Features of a two-dimensional photonic crystal filled with resonance gas

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The band structure has been calculated for a two-dimensional photonic crystal consisting of infinite cylindrical openings filled with a resonance gas and forming a square lattice in a dielectric matrix. An additional narrow transmission band close to the edge of the band gap has been detected, along with an additional band gap in the continuous spectrum of the photonic crystal. The novel dispersion properties substantially depend on the fraction of resonance gas in the photonic crystal, as well as on the density of the resonance gas and the position of the resonance frequency relative to the edge of the band gap. © *2010 Optical Society of America*.

The spectral properties of a photonic crystal (PC) can be substantially varied by placing resonance media (atomic or molecular gases, quantum dots) inside the periodic structure. The easiest way to implement a one-dimensional resonance photonic crystal (RPC) is by means of layered structures that consist of alternating layers of two materials, one of which acts as a resonance gas. The most interesting RPCs are those in which the optical resonances of the materials are close to the Bragg frequencies of the lattice.[1–3] The combination of the resonance dispersion of the gas with the dispersion of the PC structure qualitatively changes the PC spectra, and narrow transmission bands appear in the photonic band gap (PBG), along with additional band gaps in the transmission spectrum of the PC structure.

This paper uses the method of expanding the eigenfunctions in plane waves to investigate the spectrum of *s*-polarized electromagnetic waves of a two-dimensional structure with a PBG, filled with a resonance gas. We shall consider an RPC consisting of infinite cylindrical openings filled with a resonance gas, whose intersections with the perpendicular *xy* plane form a square lattice in a dielectric matrix.

The structure of the RPC is characterized by the permittivities of the matrix, ε_1, and of the resonance gas, $\varepsilon_2(\omega)$. The permittivity of a gas is given in the Lorenz model by

$$\varepsilon_2 = 1 + \omega_p^2/(\omega_0^2 - \omega^2 + i\gamma\omega),$$

where $\omega_p^2 = 4\pi NFe^2/m$, e is the charge of the electron, m is the mass of the electron, N is the density of resonant atoms, F is the oscillator strength, γ is the line width, ω_0 is the central resonance frequency, and ω is the radiation frequency. The fill factor, i.e., the fraction of resonance gas in the PC, is defined by $f = \pi r^2/a^2$, where r is the radius of a cylinder and a is the period of the structure.

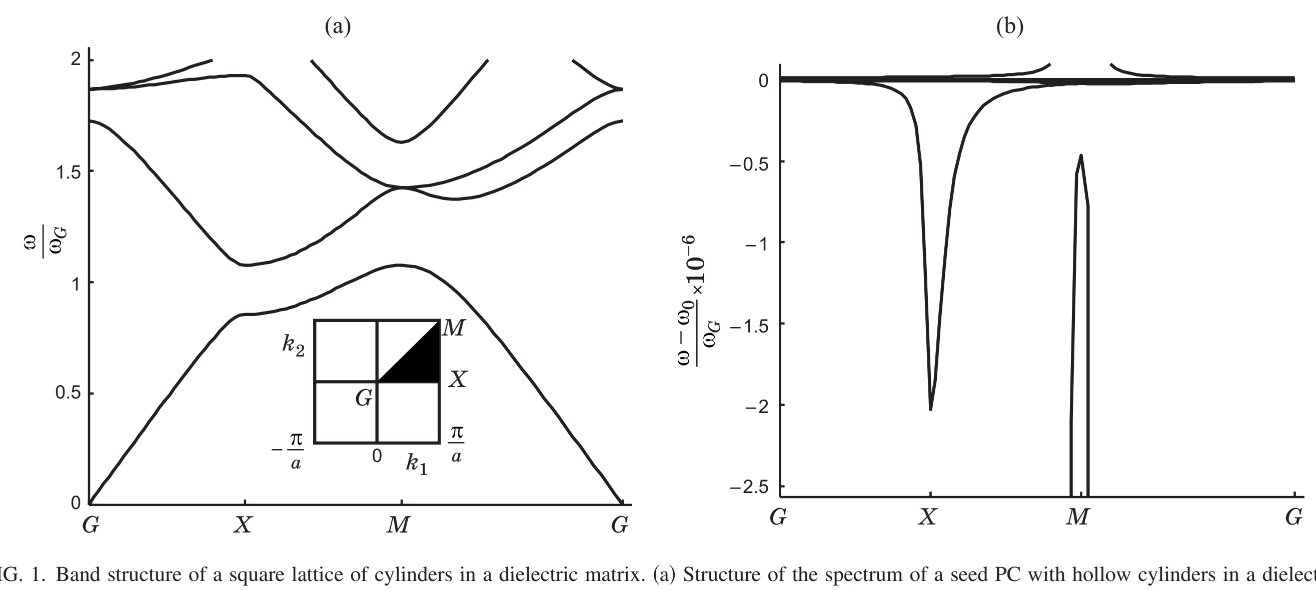

FIG. 1. Band structure of a square lattice of cylinders in a dielectric matrix. (a) Structure of the spectrum of a seed PC with hollow cylinders in a dielectric matrix, $\varepsilon_1 = 3.24$, $\varepsilon_2 = 1$. The inset shows the Brillouin zone with the nonconductive zone shaded. (b) Segment of the band structure in which the ratio of the resonance frequency and the parameters of the PC structure is $\omega_0/\omega_G = 1.071$, $f = 80\%$.

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Calculations were carried out first of all for an RPC with $\varepsilon_1=3.24$ and structural period $a=158$ nm. The fill factor is $f=80\%$, and the line width and plasma frequency of the resonance gas, taken to be close to their values for mercury vapor,[1] equal, respectively, $\gamma=2.19\times10^{-7}\omega_G$ and $(\omega_p)^2=9.5\times10^{-8}(\omega_G)^2$, where $\omega_G=\pi c n_G/a$ is the characteristic PBG frequency, and $n_G=f+(\varepsilon_1)^{1/2}(1-f)$ is the averaged refractive index of the medium. The resonance of the mercury atoms at a wavelength of $\lambda_0=253.7$ nm corresponds to the line width $\gamma=1.2$ GHz.

Figure 1 shows the band structure of the spectrum of the seed PC and a segment of the spectrum of an RPC with cylinders filled with resonance gas. For the seed PC, the PBG in the direction of Brillouin zone X lies in the frequency range ω/ω_G from 0.854 to 1.077 (Fig. 1a). The combination of the dispersion of the PC structure with the dispersion of the gas results in the appearance of additional band gaps in the continuous spectrum of the seed PC and additional narrow transmission bands in the PBG, which are negligible on the scale of Fig. 1a. These effects are illustrated in Fig. 1b. The widths $\Delta\omega=\omega-\omega_0$ of the additional band gaps and the transmission bands exceed the resonance line width γ by an order of magnitude.

When the fill factor f varies and the other parameters of the system remain constant, the boundaries of the PBG are displaced relative to the resonance frequency ω_0 of the gas. Even an insignificant change of the position of ω_0 relative to the band boundary can cause a substantial transformation of the additional transmission bands and the band gap. This effect is illustrated in Fig. 2.

It can be seen from a comparison of Fig. 2 with Fig. 1b that, as f decreases by 2%, i.e., to 78%, the resonance frequency ω_0 at point X recedes from the high-frequency edge of the band gap, and the width of the additional transmission band $\Delta\omega=\omega-\omega_0$ accordingly decreases by almost a factor of 4. At point M of the Brillouin zone, the width of the additional band gap decreases by a factor of 5. The width of the additional transmission band or band gap can be controlled

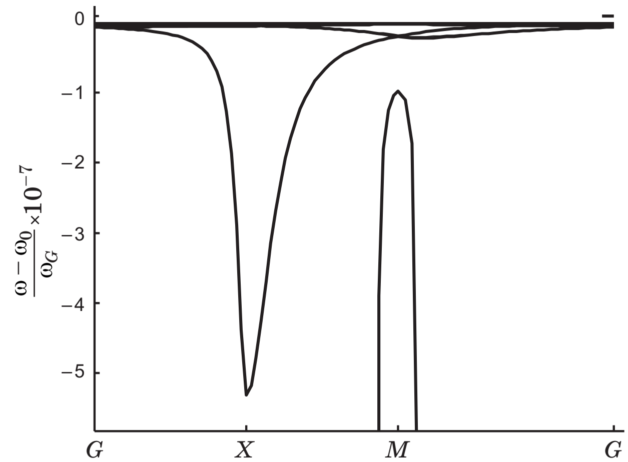

FIG. 2. Segment of the band structure in which the ratio is $\omega_0/\omega_G=1.056$, $f=78\%$. The other parameters are the same as in Fig. 1.

by varying the gas pressure. In the case of an impact broadening mechanism, these widths have a linear character of the pressure dependence.

The effects under consideration make it possible to extend the possibilities of creating new PCs with specified properties. Such RPCs can be promising for creating narrowband filters with high contrast of the optical radiation filtering and spectral prisms with increased dispersion.

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