Theoretical Analysis of Integrated Optical Nested Ring Coupled Dual Ring Resonator (NCDRR) For Filtering Applications

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Abstract

We propose and theoretically analyze a nested ring coupled dual ring resonator structure. A notch spectrum is obtained at the through port, with 3dB Bandwidth (BW) of 7 GHZ, Free Spectral Range (FSR) of 253 GHZ and Extinction Ratio (ER) well below -35 dB.The center frequency can be tuned with a range of 168 GHz. A coarse tolerance analysis is also presented to demonstrate the BW and FSR variation with respect to the device length.

1 Introduction

Integrated Optical Filters play prominent roles in wide range of applications like signal processing, communication, and spectroscopy. These devices have attracted great interest as they can fairly satisfy frequency selective requirements along with the inherent advantages such as low loss, high bandwidth, immunity to electromagnetic interference (EMI), tunability, and reconfigurability [1, 2]. Notch Filters are one of the key components in these photonic devices, which attenuates a small portion of frequency from a large spectrum. Optical microring resonators (MRRs) are used in such devices. Among these, double ring resonator with Mach-Zehnder interferometer (MZI), is quite popular structure for filtering applications [4]. Passive filters based on nested configuration are also explored for wavelength selective applications [5, 6]. Analysis of triple-coupler ring-based optical guided wave resonator for frequency division multiplexing applications has been analyzed [7], however, there is a need to improve the transmittance characteristics of integrated optical filters for filtering applications.

In this work, we propose and analyze a novel optical device configuration comprising of a nested ring coupled with two racetrack ring resonator. With proper selection of device length and coupling coefficient, the device is capable of generating a notch spectrum with tunable center frequency and ER well below -35 dB. The device has smaller footprint compared to other devices proposed in the literature [3]. Also a coarse tolerance analysis of length of device is provided, to show the change in BW and FSR.

2 Device Structure

The schematic of the proposed structure (top-view) is shown in Fig 1. This consists of a nested ring along with two rings and a bus waveguide. Coupling regions of NCDRR are shown by 1,2,3,4, which are incorporated using MZIs. To tune the center frequency, phase shifters PS1,PS2 and PS3 are used, which can be implemented by thermo-optic or electro-optic effects. The structure is a 2x2 port device, but in this paper, we have carried out the analysis considering A as input and B as oputput.

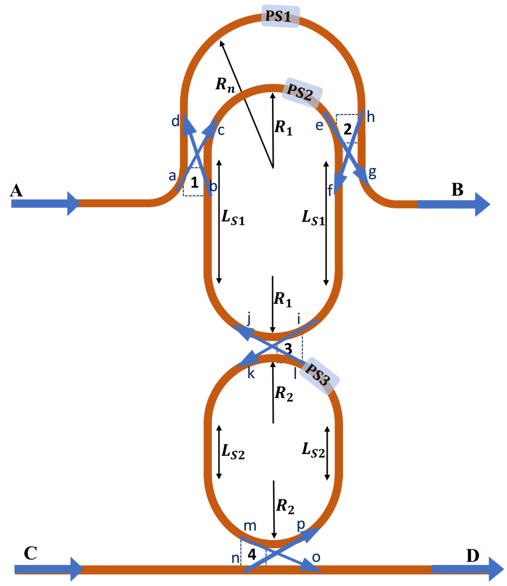

Figure 1. Schematic of nested ring coupled dual ring filter (blue color for field propogation direction).

We have considered the structure based on silicon on insulator (SOI).The analysis consists of propogation of the field in various coupling regions. Making use of effective index method (EIM), we reduce the 3-D waveguide analysis of NCDRR to 2-D analysis. The nested ring has the radius shown by R_n. The upper and lower rings has the racetrack configuration with bending radius and straight waveguide section shown by R_1, L_{S1} and R_2, L_{S2} respectively. The nested ring and resonator cavities has length of 280.44 μm, 514.14 μm, 350.55 μm respectively. All the phase shifters have the same value, which result in the tuning of center frequency without affecting the BW.

3 Mathematical Modelling and Transmittance Characteristics

When the input light is launched at port A, it encounters various coupling regions of NCDRR and depending on the coupling coefficient values, part of light is coupled and propagates to different section of the NCDRR. Various approaches have been illustrated to derive the transmittance characteristics of such configurations [7, 9]. We have solved the structure using Signal Flow Graph method, popularly known as Mason's Gain Formula. From input A to output B, we obtain a total of six forward propagating paths, as follows,

$$
\begin{aligned}
&F_1 = A \rightarrow a \rightarrow d \rightarrow h \rightarrow g \rightarrow B \\
&F_2 = A \rightarrow a \rightarrow c \rightarrow e \rightarrow g \rightarrow B \\
&F_3 = A \rightarrow a \rightarrow d \rightarrow h \rightarrow f \rightarrow i \rightarrow j \rightarrow b \rightarrow c \rightarrow e \rightarrow g \rightarrow B \\
&F_4 = A \rightarrow a \rightarrow c \rightarrow e \rightarrow f \rightarrow i \rightarrow j \rightarrow b \rightarrow d \rightarrow h \rightarrow g \rightarrow B \\
&F_5 = A \rightarrow a \rightarrow c \rightarrow e \rightarrow f \rightarrow i \rightarrow k \rightarrow m \rightarrow p \rightarrow l \rightarrow j \rightarrow b \\
&\quad \rightarrow d \rightarrow h \rightarrow g \rightarrow B \\
&F_6 = A \rightarrow a \rightarrow d \rightarrow h \rightarrow f \rightarrow i \rightarrow k \rightarrow m \rightarrow p \rightarrow l \rightarrow j \rightarrow b \\
&\quad \rightarrow c \rightarrow e \rightarrow g \rightarrow B
\end{aligned}
$$

Similarly for loops, we get

$$
\begin{aligned}
&L_1 = b \rightarrow c \rightarrow e \rightarrow f \rightarrow i \rightarrow j \rightarrow b \\
&L_2 = k \rightarrow l \rightarrow p \rightarrow m \rightarrow k \\
&L_3 = b \rightarrow d \rightarrow h \rightarrow f \rightarrow i \rightarrow j \rightarrow b \\
&L_4 = b \rightarrow d \rightarrow h \rightarrow f \rightarrow i \rightarrow k \rightarrow m \rightarrow p \rightarrow l \rightarrow j \rightarrow b \\
&L_5 = b \rightarrow c \rightarrow e \rightarrow f \rightarrow i \rightarrow k \rightarrow m \rightarrow p \rightarrow l \rightarrow j \rightarrow b
\end{aligned}
$$

After putting the terms in formula and rearranging, we get the output transmittance as:

$$T = |\frac{Nr}{Dr}|^2 \tag{1}$$

$$
\begin{aligned}
Nr = {} & c_4 e^{-j\beta(L_1+L_2+L_n)} - c_1 c_2 c_3 c_4 e^{-j\beta(L_2+L_n)} - \\
& c_3 e^{-j\beta(L_1+L_n)} + s_1 s_2 c_3 c_4 e^{-j\beta(L_{R1}+L_2)} + c_1 c_2 e^{-j\beta L_n} \\
& - s_1 s_2 e^{-j\beta(L_{R1})}
\end{aligned} \tag{2}
$$

$$
\begin{aligned}
Dr = {} & 1 - c_1 c_2 c_3 e^{-j\beta(L_1)} - c_3 c_4 e^{-j\beta(L_2)} + \\
& s_1 s_2 c_3 e^{-j\beta(L_n+L_1-L_{R1})} + c_1 c_2 c_4 e^{-j\beta(L_1+L_2)} - \\
& s_1 s_2 c_4 e^{-j\beta(L_n+L_1+L_2-L_{R1})}
\end{aligned} \tag{3}
$$

where,

$$
\begin{aligned}
L_1 &= 2\pi R_1 + 2L_{S1} \\
L_2 &= 2\pi R_2 + 2L_{S2} \\
L_{R1} &= \pi R_1 \\
L_n &= \pi R_n \\
\beta &= \frac{2\pi n_{eff}}{\lambda}
\end{aligned}
$$

β is the propagation constant and n_{eff} refers to the effective refractive index of the waveguide. λ is the wavelength of operation, c_i and s_i are the self coupling and cross coupling coefficients for i^{th} coupling region.

4 Results

The lengths and radii of the device is decided by Vernier effect, such that the resonance condition of the various rings are satisfied at the same time [10]. Coupling coefficients are optimized such that there are no ripples in the notch filter. The output spectrum of through port is shown in Fig 2. A notch of BW of 7 GHz and FSR of 253 GHz is obtained. Fig 3 displays the output in GHz scale, centered at 192.8 THz. As depicted from figure, the ER is well below -35dB. A tuning range of 168 GHz is obtained as shown in the Fig 4. The length of the device is chosen such that the spectrum retains its shape even by changing the length. The tolerance analysis of the device length, with change in BW and FSR is depicted in the Fig 5.

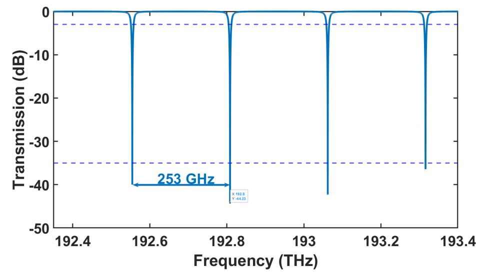

Figure 2. Transmittance characteristics.

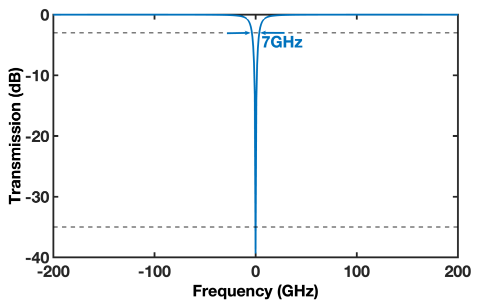

Figure 3. Transmittance characteristics centered at 192.8 THz.

5 Conclusion

We have proposed NCDRR structure which finds potential applications in filtering. In this paper, we have shown the

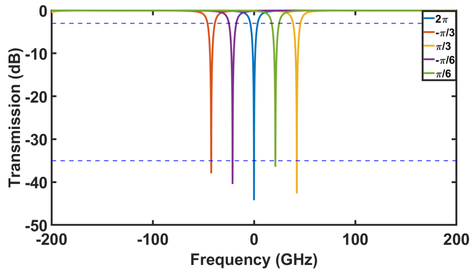

Figure 4. Tunable notch filter response with different values of phase shifters.

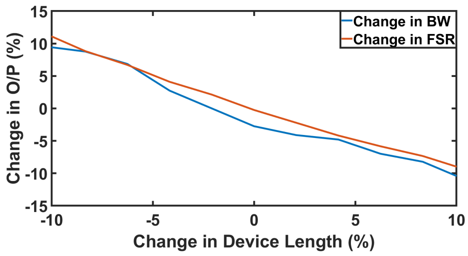

Figure 5. Tolerance analysis : Change in FSR and BW with respect to change in device length.

theoretical analysis of the structure which generates a tunable notch output with smaller footprint. By changing the length of device same notch response with a different set of BW and FSR can be obtained. The device is considered on silicon-on-insulator(SOI) technology which can be extended to other technologies as well.

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