Optimization of a High-Performance WGM Sensor Design for Glucose Detection in Urine

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***Abstract*— The aim of the paper is to design and optimize a sensor based on the excitation of Whispering Gallery Modes (WGMs) in a ring microresonator for the detection of glucose in urine. A numerical study is performed using the Finite Element Method (FEM) to investigate the impact of sensor geometry on its performance, specifically focusing on the distance coupling (dx) and the waveguide width (W) parameters. The best performance of the WGM sensor is achieved when distance coupling is set to 200 nm and the waveguide width is set to 500 nm. These optimized dimensions led to several notable improvements in sensor performance as a narrower FWHM, high Quality Factor (Q) of 2.2×10^4, outstanding FOM of 2.71×10^3 RIU−1. Moreover, the high linearity exhibited by our sensor, for the urine RI variation as well as for the urine glucose concentration rise, proves the efficiency of our biosensor for glucose monitoring in urine.**
Key words: WGM sensor, Finite element method, Glucose *detection in urine, Glycosuria detection, High Q-factor.*

I. INTRODUCTION

Glucose detection in urine plays a pivotal role in the management of diabetes and various metabolic disorders. Continuous and accurate monitoring of glucose levels in bodily fluids is essential for timely diagnosis, effective treatment, and improved patient outcomes. To address this critical need significant efforts have been dedicated to the development of sensitive and reliable sensing technologies, such as Whispering Gallery Mode (WGM) sensors which has emerged as a promising class of optical sensors due to their exceptional sensitivity, label-free operation and potential for real-time monitoring [1],[2]. The objective of this study is to investigate, by the Finite Element Method (FEM), the impact of the WGM Sensor's geometry specially coupling distance (dx) and waveguide width (W) on its performance for detecting the glucose in urine.

II. DESIGN AND THEORY

The proposed sensor structure, shown in Figure 1, consists of a ring resonator with a radius of R = 6.2 µm. It is coupled to a microfiber of width W and length L. The coupling distance, often denoted as dx, refers to the distance between the micro-ring and the waveguide. Based on the analysis of the impact of the sensor's material [3], we have selected the silicon (Si) as an appropriate material due to its narrowest FWHM leading to the highest Q and Finesse. The sensor is surrounded by human urine with a varying refractive index RI.

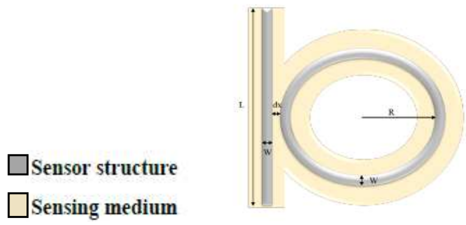

Fig. 1. The proposed WGM ring resonator sensor and its Parameters.

When light travels through the straight optical fiber, it couples to the ring and propagates as Whispering Gallery Modes (WGMs) due to internal reflection along the curved boundary. Only wavelengths that satisfy the constructive interference based on resonance condition are coupled into the microresonator. The resonance condition can be expressed as follows [1]:

$$m\lambda_{res} = 2\pi R n_{eff} \quad (1)$$

Where λ_{res} is the resonance wavelength, R is the resonator radius, n_{eff} is the effective index of resonance mode and m is an integer representing the resonance mode order. When molecules of surrounding medium bind to the surface of the resonator, they affect the local refractive index in the vicinity of the WGM. This alteration in the refractive index modifies the effective optical path length of the resonant mode. Subsequently, the changes in the effective optical path length led to a variation in the effective refractive index of the resonant mode. As a result, the resonant wavelength of the mode experiences a shift (equation1). Our biosensor utilizes this sensing mechanism to detect the concentration of glucose in urine.

III. SIMULATION AND RESULTS

We first investigate the influence of the coupling distance over the designed sensor performance by varying, it gradually from 100 to 600 nm.

Table I
THE SENSOR'S PERFORMANCE FOR DIFFERENT DISTANCES COUPLING.

dx (nm)	100	200	300	400	500	600
FWHM(nm)	7.25	2.29	0.375	0.075	0.024	0.1
Q-factor $\times10^3$	0.24	2.75	4.6	23	70.3	22.2
S (nm/RIU)	71.34	67.58	67.58	63.83	64.7	49.23

From the table I, we note that the coupling distance directly affects the sensor's performance in terms of FHWM, Q and S. FWHM decreases as dx increases while the quality factor increases significantly until dx=500nm. The sensitivity is not significantly influenced by 'dx' changes which means that the shift in resonance remains relatively stable, even though there is change in the shape of the resonance peaks as it is shown in figure2.

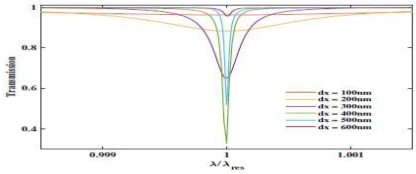

Fig. 2. Transmission spectrum of WGM sensor for different coupling distances.

The selection of the optimal coupling distance is determined by choosing the value that results in the best FWHM, best quality factor and FOM. The value of dx = 500 nm seems to be the best coupling distance. Once the optimum coupling distance has been determined, we focus on another relevant dimension, namely the width of the waveguide and the resonator (W) which is a critical parameter in controlling the guidance properties of both the waveguide and the resonator simultaneously. By evaluating S, FWHM, Q and FOM for different values of W ranging from W = 200 nm to W = 500 nm, the optimal width providing the best sensor's performance can be identified.

TABLE II

THE SENSOR'S PERFORMANCE FOR DIFFERENT WIDTHS OF WAVEGUIDE AND RESONATOR.

W (nm)	200	250	300	350	400	450	500
FWHM()	0.08	0.04	0.1	0.15	0.26	0.46	1.77
Q-factor $\times 10^4$	2.13	3.77	1.633	1.1	0.64	0.38	0.1
S $(/RIU)$	67.36	36	26	39	79.11	18	59
FOM (RIU^{-1})	827.52	845.07	253.41	254.40	303.92	39.16	33.34

The results presented in the table II reveals that the width of the waveguide has an important impact on the resonance peak shape which means that increasing W affects the FWHM and therefore the Q-factor and FOM. The sensitivity is randomly altered and reaches the highest value for w = 400 nm. The highest Q-factor is achieved at W = 250nm due to a very narrow FWHM of 0.0426 nm but the low sensitivity excludes the possibility of choosing this value as the optimum. The width of 200 nm is deemed optimal for the proposed WGM sensor, as it strikes a balance between high-quality factor of 2.13 * 10^4, acceptable sensitivity of 67.3 nm/RIU and a high FOM of 825.26 RIU^{-1}. The geometrical optimization reveals that the best performance was found when the coupling distance dx is 500 nm and the waveguide width W is set to 250 nm. The optimized WGM sensor is applied to detect the glucose concentrations ranging from 0g/dl to 5 g/dl in urine. The transmission spectrum of the WGM biosensor shown in Figure 3 indicates that the sensor's response is distinctively altered in reaction to different glucose concentrations in urine. This alteration is observed as a shift in the resonance wavelength of the sensor. The different curves of figure 3 reveal a narrow FWHM allowing a relevant determination of λ_{res} and a high-quality factor of 2.21 × 10^4 due to the long lifetime of the photon inside the resonator meaning that the interaction between the WGMs and the glucose molecules remains longer. The high Q factor enhances the sensor's ability to accurately detect and differentiate glucose concentrations based on the corresponding λ_{res}.

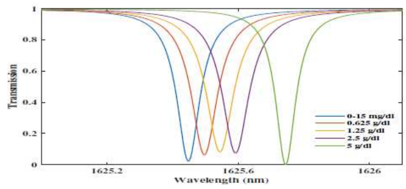

Fig. 3. Transmission spectrum of optimized WGM sensor for different concentrations of glucose in urine.

Figure 4 demonstrates the efficiency of our biosensor where the simulation results agree well with the set fitting showing perfect linearity, both for the urine RI variation as well as for the urine glucose concentration. The feature of high linearity of the regression line fit is confirmed by the strong R-squared which is 0.9997 for the variation of $\Delta\lambda_{res}$. The linear fitting follows the next equation

$$\Delta\lambda_{res} = 49.66\Delta n + 0.003048 \quad (2)$$

From the equation2 we can deduce the sensitivity S = 49.66 nm/RIU. By achieving a high FOM of 675.65 RIU^{-1} , the optimized WGM sensor demonstrates its efficiency and reliability in detecting and quantifying glucose levels in urine samples.

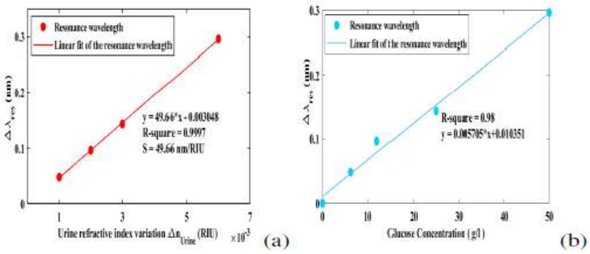

Fig. 4. (a) Resonance wavelength shifts $\Delta\lambda_{res}$ depending on urine RI. (b)Resonance wavelength shift $\Delta\lambda_{res}$ as a function of glucose concentration in humane urine.

V.CONCLUSION

The optimization of the WGM sensor proposed in this study demonstrates a significant improvement in the detection of glucose in urine compared to previous works [4][5]. Despite its limited sensitivity, the sensor remains an interesting contender due to its highly relevant quality factor and FOM.

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