Design of an Optical Filter using Side Coupled Series of Optical Ring-Resonators

Yash R Bawankar and Anamika Singh

Department of Electronics and Communications Engineering, Visvesvaraya National Institute of Technology, Nagpur, India

yash.bawankar7@gmail.com, anamikasingh@ece.vnit.ac.in

Abstract

Silicon Photonics is one of the emerging technologies which offer variety of applications and several advantages over the current technology once unified with Photonic Integrated Circuits (PIC's). This integration of both the fields is possible due to over the decade research and the compatibility of PIC's which can be fabricated using the CMOS fabrication technique once they are designed and used along with Silicon Photonics technology. In this paper, a design of optical micro-ring resonator which includes multiple rings between two waveguides adjacently placed to obtain an optical filter to drop certain band of wavelengths has been proposed. These micro-ring resonators find various applications in different fields due to their high-speed readout, compact size and very low to almost zero electromagnetic interference.

Keywords: Silicon photonics, optical filters, micro-ring resonators.

1. Introduction

Optical micro-ring resonators can be considered as one of the best example amongst the passive photonic devices. An optical micro-ring resonator is basically an integrated optic travelling wave resonator which is constructed by bending and forming a closed loop of an optical waveguide, generally racetrack and circular shape [1]. When this round-trip length is exactly equivalent to an integral multiple of wavelength of light within the waveguide, large intensity buildup and sharp resonances occurs due to constructive interference of light inside microring cavity [2]. This is possible due to bus or access waveguides through which light couples in and out of the waveguide and the microring waveguide placed adjacent to it. Depending on the number of bus waveguides placed adjacent to the microring, they are classified into different configurations. Most common configuration are "All pass ring-resonator" and "Add Drop ring-resonator". Different configuration possesses different spectral characteristics and spectral response which is shown in Fig. 1.

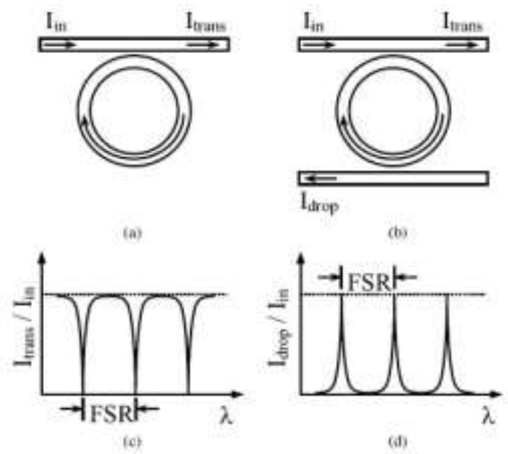

Figure 1 Two basic configuration of micro-ring resonators: (a) All Pass configuration. (b) Add-Drop configuration. (c) Spectral response at transmission ports in both configurations. (d) Spectral response at drop port in Add-Drop configuration [3]

On the basis of different configuration of microring resonators, transmission spectrum with single ring cavity placed adjacent to the bus waveguides shows dips after regular time intervals when the ring is in resonance i.e., they support multiple resonances [3]. Supporting multiple resonances is considered as one of the major property of microring resonators and spacing between respective resonances is called as *free spectral range* (FSR) which is directly proportional to the resonator length. In this way, due to its spectral response, a microring resonator can be utilized as a spectral filter in optical communication field. However, this spectral response changes due to several factors such as ring radius, distance between the waveguides, number of rings and also distance between waveguides and rings. Depending on multiple rings placed between the waveguides, two configurations named as coupled optical resonator and side coupled sequence of ring resonators were introduced.

In this paper, we have explored the side coupled sequence of ring resonators configuration of microring resonators to obtain an optical filter to drop certain band of wavelengths.

2. Theoretical Background on Optical Filters

A filter is a device or structure which alters characteristics such as phase, amplitude or group delay in a desired fashion of an input signal. Synthesis of optical filters is one of the most important applications of optical microring resonators. Due to their compact size and strong dispersive characteristics around a resonant frequency, ring resonators are widely used for construction of higher order integrated optical filters. In optical networks, important characteristic which makes optical microring resonators to be used as optical filters is their tunability. Micro-ring resonators also enables synthesis of large scale photonic integrated circuits due to their small dimensions and non requirement of grating and facets for optical feedback [4].

As shown in Fig. 2, all pass and add-drop ring resonators gives a sharp dip and highs in filter responses, they are mainly used to add and drop particular wavelengths. Hence are mostly used as optical notch filter. But to add and drop certain range of wavelengths i.e. to have control over certain band of frequencies, it was found that on adding multiple rings between waveguides similar ring resonators which acts as notch filter can be used as band stop filter [5]. This new design lead to new configuration with multiple rings namely coupled optical resonator and side coupled sequence of ring resonators configuration. The parallel cascaded array of add-drop and all pass microring resonators are called single-channel and dual-channel side coupled sequence of ring resonators, whereas serially coupled arrays are called as coupled optical resonator [6]. The double-channel side coupled sequence of ring resonators and coupled optical resonator configuration both demonstrate similar feature that distributed resonances with feedback results in photonic band structures which consists alternate transmission and stop bands in their spectrum [7].

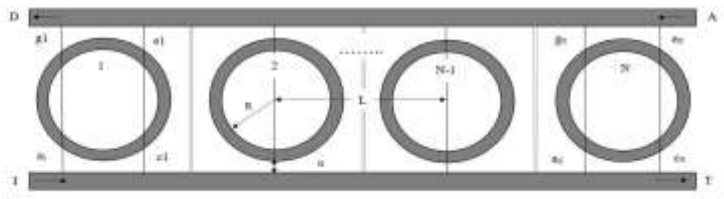

Figure 2 Sketch of a side coupled sequence of ring resonators configuration device consisting of N ring-resonators. L is distance between centres of two adjacently placed ring-resonators [7]

3. DESIGN OF SIDE COUPLED SEQUENCE OF RING RESPONSES CONFIGURATION

A single channel side coupled sequence of ring resonators where multiple rings are coupled to a single waveguide is not of much interest to investigate, since it's transfer function can be obtained by multiplying transfer function of single APF with the number of rings in the configuration. In Fig. 2, a side coupled sequence of ring resonators composed by N ring-resonators coupled indirectly between two waveguides is shown.

For calculating transfer function of N ring-resonators, we construct a new matrix $P_L{}^N$ to determine the fields propagating between *(N-1)-th* and *N-th* ring resonators [7].

$$\begin{pmatrix} a_N \\ g_N \end{pmatrix} = \begin{pmatrix} e^{-i\pi L\beta_S} & 0 \\ 0 & e^{i\pi L\beta_S} \end{pmatrix} \begin{pmatrix} c_{N-1} \\ e_{N-1} \end{pmatrix} \equiv P_L^N \begin{pmatrix} c_{N-1} \\ e_{N-1} \end{pmatrix} \tag{1}$$

where β_S is the propagation constant of the bus waveguide, L is distance between two ring-resonators. The suffix N indicates that all the resonators in the configuration can possess different parameters. Let us define matrix M^N which describes input and output fields of *N-th* ring-resonator. Hence overall matrix can be written as [7]:

$$\begin{pmatrix} a_N \\ g_N \end{pmatrix} = M^N P_L^N M^{N-1} \cdots P_L^1 M^1 \begin{pmatrix} c_{N-1} \\ e_{N-1} \end{pmatrix} \equiv s \begin{pmatrix} c_{N-1} \\ e_{N-1} \end{pmatrix} \tag{2}$$

As shown in Fig. 2, we will consider the configuration as ideal side coupled sequence of ring resonators, where the rings are identical and are separated by similar distances from each other. This side coupled sequence of ring resonators configuration also has two photonic bands i.e. bragg band (BB) and resonators band (RB) [8].

The condition of resonance for RB is that optical path in a ring resonator must be an integral multiple of wavelength ($m_R \lambda_R = 2\pi R n^b_{eff}$), where m_R is the order of the band, λ_R is the resonance wavelength, n^b_{eff} is the effective index of bend mode and R is the radius of the ring resonator. Whereas, the condition of resonance for BB is that optical path between centres of two adjacent ring resonators is half integral multiple of wavelength, i.e. $\frac{m_R \lambda_B}{2} = L n^s_{eff}$ [9]. Here, m_B is the order of the band, λ_B is Bragg Band wavelength, n^s_{eff} is the effective index of the straight mode and L is the distance between the ring resonators.

Our proposed side coupled sequence of ring resonators configuration is shown in Fig. 2. In Fig. 2, R is the radius of micro-ring resonator, G is the gap between micro-ring and adjacent bus waveguide whereas L represents distance between two respective microring resonators. Also, I represent input port from where input signal will be applied, D represents drop port where the wavelengths in resonance with ring cavity are obtained, T represents the transmission port where the remaining wavelengths not in resonance with ring cavity is measured and A represents add port from which additional wavelengths required or to be detected can be separately added provided they are in resonance with the ring cavity. Here we have used 8 rings for our side coupled sequence of ring resonators configuration i.e. N=8, where N is the number of rings in the design. We have used COMSOL Multiphysics 5.6 which is finite element analysis and multiphysics simulation software.

4. Results and Discussion

In this section, we have demonstrated our proposed model in COMSOL Multiphysics 5.6 software for side coupled sequence of ring resonators configuration of 8 rings. Fig. 3. shows the simulation of side coupled sequence of ring resonators configuration in COMSOL. For our design we have considered refractive indices of 3.48 and 1.45 for core and cladding respectively.

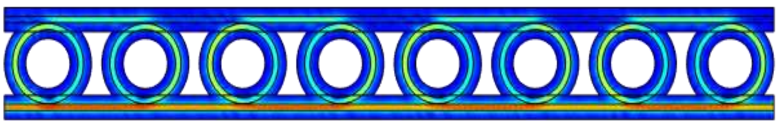

Figure 3 Simulation of proposed side coupled sequence of ring resonators configuration in COMSOL Multiphysics 5.6 software

The design parameters are: R = 1.6 μm, G = 0.931 μm and L = 4.5 μm. We have chosen width of core as 0.26 μm and width of cladding as 1μm. These parameters were chosen on the basis of the simulation performed on radius of the rings R and distance between them L as shown in Fig. 4 and Fig. 5 respectively. In Fig. 3 we can see that for R = 1.6 μm, power outflow at D port is around 0.95, which means power at input port I is coupled to D port, due to resonance within the ring. Whereas, for R = 1.6 μm if we vary distance between the rings, it was observed that for L = 4.5 μm maximum power couples to the drop port D from input port I. However, the range of the analysis was selected on the basis of calculations performed from equations

(1) and (2) respectively. On simulating the design over the range of wavelengths, we obtained reflectance, transmission and absorptance graph as shown in Fig. 6. As we can observe from the response graph, wavelengths from 1.54 μm to 1.55 μm shows the transmittance of value 0.1, means these band of frequencies are in resonance and hence their transmission coefficient is taking a dip.

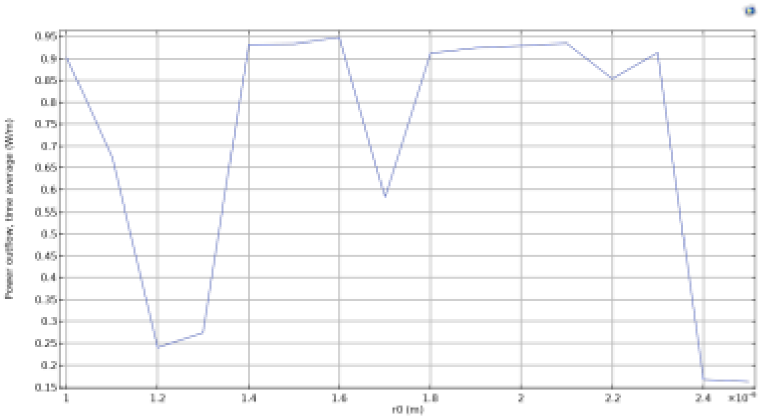

Figure 4 Power outflow (W/m) at port D with variation of ring radius R from 1 μm to 2.5 μm with step size of 0.1 μm.

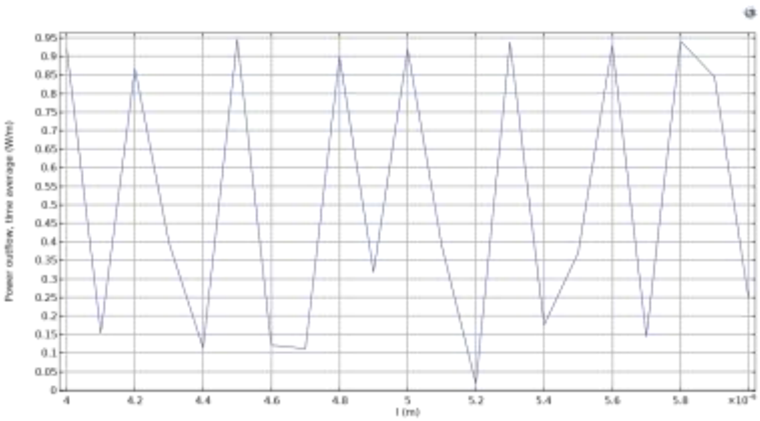

Figure 5 Power outflow (W/m) at port D with variation of distance between the rings L from 1 μm to 2.5 μm with step size of 0.1 μm.

When we compare this result with all pass notch filter which take a dip at the wavelength of the order 10^{-3}, this side coupled sequence of ring resonators configuration shows dip in transmission coefficient for the order of 10^{-1}. For optical frequencies where for large amount of bandwidths, frequencies are in nanometers, this dip for 0.1 μm range is huge or we can say 100 nm range of dip in optical frequencies. For optical frequencies range this configuration can easily be used to drop a range of frequencies. This transmission coefficient of 0.1 can be neglected for certain applications. However, further study is required with the coupling coefficient and certain parameters to rectify this error.

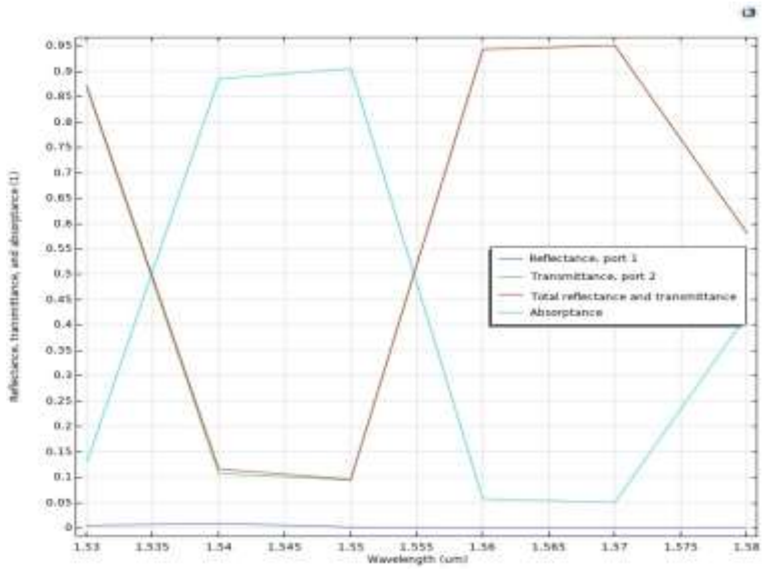

Figure 6 1.53 μm to 1.58 μm spectral response of designed side coupled sequence of ring resonators configuration for R = 1.6 μm, G = 0.931 μm and L = 4.5 μm

5. CONCLUSION AND FUTURE PERSPECTIVES

In this paper, a design to obtain an optical filter using side coupled sequence of ring resonators configuration of micro-ring resonators has been proposed. In this study we found that the optical micro-ring resonators with various different configuration along with suitable parameters can be used to obtain optical filters as per our need. The optical filter design also shows different behaviour for different number of rings, their radius and distance between them. These parameters must be primarily considered while designing the optical filter required for certain application. However, integration of Silicon Photonics and CMOS fabrication have led path and open various opportunities for fabrication of various Photonic Integrated Circuits (PIC's) at affordable prices which was never possible before. In our design study it was also observed that with increase in number of rings between the waveguides, the width of stop band can be increased. However, this was only observed for ring radius taken into account under study. This design can be further extended by studying the variations of ring radius between the two waveguides and also by choosing different materials having large refractive index difference between them.

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Biographies

Yash R Bawankar, currently in the final year of M.Tech in Communication System Engineering at Visvesvaraya National Institute of Technology. Academic interests consist of Optical Communication Systems.

Dr. Anamika Singh, works as an Assistant Professor at Electronics and Communications Engineering, Visvesvaraya National Institute of Technology. General interests include Optical Communication and Silicon Photonics.