All-pass transmission or flattop reflection filters using a single photonic crystal slab

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(Received 29 December 2003; accepted 21 April 2004; published online 25 May 2004)

We show that a single photonic crystal slab can function either as optical all-pass transmission or flattop reflection filter for normally incident light. Both filter functions are synthesized by designing the spectral properties of guided resonance in the slab. The structure is extremely compact along the vertical direction. We expect this device to be useful for optical communication systems. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1763221]

Compact optical filter structures are of great interest for optical communication applications. In particular, optical all-pass transmission filters, which generate significant delay at resonance, while maintaining 100% transmission both on and off resonance, are useful for applications such as optical delay or dispersion compensation.[1,2] Also, flattop reflection filters, which completely reflect a narrow range of wavelengths while letting other wavelengths pass through, are important for channel selection in wavelength-division multiplexing systems.[3]

Guided resonances in photonic crystal slabs[4–11] provide a very compact way to generate useful spectral functions for externally incident light. An example of a photonic crystal slab consists of a periodic array of air holes introduced into a high index dielectric slab, as shown in Fig. 1(a). Wang and Magnusson showed that a slab can function as a notch filter with a Lorentzian reflection line shape, when the slab thickness is appropriately chosen and a single resonance is placed within the vicinity of the signal frequency.[12] Based upon guided resonance effects, a number of novel spectral filters have been proposed.[13–17] It was recently shown that by coupling two photonic slabs together, all-pass transmission or flattop reflection could be synthesized.[18] In this letter, we show that a *single photonic crystal slab* can function either as an all-pass transmission filter or as a flattop reflection filter, thus providing an extremely compact way of generating useful filter functions, and further demonstrating the versatility of photonic crystal structures.

To generate either an all-pass transmission or narrowband reflection filter functions, one will need to have two resonant modes in the vicinity of the signal frequencies, which possess opposite symmetry with respect to the mirror plane perpendicular to the propagating direction.[18] In the photonic crystal slab as shown in Fig. 1(a), the resonant modes required are provided by the guided resonances. A guided resonance originates from the guided modes in a uniform dielectric slab, and is therefore strongly confined within the slab. And yet the periodic index contrast provides the phase matching mechanisms that allow these modes to couple into free space radiations in the vertical direction. Since a dielectric slab structure supports TE or TM guided modes that are even or odd with respect to the mirror plane at the center of the slab, a guided resonance could also be designed to have either even or odd symmetry. By appropriately choosing the structural parameters, it is then possible to place both an even resonance and an odd resonance in the vicinity of the signal frequency.

The transmission properties of a photonic crystal slab for externally incident light are determined by a Fano interference between a direct and an indirect transmission pathway.[19] In a direct pathway, the incident light passes through the slab without exciting the guided resonance. In an indirect pathway, the incident light first excites the guided resonance. The power in the resonance then slowly decays into the free space. For a structure with two resonances, such interference effects can be described by a theoretical model, schematically shown in Fig. 1(b). This model is based upon coupling of modes in a time-dependent formalism for optical resonators, which is generally valid when the quality factor of the resonance is high:[20]

$$\frac{da_{\text{even}}}{dt} = (j\omega_{\text{even}} - \gamma_{\text{even}})a_{\text{even}} + j\sqrt{\gamma_{\text{even}}}s_{1+} + j\sqrt{\gamma_{\text{even}}}s_{2+}, \tag{1}$$

$$\frac{da_{\text{odd}}}{dt} = (j\omega_{\text{odd}} - \gamma_{\text{odd}})a_{\text{odd}} + j\sqrt{\gamma_{\text{odd}}}s_{1+} - j\sqrt{\gamma_{\text{odd}}}s_{2+}, \tag{2}$$

$$s_{1-} = s_{2+} + j\sqrt{\gamma_{\text{even}}}a_{\text{even}} + j\sqrt{\gamma_{\text{odd}}}a_{\text{odd}}, \tag{3}$$

$$s_{2-} = s_{1+} + j\sqrt{\gamma_{\text{even}}}a_{\text{even}} - j\sqrt{\gamma_{\text{odd}}}a_{\text{odd}}. \tag{4}$$

Here a_{even} and a_{odd} are the amplitudes in the even and odd resonances, respectively. ω_{even} and ω_{odd} represent their frequencies, and γ_{even} and γ_{odd} are their decay rates. The outgoing wave amplitude, s_{1-} or s_{2-}, each consists of a sum of a direct term that is equal to the incoming wave amplitude, s_{1+} or s_{2+}, and two indirect terms that are proportional to the amplitudes of even and odd resonances a_{even} and a_{odd}. The indirect terms describe the decay of the resonances [Eqs. (3) and (4)]. In the direct terms, we assume that the partial transmission coefficient through the slab is unity. This is important for creating both all-pass transmission and flattop reflection filter characteristics, and can be accomplished by choosing an appropriate optical thickness of the slab.[12] We note that the indirect terms from a_{even} and a_{odd} are of

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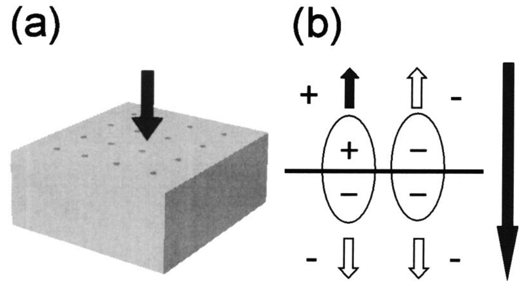

FIG. 1. (a) Schematic of a photonic crystal filter consisting of a single photonic crystal slab. The arrow represents the direction of the incident light. The radius of air holes is $0.12a$, and the thickness is $2.05a$, where a is the lattice constant. (b) Schematic of a theoretical model for a resonator system that supports two resonant states with opposite symmetry with respect to the mirror plane perpendicular to the incident light.

opposite signs due to the different symmetry properties of the modes. Using this model, the transmission coefficient through the slab can be calculated as

$$t=1-\frac{\gamma_{\mathrm{even}}}{(j\omega-j\omega_{\mathrm{even}}+\gamma_{\mathrm{even}})}-\frac{\gamma_{\mathrm{odd}}}{(j\omega-j\omega_{\mathrm{odd}}+\gamma_{\mathrm{odd}})}. \quad (5)$$

When the condition of an accidental degeneracy is satisfied, i.e., $\gamma_{\mathrm{even}}=\gamma_{\mathrm{odd}}=\gamma$, $\omega_{\mathrm{even}}=\omega_{\mathrm{odd}}=\omega_o$, the transmission coefficient becomes

$$t=\frac{j(\omega-\omega_o)-\gamma}{j(\omega-\omega_o)+\gamma}, \quad (6)$$

and the structure behaves as an all-pass filter. The amplitudes of the transmission are unity both on and off resonance, while the phase goes through a very rapid change from 0 to 2π in the vicinity of the resonance, and thus gives rise to a strong resonant delay. On the other hand, when $\gamma_{\mathrm{even}}=\gamma_{\mathrm{odd}}=\gamma$, $|\omega_{\mathrm{even}}-\omega_{\mathrm{odd}}|=2\gamma$, the transmission becomes

$$|t|^2=\frac{(\omega-\omega_o)^4}{(\omega-\omega_o)^4+4\gamma^4}, \quad (7)$$

where $\omega_o=(\omega_{\mathrm{even}}+\omega_{\mathrm{odd}})/2$. The structure shows flat-top reflection characteristics, with a narrow range of frequency in the vicinity of ω_o completely reflected, while all other frequencies are passing through. Therefore, depending on the choice of ω_{even}, ω_{odd}, γ_{even}, and γ_{odd}, the transmission coefficient in Eq. (5) exhibits either all-pass transmission or flattop reflection filter characteristics.

Both filter characteristics can be physically realized in the single slab structure as shown in Fig. 1(a). In a finite-difference time-domain (FDTD) simulation,[21] we excite the resonant modes by a pulse of a normally incident plane wave. The line shapes of even and odd modes can then be obtained by Fourier-transforming the temporal decay of the resonance amplitudes. When the structure is chosen to have a thickness of $2.05a$ where a is the lattice constant, a radius of air holes of $0.12a$, and a dielectric constant of 10.07, which corresponds to that of AlGaAs in optical frequencies,[22] both the even and odd mode have the same frequency and widths as shown in Fig. 2(a). The transmission spectrum therefore shows near 100% transmission over the entire bandwidth both on and off resonance as can be seen in Fig. 2(b), while a large resonant delay is generated in the vicinity of the resonant frequency [Fig. 2(c)]. To compare the simulation

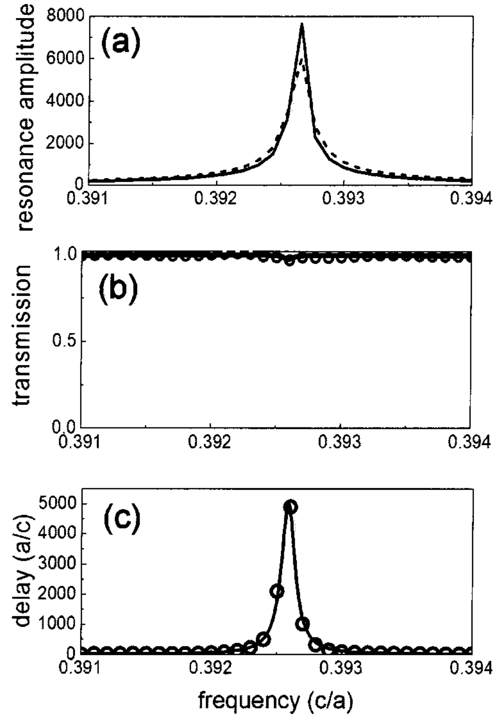

FIG. 2. Spectral response functions for the one slab structure shown in Fig. 1(a) with a dielectric constant of 10.07. (a) The spectra of resonance amplitudes for the even mode (dashed line) and the odd mode (solid line). (b) Transmission spectrum for normally incident light. (c) Group delay spectrum. In both (b) and (c), the solid line represents the theory and the open circles correspond to FDTD simulations.

results with the theoretical analysis, we extract the parameters from Fig. 2(a) and generate the theoretical spectra by using Eq. (5). We see excellent agreement between the simulation and the theory [Figs. 2(b) and (c)]. The peak delay of $5000(a/c)$ corresponds to 10.14 ps, when the operating wavelength is at 1550 nm. For such a delay, the structure is only 1.2 μm thick.

A flattop reflection filter can also be designed in a single photonic crystal slab, by choosing a different set of either structural or dielectric parameters. For simplicity, we fix the thickness and the radius of air holes, and vary only the dielectric constant. Our simulations show that the frequency of the even and odd mode varies with the dielectric constant in a different fashion, while the width of the resonance is largely insensitive to the dielectric constant (Fig. 3). Therefore, by choosing the dielectric constant to 10.9 (which is still accomplishable using AlGaAs with a different aluminum content), we obtain the flattop behavior as seen in Fig. 4. Again, the simulation shows excellent agreement with the

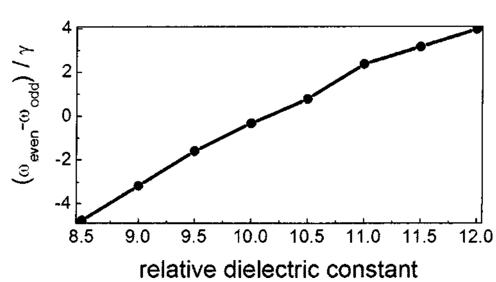

FIG. 3. Difference of the resonance frequencies for even and odd modes normalized by the decay rate as a function of the slab dielectric constant, for the structure shown in Fig. 1(a).

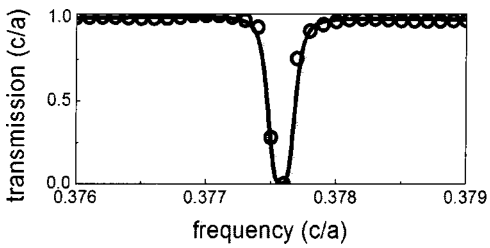

FIG. 4. Transmission spectrum for normally incident light upon the structure in Fig. 1(a), when the dielectric constant is 10.9. Solid line represents the theory and the open circles are FDTD simulations.

theoretical prediction, generated using a similar procedure as outlined previously.

We note that the all-pass filter proposed here can be readily cascaded to create optical delay lines since the filter operates in a transmission mode. In such an optical delay line, it has been shown that the maximum capacity is inversely related to the dimension of each stage.[23] Consequently, our filter structure, which is extremely compact, is useful for increasing the capacity of such delay lines. Also, unlike many single-mode integrated optical devices, both filter structures proposed here couple easily with optical fibers, since the mode of a fiber is typically far larger than the periodicity of the crystal. With a square lattice, at normal incidence the structure possesses a C_{4v} symmetry.[24] Consequently the spectral functions are inherently polarization independent, which is required for most communication applications. Polarization-selective dispersion characteristics, on the other hand, can also be readily designed by simply choosing a crystal lattice with less symmetry. Finally, these structures are far more compact than conventional multilayer thin film devices commonly used, where the use of up to 100 dielectric layers is often required to accomplish a Q-factor of a few thousands with a desired line shape. We therefore expect these compact devices to be useful in optical communication systems.

This work was partially supported by the US Army Research Laboratories under Contract No. DAAD17-02-C-0101, and by the National Science Foundation (NSF) Grant No. ECS-0200445. The computational time was provided by the NSF NRAC program.

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