Photonic Crystal Based Ring Resonator Sensor for Detection of Glucose Concentration for Biomedical Applications

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Abstract—In this paper, we have proposed an optical sensor design for urine analysis for diabetic applications. The sensor design consists of a two-dimensional photonic crystal ring resonator structure. Finite Difference Time Domain (FDTD) method has been used for the analysis. MEEP (MIT Electromagnetic Equation Propagation) simulation tool has been used for modeling and designing of photonic crystal ring resonator structure. The optical properties of glucose in urine are studied and average value of refractive index for different samples is taken as input. The change in the normalized output power and Q factor has been observed with the change in the concentration of glucose in urine and thus by capturing these changes the concentration of glucose in urine has been detected.

Keywords—Diabetes, Photonic crystal ring resonator, Refractive index, MEEP, Urine analysis.

I. INTRODUCTION

According to the American Diabetes Association’s data, from the National Diabetes Fact sheet (January 26, 2011), 8.3% of the total population, i.e., around 25.8 million people are affected by diabetes each year in the United States [10]. According to World Health Organization (WHO) about 347 million people worldwide have diabetes in the year 2013 [11]. Also WHO projects that diabetes is going to be the seventh leading disease. Diabetes is not only chronic but it is also fatal. It causes over 3 million deaths per year due to high fasting blood sugar. Moreover, it is root cause for the damage of heart, blood vessels, eyes and kidneys [1]. Research is going on for surveillance, control and prevention of diabetes through new inventions and modern techniques. Integrated photonics has opened the ways to modernize diabetes monitoring with the development of non-invasive methods for glucose concentration detection [4].

The conventional methods for diabetes monitoring are invasive methods which consist of analysis of glucose concentration in blood samples. Main disadvantage of the blood analysis method is that these methods are invasive. Thousands of blood samples are collected and are assessed in laboratories. Other methods involve urine analysis with test strip color change. The color changes in test strips can be biased due to airborne or finger borne contamination or interference with light source or light sensor and can give inaccurate results.

Urine analysis method can be explored for further research since it provides way of non-invasive analysis of glucose concentration.

Photonic sensing technology enables the new measurement possibility through accurate urine analysis for glucose concentration. Photonic crystal bandgap structures can be utilized for glucose detection. Since the input refractive index variation is very minute, these photonic crystal band gap structures can be less sensitive. In this paper we have explored the photonic crystal ring resonator structure for analysis of glucose concentration in urine samples. The two-dimensional square lattice photonic crystal ring resonator structure with rectangular ring waveguide is designed and simulated. The ring resonator structure provides accurate and highly reliable results. Even for the minute variation in the input refractive index, the ring resonator structure provides distinct change in the output frequency and power, giving very sensitive results.

Thus the purpose of the paper is to develop and simulate the two-dimensional square lattice photonic crystal sensor which can be developed as lab-on-a-chip sensor for detection of glucose concentration in urine.

II. THEORY

The presence of glucose in urine is indication of not only high glucose percentage in blood but also the inability of kidney for glucose filtration, hence kidney disorder or malfunction. The negligible range of 0-15mg/dl amount of glucose can exist in urine. This range is called ‘Renal Threshold of Glucose’. Beyond RTG is clear indication of ‘Glycosuria’ [1][2]. The concept behind the photonic crystal as a sensor is that the refractive index of urine sample alters as the glucose concentration in the urine changes. As a result the electromagnetic propagation in the photonic crystal is modified. By capturing the modification of the electromagnetic properties like center frequency, transmitted power, the glucose concentration can be detected. Thus the photonic crystal structure can be explored for sensing applications. The advantages of these sensor technologies are the low cost, low energy, contact-free and provide direct measurements and analyses of substances.
The photonic crystal function as sensor can be proved by using a master equation evaluated by solving the Maxwell's basic equations [14][16].

\[ \nabla \times \left( \epsilon \frac{1}{c} \nabla \times \mathbf{H} \right) = \left( \frac{\omega}{c} \right)^2 \quad \text{(1)} \]

Here, in Equation (1) 'H' is the magnetic field and 'c' is speed of light. In the above master equation, it can be observed as the dielectric function (\( \epsilon \)) changes the frequency (\( \omega \)) of resonance changes. Thus, the photonic crystal structures can be used as sensor. Different methods such as photonic bandgap method, effective refractive index method, spectroscopy, optical imaging can be explored [4][7]. But as the input variations are very low the sensitivity of these methods and structures are also very less.

To increase the sensitivity of the photonic crystal structures the ring resonator waveguide structures can be used. In ring resonator structure the resonance or the output power of waveguide alters as the refractive index of sample is changed. The variation in resonance can be captured and thus the structure can be used for sensing applications. As the refractive index of urine samples with different concentration of glucose changes, the overall refractive index profile of the photonic crystal ring resonator structure is modified, changing the resonance. Assessment of Q factor ensures the reliability of the results. Even the change in Q factor is observed as the input parameter varies.

The ultimate goal of the paper is to develop a sensor based on two dimensional square lattice ring resonator structure for detection of glucose amount in urine samples, with improved sensitivity and efficiency.

III. SENSOR DESIGN

The design of the sensor consists of 2-dimensional, square lattice ring resonator structure. The rod in air configuration is used. When the sensor device is dipped in urine sample, the air is replaced by urine sample. The light is passed through the photonic crystal from one end and detected from the other end. The light will interact with the components in the urine, when the sensor is dipped in the sample. Depending on the dielectric constant the propagation of the light will vary in the photonic crystal. Design of the sensor device is shown in Fig.1.

Source code for modeling and designing of photonic crystal waveguide is developed with MEEP and MATLAB software. The MEEP tool uses scripting language and the simulation is carried out by this tool [28][34]. This tool is used for finding the field distribution of electromagnetic wave.

1. Rods in air configuration
2. Square lattice structure
3. Lattice constant 'a'=1μm
4. Radius of holes 'r'=0.19μm
5. Dielectric constant of rod is 12(silicon)
6. Background dielectric constant is changed with respect to urine sample taken
7. Height of rods is infinity
8. Light source: Unit Gaussian Pulse with center frequency at 0.4, width of the pulse is 0.3

Detailed study has been done regarding the amount of glucose in urine. A detailed database has been prepared to record refractive index of different concentration of glucose in urine [2][3]. The refractive index of these concentrations of glucose is taken into consideration as input for MEEP is in terms of refractive index [26]. The dielectric constant (epsilon) is square of refractive index in optical domain. The change in the frequency can be observed as the refractive index in the defected rods is changed according to the concentration of normal (0-15 mg/dl), 1.25 gm/dl, 2.5 gm/dl, 5 gm/dl and 10 gm/dl glucose in urine. The detailed database is given in Table I [2][3].
Input database for different concentrations of glucose

<table>
<thead>
<tr>
<th>Urine sample with glucose concentration</th>
<th>Refractive index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal urine (0-15 mg/dl)</td>
<td>1.335</td>
</tr>
<tr>
<td>1.25 gm/dl</td>
<td>1.337</td>
</tr>
<tr>
<td>2.5 gm/dl</td>
<td>1.338</td>
</tr>
<tr>
<td>5 gm/dl</td>
<td>1.341</td>
</tr>
<tr>
<td>10 gm/dl</td>
<td>1.347</td>
</tr>
</tbody>
</table>

### IV. EXPERIMENTAL RESULTS

MEEP simulation tool results comprise of the transmission spectrums obtained for different concentration of glucose in urine and are shown in Fig. 2 given below.

![Transmission Spectrum for different glucose concentrations in urine](image)

**Fig.2. Transmission spectrum for different concentrations of glucose**

The png image of the transmission of light wave propagation with respect to time is shown in Figure 3.

![Fig.3. Images for transmission of light through waveguide using MEEP simulation tool.](image)

**TABLE I**

<table>
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<td>1.347</td>
</tr>
</tbody>
</table>

**TABLE II**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Refractive index</th>
<th>Q factor</th>
<th>Frequency</th>
<th>Transmitted power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal (0-15 mg/dl)</td>
<td>1.335</td>
<td>73</td>
<td>0.424349</td>
<td>16.41984</td>
</tr>
<tr>
<td>1.25 gm/dl</td>
<td>1.337</td>
<td>116</td>
<td>0.423747</td>
<td>16.30274</td>
</tr>
<tr>
<td>2.5 gm/dl</td>
<td>1.338</td>
<td>102</td>
<td>0.423146</td>
<td>16.24668</td>
</tr>
<tr>
<td>5 gm/dl</td>
<td>1.341</td>
<td>140</td>
<td>0.422545</td>
<td>16.06905</td>
</tr>
<tr>
<td>10 gm/dl</td>
<td>1.347</td>
<td>210</td>
<td>0.421944</td>
<td>15.76348</td>
</tr>
</tbody>
</table>

As observed from the transmission spectrum for different amount of glucose present in urine, the transmitted power for normal concentration (0-15 mg/dl) is 16.41984 at the frequency of 0.424349, the transmitted power for 1.25 gm/dl concentration is 16.30274 at the frequency of 0.423747, the transmitted power for 2.5 gm/dl concentration is 16.24668 at the frequency of 0.423146, the transmitted power for 5 gm/dl concentration is 16.06905 at the frequency of 0.422545, the transmitted power for 10 gm/dl concentration is 15.76 at the frequency of 0.421944.
From the above plots and Table II, we observe the variation in the peak transmission as well as the variation in frequency as the index of refraction for different components in urine is changing, indicating the presence of the different concentrations of glucose in urine. Spectral analysis has been done for different concentrations of glucose in urine samples. The transmission spectrum acts as a signature for detection of different concentration of glucose present in urine sample and thus detected.

| CONCLUSION |
| V. CONCLUSION |

The photonic crystal ring resonator structure based sensor is designed and simulated using MEEP simulation tool. The sensor can detect the glucose concentrations in urine samples. The shift in the frequency and change in the power is observed for different amount of glucose present in urine samples. The sensor is very helpful in detection of chronic conditions like 'Glycosuria' and kidney disorders. Thus, the designed sensor provides a modernized non-invasive way of glucose concentration detection for diabetic applications.

REFERENCES


