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سنسورهای زیستی نوری بر پایه ی ریزتشدیدگرهای حلقوی بزیر

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چکیده – امروزه پژوهش‌های زیادی درزمینه بکار گیری سنسورهای زیستی نوری صورت گرفته است ولی یکی از چالش‌های اصلی، فاکتور کیفیت و حساسیت آن‌ها است. در این پژوهش به شبیه‌سازی یک سنسور نوری بر پایه‌ی میکرو رزوناتور حلقوی بزیر با موجبر مستقیم پرداخته شده و درنهایت با روش‌های طراحی آزمایش با الگوریتم تاگوچی، بهینه‌ترین ضریب کیفیت با ثابت نگه‌داشتن پارامتر شعاع و تغییر پارامتر های گاف، ارتفاع و پهنای موجبر، بدست آمده است. بهترین ساختار رزوناتور بهینه‌شده، رزوناتور با عدد بزیر ۰٫۴ است که با داشتن گاف ۲۵۰ نانومتر، ارتفاع ۲۵۰ نانومتر و پهنای ۴۸۰ نانومتر به بیشترین ضریب کیفیت ۶۶۲۳۶ و مقدار FSR ۲۸٫۸ نانومتر دست یافته است. این ساختار در مقایسه با ابعاد مشابه رزوناتور بزیر از ساختارهای مختلف، با افزایش ۴٫۴۳ برابری ضریب کیفیت روبه‌رو بوده است.

کلید واژه- بهینه‌سازی تاگوچی، سنسور بدون برچسب، سنسور زیستی نوری، فاکتور کیفیت، میکرو رزوناتور حلقوی

Optical Biosensors Based on Bezier Micro-ring Resonators

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Abstract- Nowadays, many researches have been conducted on utilizing optical biosensors but main challenges regarding this type of biosensor are sensitivity and detection limit. In this research design and simulation of optical biosensor based on micro Bezier ring resonator were studied, which includes a ring resonator with a bus waveguide. Finally, the optimum quality factor has been obtained via Taguchi algorithm, in which optimum values of geometrical parameters are calculated while the ring radius is fixed. The best optimized structure is acquired to be Bezier ring resonator with a Bezier number of 0.4, a gap of 250 nm, height of 250 nm and width of 480 nm, which yields a quality factor of 66236, and an FSR of 28.8 nm. This structure has 4.43 times more quality factor in comparison with the other type of Bezier ring resonator.

Keywords: Label-free sensor, Micro-ring resonator, Optical biosensor, Quality factor, Taguchi optimization

1. Introduction

Almost every bio-sensor deploys reporter molecules and particles- label, in order to measure the desired variable quantity. In most cases these labels are either chemical or radioactive substances. Label free bio-sensors are able to swiftly provide quantitative information in biochemical reactions with putting the studied sample at risk of interfering with the labels [1]. Recently optical bio-sensors based on Silicon-On-Insulator (SOI) micro ring resonators, have drawn substantial attentions on the grounds of their high sensitivity, void of side effects, and trifling production costs [2]. In this study, while considering the objective function as the quality factor of the resonator and constant radius for the ring, it has been pursued to attain the optimal geometrical parameters such as gap, height and width for a ring resonator with different Bezier, using Taguchi experimental design method. First attempts to address such an intricate problem have been taken by Hu et al. [3], which brought about significant outcomes. They managed to introduce a single mode 20 micrometer disk chalcogenide made micro resonator with a quality actor of $2*10^5$. Most recently, because of occurring abrupt mode mismatch, it has become prevalent to deploy Bezier resonators so as to decrease the attenuations and reflections between the waveguide and the circular bend [4]. Bazargani et al [5], also employed a Bezier structure for their micro-resonator with a radius of 5 micrometer and achieved a quality factor of 14934.

2. Methodology

Generally, a ring resonator consists of a ring and a coupling mechanism to easily access the ring, which signifies resonance frequencies. Fig. 1 illustrates an integrated Bezier optical resonator with four ports. This sort of structuring is called add-drop filter, in which the entering light from input port is coupled with the ring, only if it superposes with a resonance frequency. Input, Drop, Through, and Add are the four ports associated with an add-drop filter.

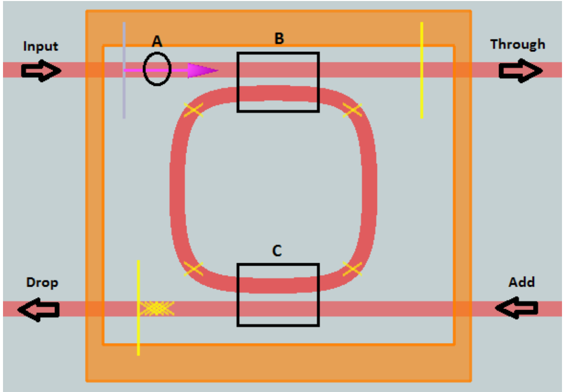

Fig. 1: Bezier micro ring resonator

Input port is used for supplying light, and Drop port is used for adding signal into the structure. A fraction of the input light couples with the ring, and then exits from Drop port, while the remaining portion exits from Through port of the structure. A region is the place where the input pulse is applied, and B and C are the regions where light couples with the ring.

As shown in Fig. 2, Free Spectrum Range (FSR) is defined as the difference of the resonance peak wavelength between two subsequent peaks within the ring resonator transmission spectrum. At the resonance peak $\omega T_R = m2\pi$, where T_R is the light circulation period inside the ring, and m is a natural domain number. The two resonance peaks are correlated to each other according to Eq. (1) [6]:

$$FSR_{frequency} = \omega_1 - \omega_2 = \frac{2\pi}{T_R} \qquad (1)$$

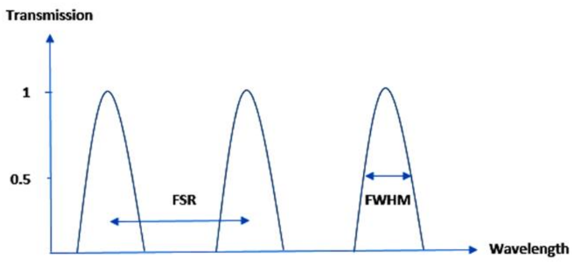

Fig. 2: Free spectrum range and resonance width within the resonance transmission range

Quality factor in fact measures the resonance peak with respect to the central frequency. Quality factor is formulated as below where L is the optical length path, n_g is the group refractive index and R is the reflectivity, Eq. (2):

$$Q = \frac{\lambda}{FWHM} = \frac{\pi L.n_g}{\lambda} . \frac{\sqrt{R}}{1-R} \tag{2}$$

Taguchi experimental design method was first introduced in 1960 for optimization. Using least possible number of experiments, this method is capable of finding the solution while minimizing the solution run time and experiment costs. In this method, variations are exemplified by a namely signal to noise ratio parameter. Therefore, the experiment with the highest signal to noise ratio is opted as the optimal solution in this method [7].

3. Result and Discussion

In this study, 4 different ring with Bezier numbers (dimensions) of 0.2, 0.3, 0.4, and 0.45 are simulated, respectively. At last, the Bezier number associated with the highest quality factor is reported as the optimum Bezier number. In Taguchi experimental design method, optimization is conducted on the geometrical parameters of the best Bezier number on order to obtain the highest quality factor in that structure. In order for the waveguide input to enter the structure as single mode, waveguide's width (w) and length (h) should follow Eq. (3) [8].

$$w.h \leq 0.13\ um^2 \tag{3}$$

By conducting several simulations it has been observed that with large values for the waveguide's width, all the entering light trapped with the waveguide and can't couple to the ring. So by using Taguchi method, Table I is proposed quality factor optimization, where 3 parameters of gap, width, and length is evaluated in 5 levels.

Table I. ring resonator optimization parameters for various Bezier numbers

Level	Gap (nm)	Width (nm)	Height (nm)
1	50	320	150
2	100	400	180
3	150	420	200
4	200	450	220
5	250	480	250

Taguchi method designs 25 experiments for this number of parameters and levels so after simulating these 25 experiments, the quality factor and FSR optimal solutions for each of the 4 Bezier numbers are reported in Table II. As could be seen in Table II, the best quality factor is allotted to the Bezier number of 0.4.

Table II. Taguchi optimization results for various Bezier numbers

Bezier number	B=0.2	B=0.3	B=0.4	B=0.45
FSR (nm)	27.15	27.20	27.97	28.09
Q factor	16752	13105	46831	37235

For the best reported experiment Bezier ring resonator (B=0.4), the Taguchi model outputs are depicted in three graphs as Fig. 3.

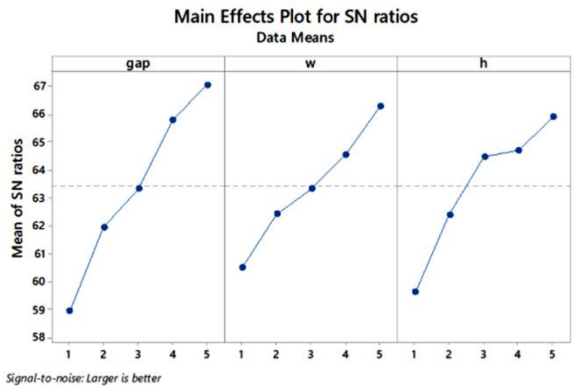

Fig. 3: Taguchi optimization graph for a ring resonator with Bezier number of 0.4 and a radius of 3 micrometer

As shown in Fig. 3, with increasing the gap, width, and height, the quality factor tends to increase correspondingly. The best resulted experiment simulation has a gap of 250 nm, width of 280 nm, and height of 250 nm. The final reported experiment by the Taguchi paradigm is simulated again to verify the solution. The simulated experiment results signify a 66237 quality factor within a 1.595 wavelength and a 28.8 micrometer FSR.

Fig. 4 demonstrates the Drop output of the optimized Bezier ring resonator with a Bezier number of 0.4. As could be elicited, the spectrum has 4 resonance peaks within a wavelength range between 1.5 and 1.6 micrometers.

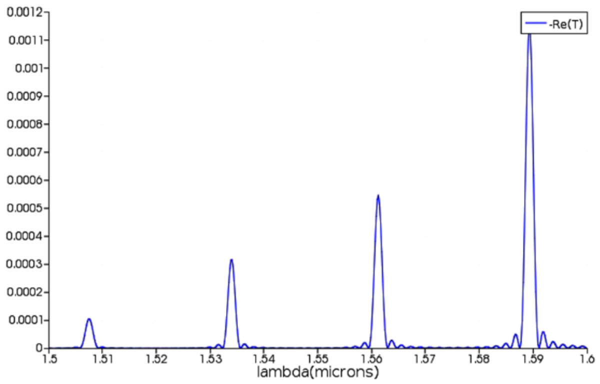

Fig. 4: Optimized ring resonator Drop port spectrum

Fig. 5, shows the quality factor within the mentioned wavelength range. The maximum Q factor value is 66236 according to Fig. 5.

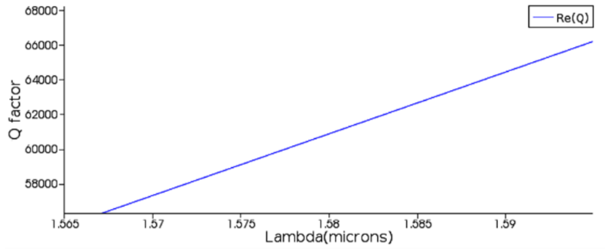

Fig. 5: Quality factor of the simulated optimized structure

To further investigate the optimum Bezier ring resonator, an analyte with refractive index variation of 10^{-4} is applied on the surface of ring. The newly introduced refractive index induces resonance wavelength shift. Sensors sensitivity is defined as resonance wavelength to refractive index variations. In the optimized resonator, with 10^{-4} refractive index variations, the resonance wavelength shifts as much as 50 pm, thus the ring resonator's sensitivity yields as 500 nm/RIU. Fig. 6 shows 5 wavelength shifts with respect to refractive index variations.

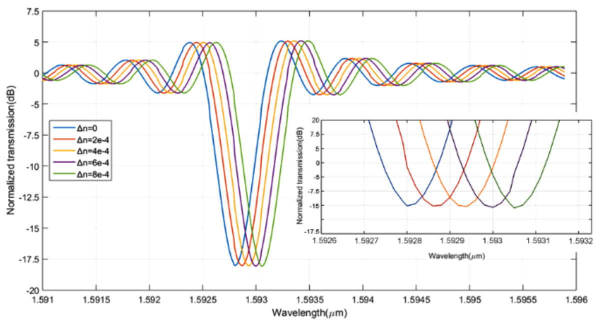

Fig. 6: Wavelength variation due to refractive index variations of 10^{-4}

4. Conclusion

In this study, using Taguchi experimental design method, the quality factor of a Bezier ring resonator has been optimized, while considering a constant radius. The outcomes demonstrate that the best Bezier structure with a Bezier number of 0.4, gap of 250 nm, width of 480 nm, and a height of 250 nm, has a quality factor of 66237, and an FSR of 28.8. In a comparison with previous research result of Bazargani et al [5], the optimized ring resonator has undergone a 4.43 fold increase in Q factor. At the end, by adding an assumptive analyte which is detected by proposed optical biosensor, the sensitivity reaches to 500 nm/RIU per each 10^{-4} variation for refractive index.

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