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

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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. 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.

Guided resonances in photonic crystal slabs 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. Based upon guided resonance effects, a number of novel spectral filters have been proposed. It was recently shown that by coupling two photonic slabs together, an all-pass transmission or flattop reflection could be synthesized. 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 frequency, which possess opposite symmetry with respect to the mirror plane perpendicular to the propagating direction. 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 propagation of light in the vertical direction. We expect this device to be useful for optical communication systems.
corresponds to that of AlGaAs in optical frequencies, both air holes of 0.12 \( a \) thickness of 2.05 \( a \) resonance amplitudes. When the structure is chosen to have a resonant modes by a pulse of a normally incident plane wave as shown in Fig. 2 the even and odd mode have the same frequency and widths in the vicinity of the reflection characteristics, with a narrow range of frequency in \( v \) the phase goes through a very rapid change from 0 to \( 2\pi \) in the vicinity of the resonance, and thus gives rise to a strong resonant delay. On the other hand, when \( \gamma_{\text{even}} = \gamma_{\text{odd}} = \gamma \), \( \omega_{\text{even}} = \omega_{\text{odd}} = \omega_0 \), the transmission coefficient becomes
\[
|t|^2 = \frac{(\omega - \omega_0)^4}{(\omega - \omega_0)^4 + 4 \gamma^4},
\]
where \( \omega_0 = (\omega_{\text{even}} + \omega_{\text{odd}})/2 \). The structure shows flat-top reflection characteristics, with a narrow range of frequency in the vicinity of \( \omega_0 \) completely reflected, while all other frequencies are passing through. Therefore, depending on the choice of \( \omega_{\text{even}}, \omega_{\text{odd}}, \gamma_{\text{even}}, \) and \( \gamma_{\text{odd}} \), the transmission coefficient in Eq. (5) exhibits either all-pass transmission or flat-top 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, 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 2.05\( a \) where \( a \) is the lattice constant, a radius of air holes of 0.12\( a \), and a dielectric constant of 10.07, which corresponds to that of AlGaAs in optical frequencies, 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 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 \( \mu \)m thick.

A flat-top 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
incidence the structure possesses a periodicity of the crystal. With a square lattice, at normal incidence 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.

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