Project Report On

"OPTICAL FILTER DESIGN AND SIMULATION USING RING RESONATOR IN SILICON-ON-INSULATOR"

Submitted in partial fulfilment of requirement for the award of degree of

BACHELOR OF TECHNOLOGY

In

ELECTRONICS & COMMUNICATION ENGINEERING

Submitted by

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Affiliated to Aryabhatta Knowledge University, Patna

MARCH 2022

Bhagalpur College of Engineering, Bhagalpur

Department of Electronics and Communication Engineering

CERTIFICATE

This is certified that the present project work entitled

"OPTICAL FILTER DESIGN AND SIMULATION USING RING RESONATOR IN SILICON-ON-INSULATOR"

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in partial fulfillment of requirement for the award of degree of Bachelor of Technology in**Electronics & Communication Engineering** to the **ARYABHATTA KNOWLEDGE UNIVERSITY, PATNA**, in an authentic record of our work carried out at **Bhagalpur College of Engineering, Bhagalpur,** under my supervision and guidance.

________________________ ________________________

Prof. Pushpendra Dwivedi
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Examined and approved on ______________

Internal Examiner______________________ External Examiner __________

Bhagalpur College of Engineering, Bhagalpur
Department of Electronics and Communication Engineering

DECLARATION

I, **Ravi Shankar (18104108015), Manisha Kumari (18104108019), Sumitesh Kumar (18104108025), Prabhat Priydarshi (18104108027)** Student of Bachelor of Technology (2018- 2022) hereby declare that the work which is being presented in the report entitled **"OPTICAL FILTER DESIGN AND SIMULATION USING RING RESONATOR IN SILICON-ON-INSULATOR"** in partial fulfilment of the requirement for the award of the **Degree of Bachelor of Technology in Electronics Engineering.** The work has been carried out at **Bhagalpur College of Engineering, Bhagalpur** (Affiliated to AKU Patna) and is an authentic record of my own work carried out under the supervision and guidance of **Dr. Parimal Sah (Asst. Prof. ECE dep.)**

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We express our sincere thanks and profound gratitude to **Dr. Parimal Sah** (Assistant Professor, Dept. of Electronics & Communication Engineering) for assigning us such an interesting project, for his guidance and constant supervision amid the study and implementation of this project. I acknowledge his valuable and timely help and morale boosting without which this project would not have been possible. His insights, knowledge, experience and technical skills have always guided me in my work.

We are also thankful to **whole Electronics & Communication Engineering department** for providing us the technical support to carry out the project work, to let us utilize all the necessary facilities of the institute and guidance at each and every step during project work.

I feel a deep sense of gratitude for my parents who formed a part of my vision and taught me the good things that really matter in life. I would like to thank family members for their support.

Thanking You

ABSTRACT

KEYWORDS: Silicon-on-Insulator, Ring Resonator, Waveguides, Integrated Optics ,Self coupling coefficient, Effective Index, Loss Coefficient, Radius of the ring, Resonant wavelength, 3-db Wavelength, Free Spectral range.

A wide free spectral range (FSR) quadruple optical ring resonator made of silicon on insulator (SOI) as an optical filter has been experimented in this project. We apply a ring resonator consist of waveguide which interacts with a ring through a coupler to implement a optical filter using a SOI material. In this project work, we varying the various input parameters like Self Coupling Coefficient, Effective Index, Loss Coefficient, Radius of the Ring and corresponding to varying parameter, we obtain different parameters like Resonant Wavelength, 3-db Frequency and Free Spectral Range. Ring Resonator inherently small size (with typically diameters in the range between several to tens of micro meters), their filter characteristics and their potential for being used in complex and flexible configurations make these devices particularly attractive for integrated optics or VLSI photonics applications. Ring resonator for filter applications, delay lines, as add/drop multiplexes, and modulators will be covered in this project. Lastly, we observe the graph of different parameters which is changing with respect to the varying different input parameters. Applications of this project as in medical science to detect cancer cells in the body, also as temperature sensitive device and as multiplexer and demultiplexer in communication system. For design and stimulation, we use MATLAB Software.

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LIST OF ABBREVIATIONS

SOI	Silicon-On-Insulator
TE	Transverse Electric
TM	Transverse Magnetic
FSR	Free Spectral Range
t	Self Coupling Coefficient
$\boldsymbol{n_{eff}}$	Effective Index
$\boldsymbol{\alpha}$	Loss Coefficient
r	Radius of the Ring
$\boldsymbol{\lambda_r}$	Resonant Wavelength($\boldsymbol{\lambda_r}$)
λ3-db	3-dbWavelength(λ3-db)
$\boldsymbol{n_g}$	Group Index

CHAPTER 1. INTRODUCTION

The ring resonators are typically used in integrated optics/optoelectronics to obtain functions like wavelength filters/add-drop multiplexers, modulators/switches, delay lines etc.

Passive optical filters made up of a periodic structure possess a stopband in their transmission spectra.

In this project, we apply a ring resonator consist of waveguide which interacts with a ring through a coupler to implement a optical filter using a silicon-on-insulator (SOI) material system.

1.1. Introduction of Ring Resonator:

A ring resonator is a very useful device that acts as a high-Q filter for applications that require wavelength selectivity. This type of device has many resonances, and only these resonant wavelengths are coupled to the output waveguide. All other wavelengths are allowed to pass uncoupled through the input waveguide, hence the ring resonator is essentially an optical notch. In the past few years, optical ring resonators have received a lot of attention as one of the most promising biological sensors. The optical ring resonator measures the target molecules through assessing the deviations in light behavior, which is caused by interaction between electromagnetic wave and biological molecules such as proteins, bacteria, cells, or DNA samples. This change in the behavior of the light is because of interaction between evanescent field of the resonating light inside the resonator and bioparticle that exist in the ambient. Existence of bioparticles in the medium changes the effective refractive index of surrounded medium, which results in deviation of resonance conditions of the resonator. Consequence of such an interaction is resonance wavelength deviation of the resonator that is related to the number for bioparticles in the medium. A sensing mechanism is depicted schematically . To enable the periphery of the resonator to absorb bioparticles, an active polymer layer can be deposited on the boundary of the resonator. This layer is able to mechanically absorb or chemically react with the target bioparticle, resulting in a change in the effective refractive index of the resonating mode.

In general, ring resonators can be designed and fabricated in two models. First model is optical fiber configuration in which a ring resonator can be realized by connecting both the ends of an optical fiber. Another optical fiber can be used to couple light into the ring. The second model is integrated optical structures (which is created by integrated optics technology). Optical resonators built with this method are repeatable and more reliable. Integrated ring resonators enable parallel detection of multiple bioparticles simultaneously by fabrication of identical ring resonators on the same chip and activation of each of them with a different active layer. The latter is the subject of interest in this paper, in which a waveguide is fabricated near the ring resonator and is utilized to inject light to the ring. This happens because of evanescent nature of the propagating light through the waveguide. High-contrast refractive index between resonator and surrounding medium makes it possible to have a higher sensitive as well as more compact resonator. Silicon with high refractive index 3.47 and advanced nanofabrication technology (microelectronics technology) are one of the best choices to develop high sensitivity integrated optical resonators.

1.1.a. Device Layout

The structure used in this example consists of waveguides that are 0.2 μm in width, and have a refractive index of 3. We will be looking in detail at resonances around a wavelength of 2 μm. These waveguides are separated from the ring by 0.2 μm, and the inner and outer radii of the ring are R-width/2, and R2=R+width/2, respectively, where R=1.7 μm.

1.1.b.Theory of Optical Ring Resonator:

To make an optical ring resonator, a single-mode waveguide can be bent at its both ends that meet each other. The cavity made by this way can capture and immure the light at certain wavelengths. At resonance wavelength, the propagating light inside the ring, after completing one round trip, constructively interferes with itself. The constructive interference of an electromagnetic wave trapped inside a closed medium can be written as follows:

$$kd = 2\pi m \qquad (1)$$

where $k = nk_0$ is the wave number of the light, *d* is the distance between forward and backward waves in a standing wave or the distance of one round-trip for a propagating wave, and *m* is the resonance mode. For a ring resonator, someone can replace *d* with perimeter of the ring and substitute $k = 2\pi n_{eff}/\lambda_0$, in which n_{eff} is the effective refractive index of the resonating mode and

λ_0 is the free space wavelength. Applying the aforementioned changes to Equation (1) and rearranging the parameters, following relation is obtained:

$$\lambda_0 = \frac{2\pi n_{eff} R}{m} \qquad (2)$$

Where *R* is radius of the ring. This equation clearly indicates that changing the effective refractive index of the mode due to existence of bioparticles leads to a change in the resonance wavelength.

The principal concept of two different configurations of optical ring resonators that has been presented in the next section is depicted here. On the basis of the number of couplers that interacts with the ring resonator, optical ring resonators could be divided into different categories. The one with one coupler is named all-pass filter, and the resonator that interacts with two waveguides is of add-drop configuration. The spectral response of these two different configurations has been extensively described in literatures.

All-pass Filter

Structure with one waveguide, called all-pass optical filter. Role of the waveguide is to couple light into the resonator. As it is one input and one output port can be introduced for this filter. The output port usually is named through port. The optical signal injected to the input port propagates through waveguide to reach to the coupling region, which is the area of waveguide with minimum distance with ring resonator. In this section, a part of light evanescently couples to the ring. Amount of coupling depends on the gap spacing between waveguide and ring, as well as matching between propagation constant of propagating mode through the waveguide and resonating mode inside the ring. The coupled light at resonance wavelengths traps and builds up energy inside the ring. At other wavelengths, the light passes through coupling region and reaches to the through port.

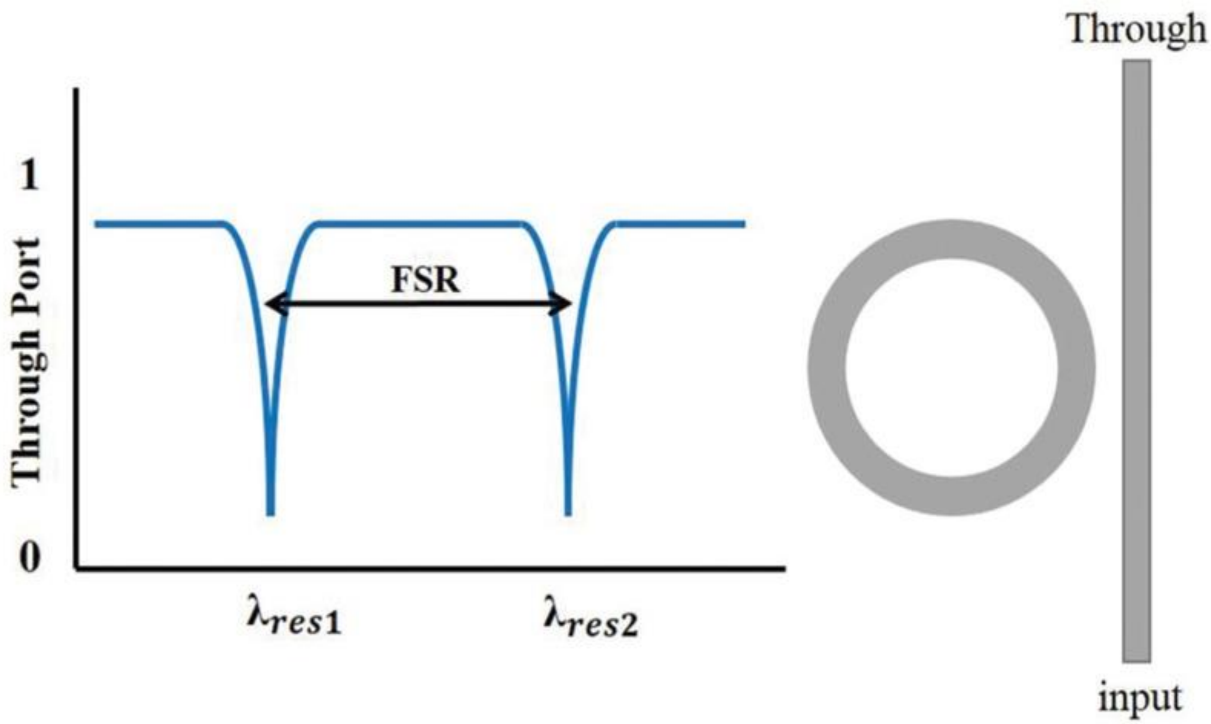


Figure 1:All-pass ring resonator and its typical spectral response

1.1.c. Theory of Lumerical Suite

- Lumerical Suite is a powerful application which is used for designing and analyzing the photonics.
- This software is used for photonics as well as electromagnetism from composite to system stages.
- This latest edition of Lumerical analyzes the integrated photonics, photovoltaics and electron or photonic design tools are offered.
- Improved electronic applications which include regulated thermal waveguides, modulators and switch matrices.
- Four parts of Lumerical which include FDTD, MODE, INTERCONNECT and DEVICE.
- FDTD solves Mathematical equations directly without any physical approximation.
- The MODE serves as the full space for the waveguide design for analysis and optimization of integrated and flat optical waveguides.
- This software is able to inject limited and measured beams with the steady gradients which does not change with frequency.
- FDTD solves Mathematical equations directly without any physical approximation.

The Finite-Difference Time-Domain (FDTD)

- We have extended our work beyond this we have validated all the theoretical result with FDTD simulation.
- The Finite-Difference Time-Domain (FDTD) method is a rigorous and powerful tool for modeling nano-scale optical devices.
- FDTD solves Mathematical equations directly without any physical approximation, and the maximum problem size is limited only by the extent of the computing power available.

1.2. History

Since years earlier scientists and researchers have used mechanical filters, more or less electrical filters. But using and employing Optical filters today is worth more futuristic and exploring, because this technology is worth emerging and more will be used in future requirements.

In the past few years, optical ring resonators have received a lot of attention as one of the most promising biological sensors. The optical ring resonator measures the target molecules through assessing the deviations in light behavior, which is caused by interaction between electromagnetic wave and biological molecules such as proteins, bacteria, cells, or DNA samples. This change in the behavior of the light is because of interaction between evanescent field of the resonating light inside the resonator and bioparticle that exist in the ambient. Existence of bioparticles in the medium changes the effective refractive index of surrounded medium, which results in deviation of resonance conditions of the resonator. Consequence of such an interaction is resonance wavelength deviation of the resonator that is related to the number for bioparticles in the medium.[1] A sensing mechanism is depicted schematically in Figure 1. To enable the periphery of the resonator to absorb bioparticles, an active polymer layer can be deposited on the boundary of the resonator. This layer is able to mechanically absorb or chemically react with the target bioparticle, resulting in a change in the effective refractive index of the resonating mode.

1.3. Objective of Project work

To design and simulate the Optical Filter using ring resonator by correspondingly varying the various input parameters like :-

1. Self coupling coefficient(t)
2. Effective Index (n_{eff})
3. Loss Coefficient (α)
4. Radius of the Ring (r)

Obtaining parameters like :-

1. Resonant Wavelength(λr)
2. 3-db Wavelength(λ3-db)
3. Free Spectral Range(FSR)

To design and simulate the Optical Filter using Lumerical Suite in ring resonator by correspondingly varying the various input parameters like :-

1. Radius of the Ring
2. Coupling Length (L_c)
3. Gap between wave guide and ring resonator

To obtain Output parameters like :-

1. Free Spectral Range (FSR)
2. Full width at half maximum (FWHM)
3. Extinction ratio (ER)

1.3.a. Explanation of Various input parameters of Ring Resonators :-

1. **Self coupling coefficient(t) :-**

   The **coupling coefficient of resonators** is a dimensionless value that characterizes interaction of two resonators. Coupling coefficients are used in resonator filter theory. Resonators may be both electromagnetic and acoustic. Coupling coefficients together with resonant frequencies and external quality factors of resonators are the generalized parameters of filters. In order to adjust the frequency response of the filter it is sufficient to optimize only these generalized parameters.

2. **Effective Index(n_{eff}) :-**

   For plane waves in homogeneous transparent media, the refractive index n can be used to Quantify the increase in the wavenumber (phase change per unit length) caused by the Medium : the wavenumber is n times higher than it would be in vaccum. The effective Refractive index n_{eff} has the analogous meaning for light propagation in waveguide with restricted transverse extension : the β value (phase constant of the waveguide (for some wavelength) is the effective index times the vaccum wavenumber.

3. **Loss Coefficient (α) :-**

   The propagation losses in a medium can be quantified with a propagation loss coefficient α, which is the sum of contributions from absorption and scattering and has units of m−1. If the loss coefficient is constant, the optical power is proportional to exp(−α z) where z is the propagation distance.

   Alternatively, the losses can be quantified in decibels per meter (dB/m); the numerical values are then ≈4.34 times higher than those of the loss coefficient in m−1.

4. **Radius of the Ring (r):-**

   Radius of Ring is ring radius. If the radius is too much maximum then density of the device will be much less.

   So maximum radius of the ring is taken as 7e-6

   If the radius of the ring is taken too much minimum then device will be too small and it will be difficult for fabrication process. So minimum value of ring is taken as 3e-6.

1.3.b. Explanation of Various Obtaining parameters of Ring Resonators

1. **Resonant wavelength(λr):** -

   The wavelength in free space electromagnet radiation having a frequency equal to natural resonance frequency of a cavity resonator.

2. **3-db Wavelength(λ3-db):-**

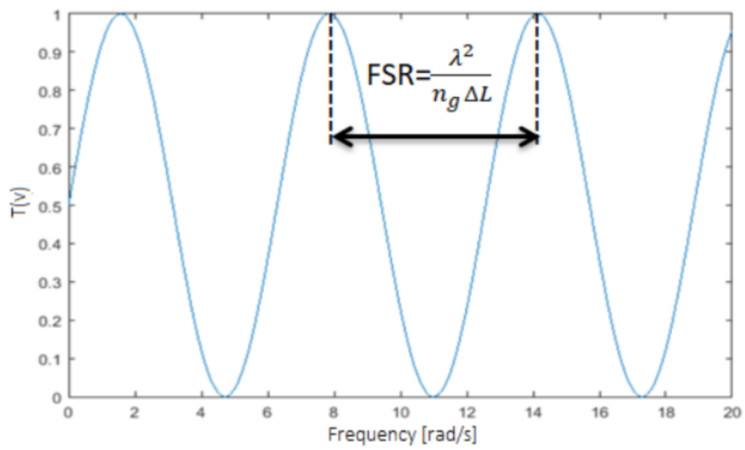
   The 3 dB bandwidth is the frequency at which the signal amplitude reduces by 3 dB i.e. becomes half its value.

3. **Free Spectral Range(FSR) :-**

   Free spectral range (**FSR**) is the spacing in optical frequency or wavelength between two successive reflected or transmitted optical intensity maxima or minima of an interferometer or diffractive optical element.

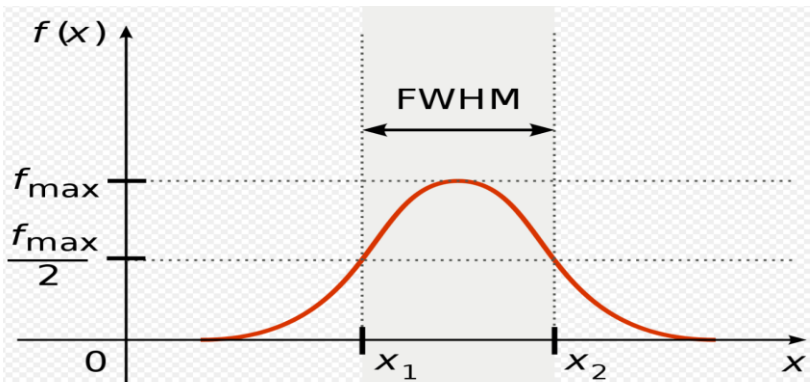
Free Spectral Range (FSR)

The separation between two consecutive resonant wavelength is known as free spectral range (FSR) of the resonator.



Full width at half maximum (FWHM)

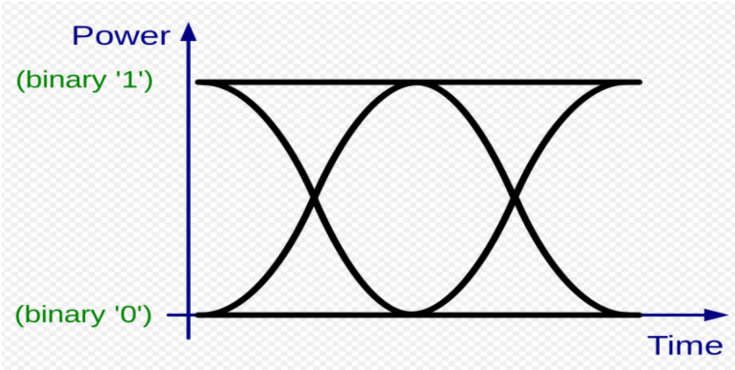
The difference between the two values of the independent variable at which the dependent variable is equal to half of its maximum value.



Extinction ratio(ER)

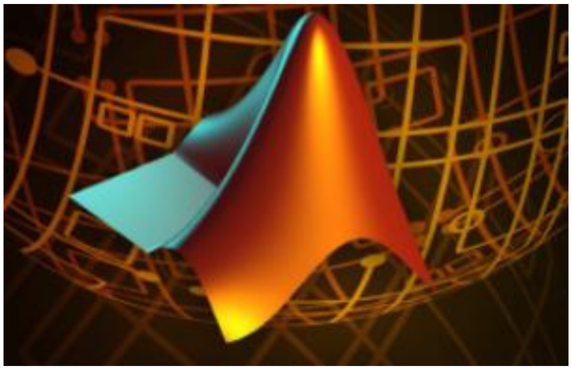
In telecommunications , extinction ratio (r_e) is the ratio of two optical power levels of a digital signal generated by an optical source. The extinction ratio may be expressed as a fraction, in dB, or as a percentage. It may be given by:

ER = 10 log ($\frac{T_{max}}{T_{min}}$)



CHAPTER 2. SOFTWARE REQUIREMENT

2.1. MATLAB :



MATLAB (an abbreviation of "matrix laboratory") is a proprietary multi-paradigm programming language and numerical computing environment developed by MathWorks. MATLAB allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages.

Although MATLAB is intended primarily for numerical computing, an optional toolbox uses the MuPAD symbolic engine allowing access to symbolic computing abilities. An additional package, Simulink, adds graphical multi-domain simulation and model-based design for dynamic and embedded systems.

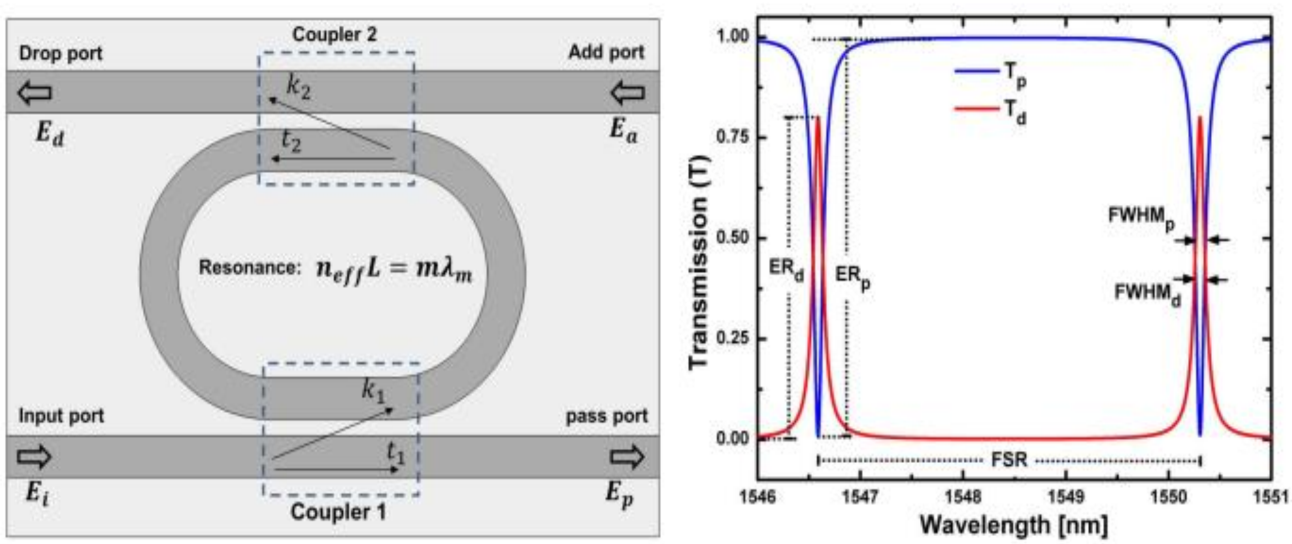
As of 2020, MATLAB has more than 4 million users worldwide MATLAB users come from various backgrounds of engineering, science, and economics.

MATLAB Advantages :

- Implement and test your algorithms easily.
- Develop the computational codes easily.
- Debug easily.
- Use a large database of built in algorithms.
- Process still images and create simulation videos easily.
- Symbolic computation can be easily done.

CHAPTER 3. SCHEMATIC DIAGRAM OF RING RESONATOR

Schematic top view of a typical micro ring resonator in add-drop configuration is shown in Figure 3.1(a), where, Ei and Ep, Ea and Ed are the electric field amplitudes at input, pass, add and drop



ports, respectively. t1 and t2 are the self coupling coefficients at coupler 1 and 2, respectively; similarly k1 and k2 are the cross-coupling coefficients at coupler 1 and 2, respectively. The transmission at the pass (Tp) and drop (Td)

Figure 2: Schematic top view of a micro ring resonator in add-drop configuration : Ei , Ep, Ea and Ed are the electric field amplitudes at input, pass, add and drop ports, respectively. t1 and t2 are the self coupling coefficients at the coupler 1 and 2, respectively. k1 and k2 are the cross-coupling coefficients at coupler 1 and 2, respectively. n_{eff} - effective index of the guided mode, L - ring perimeter, m - order of resonance, λm – resonant wavelength.
Figure 3: Typical transmission characteristics at the pass (Tp) and drop (Td) ports of add-drop ring resonator: ERp/d - extinction ratio at pass/drop port, FSR - free spectral range and FWHMp/d - full width at half maxima at pass/drop port.
ports can be written as:

$$\mathbf{T_P} = \frac{|\mathbf{E_p}|^2}{|\mathbf{E_i}|^2} = \frac{\mathbf{t_2^2 a^2 - 2t_1 t_2 a\cos(\theta) + t_1^2}}{\mathbf{1 - 2t_1 t_2 a\cos(\theta) + (t_1 t_2 a)^2}}$$

$$\mathbf{T_d} = \frac{|\mathbf{E_d}|^2}{|\mathbf{E_i}|^2} = \frac{\mathbf{(1-t_1^2)(1-t_2^2)a}}{\mathbf{1 - 2t_1 t_2 a\cos(\theta) + (t_1 t_2 a)^2}}$$

where, a = e −αL is the round trip loss factor with a loss coefficient α, L is the perimeter of the ring, θ = 2πn_{eff} L/λ is the round trip phase factor, n_{eff} is the effective index of the guided mode and λ is the wavelength of operation. The coupler sections are assumed to be loss-less ie, t 2 1 + k 2 1 = t 2 2 + k 2 2 = 1. Figure 3.1(b) shows typical transmission characteristics of a submicron photonic wire add-drop micro ring resonator plotted using eq. 1.1 and 1.2, where the ring parameters are considered to be L = 167 µm, α = 5 dB/cm, n_{eff} = 2.76 and t1 = t2 = 0.96 (for λ ∼ 1550 nm). From the pass port transmission characteristics, it can be noticed that the output of certain wavelengths are much less than the input. The wavelengths with minimum Tp are said to be the resonant wavelength which satisfy the resonance condition n_{eff}L=mλm of the ring resonator, where m is integer number representing the order of resonance. From the transmission characteristics of drop port (Td), it is clear that the resonant wavelengths are dropped at the drop port using the coupler 2 (see Figure 3.1(b)). Similarly, the resonant wavelengths can be added to the pass port through coupler 1 and 2 when they are given to the add port, hence this ring resonator configuration is known as add/drop multiplexer. Since the resonant wavelengths are circulating inside the ring cavity multiple times by satisfying the constructive interference condition, the effective length of the resonator for the resonant wavelength can be very long. For example, in the case of a ring resonator sensor, in contrast to a simple straight waveguide, ring resonator interaction with the analyte is not estimated using the physical length of the resonator but with number of revolutions inside the ring and which would be indicated by the quality factor (Q-factor) of the resonator. The effective length (Leff)of a ring resonator can be related to its Q-factor as

$$L_{eff} = \mathrm{Q}\frac{\lambda_m}{2\pi n_{eff}}$$

where Q-factor is defined as:

$$\text{Q-factor} = \frac{\lambda_m}{FWHM}$$

3.1. Minimum and Maximum value of each parameter that we varied as:

SL. No.	Parameters	Minimum value	Maximum Value	No. of Values Taken
1	Self coupling coefficient(t)	0.33	0.83	5
2	Effective Index (n_{eff})	2.76	3.00	5
3	Loss Coefficient (α)	800	10000	5
4	Radius of the Ring (r)	5.0e-6	7.0e-6	5

3.2 : Limitation of maximum and minimum value of each parameter :-

For Self Coupling Coefficient(t) : [a] if we increased 't' too much then nothing will be coupled into the rings, so 0.83 maximum value is taken. **[b]** if we reduce 't' too much then every thing will be cross coupled into the ring, after that nothing will be transmitted so minimum value 0.33 is taken.

For Effective Index (n_{eff}) :[a] when n_{eff} is too much maximum then cross-section of waveguide is more so the device will be too bulky. **[b]** if n_{eff} is too minimum then cross-section of waveguide will be much less so it will be difficult for fabrication process.

For Loss Coefficient (α) :[a] if α is too much maximum then device will be too much lossy and it will be not suitable for use. **[b]** if α is too much minimum then there will be technology limitation because of inheritance property of silicon.

For Radius of the Ring (r) : [a] if the radius is too much maximum then density of the device will be much less. So maximum radius of the ring is taken as 7e-6 **. [b]** if the radius of the ring is taken too much minimum then device will be too small and it will be difficult for fabrication process. So minimum value of ring is taken as 3e-6.

CHAPTER 4. METHODLOGY

A ring resonator in its simplest form consists of a straight waveguide which interacts with a ring through a coupler section. The coupler section is used to feed a part of the light from the input waveguide to the ring and simultaneously the circulated light from the ring back again to add into output waveguide.

In the coupler section, t is the self coupling coefficient (fraction of input amplitude passed through bus waveguide) and k is the cross-coupling coefficient (fraction of input amplitude coupled to the ring)

Assuming that the unidirectional mode of the resonator is excited, the interaction between bus waveguide and ring can be described by the matrix relation:

$$\begin{bmatrix} \text{Eout} \\ \text{E2} \end{bmatrix} = \begin{bmatrix} t & k \\ -k^* & t^* \end{bmatrix} \times \begin{bmatrix} \text{Ein} \\ \text{E3} \end{bmatrix} \qquad \text{(eq. a)}$$

where, E3 is related to E2 by the following equation:

$$\text{E3} = \text{a E2 } e^{-j\theta} \qquad \text{(eq. b)}$$

and a = $e^{-\alpha L}$is the round trip loss factor with a loss coefficient α, L is the perimeter of the ring, θ = $2\pi n_{eff}$(L/λ) is the round trip phase factor, n_{eff}f is the effective index of the waveguide and λ is the wavelength of operation.

Using eq. a and eq. b, the transmitted power at the output can be written as :

$$P_{out} = \frac{a^2 - 2\,a\,t\cos(\theta) + t^2}{1 - 2\,a\,t\cos(\theta) + a^2t^2}$$

The wavelength separation (or corresponding frequency separation) between two consecutive resonant resonances is known as free spectral range (FSR) of the resonator. In terms of wavelength separation, it is defined by:

$$\mathrm{FSR} = \frac{\lambda^2}{n_g L}$$

where n_g is the group index and it is defined as:

$$n_g = n_{eff} - \lambda\frac{dn_{eff}}{d\lambda}$$

Extinction ratio (ER) is another figure of merit of a ring resonator which measures the ratio of maximum (Pout at off-resonance) to minimum (Pout at resonance) power levels of the transmission spectrum and which can be derived from Eq:

$$\mathrm{ER} = \frac{(t+a)^2}{(t-a)^2} \times \frac{(1-t\,a)^2}{(1-t\,a)^2}$$

The ER at resonance wavelengths can be made to infinity when a = t, this condition is known as critically coupled resonance. The full width at half maximum (FWHM) of

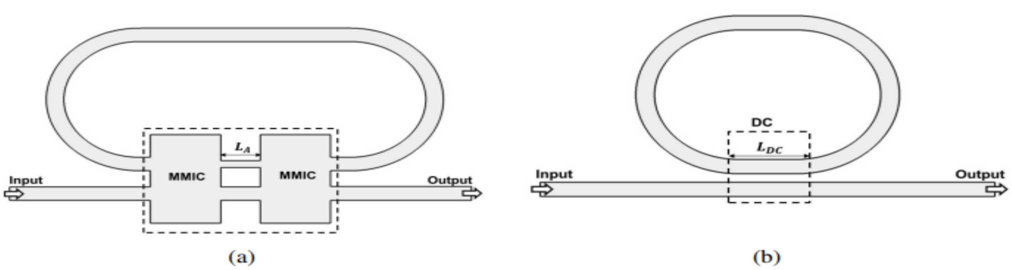


Figure 4 : Schematic top views of ring resonator with (a) cascaded multi-mode interference coupler (MMIC) or asymmetric Mach-Zehnder inter ferrometer (MZI) and (b) directional coupler (DC). The coupling strengths of (a) and (b) are controlled by the lengths LA and LDC, respectively.The resonance can be expressed as:

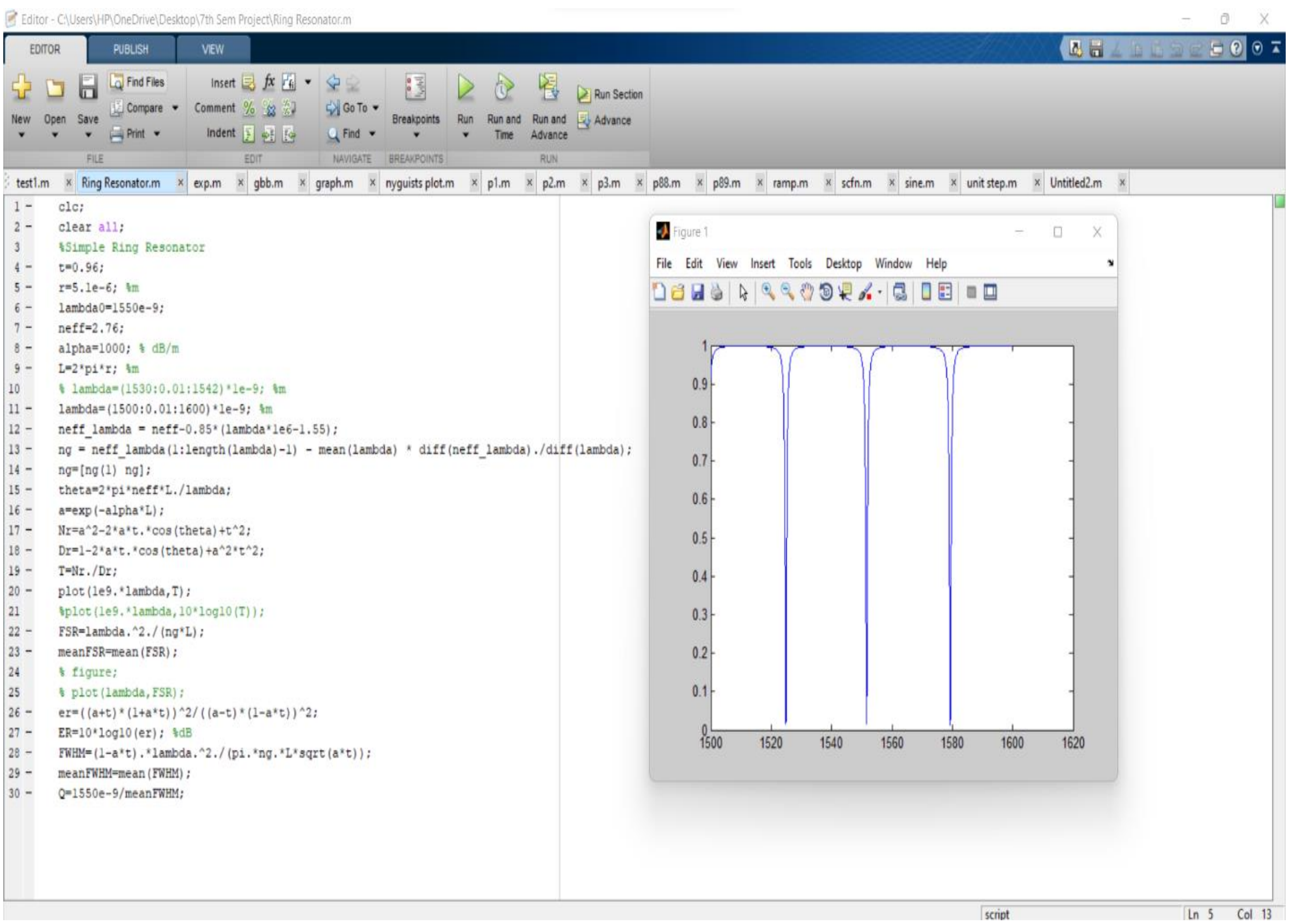
$$\mathrm{FWHM} = \frac{(1-a\,t)\lambda_m^2}{\pi\, n_g\, L\sqrt{a\,t}}$$

Performance of a ring resonator for any functional application depends on the Q-factor of the resonator and it is expressed as :

$$\text{Q-factor} = \frac{\lambda_m}{\text{FWHM}} = \frac{\pi\, n_g\, L\sqrt{t\,a}}{\lambda_m(1 - t\,a)}$$

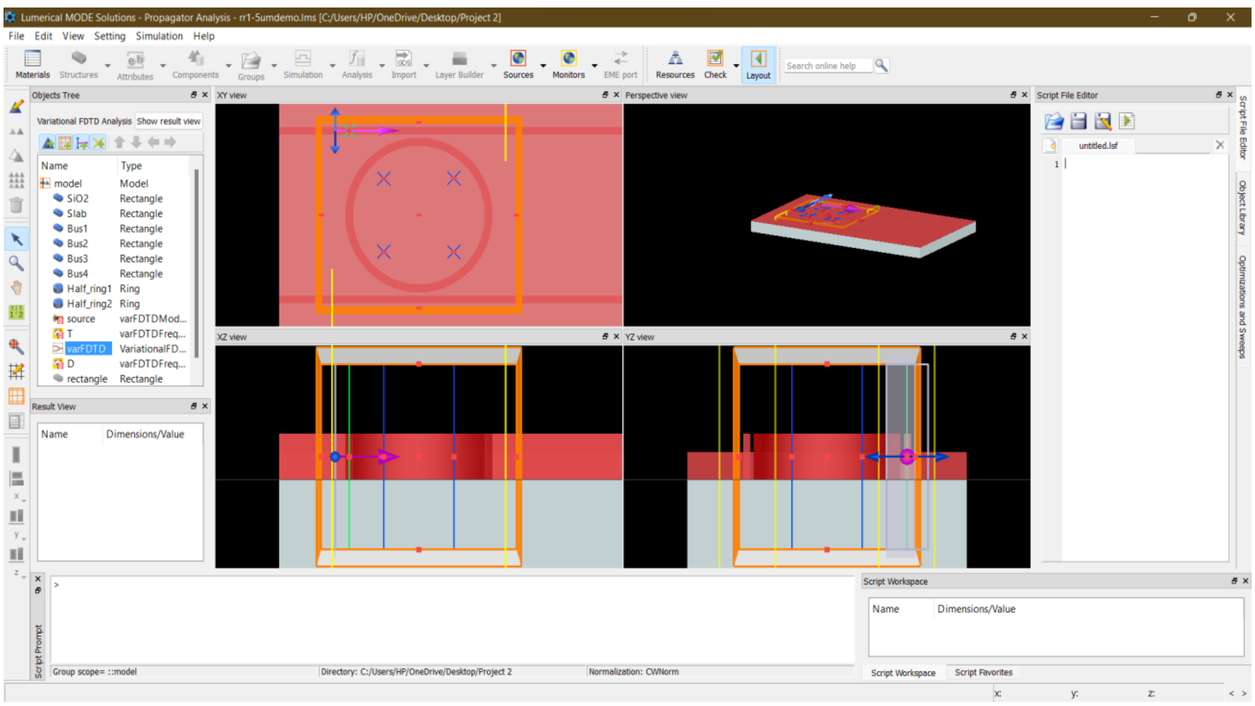
Q-factor of a ring resonator decides the amount of energy stored inside the ring at and around a resonance wavelength. In most of the ring resonator applications, high Q-factor is preferred. However, the properties of the ring resonator has to be designed depending on the application. In modulator devices, as it requires higher extinction one should expect very low output power for the resonant wavelength, i.e., critically coupled (a = t) ring resonator is preferred. However, in delay line applications, higher throughput power and maximum delay are expected for the resonant wavelengths which requires a different situation than in the case of modulator.

CHAPTER 5. 1. ANALYSIS USING MATLAB



- When self coupling coefficient varies with respect to different parameters then first resonant frequency and FSR remains constant but λ3-db changes.
- When Effective index varies with respect to different parameters then first resonant frequency remains constant but λ3-db and FSR changes.
- When loss coefficient varies with respect to different parameters then first resonant frequency and FSR remains constant but λ3-db changes.
- When radius of the ring varies with respect to different parameters then all the parameters like first resonant frequency , λ3-db and FSR changes.

5.2. Result Analysis After Simulation using Lumerical Suit:-



Step to Design Model

- File = > default project
- First step is to go structure and select a rectangle and edit it as Sio2 which is our lower cladding taking x-span as 30 um and y-span 20 um and center as 0 and z-span as 4um.
- Second step is selecting a material and select a material as Sio2 after that slab is taken whose dimension is taken as 150 nm and as a material Si is taken
- Third step is ring is taken having inner radius as 5um and outer radius 5.5 um and Zmin 0.15 and Zmax 0.25 and material as silicon.

- Further slab is duplicate and taken y-axis and defined maximum amd minimum value as 6.1 and 5.6 um and we have a bus waveguide having a gap of 100 nm.
- Fourth step is to go simulation and select VarFDT and geometry is changed as per our requirement.
- Further go to source and select a mode and a source can be see.
- We have a four bus waveguide as bus1 has center at 5.85 um and bus 2 has 5.65 um as center bus3 has 5um as center bus 4 has 5 um as center.
- Next step is to make a monitor as center 5.85.
- After all these installation save this file and run it and we can easily see our result.
- Run this program after saving and when running is complete we can get a transmitted power at this point , through put as we can see this.
- In design we can see SiO2, salb, Bus1 and Bus2 and Ring.
- Radius (varying result) ,FSR,FWHM, ER

CHAPTER 6.OBSERVATION

6.1.USING MATLAB

Graphs obtained by variation of input parameters like

CASE 1: When Self coupling coefficient (t) varies:-

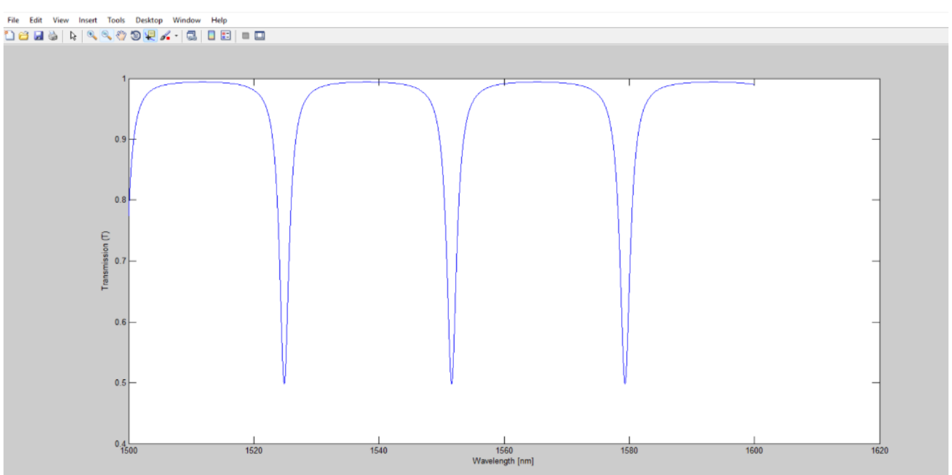
1) When t=0.8

MATLAB Code:

```
clc;
clear all;
%Simple Ring Resonator
t=0.96;
r=10.1e-6; %m
lambda0=1550e-9;
neff=2.76;
alpha=1000; % dB/m
L=2*pi*r; %m
% lambda=(1530:0.01:1542)*1e-9; %m
```

```
lambda=(1500:0.01:1600)*1e-9; %m
neff_lambda = neff-0.85*(lambda*1e6-1.55);
ng = neff_lambda(1:length(lambda)-1) - mean(lambda) * diff(neff_lambda)./diff(lambda);
ng=[ng(1) ng];
theta=2*pi*neff*L./lambda;
a=exp(-alpha*L);
Nr=a^2-2*a*t.*cos(theta)+t^2;
Dr=1-2*a*t.*cos(theta)+a^2*t^2;
T=Nr./Dr;
plot(1e9.*lambda,T);
%plot(1e9.*lambda,10*log10(T));
FSR=lambda.^2./(ng*L);
meanFSR=mean(FSR);
% figure;
% plot(lambda,FSR);
er=((a+t)(1+a*t))^2/((a-t)(1-a*t))^2;
ER=10*log10(er); %dB
FWHM=(1-a*t).*lambda.^2./(pi.*ng.*L*sqrt(a*t));
meanFWHM=mean(FWHM);
Q=1550e-9/meanFWHM;
xlabel('Wavelength [nm]');
ylabel('Transmission (T)');
```

OUTPUT:



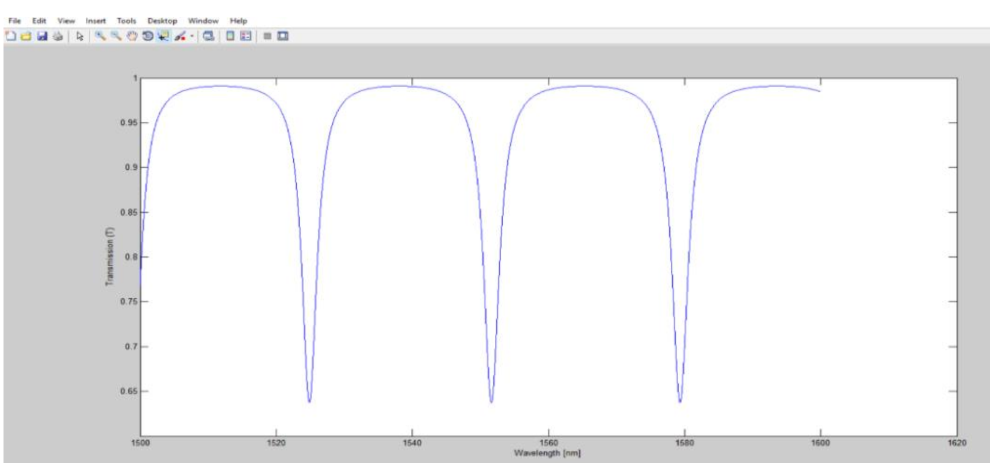
2) When t=0.75

MATLAB Code:

```
clc;
```

```
clear all;
%Simple Ring Resonator
t=0.75;
r=10.1e-6; %m
lambda0=1550e-9;
neff=2.76;
alpha=1000; % dB/m
L=2*pi*r; %m
% lambda=(1530:0.01:1542)*1e-9; %m
lambda=(1500:0.01:1600)*1e-9; %m
neff_lambda = neff-0.85*(lambda*1e6-1.55);
ng = neff_lambda(1:length(lambda)-1) - mean(lambda) * diff(neff_lambda)./diff(lambda);
ng=[ng(1) ng];
theta=2*pi*neff*L./lambda;
a=exp(-alpha*L);
Nr=a^2-2*a*t.*cos(theta)+t^2;
Dr=1-2*a*t.*cos(theta)+a^2*t^2;
T=Nr./Dr;
plot(1e9.*lambda,T);
%plot(1e9.*lambda,10*log10(T));
FSR=lambda.^2./(ng*L);
meanFSR=mean(FSR);
% figure;
% plot(lambda,FSR);
er=((a+t)(1+a*t))^2/((a-t)(1-a*t))^2;
ER=10*log10(er); %dB
FWHM=(1-a*t).*lambda.^2./(pi.*ng.*L*sqrt(a*t));
meanFWHM=mean(FWHM);
Q=1550e-9/meanFWHM;
xlabel('Wavelength [nm]');
ylabel('Transmission (T)');
```

OUTPUT:

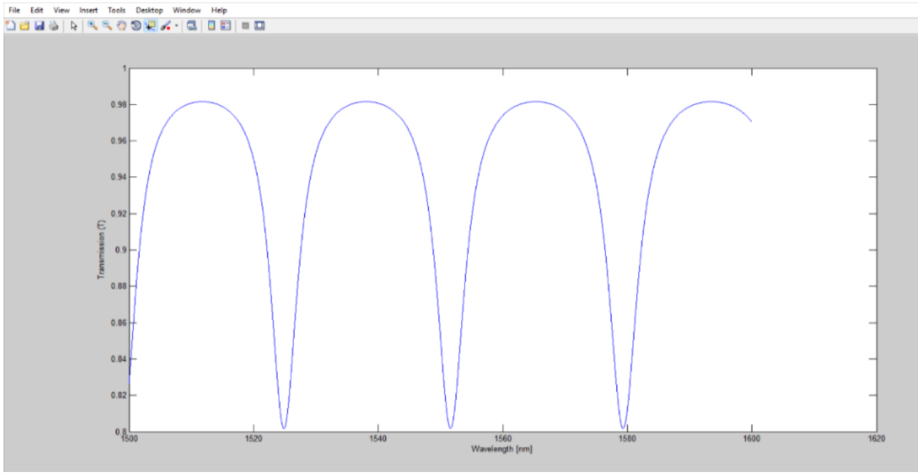


3) When t=0.55

MATLAB Code:

```
clc;
clear all;
%Simple Ring Resonator
t=0.55;
r=10.1e-6; %m
lambda0=1550e-9;
neff=2.76;
alpha=1000; % dB/m
L=2*pi*r; %m
% lambda=(1530:0.01:1542)*1e-9; %m
lambda=(1500:0.01:1600)*1e-9; %m
neff_lambda = neff-0.85*(lambda*1e6-1.55);
ng = neff_lambda(1:length(lambda)-1) - mean(lambda) * diff(neff_lambda)./diff(lambda);
ng=[ng(1) ng];
theta=2*pi*neff*L./lambda;
a=exp(-alpha*L);
Nr=a^2-2*a*t.*cos(theta)+t^2;
Dr=1-2*a*t.*cos(theta)+a^2*t^2;
T=Nr./Dr;
plot(1e9.*lambda,T);
%plot(1e9.*lambda,10*log10(T));
FSR=lambda.^2./(ng*L);
meanFSR=mean(FSR);
% figure;
% plot(lambda,FSR);
er=((a+t)(1+a*t))^2/((a-t)(1-a*t))^2;
ER=10*log10(er); %dB
FWHM=(1-a*t).*lambda.^2./(pi.*ng.*L*sqrt(a*t));
meanFWHM=mean(FWHM);
Q=1550e-9/meanFWHM;
xlabel('Wavelength [nm]');
ylabel('Transmission (T)');
```

OUTPUT:



4) When t=0.45

MATLAB Code:

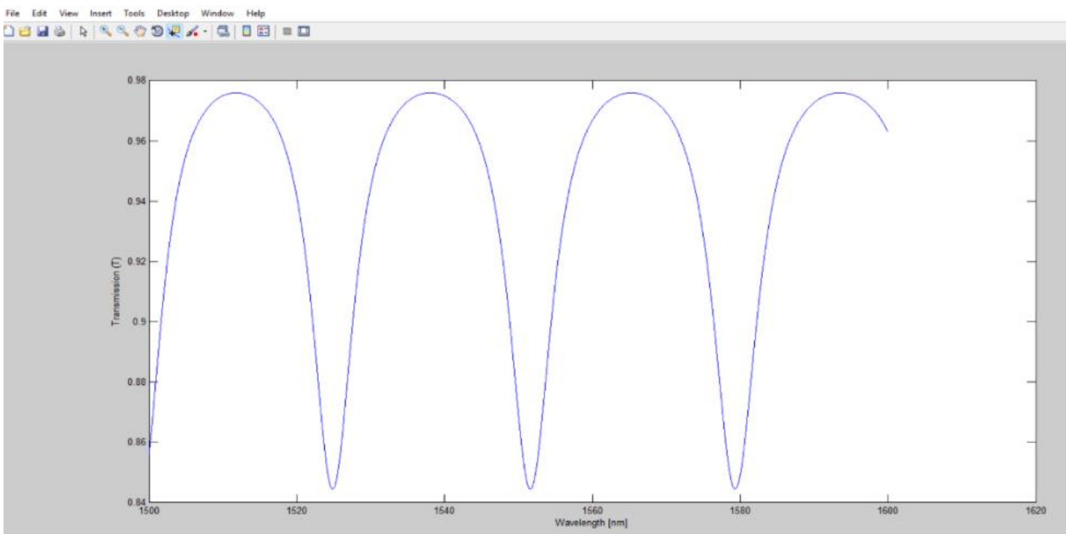
```
clc;
clear all;
%Simple Ring Resonator
t=0.45;
r=10.1e-6; %m
lambda0=1550e-9;
neff=2.76;
alpha=1000; % dB/m
L=2*pi*r; %m
% lambda=(1530:0.01:1542)*1e-9; %m
lambda=(1500:0.01:1600)*1e-9; %m
neff_lambda = neff-0.85*(lambda*1e6-1.55);
ng = neff_lambda(1:length(lambda)-1) - mean(lambda) * diff(neff_lambda)./diff(lambda);
ng=[ng(1) ng];
theta=2*pi*neff*L./lambda;
a=exp(-alpha*L);
Nr=a^2-2*a*t.*cos(theta)+t^2;
Dr=1-2*a*t.*cos(theta)+a^2*t^2;
T=Nr./Dr;
plot(1e9.*lambda,T);
%plot(1e9.*lambda,10*log10(T));
FSR=lambda.^2./(ng*L);
meanFSR=mean(FSR);
% figure;
% plot(lambda,FSR);
er=((a+t)(1+a*t))^2/((a-t)(1-a*t))^2;
ER=10*log10(er); %dB
```

FWHM=(1-a*t).*lambda.^2./(pi.*ng.*L*sqrt(a*t));
meanFWHM=mean(FWHM);

SL NO.	t [unitless]	λr1 [nm]	λ3-db [nm]	FSR [nm]
1	0.83	1525	1526-1524=2	27
2	0.75	1525	1526-1524=2	27
3	0.55	1525	1527-1522=5	27
4	0.45	1525	1528-1522=6	27

Q=1550e-9/meanFWHM;
xlabel('Wavelength [nm]');
ylabel('Transmission (T)');

OUTPUT:

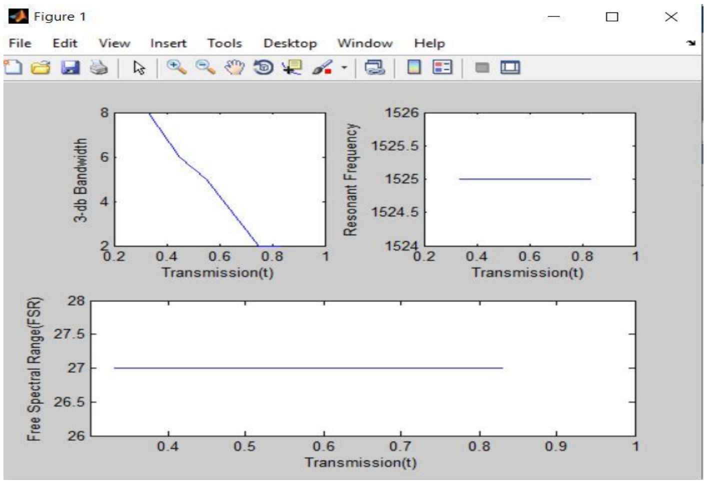


Self coupling coefficient (t) varies with respect to different parameters

3-db Bandwidth Vs Transmission
Graph is linearly decreasing

Resonant frequency Vs Transmission
Graph is Constant

Free Spectral Range Vs Transmission
Graph is Constant



CASE 2:- When Effective Index (n_{eff}) varies: –

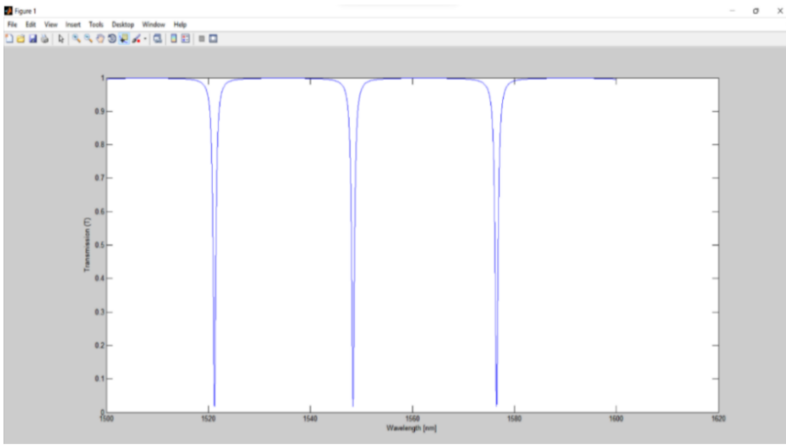
1) When n_{eff} =2.76

MATLAB CODE:

```
clc;
clear all;
%Simple Ring Resonator
t=0.45;
r=10.1e-6; %m
lambda0=1550e-9;
neff=2.76;
alpha=1000; % dB/m
L=2*pi*r; %m
% lambda=(1530:0.01:1542)*1e-9; %m
lambda=(1500:0.01:1600)*1e-9; %m
neff_lambda = neff-0.85*(lambda*1e6-1.55);
ng = neff_lambda(1:length(lambda)-1) - mean(lambda) * diff(neff_lambda)./diff(lambda);
ng=[ng(1) ng];
theta=2*pi*neff*L./lambda;
a=exp(-alpha*L);
Nr=a^2-2*a*t.*cos(theta)+t^2;
Dr=1-2*a*t.*cos(theta)+a^2*t^2;
T=Nr./Dr;
plot(1e9.*lambda,T);
%plot(1e9.*lambda,10*log10(T));
FSR=lambda.^2./(ng*L);
meanFSR=mean(FSR);
% figure;
% plot(lambda,FSR);
```

```
er=((a+t)(1+a*t))^2/((a-t)(1-a*t))^2;
ER=10*log10(er); %dB
FWHM=(1-a*t).*lambda.^2./(pi.*ng.*L*sqrt(a*t));
meanFWHM=mean(FWHM);
Q=1550e-9/meanFWHM;
xlabel('Wavelength [nm]');
ylabel('Transmission (T)');
```

OUTPUT:



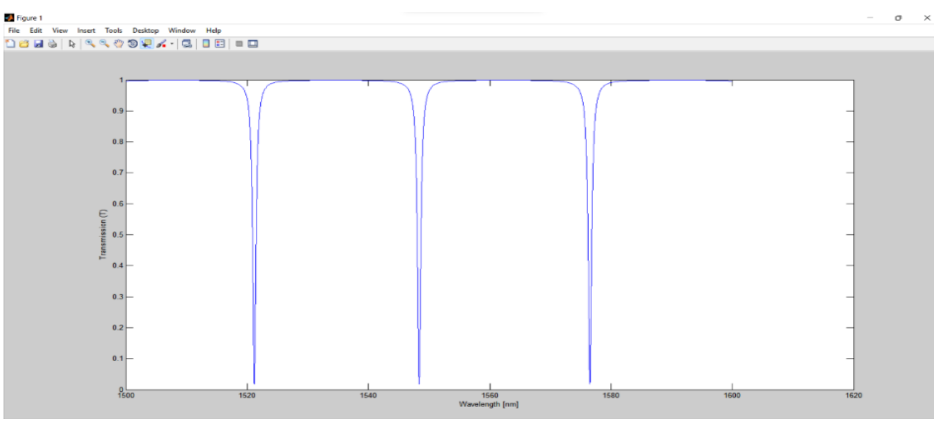
2) When n_{eff} =2.79

MATLAB CODE:

```
clc;
clear all;
%Simple Ring Resonator
t=0.45;
r=10.1e-6; %m
lambda0=1550e-9;
neff=2.79;
alpha=1000; % dB/m
L=2*pi*r; %m
% lambda=(1530:0.01:1542)*1e-9; %m
lambda=(1500:0.01:1600)*1e-9; %m
neff_lambda = neff-0.85*(lambda*1e6-1.55);
ng = neff_lambda(1:length(lambda)-1) - mean(lambda) * diff(neff_lambda)./diff(lambda);
ng=[ng(1) ng];
```

```
theta=2*pi*neff*L./lambda;
a=exp(-alpha*L);
Nr=a^2-2*a*t.*cos(theta)+t^2;
Dr=1-2*a*t.*cos(theta)+a^2*t^2;
T=Nr./Dr;
plot(1e9.*lambda,T);
%plot(1e9.*lambda,10*log10(T));
FSR=lambda.^2./(ng*L);
meanFSR=mean(FSR);
% figure;
% plot(lambda,FSR);
er=((a+t)(1+a*t))^2/((a-t)(1-a*t))^2;
ER=10*log10(er); %dB
FWHM=(1-a*t).*lambda.^2./(pi.*ng.*L*sqrt(a*t));
meanFWHM=mean(FWHM);
Q=1550e-9/meanFWHM;
xlabel('Wavelength [nm]');
ylabel('Transmission (T)');
```

OUTPUT:



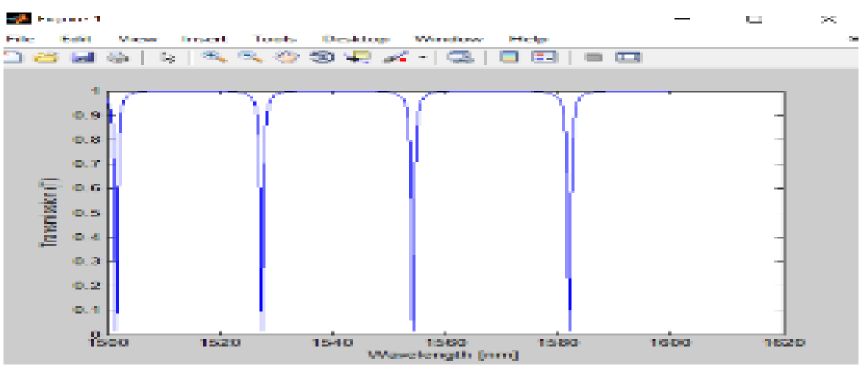
3) When n_{eff} =2.82

MATLAB CODE:

```
clc;
clear all;
%Simple Ring Resonator
t=0.45;
r=10.1e-6; %m
lambda0=1550e-9;
neff=2.82;
alpha=1000; % dB/m
L=2*pi*r; %m
% lambda=(1530:0.01:1542)*1e-9; %m
lambda=(1500:0.01:1600)*1e-9; %m
```

```
neff_lambda = neff-0.85*(lambda*1e6-1.55);
ng = neff_lambda(1:length(lambda)-1) - mean(lambda) * diff(neff_lambda)./diff(lambda);
ng=[ng(1) ng];
theta=2*pi*neff*L./lambda;
a=exp(-alpha*L);
Nr=a^2-2*a*t.*cos(theta)+t^2;
Dr=1-2*a*t.*cos(theta)+a^2*t^2;
T=Nr./Dr;
plot(1e9.*lambda,T);
%plot(1e9.*lambda,10*log10(T));
FSR=lambda.^2./(ng*L);
meanFSR=mean(FSR);
% figure;
% plot(lambda,FSR);
er=((a+t)(1+a*t))^2/((a-t)(1-a*t))^2;
ER=10*log10(er); %dB
FWHM=(1-a*t).*lambda.^2./(pi.*ng.*L*sqrt(a*t));
meanFWHM=mean(FWHM);
Q=1550e-9/meanFWHM;
xlabel('Wavelength [nm]');
ylabel('Transmission (T)');
```

OUTPUT:



4) When n_{eff} =2.85

MATLAB CODE:

```
clc;
clear all;
%Simple Ring Resonator
t=0.45;
r=10.1e-6; %m
lambda0=1550e-9;
neff=2.85;
alpha=1000; % dB/m
L=2*pi*r; %m
```

```
% lambda=(1530:0.01:1542)*1e-9; %m
lambda=(1500:0.01:1600)*1e-9; %m
neff_lambda = neff-0.85*(lambda*1e6-1.55);
ng = neff_lambda(1:length(lambda)-1) - mean(lambda) * diff(neff_lambda)./diff(lambda);
ng=[ng(1) ng];
theta=2*pi*neff*L./lambda;
a=exp(-alpha*L);
Nr=a^2-2*a*t.*cos(theta)+t^2;
Dr=1-2*a*t.*cos(theta)+a^2*t^2;
T=Nr./Dr;
plot(1e9.*lambda,T);
%plot(1e9.*lambda,10*log10(T));
FSR=lambda.^2./(ng*L);
meanFSR=mean(FSR);
% figure;
% plot(lambda,FSR);
er=((a+t)(1+a*t))^2/((a-t)(1-a*t))^2;
ER=10*log10(er); %dB
FWHM=(1-a*t).*lambda.^2./(pi.*ng.*L*sqrt(a*t));
meanFWHM=mean(FWHM);
Q=1550e-9/meanFWHM;
xlabel('Wavelength [nm]');
ylabel('Transmission (T)');
```

OUTPUT:

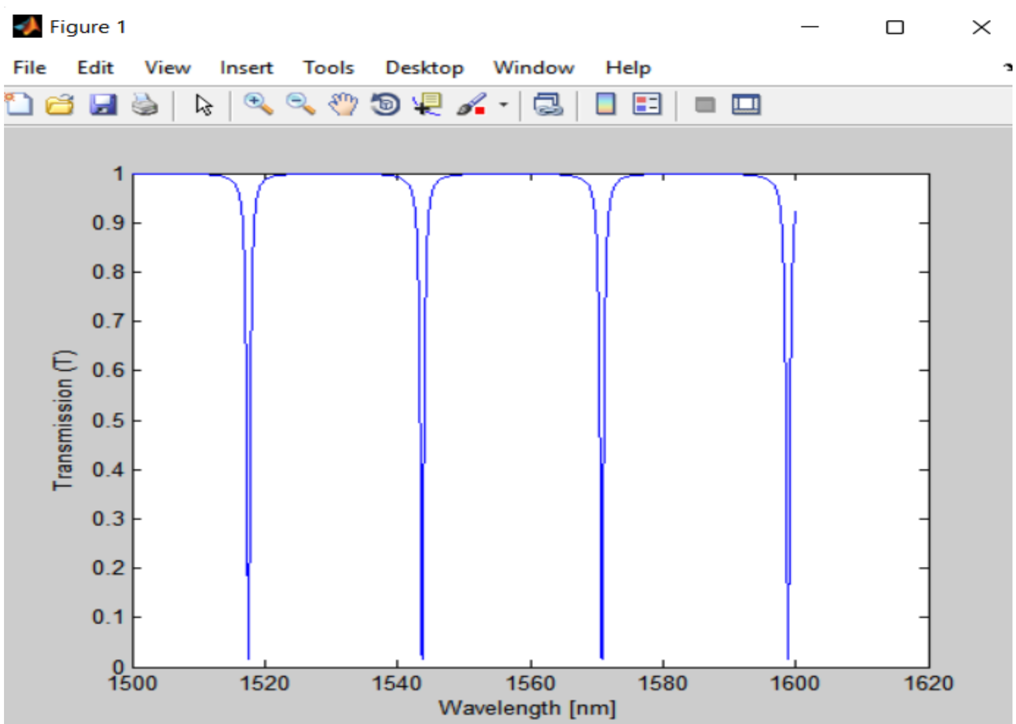


TABLE:-

SL. NO	n_{eff} [unitless]	λr1 [nm]	λ3-db [nm]	FSR [nm]
1	2.76	1521	1522-1521=1	27
2	2.79	1511	1512-1511=1	27
3	2.82	1502	1502-1501=1	25
4	2.85	1518	1518-1517=1	26
5	3.00	1520	1521-1520=1	25

<u>Effective Index (n_{eff}) varies with respect to different parameters</u>

<u>3-db Bandwidth Vs n_{eff}</u>

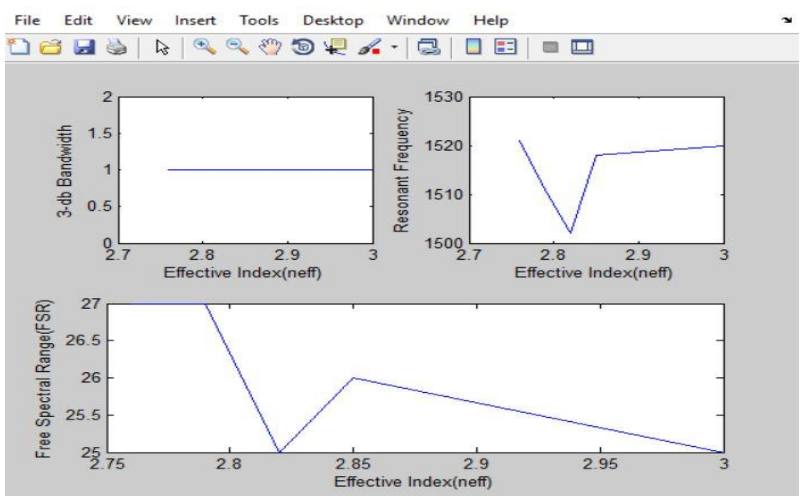
Graph is Constant

<u>Resonant frequency Vs n_{eff}</u>

Graph is non-linear

<u>Free Spectral Range Vs n_{eff}</u>

Graph is non-linear



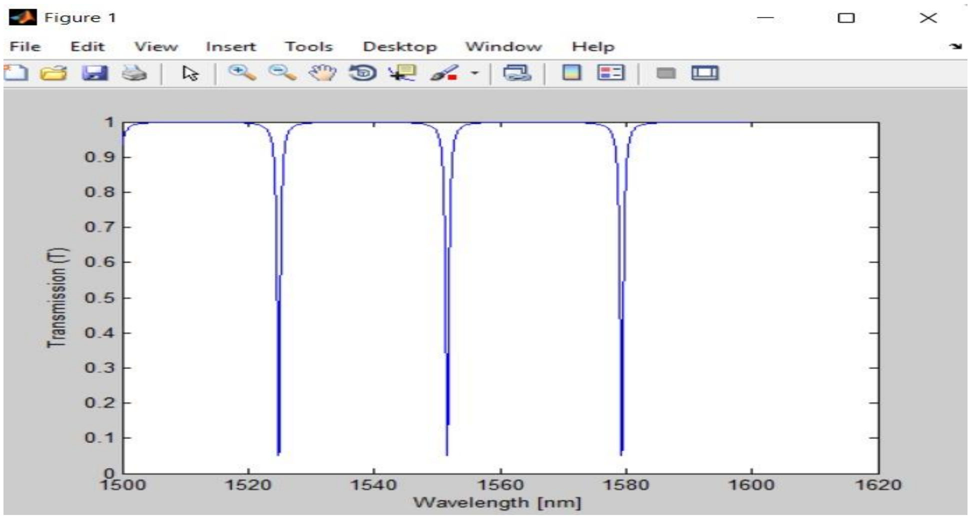
Case 3: When Loss Coefficient(α) Varies:-

1) When α = 800 dB/cm

MATLAB CODE:

```
clc;
clear all;
%Simple Ring Resonator
t=0.45;
r=10.1e-6; %m
lambda0=1550e-9;
neff=2.82;
alpha=1000; % dB/m
L=2*pi*r; %m
% lambda=(1530:0.01:1542)*1e-9; %m
lambda=(1500:0.01:1600)*1e-9; %m
neff_lambda = neff-0.85*(lambda*1e6-1.55);
ng = neff_lambda(1:length(lambda)-1) - mean(lambda) * diff(neff_lambda)./diff(lambda);
ng=[ng(1) ng];
theta=2*pi*neff*L./lambda;
a=exp(-alpha*L);
Nr=a^2-2*a*t.*cos(theta)+t^2;
Dr=1-2*a*t.*cos(theta)+a^2*t^2;
T=Nr./Dr;
plot(1e9.*lambda,T);
%plot(1e9.*lambda,10*log10(T));
FSR=lambda.^2./(ng*L);
meanFSR=mean(FSR);
% figure;
% plot(lambda,FSR);
er=((a+t)(1+a*t))^2/((a-t)(1-a*t))^2;
ER=10*log10(er); %dB
FWHM=(1-a*t).*lambda.^2./(pi.*ng.*L*sqrt(a*t));
meanFWHM=mean(FWHM);
Q=1550e-9/meanFWHM;
xlabel('Wavelength [nm]');
ylabel('Transmission (T)');
```

OUTPUT:



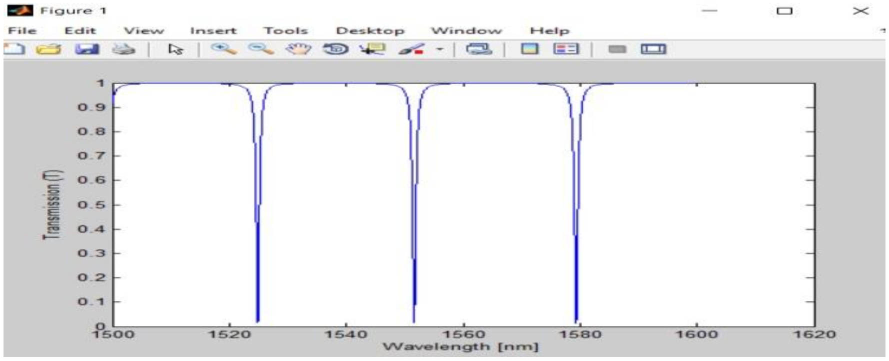
2) When α= 1000 dB/cm

MATLAB CODE:

```
clc;
clear all;
%Simple Ring Resonator
t=0.45;
r=10.1e-6; %m
lambda0=1550e-9;
neff=2.82;
alpha=1000; % dB/m
L=2*pi*r; %m
% lambda=(1530:0.01:1542)*1e-9; %m
lambda=(1500:0.01:1600)*1e-9; %m
neff_lambda = neff-0.85*(lambda*1e6-1.55);
ng = neff_lambda(1:length(lambda)-1) - mean(lambda) * diff(neff_lambda)./diff(lambda);
ng=[ng(1) ng];
theta=2*pi*neff*L./lambda;
a=exp(-alpha*L);
Nr=a^2-2*a*t.*cos(theta)+t^2;
Dr=1-2*a*t.*cos(theta)+a^2*t^2;
T=Nr./Dr;
plot(1e9.*lambda,T);
%plot(1e9.*lambda,10*log10(T));
FSR=lambda.^2./(ng*L);
meanFSR=mean(FSR);
% figure;
% plot(lambda,FSR);
er=((a+t)(1+a*t))^2/((a-t)(1-a*t))^2;
ER=10*log10(er); %dB
FWHM=(1-a*t).*lambda.^2./(pi.*ng.*L*sqrt(a*t));
```

```
meanFWHM=mean(FWHM);
Q=1550e-9/meanFWHM;
xlabel('Wavelength [nm]');
ylabel('Transmission (T)');
```

OUTPUT:



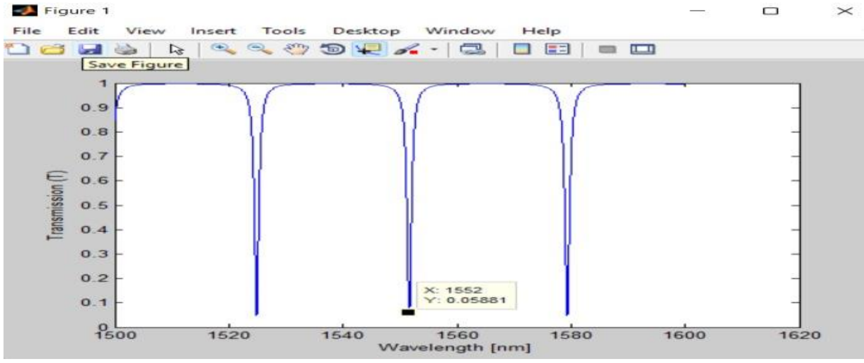
3) When α= 2000 dB/cm

MATLAB CODE:

```
clc;
clear all;
%Simple Ring Resonator
t=0.45;
r=10.1e-6; %m
lambda0=1550e-9;
neff=2.82;
alpha=2000; % dB/m
L=2*pi*r; %m
% lambda=(1530:0.01:1542)*1e-9; %m
lambda=(1500:0.01:1600)*1e-9; %m
neff_lambda = neff-0.85*(lambda*1e6-1.55);
ng = neff_lambda(1:length(lambda)-1) - mean(lambda) * diff(neff_lambda)./diff(lambda);
ng=[ng(1) ng];
theta=2*pi*neff*L./lambda;
a=exp(-alpha*L);
Nr=a^2-2*a*t.*cos(theta)+t^2;
Dr=1-2*a*t.*cos(theta)+a^2*t^2;
T=Nr./Dr;
plot(1e9.*lambda,T);
%plot(1e9.*lambda,10*log10(T));
FSR=lambda.^2./(ng*L);
meanFSR=mean(FSR);
% figure;
% plot(lambda,FSR);
er=((a+t)(1+a*t))^2/((a-t)(1-a*t))^2;
```

```
ER=10*log10(er); %dB
FWHM=(1-a*t).*lambda.^2./(pi.*ng.*L*sqrt(a*t));
meanFWHM=mean(FWHM);
Q=1550e-9/meanFWHM;
xlabel('Wavelength [nm]');
ylabel('Transmission (T)');
```

OUTPUT:



4) When α= 5000 dB/cm

MATLAB CODE:

```
clc;
clear all;
%Simple Ring Resonator
t=0.45;
r=10.1e-6; %m
lambda0=1550e-9;
neff=2.82;
alpha=5000; % dB/m
L=2*pi*r; %m
% lambda=(1530:0.01:1542)*1e-9; %m
lambda=(1500:0.01:1600)*1e-9; %m
neff_lambda = neff-0.85*(lambda*1e6-1.55);
ng = neff_lambda(1:length(lambda)-1) - mean(lambda) * diff(neff_lambda)./diff(lambda);
ng=[ng(1) ng];
theta=2*pi*neff*L./lambda;
a=exp(-alpha*L);
Nr=a^2-2*a*t.*cos(theta)+t^2;
Dr=1-2*a*t.*cos(theta)+a^2*t^2;
T=Nr./Dr;
plot(1e9.*lambda,T);
%plot(1e9.*lambda,10*log10(T));
FSR=lambda.^2./(ng*L);
meanFSR=mean(FSR);
% figure;
```

```
% plot(lambda,FSR);
er=((a+t)(1+a*t))^2/((a-t)(1-a*t))^2;
ER=10*log10(er); %dB
FWHM=(1-a*t).*lambda.^2./(pi.*ng.*L*sqrt(a*t));
meanFWHM=mean(FWHM);
Q=1550e-9/meanFWHM;
xlabel('Wavelength [nm]');
ylabel('Transmission (T)');
```

OUTPUT:

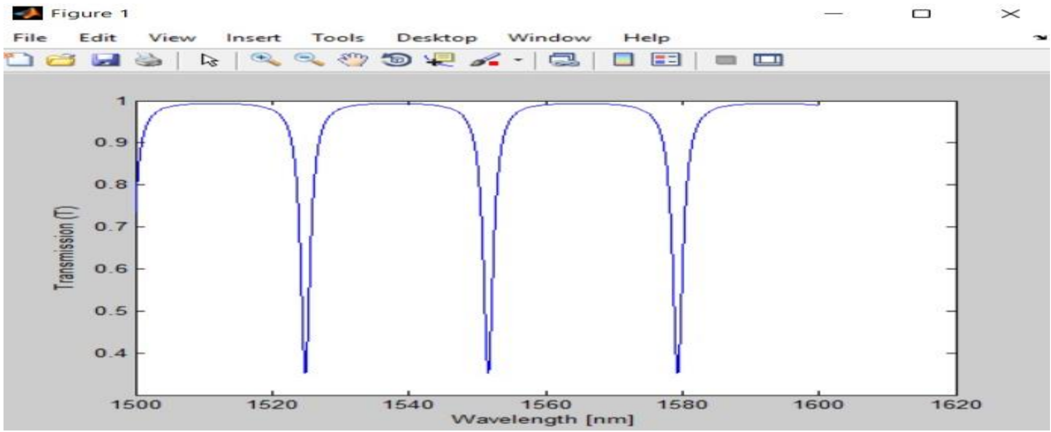


TABLE:-

SL. No.	α [dB/cm]	λr1 [nm]	λ3-db [nm]	FSR [nm]
1	800	1525	1525-1524=1	27
2	1000	1525	1525-1524=1	27
3	2000	1525	1526-1524=2	27
4	5000	1525	1526-1524=2	27
5	10000	1525	1526-1524=2	27

Loss Coefficient (α) varies with respect to different parameters:

3-db Bandwidth Vs Loss Coefficient

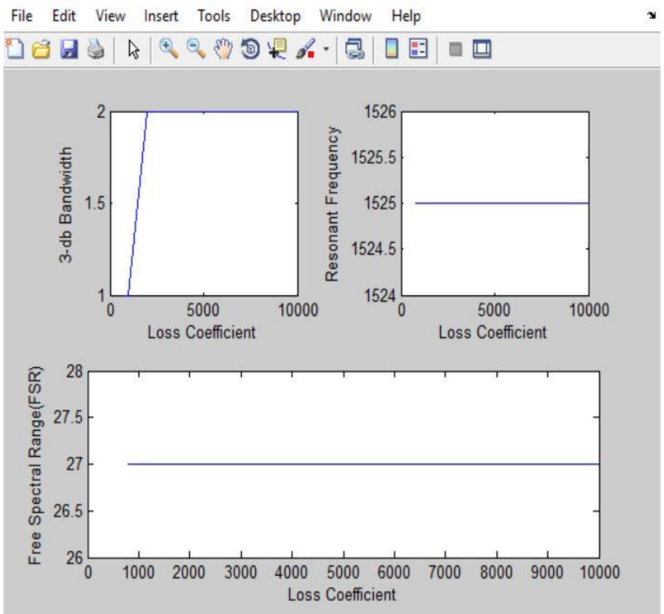
Graph is linearly increasing

Resonant frequency Vs Loss Coefficient

Graph is Constant

Free Spectral Range Vs Loss Coefficient

Graph is Constant



Case 4: When Radius of the Ring(r) is Varying**:**

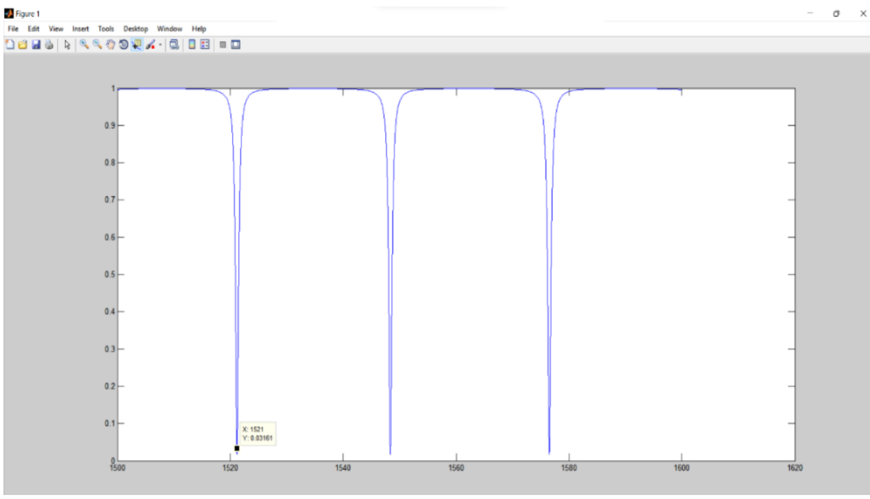
1) When Radius of the Ring(r)= 5.0e-6

MATLAB CODE:

```
clc;
clear all;
%Simple Ring Resonator
t=0.45;
r=5.0e-6; %m
lambda0=1550e-9;
neff=2.82;
alpha=1000; % dB/m
L=2*pi*r; %m
% lambda=(1530:0.01:1542)*1e-9; %m
lambda=(1500:0.01:1600)*1e-9; %m
neff_lambda = neff-0.85*(lambda*1e6-1.55);
ng = neff_lambda(1:length(lambda)-1) - mean(lambda) * diff(neff_lambda)./diff(lambda);
ng=[ng(1) ng];
theta=2*pi*neff*L./lambda;
a=exp(-alpha*L);
Nr=a^2-2*a*t.*cos(theta)+t^2;
```

```
Dr=1-2*a*t.*cos(theta)+a^2*t^2;
T=Nr./Dr;
plot(1e9.*lambda,T);
%plot(1e9.*lambda,10*log10(T));
FSR=lambda.^2./(ng*L);
meanFSR=mean(FSR);
% figure;
% plot(lambda,FSR);
er=((a+t)(1+a*t))^2/((a-t)(1-a*t))^2;
ER=10*log10(er); %dB
FWHM=(1-a*t).*lambda.^2./(pi.*ng.*L*sqrt(a*t));
meanFWHM=mean(FWHM);
Q=1550e-9/meanFWHM;
xlabel('Wavelength [nm]');
ylabel('Transmission (T)');
```

OUTPUT:



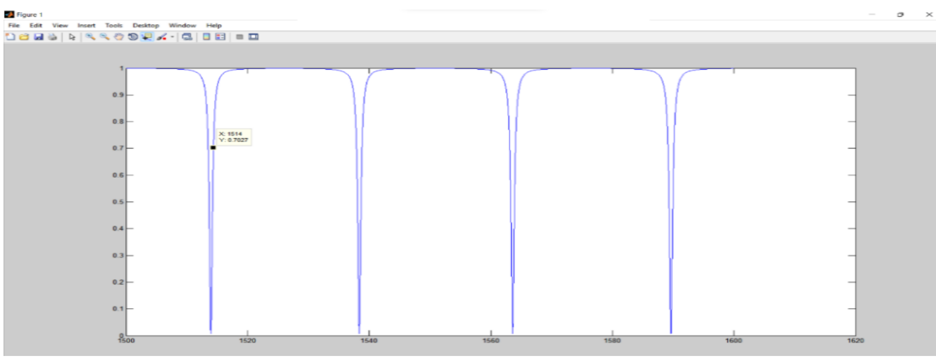
2) When Radius of the Ring(r)= 5.5e-6

MATLAB CODE:

```
clc;
clear all;
%Simple Ring Resonator
t=0.45;
r=5.5e-6; %m
lambda0=1550e-9;
neff=2.82;
alpha=1000; % dB/m
L=2*pi*r; %m
% lambda=(1530:0.01:1542)*1e-9; %m
lambda=(1500:0.01:1600)*1e-9; %m
```

```
neff_lambda = neff-0.85*(lambda*1e6-1.55);
ng = neff_lambda(1:length(lambda)-1) - mean(lambda) * diff(neff_lambda)./diff(lambda);
ng=[ng(1) ng];
theta=2*pi*neff*L./lambda;
a=exp(-alpha*L);
Nr=a^2-2*a*t.*cos(theta)+t^2;
Dr=1-2*a*t.*cos(theta)+a^2*t^2;
T=Nr./Dr;
plot(1e9.*lambda,T);
%plot(1e9.*lambda,10*log10(T));
FSR=lambda.^2./(ng*L);
meanFSR=mean(FSR);
% figure;
% plot(lambda,FSR);
er=((a+t)(1+a*t))^2/((a-t)(1-a*t))^2;
ER=10*log10(er); %dB
FWHM=(1-a*t).*lambda.^2./(pi.*ng.*L*sqrt(a*t));
meanFWHM=mean(FWHM);
Q=1550e-9/meanFWHM;
xlabel('Wavelength [nm]');
ylabel('Transmission (T)');
```

OUTPUT:



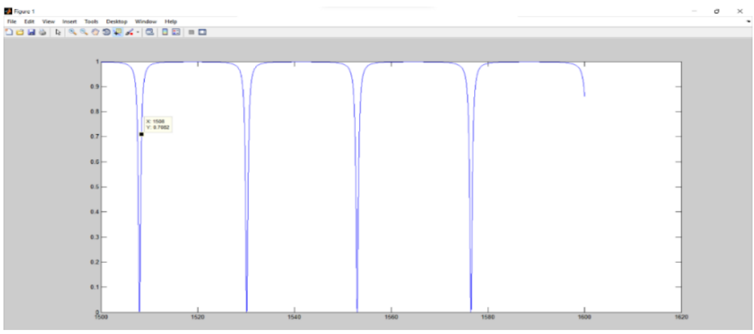
3) When Radius of the Ring(r)= 6.0e-6

MATLAB CODE:

```
clc;
clear all;
%Simple Ring Resonator
t=0.45;
r=6.0e-6; %m
lambda0=1550e-9;
neff=2.82;
alpha=1000; % dB/m
L=2*pi*r; %m
```

```
% lambda=(1530:0.01:1542)*1e-9; %m
lambda=(1500:0.01:1600)*1e-9; %m
neff_lambda = neff-0.85*(lambda*1e6-1.55);
ng = neff_lambda(1:length(lambda)-1) - mean(lambda) * diff(neff_lambda)./diff(lambda);
ng=[ng(1) ng];
theta=2*pi*neff*L./lambda;
a=exp(-alpha*L);
Nr=a^2-2*a*t.*cos(theta)+t^2;
Dr=1-2*a*t.*cos(theta)+a^2*t^2;
T=Nr./Dr;
plot(1e9.*lambda,T);
%plot(1e9.*lambda,10*log10(T));
FSR=lambda.^2./(ng*L);
meanFSR=mean(FSR);
% figure;
% plot(lambda,FSR);
er=((a+t)(1+a*t))^2/((a-t)(1-a*t))^2;
ER=10*log10(er); %dB
FWHM=(1-a*t).*lambda.^2./(pi.*ng.*L*sqrt(a*t));
meanFWHM=mean(FWHM);
Q=1550e-9/meanFWHM;
xlabel('Wavelength [nm]');
ylabel('Transmission (T)');
```

OUTPUT:



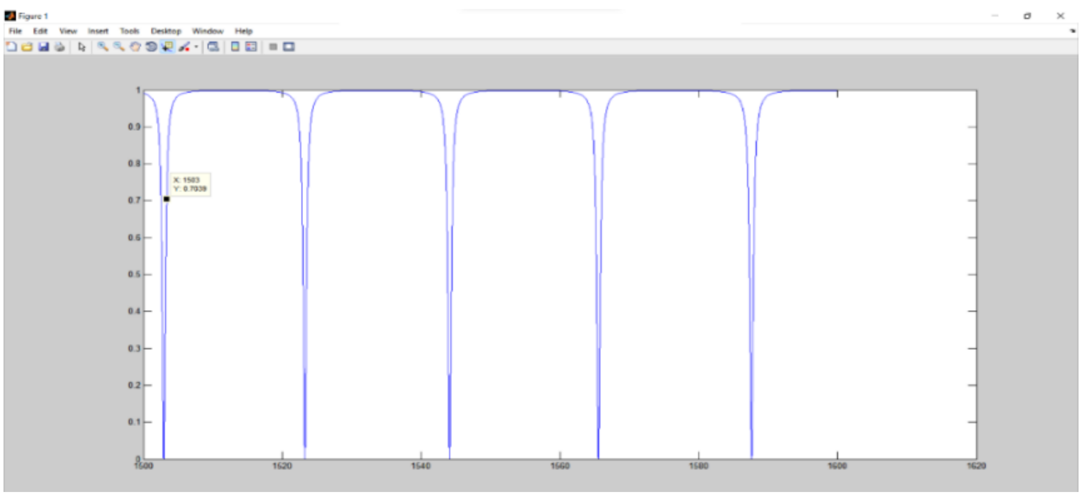
4) When Radius of the Ring(r)= 6.5e-6

MATLAB CODE:

```
clc;
clear all;
%Simple Ring Resonator
t=0.45;
r=6.5e-6; %m
lambda0=1550e-9;
neff=2.82;
alpha=1000; % dB/m
```

```
L=2*pi*r; %m
% lambda=(1530:0.01:1542)*1e-9; %m
lambda=(1500:0.01:1600)*1e-9; %m
neff_lambda = neff-0.85*(lambda*1e6-1.55);
ng = neff_lambda(1:length(lambda)-1) - mean(lambda) * diff(neff_lambda)./diff(lambda);
ng=[ng(1) ng];
theta=2*pi*neff*L./lambda;
a=exp(-alpha*L);
Nr=a^2-2*a*t.*cos(theta)+t^2;
Dr=1-2*a*t.*cos(theta)+a^2*t^2;
T=Nr./Dr;
plot(1e9.*lambda,T);
%plot(1e9.*lambda,10*log10(T));
FSR=lambda.^2./(ng*L);
meanFSR=mean(FSR);
% figure;
% plot(lambda,FSR);
er=((a+t)(1+a*t))^2/((a-t)(1-a*t))^2;
ER=10*log10(er); %dB
FWHM=(1-a*t).*lambda.^2./(pi.*ng.*L*sqrt(a*t));
meanFWHM=mean(FWHM);
Q=1550e-9/meanFWHM;
xlabel('Wavelength [nm]');
ylabel('Transmission (T)');
```

OUTPUT:



TABLE

SL. NO	r [um]	λr1 [nm]	λ3-db [nm]	FSR [nm]
1	5.0e-6	1521	1522-1521=1	27
2	5.5e-6	1514	1514-1514=0	24
3	6.0e-6	1508	1508-1508=0	22
4	6.5e-6	1503	1503-1503=1	20
5	7e-6	1517	1518-1517=1	20

Radius of the Ring (r) varies with respect to different parameters:

3-db Bandwidth Vs Ring Radius

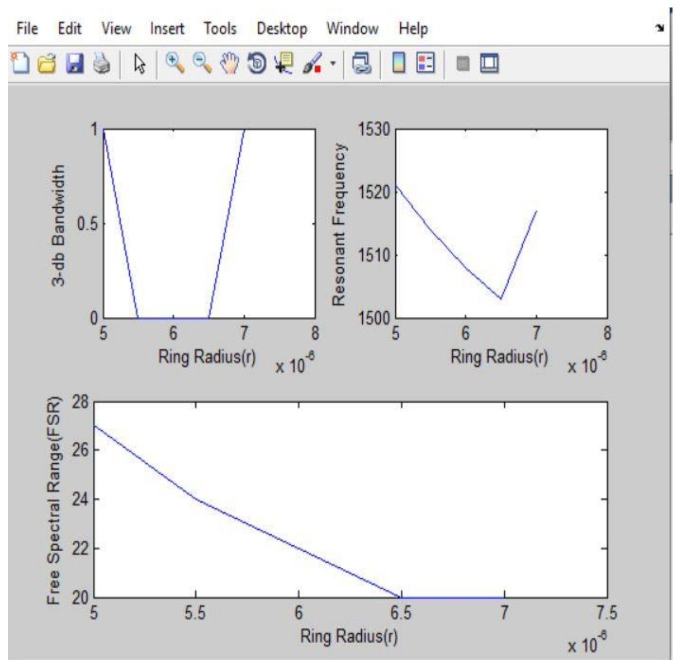
Graph linearly decreases to point 5.5 and starts increases at 6.5

Resonant frequency Vs Ring Radius

Initially Graph decreases at point 6.5 after that it increases linearly

Free Spectral Range Vs Ring Radius

Graph is non linearly decreasing

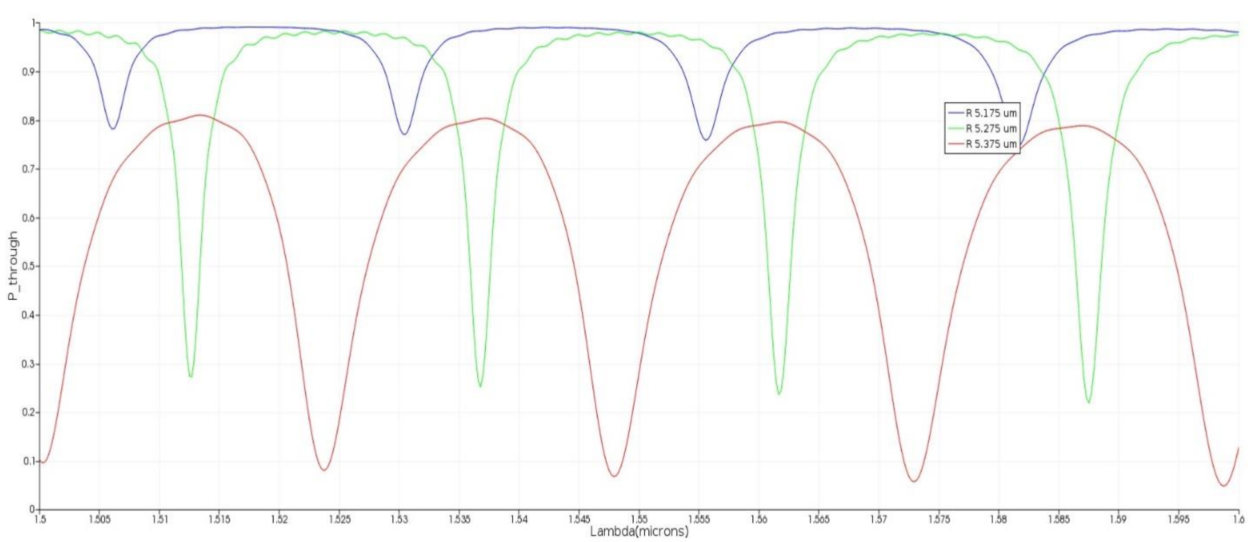


6 .2. OBSERVATION Using LUMERICAL SUIT

When radius Of Ring is Varying:-

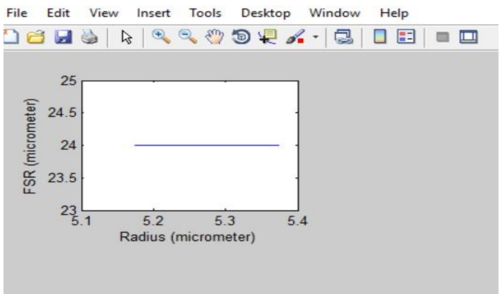
Radius(µm) (Outer radius – Inner radius)	**FSR(µm)**	**FWHM(µm)**	**ER**
1) 5.175 – 4.725	1555-1530=25	1507-1504=3	10log(0.98/0.78)=1.003
2) 5.275-4.625	1536-1512=24	1513-1511=2	10log(0.98/0.27)=5.56
3) 5.375-4.525	1547-1523=24	1520-1526=6	10log(0.8/.009)=9.48

Output Obtained after taking different radius value of Ring Resonator:-



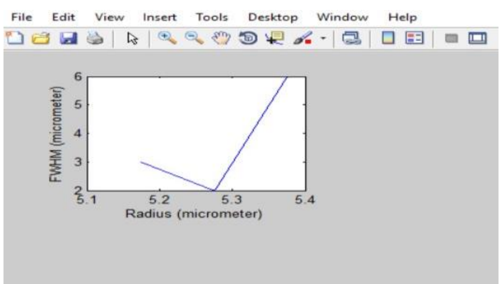
Free Spectral Range (FSR) Vs Radius

When we increase radius of ring resonator then FSR is constant.



Full width at half maximum (FWHM) Vs Radius

When we increase radius of ring resonator then FWHM is first decrease and then increase.



Extinction ratio (ER) Vs Radius

When we increase radius of ring resonator then ER is increasing linearly.

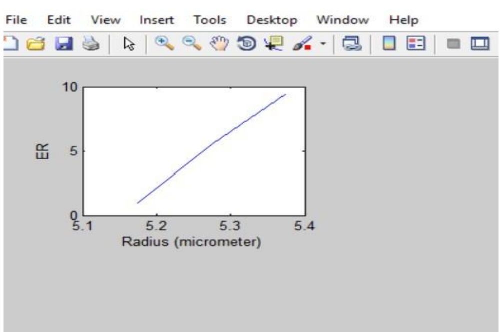
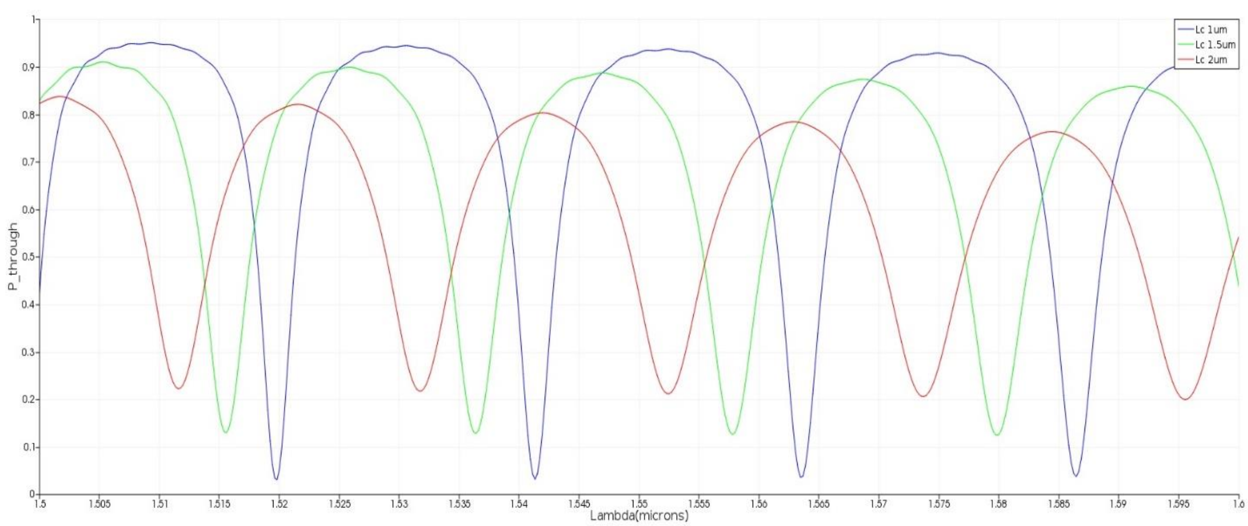


Table Obtained after taking different Coupling Length (Lc) of Ring Resonator :-

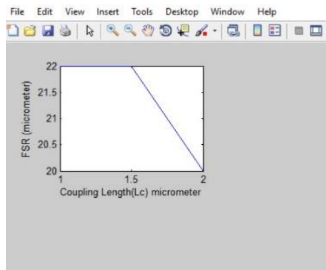
Coupling Length(Lc) (µm)	FSR(µm)	FWHM(µm)	ER
1) 1	1541-1519=22	1521-1518=3	10log(0.95/0.03)=15
2) 1.5	1558-1536=22	1537-1535=2	10log(1.0/0.45)=3.46
3) 2	1531-1511=20	1514-1508=6	10log(0.82/0.22)=5.713

Output Obtained after taking different Coupling Length(Lc) of Ring Resonator:-



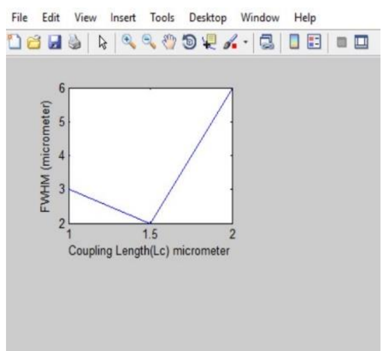
Free Spectral Range (FSR) Vs Coupling Length(Lc)

When we increase Coupling Length(Lc) of ring resonator then FSR is decreasing.



Full width at half maximum (FWHM) Vs Coupling Length (Lc)

When we increase of ring resonator then FWHM is Coupling Length(Lc) first decreasing and then increasing linearly.



Extinction ratio (ER) Vs Coupling Length (Lc)

When we increase Coupling Length(Lc) of ring resonator then ER is first decreasing and then increasing linearly.

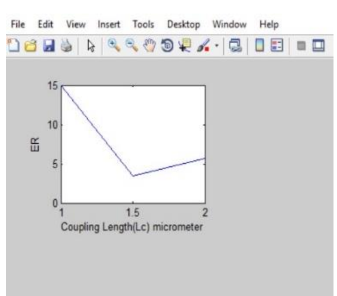
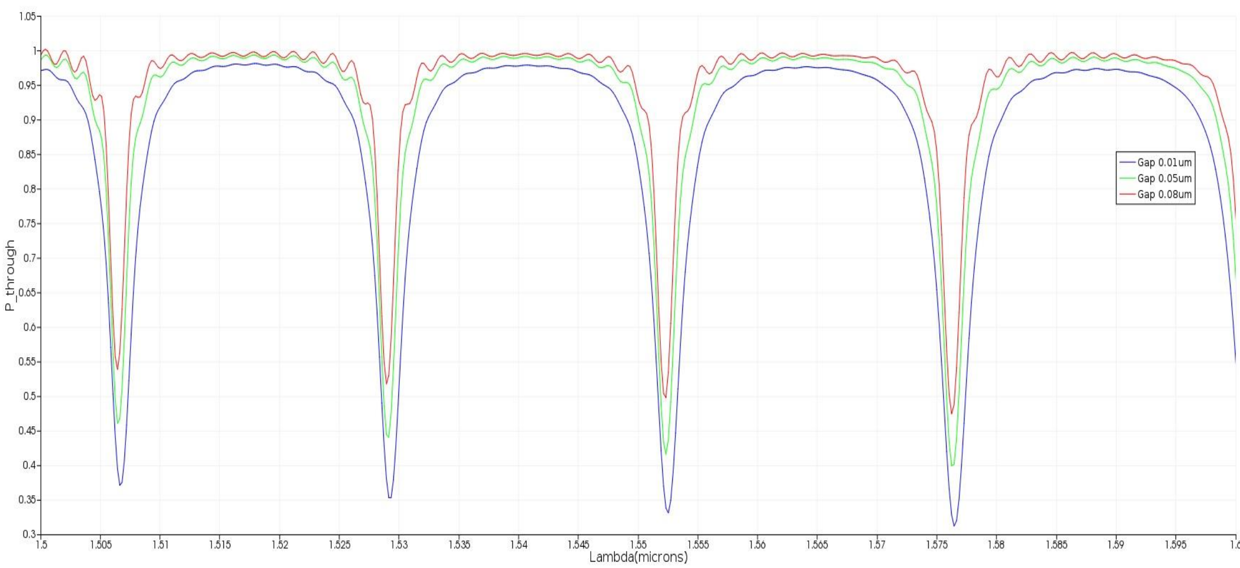


Table Obtained after taking different Gap between waveguide and ring resonator (µm)

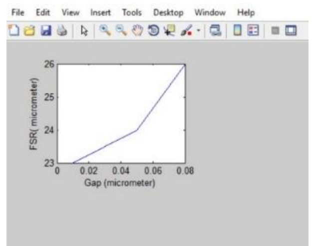
Gap between waveguide and ring resonator (µm)	FSR(µm)	FWHM(µm)	ER
1) 0.01	1552-1529=23	1530-1527=3	10log(0.97/0.35)=5.713
2) 0.05	1552-1528=24	1529-1528=1	10log(0.98/0.44)=3.48
3) 0.08	1552-1528=26	1553-1551=2	10log(0.99/0.51)=2.88

Output Obtained after taking different Gap between waveguide of Ring Resonator:-



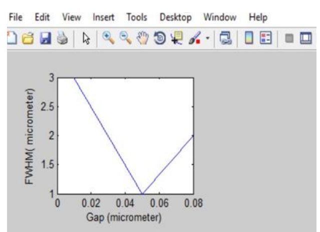
Free Spectral Range (FSR) Vs Gap between waveguide and ring resonator

When we increase Gap between waveguide and ring resonator of ring resonator then FSR is decreasing.



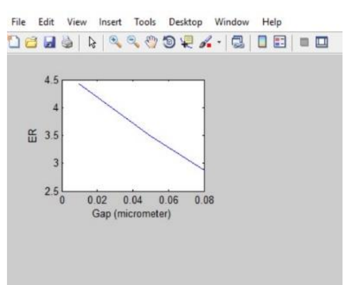
Full width at half maximum (FWHM) Vs Gap between waveguide and ring resonator

When we increase Gap between waveguide and ring resonator of ring resonator then FWHM is first decreasing and then increasing after certain point.



Extinction ratio (ER) Vs Gap between waveguide and ring resonator

When we increase Gap between waveguide and ring resonator then ER is decreasing.



CHAPTER 7. APPLICATION

7.1. Biological sensors

Biological sensors, as a bioanalytic tool, play an important role in food sciences and biotechnology. Many investigations are conducted to increase the accuracy, sensitivity, and functionality of these sensors; at the same time, there is a tendency to decrease the size and price of these devices.

In the past few years, optical ring resonators have received a lot of attention as one of the most promising biological sensors. The optical ring resonator measures the target molecules through assessing the deviations in light behavior, which is caused by interaction between electromagnetic wave and biological molecules such as proteins, bacteria, cells, or DNA samples. This change in the behavior of the light is because of interaction between evanescent field of the resonating light inside the resonator and bioparticle that exist in the ambient. Existence of bioparticles in the medium changes the effective refractive index of surrounded medium, which results in deviation of resonance conditions of the resonator. Consequence of such an interaction is resonance wavelength deviation of the resonator that is related to the number for bioparticles in the medium. A sensing mechanism is depicted schematically. To enable the periphery of the resonator to absorb bioparticles, an active polymer layer can be deposited on the boundary of the resonator. This layer is able to mechanically absorb or chemically react with the target bioparticle, resulting in a change in the effective refractive index of the resonating mode.

Due to the nature of the optical ring resonator and how it "filters" certain wavelengths of light passing through, it is possible to create high-order optical filters by cascading many optical ring resonators in series. This would allow for "small size, low losses, and integrability into [existing] optical networks. "Additionally, since the resonance wavelengths can be changed by simply increasing or decreasing the radius of each ring, the filters can be considered tunable. This basic property can be used to create a sort of mechanical sensor. If an optical fiber experiences mechanical strain, the dimensions of the fiber will be altered, thus resulting in a change in the resonant wavelength of light emitted. This can be used to monitor fibers or waveguides for changes in their dimensions. The tuning process can be effected also by a change of refractive index using various means including thermo-optic, electro-optic or all-optical effects. Electro-optic and all-optical tuning is faster than thermal and mechanical means, and hence find various applications including in optical communication. Optical modulators with a high-Q micro ring are reported to yield outstandingly small power of modulation at a speed of > 50 Gbit/s at cost of a tuning power to match wavelength of the light source. A ring modulator placed in a Fabry-Perot laser cavity was reported to eliminate the tuning power by automatic matching of the laser wavelength with that of the ring modulator while maintaining high-speed ultralow-power modulation of a Si micro ring modulator.

Optical ring, cylindrical, and spherical resonators have also been proven useful in the field of biosensing and a crucial research focus is the enhancement of biosensing performance One of the main benefits of using ring resonators in biosensing is the small volume of sample specimen required to obtain a given spectroscopy results in greatly reduced background Raman and fluorescence signals from the solvent and other impurities. Resonators have also been used to characterize a variety of absorption spectra for the purposes of chemical identification, particularly in the gaseous phase.

Another potential application for optical ring resonators are in the form of whispering gallery mode switches. "[Whispering Gallery Resonator] micro disk lasers are stable and switch reliably and hence, are suitable as switching elements in all-optical networks." An all-optical switch based on a high Quality factor cylindrical resonator has been proposed that allows for fast binary switching at low power Material.

Many researchers are interested in creating three-dimensional ring resonators with very high quality factors. These dielectric spheres, also called microsphere resonators, "were proposed as low-loss optical resonators with which to study cavity quantum electrodynamics with laser-cooled atoms or as ultrasensitive detectors for the detection of single trapped atoms.

Ring resonators have also proved useful as single photon sources for quantum information experiments. Many materials used to fabricate ring resonator circuits have non-linear responses to light at high enough intensities. This non-linearity allows for frequency modulation processes such as four-wave mixing and Spontaneous parametric down-conversion which generate photon pairs. Ring resonators amplify the efficiency of these processes as they allow the light to circulate around the ring.

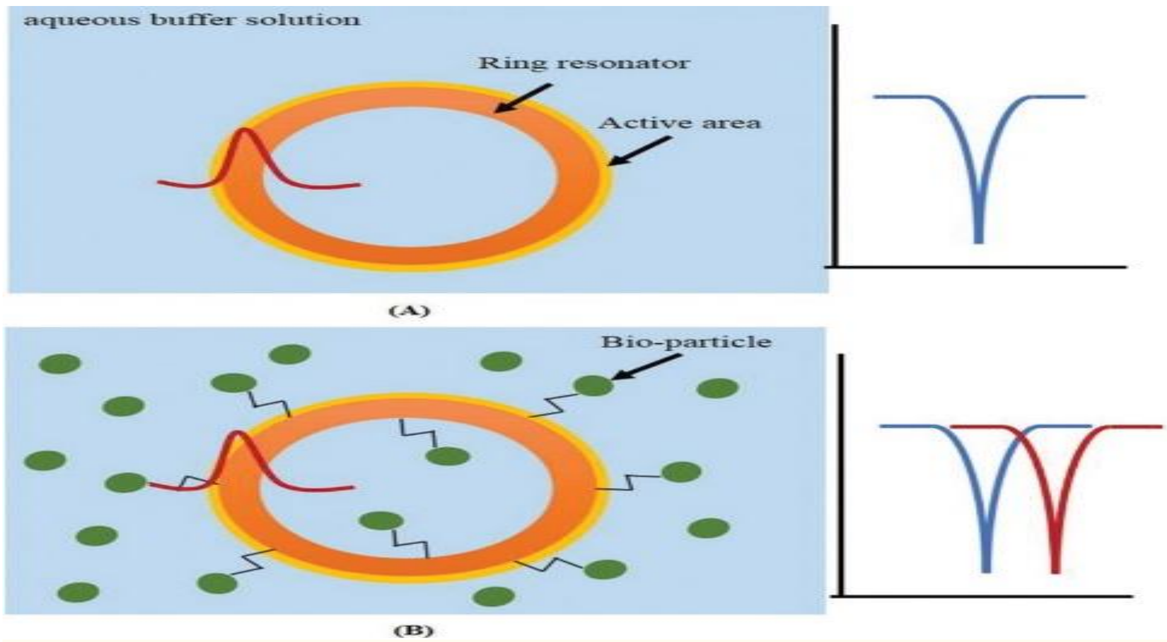


FIGURE 5 : Optical ring resonator as a biological sensing platform; (a) ring resonator is placed in an aqueous buffer solution. (a) There are no bioparticles in the buffer solution. (b) There are bioparticles in the medium. The bioparticles captured by the active polymeric layer interact with evanescent field of the light which results in a shift in resonance wavelength of the resonator.

- It is used as filter where one can transmit or receives particular frequency or range of frequency.
- It is also used as temperature sensitive devices.
- It is also used in medical sciences like to detect cancer cells in the body , different blood samples.
- It can also be used as multiplexer and demultiplexer in communication system.

CHAPTER 8. CONCLUSION

Working of Optical Filter Using Ring Resonator in Silicon-On-Insulator with the help of MATLAB

- ➨ Variation of Several Parameters like :

1. Self coupling coefficient(t)
2. Effective Index (n_{eff})
3. Loss Coefficient (α)
4. Radius of the Ring (r)

Working of Optical Filter Using Ring Resonator in Silicon-On-Insulator with the help of Lumerical Suite .

- ➨ Variation of Several Parameters like :

1. Radius of the Ring
2. Coupling Length (Lc)
3. Gap between wave guide and ring resonator

Results were obtained and graph plotted between transmission Vs wavelength

Results were obtained and graph plotted between Output parameters Vs varying the various input parameters.

CHAPTER 9. APPENDIX

Simulation Code

```
clc;
clear all;
%Simple Ring Resonator
t=0.96;
r=10.1e-6; %m
lambda0=1550e-9;
neff=2.76;
alpha=1000; % dB/m
L=2*pi*r; %m
% lambda=(1530:0.01:1542)*1e-9; %m
lambda=(1500:0.01:1600)*1e-9; %m
neff_lambda = neff-0.85*(lambda*1e6-1.55);
ng = neff_lambda(1:length(lambda)-1) - mean(lambda) * diff(neff_lambda)./diff(lambda);
ng=[ng(1) ng];
theta=2*pi*neff*L./lambda;
a=exp(-alpha*L);
Nr=a^2-2*a*t.*cos(theta)+t^2;
Dr=1-2*a*t.*cos(theta)+a^2*t^2;
T=Nr./Dr;
plot(1e9.*lambda,T);
%plot(1e9.*lambda,10*log10(T));
FSR=lambda.^2./(ng*L);
meanFSR=mean(FSR);
% figure;
% plot(lambda,FSR);
er=((a+t)(1+a*t))^2/((a-t)(1-a*t))^2;
ER=10*log10(er); %dB
FWHM=(1-a*t).*lambda.^2./(pi.*ng.*L*sqrt(a*t));
meanFWHM=mean(FWHM);
Q=1550e-9/meanFWHM;
xlabel('Wavelength [nm]');
ylabel('Transmission (T)');
```

CHAPTER 10. REFERENCES

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