All-Photonic-Crystal Add-Drop Filter Exploiting Low Group-Velocity Modes

S. Olivier, H. Benisty(*), C. Weisbuch
Laboratoire PMC, Ecole Polytechnique, 91128 Palaiseau cedex, France
(*) also at LCFIO, Institut d'Optique, 91403 Orsay, France
hb@pmc.polytechnique.fr

C.JM. Smith, T.F. Krauss(**),
Optoelectronics Research Group, University of Glasgow, Glasgow G12 8LT, Scotland
(**) now at School of Physics and Astronomy, University of St Andrews, Fife, KY16 9SS, Scotland

R. Houdré, U. Oesterle
IPEQ, Ecole Polytechnique Fédérale de Lausanne, CH-1015

We propose and give a preliminary measurement of a compact, fault-tolerant add-drop filter based on coupling the fundamental mode to "slow" modes in a pair of adjacent photonic crystal channel waveguides.

Keywords: photonic crystals, coupled-mode theory, add-drop filter, losses.

Introduction

The hope that photonic crystals (PhC's) help implementing miniature integrated optics functions concerns particularly the add-drop filter (ADF) for WDM networks. While the 50%-drop function has been realised in the lab [1], the reproducibility of tiny high-Q cavities seems too delicate in real environments[2]. Furthermore, substrate-type PhC, require loss-compliant designs: the losses of photonic-crystal channel waveguides (PCCW) is expected to lie around 10-20 cm^{-1}.

We show here that using distributed action, inherent to the periodicity of PCCW's, together with low-group velocity modes, one can retain compactness but largely alleviate the difficulties encountered towards real-life devices. We did not fully explore all the potential and variants of the present proposal but have convincing theoretical and experimental data, illustrated by a specific examples as well as a first successful measurement at around 1000 nm on a GaAs substrate PhC.

The generally accepted scheme for a compact ADF between two adjacent waveguides comprises typically either two cavities [3] or a ring, supporting two quasi-degenerate resonant modes that ensure both selectivity (related to the cavity/ring Q) and directionality by interference of the two modes in the second guide. In a ring, the two counterpropagating whispering-gallery modes are used, but in PhCs, the splitting in ring-like systems is too large and only cavities are presently used.

Photonic crystal Add-Drop Scheme using Low-Group Velocity Modes : principle

Our compact design is based on adjacent coupled *multimode* photonic-crystal waveguides whose fundamental modes are used for propagation and well-defined higher modes for selective and directional coupling. In straight PCCWs themselves (carved in a triangular array of holes etched through a GaAs or InP heterostructure [4-6]), corrugation of the boundaries induces an inter-modal coupling [7], appearing as a mini-stop-band (MSB) or mode gap, (see also [8]). This coupling (Fig.1a) generalises the counterpropagating DBR. The advantage of PCCWs is to have specific coupling of the fundamental mode to very low group velocity modes fully confined in the guide and not leaking as they would in ordinary rib or stripe loaded waveguides. A signal launched in the input guide at the MSB normalised frequency u_o in the fundamental mode feeds a higher-order, low group velocity mode, which easily traverses the inter-guide "wall" (Fig.1b). Because it retains, through this process, a well-defined wavevector k, it undergoes the reciprocal coupling to the fundamental mode in the proper direction. A four-wave coupled-mode theory was devised to model the filter. The following formulation between the amplitudes A_1, A_2, B_1, B_2 of fundamental (A's, subscript a) and higher-order (B's, subscript b) modes in the upper (1) and lower (2) waveguides describes the core of the ADF :

$$\frac{d}{dz}\begin{pmatrix} A_1 \\ B_1 \\ A_2 \\ B_2 \end{pmatrix} = \begin{pmatrix} -i\delta_a & -i\kappa_{ab} & 0 & 0 \\ i\kappa_{ab} & i\delta_b & 0 & i\kappa_{bb} \\ 0 & 0 & -i\delta_a & -i\kappa_{ab} \\ 0 & i\kappa_{bb} & i\kappa_{ab} & i\delta_b \end{pmatrix}\begin{pmatrix} A_1 \\ B_1 \\ A_2 \\ B_2 \end{pmatrix}, \quad (1)$$

In this equation, κ_{ab} describes the mechanism of Fig.1a, whereas κ_{bb} describes the coupling between higher order "b" modes, "aa" coupling being neglected. δ_a and δ_b are the detuning with respect to the Bragg condition. Extreme asymptotic regimes are $\kappa_{ab} >> \kappa_{bb}$ (coupling of "b" modes is a perturbation to single MSB's)) and $\kappa_{ab} << \kappa_{bb}$ (there are two split modes $b_1 \pm b_2$ built from the "b" modes, and separate MSB effects occur with the two degenerate "a" modes). Note that we have separately validated the two-modes case (Fig.1a) for an isolated three-missing-rows PCCW ("W3") with the same losses as in [9], as will be presented elsewhere.

Using eqns. (1) and standard calculations, we find the optimal design *analytically* in the lossless case, when only mode "a" is launched in channel 1 and unity amplitude is imposed in the cross port ($A_2(L_{opt})=1$) and zero in the bar port ($A_1(L_{opt})=0$). Simply speaking, power flows through the barrier just at the same rate as it is created by the exciting wave. One finds :

$$\sqrt{\frac{\kappa_{bb}^2}{4} - \kappa_{ab}^2} = \frac{\kappa_{bb}}{3} \iff \kappa_{ab} = \frac{\sqrt{5}}{6}\kappa_{bb} \quad \text{and} \quad L_{opt} = \pi\left(\frac{\kappa_{bb}^2}{4} - \kappa_{ab}^2\right)^{-1/2} = \frac{3\pi}{\kappa_{bb}} \qquad (2)$$

Also, the quality factor Q at optimal condition is, fortunately, far smaller than the MSB width.

Design example with a pair of "W4" PCCWs

We consider an example based on 4-missing-rows ("W4"[CJMS]) PCCW's with a spacing formed by 4 rows of holes, shifted by $a/2$ to get PCCWs with symmetric boundaries (air-filling factor f=0.37 and background dielectric constant $\varepsilon=10.4$). Fig. 2a shows the mode dispersion relations for an isolated W4 waveguide computed by the plane wave method [7]. A minigap of width $\delta u_{ab} = 1.14\ 10^{-3}$ between modes a(#1) and b(#7) occurs at the normalised frequency $u_o = a/\lambda = 0.282$ ($n_{ga}=3.28$, $n_{gb}=71$) leading to a dimensionless coupling constant $a\kappa_{ab} = \pi\delta u_{ab}(n_{ga}+n_{gb})/2 = 0.133$. Then eq.(2), dictates $a\kappa_{bb} = 0.357$ for optimal operation.

A close value, $a\kappa_{bb} = 0.361$ is obtained for the 4-rows separation (we do not even change f to stress how easy first-order design is), related to a bb splitting $\delta u_{bb} = 1.62\ 10^{-3}$determined far from the MSB regions. Fig.2b shows the dispersion relation of the two coupled waveguides. The optimal length L_{opt} (cross operation) is then $L_{opt}=26a$, hence 11 µm in a $\lambda=1.5$ µm application ($a\sim0.44$ µm). Fig. 3 shows the bar and cross signal vs. frequency around the frequency u_o calculated in the lossless case by the coupled-mode theory. The peak at the u_o has a 98.7% transmission and a quality factor Q=1500. At the stage of the present proposal, there is a larger window (Q~100) related to the basic W4 MSB where partial transfer occur, especially at MSB edges. In the 100 or 50 GHz WDM scheme, with tens of close channels, this would restrain the use of the present filter to the specific case of interleaved set of signals, where sub-combs with e.g. 800 GHz spacings are used in local loops. However, clever extensions of the present scheme should alleviate this penalty. One simple way to limit the unwanted leakage at ~ constant κ_{bb} would be to insert an extra 24a-long cavity between the two parallel waveguides ([10]), as sketched in Fig.1c . One property of foremost importance in the WDM networks is the very neat zero at u_o to allow direct re-use of the dropped channel. We checked that this signal remains below 5% (-13 dB) for fluctuation of the air-filling factor $\delta f \sim \pm 0.01$ (in fact $\delta(a\kappa_{bb}) \sim \pm 0{,}01$), for losses α_b up to about 1200 cm^{-1} (note that n_{gb}=71.0, however) and losses α_a up to ~100 cm^{-1} (far more than published in the more lossy W3 case [6,9]). Losses even tend to make the bar-spectrum "flat-bottomed". Drop efficiency in this first proposal spans the range –1.5 dB to -4 dB with the same values. Finally, dropped power in the wrong direction takes the form of only a small amount of higher mode B_2 ($A_2(0)=0$) that will not sizably propagate back, i.e. crosstalk is by construction negligible. Detailed investigation of fault-tolerance among holes is the next step allowed specifically by, e.g. FDTD modeling [11].

Experimental realization based on "W3" and "W5" PCCW's

In our GaAs-based prototype, the air filling factor f~37%. The 60*a*-long guides have five-missing rows ("W5") along ΓK [5,7], and are separated by 5 rows. They are fed by three-missing-rows "W3" guides on all ports. For the a=260 nm period of the PhC, the ADF is 15 µm long. We excited at the focus of a laser diode the PL of InAs dots in the GaAs guide core and collected spectra at a nearby cleaved edge the guided PL light crossing the structures [5] as follows : Fig.4a, W5 guide alone, 100a-long, shows the 7-nm-wide MSB-dip at 920 nm [7-9]. Fig.4b shows that this dip is modified by the presence of the adjacent W5 guide, shifting to 930-935 nm. Fig.4c shows the energy dropped with Q~>100 at 935 nm in the adjacent waveguide, when detection is shifted to the adjacent channel. To avoid parasitic light from the through channel, its end is fitted with a "photon dumper" PC pattern that does not impact on the coupler. Grey lines are coupled-mode curves using the MSB fit of Fig. 4a. The Q degradation has here two extrinsic causes : out-of-plane losses of our basic PC structure [9,11] and losses induced by the embedded InAs dots [4]. It is obvious that in our prototype, the coupling length L and strength $a\kappa_{bb}$ were not adjusted to the optimum. However, the dropping effect is well present and this was checked for other separations and lengths.

Conclusion

We believe that photonic crystals have a good chance to go to real-life devices if the options exemplified here, namely distributed action and confined low-group velocity modes, are further pursued. Already at the present stage, we are able to envision acceptable performances penalties for modal propagation losses which are in the state-of-the-art range and a Q value of 1500 compatible with WDM. Enhancing the design to cover multiple channel ADF and making it adequate to close-spaced WDM channels seems at hand in the space of parameters yet unexplored. The future of this class of PhC-based concept is therefore extremely promising

The present work was supported by the EU IST project 11239 "PCIC".

[1] S. Noda, A. Chutinan, M. Imada, *Nature,* **407**, 608-610, 2000.
[2] Yoshie et al., Appl. Phys. Lett. **79**, 4289-4291, 2001.
[3] S. Fan, et al. *Phys. Rev. Lett.*, **80**, 960-963 (1996).
[4] D. Labilloy, et al., *Phys. Rev.*, **B59** 1649-1652, 1999.
[5] C. J. M. Smith et al. *Appl. Phys. Lett.*,**77**, 2813-2815, 2000.
[6] A. Talneau, L. Le Gouezigou, and N. Bouadma, *Opt. Lett.* **26**, 1259-1261, 2001.
[7] S. Olivier,et al., *Phys. Rev.* **B63**, 113311, 4 pages, 2001.
[8] C. J. M. Smith et al. *Appl. Phys. Lett.*, **78**, 1487-1489 (2001).
[9] E. Schwoob et al. *J. Opt. Soc. Am. B,* **VV**, ppp-ppp 2002.
[10] H. Benisty, S. Olivier, C. Weisbuch, French patent pending n°0207957
[11] H. Benisty, et al. *IEEE J. Quantum Electron.* **QE-38**, 770-785, 2002.
[12] M. Notomi et al. *Phys. Rev. Lett.* **87**, p.253902, 2001.

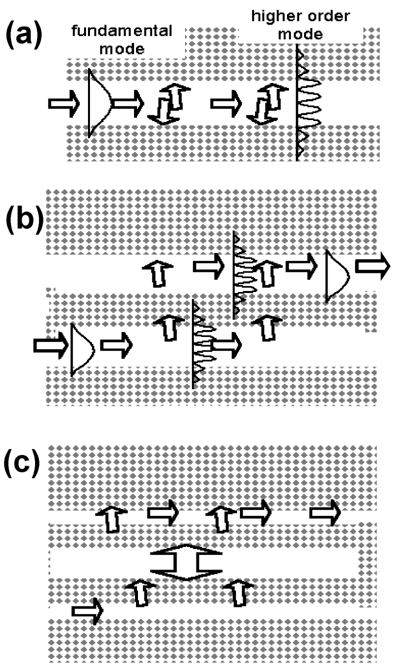

Fig.1 : (a) Principle of MSB in a multimode photonic-crystal waveguide, $\Delta k_{//} = 2\pi/a$ between the two modes; (b) the MSB-based Add-Drop Filter proposal ; (c) Insertion of an elongated cavity to raise the ADF selectivity.

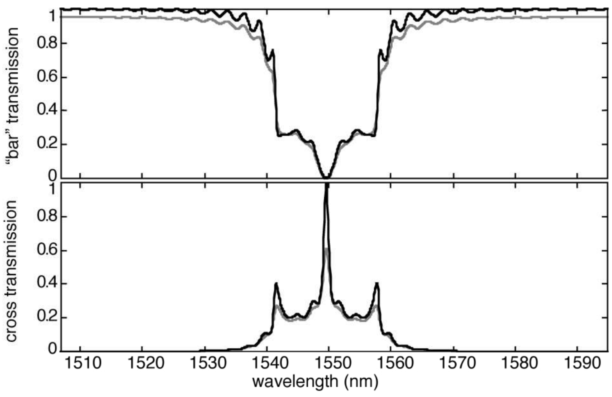

Fig.3 : black line : "bar" and "cross" transmission spectra as indicated, on a linear scale in the lossless case; Q=1600 at the peak ; grey line, same quantities with propagation losses α_a = 20 cm^{-1} (fundamental mode) and α_b = 400 cm^{-1} (higher-order mode)

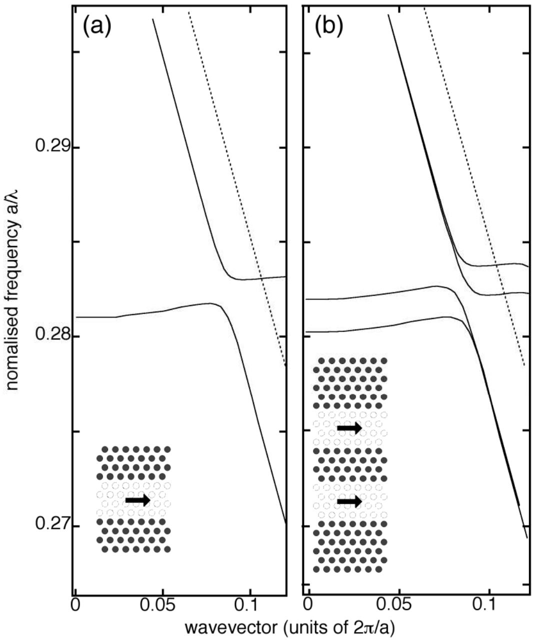

Fig.2 : (a) dispersion relation of an isolated "W4" waveguide; (b) dispersion of the two coupled waveguides at optimum of eq.(2).

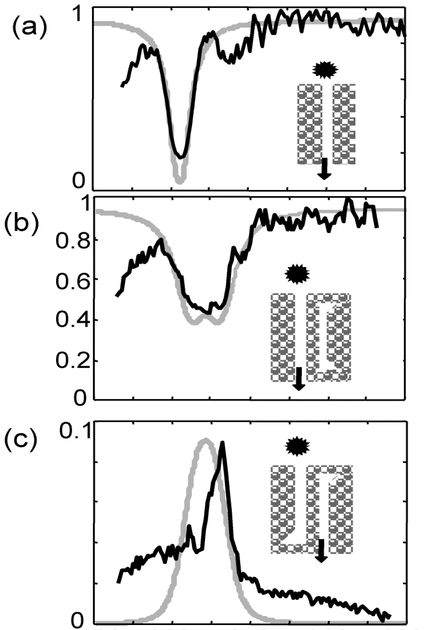

Fig.4 : (a) transmission spectrum through the W5 guide, with the MSB dip at 920 nm; (b) Same but now through the ADF, with 5 rows separation from the other W5; (c) Cross signal, Q~100. Note the triangular cavity, reflection-free, "photon dumpers" at guide ends to avoid collection of spurious signal.