CHIN. PHYS. LETT. Vol. 30, No. 3 (2013) 034210

Ultracompact, Reflection-Free and High-Efficiency Channel Drop Filters Based on Photonic Crystal Nanobeam Cavities *

YU Ping(喻平)[1], HU Ting(胡挺)[1], QIU Chen(邱晨)[1], SHEN Ao(沈奥)[1], QIU Hui-Ye(邱晖晔)[1], WANG Fan(王帆)[2], JIANG Xiao-Qing(江晓清)[1], WANG Ming-Hua(王明华)[1], YANG Jian-Yi(杨建义)[1,3]**

[1]*Department of Information Science and Electronic Engineering, Zhejiang University, Hangzhou 310027*
[2]*Suzhou Institute of Biomedical Engineering and Technology, Chinese Academy of Sciences, Suzhou 215163*
[3]*Cyrus Tang Center for Sensor Materials and Applicatons, Zhejiang University, Hangzhou 310027*

(Received 27 August 2012)

We propose an ultracompact channel drop filter (CDF) based on photonic crystal nanobeam cavities. The conditions for implementing such an ideal CDF are derived from the temporal coupled-mode equations governing the operation of the CDF. By considering the intercoupling of the two involved nanobeam cavities, some ambiguities of the previous equivalent circuit model analysis are cleared up. Practical configurations on silicon-on-insulator (SOI) for the proposed CDF are suggested with a typical length less than 15 μm. Finite difference time domain (FDTD) method calculations show that the proposed filter can achieve drop efficiency higher than 99% without any reflection. Compared to the λ/4-shifted Bragg grating resonators based CDF, the proposed CDF is more compact, high-efficient and reflection-free. It is also easy to implement a low-power tunable filter due to the ultrahigh quality factor Q and ultrasmall modal volume V of the involved photonic crystal nanobeam cavities.

PACS: 42.79.Sz, 42.79.Ci, 42.82.Et, 42.82.Gw DOI: 10.1088/0256-307X/30/3/034210

Optical channel drop filters (CDFs) are essential components in many fields including integrated optoelectronics, optical communication, and interconnect systems.[1,2] These CDFs usually encompass some resonators, gratings or other wavelength-dependent parts. For instance, microring resonator[3] based CDFs were widely used as optical modulators, switches, routers, and other components in on-chip optical circuits. Like other channel-select components such as array waveguide gratings (AWGs),[4] a ring resonator based filter occupies a large footprint, which is undesirable in large-scale photonic integration. CDFs based on two-dimensional photonic crystal are also considered in order to realize an ultracompact footprint,[1,5] but actually the footprint is not as much smaller as claimed because these configurations require a number of ambient lattice cells.

Recently, Veerasubramanian *et al.*[6] demonstrated a compact λ/4-shifted Bragg grating resonator based CDF on a silicon-on-insulator (SOI) platform. The concept of this type of CDF was firstly proposed by Haus *et al.*[7] with the equivalent-circuit model and further analyzed by Damask[8] using the coupling mode theory in space. However, the CDF shows a relative low drop efficiency of 65% (theoretically) and its typical length is about 70 μm.[6,8] In addition, the unwanted reflection and the spectrum side lobe intrinsically involved in this CDF due to the presence of a grating are other critical issues that need be addressed.

In this Letter, we propose and analyze a CDF based on photonic crystal nanobeam cavities (PCNC). We recast the description and the explanation of its operation into temporal coupled-mode theory. Considering the intercoupling of the two involved PCNCs, we also obtain the condition for implementing a non-reflective CDF. Compared to the λ/4-shifted Bragg grating resonator, the PCNC endures lower intrinsic loss and features a ultracompact footprint.[9–15] The waveguide-perforated one-dimensional photonic crystal also opens up a wide bandgap due to its strong index modulation. With these merits, ultracompact configurations on SOI for the proposed CDF are suggested and are verified by using the finite difference time domain (FDTD) method.

Figure 1 shows the model of the proposed CDF, in which two highly-intrinsic-Q PCNCs (a and b) are side-coupled to the bus and a drop waveguide is directly coupled to the PCNC a. Intuitively, this structure allows the nonresonant wave to pass through the bus waveguide instead of being reflected toward the injection port. Here we focus on how to remove the unwanted but actually existing reflection at the input port and derive the condition that an ideal CDF can be achieved. By choosing the reference planes in the centers of the PCNCs and assuming that there is no direct mutual coupling between a and b, the temporal change of the normalized amplitude of the two PCNCs

*Supported by the National Natural Science Foundation of China under Grant Nos 60977043 and 61228501, the National Basic Research Program of China under Grant No 2012AA012203, and Tang Zhongyin Fund of ZJU.
**Corresponding author. Email: yangjy@zju.edu.cn
© 2013 Chinese Physical Society and IOP Publishing Ltd

is described by the temporal coupled-mode theory:[16]

$$\frac{da}{dt} = (j\omega_0 - \frac{1}{\tau_1} - \frac{1}{\tau_2} - \frac{1}{\tau_0})a + k_1(s_{+1} + s'_{+1}) + k_2 s_{+2}, \quad (1)$$

$$\frac{db}{dt} = (j\omega'_0 - \frac{1}{\tau_3} - \frac{1}{\tau'_0})b + k_3(s_{+3} + s'_{+3}), \quad (2)$$

where ω_0, ω'_0 and $1/\tau_0$, $1/\tau'_0$ are the resonant frequencies and decay rates due to intrinsic radiation loss of the PCNC a and b, respectively; s_{+i} and s_{-i} $(i = 1, 2, 3)$ are the amplitudes of forward and backward guided waves in various waveguides, as indicated in Fig. 1; k_i $(i = 1, 2, 3)$ is the input coupling coefficient associated with $1/\tau_i$ and phase θ_i:

$$k_1 = \sqrt{\frac{1}{\tau_1}} e^{j\theta_1}, \quad (3)$$

$$k_2 = \sqrt{\frac{2}{\tau_2}} e^{j\theta_2}, \quad (4)$$

$$k_3 = \sqrt{\frac{1}{\tau_3}} e^{j\theta_3}. \quad (5)$$

The decay rates of the PCNCs to the bus or the drop waveguide $\frac{1}{\tau_i}$ are related with partial Q_i using the relations $Q_i = \omega_0\tau_i/2$ $(i = 1, 2)$ and $Q_3 = \omega'_0\tau_3/2$.

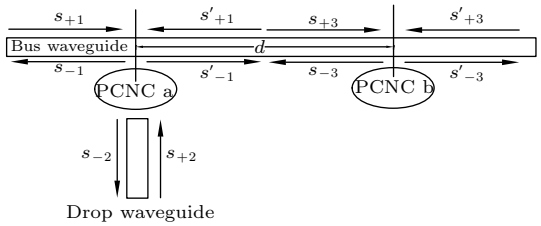


Fig. 1. Schematic model of the PCNC-based CDF.

It is important to note that Eqs. (1) and (2) are coupled equations through $s'_{+1} = s_{-3}e^{-j\phi}$ and $s_{+3} = s'_{-1}e^{-j\phi}$, where $\phi = 2\beta d$ is the phase retardation between the PCNC a and b. Using these relations and under the assumption $\frac{1}{\tau_0}, \frac{1}{\tau'_0} \ll \frac{1}{\tau_i}$ (the assumption is reasonable in the case of high-intrinsic-Q PCNCs), one can derive the drop and reflection of the CDF as

$$D(\omega) = \left|\frac{s_{-2}}{s_{+1}}\right|^2 = \left|\left[(j\omega - j\omega'_0)k_1k_2^* + (1 - e^{-j2\beta d}) \cdot k_1k_2^*\frac{1}{\tau_3}\right]\left\{\left[j(\omega - \omega'_0) + \frac{1}{\tau_3}\right]\left[j(\omega - \omega_0) + \frac{1}{\tau_1} + \frac{1}{\tau_2}\right] - \frac{1}{\tau_1\tau_3}e^{-j2\beta d}\right\}^{-1}\right|^2 \quad (6)$$

$$R(\omega) = \left|\frac{s_{-1}}{s_{+1}}\right|^2 = \left|\left\{\left[\frac{1}{\tau_1} - \frac{1}{\tau_2} - j(\omega - \omega_0)\right]\frac{1}{\tau_3}e^{-j2\beta d} - \left[\frac{1}{\tau_3} + j(\omega - \omega'_0)\right]\frac{1}{\tau_1}\right\}\left\{\left[j(\omega - \omega'_0) + \frac{1}{\tau_3}\right] \cdot \left[j(\omega - \omega_0) + \frac{1}{\tau_1} + \frac{1}{\tau_2}\right] - \frac{1}{\tau_1\tau_3}e^{-j2\beta d}\right\}^{-1}\right|^2. \quad (7)$$

Firstly, we consider a special and desired case that $\omega'_0 = \omega_0$. It is easily deduced from Eq. (6) that the CDF achieves 100% drop efficiency at $\omega = \omega_0$ when

$$\tau_1/\tau_2 = 2, \quad (8)$$

$$\phi = (2m + 1)\pi. \quad (9)$$

The above phase and decay rate conditions for complete dropping are the same as that derived from the coupling mode theory in space.[8] Moreover, we note that the reflection described by Eq. (7) is a frequency dependent function and always exists. Inserting Eqs. (8) and (9) into Eq. (7), one can derive that the reflection can be removed totally $(R(\omega) = 0)$ all over the studied frequencies if

$$\tau_1 = \tau_3. \quad (10)$$

Complete dropping can also be achieved when $\omega = \omega'_0$, $\omega_0 = (1 - \frac{\sin\phi}{\tau_1\omega_0})\omega'_0$ and $\phi = 2m\pi + \arccos(1 - \frac{\tau_1}{\tau_2})$,[17] whereas the reflection can not be eliminated according to Eq. (8). Generally, the PCNC b does not act like a pure mirror because of its indirect coupling with the PCNC a through the bus. According to Eqs. (1) and (2) of the coupled cavities system, the mode splitting due to the indirect mutual coupling is written as

$$\Delta\omega = \left[\left(\frac{1}{\tau'_0} + \frac{1}{\tau_3} - j\omega'_0 - \frac{1}{\tau_0} - \frac{1}{\tau_1} - \frac{1}{\tau_2} + j\omega_0\right)^2 + 4\frac{1}{\tau_1}\frac{1}{\tau_3}e^{-j2\beta d}\right]^{1/2}. \quad (11)$$

The mode coupling induced frequency splitting results in the two-peak lineshape, which is usually undesired in practical applications. Therefore, the CDF does not behave simply as a feedback system as claimed in Refs. [7,8,17], because the side-coupled PCNC b in the two-cavities-involved coupled system does not act as an independent mirror. Fortunately, under the condition described by Eqs. (8)–(10), one can observe that the mode splitting is eliminated ($\Delta\omega = 0$, assuming $\omega'_0 = \omega_0$ and $1/\tau'_0 = 1/\tau_0$). Therefore, to construct an ideal nonreflective Lorentz-lineshape CDF, Eqs. (8)–(10) must be satisfied at the same time.

Figure 2 shows the configurations of the proposed CDFs, which include two high-intrinsic-Q PCNCs. The devices are envisioned to be implemented on 220-nm-thick silicon with air cladding. The width of the bus waveguide is chosen to be 450 nm for single mode operation in the communication band. The bent sections in the bus waveguides are designed to control the coupling between the bus and the cavities without significantly decreasing the intrinsic Q of the cavities. Due to the linearly tapered lattice constants (the lattice constant a=430 nm is linearly tapered over a five hole section to a=330 nm and the radii of these holes are $r_i = 0.28a_i$) near the cavity

center, the separate PCNC supports a fundamental quasi-TE mode (electric field in the plane, we will only focus on the TE mode in this study) with an unloaded intrinsic Q_0 of 10^7 and an ultrasmall mode volume of $V = 0.39(\lambda/n)^3$.[9] The number of holes and lattice constants adjacent to the drop waveguide in the PCNC a are carefully engineered to obtain a desired τ_2 ($Q_2 \sim 1800$). It should be noted that in Fig. 3, the PCNC b can be put to the other side of the bus [Fig. 3(a)] or separated far enough with respect to the PCNC a [Fig. 3(b)]. The drop waveguides can also be coupled to the right-hand side of the drop cavity, which makes the path steering more flexible. However, here we investigate a typical configuration which is more neat and compact [Fig. 3(b)]. Although the two cavities are designed to be fabricated in the same nanobeam, it can be regarded as having no direct coupling if there is enough distance between them (that is the case a long nanobeam cavity we consider here). In the numerical calculation, τ_i is obtained using the relation $Q_i = \omega_0\tau_i/2$ and Q_i is calculated by

$$Q_i = \omega_0 \frac{\text{stored energy}}{i\text{th power lost}}.$$

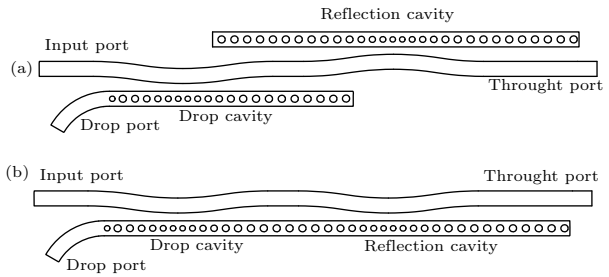


Fig. 2. Configurations of the PCNC based CDF.

In order to meet Eq. (8), we calculate Q_i as a function of p_d, the bus-drop-cavity pitch. As shown in Fig. 3(a), Q_1 increases gradually while Q_2 keeps nearly invariant around 1800 with the increasing p_d. Q_0 also keeps well above 10^6, which ensures the premise of $1/\tau_0 \ll 1/\tau_i$ reasonably. The optimal p_d satisfying Eq. (8) is derived from the data in this figure. A numerical transmission experiment confirms that the corresponding drop and the through efficiency are 44.35% and 44.64% in the case without the reflection cavity, respectively [Fig. 3(b)]. It is also observed that there are some reflections at resonance which can not be removed in the single-PCNC situation. To verify Eq. (9), we investigate the peak drop and reflection efficiency versus d, and the numerical results are shown in Fig. 3(c). However, as for the CDF in Fig. 3(c) where the τ_i is intentionally set to deviate from Eq. (10) ($\tau_1 \neq \tau_3$), the response spectra show some jitters and split double peaks (λ and λ'), which corresponds to the mode splitting predicted by Eq. (11). It is obvious that the reflection always exists over the d investigated.

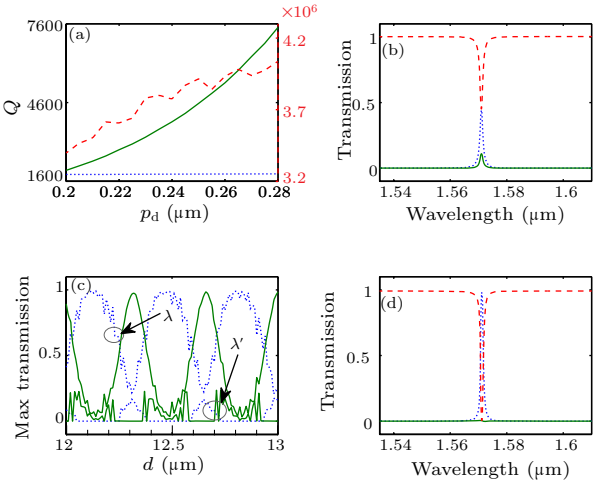


Fig. 3. Q_i (Q_2: blue, Q_1: green, Q_0: red) and transmission (drop: blue, reflection: green, through: red) of the CDF operating in TE-polarized mode. (a) Q_i and (b) transmission of the bus coupled drop cavity without reflection cavity, (c) peak transmission efficiency as a function of d, and (d) transmission of the optimized CDF.

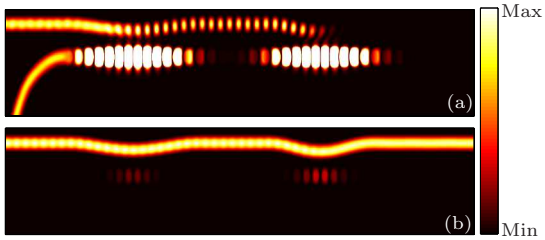


Fig. 4. Mode profiles (H_z of TE-polarized mode) of (a) drop and (b) through steady states of the CDF shown in Fig. 2(b).

In the presented configurations, the design is more flexible than that in the 2D photonic crystal regime.[1] Here d can be tuned continuously by changing the radius and range of the bends in the bus. Therefore, the design is not constrained by the discrete number of holes and lattice constants even in the case that the drop cavity and reflection cavity are adjacent (Fig. 2(b)). Figure 3(d) shows the transmission of the optimized CDF, in which all conditions in Eqs. (8)–(10) are satisfied. From Fig. 3(d), one can find that the reflection is thoroughly eliminated all over the studied frequency range and the maximum drop efficiency is larger than 99%. The steady-state TE-mode profiles of the optimized CDF are shown in Figs. 4(a) and 4(b), respectively. At the drop state, the modes are confined tightly around the cavity center and the fields in the PCNCs are enhanced significantly relative to that in the waveguides. These characteristics of the mode profiles account for the ultrasmall-V and ultrahigh-intrinsic-Q of the two PCNCs. Therefore,

it is beneficial to implement low-power active control using thermo-optics or the carrier dispersion effect of silicon.

In conclusion, we have proposed and investigated channel drop filters which are composed of conventional waveguides and photonic crystal nanobeam cavities. Temporal coupled mode theory analysis shows that it is possible to construct a nonreflective CDF based on high-Q photonic crystal nanobeam cavities by choosing appropriate parameters. The finite-difference-time-domain method confirms that the dropping efficiency of the proposed channel drop filters can approach 100% without obvious reflection. The effective length of a typical CDF implemented on SOI is only 15 μm, and so it is very promising for future on-chip large-scale integration. Due to the ultrasmall V of the involved cavities, the proposed CDFs can also be applied in low-power/high-sensitive tunable devices and would benefit an abundance of applications.

References

[1] Fan S, Villeneuve P R and Joannopoulos J D 1998 *Phys. Rev. Lett.* **80** 960
[2] Yu P and Ou H 2009 *Chin. Phys. Lett.* **26** 107802
[3] Little B et al 1997 *IEEE J. Lightwave Technol.* **15** 998
[4] Smit M and Van Dam C 1996 *IEEE J. Sel. Top. Quantum Electron.* **2** 236
[5] Fan S, Villeneuve P, Joannopoulos J and Haus H 1998 *Opt. Express* **3** 4
[6] Veerasubramanian V et al 2012 *Opt. Express* **20** 15983
[7] Haus H and Lai Y 1992 *IEEE J. Lightwave Technol.* **10** 57
[8] Damask J 1996 *IEEE J. Lightwave Technol.* **14** 812
[9] Deotare P B et al 2009 *Appl. Phys. Lett.* **94** 121106
[10] McCutcheon M W, Deotare P B, Zhang Y and Loncar M 2011 *Appl. Phys. Lett.* **98** 111117
[11] Yu P et al 2011 *Opt. Lett.* **36** 1314
[12] Desiatov B, Goykhman I and Levy U 2012 *Appl. Phys. Lett.* **100** 041112
[13] Pernice W H P, Xiong C, Schuck C and Tang H X 2012 *Appl. Phys. Lett.* **100** 091105
[14] Ryckman J D and Weiss S M 2012 *Appl. Phys. Lett.* **101** 071104
[15] Sergent S et al 2012 *Appl. Phys. Lett.* **100** 121103
[16] Haus H A 1984 *Waves and Fields in Optoelectronics* (New Jersey: Prentice-Hall) p 211
[17] Ren H et al 2006 *Opt. Express* **14** 2446