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# Coupled mode analysis of in-plane channel drop filters with resonant mirrors

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**Abstract**

A channel drop filter system that consists of two waveguides and three cavities is studied. One cavity couples with both waveguides, while the other two work as resonant mirrors to reflect the selected channel back into the system. The operation of this configuration is analyzed, using coupled mode theory. The conditions to achieve 100% in-plane channel transfer are derived. A method to suppress the side lobes of reflection and backward drop is also proposed. The direct coupling between the cavities is not required. The analysis is verified by two-dimensional finite difference time domain simulations in 2D hexagonal photonic crystals.


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## 1. Introduction

Channel drop filters (CDFs), which single out one channel from wavelength division multiplexed signals, while passing through other channels undisturbed, are the essential components of photonic integrated circuits (PICs) and dense wavelength division multiplexing (DWDM) optical communication systems. Various CDFs exist, such as fiber Bragg gratings, Fabry-Pérot filters, and arrayed waveguide gratings. Resonant CDFs, which involve waveguide/cavity interaction, have attracted much attention as they can potentially be used to select a channel with very narrow line-width. In particular, resonant CDFs implemented in photonic crystals can be made ultra-compact and highly wavelength selective [1–4]. They are believed to serve as a good candidate for future channel filtering devices.

The operating principles of the in-plane resonant CDFs using degenerate cavity have matured over the years [5–7] followed by many novel designs [8–11]. We have recently proposed an in-plane CDF system, where the cavity only needs to support a single mode and the two waveguides are terminated by mirrors [12]. Some interesting phenomena have been discovered in the two-mirror system. In this paper, we continue the studies by replacing the frequency-independent mirrors with resonant mirrors which, in essence, are the same single mode cavities. Using coupled mode theory, we derive the conditions for maximum channel transfer and then demonstrate the three-cavity system in 2D hexagonal photonic crystals.

## 2. Three-cavity system

A schematic of the three-cavity system is shown in Fig. 1 and can be divided into three joined four-port

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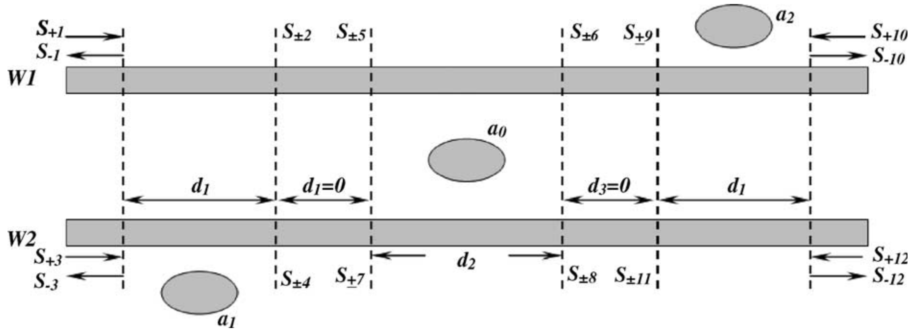


Fig. 1. Schematic representation of the in-plane CDF system. The three cavities are identical. Cavity $a_0$ decays into both waveguides with rate $1/\tau_e$, while cavity $a_1$ and $a_2$ only decay into one waveguide with the same rate and work as resonant mirrors.

systems. A single mode cavity, $a_0$, is placed symmetrically between the two waveguides. The three individual single mode cavities are identical with the same resonant frequency, $\omega_0$, decay rate into waveguide, $1/\tau_e$, and decay rate due to intrinsic loss, $1/\tau_0$. While cavity mode $a_0$ decays into both waveguides, $a_1$ and $a_2$ only decay into one waveguide and serve as resonant mirrors for the channel with central frequency $\omega_0$. The two waveguides, W1 and W2, are identical. They support a first-order guided mode at frequency, $\omega_0$, with propagation constant $\beta$.

The amplitudes of the incoming waves into a four-port system are denoted by $s_{+i}$, and $s_{-i}$ are the amplitudes for the outgoing waves ($i = 1, 2, \ldots, 12$). The time evolutions of the cavity modes can be described by [6]

$$\frac{da_0}{dt} = \left(j\omega_0 - \frac{1}{\tau_0} - \frac{2}{\tau_e}\right)a_0 + \kappa_5\, e^{-j\beta d_2/2} s_{+5} + \kappa_6\, e^{-j\beta d_2/2} s_{+6} + \kappa_7\, e^{-j\beta d_2/2} s_{+7} + \kappa_8\, e^{-j\beta d_2/2} s_{+8}, \quad (1)$$

$$\frac{da_1}{dt} = \left(j\omega_0 - \frac{1}{\tau_0} - \frac{1}{\tau_e}\right)a_1 + \kappa_3\, e^{-j\beta d_1/2} s_{+3} + \kappa_4\, e^{-j\beta d_1/2} s_{+4}, \quad (2)$$

$$\frac{da_2}{dt} = \left(j\omega_0 - \frac{1}{\tau_0} - \frac{1}{\tau_e}\right)a_2 + \kappa_9\, e^{-j\beta d_1/2} s_{+9} + \kappa_{10}\, e^{-j\beta d_1/2} s_{+10}. \quad (3)$$

Since we assume the cavity modes decay equally into the waveguide, the coupling coefficients can be written as

$$\kappa_i = \sqrt{\frac{1}{\tau_e}}\, e^{j\theta_i}, \quad i = 1, 2, \ldots, 8. \quad (4)$$

Without losing generality, we assume the cavity mode is symmetric in both in-plane directions and set $\theta_i = 0$.

It is worth mentioning that the decay rates are related to the $Q$ factors. The intrinsic $Q$ factor is $Q_0 = \omega_0\tau_0/2$ and the coupling $Q$ factor $Q_e = \omega_0\tau_e/2$.

By power conservation, the outgoing waves are related to the incoming ones by subtracting the part that is coupled into the cavity. For example, at port 5, the outgoing wave $s_{-5}$ can be written as

$$s_{-5} = e^{-j\beta d_2} s_{+6} - e^{-j\beta d_2/2} \kappa_6^* a_0. \quad (5)$$

Between ports 1 and 2, there is no cavity/waveguide interaction involved and thus

$$s_{-1,-2} = e^{-j\beta d_1} s_{+2,+1}. \quad (6)$$

The waves are continuous at the interface between two four-port systems. For example,

$$s_{\pm 2} = s_{\mp 5}, \quad (7)$$

$$s_{\pm 4} = s_{\mp 7}. \quad (8)$$

We assume $e^{j\omega t}$ time dependence for both the cavity mode and the propagation mode in the waveguides. Port 1 is chosen as input and the initial conditions are

$$s_{+1} = 1, \quad (9)$$

$$s_{+3} = s_{+11} = s_{+12} = 0. \quad (10)$$

Solve the equations above and the intensities of the outgoing waves are found to be

$$\left|s_{-1}\right|^2 = \left|\frac{e^{2j\beta d} S((1 + e^{2j\beta d})S - 1) - 1}{S(e^{2j\beta d} S(S+1) - 2)}\right|^2, \quad (11)$$

$$\left|s_{-3}\right|^2 = \left|\frac{e^{2j\beta d} S^2 - (1 + e^{2j\beta d})S + 1}{S(e^{2j\beta d} S(S+1) - 2)}\right|^2, \quad (12)$$