Chapter 8

Summary and Conclusions
An attempt was made in this thesis for modeling of multiple optical ring resonators in z-domain and its performance as optical filter was evaluated in MATLAB environment. The key parameters of multiple optical ring resonators useful for multichannel communication systems, namely Free Spectral Range (FSR), crosstalk, dispersion etc. has been addressed in detail in the present thesis. Several structures of multiple optical ring resonators have been proposed and their mathematical modeling in z-domain has been developed in the present thesis. The performances of the proposed multiple optical ring resonators were evaluated in MATLAB environment.

The unresolved issues addressed in the present thesis to make multiple optical resonators based integrated optic device a more versatile and effective component in the field of efficient optical communication system are:

a) Requirement of very wide free spectral range (FSR) without impairing resonance characteristics and with minimum spurious transmission.

b) The appropriate device geometry for lower footprint and resulting higher integration density.

c) A trade-off between bending loss and FSR.

8.1 Conclusions

In Chapter 5 an FSR of 200 GHz was obtained using double ring resonator (DRR) with better design parameters like ring lengths of 13.39 and 14.42 mm and unit delay length of 0.103mm. A detailed view of all loops and paths of equivalent signal flow graph of a double ring resonator(DRR) have been shown in Figure 5.5 for easy and clear understanding and further analysis of such structure using Mason’s gain formula. Frequency response characteristics of such devices largely depend on coupling coefficients. It was observed that higher value of $\kappa_1$ is advantageous in enhancing the resonance peaks but at the same time it increases the secondary peaks, resulting in deterioration of cross talk level. A plot showing the variation of crosstalk and resonance losses with coupling coefficients have been given in Figure 5.6(b), from where optimal values of coupling coefficients can be determined. These results and analysis are far more superior in meeting the requirements of wider FSR.
Further a triple ring resonating device has been designed and its performance analysis has been carried out in Chapter 5. Ring lengths were designed as 11.90mm, 14.28mm and 16.32mm respectively with coupling coefficients of $\kappa_1 = \kappa_2 = 0.036$ and $\kappa_3 = \kappa_4 = 0.012$. Glass silica (with refractive index 1.456) has been used as waveguide material. A free spectral range (FSR) of 605 GHz was obtained. It is seen that as the values of $\kappa_1$ and $\kappa_3$ are increased, crosstalk values are increasing but the resonance loss decreases. Additional efforts have been made to find the optimum values of coupling coefficients. It is found that values of $\kappa_1 = \kappa_2$ varies between 0.0355~0.0364 and $\kappa_3 = \kappa_4$ varies between 0.0115~0.0124. Again a confirmatory scheme of triple ring resonator (TRR) was designed with ring lengths of 11.40 mm, 14.00 mm and 16.00 mm to produce FSR of 1029 GHz. Group delay and dispersion characteristics were also determined in both the cases. It was found that group delay and resulting dispersion are the maximum around resonant frequencies. Ideally, group delay should be constant so that dispersion will be zero. These key parameters are useful to select the operating regions judiciously to minimize the effects of group delay and dispersion.

The method of delay line signal processing in $z$-domain was further extended in analyzing higher order ring based devices also. A quadruple optical ring resonator (QORR) was designed and its performance as a filter was analyzed in Chapter 6. Ample instructions for finding different parameters like resonant numbers, $FSR$ extension factor $(a)$ etc. which were missing earlier have been provided. Also it is established fact that by reducing the ring length FSR cannot be enhanced infinitely, because beyond a certain limit this will give rise to several undesirable effects including bending loss. Further when optical waveguides are tightly curved, polarization rotation (PR) effects can arise which may severely impair the expected behavior of optical devices. When such bend waveguides are closed in forming ring resonator configuration, PR effects get enhanced at the resonance frequencies by light trapping and become strongly frequency dependent. So a bend loss model is typically used to estimate the critical radius for optimum performance. Vernier principle has been employed to enhance FSR using asymmetric ring lengths here. Further this principle is effective to suppress interstitial modes between two resonant peaks.

Although glass silica waveguide with moderate refractive index contrast ($\Delta n \%$) is a convenient means of fabricating ring resonator, performance of such devices is not
satisfactory as ultra-compact optical filter used in commercial DWDM systems. High index contrast material like Silicon-on-Insulator (SOI) is very much useful to mitigate the effect of bending loss with reduced footprint and thus enables higher integration density. Further SOI based devices are compatible with their electronic counterpart i.e., CMOS devices. For these novel characteristics microring resonators on SOI platform have great potential and future in the integration of electronic-to-optic(EO) or optic-to-electronic (OE) devices so that they can immensely help in realizing cost effective optical interconnects in future computing and communication systems.

Upto the Chapter 5 all the ring dimensions were in millimeter ranges. The advantages of using SOI as waveguide material helped ring resonator architecture further miniaturizing. Therefore, a fourth ring has been introduced in the existing triple ring resonator (TRR) architecture with ring lengths at micrometer range. In the novel quadruple optical ring resonator (QORR) architecture the fourth ring eventually modulates the effective unit delay to half in comparison to TRR and thus the FSR gets enhanced further. The FSRs obtained from different models are: 342.4THz (using SOI waveguides) and 264.6 THz (using SiN waveguides) with cross talks around -30dB and zero resonance loss in each case. Four such prototypes have been simulated with consistent results. Performance comparison is shown in Table 6.1. One model with superior parameter using SOI waveguide material is capable of providing yet another better result with FSR of 705THz with cross talk level of -35 dB have been achieved. A QORR structure with glass-silica waveguides and ring lengths in millimeter range have also been investigated to compare and contrast the performance (refer Table 6.1). Yet another QORR model in SOI material exhibits consistencies in its characteristics with an FSR of 1175 THz with crosstalk level around -50 dB. In all the cases group delay and dispersion characteristics have been investigated.

In Chapter 7, a model of Pentuple optical ring resonator (PORR) with five optical ring waveguides and six directional optical couplers have been analyzed. The asymmetric ring diameters were set to be 4.45 μm, 5.09 μm, 5.41 μm, 5.73 μm and 6.06 μm respectively. It is a proven fact that silicon on insulator (SOI) is effective in mitigating bending loss in ring waveguide. So device footprint can be reduced considerably. Two samples of SOI materials, one with effective refractive index 1.7 and
another with effective refractive index of 2.811 have been used as waveguide materials. From the first sample an efficacious FSR of 3527 THz with interstitial mode suppression up to -30dB was obtained. From the second sample an FSR of 2213 THz with interstitial mode suppression up to -35 dB was obtained. In the second case better results in terms of cross-talk was obtained at the cost of lower value of FSR. In both the cases the results were without resonance losses. Further, in both the cases, the split in the resonant peak is due to coupling and the number of splits is equal to the number of ring resonators in the series coupled ring resonator regardless of whether the ring lengths are asymmetric or not. Sometimes small mismatch in resonance frequency of the five individual microrings cause split in resonant peaks. Light scattering at sidewall roughness has its strongest effect on propagation. This roughness on the vertical sidewalls of the waveguide is unavoidable due to the nature of fabrication process involved. However, minimizing this roughness, split in resonant peaks can be controlled.

From Figure 7.2(b) calculated value of full width at half maxima (FWHM) is approximately 0.8 THz, which results in finesse of 4409. This is the maximum value of finesse obtainable out of two cases just discussed. The quality factor (Q) obtained from this design is $4.41 \times 10^3$.

The group delay and dispersion characteristics are also shown in Figures 7.2(c) and (d). Like in earlier cases, group delay and resulting dispersions are prominent around high resonant frequencies. Ideally, this dispersion should be zero. But in the present PORR architecture, there are certain regions where group delays are constant, i.e., these regions are independent of frequency or wavelength variation. So, those regions are relatively dispersionless. A judicious choice is to be made for optimal performance of this class of integrated optic devices. An interesting fact is that, in spite of using increased number of couplers in PORR architecture, loss does not increase.

FSR obtained from PORR structure is the maximum for the similar class of ring resonator devices and offers the best performance in terms of cross talk, resonance loss and finesse.

So far the issues mentioned at the beginning of this chapter have been adequately addressed through exhaustive mathematical modeling. Subsequently
mathematical results have been strengthened by software simulation using MATLAB, 7.9 version platforms. Better results can be obtained with a system of higher resolution.

### 8.2 Limitations of designing microring resonator based devices

To accommodate possibly a large numbers of communication channels in commercial dense wavelength multiplexed system (DWDM) a very wide Free Spectral Range (FSR) is necessary.

Mathematical expression for FSR can be written as

\[
\text{FSR} = \frac{1}{T} = \frac{c}{nL_u}
\]

(8.1)

It is obvious from Equation (8.11), that FSR depends on unit delay length \(L_u\). FSR expansion is possible by reducing the ring perimeter. But reduction of ring perimeter is not possible infinitely, because bending loss will creep in. As the bending radius decreases bending loss increases exponentially [1], a bend loss model is typically used to estimate the critical radius for optimum performance. To determine the minimal radius for a particular application, it is required first to determine the optimal quality factor (Q) for that application.

To counter the effect of bending loss, high index contrast waveguides are used. Bending loss in smooth, high index contrast rings is negligible. So the advantage of using high index contrast material is that device miniaturization is possible.

Therefore enhancement of Free Spectral Range (FSR) is possible by use of Vernier principle where rings of asymmetric diameter are serially coupled to get the resultant FSR increased.

But use of high index contrast material is not free from problems. Here the loss is mainly due to scattering because of waveguide sidewall roughness. The important point is that, the larger is the index contrasts; the more will be the scattering from sidewall imperfections.

Round trip loss (\(\gamma\)) in the waveguide discussed earlier mainly contributed by three sources; namely, propagation loss, coupler loss and bending loss. The relation between the losses is related by the following expression:

\[
\gamma [\text{dB}] = \gamma_{\text{propagation}} L + 2\gamma_{\text{coupler}} + 4\gamma_{\text{bend}}
\]

(8.2)
where $\gamma_{\text{propagation}}$ is the propagation loss per unit length.

Losses in the coupling section originate from propagation losses. Additional sidewall roughness affects the distributed intensity. Even from a mismatch in waveguide width caused by the fabrication process contribute to propagation losses.

If number of rings is increased to enhance FSR, there is a very good chance of increasing losses mentioned above albeit propagation losses are diminished with the use of high refractive index contrast waveguide material like SOI. Light scattering at sidewall roughness again has its strongest effect on propagation. This roughness on the vertical sidewalls of the waveguide is unavoidable due to the nature of the lithography fabrication process involved.

Directional optical couplers play vital role in coupling light wave from waveguide to the ring resonators. For higher order ring resonator structures, number of such directional optical couplers is also more. It is important to design ring resonator with better coupling control between the bus-ring and ring-ring waveguides and the ring to get desired spectral features. In multiple ring resonators devices, coupling gap between bus-to-ring and ring-to-ring play very crucial role. Even a nanometer-scale deviation on coupling gap may give noticeable effects on device performance. The complexity of such coupling will grow with increasing number of rings, limiting the size of ring resonator.

One major concern of using high index contrast SOI waveguide in ring resonator is that, these devices become very much dimension-sensitive. Even within the chip the ring resonators designed to be identical may not produce identical characteristics. This is due to non-uniformity in height and width of waveguide during fabrication using lithography and etching. Further sensitivity of resonance frequencies and bus-ring and ring-ring coupling to dimensional variations makes polarization-independent operation difficult to achieve in ring resonators made of high index contrast materials.

8.3. Future works

A roadmap of very wide Free Spectral Range (FSR) optical filter design based on waveguide based ring resonators have been provided in this thesis. These new design concepts need further experimental investigation which could not be undertaken due to lack of state-of-art infrastructural facilities, although the results are validated on the
basis of experimental works by other researchers. Device design and performance analysis done in Chapters 6 and 7 indicate that quadruple (QORR) and pentuple optical ring resonator (PORR) devices provide FSR in the terahertz (THz) range. So these devices may well be utilized to bridge the terahertz gap, the relatively unexplored region of the electromagnetic spectrum. Bragg gratings can be implemented using these ring resonator based devices. As resonance of these optical ring resonator devices largely depends on the optical path length and roundtrip losses accumulated, these devices are highly sensitive to a multitude of effects. So microring resonator based devices can be very attractive candidates for use in sensing applications.