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PHYSICAL AND QUANTUM OPTICS

Controlling Dispersion and Transmission Spectra of Hybrid Resonant-Gas-Filled Photonic-Crystal Optical Components

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Abstract—Using the model of an infinite one-dimensional periodic layered structure, we consider the possibilities of controlling dispersion properties and transmission spectra of hybrid optical components consisting of photonic band-gap structures filled with a resonant gas. It is shown that the combination of resonance-enhanced gas dispersion with the dispersion of a photonic band-gap structure may give rise to new features in the dispersion and transmission of hybrid spectral elements. These effects can be employed to create narrow-band filters and ultrarefractive prisms with controllable parameters. *© 2000 MAIK “Nauka/Interperiodica”.*

INTRODUCTION

Atomic and molecular resonance filters enable one to achieve high resolution in the discrimination of optical signals [1]. Currently, such spectral elements are widely employed for spectroscopic studies of gas media and diagnostics of luminous flows. The use of resonance filters under these conditions allows the informative signal to be selected from the luminescence background [2, 3]. In particular, as demonstrated by Finkelstein *et al.* [4], the use of absorption and subsequent refluorescence of a mercury vapor makes it possible to create a narrow-passband filter whose spectral resolution was sufficient to measure individual rotational Raman lines of nitrogen and oxygen and whose efficiency was sufficient to image gas flows. A useful application of resonance-enhanced dispersion of an atomic mercury vapor has been recently demonstrated by Finkelstein *et al.* [5], who proposed a new filtering technique for Raman imaging by creating a prism filled with mercury vapor, which provides a high spectral resolution in one dimension, keeping the high spatial resolution of imaging in the other dimension. This approach offers much promise for the imaging of Raman-active media, as strong elastic and Rayleigh-scattering components are efficiently suppressed by this prism due to the resonant absorption of mercury.

In this paper, we will demonstrate that the combination of resonance-enhanced dispersion of an atomic or molecular gas with the dispersion of a photonic band-gap (PBG) structure [6, 7] may give rise to new features in the dispersion and transmission of hybrid spectral elements based on PBG structures filled with a resonant gas. In particular, we will show that narrow passbands may appear in the photonic band gap and additional narrow stopbands may arise in the transmission band at the edge of the band gap. Such hybrid spectral components can be employed as narrow-band filters and highly dispersive prisms.

STRUCTURES WITH HYBRID DISPERSION

The idea of combining the dispersion of a resonant gas and a PBG structure implies that a resonant gas (or, generally, a medium with a resonance-enhanced dispersion) is introduced into a periodic structure. This can be done, for example, with nanochannel glass samples similar to those that have been recently employed in nonlinear-optical experiments on optical limiting [8]. The generic two-dimensional hybrid PBG structure is shown in Fig. 1. It consists of a matrix made of a material with a constant refractive index n_1 and periodically arranged holes, which can be filled with a gas or some other dispersive material with a refractive index $n_2(\omega)$. Obviously, the rigorous two-dimensional analysis of such hybrid PBG structures requires numerical simulations. Such simulations can be accomplished, for example, by direct integration of Maxwell’s equations with the use of the finite-difference time-domain technique [9], allowing not only the spectral properties of such PBG structures to be understood, but also the propagation of short light pulses to be investigated [10] and the electromagnetic-field distribution in such structures to be calculated [11, 12]. However, the basic physics behind the filtering and refraction of light in such hybrid-dispersion structures, allowing the creation of a new class of spectral components, can be illustrated in terms of a simple model of an infinite one-dimensional periodic structure consisting of alternating layers with refractive indices n_1 and $n_2(\omega)$.

NARROW-BAND FILTERS

In this section, we will examine the possibility of creating narrow-band filters based on resonant-gas-filled PBG structures by considering a model of an infinite one-dimensional PBG structure consisting of alternating layers with thicknesses a and b and refractive indices n_1 and n_2. The dispersion relation for such a structure is given by the well-known formula [13]

$$\cos(Kd) = \cos\left(\frac{\omega}{c}n_1 a\right)\cos\left(\frac{\omega}{c}n_2 b\right) - \frac{n_1^2+n_2^2}{2n_1 n_2}\sin\left(\frac{\omega}{c}n_1 a\right)\sin\left(\frac{\omega}{c}n_2 b\right), \qquad (1)$$

where K is the Bloch wave number, ω is the radiation frequency, c is the speed of light, and $d = a + b$ is the constant of the one-dimensional lattice.

The resonant gas dispersion can be plugged in dispersion relation (1) through some model of a gas dispersion. We will assume that the line shape in the case under study can be approximated with a Lorentzian contour:

$$n_2 = 1 - F\frac{\omega^2 - \omega_0^2}{(\omega^2-\omega_0^2)^2 + \omega^2\gamma^2}, \qquad (2)$$

where $F = (e^2/2m)(Nf/\varepsilon_0)$, e is the electron charge, m is the electron mass, N is the number density of resonant atoms, f is the oscillator strength, ε_0 is the dielectric permittivity, γ is the line width, and ω_0 is the central frequency of the resonance.

Note that the main restrictions of the considered model are associated with the fact that such a model includes neither diffraction effects, which sometimes may be very important (e.g., see [11, 12]), nor effects due to the lattice geometry. The main advantage of this model is that it provides some useful insight into dispersion and transmission properties of hybrid gas-filled PBG structures, giving a qualitative understanding of how a new class of optical components with a tunable dispersion can be created.

Figure 2 shows the real part of the effective refractive index $n_{\text{eff}} = Kc/\omega$ of a one-dimensional PBG structure with $a/d = b/d = 0.5$, $n_1 = 1.8$, and $n_2 = 1$ as a function of the frequency ω normalized to the characteristic band-gap frequency

$$\omega_G = \frac{c\pi}{d\bar{n}}, \qquad (3)$$

where $\bar{n} = (n_1 a + n_2 b)/d$.

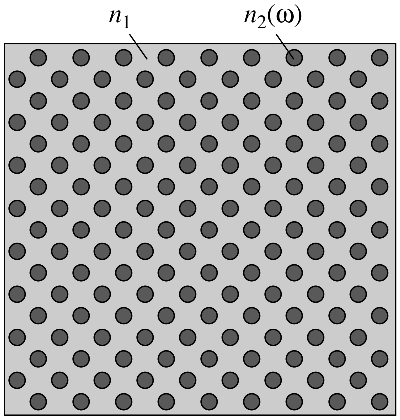

Fig. 1. Top view of a generic hybrid two-dimensional PBG structure consisting of a matrix made of a material with a constant refractive index n_1 and periodically arranged holes filled with a gas with a refractive index $n_2(\omega)$.

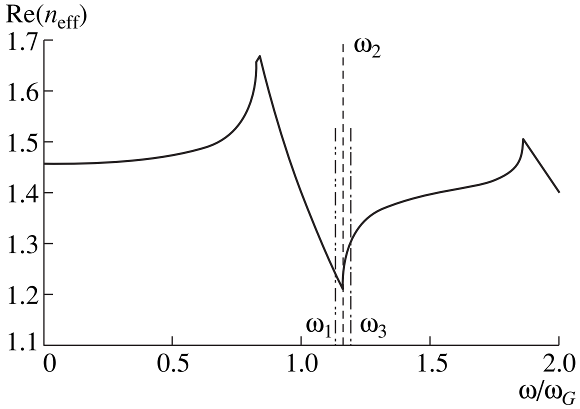

Fig. 2. The real part of the effective refractive index for a one-dimensional PBG structure with $a/d = b/d = 0.5$, $n_1 = 1.8$, and $n_2 = 1$ as a function of the frequency ω normalized to the characteristic band-gap frequency ω_G. The frequencies ω_1, ω_2, and ω_3 correspond to the gas-dispersion-induced transmission peak in the band gap (Fig. 3a), the right-hand edge of the band gap, and the gas-dispersion-induced stopband (Fig. 3b) of a hybrid PBG structure, respectively.

In what follows, we will employ the dimensionless frequency and dimensionless layer thicknesses of a PBG structure to make our notation more compact and general. This notation also allows a convenient scaling of the results of our analysis for arbitrary frequencies and geometric sizes. Formula (3) relates dimensionless parameters to physical ones, providing an estimate on the period of the structure once some characteristic wavelength is given. In particular, the resonant enhancement of dispersion of a PBG structure can be achieved through the use of a 253.7-nm line of mercury

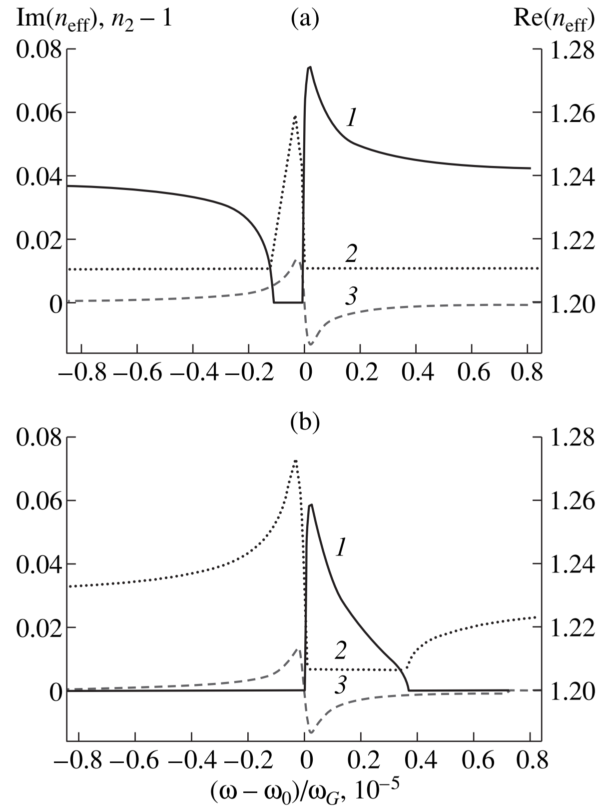

Fig. 3. (*1*) The imaginary and (*2*) real parts of the effective refractive index for an infinite one-dimensional PBG structure with a resonant gas and (*3*) the refractive index of the resonant gas as functions of the detuning of the frequency ω from the resonance frequency of the gas normalized to the characteristic frequency ω_G of the photonic band gap for (a) $\omega_0/\omega_G = 1.15642$ and $\gamma/\omega_G = 4.5 \times 10^{-7}$ and (b) $\omega_0/\omega_G = 1.16043$ and $\gamma/\omega_G = 4.5 \times 10^{-7}$.

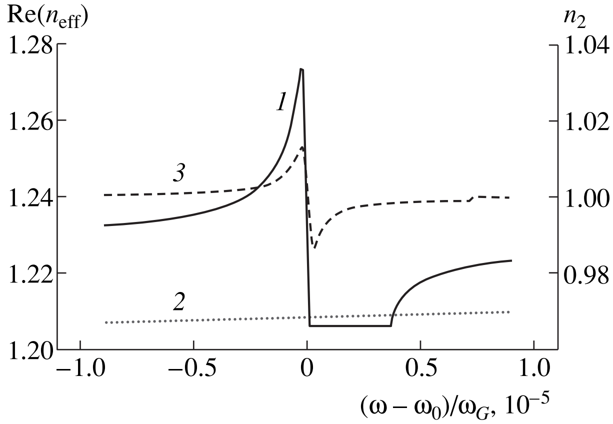

Fig. 4. The frequency dependences of the real part of the effective refractive index for an infinite one-dimensional PBG structure with $a/d = b/d = 0.5$ and $n_1 = 1.8$ (*1*) with and (*2*) without a resonant gas and (*3*) for the resonant gas with $\omega_0/\omega_G = 1.16043$, $\gamma/\omega_G = 4.5 \times 10^{-7}$, and $F/(\omega_G)^2 = 7 \times 10^{-8}$.

atoms, employed in experiments [4, 5], when the characteristic period of the PBG structure is $d \approx 105$ nm. Obviously, atomic or molecular resonances with longer wavelengths can also be used, leading to less stringent requirements on the period of the PBG structure.

Importantly, the change in the refractive index of a resonant gas is very sharp on the frequency scale (for realistic F, the changes in the dispersion of the structure are not visible on the frequency scale of Fig. 2). In particular, the line width γ of the 253.7-nm resonance of mercury atoms is about 1.2 GHz at the temperature of mercury vapor of 190°C and the pressure of 6.3 Torr [5]. With such abrupt changes in the refractive index of a gas, the steepness of the band-gap edge can be controlled by varying the pressure of the gas or by tuning the frequency of the band-gap edge with respect to the central frequency of an atomic or molecular resonance, thus allowing high-contrast filtering of optical signals.

Figure 3a shows how the resonance-enhanced gas dispersion described by expression (2) with $\omega_0/\omega_G = 1.16043$, $\gamma/\omega_G = 4.5 \times 10^{-7}$, and $F/(\omega_G)^2 = 7 \times 10^{-8}$ changes the dispersion of an infinite one-dimensional PBG structure. As can be seen from Fig. 3a, a narrow passband may arise in the band gap of such a structure in the range where the imaginary part of the effective refractive index vanishes (at the point ω_1 in Fig. 2). The width of this transmission peak is comparable with the width of the resonance line, but the contrast of light filtering achieved with such a passband may be very high, since the transmission peak is observed within the band gap, where the attenuation of light is extremely high everywhere except for this gas-dispersion-induced passband.

Along with transmission peaks in the band gap, the combination of the resonance-enhanced gas dispersion with the dispersion of a PBG structure may give rise to additional stopbands on the edge of the main band gap of the structure in the area where the effective refractive index becomes complex in Fig. 3b (at the point ω_3 in Fig. 2). Similar to passbands arising in the main band gap, the width of this additional stopband can be controlled by varying the gas pressure and parameters of the structure. The new features arising in the dispersion of gas-filled PBG structures can be employed for the creation of narrow-stopband and narrow-passband tunable filters.

HIGHLY DISPERSIVE PRISMS

The fact that two-dimensional PBG structures can be employed for the creation of ultrarefractive prisms in the radio-frequency range has been demonstrated by Lin *et al.* [14]. Recent experiments [8], which were devoted to optical limiting in two-dimensional PBG structures made of nanochannel glass plates, exhibiting a photonic band gap in the range from 500 to 600 nm, show the way to extend the concept of ultrarefractive PBG prisms to the optical range. These prospects

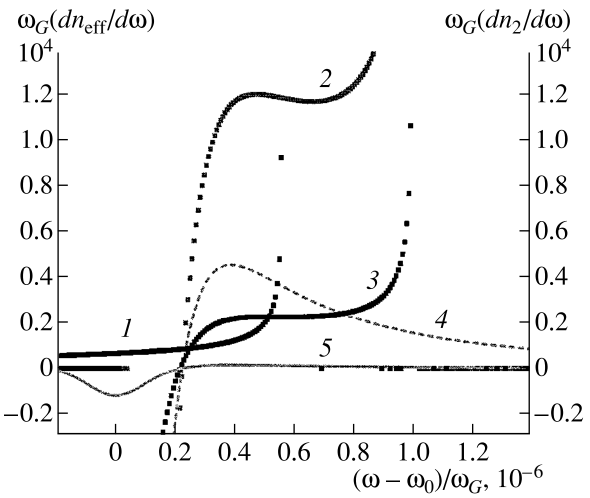

Fig. 5. The frequency dependences of the frequency derivatives (the frequency variable is normalized to the characteristic frequency ω_G of the photonic band gap) of the effective refractive index of the considered infinite one-dimensional PBG structure $\left(\omega_G \frac{dn_{\text{eff}}}{d\omega}\right)$ (*1–3*) with $a/d = b/d = 0.5$ and $n_1 = 1.8$ (*1*) without and (*2, 3*) with a resonant gas and (*4, 5*) the refractive index of the resonant gas $\left(\omega_G \frac{dn_2}{d\omega}\right)$ for (*2, 4*) $\omega_0/\omega_G = 0.82855$ and (*1, 3, 5*) 0.82847, (*2, 4*) $F/(\omega_G)^2 = 1.5 \times 10^{-8}$ and (*3, 5*) 5×10^{-10}, and (*2–5*) $\gamma/\omega_G = 4.5 \times 10^{-7}$.

become even more exciting if we think of the opportunity of combining the dispersion of a PBG structure with the resonant dispersion of a gas, which would allow the refractive properties of a PBG prism to be enhanced within a narrow spectral range and the dispersion of such a hybrid optical component to be tuned in a controllable way by, e.g., changing the gas pressure. To qualitatively illustrate the way a gas-filled two-dimensional PBG prism can be used for this purpose, we will again employ, similar to [14] and the previous section of this paper, a model of an infinite one-dimensional PBG structure.

Figure 4 shows the frequency dependences of the real part of the refractive index for an infinite one-dimensional PBG structure with (curve *1*) and without (curve *2*) a resonant gas. The frequency dependence of the refractive index for the resonant gas is also shown for comparison by curve *3* in this figure. Figure 5 displays the frequency dependences of the frequency derivative of the effective refractive index of the considered infinite one-dimensional PBG structure without (curve *1*) and with (curves *2*, *3*) a resonant gas, as well as the frequency derivative of the refractive index of the resonant gas (curves *4*, *5*). As can be seen from the plots presented in Figs. 4 and 5, gas-filled PBG structures allow the dispersion to be enhanced within a rather broad spectral range, opening the way for a substantial improvement of the spectral resolution with respect to the spectral resolution attainable with either a PBG structure or a conventional prism filled with a resonant gas. Dispersive properties of such spectral elements can be tuned through the variation of the gas pressure and parameters of the PBG structure. The possibility of actively tuning the dispersion relation, which was illustrated above, holds much promise for various applications, including the compression of light pulses and the control of phase matching in nonlinear-optical interactions. In particular, the dependences shown by curves *2* and *3* in Fig. 5 correspond to a hybrid spectral element where parameters of the gas and the PBG structure are chosen in such a way as to ensure a linear dispersion relation within a very broad spectral range, which would never be possible to achieve with a PBG structure without a gas (curve *1* in Fig. 5) or a resonant gas alone (curves *4* and *5* in Fig. 5).

CONCLUSIONS

Thus, the qualitative analysis of the properties of hybrid-dispersion structures within the framework of a simple model of an infinite one-dimensional PBG structure shows that the combination of resonance-enhanced dispersion of an atomic or molecular gas with the dispersion of a photonic band-gap structure may give rise to new features in the dispersion and transmission of a hybrid gas-filled PBG system, which are of interest from the physical point of view and which can be employed to improve the parameters of optical components. In particular, the enhancement of the dispersion of gas-filled PBG structures and the appearance of narrow pass- and stopbands in transmission spectra of such structures offer much promise for creating highly dispersive prisms and narrowband filters. Transmissive and dispersive properties of such hybrid optical components can be tuned in a controllable way by varying the gas pressure and by scanning the photonic band gap with respect to the frequency of the atomic or molecular resonance in a gas.

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