DESIGN AND FABRICATION OF
ONE-DIMENSIONAL PHOTONIC CRYSTAL
AS A REAL TIME OPTICAL SENSOR
FOR SUGAR SOLUTION CONCENTRATION DETECTION

MAMAT RAHMAT

GRADUATE SCHOOL
BOGOR AGRICULTURAL UNIVERSITY
2009
STATEMENT ON THESIS

I hereby declare that the thesis of “Design and fabrication of one-dimensional photonic crystal as a real time optical sensor for sugar solution concentration detection” is my work with the direction of the supervising committee and has not been submitted in any form to any college. Sources of information derived or quoted from the work published or not published by other authors mentioned in the text and listed in the reference at the end of this thesis.

Bogor, Desember 2009

Mamat Rahmat
ID G751080011
ABSTRACT

MAMAT RAHMAT. Design and fabrication of one-dimensional photonic crystal as a real time optical sensor for sugar solution concentration detection. Supervised by HUSIN ALATAS, dan IRMANSYAH

A previous theoretical study of a finite one-dimensional photonic crystal composed of 12 unit cells with two defects had shown the existence of Photonic Pass Band (PPB) inside the Stop Band, which was suggested as a useful refractive index sensor due to the sensitive variation of PPB with respect to the change of refractive index of either defect layer material. We report in this presentation our successful fabrication of a prototype of this system by means of electron beam evaporation equipment in a sample chamber at pressure of $10^{-3}$ Pa with BK-7 glass substrate at temperature 573 K. Each of the photonic cells is composed of a high index layer of OS-5 with refractive index of $n = 2.10$, and an equal optical thickness low index layer of MgF$_2$ with $n = 1.38$. In the first defect cell, the high index layer has twice the thickness of the other layers with the low index layer left unchanged, while in the second defect cell separated by 6 unit cells, the first layer is void to be filled with the sample solution. The device was used for measuring the refractive index of sugar solution with concentration range of 20-100 g/L in the real time mode. The result was found to achieve determination coefficient up to 98%. Further measurement performed has demonstrated a result in good agreement with theoretical prediction reported previously.

Keyword: photonic crystal, photonic pass band, sensor, solution concentration, real time
SUMMARY

MAMAT RAHMAT. Design and fabrication of one-dimensional photonic crystal as a real time optical sensor for sugar solution concentration detection. Supervised by HUSIN ALATAS, dan IRMANSYAH

This study is developed from the results of theoretical study of one-dimensional photonic crystals with two defects that have unique characteristics in response of Photonic Band Pass (PPB) on the frequency interval of Photonic Band Gap (PBG). This study focused on prototyping photonic crystal sensor based on refractive index changes in a second defect that serves as a receptor in which to respond transmitansi value changes, so that could be used as a single-frequency index sensing. The reference wavelength that used in this study is 525 nm.

This research was conducted with some of the following stages: theoretical model of observation through implementation and simulation, fabrication of photonic crystal, characterization, sensing test, assembly and instrumentation devices, and device performance measurement. Fabrication process of a prototype of this system by means of electron beam evaporation equipment in a sample chamber at pressure of $10^{-3}$ Pa with BK-7 glass substrate at temperature 573 K. Each of the photonic cells is composed of a high index layer of OS-5 with refractive index of $n=10.2$, and an equal optical thickness low index layer of MgF$_2$ with $n=38.1$. In the first defect cell, the high index layer has twice the thickness of the other layers with the low index layer left unchanged, while in the second defect cell separated by 6 unit cells, the first layer is void to be filled with the sample solution.

This research shown that the prototype of one-dimension photonic crystal with two defects could be implemented as an optical sensor to measure a certain solution's concentration. In this case, we used sugar solution with the concentration range from 20 to 500 g / L and the measured refractive index between 1.332 and 1.415 as a sample target. To analyze the result, we used the linear regression method. We divide the data into a linear two areas: the first is the area with 20-100 g / L and, and second, the area with 100 - 500 g / L. The results shown that the determination coefficient could be reached up to 98%. Based on this fact, we are certain that this device can be used to measure the solution's concentration in varieties of applications; for instance, to measure the water sanitation for the environment, blood sugar for medical fields, sugar content in the beverage industries, and many others. This measurement can also be carried out by using the in situ and real-time mechanism.

Keyword: photonic crystal, photonic pass band, sensor, solution concentration, real time
DESIGN AND FABRICATION OF ONE-DIMENSIONAL PHOTONIC CRYSTAL AS A REAL TIME OPTICAL SENSOR FOR SUGAR SOLUTION CONCENTRATION DETECTION

MAMAT RAHMAT

Thesis
Submitted to
Bogor Agricultural University
in Partial Fulfillment of the Requirement for the Master Degree in Biophysics

GRADUATE SCHOOL
BOGOR AGRICULTURE UNIVERSITY
2009
Research Title : Design and fabrication of one-dimensional photonic crystal as a real time optical sensor for sugar solution concentration detection

Name : Mamat Rahmat
Student ID : G751080011

Approved by,

Advisory Board

Dr. Husin Alatas, M.Si.  
Supervisor

Dr. Irmansyah, M.Si.  
Co-supervisor

Endorsed by,

Biophysics Program Coordinator  
Dean of Graduate School

Dr. Akhiruddin Maddu, M.Si.  
Prof. Dr. Ir. Khairil Anwar Notodiputro, MS.

Tanggal Ujian :  
Tanggal Lulus :
PREFACE

Praise and thank author prayed to the God for all His gifts so that this scientific work is completed successfully. Selected theme in the research that conducted since December 2008 until December 2009 is the biosensor, with the title “Design and fabrication of one-dimensional photonic crystals as a real time optical sensor for sugar solution concentration detection”. This research held in PT. Nagata Opto Indonesia and Biophysics Laboratory of Bogor Agricultural University.

The result of this research has been presented in some publication. Scientific Poster entitled Design and Fabrication of One-Dimensional Photonic Crystal-Based Optical Sensors is presented at the International Symposium on Modern Optics and Its Application on 12-14 August 2008 in Bandung. Scientific work titled Sensor Design and Fabrication optical sensor based on One dimension photonic crystal is presented in National Seminar of Science 2009 on November 15, 2009 in Bogor. Scientific paper entitled Real-Time Optical Sensor Based on One Dimensional Photonic Crystals with Defects is presented at the International Conference on Information Communication Instrumentation and Biomedical Engineering (ICICI-BME) on 23 to 24 November 2009 in Bandung.

Author wish thank to Dr. Husin Alatas, M.Si. and Dr. Irmansyah, M. Si. as supervisor, Mr. Siswanto as Operational Director and Mr. Kazuhiro Shimazu as Director of PT. Opto Nagata Indonesia which has provided aid research facilities. In addition, author’s appreciation goes to Mr. Bregas Budianto from Department of Geophysics and Meteorology FMIPA IPB, Mr. Arif Mulyana, and Mr. Zuhdi Syakuri as team of Lens Production and Coating Division of PT. Opto Nagata Indonesia, and Mr. Kamaluddin, Mr. Slamet Widodo as team Jigs & Tools Workshop Unit, which has helped in the fabrication process. Gratitude is also conveyed to my beloved wife, and mother’s, father’s and the whole family for all the prayers and affection. Thanks also goes to all my friends and companions who are always together in the learning process through the Biophysics Study Program, which has given the motivation and togetherness in raising achievement and friendship.

Hopefully this scientific work is useful.

Bogor, December 2009

Mamat Rahmat
CURRICULUM VITAE

The author was born in Bandung on August 5, 1976 as the third child of four children of the couple Wihanta Maman and Cacih. Pursued graduate education in Physics Studies Program at Faculty of Mathematics and Natural Sciences, graduating in 2000. In 2008, the author received at the Master Biophysics Study Program at the Graduate School of Bogor Agricultural University with Beasiswa Unggulan support from the National Education Ministry of the Republic of Indonesia.

The author worked as an Assistant Manager of the Department ISO / Strategic Management Team in PT. Opto Nagata Indonesia since 2008. Previously, the author worked as Production Optical Engineer at PT. Honoris Industry since 2000.

During the master program, the author followed the International Workshop on Modern Optics ant Its Application on August 10 to 11, 2008. Scientific Poster entitled Design and Fabrication of One-Dimensional Photonic Crystal-Based Optical Sensors have been presented at the International Symsposium on Modern Optics and Its Application on 12-14 August 2008 in Bandung. Scientific work titled Sensor Design and Fabrication optical sensor based on One dimension photonic crystal is presented in National Seminar of Science 2009 on November 15, 2009 in Bogor. Scientific paper entitled Real-Time Optical Sensor Based on One Dimensional Photonic Crystals with Defects is presented at the International Conference on Information Communication Instrumentation and Biomedical Engineering (ICICI-BME) on 23 to 24 November 2009 in Bandung. Another article titled Experimental observation on In-gap Photonic band Pass-variation of One-dimensional photonic crystal with two defects in preparation for submission to Applied Optics Journal. Scientific works are part of the author’s master program.
# CONTENTS

| LIST OF FIGURES                          | ix |
| LIST OF TABLES                           | xi |
| LIST OF APPENDICES                       | xi |
| LIST OF PUBLICATION                     | xi |

I. INTRODUCTION

1.1. Background ..................................................... 1
1.2. Purpose of the Research ......................... 2
1.3. Scope of the Research .............................. 2

II. THEORETICAL BACKGROUND

2.1. Light Propagation in Photonic Crystal .......... 3
2.2. Modelling and Mathematical Formulation ........ 6
2.3. The Condition of Quarter Wave Stack ............ 7
2.4. Field Distribution inside the Defect Layer .... 8
2.5. Transmittance of the Photonic Pass Band in Defect Cell ...... 8
2.6. One-Dimensional of Photonic Crystal with Two Defects .... 9
2.7. Photonic Crystal Model for Optical Biosensor .......... 11
2.8. Sensor Device .............................................. 11

III. RESEARCH METHODOLOGY

3.1. Modeling and Simulation .............................. 13
3.2. Fabrication Process ..................................... 14
3.3. Optical Characterization ............................ 15
3.4. Devices Making ......................................... 15

IV. RESULT AND DISCUSSION

4.1. Numerical Simulation Results ..................... 17
4.2. Characterization and Sensing Test ............... 18
4.3. Designing and Making Sensor Devices .......... 19
4.4. Devices Performance Measurement ............... 21
4.5. Alternative Design .................................. 24
4.6. Design Optimization ................................. 28

V. CONCLUSION

5.1. Conclusion .................................................. 29
5.2. Future Work ............................................... 29

REFERENCES ......................................................... 30
APPENDICES .......................................................... 31
PUBLICATION ........................................................ 41
LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 2.1</td>
<td>Illustration of the Photonic Crystal Structure of Research</td>
<td>3</td>
</tr>
<tr>
<td>Figure 2.2</td>
<td>Field Distribution in the Defect inside the Photonic Crystal</td>
<td>8</td>
</tr>
<tr>
<td>Figure 2.3</td>
<td>Profile of PBG in the Photonic Crystal Structure (a). PBG for Photonic Crystal without Defect. (b) PPB that happens inside PBG for Photonic Crystal with Defect</td>
<td>9</td>
</tr>
<tr>
<td>Figure 2.4</td>
<td>Structures of One Dimension Photonic Crystal with Two Geometric Defects</td>
<td>9</td>
</tr>
<tr>
<td>Figure 2.5</td>
<td>Curve for One Dimension Photonic Crystal Transmittance with Two Geometric Defects. (a) Changes in the Regulator’s Defect Cause the PPB Shiftment. (b) Changes in Defect 2 (Receptor) Cause the Maximum Transmittance of PBB Decreased</td>
<td>10</td>
</tr>
<tr>
<td>Figure 2.6</td>
<td>The Relationship between Defect’s Refractive Index and the Transmittance of Photonic Pass Band that was Used for Refractive Index Sensor</td>
<td>10</td>
</tr>
<tr>
<td>Figure 2.7</td>
<td>One Dimension Photonic Crystal Model with M = 4, N = 6 and L =2</td>
<td>11</td>
</tr>
<tr>
<td>Figure 2.8</td>
<td>Illustration of the Sensor Device that is Photonic Crystal-Based to Detect a Solution’s Concentration</td>
<td>12</td>
</tr>
<tr>
<td>Figure 3.1</td>
<td>Design of Photonic Crystal Arrangement M + L = N</td>
<td>13</td>
</tr>
<tr>
<td>Figure 3.2</td>
<td>The Simulation of the Refractive Index Changes’ Effect in Defect-2 toward the Photonic Crystal Transmittance Changes</td>
<td>13</td>
</tr>
<tr>
<td>Figure 3.3</td>
<td>The Equipments that was Used for Fabrication of Photonic Crystal</td>
<td>14</td>
</tr>
<tr>
<td>Figure 3.4</td>
<td>Schematic Diagram for Characterization and Sensing Test</td>
<td>15</td>
</tr>
<tr>
<td>Figure 3.5</td>
<td>Illustration of devices of photonic crystal-based sensors for detecting the concentration of solution</td>
<td>16</td>
</tr>
<tr>
<td>Figure 4.1</td>
<td>(A) Transmittance Response (PPB) that were Influenced by Variations of Refractive Index in the Second Defect. (B) The Relationship between PPB Transmittance toward the Refractive Index</td>
<td>17</td>
</tr>
</tbody>
</table>
Figure 4.2. Profile of Field Intensity in the Photonic Crystal for the Configuration of 2-4-2 and 4-6-2 ................................................. 17

Figure 4.3. The equipment that used for optical characterization and sensing testing of photonic crystal ...................................................... 18

Figure 4.4. Measurement Results of the Optical Characterization and Sensing Test of Photonic Crystal .................................................. 19

Figure 4.5. The design size of the sensor devices ..................................... 19

Figure 4.6. Design of the sensor devices in three-dimensional illustrations ......................................................................................... 20

Figure 4.7. Sensor devices fabricated with the techniques of lathe ........... 20

Figure 4.8. Scheme for Device Performance Measurement ....................... 21

Figure 4.9. Electronic circuit for light source controlling and light intensity detecting ................................................................. 22

Figure 4.10. The Relationship between Light Intensity (Volt) and Sugar Solution Concentration (g/L) for Configuration 242 and 462 of the Photonic Crystal ........................................ 23

Figure 4.11. A Linear Regression Analysis for the Measurement Data with range of concentration : A. Between 20 and 100 g/L ; B. Between 100 and 200 g/L ...................................................... 23

Figure 4.12. Design of photonic crystal by using reflection method ........... 24

Figure 4.13. Illustration design sensor devices by using reflection method .............................................................................................. 25

Figure 4.14. The results of measurement of sugar solutions concentration by using reflection method. A. Range of Concentration 20 - 500 g/L, B. 20 -100 g/L, C. 100 - 500 g/L ......................................................................................... 26

Figure 4.15. Alternative design sensor devices for various applications ..................................................................................... 27

Figure 4.16. Reflection measurement of Substrate BK-7 before and after giving antireflection coating layer .................................................. 28
LIST OF APPENDICES

<table>
<thead>
<tr>
<th>Appendix</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appendix 1</td>
<td>Process Program</td>
<td>35</td>
</tr>
<tr>
<td>Appendix 2</td>
<td>2D Design of Transmission Device</td>
<td>36</td>
</tr>
<tr>
<td>Appendix 3</td>
<td>2D Design of Transmission Device (Detail)</td>
<td>37</td>
</tr>
<tr>
<td>Appendix 4</td>
<td>3D Design of Transmission Device</td>
<td>38</td>
</tr>
<tr>
<td>Appendix 5</td>
<td>2D Design of Reflection Device</td>
<td>39</td>
</tr>
<tr>
<td>Appendix 6</td>
<td>3D Design of Reflection Device</td>
<td>40</td>
</tr>
<tr>
<td>Appendix 7</td>
<td>2D Design of Drop System Device</td>
<td>41</td>
</tr>
<tr>
<td>Appendix 8</td>
<td>2D Design of Drop System Device (Detail)</td>
<td>42</td>
</tr>
<tr>
<td>Appendix 9</td>
<td>3D Design of Drop System Device</td>
<td>43</td>
</tr>
</tbody>
</table>

LIST OF PUBLICATION

<table>
<thead>
<tr>
<th>No</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1]</td>
<td>Design and Fabrication of One-Dimensional Photonic Crystal Based Optical Sensor</td>
<td>42</td>
</tr>
<tr>
<td>[3]</td>
<td>Real-Time Optical Sensor Based on One Dimensional Photonic Crystals with Defects</td>
<td>53</td>
</tr>
</tbody>
</table>
CHAPTER I

INTRODUCTION

1.1. Background

Photonics is a field of study that observes the interaction of light with the material that becomes the key of technology in the 21st century. The relationship between photonic and nanotechnology is relatively close. The photonic technology plays vital roles in the development of communication and information technology, lightning, manufacturing and life sciences. Photonics stimulates technology innovations and device production creativity. Moreover, photonic technology has influenced the development of data capacity in the telecommunication networks. This technology develops incredibly fast, and in order to maintain this condition, strong industries are needed. In order to develop this photonic technology, it needs many innovations, whether it is in theory or technology. In daily life, without realizing it, humans have taken the benefits of photonic, such as the usage of cell phones, CD, laser, and others. Therefore, it needs public relations to introduce this photonic field to the society.

Numerical studies toward one dimension of photonic crystal with two defects showed that the position of photonic pass-band (PPB) in the photonic band-gap (PBG) could vary with respect to the changes of refractive index and the geometrical thickness in both defects. Those two defects, furthermore, will be called regulator and receptor, each of them will show special function of its own. The effect of changing the regulator causes the changes in frequency or wavelength transmitted by EM waves that went through the photonic crystal. The effect of changing the receptor, however, can cause changes in peaks of the transmittances. Therefore, it will allow the development of a device that can manipulate the changes in the defect layer and utilize the response changes.

In this research, a design and fabrication of photonic crystal with the changes in the refractive index defect in the receptor layer will be studied, so that the changes in transmittance response will be enabled to happen. The variations in
this refractive index are conducted by making a defect from sugar solution with various concentrations. The purpose is to make the photonic crystal able to be used as a sensitive sensor for the varying concentration in the sugar solution. In accordance with this, an adequate device or measuring tool for this purpose will be built. The aim for this research is to create a measuring tool for sugar solution that is accurate, sensitive, and able to measure fast and real time.

1.2. Purpose of the Research

The purpose of this research is to design and fabricate a photonic crystal based sensor for sugar solution’s concentrations. In order to do the design, the Film Star Software is used to simulate the fabricated photonic crystal prior to fabrication. The photonic crystal is further synthesized by using electron beam evaporation method in nanometer order with a high standard precision optical process. The performance of sensing capability of photonic crystal is tested by using VIS-NIR spectroscopy method in a real time test mode.

1.3. Scope of the Research

This research includes several activities regarding the production of photonic crystal namely: theoretical simulation, fabrication, characterization, sensing test, design and instrumentation of the sensing device as well as its measurement performance.
CHAPTER II
THEORETICAL BACKGROUND

2.1. Light Propagation inside the Photonic Crystal

The first person that studies the one dimension photonic crystal is Lord Rayleigh in 1887. He showed that the light propagation depend on the forbidden angle for a certain range of frequency. Many optoelectronic devices use one dimension photonic crystal as a frequency filter or dielectric mirror. When the light hits the layer, each surface reflects a part of the field. If we choose the thickness of each layer for a suitable value, the reflected field will combine a constructive phase, producing constructive interference and strong reflectance called Bragg Reflection. It is shown that the Bragg Reflection in the periodical dielectric structure create a photonic band gap (PBG). When the periodicity destroyed by the present of defects in the photonic crystal, the localization of the defect mode will appear inside the PBG due to of the changes in light interference.

Figure 2.1. Illustration of the Photonic Crystal Structure
As discussed in the previous chapter, the search of the best way to control the light propagation always becomes the main priority. The main concern of this research focused on the interaction between the electromagnetic field with solid-like-structure photonic crystal. The Maxwell Equation is the first and definitely the most important one in this theory. The first step is to derive all the formula in the Maxwell Equation. The components in the electromagnetic wave, electric field and magnetic field will move through a medium that is load free and the free wave has been connected through 4 Maxwell Equation, as follows;

\[ \nabla \times \vec{B}(\vec{r},t) = -\frac{\partial}{\partial t} \vec{E}(\vec{r},t) \]  
\[ \nabla \times \vec{H}(\vec{r},t) = \frac{\partial}{\partial t} \vec{D}(\vec{r},t) + \vec{J}(\vec{r},t) \]  
\[ \nabla \cdot \vec{B}(\vec{r},t) = 0 \]  
\[ \nabla \cdot \vec{D}(\vec{r},t) = \rho(\vec{r},t) \]

The standard notation for electric field (\( \vec{E} \)), magnetic field (\( \vec{H} \)), electricity propagation (D), and magnetic induction (\( \vec{B} \)) have been used in this equation. Remembering again a certain identity from the vector arithmetic:

\[ \nabla \times \nabla \times (A) = \nabla (\nabla \cdot A) - \nabla^2 A \]  

and adjust it with the Maxwell Equation, where \( \nabla \cdot \mathbf{E}(r) = 0 \) and \( \mu(r) \approx 1 \)

\[ \nabla^2 \vec{E} = \mu_0 \varepsilon_0 \frac{\partial^2 \vec{E}}{\partial t^2} \]  
\[ \nabla^2 \vec{H} = \mu_0 \varepsilon_0 \frac{\partial^2 \vec{H}}{\partial t^2} \]

The equations are the equation of standard wave that has many solutions, one of which is the equation for an area with the shape of \( E = E_0 e^{i(k \cdot \vec{r} - \omega t)} \) and
\[ H = H_0 e^{j(\mathbf{k} \cdot \mathbf{r} - \omega t)} \], where the wave’s vector and frequency are shown by \( k \) and \( \omega \) simultaneously. Furthermore, the equation for wave produces:

\[
\frac{1}{\varepsilon(r)} \nabla \times [\nabla \times \mathbf{E}(r,t)] = \left( \frac{\omega}{c} \right)^2 \mathbf{E}(r,t)
\]

(8)

\[
\nabla \times \frac{1}{\varepsilon(r)} [\nabla \times \mathbf{H}(r,t)] = \left( \frac{\omega}{c} \right)^2 \mathbf{H}(r,t)
\]

(9)

The equations above usually called as master equation by the researchers in photonic crystal. Although it does not show something new from the perspective of the researchers, the test by using Schrodinger’s Eigen-value equation that is more familiar in the quantum mechanics has opened a new point of view. Object with mass \( m \) obey the Schrodinger equation, and its energy can be calculated through the corresponding equation. Therefore, the equation for electric field or magnetic field has an analogy with Schrodinger’s [4] wave equation.

One of the general solutions for equation (8) is monochromatic harmonic plain wave that depends on time \( \mathbf{E}(r,t) = E(r)e^{-i\omega t} \) that is reinserted into equation (9), producing EM wave in the frequency domain of

\[
(\nabla^2 + k^2)\mathbf{E}(r,\omega) = 0
\]

(10)

In the cartesian coordinate system, equation (10) reduced into three scalar equations for each electric field components \( E_z, E_x, \) and \( E_y \). This equation can be solved through separation of variables method. For the TE wave, electric field \( \mathbf{E} = (0, E_x, 0) \) is linearly polarized in the y direction and described in the form of scalar function \( E_y(z, y) \), so it produces:

\[
\overline{E}(z, y) = \bar{E}(z)e^{ik_yy}
\]

(11)

By using the same variable separation method, a general solution for harmonic plain wave is given as follows:
\[ \bar{E} = (A e^{i(k_z z - \omega t)} + B e^{-i(k_z z - \omega t)}) e^{ik_y} \]  
(12)

2.2. Modeling and Mathematical Formulation

Matrix method is the best way to perform an accurate analysis of the EM wave transmission in a layered medium. Generally, matrix formalism is used to relate electric field and magnetic field components in each layer [8]. We use the standard transfer matrix method to observe TE and TM wave’s transmittance.

The advantage of this transfer matrix method is that it gives the exact numeric solution from the model made and is relatively easier modified if the structure of the model needs to be changed. The field in the last layer of the photonic crystal for both refractive polarizations can be calculated from the following relation:

\[
\begin{pmatrix}
E_i / E_i \\
E_r / E_r
\end{pmatrix} = \tau_{TE(TM)} \begin{pmatrix} 1 \\
0
\end{pmatrix}
\]  
(13)

where \( E_i, E_r \) and \( E_t \) are electric fields that came, reflected, and transmitted and matrix:

\[
\tau = P_0^{-1}(Q_1 P_1^{-1}Q_2 P_2^{-1})^M(Q_1 P_1^{-1}Q_2 P_2^{-1})^N(Q_1 P_1^{-1}Q_2 P_2^{-1})^L
\]  
(14)

is a transfer matrix where matrix \( P_i \) and \( Q_i \) for TE and TM polarizations are given by:

\[
P_{iTE} = \begin{pmatrix}
1 & 1 \\
k_i \cos \theta_i & -k_i \cos \theta_i
\end{pmatrix}, \quad Q_{jTE} = \begin{pmatrix}
e^{ik_j d_j \cos \theta_j} & e^{-ik_j d_j \cos \theta_j} \\
k_j \cos \theta_j e^{ik_j d_j \cos \theta_j} & -k_j \cos \theta_j e^{-ik_j d_j \cos \theta_j}
\end{pmatrix}
\]

\[
P_{iTM} = \begin{pmatrix}
\cos \theta_i & \cos \theta_i \\
k_i & -k_i
\end{pmatrix}, \quad Q_{jTM} = \begin{pmatrix}
\cos \theta_j e^{ik_j d_j \cos \theta_j} & \cos \theta_j e^{-ik_j d_j \cos \theta_j} \\
k_j e^{ik_j d_j \cos \theta_j} & -k_j e^{-ik_j d_j \cos \theta_j}
\end{pmatrix}
\]  
(15)
with \( k_i = n_i \omega / c, \ i = 0, 1, 2 \) for fixed structures, meanwhile \( k_{d1} = n_{d1} \omega / c, \ k_{d2} = n_{d2} \omega / c \), are for defect layers, \( \theta_i \) shows the coming angle in each layer. The transmittance of the electric field is given below:

\[
T = \frac{|E_2|^2}{|E_1|^2}
\]  (16)

2.3. The Condition of Quarter-Wave Stack

The thickness of each medium layer (\( n_1 \) and \( n_2 \)) can be chosen to fulfill the quarter-wave stack condition, that is: \( d_1 = \frac{\lambda_o}{4n_1} \) and \( d_2 = \frac{\lambda_o}{4n_2} \), so both layers have the same optic length (\( n_1 d_1 = n_2 d_2 \)). Moreover, \( \lambda_o \) is called the operational wavelength and is the centre of the first PBG frequency that is formed (for \( m=1 \)), equation:

\[
m\lambda_o = 2n_{eff} L
\]  (17)

where \( n_{eff} \) is the effective refractive index that can be stated as:

\[
n_{eff} = \frac{n_1 d_1 + n_2 d_2}{L}
\]  (18)

and \( L \) is the crystal’s periods, which is \( d_1 + d_2 \), meanwhile \( \lambda_o \) is usually stated in a frequency form

\[
\omega_o = \frac{2 \pi c}{\lambda_o} = \frac{c \pi}{2n_1 d_1} = \frac{c \pi}{2n_2 d_2}
\]  (19)

and if it is compared with \( \omega_Bragg \), for \( n_1 d_1 = n_2 d_2 \) and \( n_{eff} \), and defined in equation (3), the Bragg frequency can be simplified into:

\[
\omega_{Bragg} = m \frac{c \pi}{2n_1 d_1} = m \frac{c \pi}{2n_2 d_2}
\]  (20)

so from the equation we can get

\[
\omega_{Bragg} = m \omega_o
\]  (21)

with \( m = 1, 3, 5, \) and so on, for the quarter-wave stack case.
2.4. Fields Distribution inside the Defect Layer

In the photonic crystal with imperfectly periodicity, there will be a resonance mode in the PBG range where EM wave frequency that exists is the same as the frequency of the imperfect mode of the crystal. The wave with the imperfect mode or frequency will be reflected simultaneously in harmony (back and forth) around the imperfect mode by DBR (distributed Bragg reflector) in the left and right sides of the imperfect layer that functioned as PBG mirror. This causes the photons to localize around the imperfects and cause high field enhancement. Field enhancement in the defect area leads to a full transmittance in the PBG in its resonance frequency, which is usually defect mode.

![Figure 2.2. Field Distribution in the Defect inside the Photonic Crystal](image)

The EM field’s profile which is propagating inside the photonic crystal layer can be described by using the transfer matrix method and by considering the translation’s symmetry. The solution for the EM field that comes in the z direction which is vertical with the crystal layer and move in layer $n_1$ and $n_2$ can be written as:

$$E(z) = A_i e^{i k_1 z} + B_i e^{-i k_1 z}$$  \hspace{1cm} (22)

$$E(z) = A_z e^{i k_2 (z-d)} + B_z e^{-i k_2 (z-d)}$$  \hspace{1cm} (23)

2.5. Transmittance of Photonic Pass Band in the Defect Cell

The effect of defects existence inside the photonic crystal leads to a resonance in the defect, causing a very large field with high transmittance. This
transmittance is known as Photonic Pass Band (PPB) that is located inside the PBG that should be a forbidden area for the periodic crystal structure. The existence of defect inside this photonic crystal is analog with the existence of impurity inside the material structure of a semiconductor.

Figure 2.3. Profile of PBG in the Photonic Crystal Structure (a) PBG for Photonic Crystal without Defect. (b) PPB that happens inside PBG for Photonic Crystal with Defect

2.6. One Dimension Photonic Crystal with Two Defects

One dimension photonic crystal with two defects has a more interesting phenomenon. The structure of one dimension photonic crystal with two geometric asymmetric defects is illustrated in the Figure 2.4. below:

Figure 2.4. Structures of One Dimension Photonic Crystal with Two Geometric Defects.
Figure 2.5. Curve for One Dimension Photonic Crystal Transmittance with Two Geometric Defects. (a) Changes in the Regulator’s Defect Cause the PPB Shiftment. (b) Changes in Defect 2 (Receptor) Cause the Maximum Transmittance of PBB Decreased (H. Alatas, 2006)

The structural different between the one dimensional photonic crystal with two asymmetric defects and one dimensional photonic crystal with one defect is that in the former structure, the refractive index in the left corner of the crystal is not the same with the refractive index in the right corner of the crystal. PPB that used to form in the photonic crystal with two asymmetric geometric defects has the same response toward the changes in defect width ($d_{D2}$).

Figure 2.6. The Relationship between Defect’s Refractive Index and the Transmittance of PPB that is Used for Refractive Index Sensor. (H. Alatas, 2006)
2.7. Photonic Crystal Model for Optical Biosensor

One dimensional Photonic crystal model that we made consists of a fixed layer of dielectric layer that criss-crossed along with two defect layers, they are: 

\[ n_0 n_s (n_1 / n_2)^M D_1 (n_1 / n_2)^N D_2 (n_1 / n_2)^L n_s n_0, \]

like the structure described in Figure 4.1.1. \( n_1 \) and \( n_2 \) showed the refractive index in the fixed layer \((n_1 / n_2)\) and its thickness is is marked by \((d_1 / d_2)\). Two defect layers were marked by \((D_1) \equiv (n_{d1} / n_2)\), and \((D_2) \equiv (n_{d2} / n_2)\) that were related with its thickness \((d_{d1} / d_2)\) and \((d_{d2} / d_2)\) simultaneously. The refractive index of the substrate and background medium are \( n_s \) and \( n_0 \) respectively.

![Figure 2.7. One Dimension Photonic Crystal Model with M = 4, N = 6 and L = 2.](image)

The total number of cell layers in the left side of \( D_1 \), between \( D_1 \) and \( D_2 \) also after \( D_2 \), is given by \( M, L, \) and \( N \), in orders. In the numerical studies, we assumed that the materials used have low capability to absorb the TM wave (low-loss media). The parameter used are given by \( n_0 = 1 \) (air), \( n_s = 1.52 \) (BK7), \( n_1 = 2.1 \) (OS-5), \( n_2 = 1.38 \) (MgF2) and the optical thickness fulfills the quarter wave stack condition: 525 nm. First defect of cell is made by \( d_{d1} = \lambda_d/2 \), whereas the second one is made empty space to insert the sugar solution as sensing material.

2.8. Sensor Device

In the last year, several applications of biosensor were already exist and based on the characteristics of transmission spectrum and reflection in the surface of the object. The Surface Plasmon Resonance (SPR) sensor has been used widely for screening the biochemistry interactions, while other researcher groups developed an optical biosensor based on Fabry-Ferot cavities in the porous
silicon or guided mode resonance reflectance filters. Other application used the optical resonance shiftment to test the DNA.

The unique characteristics of the PPB is that it is not only used as a filter but also can be developed as an optical sensor related to the function of defect, one of which is as a regulator and the other is as a receptor. A type of an optical sensor that can be developed is the refractive index sensor that can measure the substance concentration in a solution, such as sugar solution sensor or salt concentration. As an example, the refractive index of the sugar solution for a 30% concentration is 1.37, meanwhile for a 50% concentration, the refractive index is 1.42.

To develop a biosensor, a photonic crystal can be used so that it produces a narrow resonance mode where the wavelength is very sensitive toward the modulation that is inducted by the biochemistry material deposition in the defect layer. A structure of sensor consists of a transparent material that has low refractive index with the periodic surface structure coated with a thin layer that has high index.

Figure 2.8. Illustration of the Sensor Device that is Photonic Crystal-Based to Detect a Solution’s Concentration
CHAPTER III
RESEARCH METHODOLOGY

3.1.  Modeling and Simulation

Prior to the fabrication, we do a simulation by using FilmStar Software. Photonic Crystal for a pattern of \( N = 2, L = 4 \) and \( M = 2 \), with one defect as a fixed regulator and one defect change in the receptor. The refractive index of the material used is OS-5, with an refractive index 2.1, and also MgF\(_2\) with the refractive index of 1.38 - a product from Soltex Co. Ltd., each of which plays its role as a High Index and Low Index.

The Figure 3.1 below is the arrangement of photonic crystal design and the simulation results.

![Figure 3.1. Design of Photonic Crystal Arrangement M + L = N](image)

![Figure 3.2. The Simulation of the Refractive Index Changes’ Effect in Defect-2 toward the Photonic Crystal Transmittance Changes.](image)
3.2. Fabrication Process

After the simulation, the design is implemented in the coating machine for fabrication, which is conducted at PT. Nagata Opto Indonesia. This process is carried out by using electron beam evaporation method in the Optorun Generator-1300 machine. The pressure of the vacuum room $= 1.0 \times 10^{-3}$ Pa and the temperature $= 300 \, ^\circ\text{C} (573 \, \text{K})$.

Further, the coating process is performed in two steps. First, coating 22 layers from layer-1 until layer-22 before the second defect. In this first process, the first defect in layer-9 is already included. This process is implemented in substrate-1 that is in the form of glass BK-7 (refractive index = 1.52). Second, coating 5 layers from layer-28 until layer-24, meanwhile layer-23 is emptied to place the sugar solution that will be further analyzed. This process is implemented in substrate-2 that is also in form of glass BK-7 (refractive index = 1.52).

Figure 3.3. The Equipments that is Used for Fabrication of Photonic Crystal
3.3. Optical Characterization

Characterization is carried out by using the Spectrophotometer Olympus USPM method to test the compatibility of the fabrication result with the simulation result and by using Spectrophotometer UV-VIS Ocean Optics USB 1000 to measure the photonic crystal’s transmittance with the defect’s refractive index of the receptor. The following is the scheme for the implementation of the experiments where sample of sugar solution with the concentration of 20, 40, 60, 80 and 100 g/L is given in the defect.

![Figure 3.4. Schematic Diagram for Characterization and Sensing Test](image)

3.4. Device Realization

Device realization is conducted by considering several aspects, they are the photonic crystal design, selecting the light sources that will be used, selecting the photodetector, operational amplifier, and instrumentation system.

The design of the photonic crystal is based on simulation result and fabrication is targeted with the centre in PPB in the value of 525 nm by considering the light source that probably used based on the existing reference. The desired design is easily gotten through the simulation by using FilmStar Software, but in the fabrication process there had to be an arrangement of the machine condition so the desired value can be obtained. To ensure this, quality test is preformed as illustrated in Figure 3.5.

The selection of light source and detector is a real consideration related to the design of photonic crystal. The value of PPB amounting to 525 nm, is determined based on references that stated that the light source that will be used,
namely LED, had the wavelength of 525 nm as a specification. Similarly, detector is selected when one is going to detect photon that ranges of wavelength.

The purpose of making of operational amplifier is to enlarge the signal obtained by the detector, so the signal value that is measured can be detected by the voltmeter as an early measurement. So, the sensitivity test for the device can be electronically conducted. This test is advantageous for calibration and characterization of the device (See Figure 3.5).

Figure 3.5. Illustration of devices of photonic crystal-based sensors for detecting the concentration of solution
CHAPTER IV
RESULT AND DISCUSSION

4.1. Numeric Simulation Results

Numeric simulation is carried out by configuring the design of photonic crystal 462 and 242 as a comparison (see Figure 4.1). Such an action is to find the formation process of the PPB phenomenon predicted by previous publications and to show the influence of the number of photonic crystal cell units toward the sensitivity of the device that will be created, so it can give the description for the next development.

Figure 4.1. (A) Transmittance Response (PPB) that were Influenced by Variations of Refractive Index in the Second Defect. (B) The Relationship between PPB Transmittance toward the Refractive Index (TP Negara, 2009)

The existence of defect cause the field to localize around the defect, thus, there is an intensity enhancement in the defect layer. In Figure 4.2, a high
intensity in the defect layer enabled a field to go out of the defect layer and formed enhanced intensity of the new field in the next defect layer, depending on the system configuration and the refractive index value in each defect layers. For system 2-4-2, it seems that an enhancement of field in the first defect produced a new resonance in the second defect.

4.2. Characterization and Sensing Test

The optical characterization and sensing performance conducted to the fabricated photonic crystal by making a spacer with a distance of 2 mm to be filled with sugar solution inside the photonic crystal system before it is made in the form of optical sensor device. The measurement is carried out by using Ocean Optics Spectrophotometer UV Vis USB 2000. The sugar solution used in this test is made with the concentration of 20, 40, 60, 80 and 100 g/L. The measurement is carried out as shown in Figure 4.3 below:

Figure 4.3. The equipment that used for optical characterization and sensing testing of photonic crystal

The measurement result shown that there exist a PPB phenomenon in the PBG area that have a suitable operation wavelength as a design result from numeric studies. In addition, if the peak of the transmittance is plotted toward the concentration of the sugar solution, then the result will be quite linear as presented in Figure 4.4 below:
4.3. Design and Realization of the Sensor Devices

Before making the sensor devices is the design by using AutoCAD 2009 software. This step is performed to obtain a precision devices and has a standardized form that can be done if the mass production in time to come. Figure 4.5. below shows the complete two-dimensional image with a size devices that will be made.
To provide a clearer illustration in Figure 4.6. for the manufacture of sensor devices made complete three-dimensional design for all parts are required, making it easier manufacturing techniques.

![Figure 4.6. Design of the sensor devices in three-dimensional illustrations.](image)

By considering the above design, the sensor devices are made with material POM (Polyoxyethylene), a plastic material readily available on the market. But this material can be replaced by other materials in accordance with field conditions and the sensing material that will be measured. The following Figure 4.7. shows the results of sensor devices fabricated by using lathe techniques:

![Figure 4.7. Sensor devices fabricated with the techniques of lathe.](image)

This device will be used to test the sensor performance as a tool for the detection of the concentration of sugar solution.
4.4. Device Performance Measurement

The measuring technique is carried out by making a 500g/L of sugar solution as much as 100 mL, and then this solution is poured inside a goblet to be measured. This goblet is placed on top of a magnetic stirrer to ensure that the measurement of the sugar solution is in a homogen condition. The measurement for a lower concentration is conducted by adding into the solution in a certain amount until the solution’s concentration can be measured, and then the measurement can directly be conducted in the voltmeter screen. The recording of measuring results is performed when the solution can already be stated as homogen.

![Figure 4.8. Scheme for Device Performance Measurement](image)

From the measurement, the relationship curve between the light intensity measured by photodetector that is seen in the voltmeter (V) screen toward the concentration of the sugar solution (g/L) can be made. This measurement result showed the same phenomenon with the simulation result and sensing test in the early step of test, therefore, this result can be considered to be consistent.

The fabricated 1-D PC is in the form of a circular disk with a diameter of 10 mm. The device is constructed by setting a light source above the photonic crystal system and the photo detector below, so that light will pass through the photonic crystal before received by the photo detector. Sugar solution is inserted with a spacer interval of 1 - 2 mm which allow easy and continuous flow. The
lightening and light detection received by the photo detector is controlled by the electric circuit depicted in Fig. 4.9.

![Electronic circuit for light source controlling and light intensity detecting.](image)

From the electrical circuit in Figure 4.6, the intensity of the light source can be altered by using the variable resistor VR1, so that the required light for the LDR during detection can be adjusted. Meanwhile, the variable resistor VR2 can be applied for measurement system calibration as well as adjustment of the measurement value upon the reference solution. For the measurement stability a voltage follower in both measurement points and a signal amplifier in the form of differential operational amplifier are installed. Measurement is carried out using a simple voltmeter with amplification according to the following equation (24)

\[
V_{out} = -\frac{R_4}{R_3} (V_2 - V_1) \tag{24}
\]

where \(R_3 = R_5\) dan \(R_4 = R_6\).

The curve resulting from the measurement in Figure 4.10 shows that the design for photonic crystal with the configuration of 462 and 242 gives a respond that is a little bit different: visually we see that the steepness for configuration 462 is steeper compared to configuration 242. This shows that the desired result is more sensitive for more layers. Further analysis will be conducted by using linear regression analysis by dividing the linear part from each curve.
The results of these measurements are not linear, which is caused by electronic part and mechanism in electronic circuit system, so we can approach these curves by polynomial regression. These curves can be used to calculate measurement data for application in several fields. This calculation is easy for automatic digitalized or computerized measurement, but for simpler calculation we have to use a linear regression approach.

In order to conduct a linear regression analysis, the curve in Figure 4.10 is divided into two linear areas: the one with the concentration that ranges from 20 – 100 g/L and the other one with the concentration that ranges from 100 – 500 g/L. The result from the linear regression analysis can be seen in Figure 4.11A and 4.11B.
From Figure 4.11, the linear regression analysis results toward the photonic crystal configuration of 242, it is found that the sensitivity is 7.6 mV/(g/L) and the determination coefficient is 97.85% for the concentration 100 – 500 g/L. Meanwhile in the range of 20 – 100 g/L, it is found that the sensitivity is 3.2 mV/(g/L) and the determination coefficient is 93.35%.

For the photonic crystal with the configuration 462, it showed that the sensitivity is 8.2 mV/(g/L) with the determination coefficient of 98.50% for the concentration range of 100 – 500 g/L. Meanwhile, in the range of 20 – 100 g/L, the sensitivity of the photonic crystal is 3.5 mV/(g/L) with the determination coefficient of 93.46%.

If we compare the sensitivity value and the determination coefficient from each photonic crystal’s configuration, it can be stated that the configuration 462 is relatively better than configuration 242.

4.5. Alternative Design

In this study is conducted development of sensor mechanism to increase sensitivity factor of devices. If before the sensor is made by using light transmission, made possible by the reflection method in the hope of having a higher sensitivity because the light will pass through the photonic crystal system twice in the forward and backward direction.

This development requires the reflector at the end of the photonic crystal system. This is conducted by adding a layer 100 nm thick aluminum as reflector and an added layer MgF$_2$ as protector coating because aluminium layer is very easily scratches if it exposed.

Figure 4.12. Design of photonic crystal by using reflection method.
Because there are changes in measurement methods, the mathematical formulation used should be modified as the illustration shown in below equation:

\[
\begin{align*}
\begin{pmatrix}
E_i/E_t \\
E_r/E_t
\end{pmatrix}
&= \mathbf{T}^{-1} \begin{pmatrix}
1 \\
0
\end{pmatrix} \\
\begin{pmatrix}
E_i/E_t \\
E_r/E_t
\end{pmatrix}
&= \mathbf{T}^{-1} \begin{pmatrix}
0 \\
1
\end{pmatrix} \\
T &= \frac{|E_r|^2}{|E_t|^2} \\
R &= \frac{|E_r|^2}{|E_t|^2}
\end{align*}
\]  

(25)  

(26)

Then do the same thing in the design of the sensor devices. The following image shows the design tool in the form of two and three dimensions.

Figure 4.13. Illustration design sensor devices by using reflection method.
The advantage of sensor devices with a design method is a form of reflection that are simpler and smaller (compact) and can be used in the measurements with a high risk because this device does not include electronic devices in it, so secure in the measurement of flammable materials such as the measurement of alcohol levels, the octane in the fuel and others. Shortcomings, this device requires a tool with a Y junction fiber optic or a beam splitter to separate the light coming from the light source and reflected light that is detected by photodetector. However, it is still tolerable because for applications with a higher sensitivity level and the security level, so that is still competitive for specific applications, especially for the needs of industry.

The next testing sensor devices with reflection method to prove that this method has a higher sensitivity. Figure 4.14 below are the results of measurements by using the reflection method.

![Image](image_url)

**Figure 4.14.** The results of measurement of sugar solutions concentration by using reflection method. A. Range of Concentration 20 - 500 g/L, B. 20 -100 g/L, C. 100 - 500 g/L.
In Figure 4.14 A, we can see that the curve of measurement data is approached by polynomial regression. The result is not linear. This result is influenced by electronic circuit system and part that used in the apparatus. So, we can simplify calculation by using linear regression analysis. Here, we have to divide the curve become two linear region i.e. between 20 and 100 g/L and between 100 and 500 g/L, see in Figure 4.14A and 4.14B. This approach result sensitivity of sensor is 0.1138 %/(g/L) and determination coefficient is 98.45% for range of concentration between 20 and 100 g/L, and for range between 100 and 500 g/L, sensitivity of sensor is 0.0306%/(g/L) and coefficient determination is 97.09%.

If we compared the results of measurements data from transmission method and reflection method in Figure 4.4 and 4.14B, we can see that device with reflection method show better results. In the transmission method shown sensitivity from the gradient of linear regression curve of 0.0585% / (g / L), whereas the gradient method of reflection obtained linear regression curves of 0.1138% / (g / L). These results indicate that the sensitivity of the device with the reflection method has a greater sensitivity, almost double, if we compared with device with transmission method.

By utilizing these two measurement methods mentioned above, the transmission and reflection, made various forms of sensors for various measurement needs in the field. Following a successful sensor devices are made for each application required.

Figure 4.15. Alternative design sensor devices for various applications.
4.6. Design Optimization

Design optimization in the manufacture of optical sensors based on one-dimensional photonic crystal is to add antireflection coating on the glass substrate to anticipate a weakening of the light source will enter into the system of photonic crystal structures and light to be received by photodetector. The following figure is measured reflection curve glass substrate before and after the given antireflection layer.

Figure 4.16. Reflection measurement of Substrate BK-7 before and after giving antireflection coating layer.

From the picture above it is clear that the light reflected by the prior given range antireflection layer 4%, whereas after a given layer antireflection less than 0.5% in the wavelength interval from 450 to 700 nm. In the area sensor operating at 525 nm wavelength range from 0.06%. This means that the transmitted light from light source to the photonic crystal system reaches 99.94%.
CHAPTER V
CONCLUSION

5.1. Conclusion

This research shown that the prototype of one dimension photonic crystal with two defects could be implemented as optical sensor to measure a certain solution’s concentration. In this case, we used sugar solution with the concentration range from 20 - 500 g / L and the measured refractive index between 1.332 and 1.415 as a sample target. To analyze the result, we used the linear regression method. We divide the data into two linear areas: the first is the area with 20-100 g / L and, and second, the area with 100 - 500gr / L. The results shown that the determination coefficient could be reached up to 98%. Based on this fact, we are certain that this device can be used to measure the solution’s concentration in varieties of applications; for instance, to measure the water sanitation for the environment, blood sugar for medical field, sugar content in the beverage industries, and many others. This measurement can also be carried out by using the in situ and real time mechanism.

5.2. Future Work

This research is an initial step for the making of measurement tool with an adequate instrumentation. For the next step, we will develop an instrumentation that can be controlled by computer through a series of preludes.
REFERENCES


APPENDICES
## PROCESS PROGRAM

<table>
<thead>
<tr>
<th>Material Name</th>
<th>Control Type</th>
<th>Light Direction</th>
<th>Wavelength (nm)</th>
<th>Light Value</th>
<th>M/C No.</th>
<th>Peak No.</th>
<th>Film Index</th>
<th>FB GUN</th>
<th>Drawn Temperature</th>
<th>Pressure</th>
<th>APC Film</th>
<th>Time</th>
<th>Rate</th>
<th>Crystal Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>OS-5</td>
<td>Optical</td>
<td>-</td>
<td>590.00</td>
<td>1,1</td>
<td>26.00</td>
<td>66.37</td>
<td>66.37</td>
<td>2,123</td>
<td>229</td>
<td>535</td>
<td>1000</td>
<td>300</td>
<td>0.10E-02</td>
<td></td>
</tr>
<tr>
<td>MgF₂</td>
<td>Optical</td>
<td>-</td>
<td>590.00</td>
<td>2,2</td>
<td>20.00</td>
<td>46.57</td>
<td>46.57</td>
<td>2,129</td>
<td>229</td>
<td>239</td>
<td>1000</td>
<td>300</td>
<td>1.02E-02</td>
<td></td>
</tr>
<tr>
<td>OS-5</td>
<td>Optical</td>
<td>-</td>
<td>590.00</td>
<td>3,3</td>
<td>16.00</td>
<td>66.57</td>
<td>66.57</td>
<td>2,131</td>
<td>229</td>
<td>249</td>
<td>1000</td>
<td>300</td>
<td>1.02E-02</td>
<td></td>
</tr>
<tr>
<td>MgF₂</td>
<td>Optical</td>
<td>-</td>
<td>590.00</td>
<td>4,4</td>
<td>10.00</td>
<td>46.57</td>
<td>46.57</td>
<td>2,134</td>
<td>229</td>
<td>259</td>
<td>1000</td>
<td>300</td>
<td>1.02E-02</td>
<td></td>
</tr>
<tr>
<td>OS-5</td>
<td>Optical</td>
<td>-</td>
<td>590.00</td>
<td>5,5</td>
<td>6.00</td>
<td>66.57</td>
<td>66.57</td>
<td>2,135</td>
<td>229</td>
<td>269</td>
<td>1000</td>
<td>300</td>
<td>1.02E-02</td>
<td></td>
</tr>
<tr>
<td>MgF₂</td>
<td>Optical</td>
<td>-</td>
<td>590.00</td>
<td>6,6</td>
<td>3.00</td>
<td>66.57</td>
<td>66.57</td>
<td>2,136</td>
<td>229</td>
<td>279</td>
<td>1000</td>
<td>300</td>
<td>1.02E-02</td>
<td></td>
</tr>
<tr>
<td>OS-5</td>
<td>Optical</td>
<td>-</td>
<td>590.00</td>
<td>7,7</td>
<td>1.00</td>
<td>66.57</td>
<td>66.57</td>
<td>2,137</td>
<td>229</td>
<td>289</td>
<td>1000</td>
<td>300</td>
<td>1.02E-02</td>
<td></td>
</tr>
<tr>
<td>MgF₂</td>
<td>Optical</td>
<td>-</td>
<td>590.00</td>
<td>8,8</td>
<td>0.00</td>
<td>66.57</td>
<td>66.57</td>
<td>2,138</td>
<td>229</td>
<td>299</td>
<td>1000</td>
<td>300</td>
<td>1.02E-02</td>
<td></td>
</tr>
<tr>
<td>OS-5</td>
<td>Optical</td>
<td>-</td>
<td>590.00</td>
<td>9,9</td>
<td>0.00</td>
<td>66.57</td>
<td>66.57</td>
<td>2,139</td>
<td>229</td>
<td>309</td>
<td>1000</td>
<td>300</td>
<td>1.02E-02</td>
<td></td>
</tr>
<tr>
<td>MgF₂</td>
<td>Optical</td>
<td>-</td>
<td>590.00</td>
<td>10,10</td>
<td>0.00</td>
<td>66.57</td>
<td>66.57</td>
<td>2,140</td>
<td>229</td>
<td>319</td>
<td>1000</td>
<td>300</td>
<td>1.02E-02</td>
<td></td>
</tr>
<tr>
<td>OS-5</td>
<td>Optical</td>
<td>-</td>
<td>590.00</td>
<td>11,11</td>
<td>0.00</td>
<td>66.57</td>
<td>66.57</td>
<td>2,141</td>
<td>229</td>
<td>329</td>
<td>1000</td>
<td>300</td>
<td>1.02E-02</td>
<td></td>
</tr>
<tr>
<td>MgF₂</td>
<td>Optical</td>
<td>-</td>
<td>590.00</td>
<td>12,12</td>
<td>0.00</td>
<td>66.57</td>
<td>66.57</td>
<td>2,142</td>
<td>229</td>
<td>339</td>
<td>1000</td>
<td>300</td>
<td>1.02E-02</td>
<td></td>
</tr>
<tr>
<td>OS-5</td>
<td>Optical</td>
<td>-</td>
<td>590.00</td>
<td>13,13</td>
<td>0.00</td>
<td>66.57</td>
<td>66.57</td>
<td>2,143</td>
<td>229</td>
<td>349</td>
<td>1000</td>
<td>300</td>
<td>1.02E-02</td>
<td></td>
</tr>
<tr>
<td>MgF₂</td>
<td>Optical</td>
<td>-</td>
<td>590.00</td>
<td>14,14</td>
<td>0.00</td>
<td>66.57</td>
<td>66.57</td>
<td>2,144</td>
<td>229</td>
<td>359</td>
<td>1000</td>
<td>300</td>
<td>1.02E-02</td>
<td></td>
</tr>
<tr>
<td>OS-5</td>
<td>Optical</td>
<td>-</td>
<td>590.00</td>
<td>15,15</td>
<td>0.00</td>
<td>66.57</td>
<td>66.57</td>
<td>2,145</td>
<td>229</td>
<td>369</td>
<td>1000</td>
<td>300</td>
<td>1.02E-02</td>
<td></td>
</tr>
<tr>
<td>MgF₂</td>
<td>Optical</td>
<td>-</td>
<td>590.00</td>
<td>16,16</td>
<td>0.00</td>
<td>66.57</td>
<td>66.57</td>
<td>2,146</td>
<td>229</td>
<td>379</td>
<td>1000</td>
<td>300</td>
<td>1.02E-02</td>
<td></td>
</tr>
<tr>
<td>OS-5</td>
<td>Optical</td>
<td>-</td>
<td>590.00</td>
<td>17,17</td>
<td>0.00</td>
<td>66.57</td>
<td>66.57</td>
<td>2,147</td>
<td>229</td>
<td>389</td>
<td>1000</td>
<td>300</td>
<td>1.02E-02</td>
<td></td>
</tr>
<tr>
<td>MgF₂</td>
<td>Optical</td>
<td>-</td>
<td>590.00</td>
<td>18,18</td>
<td>0.00</td>
<td>66.57</td>
<td>66.57</td>
<td>2,148</td>
<td>229</td>
<td>399</td>
<td>1000</td>
<td>300</td>
<td>1.02E-02</td>
<td></td>
</tr>
<tr>
<td>OS-5</td>
<td>Optical</td>
<td>-</td>
<td>590.00</td>
<td>19,19</td>
<td>0.00</td>
<td>66.57</td>
<td>66.57</td>
<td>2,149</td>
<td>229</td>
<td>409</td>
<td>1000</td>
<td>300</td>
<td>1.02E-02</td>
<td></td>
</tr>
<tr>
<td>MgF₂</td>
<td>Optical</td>
<td>-</td>
<td>590.00</td>
<td>20,20</td>
<td>0.00</td>
<td>66.57</td>
<td>66.57</td>
<td>2,150</td>
<td>229</td>
<td>419</td>
<td>1000</td>
<td>300</td>
<td>1.02E-02</td>
<td></td>
</tr>
<tr>
<td>OS-5</td>
<td>Optical</td>
<td>-</td>
<td>590.00</td>
<td>21,21</td>
<td>0.00</td>
<td>66.57</td>
<td>66.57</td>
<td>2,151</td>
<td>229</td>
<td>429</td>
<td>1000</td>
<td>300</td>
<td>1.02E-02</td>
<td></td>
</tr>
<tr>
<td>MgF₂</td>
<td>Optical</td>
<td>-</td>
<td>590.00</td>
<td>22,22</td>
<td>0.00</td>
<td>66.57</td>
<td>66.57</td>
<td>2,152</td>
<td>229</td>
<td>439</td>
<td>1000</td>
<td>300</td>
<td>1.02E-02</td>
<td></td>
</tr>
</tbody>
</table>
Appendix 2: 2D Design of Transmission Device

<table>
<thead>
<tr>
<th>TITLE</th>
<th>MP2CIS T101</th>
<th>Material</th>
<th>Polyoxymethylene [POM]</th>
<th>Date</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>APPLIED PHYSICS DIVISION</td>
<td></td>
<td></td>
<td></td>
<td>25 May 09</td>
<td>Arief Mulyana</td>
</tr>
<tr>
<td>DEPARTMENT OF PHYSICS</td>
<td></td>
<td></td>
<td></td>
<td>25 May 09</td>
<td>M. Rahmat</td>
</tr>
<tr>
<td>BOGOR AGRICULTURAL UNIVERSITY</td>
<td></td>
<td></td>
<td></td>
<td>25 May 09</td>
<td>Husin Alatas</td>
</tr>
</tbody>
</table>
## Appendix 3: 2D Design of Transmission Device (Detail)

<table>
<thead>
<tr>
<th>TITLE</th>
<th>Material</th>
<th>Polyoxymethylene [POM]</th>
<th>Date</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>MP2CIS T101 (Detail)</td>
<td>Scale 2:1</td>
<td>Draw</td>
<td>25 May 09</td>
<td>Arief Mulyana</td>
</tr>
<tr>
<td></td>
<td>Qty</td>
<td>Checked</td>
<td>25 May 09</td>
<td>M. Rahmat</td>
</tr>
<tr>
<td></td>
<td>Unit</td>
<td>Revision 00</td>
<td>Approved</td>
<td>25 May 09</td>
</tr>
</tbody>
</table>
Appendix 4: 3D Design of Transmission Device

<table>
<thead>
<tr>
<th>TITLE</th>
<th>MP2CIS T101 (3D)</th>
<th>Material</th>
<th>Polyoxymethylene [POM]</th>
<th>Date</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>APPLIED PHYSICS DIVISION</td>
<td>Scale 2:1 Draw</td>
<td></td>
<td></td>
<td>25 May 09</td>
<td>Arief Mulyana</td>
</tr>
<tr>
<td>DEPARTMENT OF PHYSICS</td>
<td>Qty Checked</td>
<td></td>
<td></td>
<td>25 May 09</td>
<td>M. Rahmat</td>
</tr>
<tr>
<td>BOGOR AGRICULTURAL UNIVERSITY</td>
<td>Unit MM</td>
<td>Revision 00 Approved</td>
<td></td>
<td>25 May 09</td>
<td>Husin Alatas</td>
</tr>
</tbody>
</table>
Appendix 5 : 2D Design of Reflection Device
Appendix 6: 3D Design of Reflection Device

<table>
<thead>
<tr>
<th>TITLE</th>
<th>MP2CIS R101 (3D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Polyoxyymethylene [ POM]</td>
</tr>
<tr>
<td>APPLIED PHYSICS DIVISION</td>
<td>Scale 2 : 1 Draw</td>
</tr>
<tr>
<td>DEPARTMENT OF PHYSICS</td>
<td>Qty Checked</td>
</tr>
<tr>
<td>BOGOR AGRICULTURAL UNIVERSITY</td>
<td>Revision 00 Approved</td>
</tr>
</tbody>
</table>
Appendix 7: 2D Design of Drop System Device

<table>
<thead>
<tr>
<th>TITLE</th>
<th>SP2CIS T102</th>
<th>Material</th>
<th>Polyoxymethylene [POM]</th>
<th>Date</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>APPLIED PHYSICS DIVISION</td>
<td></td>
<td>Scale</td>
<td>2:1</td>
<td>Draw</td>
<td>Arief Mulyana</td>
</tr>
<tr>
<td>DEPARTMENT OF PHYSICS</td>
<td></td>
<td>Qty</td>
<td>Checked</td>
<td>25 May</td>
<td>M. Rahmat</td>
</tr>
<tr>
<td>BOGOR AGRICULTURAL UNIVERSITY</td>
<td></td>
<td>Unit:</td>
<td>MM</td>
<td>Approved</td>
<td>25 May</td>
</tr>
</tbody>
</table>
Appendix 8: 2D Design of Drop System Device (Detail)
**Design and Fabrication of One-Dimensional Photonic Crystal Based Optical Sensor**

**Abstract**

A previous theoretical study of a hole one-dimensional photonic crystal composed of 52 unit cells with two defects had shown the existence of Photonic Bands (PBBs) inside the stop band, which was suggested as a useful refractive index sensor due to the sensitive variation of PBBs with respect to the change of refractive index of defect layer material. We report in this presentation our experimental fabrication of photonic crystals in the form of a photonic crystal waveguide fabricated in a sample chamber at pressure of 1000 mbar. Each of the photonic cells was composed of a high index layer of GaAs with a thickness of 30 nm, and an equal thickness (20 nm) of MgO, with a refractive index of 1.526. The first cell was sandwiched by the defect layer, and the second, third, and fourth cells were the cladding layers. The deviation from the sample solution was found to be highly sensitive to changes in the refractive index of the defect layer material. The results were found to be in agreement with theoretical predictions reported elsewhere.

**Keywords:** photonic crystal, photonic band edge, refractive index sensor, real-time measurement.

**Experimental**

- Figure 1: Schematic diagram of the optical measurement setup.
- Figure 2: Characteristic transmission spectra of the photonic crystal waveguide.
- Figure 3: Dispersive plot of the measured transmission spectrum.
- Figure 4: Comparison of measured and calculated transmission spectra.

**Results**

- Figure 5: Photoluminescence spectrum of the photonic crystal waveguide.
- Figure 6: Time-resolved photoluminescence decay curve.

**Discussion**

This experiment demonstrated that a one-dimensional photonic crystal with two defects can be applied as an optical sensor for measuring the concentration of specific solvents. The results showed that the onset of solute concentration above a certain threshold can be achieved. Upon further investigation, it was found that this sensor can be used to monitor the concentration of different solvents in various applications, such as environmental monitoring, medical analysis, and industrial processes. The measurement can also be conducted on-site in real-time systems.

**Acknowledgment**

This research was supported by XYZ Research Grant.
DESAIN DAN FABRIKASI SENSOR REAL TIME BERBASIS KRISTAL FOTONIK SATU DIMENSI UNTUK DETEKSI KONSENRASI LARUTAN GULA

(Design and Fabrication of Real Time Optical Sensor based on One-Dimensional Photonic Crystal for Sugar Solution Concentration Detection)

M. Rahmat1,2, Teguh P.N.3, H. Alatas2, Irmansyah3

rahnmat32@gmail.com

ABSTRACT

A previous theoretical study of a finite one-dimensional photonic crystal composed of 12 unit cells with two defects had shown the existence of Photonic Pass Band (PPB) inside the Stop Band, which was suggested as a useful refractive index sensor due to the sensitive variation of PPB with respect to the change of refractive index of either defect layer material. We report in this presentation our successful fabrication of a prototype of this system by means of electron beam evaporation equipment in a sample chamber at pressure of 10^-6 Pa with BK-7 glass substrate at temperature 573 K. Each of the photonic cells is composed of a high index layer of OS-5 with refractive index of n = 2.10, and an equal thickness low index layer of MgF2 with n = 1.39. In the first defect cell, the high index layer has twice the thicknes of the other layers with the low index layer left unchanged, while in the second defect cell separated by 6 unit cells, the first layer is void to be filled with the sample solution. The device was used for measuring the refractive index of sugar solution with concentration range of 20-500 g/L in the real time mode. The result was found to achieve determination coeffient up to 98%. Further measurement performed has demonstrated a result in good agreement with theoretical prediction reported previously.

Keyword : photonic crystal, photonic pass band, sensor, solution concentration, real time

PENDAHULUAN


Studi numerik terhadap kristal fotonik satu dimensi dengan dua defek menunjukkan bahwa posisi photonic pass-band (PPB) pada photonic band-gap (PBG) dapat bervariasi dengan perubahan indeks bias dan ketebalan geometri pada kedua defek tersebut. Kedua defek tersebut selanjutnya disebut sebagai regulator dan reseptor yang masing-masing menunjukkan situs yang khas. Efek perubahan dari regulator menyebabkan perubahan frekuensi atau panjang gelombang yang ditransmisikan oleh gelombang EM yang melalui kristal fotonik tersebut. Efek perubahan dari reseptor...
mengakibatkan adanya perubahan nilai transmitansiya. Sehingga memungkinkan untuk mengembangkan suatu perangkat yang memanipulasi perubahan pada lapisan defek dan memanfaatkan respons perubahannya.

Dalam penelitian ini akan dipelajari suatu desain dan fabrikasi kristal fotonik dengan perubahan defek indeks bias pada lapisan reseptor, sehingga memungkinkan terjadinya perubahan respons transmisi. Perubahan indeks bias tersebut dilakukan dengan membuat defek berupa larutan gula dengan variasi konsentrasi. Tujuannya adalah agar kristal fotonik dapat digunakan sebagai sensor yang sensitif terhadap perubahan konsentrasi larutan gula. Untuk itu, akan dibangun suatu perangkat atau alat ukur yang memadai untuk tujuan tersebut. Harapan yang ingin dicapai dengan penelitian ini adalah suatu alat ukur larutan gula yang akurat, sensitif, dan dapat melakukan pengukuran dengan cepat dan dapat digunakan secara real time.

LANDASAN TEORI

**Konfigurasi Kristal Fotonik Satu Dimensi dengan Dua Defek**

Model kristal fotonik satu dimensi yang kami buat terdiri atas lapisan tetap dari lapisan dielektrik yang berselang-seling disertai dua lapisan defek, yakni: \( n_1 n_2 (n_3/ n_2)^{M} \) \( D_1 \) \( (n_1/ n_2)^{N} \) \( D_2 \) \( (n_1/ n_2)^{N} \) \( n_0 \) sebagaimana struktur yang dilustrasikan pada Gambar 1. \( n_1 \) dan \( n_2 \) menunjukkan indeks bias lapisan tetap \( (n_1/ n_2) \) dan ketebalannya yang ditandai dengan \( (d_1/ d_2) \). Dua lapisan defek ditandai oleh \( (D_1) = (n_{D_1}/ n_1) \), dan \( (D_2) = (n_{D_2}/ n_2) \) yang dihubungkan dengan ketebalannya \( (d_{D_1}/ d_2) \) dan \( (d_{D_2}/ d_2) \) secara berturut-turut. Indeks bias substrat dan medium background berturut-turut adalah \( n_3 \) dan \( n_0 \).

Jumlah lapisan sel disebelah kiri \( D_1 \), diantara \( D_1 \) dan \( D_2 \) juga setelah \( D_2 \), diberikan oleh \( M \), \( N \), dan \( L \), secara berturut-turut. Dalam studi numerik ini, kami mengasumsikan bahan yang digunakan memiliki absbsivitas yang rendah terhadap gelombang TM (low-loss media). Nilai parameter yang diberikan adalah sebagai berikut: \( n_0 = 1 \) (udara), \( n_2 = 1.52(\text{BK}_7) \), \( n_1 = 2.1(\text{OS-5}) \), \( n_2 = 1.38(\text{MgF}_2) \) dan ketebalan optik memenuhi kondisi quarter wave stack: 525 nm.

Tahap awal penelitian ini adalah dengan melakukan tinjauan teoritis terhadap konfigurasi kristal fotonik dengan dua dimensi sesuai hasil optimasi jika memenuhi kondisi \( N = M + L \). Desain dibuat dengan konfigurasi \( M = 4 \), \( N = 6 \) dan \( L = 2 \) yang terdiri atas defek-1 yang dibuat dari high index dengan ketebalan 2 kali sistem regular periodik, sedangkan defek-2 dikosongkan untuk diisi sample larutan gula dengan variasi konsentrasi, sebagaimana ditampilkan pada Gambar 1.
Gambar 1. Model kristal fotonik satu dimensi dengan \( M = 4, N = 6 \) dan \( L = 2 \).

Medan pada lapisan akhir fotonik kristal untuk kedua polarisasi bisa dihitung dari hubungan berikut:

\[
\begin{bmatrix}
\frac{E_x}{E_y} \\
\frac{E_y}{E_x}
\end{bmatrix} = T_{P(E)} \begin{bmatrix}
1 \\
0
\end{bmatrix}
\]

(1)

dimana \( E_x \) dan \( E_y \) adalah medan listrik yang datang, yang difraksikan, dan yang ditransmisikan, dan matriks:

\[
T = R^{-1} (Q_2 R_2^{-1} Q_1 R_1^{-1}) (Q_2 R_2^{-1} Q_1 R_1^{-1})^H (Q_2 R_2^{-1} Q_1 R_1^{-1}) (Q_2 R_2^{-1} Q_1 R_1^{-1})^H \]

(2)

adalah matriks transfer dengan matriks \( R_1 \) dan \( Q_1 \) untuk polarisasi TE dan TM dibentuk oleh:

\[
P_{TE} = \begin{bmatrix}
1 & 1 \\
\cos \delta & -\cos \delta
\end{bmatrix}, \quad Q_{TE} = \begin{bmatrix}
e^{i \lambda_1 \cos \delta} & e^{i \lambda_1 \cos \delta} \\
\cos \delta e^{i \lambda_1 \cos \delta} & -\cos \delta e^{i \lambda_1 \cos \delta}
\end{bmatrix}
\]

\[
P_{TM} = \begin{bmatrix}
\cos \delta & \cos \delta \\
\cos \delta & -\cos \delta
\end{bmatrix}, \quad Q_{TM} = \begin{bmatrix}
e^{i \lambda_1 \cos \delta} & e^{i \lambda_1 \cos \delta} \\
\cos \delta e^{i \lambda_1 \cos \delta} & -\cos \delta e^{i \lambda_1 \cos \delta}
\end{bmatrix}
\]

(3)

dengan \( \delta_i = n_i \omega \mu / c, \quad i = 0, 1, 2 \) untuk susunan tetap, sedangkan \( k_{d1} = n_d \omega \mu / c \), \( k_{d2} = n_d \omega \mu / c \) adalah untuk lapisan defekt, \( \theta_i \) menunjukkan sudut datang pada masing-masing layer. Transmisansi medan listrik diberikan sebagai berikut:

\[
T = \left| \frac{E_y}{E_x} \right|^2
\]

(4)

**Hasil Simulasi Numerik**

Simulasi numerik dilakukan dengan konfigurasi desain photonic crystal 462 dan 242 sebagai pembanding. Hal ini dilakukan untuk mengetahui pembentukan fenomena photonic pass band (PPB) yang telah diprediksikan oleh publikasi-publikasi sebelumnya juga memperhitungkan pengaruh jumlah unit sel photonic crystal terhadap sensitivitas device yang akan dibuat, sehingga dapat memberikan gambaran untuk pengembangan selanjutnya.
Gambar 2. (A) Respons transmittansi (PPB) yang dipengaruhi oleh variasi indeks bias pada defek kedua. (B) Hubungan antara transmittansi PPB terhadap indeks bias.

Gambar 3. Profill intensitas median dalam fotonik kristal untuk konfigurasi 2-4-2 dan 4-6-2

Adanya defek membuat median terlokalis disekitar defek sehingga terjadi peningkatan intensitas dalam lapisan defek. Intensitas yang tinggi pada lapisan defek memungkinkan adanya medan yang keluar dari lapisan defek tersebut dan dapat pula membentuk peningkatan intensitas median yang baru pada lapisan defek berikutnya, bergantung pada konfigurasi sistem dan nilai indeks bias pada masing-masing lapisan defek. Untuk sistem 2-4-2 terlihat adanya peningkatan median pada defek pertama dan menghasilkan kavitasi baru pada defek kedua yang merupakan karakteristik resonance state.

Sistemtika Sensor

Karakteristik unik pada photonic passband selain digunakan sebagai filter, juga dapat dikembangkan sebagai sensor optik terkait dengan fungsi defek salah satunya sebagai regulator dan yang lainnya sebagai reseptor. Sensor optik yang mungkin dapat dikembangkan adalah sensor indeks bias yang dapat mengukur konsentrasi zat dalam suatu larutan, misalnya sensor konsentrasi gula atau konsentrasi garam. Sebagai contoh, indeks bias larutan gula untuk konsentrasi 20 g/L adalah 1.332, sedangkan untuk konsentrasi 500 g/L indeks biasnya 1.415.

Untuk membentuk sebuah biosensor, kristal fotonik bisa dioptimasi hingga menghasilkan mode resonansi yang sangat sempit dimana panjang gelombang sangat sensitif terhadap modulasi yang terinduksi oleh depositon material biokimia pada lapisan defek. Sebuah struktur sensor terdiri atas material transparan yang memiliki indeks bias.
rendah dengan struktur permukaan periodik yang dicover dengan lapisan tipis berindeks bias tinggi.

Gambar 4. Ilustrasi divais sensor berbasis kristal fotonic untuk deteksi konsentrasi larutan

METODOLOGI

Pemodelan dan Simulasi

Sebelum dilakukan fabrikasi, terlebih dahulu dilakukan simulasi menggunakan Software FilmStar dan Metode Transfer Matriks. Photonic Crystal dibangun dengan konfigurasi \( N = 2, L = 4 \) dan \( M = 2 \), dan konfigurasi \( N = 4, L = 6 \) dan \( M = 2 \), dengan satu defek tetap sebagai regulator dan satu defek berubah pada reseptor. Indeks bias Material yang digunakan adalah OS-5 dengan indeks bias 2.1 dan MgF\(_2\) dengan indeks bias 1.38 produk dari Softex Co. Ltd., yang berperan masing-masing sebagai High Index dan Low Index.

Proses Fabrikasi

Setelah dilakukan simulasi, kemudian desain diterapkan pada mesin coating untuk proses fabrikasi, yang dilakukan di PT. Nagata Opto Indonesia. Proses ini dilakukan dengan metode electron beam evaporation pada Mesin Optorun Gener 1300. Tekanan ruang vakum = \( 1.0 \times 10^{-3} \) Pa dan temperatur = 300 °C.

Karakterisasi dan Uji Sensing

Karakterisasi dilakukan dengan menggunakan metode Spektrofotometer Olympus USPM untuk pengujuan kesesuaian hasil fabrikasi dengan hasil simulasi dan Spektrofotometer UV-VIS Ocean Optics USB 1000 untuk mengukur transmittansi kristal fotonik dengan defek indeks bias pada reseptor. Skema pelaksanaan eksperimen di mana sampel diberi perlakuan pada defek menggunakan larutan gula dengan konsentrasi 20, 40, 60, 80 dan 100 g/L dapat dilihat pada Gambar 6.

Pembuatan Divais Sensor

Pembuatan divais dilakukan dengan mempertimbangkan beberapa hal, yaitu desain kristal fotonik, pemilihan sumber cahaya (light sources) yang akan digunakan, pemilihan photodetector, operasional amplifier, dan sistem instrumentasi.
Pemilihan sumber cahaya dan detektor merupakan pertimbangan yang sangat berkaitan dengan desain kristal fotonik. Nilai PPB sebesar 525 nm ditentukan berdasarkan rujukan bahwa sumber cahaya yang akan digunakan yaitu LED Hijau memiliki spesifikasi panjang gelombang 525 nm. Demikian pula detektor dipilih jika mau mendeteksi foton dengan rentang panjang gelombang tersebut.

Pembuatan operasional amplifier untuk memperbesar sinyal yang didapatkan dari detektor, sehingga nilai sinyal terukur dapat dideteksi dengan voltimeter sebagai pengukuran awal. Sehingga dapat dilakukan pengujian sensitivas divais secara elektronik. Penguatan ini bermanfaat untuk melakukan kalibrasi dan karakterisasi devais. Sistem pencahayaan dan deteksi cahaya yang diterima oleh photodetector dikendalikan dengan rangkaian elektronika yang tampak pada Gambar 5 berikut ini:

Gambar 5. Rangkaian elektronika untuk pengatur sumber cahaya dan deteksi intensitas cahaya

Dari rangkaian elektronika di atas dapat kita perhatikan bahwa intensitas sumber cahaya dapat diatur dengan variabel resistor VR1, sehingga cahaya yang diperlukan oleh LDR saat deteksi dapat disesuaikan. Sedangkan variabel resistor VR2 digunakan untuk kalibrasi sistem pengukuran dan penyesaianan nilai pengukuran terhadap larutan referensi yang akan dijadikan acuan dalam pengukuran. Untuk stabilitas pengukuran diberikan voltage follower pada kedua titik pengukuran kemudian berikan penguat sinyal berupa differential operational amplifier. Pengukuran dilakukan dengan menggunakan voltimeter sederhana dengan pembesaran sesuai dengan persamaan berikut ini:

\[ V_{out} = -\frac{R_4}{R_3} (V_2 - V_1) \] (5)

Dimana \( R_3 = R_5 \) dan \( R_4 = R_6 \)
HASIL DAN PEMBAHASAN

Karakterisasi dan Uji Sensing

Pengujian karakteristik optik dan kinerja sensing dilakukan terhadap photonic crystal hasil fabrikasi sebelum dibuat dalam bentuk optical sensor device dengan membuat spacer berjarak 2 mm untuk diisi larutan gula dalam photonic crystal system. Pengukuran dilakukan menggunakan Ocean Optics Spectrophotometer UV Vis USB 2000. Larutan gula yang digunakan dalam pengujian ini dibuat dengan konsentrasi 20, 40, 60, 80 dan 100 g/L. Pengukuran dilakukan seperti yang diperlihatkan pada gambar 6 berikut ini:

Gambar 6. Skema untuk karakterisasi optik dan uji sensing kristal fotonik

Hasil pengukuran menunjukkan bahwa muncul fenomena photonic pass band pada daerah photonic band gap dengan panjang gelombang operasi yang sesuai dengan hasil desain studi numerik. Dan jika puncak transmisi diplot terhadap konsentrasi larutan gula maka didapatkan hasil yang cukup linier seperti yang ditampilkan pada Gambar 7 berikut ini:

Gambar 7. Hasil pengukuran karakterisasi optik dan uji sensing untuk kristal fotonik

Pengukuran Kinerja Alat

Teknik pengukuran dilakukan dengan cara membuat larutan gula 500g/L sebanyak 100 mL, kemudian larutan ini dimasukan dalam gelas piala untuk dilakukan pengukuran. Gelas piala ini ditempatkan di atas sebuah magnetic stirrer untuk memastikan pengukuran larutan gula dalam keadaan homogen. Pengukuran pada konsentrasi yang lebih rendah dilakukan dengan cara pengenceran atau menambahkan...
aquades ke dalam larutan dalam jumlah tertentu hingga konsentrasi larutan dapat dihitung, kemudian pengukuran dapat langsung dilakukan pada layar voltmeter. Pencatatan hasil pengukuran pada saat larutan sudah dapat dinyatakan homogen.

![Diagram](image)

**Figure 8. Skema untuk pengukuran kinerja divais**

Dari hasil pengukuran didapatkan kurva hubungan antara intensitas cahaya yang terukur oleh photodetector yang terlihat pada layar voltmeter (V) terhadap konsentrasi larutan gula (g/L). Hasil pengukuran ini menunjukkan fenomena yang sama dengan hasil simulasi dan uji sensing pada tahap awal pengujian, sehingga hasil ini bisa dikatakan konsisten.

Kurva hasil pengukuran yang terdapat pada Gambar 9, menunjukkan bahwa desain photonic crystal dengan konfigurasi 462 dan 242 memberikan respon yang sedikit berbeda, secara visual kita lihat bahwa kemiringan untuk konfigurasi 462 lebih curam dibandingkan konfigurasi 242. Hal ini menunjukkan hasil yang diharapkan lebih sensitif untuk jumlah layer yang lebih banyak analisis lebih lanjut kan dilakukan dengan analisis regresi linier dengan membagi bagian linier dari masing-masing kurva.

**Gambar 9. Hubungan antara intensitas cahaya (Volt) terhadap konsentrasi larutan gula (g/L) untuk konfigurasi kristal fotonic 242 dan 462**
Untuk analisis regresi linier kurva pada gambar 9 dibagi dalam dua daerah linier yaitu dari selang konsentrasi 20 – 100 g/L dan 100 – 500 g/L. Hasil dari analisis regresi linier dapat dilihat pada gambar 10A dan 10B.

![Grafik Uji Sensing Tipe 462 dan Tipe 242](image)

Figure 10. A. Analisis regresi linier untuk data pengukuran fotonik kristal dengan konfigurasi 242. B. Fotonik kristal konfigurasi 462.

Dari hasil analisis regresi linear terhadap konfigurasi photonic crystal dengan konfigurasi 242 didapatkan sensitivitas sebesar 7.6 mV/(g/L) dan koefisien determinasi 97.85% pada selang konsentrasi 100 – 500 g/L. Sedangkan pada selang 20 – 100 g/L didapatkan sensitivitas sebesar 3.2 mV/(g/L) dan koefisien determinasi 93.35%.

Untuk konfigurasi photonic crystal 462 menunjukkan sensitivitas sebesar 8.2 mV/(g/L) dengan koefisien determinasi sebesar 98.50% pada selang konsentrasi 100 – 500 g/L. Sedangkan pada selang konsentrasi 20 – 100 g/L menunjukkan sensitivitas photonic crystal sebesar 3.5 mV/(g/L) dengan koefisien determinasi sebesar 93.46%.

Jika membandingkan nilai sensitivitas dan koefisien determinasi dari masing-masing konfigurasi kristal fotonik di atas dapat dinyatakan bahwa konfigurasi 462 relatif lebih baik dibandingkan dengan konfigurasi 242.

**KESIMPULAN**

Penelitian ini menunjukkan bahwa kristal fotonik satu-dimensi dengan dua defek dapat diterapkan sebagai sensor optik untuk mengukur konsentrasi larutan tertentu. Dalam kasus ini kita menggunakan larutan gula dalam selang konsentrasi 20-500 g / L dengan indeks bias terukur antara 1,332 dan 1,415 sebagai target sampel. Untuk menganalisis hasil, kami menggunakan melode regresi linier. Kami membagi data dalam dua daerah linier, yaitu 20-100 g / L dan 100 - 500 gr / L. Hasilnya menunjukkan bahwa
koefisien determinasi dapat dicapai hingga 98%. Berdasarkan fakta ini, kami keyakinan bahwa perangkat ini dapat digunakan untuk mengukur konsentrasi larutan dalam berbagai aplikasi, misalnya untuk mengukur air sanitasi di bidang lingkungan, gula darah dalam bidang kedokteran, kandungan gula dalam industri minuman dan lain-lain. Pengukuran ini juga dapat dilakukan dengan digunakan dalam mekanisme in situ dan real time.

PROSPEK
Penelitian ini merupakan pendahuluan untuk pembuatan alat ukur dengan instrumentasi yang memadai. Selanjutnya akan dikembangkan instrumentasi yang dapat dikontrol oleh komputer melalui sebuah rangkaian antar muka.

UCAPAN TERIMA KASIH

DAFTAR PUSTAKA


Hasek, T. 2006. “Photonic crystals for fluid sensing in the subterahertz range”. American Institute of Physics. APPLIED PHYSICS LETTERS 89, 173508


Real-Time Optical Sensor Based on One Dimensional Photonic Crystals with Defects

M. Kusuma1,2, T.P. Nugraha1, H. Hardianto3,4, A. Santoso5, H. Alatas1
1Theoretical Physics Division, Department of Physics, Bogor Agricultural University
2Physics Division, Department of Physics, Bogor Agricultural University
3Applied Physics Division, Department of Physics, Bogor Agricultural University
N. Mercati, Kampus IPB Lebak Bulus, Bogor 16680, Indonesia
E-mail: abram@ipb.ac.id

Abstract — A previous theoretical study of a finite one-dimensional photonic crystal composed of Tl unit cells with two defects had shown the existence of Photonic Fano Resonance (PFR) inside the Gap Band, which was suggested as a novel refractive index sensor due to the negative variation of PFR with respect to the change of refractive index of defect layer material. We report in this presentation our successful fabrication of a prototype of this system by means of electron beam deposition equipment in a sample chamber at pressure of 1.35 Pa with BEEM-7 glow-discharge at temperature 573 K. Each of the photonic cells is composed of a high index layer of GeOx-Al with refractive index of n = 2.0, and an equal thickness of layers of MgF2, with n = 1.38. In the first defect cell, the high index layer has twice the thickness of the other layers with the layer index layer half exchanged, while in the second, defect cell is separated by 8 unit cells, and the third layer in void is filled with the sample solution. The device was used for measuring the refractive index of sugar solution with concentration range of 20-60 g in the real time mode. The result was found to achieve determination coefficients more than 90%. Further measurements performed have demonstrated a results in good agreement with theoretical predictions reported previously.

Keywords: photonic crystal, photonic pass band, refractive index sensor, sugar solution

I. INTRODUCTION

Photonic Crystals (PhC) in one, two and three dimension that consist of nano scale periodic dielectric media but attract attention in the last two decades due to its functionality that can be used as a waveguide, microcavity and sensor. The characteristics of PhC that able to block the flow of light simply by introducing defects on its structure is the basic physical mechanism responsible for that purpose. Specifically, the one dimensional (1-D) PhC in the form of stack optical grating system, which is actually the simplest structure of PhC, have also demonstrated can be applied for many practical applications such as optical filter as well as sensor. In the previous study, it has been shown that the introduction of material or structural defects could lead to the emission of the so called photonic pass band (PPB) that allows the existence of states inside the photonic band gap (FSD) of the corresponding 1-D PhC which is in the structure without defect forbids light to propagate.

The previous theoretical study have shown that for the case of 1-D PhC with two defects, the peak transmittance of PPB can be varied with respect to the refractive index change of one of the defects. This feature can thus be used for new sensing platform [1]. Physically, coupling between the two defect is responsible for this interesting characteristics. Recently, we have succeeded in fabricating the structure by means of electron beam evaporation method and the result showed a good agreement with theoretical prediction.

In this paper, we report our progress on making the optical sensor device based on on the 1-D PhC along with the instrumentation system. By measuring the concentration of sugar in sugar solution, the device shows its potential application as optical sensor.

II. THEORETICAL BACKGROUND

One dimensional photonic crystal with two defects configuration

The early step of this work was done by simulating the corresponding structure by means of the well known transfer matrix method (TMM). The structure considered, illustrated in Fig. 1, consists of two defect undulated by three regular grating with cell number M, N, L satisfying the condition M = M' + L. In the design considered we chosen defect made from high index material with its thickness twice the regular high index layer, while the second defect is left empty and to be filled with the sample solution.

![Fig. 1. Sketch of one dimensional photonic crystal with two defect for L = 4, M = 4, N = 2 configuration.](image-url)
Numerical Simulation by using Transfer Matrix Method

Further, base on the TMHM and assuming that the incoming light is incident from the left hand side, and that no reflector is present on right hand side of the grating, the relation between the incoming, reflected, transmitted fields $E_i, E_r$, and $E_t$, respectively, can be expressed by the following formula:

$$\left( \frac{E_i}{E_t} \right) = \mathbf{T}^{-1} \left( \frac{E_r}{E_t} \right)$$

where the corresponding over all transfer matrix $\mathbf{T}$ in Equation (1) is given by:

$$\mathbf{T} = \begin{bmatrix} 1 & 1 \\ \beta & -\beta \end{bmatrix} \begin{bmatrix} \exp(-i k a) & \exp(i k a) \\ 1 & -1 \end{bmatrix}$$

And the unit-cell transfer matrices are given by:

$$\mathbf{J} = \begin{bmatrix} 1 & 1 \\ \beta & -\beta \end{bmatrix} \begin{bmatrix} \exp(-i k a) & \exp(i k a) \\ 1 & -1 \end{bmatrix}$$

The transmittance of the system is then expressed as:

$$T = \frac{\left| E_t \right|^2}{\left| E_i \right|^2}$$

**III. Design of the Device**

For a sensor application, the photonic crystals can be optimized in order to produce a narrow resonance mode with a very sensitive response with respect to the modulation induced by the deposition of material on the biochemical defect layer. The sensor consists of a transparent material that has a periodic layered structure that coated by thin low and high refractive index materials.

The intensity of light coming from the light source through a photonic crystal system is then measured by the photo detector that translates the change of intensity into electric signal. The resulted electric signal is further amplified by the electronic circuits before the measurements are taken using a voltmeter. The results of voltage measurements are related to the change of the refractive index of the material defects. It is found that refractive index of solution is in line with its concentration. Therefore, the concentration of solution can be measured precisely by in situ and real time mode.

**IV. Experiments**

**Photonic crystal fabrication**

During the fabrication process, the 2D PC is deposited on a BK-7 glass substrate with a refractive index 1.52 by means of electron beam evaporation with pressure of 10⁻⁷ Torr at temperature of 573 K. The evaporation generates the electron beam using filament with electric current generated from JEOL JSM-10F EB Power Supply unit controlled by the JEOL.
CONTROLLER, whereas the vacuum condition is controlled by Vacuum Gauge Controller INXICON VGC 403 and Vacuum Chamber Controller INXICON VGC 500. On the other hand, the optical thickness is controlled by HUMID P Lamp Power Supply and HUMID D1 Data Processor for High Precision Optical Monitor, while for the physical thickness and the deposition speed we used crystallographic sensor of INXICON XTC-355 Deposition Controller.

The resulting fabricated 1.50 PC is in the form of a circular disk with a diameter of 10 mm. The device is constructed by mounting a light source above the photonic crystal system and the photo detector below, so that light will pass through the photonic crystal before reaching the photo detector. Sugar solution is injected with a spacer interval of 1.2 mm which allow easy and continuous flow. The lightening and light detection was made by the photo detector in controlled by the electronic circuit depicted in Fig. 5.

![Electrical circuit for light source controlling and light intensity detecting](image)

From the electrical circuit in Fig. 4, the intensity of the light source can be altered by using the variable resistor VR1, so that the intensity of light for the LED during detection can be adjusted. Meanwhile, the variable resistor VR2 can be applied for measurement system calibration as well as adjustment of the measurement value upon the reference solution. For the measurement stability a voltage follower in both measurement points and a signal amplifier in the form of differential operational amplifier are installed. Measurement is carried out using a simple voltmeter with amplification according to the following equation (3)

\[ I_{\text{out}} = -\frac{R_3}{R_2} I_{\text{in}} \]

where \( R_3 = R_2 \) dan \( R_4 = R_1 \)

**Optical Characterization and Sensing Test**

Optical characterization and sensing performance is performed on the photonic crystal from the fabrication process before manufactured in the form of optical sensor device using a spacer with interval of 2 mm for sugar solution filling inside the photonic crystal system. Measurement was conducted using the Ocean Optics Spectrophotometer UV Vis USH2000. The sugar solution that is prepared for the characterization are 20, 40, 60, 80 and 100 g/L. The schematic of optical characterization and sensing test for the photonic crystal is presented in Fig. 6.

![Schematic of optical characterization and sensing test for the photonic crystal](image)

**Measurement Result**

Measurement result shows that a photonic gap band inside the photonic band gap occur very similar with the theoretical calculations with an operational length that is also in agreement with numerical study (Fig. 7). If the transmittance peak is plotted on the sugar solution concentration, an approximate linear curve is obtained.

![Optical Characterization](image)

**Device Performance Measurement**

The device performance measurement is described in the schematic diagram in Fig. 8. The measurement is performed on two photonic crystal systems namely 462 which will be tested and 242 for comparison to show that there is an influence from the photonic crystal design. Measurement is performed upon changes in the sugar concentration for a 20 – 500 g/L range with a refractive index between 1.332 – 1.415. The refractive index is measured using Olympus USPH1M spectrophotometer.
The measurement technique is carried out by making a 500 
µl sugar solution of 100 Mm. The solution is then injected in a 
lab glass for measurement. The glass is then placed inside a magnetic stirrer to ensure that the sugar solution is 
homogeneous. Measurement in lower concentration is performed by adding aliquots into the solution in certain 
amount so that the solution concentration can be calculated and then result can be directly presented in the voltmeter display. The 
measurement is recorded when the solution is regarded homogeneous.

![Schematic Diagram for Device Performance Measurement](image)

Fig. 8. Schematic Diagram for Device Performance Measurement

**V. Results And Discussion**

Analysis is conducted to study the relationship between the 
light intensity displayed on the photo detector voltmeter (V) 
display versus the sugar solution concentration (x). The 
result is in very good agreement with the data from simulation 
and sensing test during the early stage of the testing process 
so that the results can be regarded as consistent.

![Intensity vs Concentration of Sugar Solution](image)

Fig. 9. Plot of Intensity light (V) vs concentration of sugar solution (x) at 
photonic configuration of 402 and 242.

The measurement curve in Fig. 9 shows that the photonic 
crystal that is designed with a configuration of 402 and 242 
gives slightly different results. Visually we see that the slope 
for the 402 PC configurations is steeper than for 242. The 
expected result is that the PC will be more sensitive for higher 
amount of sugar and then further analysis will be performed by 
linear regression analysis, namely by dividing the linear part 
of each curve.

Linear regression analysis on Fig. 9 is conducted by dividing 
the curve into two linear regions namely 20 - 100 µl and 100 
- 500 µl. The results are given in Fig. 10 and Fig. 11.

![Linear Regression Analysis](image)

Fig. 10. Plot of linear regression analysis from measurement data of 242 
configuration.

The analysis for 242 configuration shows that a sensitivity of 
7.6 mV/µl is obtained with a determination coefficient of 
97.35% within the 100 - 500 µl concentration region whereas 
a sensitivity of 3.2 mV/µl and determination coefficient of 
93.35% is obtained for the 20 - 100 µl linear region.

For the 462 photonic crystal region, the sensitivity is 8.2 
mV/µl with a determination coefficient of 98.50% within the 
100 - 500 µl region whereas for the 20 - 100 µl region, 
the photonic crystal has a sensitivity of 3.3 mV/µl and a 
determination coefficient of 93.46%.

Comparative study of the sensitivity and determination 
coefficient for each photonic crystal configuration shows that 
for this case the 462 PC configurations give better results than 
the 242 configuration.

**VI. Conclusion**

This experiment demonstrates that a one-dimensional photonic 
crystal with two defects can be applied as an optical sensor for 
measuring the concentration of sugar solutions. In this case 
we used sugar solution in range of concentration 20 - 500 µg/l 
with measured refractive indices between 1.332 and 1.443 as 
a target sample. To analyze the results, we used linear regression 
method. We split the data in two linear regions, i.e. 20 - 100 
µg/l and 100 - 500 µg/l. The result shows that the determination 
coefficient >90% can be achieved. Based on this fact, we are 
confidence that this device can be used to measure solution...
concentration in different applications, for example to measure water quality in environment, blood sugar in medical field, sugar content in beverage industries and so on. This measurement can also be conducted by using in situ and real time mechanism.

![Graph](image)

Fig. 11. Plot of linear regression analysis from measurement data of 462 concentration.

**VII. Future Work**

This research focuses on instrumentation design and fabrication. In the future a computerized controllable instrument will be developed for more practical use.

**Acknowledgment**

This research has been supported by "Penelitian Unggulan IPB" Grant under contract No. 891.3.24.4/SPK/BK/PS0/2009

**References**