



Performance investigation of triple unsymmetrical micro ring resonator as optical filter as well as biosensor

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Abstract

Representation of triple unsymmetrical micro ring resonators (TUMRR) with single input and single output waveguide has been executed in this paper. Statistical demonstration of the presented arrangement is realized in the z-domain by a delay line signal processing method. The transfer function of the triple unsymmetrical micro ring resonator is calculated by Mason's Gain rule. The offered arrangement is performed on SOI (Silicon in Insulator) platform to achieve the filtering and biochemical sensing intentions. To acquire field response of the arrangement, Finite difference time domain (FDTD) technique is used. Characteristics of optical filters are studied from the frequency response plot and the achieved free spectral range is 243.5 GHz. The shift in wavelength for biosensing application is accomplished through the OptiFDTD software. The sensitivity of the proposed TUMRR based biosensor is around 200–280 nm/RIU for different blood cells where as the Q-factor attained is 1938.

Keywords Biosensor · MicroRing resonator · Delay-line signal processing · Filter

1 Introduction

At present, several different models of multiple ring resonators having upgraded FSR with lower crosstalk, using the technique delay line signal processing and signal flow graph method were developed through many researches (Oda et al. 1991; Little et al. 1997a; Suzuki et al. 1995; Moslehi et al. 1984a; Mandal et al. 2006; Dey and Mandal 2012; Yanagase et al. 2002). Lakra et al. (2017), presented a single input and two output unsymmetrical MRR arrangements having a FSR of 446 THz. All the rings are unequal in size as well as nature in this offered paper. Ranjan et al. (2018a), presented a single input and three output arrangement with a triple optical numerous ring resonators having a FSR approximately 110 THz. Ranjan et al. (2017), offered a 2×2 input output arrangement with an unequal ring resonators having a FSR approximately 0.4 THz. FSR of the resonators are reciprocal of its radius so in order to increase the FSR, the radius resonators must be lower. Radius of ring resonators is restricted by bending loss.

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This paper, offered a single input and single output waveguide which behaves as a biosensor to detect diseases cells from prescribed blood samples. In (Liu et al. 2020), an optical fiber SPR biosensor is proposed with MoSe_2 -Au structure for biosensing application with real-time detection, higher sensitivity and superior applicability in immunoassay. In (Guan and Huang 2019) an ultrasensitive optical microfiber-based biosensors is proposed where sensitivity and LOD have increased magnificently by increasing the light-matter interaction. In (Singh and Jha 2019), fabrication and validation of optical biosensor for non-invasive monitoring of glucose using saliva is proposed where the enzymatic reaction resulted in pH variation which was detected by electronic meter. In (Divagar et al. 2021), a dip type, wash free plasmonic fiber optic absorbance biosensor (P-FAB) is proposed for point-of-care detection of SARS-CoV-2 N-protein. In (Monfared et al. 2021), a highly sensitive quasi-D-shaped fiber optic biosensor is proposed for the detection of high refractive index liquid analytes via surface plasmon resonance. The proposed biosensor has a RI detection range of 0.15 RIU from 1.45 to 1.6. Various other optical biosensors having different shapes and characteristic were reported in Olyae and Bahabady (2015), Tavousi et al. (2018), Jindal et al. (2016), Kim et al. (2008), Khozaymeh and Razaghi (2019).

The offered arrangement is designed through directionally coupled waveguide. The field investigation of the propagated wave is finished using OptiFDTD environment. This paper offers an expanded FSR which can be efficiently used in various communication platforms. The correlation between digital filters and optical waveguide were developed by Moslehi et al. (1984b), Jackson et al. (1985), has been exploited in this paper to calculate the transfer function of the offered micro ring resonator in z-domain. Mason's gain rule has been used to create a signal flow graph for non-identical ring resonators (Gad et al. 2011; D'azzo and Houppis 1995). There is various application of optical resonators like, laser resonator (McCall et al. 1992), add-drop filters (Little et al. 1997b), optical spectrum analyzers which measure and display the distribution power of an optical source over a specified wavelength span (Kalli and Jackson 1992), optical switching which amplifiers the optical signal (Vat et al. 2002), optical filter which allow the transmission of a specific wavelength (Razaghi and Laleh 2016) etc. The resonance state can be defined as (Madsen and Zhao 1999a);

$$2\pi Rn_g = M\lambda \quad (1)$$

where ring radius is R , group refractive index is n_g , number of mode is " M " and resonant wavelength is " λ ". Optical ring resonator performs an important function to construct optical filters in communication systems whereas biosensors have numerous applications in field of medical, food production, ecosystems, security and aquatic etc.

The proposed micro ring resonator is basically developed to create an integrated sensor network. Through that the inherent filter characteristic will be an added advantage to transmit the sensor data in remote location. Several sensors working in different band with spacing of around 18–20 GHz can be integrated within this FSR. Therefore the proposed TUMRR having FSR of 243.5 GHz can accommodate roughly 10–15 sensor data i.e. 15 different sensors data can be transmitted to remote location using the filter characteristic of TUMRR.

2 Basic fundamental of optical filter

To accomplish the delay line signal processing, commonly unit delay is defined as, $T = (L_u n)/c$, where " L_u " refers to the unit delay length for the shortest path duration, valuable refractive index is " n " and speed of light is " c ". To achieve discrete signal, sampling a

continuous signal at $t = nT$, where “ n ” refers sample numbers and “ T ” is for sampling space. Coupler method and delay length perform a crucial component for the valuable achievement of the optical filter. The frequency response of one period can be defined as free spectral range (FSR). The statistical correlation between FSR and unit delay is given by Ranjan and Mandal (2018b), $FSR = 1/T = c/(n L_u)$, which is correlated with discrete impulse response. An integer multiple of unit delay is consider as total delay of filter. To demonstration, the z-transform of a discrete time signal $f(z)$ is (Ranjan et al. 2016),

$$f(z) = \sum_{n=-\infty}^{\infty} \{f(z)\} z^{-n} \quad (2)$$

where z-transformed unit delay is z^{-n} . Triple unsymmetrical micro ring resonator arrangements have four directional couplers that are drawn with a delay line signal processing method. One period of optical filters with discrete time delay is equal to FSR. To demonstrate, the Free Spectral Range in background of resonant wavelength (λ) is (Ranjan et al. 2016).

$$FSR = \frac{1}{T} = \frac{c}{L_u n_g} = \frac{\lambda^2}{2\pi R n_g} \quad (3)$$

Vernier’s concept is used to prevent the tiniest and smallest twisting radius, which result in the maximum loss. Each ring resonator’s boundary has been changed such that it is now an integral multiple of the unit delay duration. With the use of discrete multiples of unit delay duration, locate the full optical loop. Vernier principle method is used to explain how to increase the Triple unsymmetrical Micro Ring Resonator’s overall FSR. Vernier principle method is demonstrated as follows (Boeck et al. 2013).

$$FSR_{overall} = N * FSR_1 = M * FSR_2 = O * FSR_3 \quad (4)$$

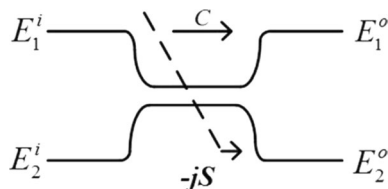
where N , M and O are introduced as co-prime resonant numbers of the triple unsymmetrical micro ring resonator whose values are $N=6$, $M=32$ and $O=5$ respectively. Radius of micro ring resonators are taken as $R_1=0.75 \mu\text{m}$, $R_2=4 \mu\text{m}$ and $R_3=0.625 \mu\text{m}$ respectively.

3 Directional couplers

The optical couplers are a key component in the coupling and breaking of optical signals. The phenomenon is known as coupling and occurs when two waveguides are positioned close enough to one another that their evanescent fields overlap. The figure of directional optical coupler is given in Fig. 1, where E_1^i , E_2^i are input fields and E_1^o , E_2^o are output fields respectively. “C” is referred as through port transmission coefficient and “S” is referred as cross port transmission coefficient (Barbarossa et al. 1995).

Here, “C” and “S” are referred as through port coupling coefficient and cross port coupling coefficient respectively. The coupling ratio is denoted by the symbol k , (Ranjan and Mandal 2018a)

$$k = \frac{P_{coupled}}{P_{input}} \quad (5)$$

Fig. 1 Directional optical coupler

where $P_{coupled}$ is referred as coupled power obtained from each coupler and P_{input} is referred as power obtained from the same coupler. The block diagram of directional optical coupler is shown in Fig. 2. Transfer matrix presented in Eq. (6), where “ q ” ($0 < q < 1$) is referred to as amplitude transmission coefficient, also determines the correlation between the input and output field (Ranjan and Mandal 2018b).

$$\begin{bmatrix} E_1^o \\ E_2^o \end{bmatrix} = q \begin{bmatrix} C & -jS \\ -jS & C \end{bmatrix} \begin{bmatrix} E_1^i \\ E_2^i \end{bmatrix} \quad (6)$$

4 Transfer function of triple unsymmetrical micro ring resonator

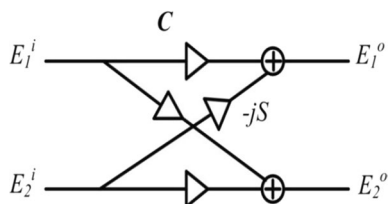
Mason’s gain rule and the signal flow graph approach are used to analyze the transfer function of the triple unsymmetrical micro ring resonators that are offered in the z-domain. The T_f is given in Eq. (7). (Mandal et al. 2006)

$$T_f = \frac{1}{\Delta} \sum_{n=1}^N P_n \Delta_n \quad (7)$$

Figure 3 depicts the offered arrangement, which consists of four directional couplers and triple unsymmetrical micro ring resonators. The input and output ports are designated as $X(z)$ and $Y(z)$, respectively. Transfer function of given signal flow graph of offered arrangement is shown in Fig. 4.

The offered TUMRR is shown in Fig. 3 as having a single input port and a single output port, $X(z)$, and $Y(z)$, respectively. According to the diagram in Fig. 3, the bus $X(z)$ is coupled serially having coupling coefficient k_1 and the bus $Y(z)$ is coupled vertically with coupling coefficient k_4 . Due to the utilisation of triple unsymmetrical micro ring resonators, the offered arrangements suggest a wide FSR. The offered circuit’s expanded FSR is utilised in communication networks to handle greater data.

The signal flow graph of the offered design in the z-domain is shown in Fig. 4. Here input port denotes the input signal and output port denotes the arrangement’s output

Fig. 2 Block representation of optical coupler

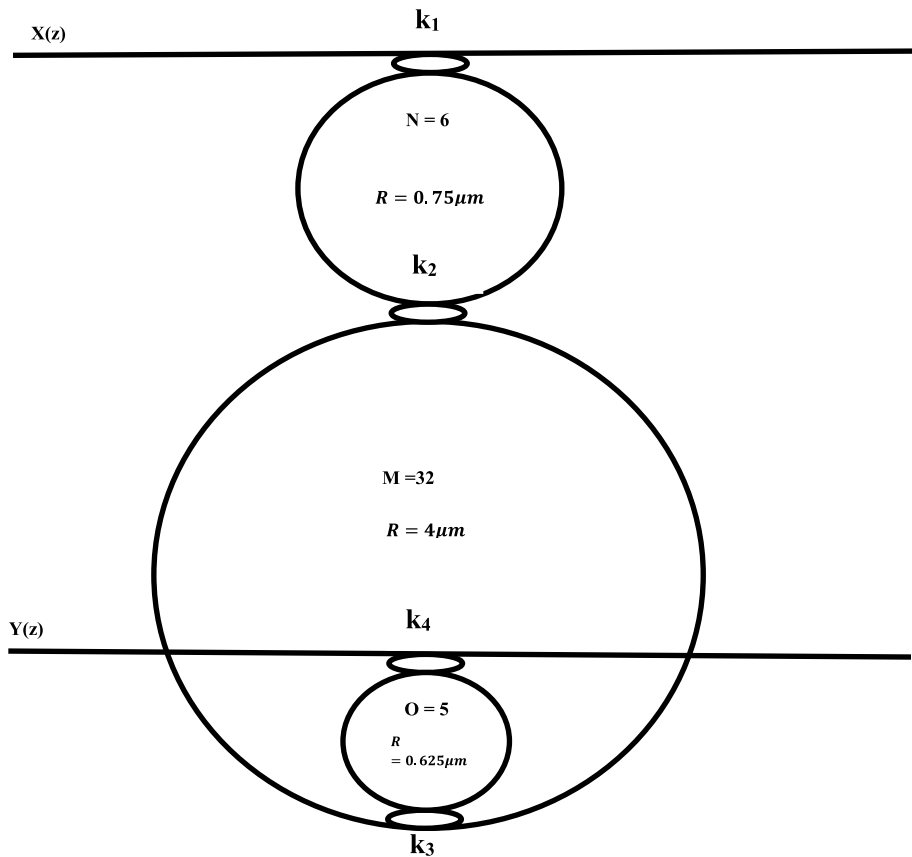


Fig. 3 Offered triple unsymmetrical micro ring resonator

signal. Equation (8) provides an illustration of the transfer function (Tf) using Mason's gain rule, i.e. (Ranjan et al. 2016)

$$Tf = \frac{Y(z)}{X(z)}$$

$$Tf = \frac{\left[S_1 S_2 S_3 S_4 Z^{-\left(\frac{N}{2} + \frac{M}{2} + \frac{O}{2}\right)} \right]}{\left[1 - C_1 C_2 Z^{-(N)} - C_2 C_3 Z^{-(M)} - C_3 C_4 Z^{-(O)} \right.} \quad (8)$$

$$\left. + C_1 C_3 Z^{-(N+M)} + C_2 C_4 Z^{-(M+O)} \right. \\ \left. + C_1 C_2 C_3 C_4 Z^{-(N+O)} + C_1 C_4 Z^{-(N+M+O)} \right]$$

In this case, the ring's encircling expedition circulation loss is expressed as $\{Y = \exp(-\alpha L)\}$ (Madsen and Zhao 1999b), where "L" stands for the ring's span and " α " for the amplitude reduction coefficient resulting from the loss purpose, material absorption, emission, and plane hardness, all losses combined. Therefore, Eq. (8) will

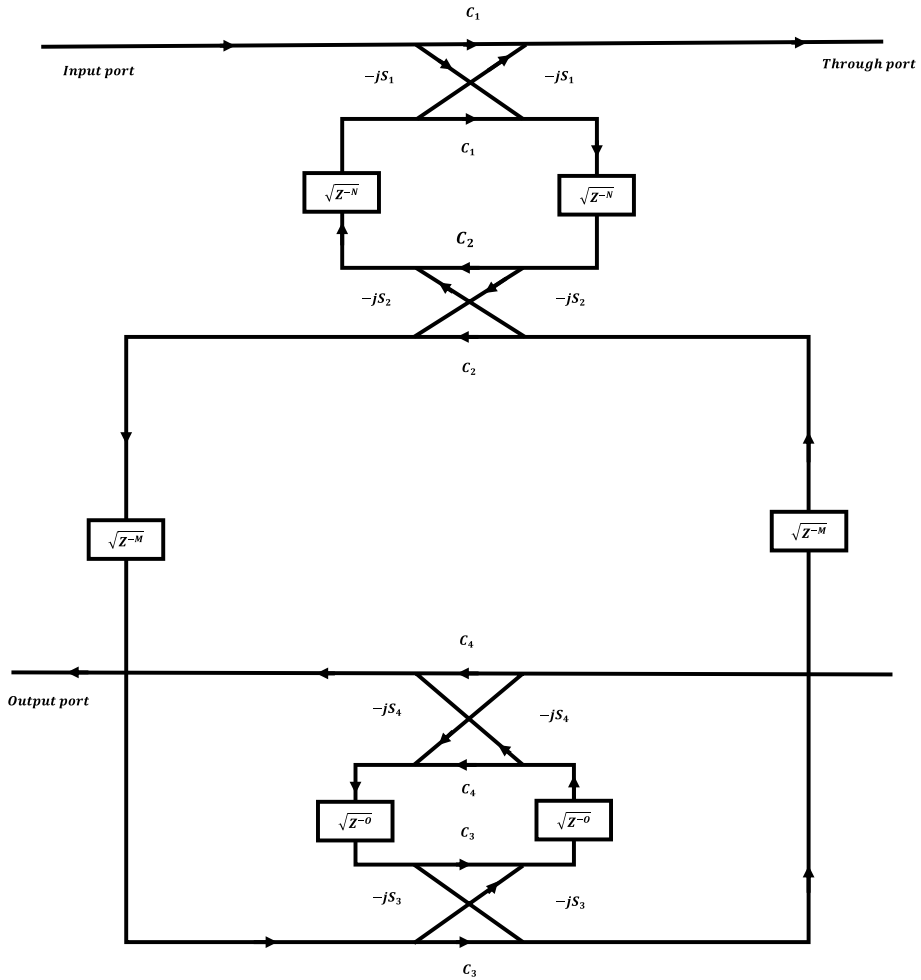


Fig. 4 Block diagram of proposed arrangement in z-domain

be changed to Eq. 9 since the amplitude spread coefficient (q) is calculated as 1 (Li et al. 2008), i.e.

$$Tf = \frac{\left[q^4 \sqrt{\gamma_1 \gamma_2 \gamma_3} S_1 S_2 S_3 S_4 Z^{-\left(\frac{N}{2} + \frac{M}{2} + \frac{O}{2}\right)} \right]}{\left[1 - q^2 \gamma_1 C_1 C_2 Z^{-(N)} - q^2 \gamma_2 C_2 C_3 Z^{-(M)} - q^2 \gamma_3 C_3 C_4 Z^{-(O)} \right.} \quad (9)$$

$$\left. + q^2 \gamma_1 \gamma_2 \gamma C_1 C_3 Z^{-(N+M)} + q^2 \gamma_2 \gamma_3 C_2 C_4 Z^{-(M+O)} \right.$$

$$\left. + q^4 \gamma_1 \gamma_3 C_1 C_2 C_3 C_4 Z^{-(N+O)} - q^2 \gamma_1 \gamma_2 \gamma_3 C_1 C_4 Z^{-(N+M+O)} \right]$$

5 Characteristics of TUMRR

Ring resonator possess certain characteristics which must be satisfied for its application. Group delay and dispersion are important factors in filter application whereas quality factor and sensitivity are important factors for application as sensor.

5.1 Group delay

Group delay is defined as negative derivation of the phase of the transmittance with respect to the angular frequency (Ali et al. 2020), it can be termed as

$$\tau_n = -\frac{d}{d\omega} \tan^{-1} \left[\frac{\text{Im}\{H(z)\}}{\text{Re}\{H(z)\}} \right]_{z=e^{j\omega}} \quad (10)$$

where $H(z)$ is referred as frequency response of the arrangement and $\text{Im}\{H(z)\}$ and $\text{Re}\{H(z)\}$ are imaginary and real part of frequency response. Slope of the phase with the frequency is termed as delay where it is being evaluated.

5.2 Dispersion

Derivative of group delay with respect to angular frequency termed as dispersion. It is the representation for deformation of signal in the region of resonant frequencies (Amoosoltani et al. 2021; Al Mahmod et al. 2018).

$$D = \frac{d(\tau_n)}{d\omega} \quad (11)$$

5.3 Quality factor

It is crucial for determining the free spectral range of the resonance state for any micro ring resonator. The Q-factor reveals the ability of a resonator to energy accumulation. The quality factor is the ratio of accumulated energy missing in a resonator arrangement. Q-factor can be determined as the sharpness of resonator crest in terms of full width half maxima (FWHM) and resonant frequency (Barbarossa et al. 1995).

$$Q = \frac{f_0}{FWHM} \quad (12)$$

5.4 Sensitivity

The ability to sense the smallest change of refractive index in a sensor is termed as sensitivity. Mathematically, it can be termed as the ratio of change in refractive index in nm to change in the refractive index solution flowing on the top of the surface of sensor.

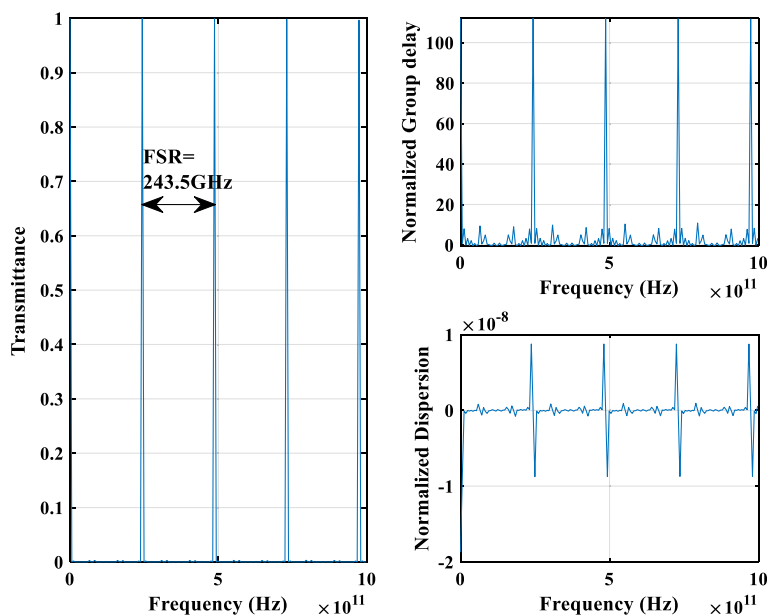


Fig. 5 Transmittance, Group delay and Dispersion plot of TUMRR

Table 1 Parameters comparison obtained using vernier principle and without vernier principle

Technique/Parameters	FSR (GHz)
TUMRR (Vernier principle)	243.5
Sanjoy Mandal et al. (2006)	200

It is articulated as nm/RIU where RIU is the refractive index unit (Madsen and Zhao 1999b; Li et al. 2008).

$$S = \frac{\Delta\lambda}{\Delta n} \quad (13)$$

6 Simulation results as optical filter

The frequency response analysis of the proposed TUMRR is done in MATLAB environment while its filed assessment is conceded out using OptiFDTD software. The micro ring perimeter sizes are taken as 4.71 μm , 25.12 μm and 3.925 μm . The corresponding co-prime resonant numbers are $N=6$, $M=32$ and $O=5$. The unit delay length is 0.785. The ring loss is taken as 0.1 dB/cm and the amplitude of transmission coefficient taken as 1. The optimal coupling coefficient is taken as $k_1=k_2=0.40$, $k_3=k_4=0.45$. The FSR determined is 243.5 GHz. The frequency response plot along with its group delay and dispersion behavior is shown in Fig. 5. Table 1 represents the enhanced FSR of proposed configuration for same class of microring resonators. The determined values of waveguides gap for the corresponding coupling coefficient is shown in Table 2.

Table 2 Calculated values of different coupling coefficient and the corresponding waveguide gap

S.L. No	Coupling coefficient	Gap (nm)
k_1	0.40	0.62
k_2	0.40	0.75
k_3	0.45	0.60
k_4	0.45	0.78

7 Validation of TUMRR as optical biosensor

The offered TUMRR biosensor was contoured with the measurement adjustment, such as tunable laser, optical power meter, polarization beam splitter and a polarizer. The SOI wafer, which is configured with a top silicon layer that is 200 nm thick and a silica buffer layer that is 2 μm thick, was utilized to model the TUMRR. When a fresh (healthy) blood cell is placed at the top layer of the TUMRR sensor, a FSR of 25 nm and full width half maxima (FWHM) of 8 nm were noticed which is shown in red color plot in Fig. 6. The Q-factor of the offered TUMRR is calculated and it is found to be 1938. To achieve the sensing application of the offered TUMRR configuration, different blood cells are applied on the top layer of the MRR. When any diseased blood sample is noticed, then the propagation of light will get disturbed, i.e. diseased blood samples occupying different refractive index. Placement of different blood sample gives freely shifts in resonant wavelength. The responsible elements which affect the shifting in resonant wavelength are bio-layer thickness, change of effective refractive index of the bond targets etc. As a result, when any diseased blood sample is located at the surface of the TUMRR, the resonant wavelength of the TUMRR moves from its initial location. The presence of different cells as compared to healthy cells is recognized via shifting in the resonant wavelength and few of them are presented in Table 3. The permittivity (ϵ) of cancer cells is proportional to the square of the refractive index (n) (Ali et al. Feb. 2020; Amoosoltani et al. 2021);

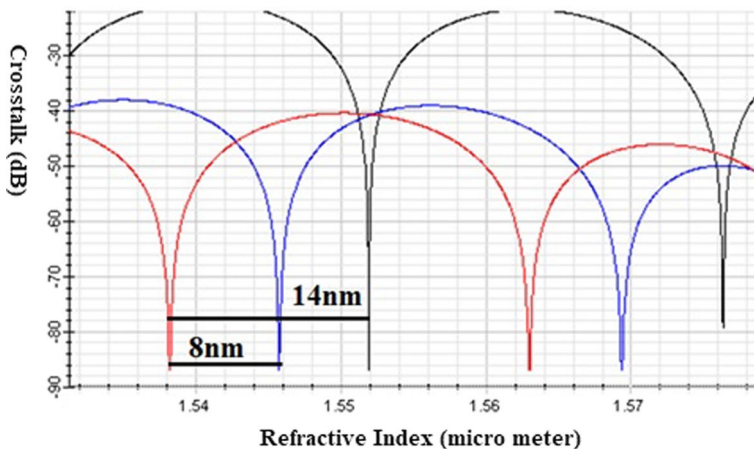


Fig. 6 Transmission spectra for a TUMRR for different cells along with their refractive indices where red represents normal blood cell, blue represent Jurkat cell and black represents MDA-MB-231 cells

Table 3 Cancer cell with refractive index of sample (Ali et al. 2020);

S.L. No	Name of cell	Disease	Refractive index
1	Normal (Healthy)	–	1.35
2	Jurkat	Leukemia	1.39
3	HeLa	Cervical cancer	1.392
4	PC-12	Brain	1.395
5	MDA-MB-231	Breast cancer	1.399
6	MCF-7	Breast cancer	1.401

In this paper, Jurkat cell which represents Leukemia and MDA-MB-231 cell which shows Breast Cancer is placed on the TUMRR surface to study the effectiveness as well as sensitivity of the offered biosensor. Jurkat cell leads to a shift of 8 nm while MDA-MB-231 leads to a shift of 14 nm with respect to healthy blood sample which is illustrated in Fig. 6. Hence, the calculated sensitivity of the offered TUMRR in case of Jurkat is 200 nm/RIU and in case of MDA-MB-231 it is computed as 285.71 nm/RIU. As discussed in (Ciminelli et al. 2013), sensitivity of micro-ring resonator is classified as:

- a. Device Sensitivity
- b. Waveguide Sensitivity

The device sensitivity depends only on the device properties, while the waveguide sensitivity depends on the waveguide structure. The design strategy is to optimize these two contributions so as to enhance the overall sensitivity.

Therefore, The comparative low sensitivity in the proposed TUMRR is mainly due to complex design of the configuration which results in dropping of waveguide sensitivity and hence overall sensitivity is reduced. Also, it has been reported that cascaded micro-ring resonators exhibit a wide transmission band rather than sharp resonances, and, thus, do not allow the quality factor to be improved without exploiting any other physical effect (i.e. a Fano resonance). (Ciminelli et al. 2013).

Figure of merit can be expressed as (Al Mahmod et al. 2018);

$$\text{FOM} = \frac{S}{\text{FWHM}} = 357.13 \text{RIU}^{-1} \quad (14)$$

The mathematical expression for calculating Limit of Detection (LOD) is (Al Mahmod et al. 2018);

$$\text{LOD} = \frac{f}{\text{FOM}} = 7.0025 \times 10^{-6} \quad (15)$$

where factor “ f ” symbolizes the fraction of resonance line-width “ $\delta\lambda$ ” that can be resolved by the detection system which taken as $f = 1/400$ (Al Mahmod et al. 2018).

Extinction ratio (ER) can be expressed as (Al Mahmod et al. 2018; Ranjan et al. 2021);

$$\text{ER} = 10 \log_{10} \left(\frac{P_L}{P_H} \right) \quad (16)$$

where P_L , P_L and P_H are the lowest amplitude and highest amplitude of the resonant peak. The computed value of $\text{ER} = 3.01$ dB.

Fig. 7 Field analysis for Off-Resonance condition TUMRR

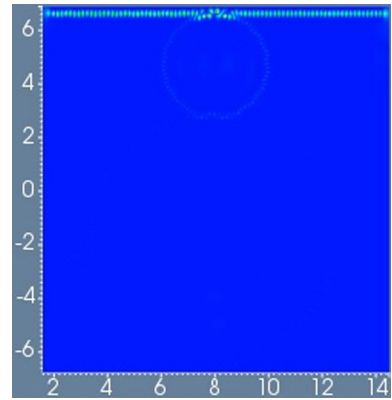
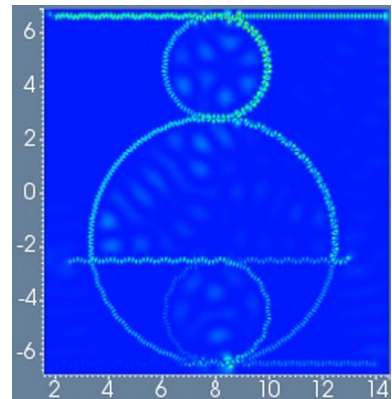


Fig. 8 Field analysis for On-Resonance condition TUMRR



The field analysis for Off-Resonance and On-Resonance condition is shown in Figs. 7 and 8 respectively.

3-D schematics of proposed TUMRR representing lateral and vertical coupling is shown in Fig. 9

8 Conclusion

The offered triple unsymmetrical micro ring resonators are designed in z-domain and its transfer function is realized using Mason's gain rule. The performance of the offered TUMRR is determined using MATLAB software. The FSR is evaluated from the frequency response investigation using MATLAB environment for single input and single output arrangement, i.e., Tf is 243.5 GHz. The proposed TUMRR provides a proportional shift in resonant wavelength when analytes of different refractive index is placed at resonator surface. The sensitivity of the proposed TUMRR based biosensor is around 200–280 nm/RIU for different blood cells where as the Q-factor attained is 1938. The proposed model can help to improve data handling capacity of an optical communication system as well as the presented results are promising candidate for biosensing applications.

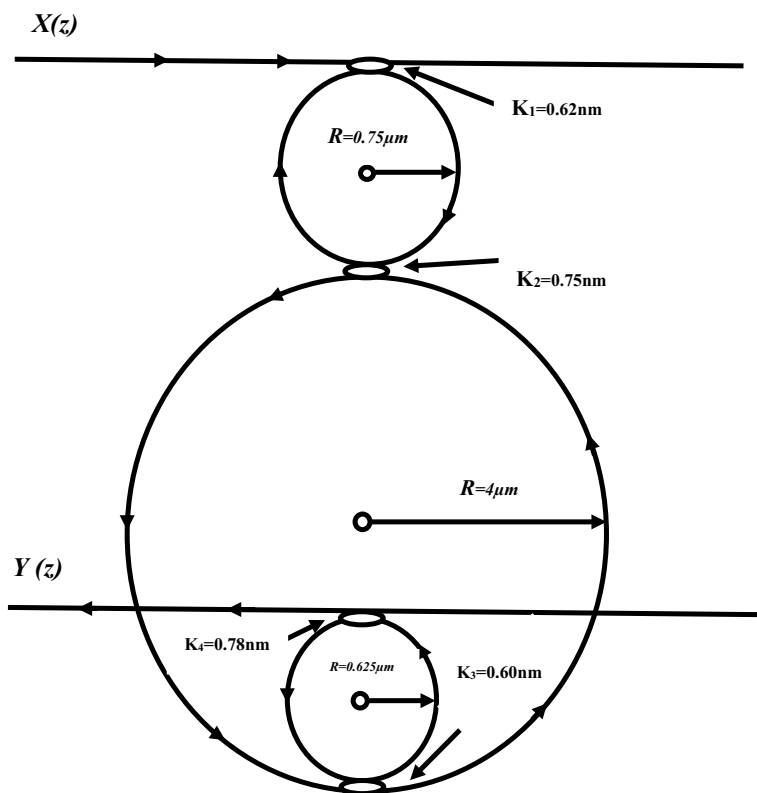


Fig. 9 3D schematics representing lateral and vertical coupling of TUMRR

Appendix

Single Loop

$$\begin{aligned}
 L_1 &= C_1 C_2 Z^{-N} \\
 L_2 &= C_2 C_3 Z^{-M} \\
 L_3 &= C_3 C_4 Z^{-O} \\
 L_4 &= -C_1 C_3 S_3^2 Z^{-(N+M)} \\
 L_5 &= -C_2 C_4 S_3^2 Z^{-(M+O)} \\
 L_6 &= C_1 C_4 S_2^2 S_3^2 Z^{-(N+M+O)}
 \end{aligned}$$

Two non-touching Loop

$$\begin{aligned}
L_{1,2} &= C_1 C_2^2 C_3 Z^{-(N+M)} \\
L_{2,3} &= C_2 C_3^2 C_4 Z^{-(M+O)} \\
L_{3,1} &= C_1 C_2 C_3 C_4 Z^{-(N+O)} \\
L_{1,5} &= -C_1 C_2^2 C_4 S_3^2 Z^{-(N+M+O)} \\
L_{3,4} &= -C_1 C_3^2 C_4 S_2^2 Z^{-(N+M+O)}
\end{aligned}$$

Three Non-touching loop

$$L_{1,2,3} = C_1 C_2^2 C_3^2 C_4 Z^{-(N+M+O)}$$

Forward Path and Path Factor

$$\begin{aligned}
P_1 &= S_1 S_2 S_3 S_4 Z^{-\left(\frac{N}{2} + \frac{M}{2} + \frac{O}{2}\right)} \\
\Delta_1 &= 1
\end{aligned}$$

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Data availability Not applicable.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no financial or personal conflict of interest.

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