

NUMERICAL SIMULATION OF ENHANCED OPTICAL FREE SPECTRAL RANGE THROUGH INTEGRATED FANO-MICRORING CONFIGURATION

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Abstract: A numerical analysis of the integrated Fano-microring (IFM) racetrack resonator spectrum was performed to investigate the enhancement of the optical system's free spectral range (FSR). The FSR is an important optical property which can contribute to the high sensitivity of optical devices. The IFM refers to the combination of Fano resonance produced in the output spectrum through the interaction of Fabry–Perot resonance and circulation resonance. This work focuses on the study of inducing Fano resonance in the microring resonator to optimize the FSR of the system. The results show that the integration of two resonances can produce a Vernier output spectrum, which significantly enhanced the FSR of the system without any need for additional ring waveguides. This work also compared the IFM resonance with the conventional microring resonance. In this simulation, the optimized FSR obtained by the IFM configuration was 266.55 nm, which is five times higher than the conventional microring configuration.

Keywords: Fano resonance, microring, free spectral range, fabry-perot resonance, numerical simulation

1. Introduction

Optical microring resonators have been applied in various devices and fields, such as sensor technology, including pressure sensors (Seyfari et al., 2020), thermal sensors (Zhu & Lou, 2020), gas sensors (Koushik & Malathi, 2020), and chemical sensors (Bavili et al., 2020). Microring has also been applied as a modulator (Moradi et al., 2021) and an optical switch (Bharti & Rakshit, 2021; Singh et al., 2021) due to its compact size (Biswas et al., 2021), high compatibility (Bogaerts et al., 2012), low cost (Kim et al., 2013), and utilization of evanescence field that makes it immune towards electromagnetic disturbances (Bogaerts et al., 2012). Consequently, performance is essential in the advancement of this technology.

Limit of detection (LOD) is one of the indicators to evaluate the performance of microring configuration in sensing application. LOD can be described as the minimum detectable change (Guider et al., 2015), which is directly related to free spectral range (FSR) (Vollmer & Schwefel, 2014). FSR can be interpreted as the distance between two adjacent peaks (Bogaerts et al., 2012). The relationship of LOD and FSR is inversely proportional, where higher FSR will offer smaller detectable scale (Chao & Guo, 2006). Hence, the FSR significantly shows the performance of the microring. Many efforts have been made to enhance the FSR, such as a double Vernier Panda-ring resonator with the maximum FSR of 90 nm (Seyfari et al., 2021), a microring with multi-Mach–Zehnder interferometers with FSR over 88 nm (Y. Chen & Qiu, 2021), a compact microring resonator using low-loss bends with FSR of 35 nm (Song et al., 2020), and a racetrack microring resonator with Fabry–Perot cavities where the FSR is over 150 nm (Kumar Bag & Varshney, 2021).

By integrating Fano resonance with the microring resonance, the FSR can be improved. The Fano resonance was applied in the microring technology through many methods such as photonic crystal cavity generation (Peng et al., 2018), nanocavities utilization in split-ring resonator (Zhang et al., 2013), double half ring resonator (He et al., 2021), and side coupled ring cavity with a metal nanowall (F. Chen et al., 2019). Fano resonance can be obtained through the interference of a continuous background mode and a discrete resonant mode (Li & Bogaerts, 2017; Zhao et al., 2016). The main attribute of Fano resonance is the asymmetric line shape which is caused by the two-resonance optical

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interference (Zhao et al., 2016). In this case, the Fano resonance is achieved by merging the circulation resonance from the ring with the Fabry–Perot resonance from the bus waveguide (Yi et al., 2010). Fano resonance also offers the potential to enhance the performance of the microring in terms of FSR, LOD, and sensitivity (Chao & Guo, 2003; Tu et al., 2017; Wang et al., 2017). However, the generated Fabry–Perot resonance, which is essential to produce the Fano resonance, has a small FSR that will affect the overall spectrum (Yi et al., 2010).

In this work, an optimized racetrack microring resonator configuration was proposed to reduce the effect of Fabry–Perot resonance, thus enhancing the FSR. Since the configuration involves a racetrack microring resonator and Fano resonance, the system is called integrated Fano-racetrack microring (IFM) configuration. For this research, two simulations were performed to achieve the maximum FSR: 1) Comparison of the resonance between IFM and conventional racetrack configuration and 2) the optimization process of IFM configuration. The optimization was performed to determine the maximum FSR with various configuration parameters such as ring radius, length of the racetrack, and distance of the reflectors from the center.

2. Model and Theory

The simulation was performed for two types of racetrack microring resonators: (1) the conventional racetrack microring resonator and (2) the racetrack microring resonator with reflectors in the bus waveguide. Figure 1 a) and b) shows both configurations with the labelled propagated electric field. The figure shows that only the IFM configuration was installed with reflectors in the bus waveguide. The reflectors play a major role in the IFM configuration to generate the Fano resonance.

Light is travelled through the input port, E_{in} and propagated in the waveguide. At the coupling region, a fraction of the light is coupled into the ring at E_1 , and another fraction is still propagating in the waveguide. The propagating light in the waveguide is partially reflected due to the presence of the reflector and partially went through the output port, E_{out} . On the other hand, light in the ring is propagated towards the coupling region at E_2 and coupled back into the waveguide. Then, the resonance from the ring is merged with the resonance in the waveguide, thus Fano-like resonance is obtained. It is necessary for the bus reflector to be made of partial reflective materials to generate the Fabry–Perot resonance (Yi et al., 2010). The combination of circulation resonance and Fabry–Perot resonance can create a Fano resonance as the output spectrum.

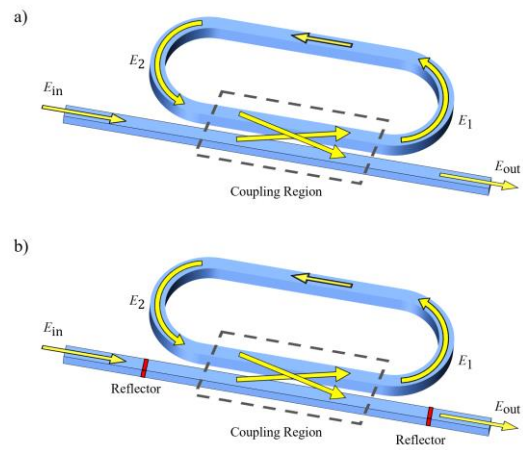


Figure 1. a) The conventional and b) the IFM configuration racetrack configurations.

The mathematical theory of optical coupling was performed for the IFM configuration to construct the numerical programming script. The coupling theory and optical phase shift with the attenuation loss were included in the computation. The transfer matrix for the whole integration system comprises the microring and Fabry–Perot resonances (Gu et al., 2019) can be expressed as follows:

$$\begin{bmatrix} E_{out} \\ E_1 \end{bmatrix} = \frac{1}{i\sqrt{1-r_h^2}} \begin{bmatrix} -1 & -r_h \\ r_h & 1 \end{bmatrix} \cdot \begin{bmatrix} e^{i2\pi n_{eff}L/\lambda} & 0 \\ 0 & e^{-i2\pi n_{eff}L/\lambda} \end{bmatrix} \cdot \begin{bmatrix} t_R & 0 \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 0 \end{bmatrix} \cdot \frac{1}{i\sqrt{1-r_h^2}} \begin{bmatrix} -1 & -r_h \\ r_h & 1 \end{bmatrix} \cdot \begin{bmatrix} E_{in} \\ E_2 \end{bmatrix} \quad (1)$$

where E_{in} is the input port, E_{out} is the output port, E_1 is the input port to the ring, and E_2 is the output port of the ring. The term n_{eff} is the effective refractive index, which represents both refractive indexes of core and cladding. L represents the distance between the reflector in the waveguide and t_R is the optical transfer function (OTF) of the racetrack microring resonator. The amplitude reflection coefficient (Yi et al., 2010) can be expressed as follows:

$$r_h = \frac{n_{eff}-1}{1-n_{eff}} \quad (2)$$

The OTF of racetrack microring (Bogaerts et al., 2012; Heebner et al., 2008) is given as below:

$$\frac{E_{out}}{E_{in}} = \frac{c - ae^{i2\pi L_R/\lambda}}{1 - cae^{i2\pi L_R/\lambda}} \quad (3)$$

where a is the single-pass amplitude and expressed as follows (Bogaerts et al., 2012; Heebner et al., 2008; Noorden et al., 2020):

$$a = \exp(-\alpha L_R) \quad (4)$$

where α is the attenuation coefficient and L_R is the perimeter of the all-pass microring resonator. c is a self-coupling coefficient which can be expressed as follows (Noorden et al., 2020):

$$c = \sqrt{1 - \kappa} \sqrt{1 - \gamma} \quad (5)$$

where κ is the coupling coefficient (Noorden et al., 2020) and γ is the propagation loss coefficient (Noorden et al., 2020).

In this study, the numerical simulation was conducted using a mathematical computation software named Gnu Octave. The Gnu Octave has a high capability in solving numerical computations and presenting data due to its powerful visualisation tools (GNU Octave, n.d.) The simulated configurations are racetrack microring with reflectors embedded in the waveguide and conventional racetrack microring. The core and substrate materials are silicon (Si) and silicon oxide (SiO₂), respectively. The cladding of the microring is air. Due to the difference in refractive index among the materials, resonance confinement can be achieved. The coupling coefficient was set as constant throughout the research.

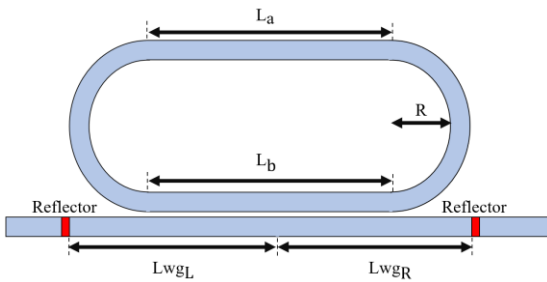


Figure 2. The optimised parameters of the configuration.

The reflectors labelled in Figure 2 are necessary to generate the Fano resonance. The reflector aids in creating interference through Fabry–Perot resonance in the waveguide (Yi et al., 2010). From Figure 2, the perimeter of the system can be calculated as follows:

$$L_R = 2\pi R + L_a + L_b \quad (4)$$

where L_a and L_b are the length of the racetrack microring. L_{wg_L} and L_{wg_R} represent the distance of the reflector from the centre of the waveguide.

Table 1. The range of optimisation for all the parameters based on two configurations.

Parameter	Integrated Fano-Microring	Conventional Microring
R	2 μm – 20 μm	2 μm – 20 μm
L _a	10 μm – 30 μm	10 μm – 30 μm
L _b	10 μm – 30 μm	10 μm – 30 μm
L _{wg_L}	2 μm – 20 μm	-
L _{wg_R}	2 μm – 20 μm	-

The optimisation of both configurations was performed based on the exhaustive search technique, where each configuration was initialised by considering all parameters’ domain as shown in Table 1. For each range of the parameter, 20 values were iterated to observe the FSR. The FSR for each configuration was measured accordingly to analyse the Fano resonance. Both conventional and IFM configurations with the highest FSR were analysed and discussed in the next section. Note that since conventional microring does not have the reflector in the waveguide, only the radius and length of the racetrack were considered.

3. Results and Discussions

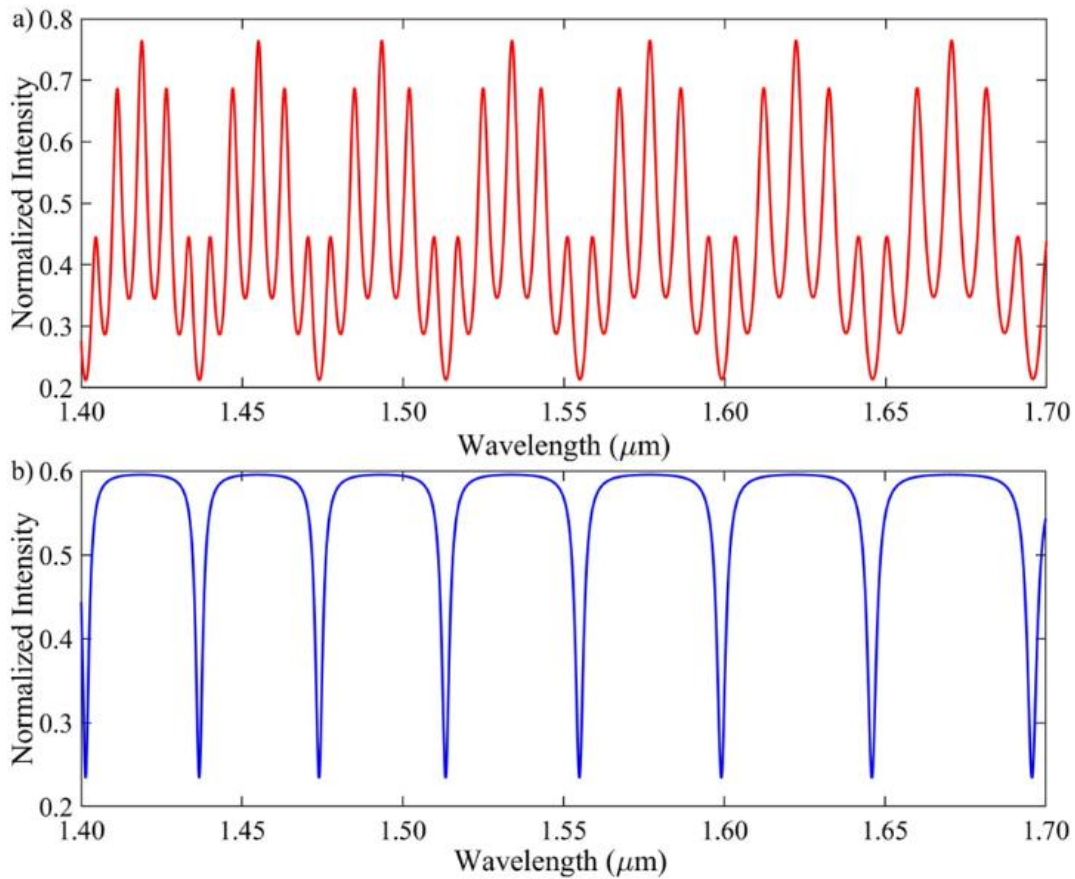


Figure 3. Output numerical simulation of a) IFM spectrum and b) conventional microring spectrum.

Figure 3 depicts the spectrum of IFM comprises numerous peaks compared to the conventional microring. Note that the position of the Lorentzian shape is similar between the two. Besides, the IFM configuration also exhibits a characteristic of Vernier effect where the resonance pattern becomes enveloped in a group (Gomes et al., 2021). The IFM spectrum also shows a Fano-like line shape credited to the reflectors in the waveguide

where a fraction of the resonance still propagates in the waveguide causing the interference of numerous resonances with different phase shifts (Yi et al., 2010). The conventional microring spectrum differs from the IFM spectrum due to the suppression of interstitial peak by Fano resonance (Boeck et al., 2010).

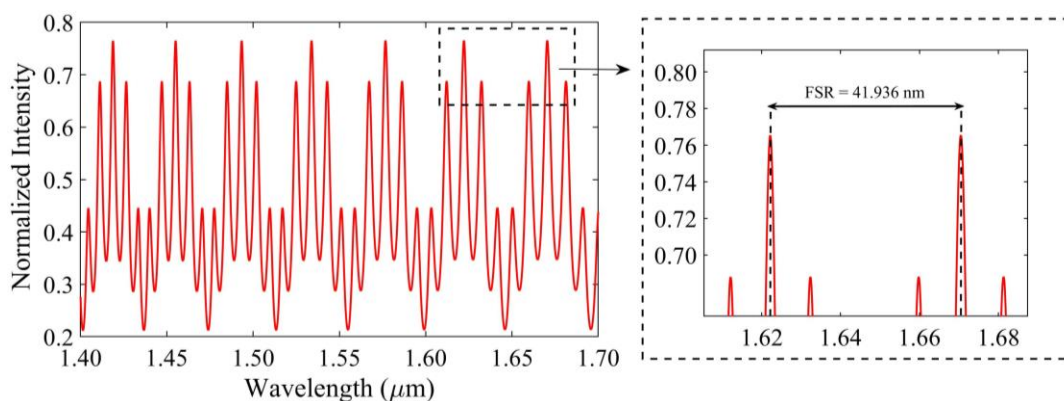


Figure 4. The unoptimised IFM spectrum and the magnified peaks for FSR measurement.

Figure 4 shows the unoptimised spectrum of IFM and the recorded FSR was 41.936 nm. Without optimising the simulation system, the IFM spectrum has a very low FSR, which will reduce

the performance of the microring. This is because, the Fabry-Perot resonance with small FSR merges with the circulation resonance (Yi et al., 2010). The collective small FSR from the

Fabry–Perot resonance affects the microring spectrum by suppressing its peaks and producing a lot of smaller peaks. Subsequently, the FSR, instead of increasing, decreases

tremendously. Therefore, the optimisation process is essential to improve the performance of the microring.

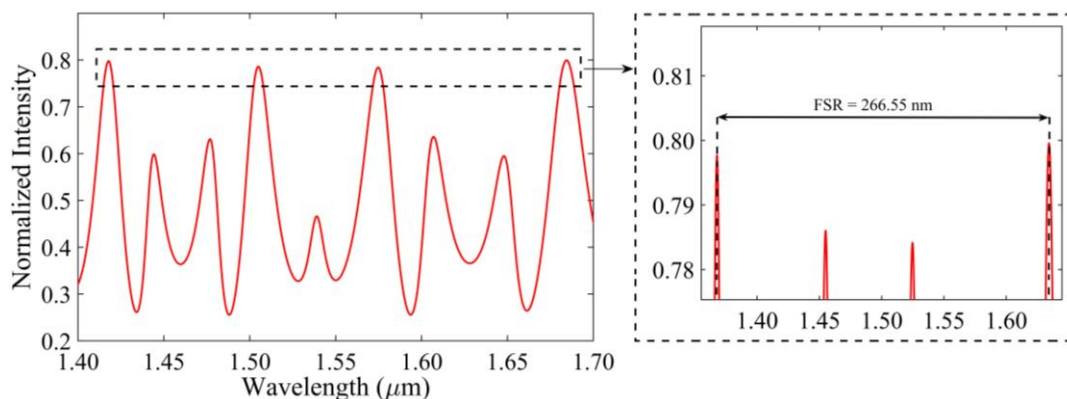


Figure 5. The optimised IFM and the magnified peaks for FSR measurement.

Figure 5 illustrates the optimised IFM spectrum where the measured FSR was 266.55 nm. The FSR of the optimised configuration was five times higher than that of the unoptimised configuration. The parameters of the optimised IFM configuration are tabulated in Table 2.

Table 2. The optimized IFM configuration

Parameter	Value
R	15.26 μm
L _a	30.00 μm
L _b	30.00 μm
L _{wGL}	2.95 μm
L _{wGR}	2.00 μm

The main contributor to the wide FSR of the IFM configuration is the Fano resonance which suppresses the interstitial resonances (Boeck et al., 2010; Schwelb, 2007). Due to the suppression of interstitial peaks in the spectrum, the Vernier effect can be observed, and the Vernier effect helps to extend the FSR of the resonance (Jin et al., 2011; Troia et al., 2014). This is because, the waveguide system of IFM consists of two resonances type: (1) circulation resonance from racetrack waveguide and (2) Fabry–Perot resonance from the reflector at the bus waveguide. In the sensing application, a large FSR benefits the system because it contributes to wider measurement range (C. Chen et al., 2021; Tian et al., 2020). Besides, wide FSR helps the system to distinguish the resonance peak and makes the detection system more accurate especially in all-optical sensing technologies. Even though the FSR is detrimental to the quality factor (QF) (Taufiqurrahman et al., 2020), high FSR is beneficial to achieve high optical sensitivity because the QF does not impose a direct impact on the sensing application. Nevertheless, the simulated system has successfully optimised the FSR of the system based on the IFM waveguide with the reflectors.

4. Conclusion

In conclusion, two simulations were performed to convey the significance of Fano resonance in the application of microring

technology. The first simulation indicates the difference between the conventional racetrack microring resonator with the IFM resonator. With the suppression by the Fano resonance, the vernier effect can be achieved, hence the FSR can be increased significantly. In the second simulation, the system was optimized successfully and a comparison between the unoptimized and optimized Fano resonance was made. The FSR of the optimized Fano resonance was 266.55 nm, which is five times higher that of the unoptimized. These simulations prove that the IFM spectrum has a huge potential and much room to be improved. Furthermore, the Fano resonance will likely help to improve the sensitivity due to its profile having numerous sharp peaks (Zhao et al., 2016). The sharp peaks may be vital in getting a more significant wavelength shift; hence, the sensitivity of the microring increase.

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