A Novel Label-free Biosensor Based on Circular Fractals

Kiana Malmir [1], Hamidreza Habibiyan [1] and Hassan Ghafoorifard [1, 2]

[1] Photonics Engineering Group, Amirkabir University of Technology, Hafez Ave, Tehran, Iran
[2] Department of Electrical Engineering, Amirkabir University of Technology, Hafez Ave, Tehran, Iran
habibiyan@aut.ac.ir

Abstract: In this paper, we propose and analyze a fractal structure-based biosensor in a silicon-on-insulator (SOI) platform. Fractal architecture is a novel structure in order to use in biosensor design. The suggested biosensor offers potential for real time detection of biomolecule interactions the specific targets in the analyte because of having the sensitivity toward surface binding events. In biosensor based on fractal structure, sensitivity and notch deep are developed in comparison with a lone disk. An SOI optical fractal consisted of uniformly distributed disks with radius of 0.1 micron meter is capable of detecting bulk refractive index changes of 10^{-4}. Its sensitivity demonstrated to this refractive index change is 400nm/RIU and 17×10^{4}dB/RIU.

[Malmir K, Habibiyan H. and Ghafoorifard H, **A Novel Label-free Biosensor Based on Circular Fractals.** *Biomedicine and Nursing* 2025;11(1):6-10]. ISSN 2379-8211 (print); ISSN 2379-8203 (online). http://www.nbmedicine.org. 02. doi:10.7537/marsbnj110125.02

Keywords: integrated optic; biosensor; fractal; microresonator

1. Introduction

In 21th century, integrated optical devices for sensing the biomolecules have pursued with interest for applications in many areas such as bacterial and virus detection, medical diagnostics, food and environmental control [1]. A biosensor detects a biomolecule such as specific DNA, protein, bacterial and virus. Biosensor transmutes biorecognition event into a measurable signal. It consists of two ingredients [2]: a biorecptor; it is a biomolecule that incorporates with target molecule so bioreceptor can identify target molecule, and another part is transducer that turns biorecognition event into a measurable signal. Figure 1 shows the components of a label-free biosensor. Some biosensors require a label attached to the target such as radioactive/fluorescent labels similar to traditional biosensors. They usually employ a label attached to target such as fluorescent dyes that labeling biomolecules can strongly alter their binding properties, and the yield of the target-label coupling reaction is highly variable [3]. This subject is problematic for some sensors especially protein targets [3]. New biosensors that are planar integrated label-free optical biosensors have attracted considerable attention; Because of label-free biosensors get rid of the dependence on the inter-reaction between target molecules and label materials that propels to inadequate reliability and complicated operation [4].

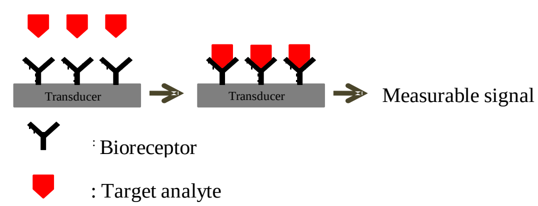

Figure 1. Schematic of a label-free biosensor

Recently for optical label-free biosensors there are some different approaches such as surface plasmon resonance [5, 6, 7], interferometer [8, 9], optical fiber [10, 11], photonic crystal [12, 13], optical micro resonator [14, 15, 16-31] and fractal structures based biosensors [32-33].

Optical sensors in silicon-on-insulator (SOI) offer sensitive and cheap sensors [34]. SOI provides low detection limit and high refractive index for the fabrication of high quality sensors. Silicon waveguides can increase the sensitivity of label-free biosensors based on refractive index measurement [35].

One of the main demands for biosensors is high sensitivity. In last decade micro resonators based optical biosensors have become popular for having potential of offering high sensitivity with a high quality Q factor [36] and very small size as compared to others [37-39]. On the other hand, using fractal architectures in manufacturing artificial materials has attracted considerable attention due to their new application potential [40]. Fractal structure can increase resonance at optical frequencies that creates high sensitivity and Q factor in sensors. For example, A. Yalcin et al., showed a vertically coupled glass microring resonator biosensor that introduced with Q factor of 12000 and the structure of sensor was similar to fractal structure [33].

More reducing size with high sensitivity would still be wanted to have optical label-free biosensor despite high sensitivity biosensors have been supplied in recent years. In this work, we propose a new optical biosensor based on silicon- on-insulator micro resonators in format of fractal structure. This new structure can provide an enhanced notch depth in resonance wavelength and finally detection with high sensitivity at real time.

2. Proposed structure and simulation result

In this paper, the optical biosensor is offered based on fractal structure. Collection of optical micro disk resonators constitutes the proposed structure. Figure 2 shows structure of proposed biosensor with radius of disks equal to 0.1µm. This sensor has been designed on silicon- on- insulator platform.

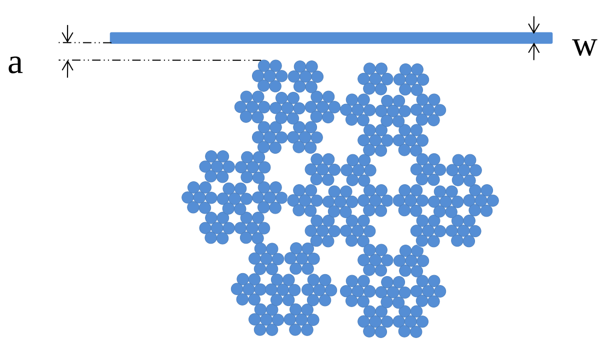

Figure. 2. Structure of suggested sensor

There are several parameters such as air gap between fractal structure (FS) and bus waveguide and width (W) of bus waveguide. We have shown air gap between FS and bus waveguide by “a”, above parameters adjustment is very effective on biosensor reply. Indeed, the right choice of them increases sensitivity in this biosensor. Optimization causes to sensitivity increasing. We displayed finite difference time domain (FDTD) for achieving optimization sizes of these parameters therefore size of them are carefully optimized the by numerical simulations that charts of them are shown in Figure 3. The transmission notch depth is studied for several widths of waveguides and several air gaps between bus and FS. Figure 3 shows that a = 0.5µm and w = 0.24µm increases notch deep and sensitivity of biosensor.

By applying these optimized measurements in design of this biosensor, output of proposed structure shows good reply for yield of this biosensor. A typical output spectrum of suggested biosensor is shown in Figure 4. The free spectral range (SPR) of the devices is approximately 3.82 nm and on resonance wavelength has notch deep of -62.6 dB.

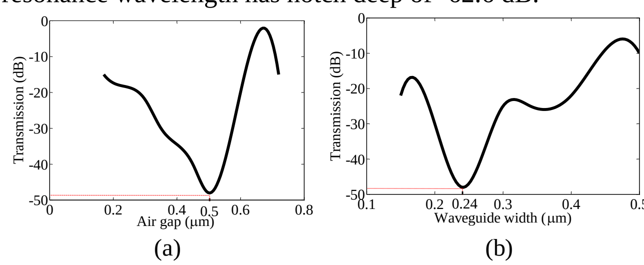

Figure. 3. Results of optimization in width of bus waveguide (a), size of air gap between bus and fractal structure (b),

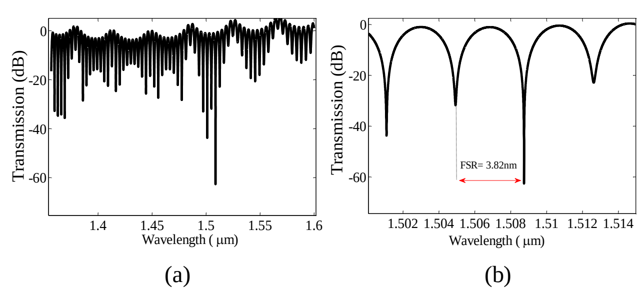

Figure. 4. Sharp response and FSR are shown in fractal structure

Response of this sensor is calculated for bulk change in refractive index. We compared the resonance wavelength of the cavity covered by special target that created effective index change 10^{-4}, before and after binding the target to surface of the fractal sensor. The alternation of the resonance wavelength is shown in Figure 5.

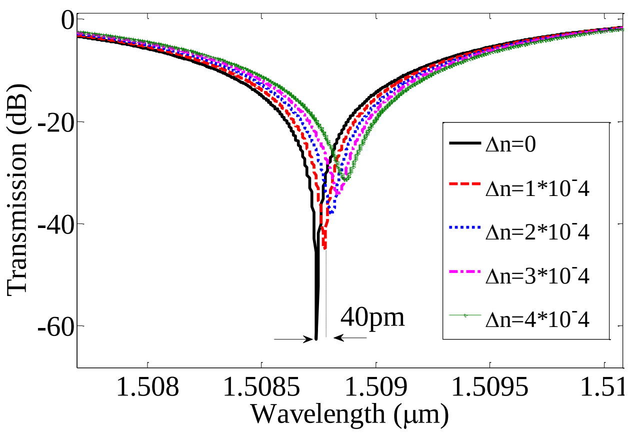

Figure. 5. Alternations of transmission with change effective index 10^{-4}

Not only effective index changes affects on wavelength, but also on notch deep. By changing notch deep or power, sensitivity can be measured via another way.

3. Conclusion

Fractal structures are relatively new concepts that used in many different fields of science. In this work, we proposed an optical label-free biosensor based on Silicon -on- Insulator fractal structure. The realization of structures resonant at optical frequencies needs the design of some configurations with circular architecture. Because of this biosensor has consisted of micro resonators in form of fractal structure. Its high sensitivity and its small size – footprint external radius of 3 µm – allow this device to sense low amounts of analyte. The simulations based on finite difference time domain (FDTD) method have shown a transmission notch depth of -62.6dB for sensor at rest mood also 0.04 nm resonance shift has been obtained as a refractive index change of 10^{-4} in optimized structure.

Corresponding Author:
Hamidreza Habibiyan
Photonics Engineering Group, Amirkabir University of Technology, Hafez Ave, Tehran, Iran
E-mail: habibiyan@aut.ac.ir

References

1. De Vos K., Bartolozzi I, Bienstman P, Baets R, Schacht E, " Optical Biosensor based on Silicon-on-Insulator Microring Resonators for Specific Protein Binding Detection,", *Proceedings Symposium IEEE/LEOS Benelux Chapter Eindhoven* (2006).
2. Zahid Ansari M and Cho Ch, "Design and Analysis of a high sensitive Microcantilever Biosensor for Biomedical Applications," *International Conference on BioMedical Engineering and Informatics* (2008).
3. Jonathan S. Daniels, Nader Pourmanda, "Label-Free Impedance Biosensors: Opportunities and Challenges," Electroanalysis **19** , 12, 1239 – 1257(2007).
4. Hao W, Wenzhen S, Xiangang L, "The Design of a Nanometer Biosensor and Its Microfluidic Integration" *Robotics, Automation and Mechatronics, IEEE Conference on* **18** 625 – 628, (2008).
5. Debackere P. P. P, Scheerlinck S, Bienstman P. and Baets R, "Surface Plasmon Interferometer in Silicon-on- Insulator: *novel concept for an integrated biosensor*," Opt. Express **14**, 7063-7072 (2006).
6. Kim Sh, Kim S J, Lee S, Park T, Byun K., Kim S G, and Shuler M L, "Detection of Avian Influenza-DNA Hybridization Using Wavelength-scanning Surface Plasmon Resonance Biosensor," *J. Opt. Soc. Korea* **13**, 392-397, (2009).
7. Byun K M, "Development of Nanostructured Plasmonic Substrates for Enhanced Optical Biosensing**,"** *J. Opt. Soc. Korea* **14,** 65-76, (2010), Invited paper
8. Prieto F, Sep´ulveda B, Calle A, Llobera A, Dom´ınguez C, Abad A, Montoya A, and Lechuga L. M, "An integrated optical interferometric nanodevice based on silicon technology for biosensor applications," *Nanotechnology* **14**, 907–912 (2003).
9. Lee T-K, Oh G-Y, Kim H-S, Kim D G, Choi Y-W, "A high-Q biochemical sensor using a total internal reflection mirror-based triangular resonator with an asymmetric Mach–Zehnder interferometer," *Optics Communications* **285**, 1807–1813, (2012).
10. Li Y and Tong L, "Mach—Zehnder interferometers assembled with optical microfibers or nanofibers," *Opt. Lett*. **33**, 303–305 (2008).
11. Guo X and Tong L, "Supported microfiber loops for optical sensing," *Opt. Express* **16**, 14429–14434 (2008).

12. Mandal S and Erickson D, “Nanoscale Optofluidic Sensor Arrays,” *Opt. Express* **16**(3), 1623–1631 (2008).
13. Mandal S, Goddard J. M, and Erickson D, “A multiplexed optofluidic biomolecular sensor for low mass detection,” *Lab Chip* **9**(20), 2924–2932 (2009).
14. Khorasaninejad M, Clarke N, Anantram M. P, Singh Saini S., “Optical bio-chemical sensors on SNOW ring resonators,” *Optical Society of America*, *Opt. Express* 17575 **19**, (2011).
15. Zhang X. Li, Z, Qin Sh, Qiu M and Su Y, “Label-free Biosensor Based on Silicon-On-Insulator Concentric Micro-Ring Resonators,” IEEE, IPGC, 1-3, (2008).
16. Flueckiger J, Grist S. M, . Bisra G, Chrostowski L, K. Cheung C, “Cascaded silicon-on-insulator microring resonators for the detection of biomolecules in PDMS microfluidic channels,” SPIE **7929**, 79290 · (2011)
17. Gohring J. T, Dale P. S, Fan X, “Detection of HER2 breast cancer biomarker using the opto-fluidic ring resonator biosensor,” *Sensors and Actuators B* **146**, 226–230, (2010)
18. Logan D. F, Velha Ph, Sorel M, R. M. Rue D. L, Jessop P. E, and Knights A. P, “Monitoring and Tuning Micro-Ring Properties Using Defect-Enhanced Silicon Photodiodes at 1550 nm,” *IEEE PHOTONICS TECHNOLOGY LETTERS* **24**, (2012)
19. Mancuso M, Goddard J. M, and Erickson D, “Nanoporous polymer ring resonators for biosensing,” *Optical Society of America, Opt. Express* **20**, (2012)
20. Delâge A, Xu D-X., McKinnon R. W, Post E, Waldron Ph, J. Lapointe, C. Storey, A. Densmore, S. Janz, Lamontagne B, Cheben P, and Schmid J. H, “Wavelength-Dependent Model of a Ring Resonator Sensor Excited by a Directional Coupler,” *Journal of lightwave technology* **27**, (2009)
21. D. T. Nguyen and R. A. Norwood, “Label-free, single-object sensing with a microring resonator: FDTD simulation,” Opt. Express 49 **21**, (2013)
22. Soltani M, Yegnanarayanan S and Adibi A, “Ultra-high *Q* planar silicon microdisk resonators for chip-scale silicon photonics,” *Opt. Express 4694* **16,** (2007)
23. Xia Zh, Eftekhar A. A, Soltani M, Momeni B, Li Q, Chamanzar M, Yegnanarayanan S, and Adibi A, “High resolution on-chip spectroscopy based on miniaturized microdonut resonators,” *Opt. Express 12356* **19,** (2011)
24. White I. M and Fan X, “On the performance quantification of resonant refractive index sensors,” *Opt. Express 1020* **16,** (2008)
25. Shah Hosseini E, Yegnanarayanan S, Atabaki A. H , Soltani,M and Adibi A, “Systematic design and fabrication of high-*Q* single-mode pulley-coupled planar silicon nitride microdisk resonators at visible wavelengths,” *Opt. Express,* **18**, 2127-2136 (2010)
26. De Vos K, Bartolozzi I, Schacht E, Bienstman P, and Baets R, “Silicon-on-insulator microring resonator for sensitive and label-free biosensing,” *Opt. Express* **15**, 7610–7615 (2007).
27. Oh G, Lee T, Kim H, Kim D, and Choi Y, “Design of ultra-sensitive biosensor applying surface plasmon resonance to a triangular resonator,” *Opt. Express* 19067 **20**, OSA, (2012)
28. Flueckiger J, Grist S. M, Bisra G, Chrostowski L, K. Cheung C, “Cascaded silicon-on-insulator microring resonators for the detection of biomolecules in PDMS microfluidic channels,” *Proc. SPIE* **7929**, 79290I-1, (2011)
29. Gylfason K.B, Carlborg C.F, Kaźmierczak A, Dortu F, Sohlström H, Vivien L, Ronan G, Barrios C.A, van der Wijngaart W, and G. Stemme, “a packaged optical slot-waveguide ring resonator sensor array for multiplex assays in Labs-On-Chip,” *Lab Chip*. 7;10 **3** 281-90 (2010).
30. Claes T, Girone`s Molera J, D Vos K., Schacht E, Baets R, and Bienstman P, “Label-Free Biosensing With a Slot-Waveguide-Based Ring Resonator in Silicon on Insulator,” *IEEE Photonics Journal*, **1** 197-205 1943-0655, (2009)
31. Claes T, Bogaerts W, and Bienstman P**, “**Experimental characterization of a silicon photonic biosensor consisting of two cascaded ring resonators based on the Vernier-effect and introduction of a curve fitting method for an improved detection limit,**”** *Opt. Express* **18**, (2010)
32. Neal D. R, Warren M. E, Gruetzner J. K, Smith T. G, Rosenthal R. R, McKechnie T. S., "Muiitiered wavefrontsensor using binary optics," *SPIE*, **2201**, 574-585 (1994).
33. Yalcin A, Popatt K. C, A-Washburn M, Chhbouki N, Desail T. A, IUnli M. S, Goldberg B. B, “Microring Resonators for Biochemical Sensing,” *Conference on Lasers & Electro-Optics (CLEO)*, (2005).
34. Arce C. L, De Vos K, Claes T, Komorowska K., Thourhout D. V, and Bienstman P, “Silicon-on-Insulator Microring Resonator Sensor Integrated on an Optical Fiber Facet,” *IEEE PHOTONICS TECHNOLOGY LETTERS*, **23**, NO. 13, (2011).

35. Xu D-X, Densmore A, Janz S, Waldron Ph, Lapointe J, Lamontagne B, Mischki T, Lopinski G, Schmid J, and Cheben P, " Label-Free Biological Sensors Based on Ring Resonators André Delâge,", *IEEE Crown* 978-1-4244-2626- (2008) .
36. Li X, Zhang Z, Qin Sh, Wang T, Liu F, Qiu M.,and Su Y, "Sensitive label-free and compact biosensor based on concentric silicon-on-insulator microring resonators," *Appl. Opt*, **48**,(2009).
37. Yalcin A, Popat K. C, Aldridge J. C, Desai T. A, Hryniewicz J, Chbouki N, Little B. E, King O, Van V, Chu S, Gill D, Anthes- Washburn M, Unlu M. S, and Goldberg B. B, "Optical sensing of biomolecules using microring resonators," *IEEE J. Sel. Topics Quantum Electron.*, **12**, 148–155, (2006).
38. Kim G. D, Son G. S, Lee H. S, Kim K. D, and Lee S. S, "Integrated photonic glucose biosensor using a vertically coupled microring resonators in polymers," *Opt. Commun.*, **281**, 4644–4647, (2008).
39. Chao C. Y, Fung W, and Guo L. J, "Polymer microring resonators for biochemical sensing applications," *IEEE J. Sel. Topics Quantum Electron.*, **12**, 134–142, (2006).
40. Sandru A, "Fractal structures for optical applications feasible with 2D nanotechnology," *Journal of Modern Optics*, **59**, 3, 199–204, (2012).

9/26/2024