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Observation of the Sensing Property of Optical Micro-Ring Resonator

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ABSTRACT : This paper has been developed to illustrate the performance of a micro-ring resonator and its effectiveness in sensing. Firstly, the performance of the ring resonator is observed by varying different structural parameters specially radius of the ring waveguide and the separation gap between bus-bar and ring. Then a structure has been built up that can be suitable for sensing. All the experiments are done according to a Finite Differential Time Domain (FDTD) approach.

KEYWORDS: Bragg-grating, Evanescent Coupling, Micro-ring Resonator, Optical Sensor, Total Internal Reflection.

I. INTRODUCTION

A sensor is a device that can quantify a particular environmental property, the measurand, through changes in the transmission spectrum of the sensing device. People don't know that they are using sensors in their daily life in some way. The sensitivity of the sensors depends on the its output variation and this variation relies on the change of measured value. For example, 1°C temperature rise in a thermocouple junction increases the output 1 volt [1]. Achieving higher and precise accuracy in sensor was a need for the researchers and this makes the area of sensor design a constantly active area of research [2].

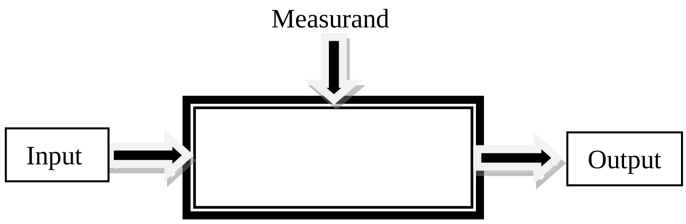

Fig. 1 Block diagram of a sensor

The resistivity-based sensor is one type of sensing mechanisms which is based on the measurement of resistivity; but long response time is its key limitation. Another type of sensing mechanism is electrochemical sensing mechanism but its limitations include its bulky, influenced by electromagnetic interference and it give inaccurate results [3]. Optical sensors have some interesting merits over all other sensors: usage in high-voltage environments, can be safely used in explosive environments, immune to electromagnetic interference (EMI), very wide operating temperature range [4], [5]. A resonator is a device or system that exhibits relative maximum amplitude swing at some frequencies and these frequencies are known as the system's resonant frequencies or resonance frequencies [6]. Resonators are used to either generate waves of specific frequencies or to select specific frequencies from a signal [7]. The first optical ring resonator consists of at least one ring and straight waveguides and exhibits a discrete set of frequency resonances. The radius of the ring of a ring resonator can be anywhere between several meters (e.g. optical fibers) to micrometers (e.g. integrated optical devices) [8].The goal of this paper is to illustrate how a micro-ring resonator can perform sensing application. A Finite Differential Time Domain (FDTD) method is applied in this simulation based project. Observation process was used in this paper rather than computational process.

II. PRINCIPLE OF OPERATION

The whole structure is made by two waveguides. One is straight, often called bus-bar and another creates closed loop path, often called ring. Fig. 2 shows the simple microring resonator structure.

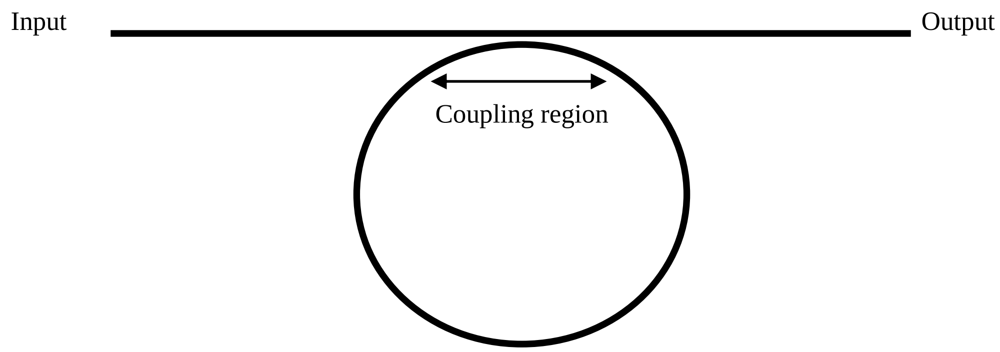

Fig. 2 Simple micro-ring resonator

Now, place a waveguide into some surrounding medium, the medium would affect the evanescent wave of the waveguide and thus affect the EM wave inside the waveguide by changing its wavelength of intensity. Therefore, by detecting the variation of some parameters of EM wave in the waveguide it could detect the variation of environment medium. In this way, a sensor could be designed as long as the relationship between the variations of what is detected can be figured out [12]. Since only some resonance frequencies are existed within the ring after evanescent coupling of light from bus-bar, a resonance frequency shift due to a suitable variation in the refractive index allows the sensing of trace amount of analyze [13]. The performance can be improved by using nonlinear effect. Introducing some periodic nano-disks within the ring waveguide, shift of the resonance peak will follow Bragg-grating Law.

III. SYSTEM DEVELOPMENT

Design Consideration: It's a need to design an optimum structure of micro-ring resonator so that it can be implemented in sensing application. The operational principle of micro-ring resonator very much depends on the width and the height of the waveguides, radius of the ring and the separation gap between bus-bar and ring. However, in this paper for easy coupling of the light from the source the height and width of the waveguides is chosen as 250nm and 500nm respectively. The light source will be Gaussian modulated continuous wave with center frequency 1550 nm. The particular interest in this wavelength is due to fast response and narrow band beam generation. Therefore, a ring radius is picked up and determines the gap between the ring and bus-bar.

Determination of Ring Radius : For finding out an optimum radius of the microring resonator, the separation gap between ring and bus-bar is kept constant at 50 nm. Without any mathematical modeling several radii of observation: 1500nm, 1550nm, 1750 nm, 1800 nm, 3100 nm and 4650 nm are predicted. In the design process, figure 3-8 shows the output of the ring resonator by varying only the radius keeping other parameters as it is.

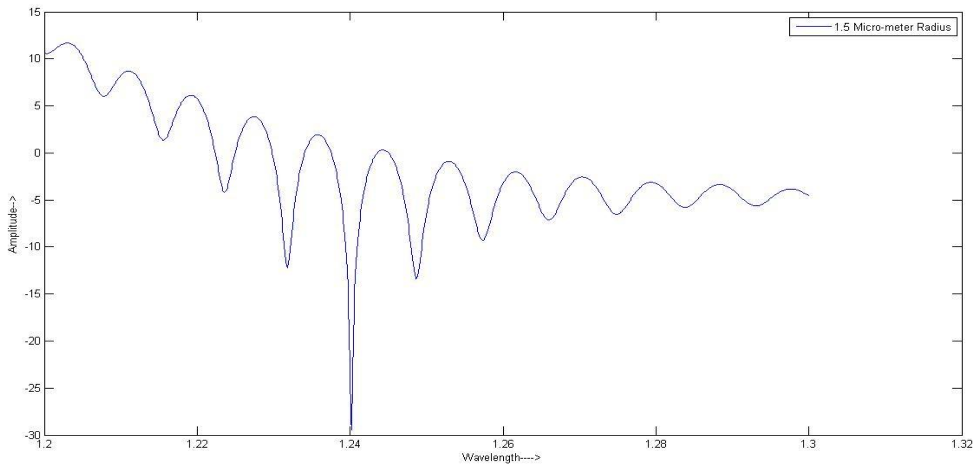

Fig. 3 Output of Micro-ring with radius 1500 nm

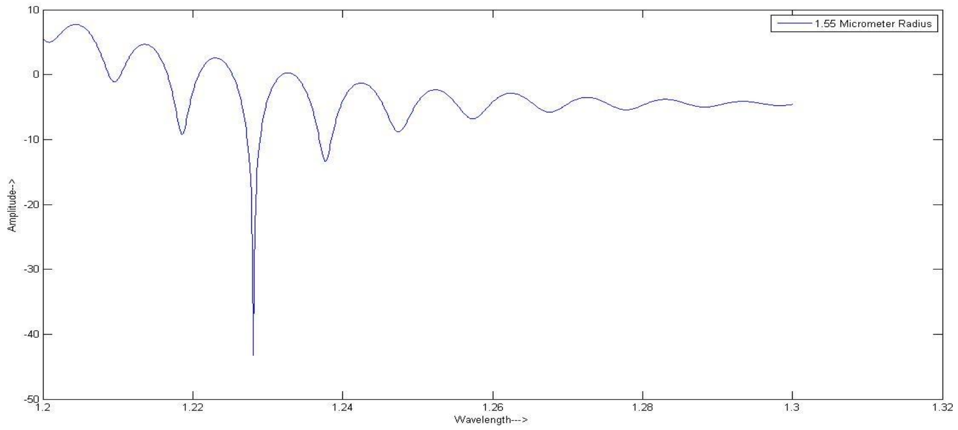

Fig. 4 Output of Micro-ring with 1550 nm radius

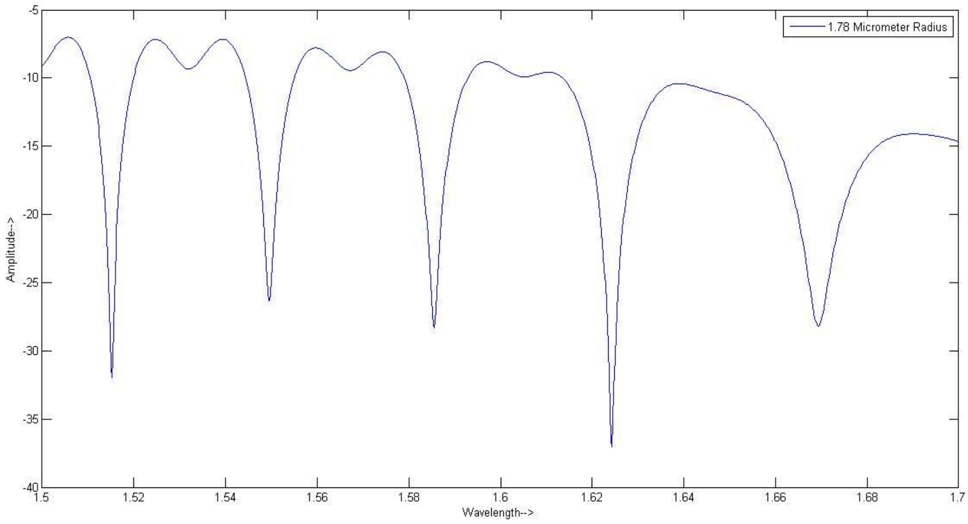

Fig. 5 Output of Micro-ring with radius 1778 nm

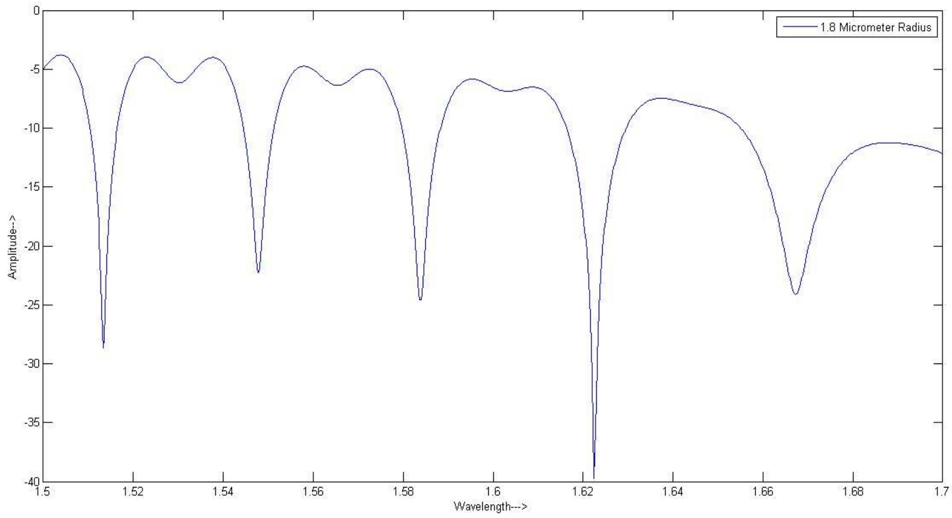

Fig. 6 Output of Micro-ring with radius 1800 nm

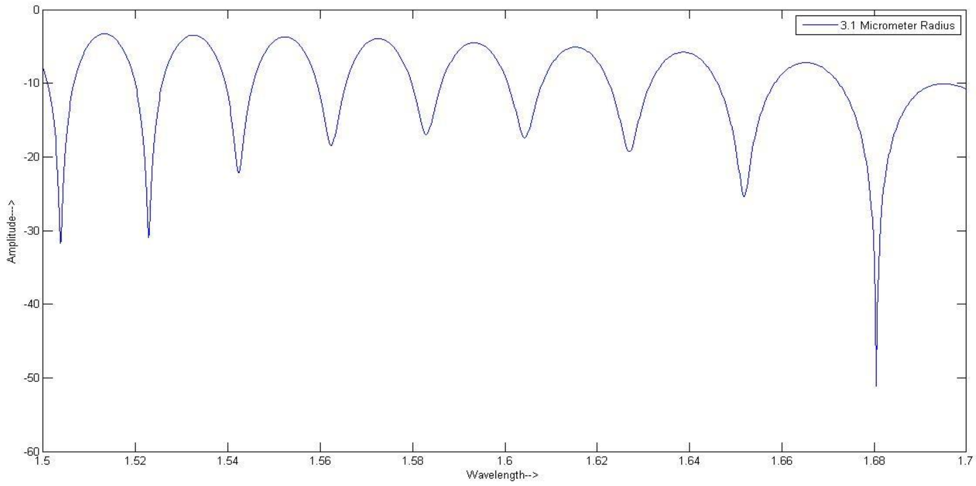

Fig. 7 Output of Micro-ring with radius 3100 nm

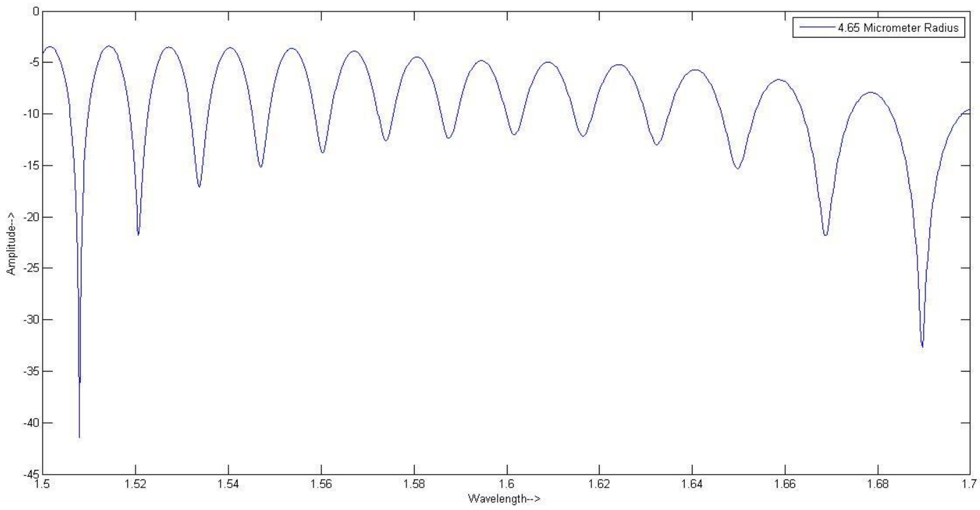

Fig. 8 Output of Micro-ring with radius 1465 nm

From the output of the resonator, obtained by opti FTDT simulator, the radius can be chosen by the following process: Firstly, try to choose a single resonance frequency that close to your center frequency. Secondly, if there is no single resonance frequency, try to choose which have less number of resonance peaks and smallest gap among these peaks. Fig. 3 shows the output of micro-ring resonator with radius 1500 nm. One can easily observe that resonance peak have been found at 1240 nm. This is very much away from our sources center frequency 1550 nm. Fig. 4 shows the output of micro-ring resonator with radius 1550 nm. One can easily observe that resonance peak have been found at 1230 nm. This is also very much away from our sources center frequency 1550 nm. But an important property has been noticed here, a slight increase of radius shift the resonance peak slightly left. Fig. 5 and Fig. 6 show the output of micro-ring resonator with radius 1780 nm and 1800 nm respectively. As the two radii are so close to each other, their response should also be similar. There are two significant resonant frequencies: one is close to 1510 nm and other is close to 1620 nm. But the distance between to resonance peaks are large and the major resonant component lies at 1620 nm.Fig. 7 shows the output of micro-ring resonator with radius 3100 nm. One can easily observe that resonance peak have been found at 1680 nm. This is very much away from our sources center frequency 1550 nm.Fig. 8 shows the output of micro-ring resonator with radius 1465 nm. One can easily observe that major resonance peak have been found at 1510 nm. This is very much close to our source center frequency 1550 nm.

DETERMINATION OF SEPARATION GAP :

Similarly, keeping the radius constant, in this design radius is chosen as 1800 nm, and only varying the separation gap, but other parameters would remain same.

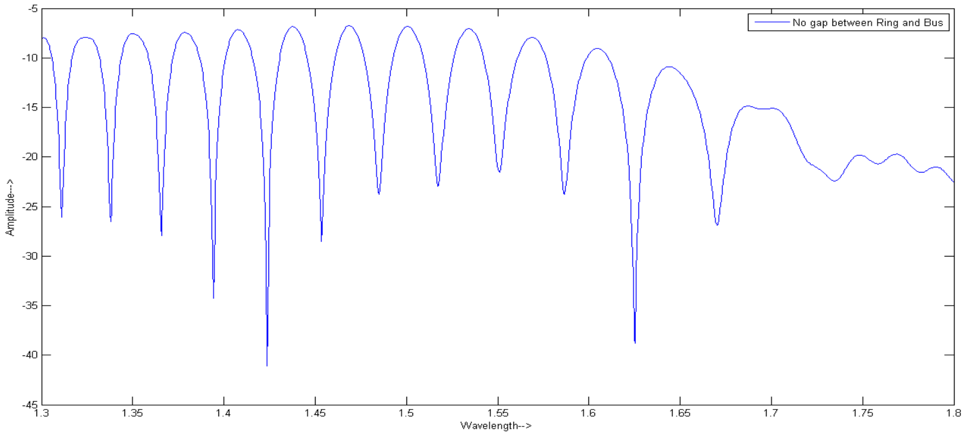

Fig. 9 Output without any gap

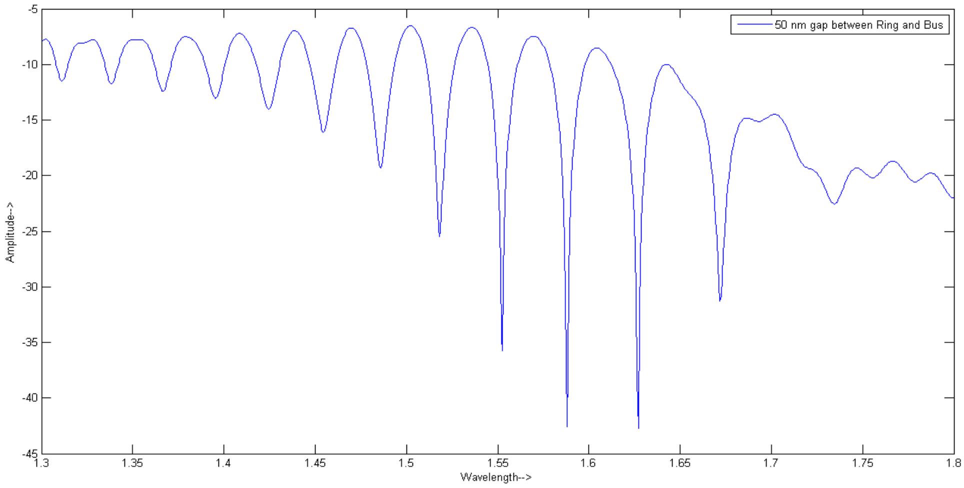

Fig. 10 Output with 50 nm gap

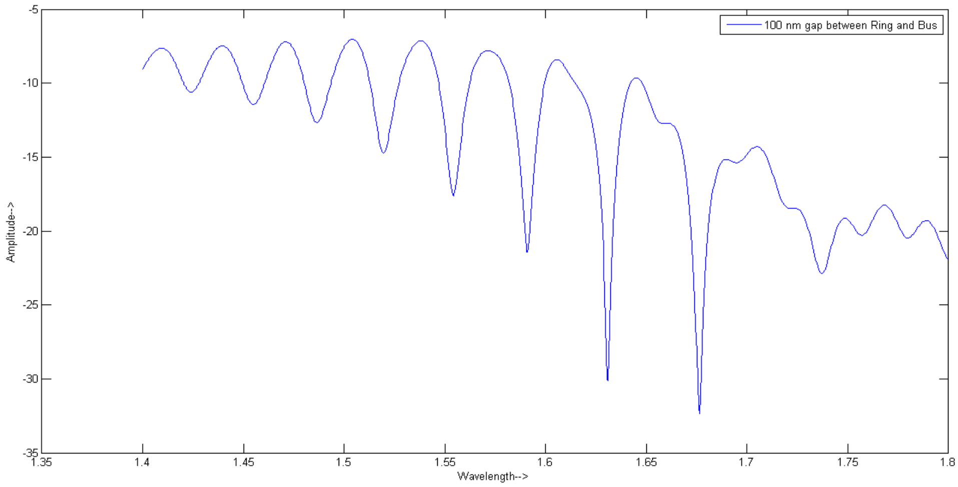

Fig. 11 Output with 100 nm gap

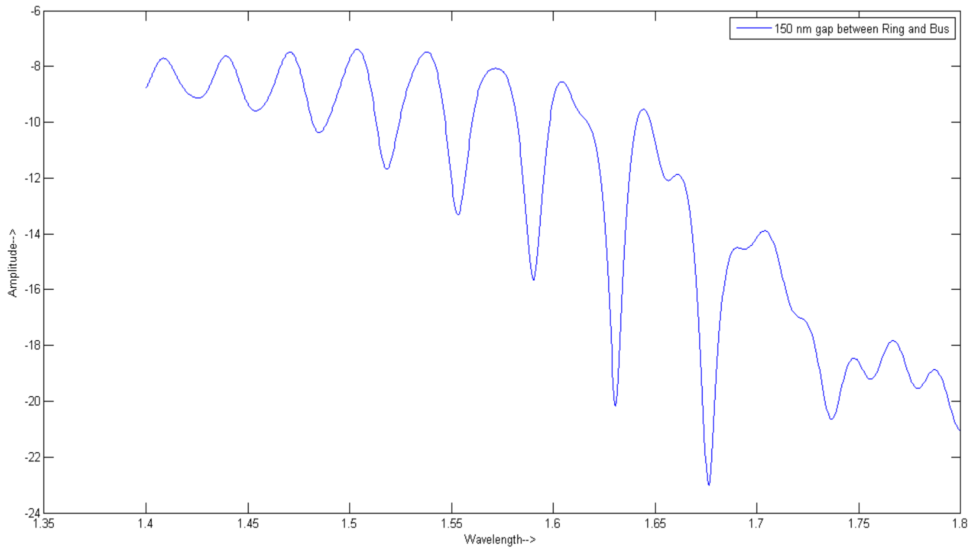

Fig. 12 Output with 150 nm gap

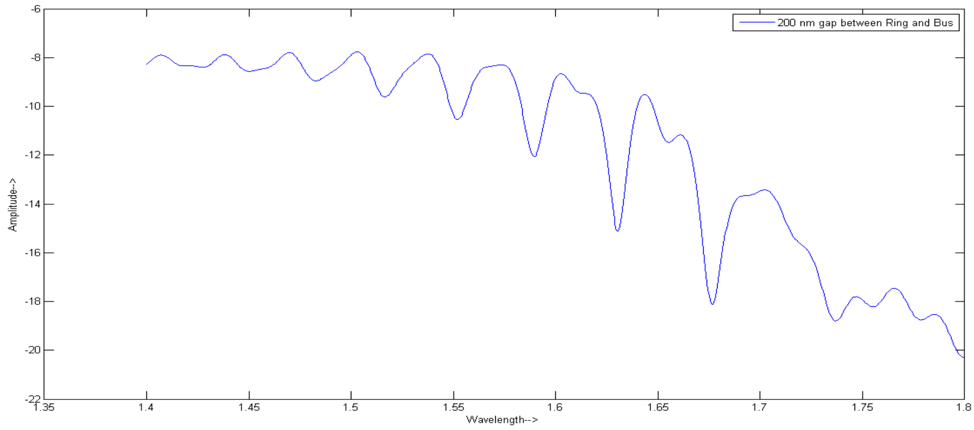

Fig. 13 Output with 200 nm gap

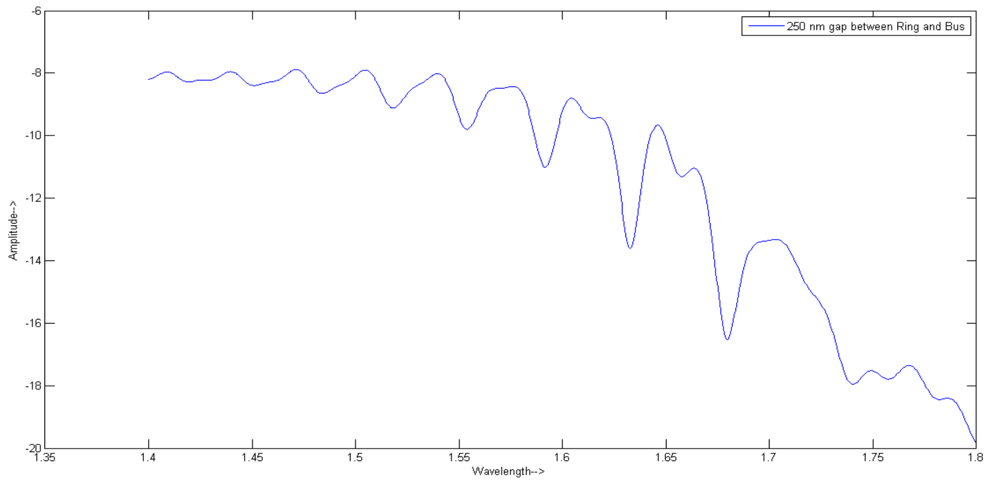

Fig. 14 Output with 250 nm gap

Fig. 9 shows the output of micro-ring resonator when there is no gap between ring and bus. The coupling of light is very much high but resonant spectrum is very large. This reduces the quality of the coupling. Fig. 10 and Fig.

11 show the output of micro-ring resonator when there is 50 nm and 100 nm gap between ring and bus respectively. Here the quality of the coupling is increased by narrowing the resonant spectrum. Fig. 12, Fig. 13 and Fig. 14 show the output of micro-ring resonator when there is 150 nm, 200 nm and 250 nm gap between ring and bus respectively. From this figures one can assume that, coupling of light is decreased gradually and it becomes less significant above 200 nm. Therefore, from the above graphical analysis, the gap that is too close or too far should not be chosen. The most useable gap lies in the range 30 nm to 160 nm.In the present case, the separation gap between bus and ring waveguide was chosen from 50 nm to 100 nm and the ring radius was selected around 3100 nm or 1465 nm. In the present work, waveguide width was chosen as 500 nm to avoid other modes except fundamental modes inside the waveguides. Coupling area improves the response as well. Elliptical ring, which has major and minor radii 1880 nm and 1780 nm respectively, provides more coupling area than circular one. Elliptical structural design was chosen in this paper.

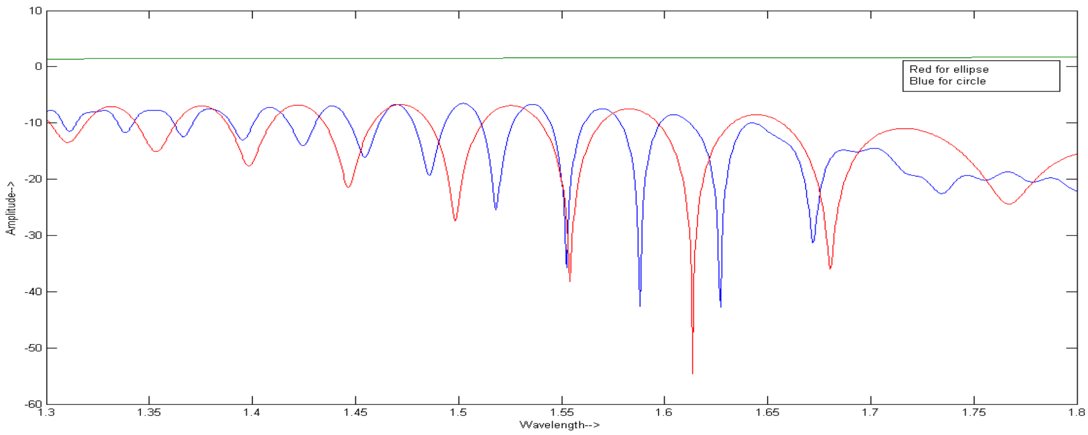

Fig. 15 Output of the circular ring and elliptical ring

IV. SIMULATION MODEL OF SENSOR

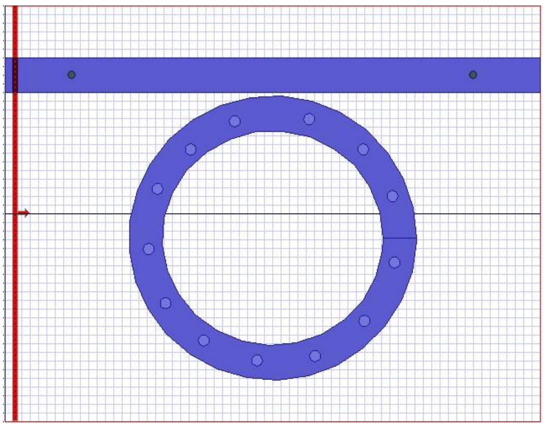

Fig. 16 The simulation model of sensor with nano disks

Fig. 16 shows the model for the simulation of a micro-ring resonator with Nano-Disks. A Finite Difference Time Domain (FDTD) simulation was performed for the TE mode. Materials were defined with a popular Drude Lorentz model and incorporated in the simulation as a function of wavelength. The simulation model consists of a silicon-on-insulator (SOI) micro-ring resonator with major and minor radii of 1880 nm and 1780 nm respectively. The refractive index of the Si is 3.48 at 1550 nm wavelength. The bus and ring waveguides are 500 nm wide and 250 nm in height. The distance (air gap) between the ring and the bus waveguides is 50 nm. An array of equally spaced nano-disks is bound to the top of the ring. The nano-disks have 80 nm radii and a 100 nm depth. The ring resonator is assumed to be operating in air. The material of the nano-disks isn't fixed. We assume that its refractive index is changed corresponding to a property that we want to detect.

V. PERFORMANCE ANALYSIS

According to the principle of operation we had placed periodic nano-disks in the ring waveguide of the resonator to utilize the Bragg-grating phenomena which causes a shift in resonant frequency. The output of the micro-ring resonator is illustrated in following figure:

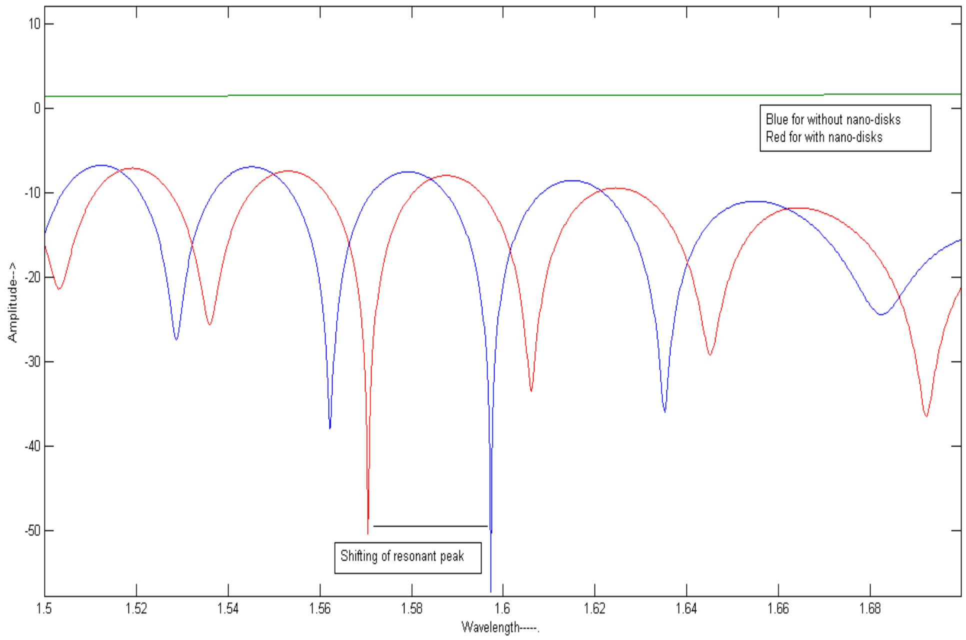

Fig. 18 shifting of resonant frequency by nano-disks

Here one can easily observe that resonance frequency shifts from ~1600 nm to ~1570 nm. Now if the refractive index of the nano-disks is varied, the resonant peak slightly shifts from its position. An increase in the refractive index of the nano-disks shifts the resonant peak toward right. A decrease in the refractive index of the nano-disks shifts the resonant peak toward left. This maintains almost a linear relationship.

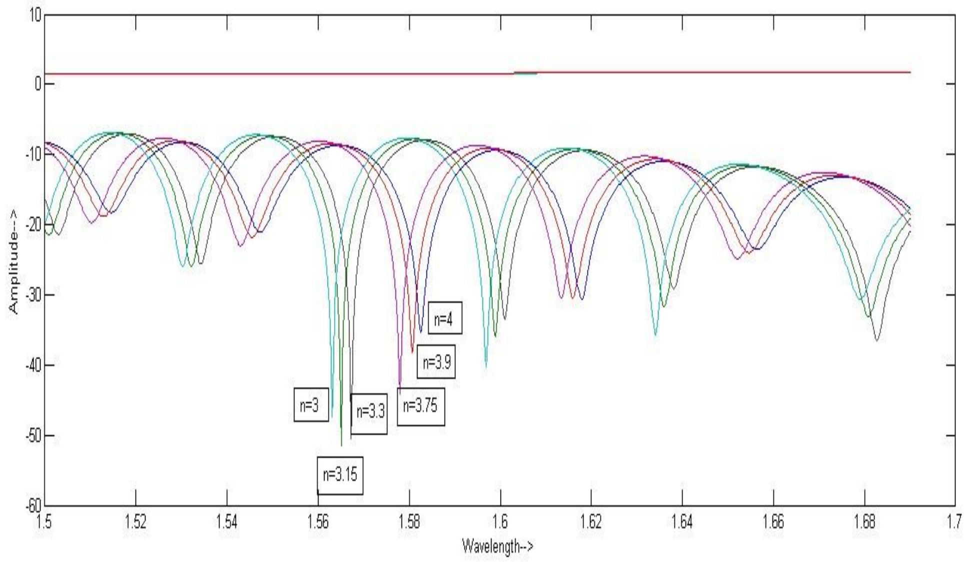

Fig. 19 shift in resonant peak with refractive index of the nano-disks

However, the relationship have grown up, we can use this in sensing. The performance of the micro-ring sensor depends on various parameters. The resonance frequency of the sensor can be tuned using the number of nano-disks, their radii and their spacing. The sensor performance with respect to the sensitivity and Q-factor has been also studied in some research works. A lower number of nano-disks, small disk radius and larger disk spacing increase the 2nd order Bragg grating spacing, and thereby enhance the sensor sensitivity and Q-factor. These performance parameters can be optimized based on the manufacturing process and desired operation range.But during the experiment, it seems that choosing waveguide refractive index for particular sensing operation plays a vital role about accuracy. When the nano-disk material's refractive index is very close to the waveguide material's refractive index, it responses in a different way. The technology will not be suffered very much by this fact. The existing advanced technology gives you to select particular refractive index by introducing contamination to silicon wafer.

VI. CONCLUSION

In summary of this project work, we can say that optical micro-ring resonator is the possible candidate of future sensing field. But the device performance depends very much on the structural parameters. We have to co-ordinate the structural parameters before commercial production. We systematically varied the ring radius and separation gap between bus-bar and ring to examine the impact of structural parameters on the device performance. Separation gap impacts on the coupling loss and quality factor (mainly free spectral range). An increase in separation gap also increases the coupling loss and quality factor. But we should not sacrifice coupling of light for quality factor. Thus we need to select the gap (actually lies between 30 nm to 150 nm) by mutual agreement of these two factors. Radius impacts on the wavelength of the resonance frequencies. To store a particular wavelength within the ring, length of the radius has to be such that constructive interference will occur. We don't get any mathematical modeling for radius determination. But one can start from around the integer multiple of the center frequency of the light source. After that one can change the circular shape of the ring into elliptical shape by varying the major axis radius of the ellipse. There may have some possibility to find out the desired response. Lastly a proper choice of waveguide material for particular application acts as a very fast and effective sensor.

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