We demonstrate an add–drop filter based on a dual photonic crystal nanobeam cavity system that emulates the operation of a traveling wave resonator, and, thus, provides separation of the through and drop port transmission from the input port. The device is on a 3 × 3 mm chip fabricated in an advanced microelectronics silicon-on-insulator complementary metal-oxide semiconductor (SOI CMOS) process (IBM 45 nm SOI) without any foundry process modifications. The filter shows 1 dB of insertion loss in the drop port with a 3 dB bandwidth of 64 GHz, and 16 dB extinction in the through port. To the best of our knowledge, this is the first implementation of a port-separating, add–drop filter based on standing wave cavities coupled to conventional waveguides, and demonstrates a performance that suggests potential for photonic crystal devices within optical immersion lithography-based advanced CMOS electronics–photronics integration. © 2015 Optical Society of America

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Wavelength division multiplexing (WDM) has become a promising scheme for high-capacity optical interconnects and communications [1]. Channel add–drop optical filters are a critical component for WDM, and have been previously demonstrated in microring resonators [1,2] whose traveling wave mode structure enables complete separation of input, drop, and through ports without the need for optical circulators. Photonic crystal (PhC) nanobeam cavities [3,4] have tight optical mode confinement and high-quality factors, enabling applications in many photonic devices including lasers, sensors, nonlinear, and opto-mechanical devices [5–8]. However, their use in add–drop filters is complicated by the inability of a standing wave resonator to separate input, through, and drop ports. This is because a standing wave resonator couples light into traveling wave modes of opposite propagation directions in its side-coupled buses, while in direct “edge-coupling schemes,” the input and reflected light coexist in the same physical port. In previous demonstrations of wavelength filtering in a PhC nanobeam cavity [8,9], a circulator is required to route the reflected wave into a through port, making it impractical for use in cascaded channel add–drop filters. Although cascaded filters for WDM applications have been proposed [10] and realized [11] in two-dimensional photonic crystal slabs, these devices rely on filtering by the waveguide itself (via heterostructure interfaces), in addition to cavities, effectively containing more components. Over 15 years ago, Manolatou et al. proposed that a channel add–drop filter could be implemented in a pair of coupled standing wave resonators [12]. However, to date this concept has not been demonstrated.

In this Letter, we demonstrate an efficient channel add–drop filter based on a pair of photonic crystal nanobeam cavities, which is directly integrable into an on-chip WDM scheme without any magneto-optic components. This device was implemented in an unmodified 45 nm SOI CMOS process, on a chip fabricated in a commercial microelectronics foundry [2,13]. The measured filter has 1 dB of insertion loss, 16 dB of through port extinction, and a 3 dB bandwidth of 64 GHz. Thus, this Letter lays the groundwork for greater utilization of photonic crystal devices in complex photonic chips. The cavities are not tuned, and the fidelity of the process is shown to be high enough to ensure degeneracy of the two adjacent PhC cavities.

The add–drop filter design proposed here consists of two identical photonic crystal nanobeam cavities and two waveguide buses with four ports [see Fig. 1(a)]. Light is coupled into the filter via an arbitrarily chosen input port. The two PhC cavities are spaced apart, and, thus, not directly coupled to each other, although direct cavity coupling can be of utility [12]. Each bus is evanescently side-coupled to both cavities with equal coupling strength, resulting in indirect coupling between the two PhC cavities and formation of symmetric and anti-symmetric supermodes. The indirect coupling between cavities is sensitive to the optical phase delays in the two connecting paths between the two cavities, denoted by $\phi_1$ and $\phi_2$. When the two phases are engineered appropriately, the two standing wave supermodes have degenerate resonant frequencies and decay rates, and light coupled out of the cavities interferes destructively in the input port and in one port in the other bus. As a result, the dual-PhC cavity system acts like a
single-mode traveling wave filter [see Fig. 1(b)], with all off-resonant light coupled to a through port and all resonant light coupled to a single drop port (limited only by optical loss in the cavities). In contrast, light resonant with a single PhC cavity couples equally to all four ports, leading to a maximum of 25% transmission to any port.

To analyze the effect of the two cavities that do not have identical resonant frequencies (e.g., because of fabrication errors), the coupled mode theory model in [12] was modified to include a resonant frequency difference between them:

\[
\frac{d \phi_1}{dt} = (j \omega_1 + \delta \omega) - 2r_o - r_s \phi_1 + \sqrt{r_e e^{j \theta} s_{n+1} - r_e e^{j \phi_1} a_R} - r_e e^{j \phi_1} a_R, \tag{1}
\]

\[
\frac{d \phi_2}{dt} = (j \omega_2 - \delta \omega) - 2r_o - r_s \phi_2 + \sqrt{r_e e^{j \theta} s_{n+1} - r_e e^{j \phi_2} a_L} - r_e e^{j \phi_2} a_L, \tag{2}
\]

where \( r_o \) is the decay rate to the bus or the receiver, \( r_s \) is the decay rate because of loss in each cavity, \( \omega_o \) is the average of the resonant frequencies of the two cavities, \( \delta \omega \) is half of the resonant frequency difference between the two cavities, and \( \theta \) is the phase of the coupling coefficient from both the bus and the receiver. All decay rates are related to the intrinsic/unloaded \( Q \) and the individual waveguide external/coupling \( Q \) by

\[
\frac{r_o}{2Q_o} \quad \text{and} \quad \frac{r_s}{2Q_s},
\]

where \( \delta \omega \) is assumed to be small compared to \( \omega_o \). For the device to act as a traveling wave cavity, the phases \( \phi_1 \) and \( \phi_2 \) can be set so that the symmetric and anti-symmetric supermodes of the device are degenerate. For degenerate cavities, this occurs when

\[
\sin(\phi_1) + \sin(\phi_2) = 0 \quad \text{and} \quad \cos(\phi_1) = \cos(\phi_2) = 0 \quad [12].
\]

We see that not only the relative difference of the two phases, but also the absolute value of each individual phase must be set. The left drop port is the active drop port when this condition is met, and the right drop port acts as an add port. In the event of fabrication variations introducing a difference in resonant frequencies between the two cavities, the nondegenerate system has a nonzero transmission into the unused drop port. In this case, the crosstalk is minimized with the same choice of arm phase shifts. The field transmission to the through port and both drop ports, in the event of nondegenerate cavities at \( \omega_o \), is

\[
s_{s,2} = \frac{\delta \omega_2 r_e}{\delta \omega_2 + (2r_o + r_s)^2}, \tag{3}
\]

\[
s_{s,3} = -\frac{2r_o (2r_o + r_s)}{\delta \omega_2 + (2r_o + r_s)^2}, \tag{4}
\]

\[
s_{s,4} = \frac{-2r_o (2r_o + r_s)}{\delta \omega_2 + (2r_o + r_s)^2}. \tag{5}
\]

Equation (4) shows that the drop loss in the left drop port is not affected greatly by a small resonant frequency difference between the cavities, as \( r_o^2 \) is expected to be large compared to \( \delta \omega_2 \) in the denominator (i.e., the resonance mismatch smaller than the bandwidth). For low drop loss, if the fabrication process has good fidelity, individual cavity tuning may not be necessary (and is not used in the device presented here). Equation (5) indicates that crosstalk to the right drop port is proportional to the detuning between the two cavities. Crosstalk to the first order is \( \frac{\delta \omega_2}{\delta \omega_2 + (2r_o + r_s)^2} \), i.e., \( \frac{\delta \omega_2}{\delta \omega_2 + (2r_o + r_s)^2} \) or, in dB, \( X \text{ dB} = 10 \log_{10}(1 + \frac{\delta \omega_2}{\delta \omega_2 + (2r_o + r_s)^2}) \). For less than 20 dB crosstalk (1%), the cavities need to be detuned from degeneracy by <1/10th of the 3 dB bandwidth (FWHM). As expected, when \( \delta \omega = 0 \), absolute traveling wave operation occurs, and the system reduces to that in [12] (without a mutual coupling term).

The device was fabricated in an unmodified commercial microelectronics 45 nm SOI CMOS process, the IBM 12SOI process. The cross section of the device is illustrated in Fig. 2(a). The main challenge in design is the sub-100-nm silicon device layer thickness. Using photonic crystal microcavity designs similar to those in [15], two cavities were cascaded. A sinusoidal waveguide on the top path was used to bias the relative phase between the top and bottom

![Fig. 1. (a) Add–drop filter based on dual photonic crystal nanobeam cavities. The two identical cavities are indirectly coupled via two common buses. Their effective coupling depends on the optical phase delays in the connecting buses, denoted as \( \phi_1 \) and \( \phi_2 \). (b) Equivalent single-mode traveling wave filter when the two supermodes of the dual cavity system are degenerate, as satisfied by \( \cos(\phi_1) = \cos(\phi_2) = 0 \) and \( \sin(\phi_1) + \sin(\phi_2) = 0 \) [12].](Image 333x91 to 532x142)

![Fig. 2. (a) Cross section of a cavity in IBM 45 nm 12SOI CMOS (see PDK [14]). (b) Relative phase offset of about 3π/4 realized with a sinusoidal waveguide. (c) 3-D rendering of a device mask-set layout.](Image 448x155 to 528x247)
paths [Fig. 2(b)]. By biasing one of the arms, the phase tuning of the device can be simplified, but is not absolutely necessary. If included, the phases of both arms can be tuned near equally to bring the device to the correct operating point without having to adjust the relative phase difference. The additional phase gained in the top arm is near $3\pi/4$ for wavelengths around 1550 nm which was the designed photonic crystal resonant frequency. A bias of $\pi$ was not chosen because of fabrication tolerances. Figure 2(c) shows a three-dimensional rendering of the device layout mask levels. Two highly doped resistive heaters implemented in the crystalline silicon layer (the active layer for transistors) are placed next to each path to act as phase tuners. Both phase tuners are needed to bring both paths to the correct absolute phase and to fine-tune the relative phase between the two paths. Figure 3(a) is a top-view optical micrograph of a 3 $\times$ 3 mm die from a 300 mm, 45 nm node SOI CMOS wafer, and a zoom in view showing grating coupler access ports to the device (not visible, under metal density fill) and heater driving pads for driving probes. Figure 3(b) is a bottom-view optical micrograph of a fabricated device (grating couplers not shown) after the silicon substrate is removed.

The spectral response of the fundamental resonance of the device without any thermal phase tuning is shown in Fig. 4(a). Figure 4(b) shows the spectra of the device after tuning the $\phi_1$ arm to bring to the best performance possible in terms of through port extinction, and, in theory, setting $|\phi_1 - \phi_2| = \pi$. A more Lorentzian shaped through port is seen, but the drop port is still asymmetrical and the drop loss is large. $\phi_1$ and $\phi_2$ were then tuned equally in additional power until the lowest drop loss was achieved. This response is shown in Fig. 4(c). For this tuning of $\phi_1$ and $\phi_2$, the device has a through port extinction of 16 dB and an insertion loss of 1 dB through the left drop port on-resonance. Transmission to the right drop port is still below $-13.6$ dB, showing successful isolation of that port over the operational wavelength range. A 3 dB bandwidth of 64 GHz (a loaded Q of 3020) is measured. Detuning the phases slightly away from this point allows for a much higher suppression with an increase of insertion loss; this is shown in Fig. 4(d). The suppression of the right drop port is 23.1 dB, with a drop loss of 1.9 dB and a through port extinction of 15.4 dB. This demonstrates operation near the degeneracy condition and indicates a traveling wave resonator-like response.

The detuning between the two cavities and the intrinsic and external Qs of the device can be estimated by assuming that the fabricated bus and receiver coupling rates are equal, fitting the measured values for the insertion loss through port extinction and the add port suppression to Eqs. (3)–(5), and utilizing the measured loaded Q. The total detuning between the two cavities is fitted to be 5.4 GHz; the intrinsic Q of each cavity is fitted to be 18,350; and the external Qs to the bus and receiver are fitted to be 7240 (corresponding to a $\delta\omega$ of 16.9 Grad/s), a $r_\omega$ of 33.2 Grad/s, and a $r_\phi$ of 84.2 Grad/s. To investigate the benefit of thermal resonant frequency tuning being added to the cavities, Fig. 5 shows the theoretical performance of a device as a function of the difference of the resonant frequencies of the two cavities with $r_\phi$ and $r_\omega$ fixed to the estimated values. The drop loss and through port extinction are not greatly limited by the resonant frequency difference of the two cavities for this bandwidth. Instead, they are limited by the ratio of the intrinsic and external Qs, which can be improved by refining the photonic crystal cavity design. For these cavities, the drop loss is less than 3 dB, up to a resonant frequency difference of 27 GHz. However, the right drop port suppression decreases quickly with the resonant frequency difference. In theory, thermal tuning could have greatly increased the right drop suppression. At resonant frequency differences greater than 32 GHz, noticeable resonance splitting occurs in the left drop port response around the center frequency.

The demonstration of cascaded photonic crystal standing wave microcavities with a response similar to a traveling wave...
A cavity (ring resonator) enables photonic crystals to be used in an add–drop filter configuration with low insertion loss and large extinction in both custom silicon photonics and monolithic CMOS electronic-photonic circuits. The device shown can be cascaded to create a WDM mux/demux system that is comparable to systems previously realized with microring resonators, with performance relevant to communication system applications. Though the cavities shown here are not tunable, highly efficient tunable PhC nanobeams have been shown within this fabrication process [16] and could be used to tune the WDM channels as needed and to reduce the resonant frequency difference between the two microcavities, further increasing the drop port transmission, through port extinction, and add port suppression. A remaining challenge preventing wide adoption of such devices is the complex implementation. However, dense integration with electronics, as enabled in this monolithic scheme, has allowed complex feedback and control of photonic devices using on-chip circuits [17]. For example, the unused drop port could have a terminating photodetector to be used in a tuning and locking control circuit (and one could further take a tap from each cavity directly).

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**REFERENCES**


![Fig. 5.](image-url)