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Low loss 2-port OADM using 1-D Photonic Crystal and 3-Port Optical Circulator

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Abstract

The simple architecture of a 2-port optical add drop multiplexer (OADM) using a 1-D photonic crystal (PC) filter and a 3-port optical circulator is presented. A low insertion loss of less than 2dB for express channels and 7dB for a drop channel is demonstrated using a superluminescent diode laser and an optical spectrum analyzer in the 1450nm-1650nm wavelength range. The channel isolation is 18dB. The main component of the OADM is the photonic crystal filter which is realized by a simple and low cost wet anisotropic etching of <110> oriented silicon. The pass band width of the drop channel at a peak wavelength of 1557nm is less than 7nm and a thermally induced wavelength drift of 0.04nm/K is experimentally measured. Therefore, this low cost solution is best suited for metro CWDM networks, where the channel spacing is 20nm.

1. Introduction

The ever increasing demands for bandwidth hogging applications like residential triple play services and high speed Internet have pushed the telecommunication industries to introduce wavelength division multiplexing (WDM) technology in the metro access network. In such a network, it is necessary to insert, remove or bypass traffic at certain network nodes for low latency dynamic provisioning of services. The network element which performs this task is known as Optical Add-drop Multiplexers (OADMs), Eldada et al [2006] and Sayeed et al [2007]. Apart from add-drop or bypass functionality, OADMs enable a flexible network by dynamically providing gain/power control, remote monitoring and configuration management. Two main types of OADMs deployed in the current metro access WDM networks are fixed OADMs and reconfigurable OADMs (ROADMs). Fixed OADMs operate on dedicated WDM channels while ROADMs enable a fully automated intelligent network by providing remote reconfiguration of WDM channels. Different technologies such as all fiber, Nykolak et al [1997], planar light wave circuit (PLC), Hattori et al [1998], and free space optics, Chiou et al [2001], are used for OADM architectures. These technologies have either high insertion loss or high cost which prevents their excessive deployment in metro and access networks where the major requirement is for devices with low capital outlay and low operational expenses.

A two-channel CWDM OADM has been reported by Paulo T. Neves Jr. et al [2006], which uses two large band width fiber Bragg gratings (FBG), two circulators and two optical switches. They reported a high insertion loss of 12dB for express channels and 4dB for drop channels. A channel switching add/drop multiplexer with a tunable FBG has been reported by Feng et al, [2000]. It uses two 3dB couplers and reported high insertion loss. In this paper, we report the architecture of a low loss fixed OADM using a 1-D PC filter and a 3-port circulator. The 1-D PC with a central planar defect layer realized by the wet anisotropic etching of (110) silicon acts as the add/drop module of the OADM. The optical add drop function of the OADM is analyzed using a superluminescent diode laser and an optical spectrum analyzer, and the insertion losses for the express and drop channels and the channel isolation are studied experimentally. We report insertion losses of less than 2dB for express channels and 7dB for dropped channels with a channel isolation of 18dB. Our OADM is best suited for operation in the coarse WDM used in metropolitan fiber optics networks in which the channel spacing is 20nm. The architecture of the OADM, design and fabrication of the PC filter and optical analysis of the OADM followed by a discussion of the results and conclusions form the rest of this paper.

2. OADM Architecture

The schematic of the proposed architecture of the OADM is shown in Figure 1. It is constructed using discrete passive optical components such as a 3-port optical circulator (OC) and a 1-D silicon/air PC which serves as a fixed drop module. The first port of the circulator acts as the input port *I* and the drop filter is connected to the second port of the circulator.

The input WDM signal is fed to the channel drop filter *F*. The filter then transmits a single WDM channel to the drop port *D* while reflecting all the others. The reflected power from the drop filter is then bypassed to port 3 of the circulator which serves as the express port *E*. A WDM signal at the

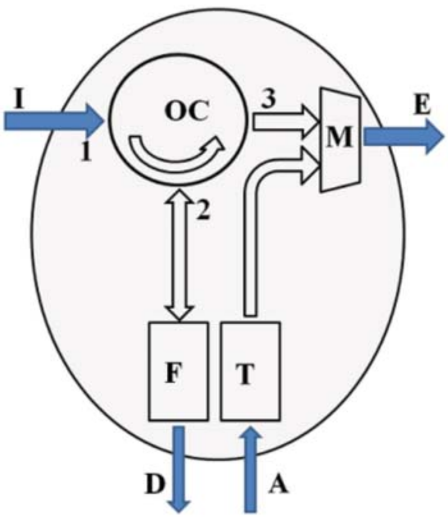


Figure 1. Architecture of the OADM

dropped wavelength is added to the add port *A* through a transmitter *T* and it is combined with the reflected signals from the drop filter by a multiplexer *M* at the express port.

3. 1-D PC Filter

The main component of the OADM is the channel drop filter realized in a 1-D silicon/air PC. Photonic crystals or photonic band gap (PBG) structures are periodic dielectric scatterers of higher and lower refractive index materials, [Joannopolous, 2007]. These periodic structures are known for their ability to completely reflect certain regions of the electromagnetic spectrum, hence forming a photonic bandgap (PBG) in which no electromagnetic eigen modes are allowed, this being similar to the energy band gap in semiconductor crystals. Light transmission can be triggered inside the PBG by either breaking the periodicity or introducing defect layers. This defect mode can be tuned to any frequencies inside the PBG by changing the properties of the defect layer, [Soukoulis, 1995; Lipson et al 2007; Mudachathi et al 2012]. Therefore one such device is explored in this paper as an optical channel drop filter for application in the architecture of an OADM. The channel drop filter explored in this paper is a one-dimensional silicon/air PC with a defect introduced by increasing the width of the central air layer. Each PC half on either side of the defect layer has three Si/air bilayers. The schematic representation of the filter is shown in Figure 2a.

The Si/air 1-D PC is modelled using the transfer matrix method (TMM). According to the TMM the propagation of an electromagnetic wave through each layer is described by a 2×2 matrix, [Busch et al 1996],

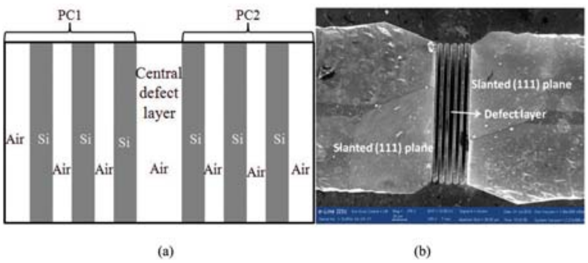


Figure 2. (a) Schematic of the 1-D PC with central defect layer forming a Fabry-Perot microcavity and (b) SEM of the PC filter

$$\begin{pmatrix} a_{n-1} \\ b_{n-1} \end{pmatrix} = M \begin{pmatrix} a_n \\ b_n \end{pmatrix}$$

Where

$$M = \begin{pmatrix} \cos\delta & i\eta^{-1}\sin\delta \\ i\eta\sin\delta & \cos\delta \end{pmatrix}$$

is the transfer matrix.

Where δ = kndcosϕ

$\eta = n\cos\phi$ for s – polarization

for p – polarization

And k=2π/λ, is the wave vector, n and d are the refractive index and thickness of the layer respectively and ö is the angle of incidence in the layer. The product of the characteristic matrices of all the layers gives the transfer function of the complete multilayered system, i.e.

$$\begin{pmatrix} a_{n-1} \\ b_{n-1} \end{pmatrix} = M_{tot} \begin{pmatrix} a_n \\ b_n \end{pmatrix} \quad (3)$$

where $M_{tot} = M_1.M_2........M_j$

Reflection and transmission coefficients are given by

$$r = \frac{m_{21}}{m_{11}} \quad (4)$$

and

$$t = \frac{1}{m_{11}} \quad (5)$$

respectively, where m_{21} and m_{11} are the matrix elements

Therefore, the reflectivity and transmissivity can be written as $R=r^2$ and $T=t^2$ respectively.

The PC filter is realized by etching vertical slits in (110) planar silicon using wet anisotropic etching. The detailed fabrication process steps and fabrication issues have been reported in our earlier publication, [Renilkumar et al 2011]. The SEM image given in Figure 2b shows the top view of the fabricated device with a central defect layer. Two slanted (111) planes inclined at 30^0 from the wafer flat are also visible on both sides of the PC layers due to anisotropic etching. The wet etching introduces asymmetry in the PC layers, i.e. the Si layer thickness is not uniform across the sample and the final structural dimensions of the sample measured from the SEM images are listed in Table 1. PC1 and PC2 refer to the photonic crystal structures on the left and right side of the central defect layer respectively.

Table 1: Structural details of the sample

Name	Si (μm)	Air (μm)	Si (μm)	Air (μm)	Si (μm)	Defect (μm)
PC1	3.15	5.9	3.93	6.4	3.57	7.398
PC2	3.25	6.31	3.73	6.64	3.24	

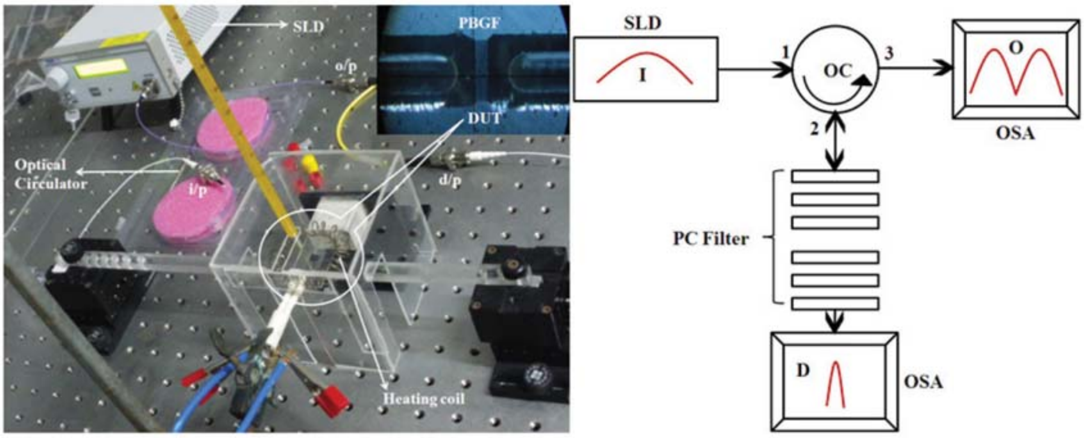
Therefore, each PC half on either side of the defect layer has distinct spectral characteristics and has been modelled separately using the transfer matrix method. Hence, the filter transfer function is modelled using the asymmetric Fabry-Perot approach in which each mirror is represented by geometrically chirped PC structures. The transmissivity of the asymmetric F-P cavity is estimated using the following equation,

$$T = \frac{(1 - r_1 r_2)^2 - (r_1 - r_2)^2}{(1 - r_1 r_2)^2 + 4 r_1 r_2 \sin^2(\delta/2)} \quad (6)$$

4. Optical Analysis of the OADM

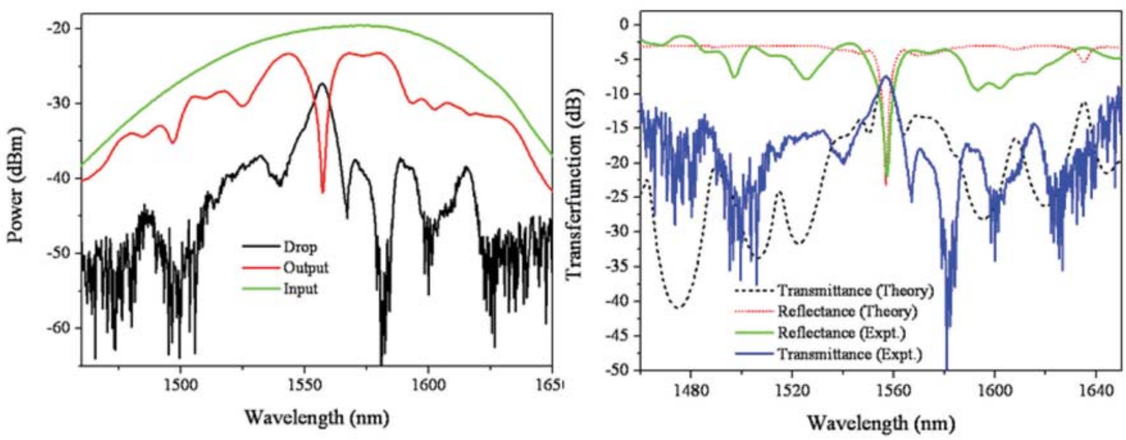
Figure 3 depicts the experimental test set up in which the superluminescent diode laser (SLD7957) of peak wavelength 1560nm and a FWHM of 93nm acts as the broadband light source. An optical spectrum analyzer (AQ6370) is used as a detector. Micro ball lensed fibers are used for coupling light in to and out of the PC filter. The insertion loss of the OC for ports 1 to 2 is 0.84dB and that for ports 2 to 3 is 0.85dB for a wavelength range of 1525nm-1610nm.

Figure 4 (a) depicts the superimposed spectrum of absolute power at different ports of the OADM. The green line represents the input power, the red line indicates the output power at the express port without the add channel and the black line represents the power at the drop port.



(a) (b)

Figure 3. (a) Photograph of the experimental set up (inset PC filter with fibers inserted in the grooves) and (b) a schematic of the same



(a) (b)

Figure 4. (a) The green, red and black lines represent the input, reflected and transmitted powers respectively and (b) compares the experimental results (solid lines) with theory (dotted line)

The peak wavelength of the dropped channel is 1557nm with a pass band width of less than 7nm. Figure 4 (b) compares the experimental (solid lines) and theoretical (dotted lines) transfer functions of the PC filter which configures as an OADM. The theoretical transfer function is simulated using the equation (6) in the general framework of the TMM. It also incorporates the insertion loss which is extracted from the experimental curve. It can be seen from Figure 4 that the insertion loss of the OADM for the drop channel is 7dB and the minimum loss for the output spectrum at the express port is 2dB. The channel isolation of our OADM is 18dB and the pass band width of the dropped channel at 1557nm is 6.48nm.

The high insertion loss for the drop channel is attributed to the coupling loss due to the fiber misalignment inside the fiber grooves and the geometrical asymmetry in the PC layers. This geometrical asymmetry within the PC structures (and hence with respect to the defect layer) will induce coupling variations between the eigenmodes of the defect layer (or the resonant modes of the FP cavity) and those at the band edges of the constituent PCs. This phenomenon is described in our previous communication, [Renilkumar et al 2011], in which we have explored the properties of

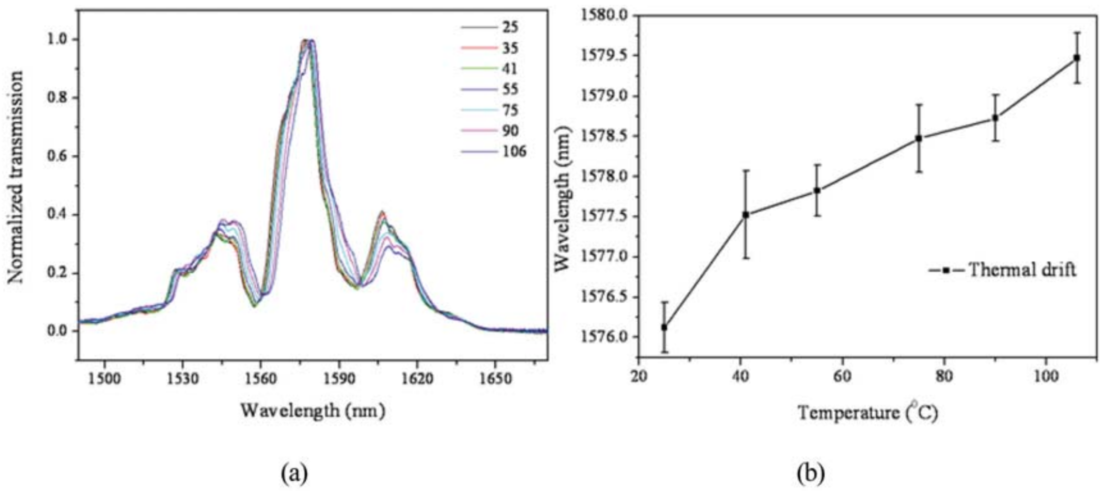


Figure 5. Spectral shift of the passband of the PC filter due to temperature variation (a) normalized transmission vs wavelength for varying temperature and (b) wavelength vs temperature

defect modes in geometrically chirped 1-D PCs.

The spectral shift of the pass band of one of the filters is measured experimentally by changing the ambient temperature around the device and is shown in Figure 5. The temperature varies from 25^0C to 106^0C.

The pass band shift measures 0.04nm/K. This is attributed to the combined thermo-optic effect and thermal expansion of the silicon layers. The overall performance of the OADM is summarized in Table 2.

Table 2: Optical performance of the OADM

Parameter		Value
Loss	Express port	2dB
	Drop port	7dB
FWHM		6.48nm
Channel isolation		18dB
Peak wavelength		1557nm
Wavelength drift due to thermal fluctuation		0.04nm/K

5. Conclusions

In conclusion, we have proposed a low cost solution for add/drop in metro CWDM networks. We have demonstrated the drop and express functionality of the OADM with low insertion loss. The wide passband width of 7nm can accommodate a thermal drift of 0.04nm/K for large temperature variations and spectral shifts of the lasers due to ageing. Therefore, this low cost and simple OADM can be used in the metro access network where the channel spacing is 20nm.

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