بیست و چهارمین کنفرانس اپتیک و فوتونیک و دهمین کنفرانس مهندسی و فناوری فوتونیک ایران
۱۰ الی ۱۲ بهمن ۹۶ - دانشگاه شهرکرد
24th Iranian Conference on Optics and Photonics (ICOP 2018) and
9th Iranian Conference on Photonics Engineering and Technology (ICPET 2018)
Jan 30 - Feb 1 , 2018 - Shahrekord University

زیست حسگرهای نوری بهینه مبنی بر ساختارهای مشدد دیسک ویسپرینگ‌گالری

[۱] فروغ خزیمه و [۲] محمد رزاقی

گروه فیزیک، دانشگاه کردستان، خیابان پاسداران، سنندج

دانشکده مهندسی برق، دانشگاه کردستان ، خیابان پاسداران، سنندج

چکیده - در این مقاله، حساسیت (*S*) و معیار شایستگی (*FOM*) زیست-حسگرهای نوری مبنی بر ساختار مشدد دیسک، بصورت تابعی از پارامتر ساختاری فاصله‌ی گاف، مطالعه می‌شوند. این زیست-حسگرها شامل یک مشدد دیسک ویسپرینگ گالری(*WG*) ، جفت‌شده به یک موجبر مستقیم هستند. فاصله ی گاف بین مشدد و موجبر مستقیم در بازه‌ی *150-350 nm* تغییر داده می‌شود. هدف یافتن پارامترهای بهینه ای است که به مقادیر بالایی از *S* و *FOM* منجر می‌شوند. محاسبات با روش‌های تحلیلی *CTM* و *CMT*، انجام شده‌اند. روش‌های تمام تحلیلی ما تاثیر به سزایی در طراحی سریع زیست-حسگرهای نوری بر مبنای مشددهای *WG*، دارند. با توجه به محاسبات، پارامترهای *S* و *FOM* در زیست-حسگر بهینه شده به بیشترین مقادیر *134 nm/RIU* و *2200 /RIU* در طول موج *1550 nm*، دست یافته‌اند. *FOM* بالا و شعاع کوچک این زیست-حسگر، می‌تواند منجر به عملکرد بالای آن در شناسایی مقادیر کم از نمونه های زیستی (آنالیت)، شود.

کلید واژه- زیست-حسگر نوری، مد ویسپرینگ گالری، حساسیت.

Optimized Photonic Biosensors Based on Whispering Gallery Mode Disk Resonato Structures

Foroogh Khozeymeh[1] and Mohammad Razaghi[2]

[1]Dept. of Physics, School of Science, University of Kurdistan, Sanandaj, Iran

[2]Dept. of Electrical Eng., School of Engineering, University of Kurdistan, Sanandaj, Iran

Email address: fkhozeymeh@yahoo.com and mrazaghi@gmail.com

Abstract- In this paper, the sensitivity (S) and figure of merit (FOM) of disk resonator based photonic biosensors as a function of the gap distance, are studied. These biosensors include a whispering gallery mode (WGM) silicon disk resonator (7µm external radius), coupled to a waveguide (500 nm wide). Gap distance is changed in the range of 150-350 nm. The target is to find the optimized parameters of biosensor device for obtaining high S and FOM. Calculations have been done based on the analytical conformal transformation method (CTM), and coupled mode theory (CMT). Our fully analytical methods have an effective role in fast design of WGM resonator based biosensors. Based on our calculations, the S and FOM parameters of optimized biosensor can be increased up to 134 nm/RIU and 2200 /RIU, at resonance wavelength of 1550 nm. The high FOM and the small size radius of this disk resonator biosensor, allow a high performance device with application in sensing of low amounts of analyte.

Keywords: Photonic biosensor, Whispering gallery mode, Sensitivity

1 Introduction

Photonic biosensors are an important group of devices with numerous applications in the food and biomedical industry including gas sensing, glucose measurement, pathogen detection, and the study of protein–protein interactions. The photonic biosensors based on surface-plasmon-resonance (SPR), [1], has become the most common commercial implementation of evanescent-wave sensors [2]. However, there is a great deal of attention into alternative evanescent-wave based sensors. These kind of sensors could provide improvements in sensitivity, robustness, device size, and easy integration with optical sources and detectors [3]. Among the evanescent wave base biosensors, Whispering gallery mode (WGM) resonator based sensors are especially gaining attention. These biosensors could show high amount of quality factor (up to 10^{11}) and narrow resonances (causes low amounts of limit of detection) [4]. In WGM resonator based photonic biosensors, evanescent-field part of electromagnetic resonance, interact with the biological samples (analyt) on the medium. If the analyts have homogeneously distributed in the biological solution, bulk sensitivity (S) can be measured [3]. Here we examine the effect of gap distance changes on S and figure of merit (FOM) of a photonic biosensor based on whispering gallery mode disk resonator. Disk resonator utilization has the advantage of decreased scattering loss, compared to a ring resonator (since there is only one edge from which light can scatter). Furthermore a disk resonator can support multi WGM propagation. Regard this property, they can be used in biosensor devices with multi-analyte detection. Using the optimum gap distance between resonator and waveguide, maximize S and FOM (S=134 nm/RIU and FOM= 2200/RIU) will be demonstrated for transverse electric (TE) disk resonator based biosensors.

2 Principle and design

A schematic of considered biosensor is presented in Fig 1.

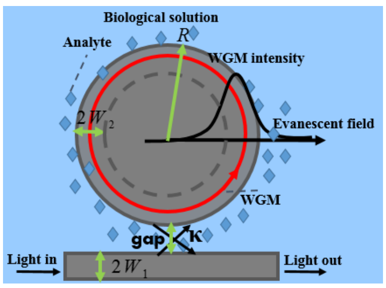

Fig. 1. A photonic WGM disk resonator based biosensor

The biosensor device consists of a WGM disk resonator laterally coupled to a straight waveguide. The input signal is directed to micro-disk. As it can be seen in Fig.1, the evanescent field of WGM resonance can interacts with biological solution. This solution including analyts, exist in close contact of resonator surface. These devices have been designed for TE modes. The core material is silicon with refractive index of n_{cor} =3.45. Both the substrate and cladding materials are silicon dioxides with n_{sub}= n_{cla}=1.46. The width of the bus waveguide ($2w_1$), has been fixed to 500 nm. Equivalent resonator waveguide width ($2w_2$) for disk resonator, is calculated as [5]. The gap distance between the straight waveguide and the WGM resonator is changed in range of 150-350 nm. The curvature radius has been imposed to be R≥7µm, in order to have negligible bending losses.

2.1 Problem formulation

When evanescent field part of a WGM (as a sensing signal), interact with analyt molecules, effective refractive index (n_{eff}) of WGM resonance wavelength, is changed. In fact, it causes a change of the effective refractive index (Δn_{eff}) of the optical confined WGM. This produces a net spectral shift in the resonator WGM resonance wavelength ($\Delta\lambda_{WGM}$). $\Delta\lambda_{WGM}$ is related to Δn_{eff} by the well-established resonance condition:

$$\Delta\lambda_{WGM} = \frac{2\pi R}{m}\Delta n_{eff} \tag{1}$$

where R is the WGM resonator radius and m is an integer representing the number of optical wavelengths around the resonator perimeter. By measuring $\Delta\lambda_{WGM}$ caused by Δn_{eff}, the analyte detection becomes possible. So first, we must be able to calculate exact amount of n_{eff}, experienced by WGM resonance wavelength in both the air and biological claddings.

2.2. Effective refractive index

For effective refractive index (n_{eff}) calculation, we use an analytical method. n_{eff} of WGM resonance wavelength in disk resonator have been found by conformal transformation (CTM), method [6]. In this method, a curved waveguide in real space is replaced with a straight waveguide in complex space. For finding n_{eff} of fundamental mode in straight waveguide, we have used a graphical method named b-v diagrams [7].

3 Result and discussion

3.1. Quality factor

After calculation of resonance mode n_{eff}, we can find the coupling coefficient (κ) between disk resonator and straight waveguide. Then, coupling quality factor (Q_k) of the resonance modes, can be obtained. A two dimensional coupled mod theory (2D CMT) [8], has been used for coupling analysis of the system. For considered disk resonator, intrinsic quality factor (Q_i) is found to be $Q_i \geq 20000$. Finally total quality factor which expressed as $Q_t^{-1}=Q_k^{-1}+Q_i^{-1}$, can be calculated. We examine variation of mentioned parameters in gap distance rage of 150-350 nm. Since the considered disk resonators can support multi-WGM propagation. All the calculations and graphs have been found for two first WGM resonance wavelength. The calculation results have been shown in Figs 2-4.

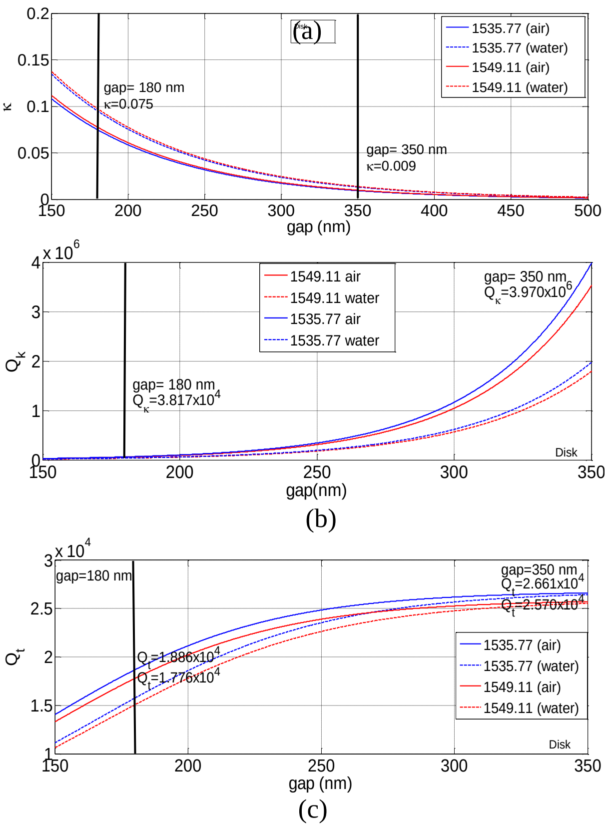

Fig. 2. Variations of a) κ, b) Q_k and c) Q_t, in different ranges of gap distance.

With increasing of gap distance (from 150 nm to 350 nm), exponential growing of Q_k factor is observed for both the TE WGM resonances. 1 and 2, (λ=1535.77 and 1549.11 nm respectively) (Fig. 2b). This behaviour is direct consequence of κ decreasing with gap distance increasing, in the same range of gap distance (Fig. 1a). Also the Q_t factor of TE WGM resonance 2, has been increased to high amount of 25700 at 350 nm gap distance, (see Fig.2c).

3.2 Sensitivity

The homogenous or bulk refractive index sensitivity of a WGM photonic based biosensor is defined as: $S=\Delta\lambda_{WGM}/\Delta n_{sol}$. Where $\Delta\lambda_{WGM}$ is calculated with using Eq.1, Δn_{sol} is bulk refractive index change of the solution flowing on top of the micro-disk. For S calculation, Δn_{eff} and $\Delta\lambda_{WGM}$ are calculated in different concentrations of glucose/water solutions (0.0 to 9.0 % weight/weight) flowing on cladding layer. To simulate these concentrations, we have changed the cladding refractive index from 1.333 to 1.350 (according to empirical relation of Δn_{sol} = $C\times1.375\times10^{-3}$ RIU/% [9], [10], between glucose concentration C and Δn_{sol}).

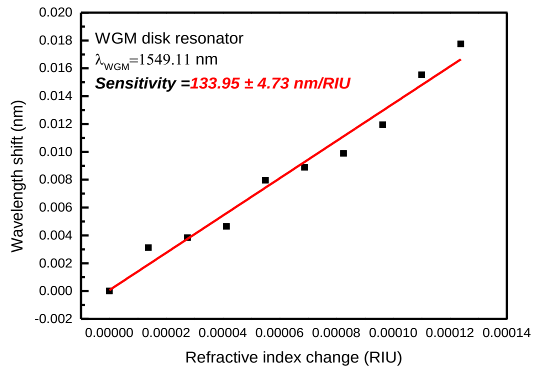

Fig. 3. Sensitivity of WGM disk resonator based biosensor with refractive index variation of solution.

3.3 Figure of merit

One of the characterizing parameters in biosensing domain is FOM. FOM depends only on the characteristics of the transducer part of an optical biosensor [11]. In case of a WGM based biosensor with total quality factor of Q_t, FOM can be defined as $FOM=Q_tS/\lambda_{WGM}$. Variation of FOM in different ranges of gap distance, has been presented in Fig. 4.

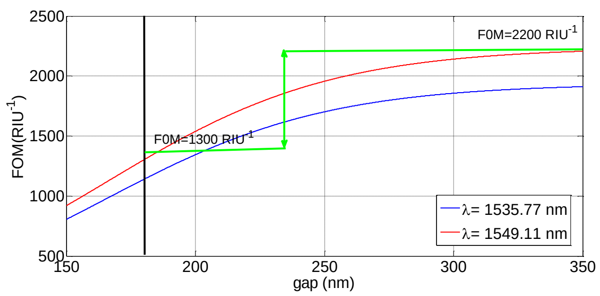

Fig. 4. Variations of FOM in different ranges of gap.

Also another parameters in bio-sensing domain, is intrinsic limit of detection (ILOD). It is defined as ILOD = FOM^{-1} = λ_{WGM} /Q_tS [12]. ILOD is the numerical amount of minimum refractive index unit change (Δn_{min}=ILOD), that can be detected by the resonator. Both the FOM and ILOD parameters, allow us to compare performance of photonic biosensors with different sensing mechanisms. Our proposed disk resonator based biosensor, shows the ILOD of $\leq 4.54\times10^{-4}$ RIU.

4 Conclusion

In the obtained optimized WGM disk resonator based biosensor, WGM with resonance wavelength of $\cong$1550 nm, is found to exhibit most S and FOM of 134 nm/RIU and 2200/RIU (at gap distance of 350 nm). Based on the high calculated Q_t values of this resonance at this resonator, in water solutions, ILOD of approximately as $\leq 4.5\times10^{-4}$ RIU for disk resonator sensor, was obtained. This amount of ILODs, have been improved by a factor of 0.6 compare with an SOI optimized strip waveguide resonator sensor with ILOD= 7.5×10^{-4}(RIU) [13]. A final remark is that we have found the optimized parameters for $\lambda\cong$1550 nm, commonly used for telecommunications. Therefore, it has been very well characterized and offers several low-cost components. This study will allow creation of a fast and reliable biosensor, based on photonic disk resonator with high performances. These biosensors have applications in the areas of refractive index-based medical diagnoses and life sciences.

References

[1] Vollmer, Frank, and Lan Yang. "Review Label-free detection with high-Q microcavities: a review of biosensing mechanisms for integrated devices." *Nanophotonics* 1.3-4 (2012): 267-291.

[2] D. Andrews, ed. Photonics, *Biomedical Photonics*, Spectroscopy, and Microscopy. John Wiley & Sons, 2015.

[3] Ciminelli, Caterina, et al. "Label-free optical resonant sensors for biochemical applications." *Progress in Quantum Electronics* 37.2 (2013): 51-107.

[4] Righini, G. C., et al. "Whispering gallery mode microresonators: fundamentals and applications." *Rivista del Nuovo Cimento* 34.7 (2011): 435-488.

[5] Rowland, D. R., and J. D. Love. "Evanescent wave coupling of whispering gallery modes of a dielectric cylinder." *IEE Proceedings J (Optoelectronics)* 140.3 (1993): 177-188.

[6] M. Heiblum and Jay Harris. "Analysis of curved optical waveguides by conformal transformation," *IEEE Journal of Quantum Electronics* 11.2 (1975): 75-83.

[7] H. Kogelnik and V. Ramaswamy. "Scaling rules for thin-film optical waveguides," *Applied Optics*, 13.8 (1974): 1857-1862.

[8] K. Okamoto, *Fundamentals of optical waveguides.* Academic press, 2010.

[9] Mancinelli, Mattia, et al. "Reconfigurable optical routers based on Coupled Resonator Induced Transparency resonances." *Optics express* 20.21 (2012): 23856-23864.

[10] bin Mat Yunus, W. Mahmood, and Azizan bin Abdul Rahman. "Refractive index of solutions at high concentrations." *Applied optics* 27.16 (1988): 3341-3343.

[11] M. White and Xudong Fan. "On the performance quantification of resonant refractive index sensors," *Optics express*, 16.2 (2008): 1020-1028.

[12] Grist, Samantha M., et al. "Silicon photonic micro-disk resonators for label-free biosensing." *Optics express* 21.7 (2013): 7994-8006.

[13] TalebiFard, Sahba, et al. "Optimized sensitivity of Silicon-on-Insulator (SOI) strip waveguide resonator sensor." *Biomedical optics express* 8.2 (2017): 500-511.