

Loss-induced on/off switching in a channel add/drop filter

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We introduce a mechanism that provides an on/off switching capability in channel add-drop filter structures. These filters consist of two waveguides, a bus and a drop, coupled through a frequency-selective element. The switching functionality is achieved by incorporating materials with variable absorbing characteristics into the coupling element. When the variable material displays minimum absorption, the frequency channel of interest is transferred completely from the bus waveguide to the drop waveguide. When the variable material displays maximum absorption, the frequency channel is not transferred and remains essentially undisturbed in the bus waveguide. We also discuss the practical feasibility of realizing this approach using either electrical or mechanical means.

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I. INTRODUCTION

Channel add/drop filters play an important role in today's fiber communication systems and photonic integrated circuits. In previous work, Fan and co-workers showed that highly efficient and ultracompact add/drop filter structures can be created in a photonic crystal.^{1,2} The structure allows a complete transfer of one or several frequency channels in a wavelength-division-multiplexed (WDM) signal from the bus waveguide through a resonator system to the drop waveguide without disturbing the other channels. The idea of using photonic crystal resonators side coupled with waveguides was since explored further both experimentally and theoretically.³⁻⁶

For communication applications, it is also desirable to be able to turn such transfer on and off. Ideally, in an "on" state, the frequency channel is completely transferred from the bus to the drop waveguide, while in the "off" state the frequency channel remains unperturbed in the bus waveguide. While it is conceivable to achieve such switching functionality by tuning the refractive index of the material, such that the resonance frequency no longer overlaps with the signal frequency, doing so tends to require a large refractive index change. For example, in a WDM system the frequency bandwidth for a single channel can be as wide as 100 GHz for high bit rate (such as 40 Gbit/s) applications. To turn a channel on and off thus requires a shifting of the resonance frequency by a single-channel spacing, resulting in a required resonant frequency shift of at least 0.5% (assuming a carrier frequency of 193 THz). Such a shift tends to require a corresponding change of about 0.5% in the refractive index, which is very significant. Moreover, a frequency shift of the resonance would cause leakage to adjacent channels.

While the achievable refractive index change in realistic materials is typically much smaller than 0.5%, the intrinsic loss of a resonator can be varied significantly, and widely tuned by a number of means. For example, a large change in

the absorption coefficient is achievable in a number of semiconductor systems.⁷⁻⁹ In a bulk silicon material, at a wavelength of 1.55 μm , the absorption coefficient can be readily changed from 10^{-1} to 10^3 cm^{-1} through free-carrier effects.⁷ The time scale of such an effect is of the order of a few nanoseconds. A quantum-well system, using the so-called "quantum-confined Stark effect," also allows a significant tuning of absorption coefficients⁹ with a time scale on the order of a few picoseconds. Using such a large absorption coefficient change, a number of electroabsorption modulators have already been proposed and demonstrated.¹⁰

In this paper, we demonstrate how tuning the optical loss in a resonator by changing the absorption coefficients can be used to induce on/off switching in an add/drop filter. Depending on the strength of absorption, the filter is switched between an on state [Fig. 1(a)], where the absorption coefficient is at a minimum and tunneling occurs, and an off state [Fig. 1(b)], where the absorption coefficient is at a maximum and the signal remains in the bus waveguide. In particular, we show that the structure can be designed such that, in both on and off states, the absorption loss of the signal can be made arbitrarily small, in spite of the large absorption coefficient that is present in the off state.

II. QUALITATIVE ARGUMENTS

The mechanism that we propose here relies on spoiling the optical resonance in the off state. This can be accomplished by introducing losses to the optical resonance using either radiation or absorption or both. For simplicity, in this paper we will focus mostly on absorption. The effects of radiation are discussed at the end of the paper. However, let us first review the basic physical processes involved in the on state, when the material in the coupling element has a minimal absorption coefficient and the structure behaves as the channel add/drop filter described in Refs. 1 and 2. In order for a complete transfer to occur, the coupling element needs to support at least two resonant modes of opposite

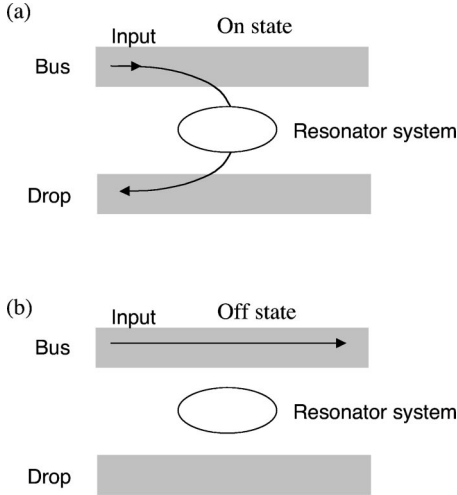


FIG. 1. An on/off switch operation in a channel add/drop filter. (a) The “on” state. The incident wave in the bus waveguide excites the resonator system. The power in the resonator system then decays into the drop waveguide, resulting in a complete transfer of power between the two waveguides. (b) The “off” state. A loss mechanism is introduced into the resonator system. No transfer occurs between the waveguides. The signals stay in the bus waveguide.

symmetry [Fig. 2(a)]. In addition, an accidental degeneracy in both the frequency and the width of these resonance modes needs to be forced. Such an accidental degeneracy ensures the cancellation of the reflection over all frequency ranges [Fig. 2(b)]. At the resonance frequency, the transmitted amplitude consists of two parts: an incident wave, and decaying waves from resonances in the resonator system. The destructive interference of these two parts lead to the cancellation of transmission at the resonant frequency, and a complete transfer of power to the drop waveguide. The transferred power originates entirely from the decaying amplitude of the resonances [Fig. 2(b)].

By increasing the absorption coefficients in the cavity, resonances in the coupling element can be spoiled and the decaying amplitudes from the resonances can therefore be eliminated. In the drop waveguide, since the transferred power originates entirely from the decaying amplitudes, the power transfer is completely turned off. In the bus waveguide, on the other hand, with the absence of the decaying amplitude there is no longer destructive interference. Hence the transmission of the incoming wave stays close to 100% over the entire frequency range. Thus, by varying the absorbing coefficients in the cavity region, we can produce an on/off switching mechanism with minimal loss in both the on and off states.

III. THEORY

The qualitative arguments described above can be quantified using the following theoretical derivation. The system described in Fig. 1 is composed of two continuums of propagating states in the bus and drop waveguides. The states in the continuums are labeled $|k\rangle$ and $|\bar{k}\rangle$, respectively, where k

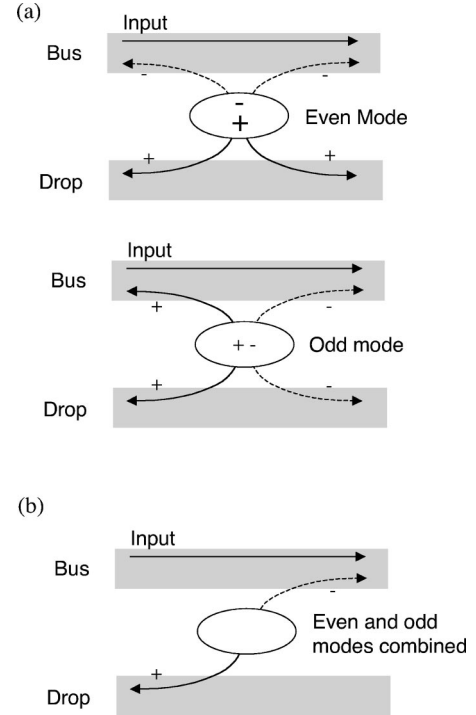


FIG. 2. The operating mechanism of a channel add/drop filter. (a) The resonator system supports two states with opposite symmetry. The incident wave excites both resonances. The power in the resonances then decays into the two waveguides. The relative phase of the decaying amplitudes into each direction of the waveguides is related to the symmetry of the resonant states. (b) The decay amplitudes of these two modes with opposite symmetry are combined, resulting in unidirectional transfer from the bus waveguide to the drop waveguide.

and \bar{k} are the corresponding wave vectors. The waveguides are side coupled through the resonator system. The resonator system supports localized resonances, labeled by $|c\rangle$, where c is an integer, taking a value between 1 and the total number of localized states. To describe the effect of intrinsic loss from the optical resonances, we also assume that each resonance couples to a set of lossy or absorption modes: $\{|a_c\rangle\}$.

The interactions as outlined above are therefore described by an effective Hamiltonian H . The Hamiltonian consists of the sum of two parts H_0 and V , where

$$H_0 = \sum_k \omega_k |k\rangle \langle k| + \sum_c \omega_c |c\rangle \langle c|, \quad (1)$$

$$V = \sum_{c_1 \neq c_2} V_{c_1, c_2} |c_1\rangle \langle c_2| + \left(\frac{1}{L}\right)^{1/2} \sum_{q, c} [V_{c, q} |c\rangle \langle q| + V_{q, c} |q\rangle \langle c|] \\ \times \langle c| + \left(\frac{1}{A}\right)^{1/2} \sum_c [V_{c, a_c} |c\rangle \langle a_c| + V_{a_c, c} |a_c\rangle \langle c|]. \quad (2)$$

Here state $|q\rangle$ represents a state in either continuum, and ω_q is its frequency. The coefficient $V_{c, q}$ measures the coupling between a localized state $|c\rangle$ and a propagating state $|q\rangle$, while the coefficient V_{c_1, c_2} describes the strength of direct

coupling between a pair of localized states $|c_1\rangle$ and $|c_2\rangle$. In addition, each localized state $|c\rangle$ is coupled to a set of lossy modes $\{|a_c\rangle\}$ with a coupling constant V_{c,a_c} . L and A are normalization constants for the states $|q\rangle$ and $|a_c\rangle$, respectively.

We now proceed to study the transport properties. In a gedanken experiment, we excite a state $|k\rangle$ at $x = -\infty$. The state propagates in the bus waveguide, and excites the localized states in the resonator system, which in turn decay along several directions in the continua. This scattering process can be described by the Lippman-Schwinger equation,² which relates the scattered wave function $|\psi\rangle$ to the incoming wave $|k\rangle$:

$$|\psi\rangle = |k\rangle + \frac{1}{\omega_k - H_0 + i\varepsilon} V |\psi\rangle \equiv T |k\rangle. \quad (3)$$

In Eq. (3), ω_k is the frequency of the incoming wave, and ε is an infinitesimally small number greater than zero. The number ε is introduced to enforce an outgoing-wave boundary condition for the scattered wave.

Following the derivation in Ref. 2, the T matrix can be related to the Green's-function matrix of the localized states by

$$T_{k'k} = \delta_{k'k} + \frac{1}{\omega_k - \omega_{k'} + i\varepsilon} \sum_{c_1, c_2} V_{k', c_2} G_{c_2, c_1}(\omega_k) V_{c_1, k}, \quad (4)$$

where

$$G_{c_2, c_1}(\omega) = \sum_{m=0}^{\infty} \langle c_2 | \frac{1}{\omega - H_0 + i\varepsilon} \left(V \frac{1}{\omega - H_0 + i\varepsilon} \right)^m | c_1 \rangle \\ = \langle c_2 | \frac{1}{\omega - H + i\varepsilon} | c_1 \rangle \quad (5)$$

is the Green's function for a pair of localized states $|c_1\rangle$ and $|c_2\rangle$.

The Green's function matrix can be evaluated exactly as

$$G = (1 - G^0 \Sigma)^{-1} G^0, \quad (6)$$

where G , G^0 , and Σ are matrices with dimensions equal to the number of localized states. G^0 is the "unperturbed" Green's function for the localized states, and it is given by

$$G_{c_1, c_2}^0 \equiv \langle c_1 | \frac{1}{\omega - H_0 + i\varepsilon} | c_2 \rangle = \frac{1}{\omega - \omega_{c_1} + i\varepsilon} \delta_{c_1, c_2}, \quad (7)$$

while Σ is the "self-energy" matrix, and is evaluated as

$$\Sigma_{c_1, c_2} = V_{c_1, c_2} + \frac{1}{L} \sum_q V_{c_1, q} \frac{1}{\omega - \omega_q + i\varepsilon} V_{q, c_2} \\ + \delta_{c_1, c_2} \frac{1}{A} \sum_{a_{c_1}} V_{c_1, a_{c_1}} \frac{1}{\omega - \omega_{a_{c_1}} + i\varepsilon} V_{a_{c_1}, c_1}. \quad (8)$$

The summation over q in Eq. (8) is performed over all propagating states in both continua.

For most practical circumstances, the Green's-function matrix can always be diagonalized by appropriately choosing a basis of localized states. In this basis, the Green's function for a localized state $|c\rangle$ can be written as

$$G_{c,c}(\omega) = \frac{1}{\omega - \omega_c - \Sigma_{c,c}}. \quad (9)$$

The real part of $\Sigma_{c,c}$ represents a shift in resonant frequency with respect to the bare frequency ω_c . The imaginary part of $\Sigma_{c,c}$ corresponds to the width of the resonance, which is related to the power decay rate from the localized state into the continua and the lossy modes. The norm square of $G_{c,c}(\omega)$ possesses a Lorentzian line shape centered at a "renormalized" resonant frequency $\tilde{\omega}_c = \omega_c + \text{Re} \Sigma_{c,c}$ with a width of $\gamma_c = \text{Im} \Sigma_{c,c}$.

From Eq. (8), the linewidth of the resonance is evaluated as

$$\gamma_c = \gamma_c^{\text{ext}} + \gamma_c^{\text{abs}}, \quad (10)$$

where γ_c^{ext} , the *external linewidth* which originates from waveguide-resonator coupling, is evaluated as

$$\gamma_c^{\text{ext}} = \frac{\pi}{L} \sum_q [|V_{c,q}|^2 \delta(\omega_c - \omega_q)] \\ + \frac{\pi}{L} \sum_{\bar{q}} [|V_{c,\bar{q}}|^2 \delta(\omega_c - \omega_{\bar{q}})] \\ = g |V_{c,q}|^2 + \bar{g} |V_{c,\bar{q}}|^2, \quad (11)$$

while γ_c^{abs} , the *absorption linewidth* which originates from resonator loss, is calculated as

$$\gamma_c^{\text{abs}} = \frac{\pi}{A} \sum_{a_c} [|V_{c,a_c}|^2 \delta(\omega_c - \omega_{a_c})] = g^{\text{abs}} |V_{c,a_c}|^2. \quad (12)$$

Here g and \bar{g} are the density of states of the propagating mode in the bus and drop waveguides, and is equal to the group velocity at the resonant frequency. g^{abs} is the density of lossy modes that couple to the resonance.

By diagonalizing the Green's-function matrix, the formula for the T matrix derived in Eq. (4) can be simplified to

$$T_{k'k} = \delta_{k'k} + \frac{1}{\omega_k - \omega_{k'} + i\varepsilon} \sum_c V_{k',c} G_{c,c} V_{c,k}. \quad (13)$$

Each localized state contributes to the T matrix as an independent scattering path. The scattering property is determined by the interference of the different amplitudes along all possible paths.

We now calculate the transmission, reflection, and transfer spectra, by evaluating the amplitudes of the scattered wave function ψ at $x, \bar{x} = \pm\infty$. The transmitted amplitude is given by

$$\langle x = \infty | \psi \rangle = \left(\frac{1}{L} \right)^{1/2} \left(1 - i \sum_c (g V_{k,c} V_{c,k}) \right. \\ \left. \times \frac{1}{\omega_k - \tilde{\omega}_c + i(\gamma_c^{\text{ext}} + \gamma_c^{\text{abs}})} \right) e^{ikx}. \quad (14)$$

Scattering amplitudes along the other directions can be obtained in a similar fashion. The reflected amplitude is given by

$$\langle x = -\infty | \psi \rangle = (-i) \left(\frac{1}{L} \right)^{1/2} \left(\sum_c (g V_{-k,c} V_{c,k}) \times \frac{1}{\omega_k - \tilde{\omega}_c + i(\gamma_c^{\text{ext}} + \gamma_c^{\text{abs}})} \right) e^{ikx}. \quad (15)$$

the forward transfer amplitude is given by

$$\langle \bar{x} = \infty | \psi \rangle = (-i) \left(\frac{1}{L} \right)^{1/2} \left(\sum_c (g V_{\bar{k},c} V_{c,k}) \times \frac{1}{\omega_k - \tilde{\omega}_c + i(\gamma_c^{\text{ext}} + \gamma_c^{\text{abs}})} \right) e^{ik\bar{x}} \quad (16)$$

and the backward transfer amplitude is given by

$$\langle \bar{x} = -\infty | \psi \rangle = (-i) \left(\frac{1}{L} \right)^{1/2} \left(\sum_c (g V_{-\bar{k},c} V_{c,k}) \times \frac{1}{\omega_k - \tilde{\omega}_c + i(\gamma_c^{\text{ext}} + \gamma_c^{\text{abs}})} \right) e^{i(\bar{k})\bar{x}}. \quad (17)$$

Of particular interest are two limiting cases. In one limit, $\gamma^{\text{abs}} \ll \min(\gamma_c^{\text{ext}}, \gamma_c^{\text{abs}})$, i.e., the absorption coefficient of the variable material in the coupling element is small. The equations describe a channel drop filter response without material absorption. By choosing the states of appropriate symmetry properties, and by forcing an accidental degeneracy between the states, all the power can be transferred from the bus waveguide to the drop waveguide. The switch is in an on state. In the opposing limit, $\gamma^{\text{abs}} \gg \max(\gamma_c^{\text{ext}}, \gamma_c^{\text{abs}})$, the absorption coefficient of the variable material in the coupling element is large. From Eq. (14), the transmission coefficient approaches unity, while the reflection and the transfer coefficients in Eqs. (15)–(17) asymptotically vanishes. Hence the switch is in the off state. The frequency channel of interest remains unperturbed in the bus waveguide. The analytical results indeed confirm the qualitative arguments presented earlier. Similar effects have also been predicted using time-coupled mode theory in the context of microring channel add/drop filter structures.^{11,12}

IV. EXAMPLES

Below, we apply the formulas in Eqs. (14)–(17) to practical examples. We will consider two cases, a two-state system and a four-state system, and calculate the effects of absorption on the transmission and transfer coefficients.

A. Two-state system

We first consider a two-state system as shown in Fig. 2, where the two states have a p -like symmetry. Taking into account the symmetry properties of the system, Eqs. (14)–(17) can be simplified to give the transmission coefficient

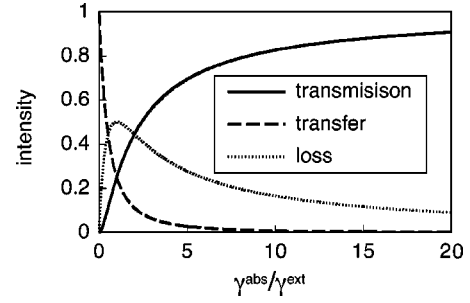


FIG. 3. Transmission, transfer, and loss coefficients, at the resonant frequency, as a function of the ratio between absorption linewidth γ^{abs} , and external linewidth γ^{ext} , for the case where the resonator system supports two-states with opposite symmetries.

T_{bus} , the reflection coefficient R_{bus} , the forward transfer T_{fdrop} , and the backward transfer T_{bdrop} , as

$$T_{\text{bus}} = \left| 1 - \frac{1}{2} \frac{i\gamma_e^{\text{ext}}}{\omega - \tilde{\omega}_e + i\gamma_e^{\text{ext}} + \gamma_e^{\text{abs}}} - \frac{1}{2} \frac{i\gamma_o^{\text{ext}}}{\omega - \tilde{\omega}_o + i\gamma_o^{\text{ext}} + \gamma_o^{\text{abs}}} \right|^2, \quad (18)$$

$$R_{\text{bus}} = \left| -\frac{1}{2} \frac{i\gamma_e^{\text{ext}}}{\omega - \tilde{\omega}_e + i\gamma_e^{\text{ext}} + \gamma_e^{\text{abs}}} + \frac{1}{2} \frac{i\gamma_o^{\text{ext}}}{\omega - \tilde{\omega}_o + i\gamma_o^{\text{ext}} + \gamma_o^{\text{abs}}} \right|^2, \quad (19)$$

$$T_{\text{fdrop}} = \left| \frac{1}{2} \frac{i\gamma_e^{\text{ext}}}{\omega - \tilde{\omega}_e + i\gamma_e^{\text{ext}} + \gamma_e^{\text{abs}}} - \frac{1}{2} \frac{i\gamma_o^{\text{ext}}}{\omega - \tilde{\omega}_o + i\gamma_o^{\text{ext}} + \gamma_o^{\text{abs}}} \right|^2, \quad (20)$$

$$T_{\text{bdrop}} = \left| \frac{1}{2} \frac{i\gamma_e^{\text{ext}}}{\omega - \tilde{\omega}_e + i\gamma_e^{\text{ext}} + \gamma_e^{\text{abs}}} + \frac{1}{2} \frac{i\gamma_o^{\text{ext}}}{\omega - \tilde{\omega}_o + i\gamma_o^{\text{ext}} + \gamma_o^{\text{abs}}} \right|^2. \quad (21)$$

Here the labels e and o represent the even and odd states, defined with respect to the symmetry plane perpendicular to the waveguides.

For complete transfer to occur, the system needs to satisfy the accidental degeneracy conditions $\tilde{\omega}_e = \tilde{\omega}_o \equiv \omega_{\text{res}}$ and $\gamma_e^{\text{ext}} = \gamma_o^{\text{ext}} \equiv \gamma^{\text{ext}}$. In addition, for simplicity, we assume that $\gamma_e^{\text{abs}} = \gamma_o^{\text{abs}} \equiv \gamma^{\text{abs}}$. The reflection and the forward drop then vanish over the entire frequency range, while the transmission and the backward drop coefficients become

$$T_{\text{bus}} = \frac{(\omega - \omega_{\text{res}})^2 + (\gamma^{\text{abs}})^2}{(\omega - \omega_{\text{res}})^2 + (\gamma^{\text{ext}} + \gamma^{\text{abs}})^2}, \quad (22)$$

$$T_{\text{bdrop}} = \frac{(\gamma^{\text{ext}})^2}{(\omega - \omega_{\text{res}})^2 + (\gamma^{\text{ext}} + \gamma^{\text{abs}})^2}. \quad (23)$$

At the resonant frequency, we plot the transmission, transfer, and signal loss coefficients as a function of the ratio $\gamma^{\text{abs}}/\gamma^{\text{ext}}$ in Fig. 3. The signal-loss coefficient is defined as $1 - T_{\text{bus}} - T_{\text{bdrop}}$. Note in the limit where strong losses occur in the resonator, i.e., when $\gamma^{\text{abs}}/\gamma^{\text{ext}} \gg 1$, the signal loss goes to zero and the system effectively becomes lossless. Also, as

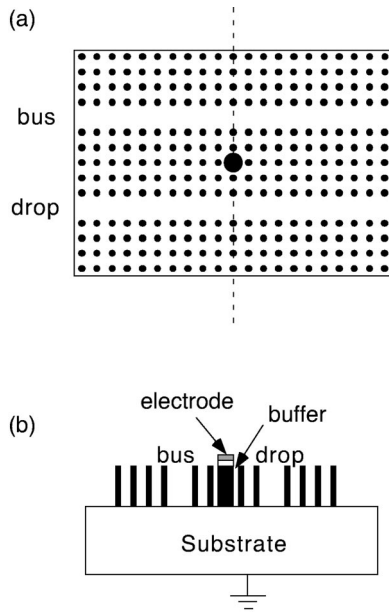


FIG. 4. (a) A top view of a channel add/drop filter structure in a photonic crystal. The black dots indicate the position of dielectric cylinders. The resonator systems consist of a large defect cylinder at the center of the structure. (b) A cross-sectional view of an on/off switch based on carrier injection. Note the presence of electrodes on the resonator.

the ratio $\gamma^{\text{abs}}/\gamma^{\text{ext}}$ increases, the transfer decreases much faster. Thus even a modest increase in the resonator loss provides an effective way to shut off transfer while still retaining of significant amount of power in the transmission direction.

In a photonic crystal, the two-state system, as described here, can be implemented using a dielectric defect in a crystal that supports an hexapole state, as shown in Fig. 4(a). The details of this structure can be found in Ref. 13. (We note that, in general, the presence of waveguides breaks the degeneracy between the even and odd hexapole states. Such degeneracy, however, can be restored by *removing* the rotational symmetry in the vicinity of the point defect, as shown in Ref. 13.) A numerical simulation shows that the external quality factor Q^{ext} , defined as $Q^{\text{ext}} = \omega_{\text{res}}/(2\gamma^{\text{ext}})$, can approach 6000.¹³ Three-dimensional simulations showed that the radiation Q of defect states in photonic crystal slab systems can be significantly larger than 6000.^{14,15} Thus structures with Q^{ext} , as assumed here, should be achievable in realistic systems.

One way to introduce intrinsic loss in the resonator is to inject of carrier into the defect region to induce free-carrier absorption, as shown in Fig. 4(b). The amount of loss can be adjusted by changing the electrical currents. For this case, here we provide a simple estimate of its feasibility. The intrinsic decay rate of a material can be related to the absorption coefficient α by

$$\gamma^{\text{abs}} = \alpha \frac{c}{n}, \quad (24)$$

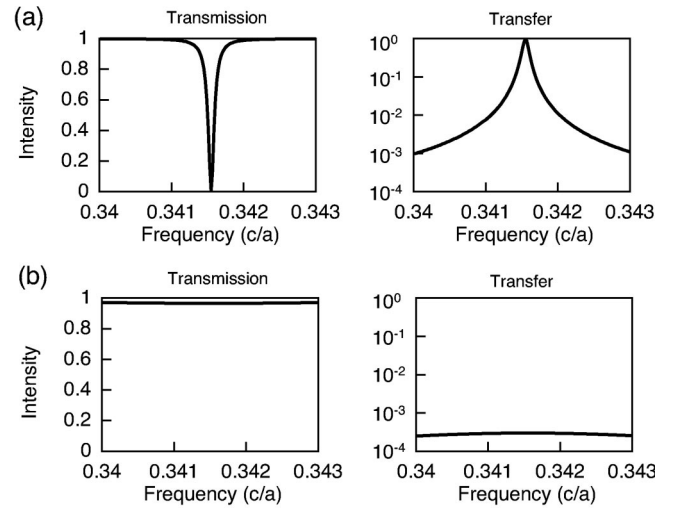


FIG. 5. (a) Transmission and transfer spectra of an add/drop filter in the “on” state, assuming minimal absorption loss in the resonator, and a resonant frequency at $0.3415c/a$ where a is the lattice constant of the photonic crystal. This frequency is the resonant frequency for the cavity structure as shown in Fig. 4(a). Also, the cavity has an external Q of 6000. (b) Transmission and transfer spectra of the add/drop filter in the “off” state, assuming that the resonator has an absorption Q of 100.

where c is the speed of light in vacuum, and n is the refractive index. Thus Q^{abs} is related to α by

$$Q^{\text{abs}} = \frac{\omega_{\text{res}} n}{2\alpha c}. \quad (25)$$

In bulk Si, at a wavelength of $1.55 \mu\text{m}$, the absorption coefficient α can be readily changed from 10^1 to 10^5 m^{-1} ,⁷ which corresponds to changing Q^{abs} from 10^6 to approximately 100. Using Eqs. (18) and (21), we calculate the transmission and transfer spectra in the on state, where no current is injected [Fig. 5(a)], and in the off state, where maximum current is injected [Fig. 5(b)]. In the off state, the transmission remains more than 97% over the entire frequency range, while the transfer coefficients drops to 2×10^{-4} . Thus this numerical example shows that it is indeed possible to switch on/off a channel add/drop filter by inducing a variation in loss in the resonator structure.

B. Four-state system

The use of more than two resonant states allows the construction of filters that exhibit maximum-flat line shapes, a key feature in many filter applications. As a specific example, we consider the case where the resonator system consists of four states, and the four states all have different symmetry properties with respect to the mirror planes perpendicular and parallel to the waveguides. And we label the states according to their symmetry properties. The state $|\text{even-odd}\rangle$, for example, is even with respect to the mirror plane perpendicular to the waveguides, and odd with respect to the mirror plane parallel to the waveguides. In order to ensure a complete cancellation of the reflection amplitude

over all frequency ranges in the absence of absorption, the following degeneracy conditions need to be imposed upon these four states:²

$$\omega_{\text{even-even}} = \omega_{\text{odd-even}} \equiv \omega_0 + \delta\omega/2, \quad (26)$$

$$\omega_{\text{odd-even}} = \omega_{\text{odd-odd}} \equiv \omega_0 - \delta\omega/2, \quad (27)$$

$$\gamma_{\text{even-even}}^{\text{ext}} = \gamma_{\text{even-odd}}^{\text{ext}} = \gamma_{\text{odd-even}}^{\text{ext}} = \gamma_{\text{odd-odd}}^{\text{ext}} \equiv \gamma^{\text{ext}}. \quad (28)$$

In addition, for simplicity, we assume that

$$\gamma_{\text{even-even}}^{\text{abs}} = \gamma_{\text{even-odd}}^{\text{abs}} = \gamma_{\text{odd-even}}^{\text{abs}} = \gamma_{\text{odd-odd}}^{\text{abs}} \equiv \gamma^{\text{abs}}. \quad (29)$$

Plugging these conditions into Eqs. (14)–(17), the transfer and transmission coefficients are then calculated as

$$T_{\text{fdrop}} = \frac{(\gamma^{\text{ext}} \delta\omega)^2}{(\omega - \omega_0)^4 + \left(\frac{\delta\omega^2}{4} + \gamma^2\right)^2 + \left(2\gamma^2 - \frac{\delta\omega^2}{2}\right)(\omega - \omega_0)^2}, \quad (30)$$

$$T_{\text{bus}} = \frac{(\omega - \omega_0)^4 + \left(-\frac{\delta\omega^2}{4} - \gamma^2 + 2\gamma^{\text{ext}}\gamma\right)^2 + \left(2\gamma^2 - \frac{\delta\omega^2}{2} - 4\gamma^{\text{ext}}\gamma^{\text{abs}}\right)(\omega - \omega_0)^2}{(\omega - \omega_0)^4 + \left(\frac{\delta\omega^2}{4} + \gamma^2\right)^2 + \left(2\gamma^2 - \frac{\delta\omega^2}{2}\right)(\omega - \omega_0)^2}, \quad (31)$$

in which $\gamma \equiv \gamma^{\text{ext}} + \gamma^{\text{abs}}$ is the *total linewidth* of the resonance.

In order to obtain a maximum flat transfer line shape in the on state, an additional constraint

$$|\delta\omega| = 2\gamma^{\text{ext}} \quad (32)$$

needs to be imposed.² Thus Eqs. (30) and (31) become

$$T_{\text{fdrop}} = \frac{4(\gamma^{\text{ext}})^4}{(\omega - \omega_0)^4 + [(\gamma^{\text{ext}})^2 + \gamma^2]^2 + (2\gamma^2 - 2(\gamma^{\text{ext}})^2)(\omega - \omega_0)^2}, \quad (33)$$

$$T_{\text{bus}} = \frac{(\omega - \omega_0)^4 + (\gamma - \gamma^{\text{ext}})^4 + 2(\gamma - \gamma^{\text{ext}})^2(\omega - \omega_0)^2}{(\omega - \omega_0)^4 + [(\gamma^{\text{ext}})^2 + \gamma^2]^2 + [2\gamma^2 - 2(\gamma^{\text{ext}})^2](\omega - \omega_0)^2}. \quad (34)$$

At the frequency $\omega = \omega_0$, we plot the transmission, transfer, and loss coefficients as a function of the ratio $\gamma^{\text{abs}}/\gamma^{\text{ext}}$ in Fig. 6. Similar to the two-state case, as $\gamma^{\text{abs}}/\gamma^{\text{ext}}$ increases, the system switch from an on state, where complete transfers occur, to an off state, where no transfer occurs and a significant amount of power remains transmitted in the bus waveguide. However, we note that as the ratio $\gamma^{\text{abs}}/\gamma^{\text{ext}}$ approaches zero (i.e., in the on state), the transmitted power vanishes asymptotically as

$$T_{\text{bus}} \sim (\gamma^{\text{abs}}/\gamma^{\text{ext}})^4. \quad (35)$$

This is to be contrasted with the two-state case [Eq. (22)], where in the on state the transmitted power vanishes quadratically as a function of the ratio $\gamma^{\text{abs}}/\gamma^{\text{ext}}$. Therefore, in the presence of a small and yet finite absorption loss in the on state, the use of multiple resonances can improve the contrast ratio in the transmission spectra between the on and off states.

V. CONCLUDING REMARKS AND SUMMARY

Finally, it is important to note that the analysis presented in this paper is also valid for other types of loss mechanisms. For example, if we have a cavity with $\gamma^{\text{abs}} \approx 0$, but with a

radiative decay rate γ^{rad} that can be varied, then all of the equations appropriate for this system can be simply obtained by replacing γ^{abs} with γ^{rad} . The important quantity thus becomes $\gamma^{\text{rad}}/\gamma^{\text{ext}}$. In Fig. 7, we illustrate an example of how γ^{rad} can be varied by mechanical means by bringing an optical fiber tip into close proximity to the resonator, and then varying the distance between the tip and the resonator. In addition, for a system where both γ^{rad} and γ^{abs} are not negligible, one simply replaces γ^{abs} in Eqs. (14)–(17) with

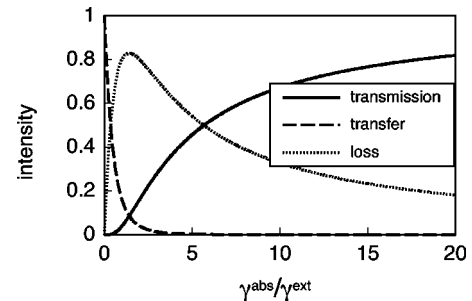


FIG. 6. Transmission, transfer, and loss coefficients, at the resonant frequency, as a function of the ratio absorption linewidth γ^{abs} and external linewidth γ^{ext} , for the case where the resonator system supports four states, all having different symmetry properties.

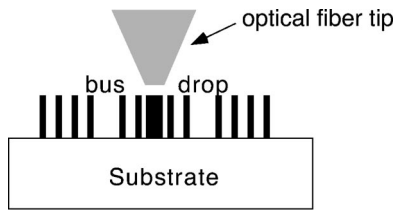


FIG. 7. A cross-sectional view of an on/off switch based on mechanical means. An optical fiber tip is brought to close proximity of a resonator. The distance between the tip and the resonator can be mechanically adjusted to vary the radiation loss from the resonator, and therefore allow for an on/off switch.

$\gamma^{\text{loss}} \equiv \gamma^{\text{abs}} + \gamma^{\text{rad}}$ and the important quantity now becomes $\gamma^{\text{loss}}/\gamma^{\text{ext}}$. Also, we note that while, in the on state, in order to satisfy the degeneracy requirement, the frequency splittings between the modes of different symmetries need to be sig-

nificantly smaller than the width of the resonance, maintaining such accidental degeneracy is *not* necessary in the off state

In summary, we have shown how optical-absorption loss in a resonator structure can be used to achieve on/off switching functionality in photonic crystal channel add/drop filters. We have shown that minimal signal loss can be achieved in both the on and off states provided that the induced difference in optical loss in the resonator is large enough to span $\gamma^{\text{loss}}/\gamma^{\text{ext}} \leq 1$ to $\gamma^{\text{loss}}/\gamma^{\text{ext}} \geq 1$. Only this ratio and these limits are important; it is not necessary in the on state for the absorption loss *itself* to be very small as long as this range is achievable.

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