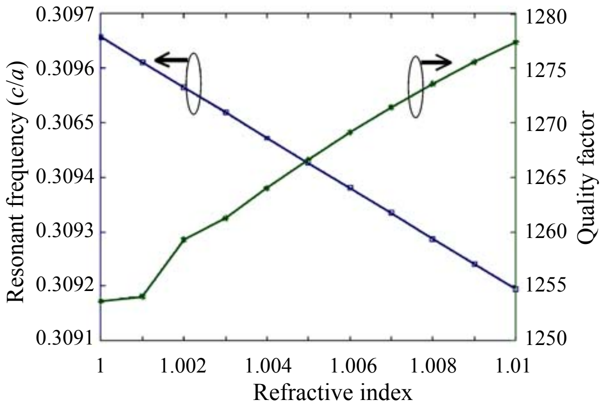

Fig.4 The resonant frequency and quality factor of the open cavity as the refractive index of the measurand (filling the 3 air wedges) varies slightly

In summary, we have introduced and designed a novel open cavity formed by a PC of negative effective refraction index. The present cavity is completely open, i.e., without any reflection (or reflective wall) in the radial direction. It is thus different from any partially opened resonator such as an open-ended enclosure or a resonator consisting of two concave mirrors facing each other. Due to the negative refraction and the high transmission at the PC/air interfaces, a closed path with zero optical path is formed for the resonance. To the best of our knowledge, such a realizable design for a completely open cavity is the first of its kind that has ever been reported in the literature. The present open cavity is more suitable for use as a biosensor as compared with a conventional PC cavity.

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