Channel drop filters in photonic crystals

Shanhui Fan, P. R. Villeneuve, J. D. Joannopoulos

Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139 USA

shanhfan@mit.edu

H. A. Haus

Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, MA 02139 USA

Abstract: We present a general analysis of channel drop filter structures composed of two waveguides and an optical resonator system. We show that 100% transfer between the two waveguides can occur by creating resonant states of different symmetry, and by forcing an accidental degeneracy between them. The degeneracy must exist in both the real and imaginary parts of the frequency. Based on the analysis we present novel photonic crystal channel drop filters. Numerical simulations demonstrate that these filters exhibit ideal transfer characteristics.

OCIS code: (060.1810) Couplers, switches, and multiplexers; (230.3990) Microstructure devices

References and links

1. R. Adar, C. H. Henry, C. Dragone, R. C. Kistler, and M. A. Milbrodt, "Broad-band array multiplexers made with silica waveguides on silicon," J. Lightwave Technol. **11**, 212 (1993).
2. H. A. Haus and Y. Lai, "Narrow-band optical channel-dropping filter," J. Lightwave Technol. **10**, 57 (1992).
3. B. E. Little, S. T. Chu, H. A. Haus, J. Foresi, and J. -P. Laine, "Microring resonator channel dropping filters," J. Lightwave Technol. **15**, 998 (1997).
4. B. E. Little, S. T. Chu, and H. A. Haus, "Estimated surface roughness loss and output coupling in microdisk resonators," Opt. Lett. **21**, 1390 (1996).
5. P. R. Villeneuve, S. Fan, and J. D. Joannopoulos, "Microcavities in photonic crystals: mode symmetry, tunability and coupling efficiency," Phys. Rev. B **54**, 7837 (1996).
6. S. Fan, P. R. Villeneuve, and J. D. Joannopoulos, "Theoretical investigation of fabrication-related disorder on the properties of photonic crystals," J. Appl. Phys. **78**, 1415 (1995).
7. S. Fan, P. R. Villeneuve, J. D. Joannopoulos and H. A. Haus, "Channel drop tunneling through localized states," Phys. Rev. Lett. **80**, 960 (1998).
8. S. Fan, P. R. Villeneuve, J. D. Joannopoulos and H. A. Haus (unpublished).
9. For a review, see K. S. Kunz and R. J. Luebbers, *The finite-difference time-domain methods* (CRC Press, Boca Raton, 1993).
10. J. C. Chen and K. Li, "Quartic perfectly matched layers for dielectric waveguides and gratings," Microw. Opt. Technol. Lett. **10**, 319 (1995).

1. Introduction

The increasing interest in photonic integrated circuits (PIC's) and the increasing use of all-optical fiber networks as backbones for global communication systems have been based in large part on the extremely wide optical transmission bandwidth provided by dielectric materials. This has accordingly led to an increase demand for the practical utilization of the full optical bandwidth available. In order to increase the aggregate transmission bandwidth, it is generally preferred that the spacing of simultaneously transmitted optical data streams, or optical data channels, be closely packed to accommodate a larger number of channels. In other words, the difference in wavelength between two adjacent channels is preferably minimized.

Channel dropping filters (CDF's) that access one channel of a wavelength division mul-

#4489 - $15.00 US
Received February 02, 1998; Revised April 28, 1998

tiplexed (WDM) signal while leaving other channels undisturbed are essential components of PIC's and optical communication systems. Among various devices introduced recently [1-3], resonant filters are attractive candidates for channel dropping because they can potentially be used to select a single channel with a very narrow linewidth. The schematic of a resonant-cavity CDF is shown in Figure 1, where two waveguides, the *bus* and the *drop*, are coupled through an optical resonator system. While WDM signals (i.e. multi-frequency signals) propagate inside one waveguide (the bus), a single frequency-channel is transferred out of the bus and into the other waveguide (the drop) either in the forward or backward propagation direction, while completely prohibiting cross talk between the bus and the drop for all other frequencies.

The performance of a CDF is determined by the transfer efficiency between the two waveguides. Perfect efficiency corresponds to 100% transfer of the selected channel into either the forward or backward direction in the drop, with no forward transmission or backward reflection into the bus. All other channels should remain unaffected by the presence of the optical resonator system.

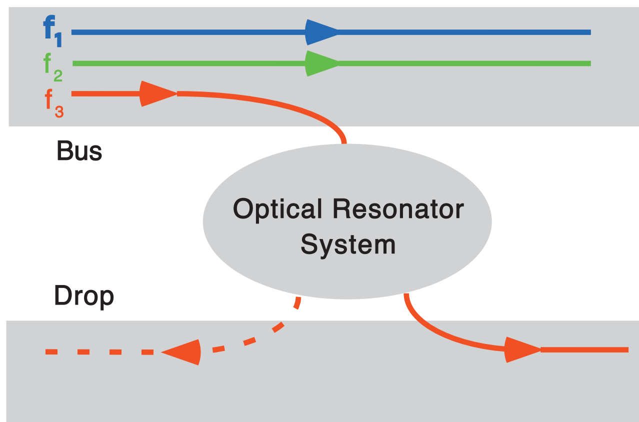

Figure 1. Schematic of a generic resonant-cavity channel drop filter.

A promising design of a CDF has been introduced recently using ring cavities as a resonant filter[3]. In such a geometry, the forward propagating wave in the bus excites a rotating mode in the ring, which in turn couples into the backward propagating mode in the drop. Ideally, at resonance, 100% transfer can be achieved. However, radiation losses inside the ring have the effect of reducing the transfer efficiency. Furthermore, the ring resonator supports multiple resonances. While mode spacing can be enlarged by further reducing the size of the ring, radiation losses increases exponentially as the radius of the ring decreases.

A multiple-ring design has also been proposed as a way to increase the free spectral range, which measures the mode spacing between the frequency channels [3]. Each ring has a different radius, and supports a different set of resonant frequencies. Maximum transfer occurs only when the resonant frequencies of both rings match with each other. Although the multiple-ring geometry can increase the free spectral range of the CDF, the transfer efficiency suffers severe reduction.

In addition to the multimode nature of a ring cavity, the quality factor is limited by intrinsic radiation losses and degrades significantly with even a moderate amount of surface roughness [4]. In contrast to ring cavities, photonic crystal microcavites do not suffer from intrinsic radiation losses [5], can be truly single mode [5], and are somewhat insensitive to fabrication-related disorder [6]. It is therefore of great practical interest to explore the possibilities of using photonic crystal microcavities in a channel drop filter.

The analysis of ring filters is usually based on the idea of phase-matched coupling between rotating waves in the ring and propagating modes in the waveguide [3]. Such an analysis is correct only in the limit where the dimensions of the ring are much larger than the wavelength of light. For wavelength-size devices such as a photonic crystal microcavity, the cavity modes in general can no longer be characterized as propagating states, and the idea of phase-matching coupling ceases to be valid. In this paper, we present an analysis of a generic resonant-cavity channel drop filter. We show that complete transfer can occur by creating resonant states of different symmetry, and by forcing an accidental degeneracy between them. The degeneracy must exist in both the real and the imaginary part of the frequency. Based on this analysis we discuss several channel drop filter structures using photonic crystal microcavities. The response of these structures are simulated using a finite-difference time-domain approach. The results of the simulation demonstrate near-ideal transfer characteristics.

2. Analysis

We start by discussing a filter structure in which the optical resonator system supports only one resonant state. We perform the gedanken experiment where we excite a propagating state in the bus waveguide and study how it is affected by the resonant state. At resonance, the propagating state excites the resonant mode, which in turn decays into both waveguides along the forward and backward directions, as illustrated in Figure 2. The reflected amplitude in the bus waveguide

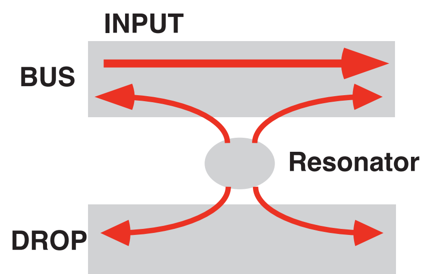

Figure 2. Channel drop tunneling process for a resonator system that supports a single resonant state.

originates solely from the decay of the localized state. Since only one localized state is present, there is only one component of decaying amplitude along this direction. Such a decaying amplitude can not be cancelled, since there is no other signal along that direction with which it can interfere. Hence, in order for complete transfer to happen, at least two states are needed for the decaying amplitudes to cancel in the backward direction of the bus waveguide.

To ensure the cancellation of the reflected signal, we consider a structure with a mirror plane symmetry perpendicular to both waveguides, and assume that there exist two localized states with different symmetry with respect to the mirror plane, one even labelled $|e\rangle$, and one odd labelled $|o\rangle$. Since the states have different symmetry, tunneling through each state constitutes an independent process. The even state decays with the same phase into the forward and backward directions (Figure 3(a)). The odd state, however, has a decaying amplitude into the forward direction which is $180°$ out of phase with the decaying amplitude along the backward direction (Figure 3(b)). When the two tunneling processes are combined, because of the phase difference, the decaying amplitudes into the backward direction of the bus waveguide cancel, as desired (Figure 3(c)). We note that in order for the cancellation to occur, the lineshapes of the two resonances should overlap to a large degree. Since each resonance possesses a Lorentzian lineshape, both resonances must have substantially the same center frequency and the same width.

We can understand the cancellation condition in an alternative way. The incoming wave e^{ikx} can be decomposed into the form $\cos(kx) + i\sin(kx)$, where x corresponds to the direction

#4489 - $15.00 US
Received February 02, 1998; Revised April 28, 1998

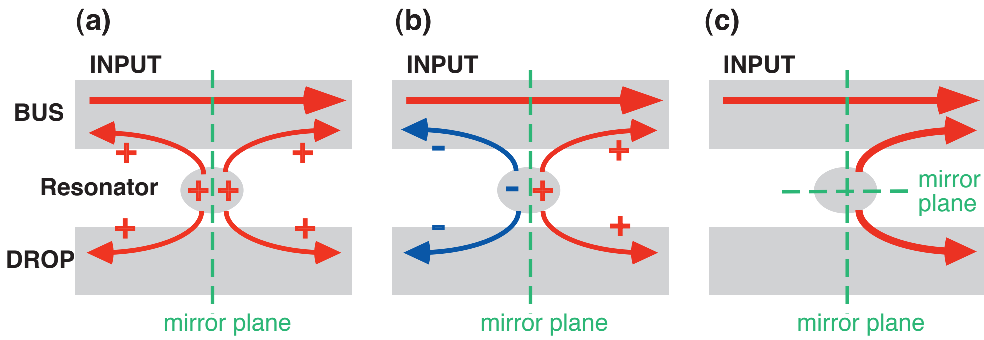

Figure 3. Channel drop tunneling process for a resonator system that supports two resonant state with different symmetry with respect to the mirror plane perpendicular to the waveguides. These two states are even with respect to the mirror plane parallel to the waveguides.

along both waveguides. The $cos(kx)$ part, which is even with respect to the mirror plane perpendicular to the waveguides, couples only to the even resonant state, and the $sin(kx)$ part, which is odd, couples only to the odd state. In the specific case where the width and the frequencies are equal for both modes, a resonant state of the form $|e\rangle + i|o\rangle$ is excited, which in turn decays in the bus waveguide only along the forward direction. As a result, reflection is completely absent.

In general, the symmetry of the channel drop systems is low such that only one-dimensional irreducible representations are allowed. Hence, the even and odd resonances belong to different irreducible representations and an accidental degeneracy between the resonances must be forced.

When such degeneracy indeed occurs, the incoming wave interferes destructively with the decaying amplitude into the forward direction of the bus waveguides, leaving all the power transferred into the drop waveguide. From conservation of energy, the amplitude of the transferred wave and that of the input wave therefore must be equal, which implies that the resonances must decay equally into the bus and the drop waveguides. This requirement can be satisfied by imposing an additional mirror-plane symmetry parallel to both waveguides.

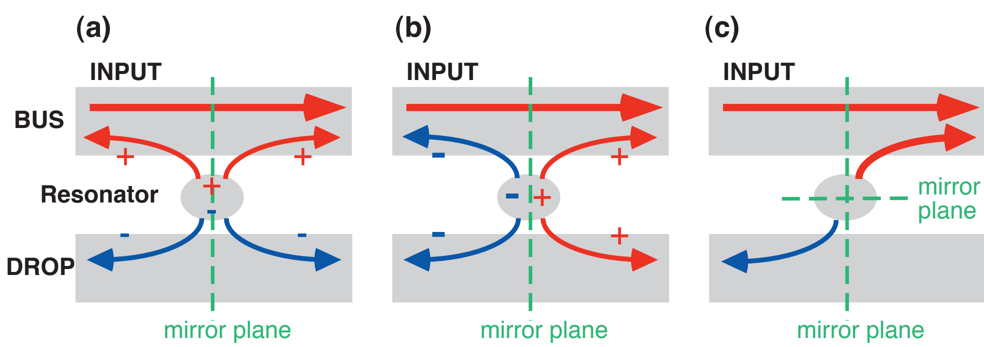

Figure 4. Channel drop tunneling process for a resonator system that supports two resonant states with different symmetry with respect to the mirror plane perpendicular to the waveguides. The states also have different symmetry with respect to the mirror plane parallel to the waveguides.

Received February 02, 1998; Revised April 28, 1998

The directionality of the transfer is dependent upon the symmetry of the resonant states with respect to the mirror plane parallel to waveguides. In the case of Figure 3, where both states are even with respect to this mirror plane, the decaying amplitudes along the backward direction of the drop waveguide cancel, leaving all the power to be transferred into the forward direction of the drop waveguide. On the other hand, the even state $|e\rangle$ could be odd with respect to the mirror plane parallel to the waveguides. When the accidental degeneracy between the states occurs, the decaying amplitudes cancel in the forward direction of the drop waveguide (Figure 4). All the power is instead transferred into the backward direction of the drop waveguide.

To summarize the discussions above, in order to create an ideal channel drop filter, the structure must possess a mirror plane perpendicular to the waveguides and must support two resonances, one even, one odd, with respect to the mirror plane. An accidental degeneracy in both the real and the imaginary parts of the resonant frequency has to be forced between the resonances. This criteria can be derived by a quantitative analysis, which also gives detailed prediction of the transfer lineshapes, as presented in refs. [7] and [8].

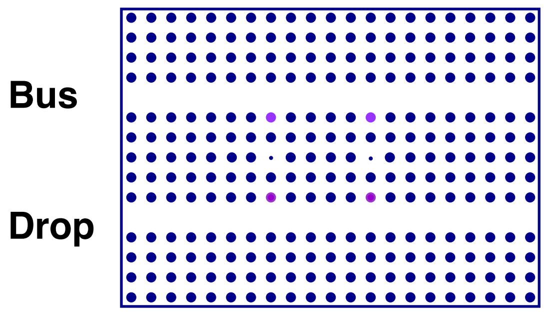

Figure 5. Photonic crystal channel drop filter structure with two waveguides and two cavities. The dark blue circles correspond to rods with a dielectric constant of 11.56, while the light blue circles correspond to rods with a dielectric constant of 9.5. The two smaller rods have a dielectric constant of 6.6, and a radius of 0.05*a*, where *a* is the lattice constant.

3. Photonic crystal channel drop filters

The inherent designing flexibility of photonic crystal microcavities allows the ideal transfer conditions to be readily satisfied by many geometries. Below we discuss two possible embodiments.

3.1 Filter structure with two single-mode cavities

The first embodiment consists of two photonic crystal waveguides and two coupled single-mode high-Q microcavities, as shown in Figure 5. The photonic crystal is made of a square lattice of high-index dielectric rods with dielectric constant 11.56 and radius 0.20*a*, where *a* is the lattice constant. The waveguides are formed by removing two rows of dielectric rods, and the cavities are introduced between the waveguides by reducing the radius of two rods. Each cavity supports a localized monopole state which is singly degenerate [5].

The even and odd states are made up of linear combinations of the two monopoles which are coupled indirectly through the waveguide and directly through the crystal. Each coupling mechanism splits the frequency of the even and odd states, but with opposite sign. An accidental degeneracy, caused by an exact cancellation between the two coupling mechanisms, is enforced by reducing the dielectric constant of four specific rods in the photonic crystal to 9.5, as shown in Figure 5. The cancellation could equally have been accomplished by reducing the size of the rods instead of their dielectric constant.

Analytically, we can show that the quality factor of the two states can be made equal provided that the wavevector k of the guided mode satisfies the relation $k \cdot d = n\pi + \pi/2$, where d is the distance between the two defects, and n is an integer [8]. This condition can be reached by separating the two defects by five lattice constants, and by choosing the size and dielectric constant of the defect posts in such a way that the guided mode at the resonant frequency has a wavevector of $0.25 \cdot 2\pi a^{-1}$.

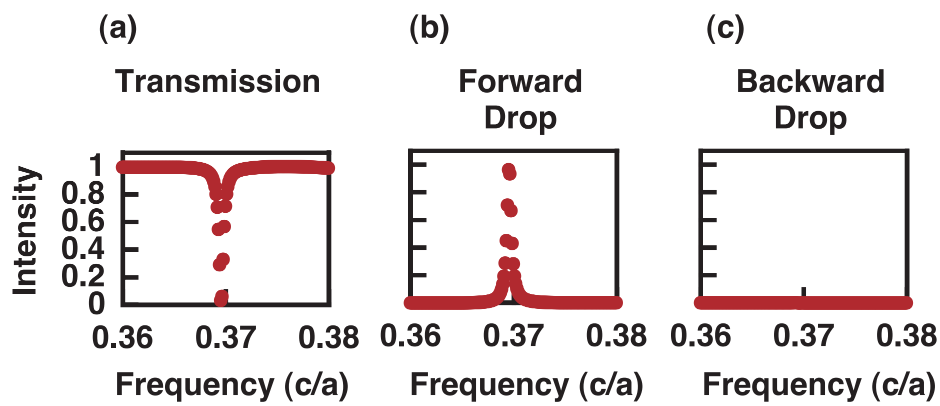

Figure 6. (a) Intensity spectrum of the transmitted signal in the structure shown in Figure 5. (b) Intensity spectrum of the transferred signal in the forward direction. (c) Intensity spectrum of the transferred signal in the backward direction.

We simulate the filter response of the structure shown in Figure 5 using a finite-difference time-domain scheme [9] with perfectly matched layer absorbing boundary condition [10]. To quantify the response function, a pulse is sent down the bus waveguide and field amplitudes at various points of the waveguides are monitored. Spectra of the transmitted and transferred signals are obtained by Fourier transforming the field amplitudes and shown in Figure 6. The transmission is close to 100% over the entire spectrum, except at the resonant frequency, where it drops to 0% (Figure 6(a)). The forward transferred signal shows a Lorentzian line shape with a maximum close to 99% at resonance. The quality factor is larger than 1000, as seen in Figure 6(b). The backward transferred signal is almost completely absent over the entire frequency range, as desired (Figure 6(c)).

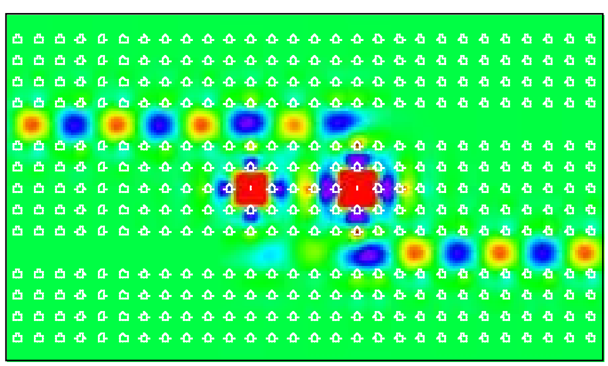

Figure 7 (Quick movie: to be played in a loop mode) Oscillation of the steady-state field distribution at the resonant frequency for the structure shown in Figure 5. Green represents zero field. Red represents positive field maximum. Blue represents negative field maximum.

Received February 02, 1998; Revised April 28, 1998

We show the oscillation of the steady-state field distribution at the resonant frequency in Figure 7. A guided mode propagates along the bus waveguide and excites the resonances. The amplitudes inside the two cavities oscillate with a $90°$ phase difference, as expected from our previous discussion. All the intensity is transferred along the forward direction of the drop waveguide. There is a complete absence of field in the forward direction of the bus waveguide and the backward direction of the drop waveguide. The simulation does indeed demonstrate complete channel drop tunneling. We also note that the wavelength of light is roughly equal to four lattice constants in the structure. Hence the filter occupies an area only a few wavelengths square. Hence photonic crystal filters are significantly more compact than other structures.

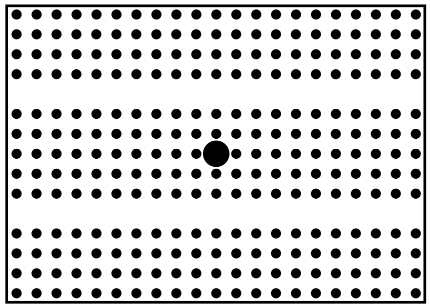

Figure 8. Photonic crystal channel drop filter structure with two waveguides and one cavity that supports two resonant states. The dark blue circle corresponds to a rod with a dielectric constant of 11.56, while the light blue circles correspond to rods with a dielectric constant of 11.90. The bigger rod has a radius of 0.60*a*, where *a* is the lattice constant.

3.2 Filter structure with a single cavity that supports doubly degenerate hexapole states

Instead of using a resonator system which contains two defects, each supporting a singly degenerate monopole state, we could also use a single defect that supports two modes with opposite symmetries (Figure 8). The defect is introduced by increasing the radius of a single rod in the crystal from $0.20a$ to $0.60a$. Such a defect supports two hexapole modes that are degenerate in frequency[5]. The degeneracy is broken, however, by the presence of the waveguides. To restore the degeneracy in frequency, we note that the even mode, as defined with respect to the mirror plane perpendicular to the waveguides, possesses a nodal plane parallel to the waveguides. The odd mode, on the other hand, reaches a maximum field amplitude at this plane [5]. Changing the dielectric constant of the rods on this plane therefore affects the frequency of the odd mode to a large degree, while barely influencing the frequency of the even mode. An accidental degeneracy in frequency is enforced by setting the dielectric constant of two rods on this plane to 11.90, as shown in Figure 8. An approximate degeneracy in width exists between the states, since the hexapole possesses large enough orbital angular momentum to ensure roughly equal decay of the even and odd modes into the waveguides. The simulated spectra exhibit near-complete channel drop transfer with the quality factor exceeding 6,000 (Figure 9). Since the even state exhibits an odd symmetric property with respect to the mirror plane parallel to the waveguides, the transfer occurs along the backward direction of the drop waveguide. Such backward transfer is also clearly demonstrated by the oscillation of the steady-state field distribution at the resonant frequency, as shown in Figure 10. The field pattern in the defect region rotates clockwise, substantiating our prediction that a resonant state of the form $|e\rangle + i|o\rangle$ is excited.

4. Summary

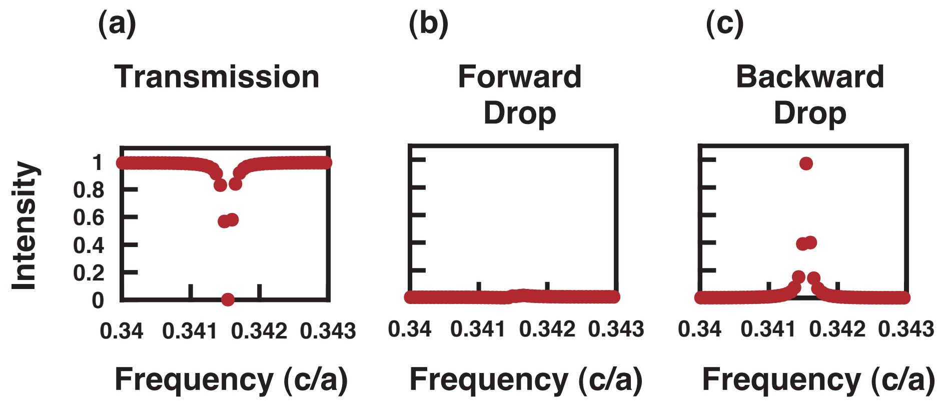

Figure 9. (a) Intensity spectrum of the transmitted signal in the structure shown in Figure 8. (b) Intensity spectrum of the transferred signal in the forward direction. (c) Intensity spectrum of the transferred signal in the backward direction.

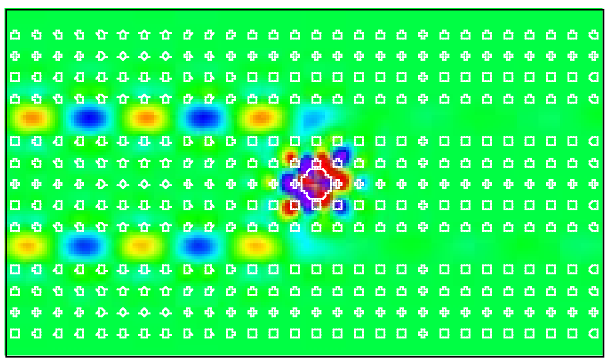

Figure 10 (Quicktime movie: to be played in a loop mode) Oscillation of the steady-state field distribution at the resonant frequency for the structure shown in Figure 8. Green represents zero field. Red represents positive field maximum. Blue represents negative field maximum.

In summary, we have presented the criteria for the optimal design of a generic resonant-cavity channel drop filter. We applied these criteria in designing photonic crystal filter structures. Numerical simulations demonstrate that these filters exhibit ideal transfer characteristics.

Acknowledgment

This work is supported in part by the MRSEC program of the NSF under award No. DMR-9400334.