



**AIN SHAMS UNIVERSITY**  
**FACULTY OF ENGINEERING**  
**Electronics Engineering and Electrical Communications**

# **Nanoantenna for Sensing Applications**

A Thesis submitted in partial fulfilment of the requirements of the degree of

Master of Science In Electrical Engineering

(Electronics Engineering and Electrical Communications )

*By*

**Ahmed Shaker Abdeen Hassanen**

Bachelor of Science In Electrical Engineering  
(Electronics Engineering and Electrical Communications )  
Faculty of Engineering, El-Shrouk Academy, 2012

*Supervised By*

**Prof. Diao Abdel-Maguid Khalil**

**Prof. Ahmed Mohamed Attiya**

**Assoc. Prof. Mohamed Abdel Azim Abdel Hamid Swillam**

**Cairo - (2020)**



AIN SHAMS UNIVERSITY  
FACULTY OF ENGINEERING  
Electronics and Communications

# Nanoantenna for Sensing Applications

*By*

**Ahmed Shaker Abdeen Hassanen**

Master of Science In Electrical Engineering  
(Electronics Engineering and Electrical Communications )  
Faculty of Engineering, Ain-Shams University, 200

## *Examiners' Committee*

| Name and Affiliation  | Signature |
|---|-----------|
| <b>Prof. Saber Helmy Zainud-Deen</b><br>Faculty of Electronic Engineering, Menoufia University,<br>Menouf, Egypt.                                       | .....     |
| <b>Prof. Amr Mohamed Ezzat Safwat</b><br>Electronics Engineering and Electrical Communications<br>Faculty of Engineering, Ain Shams University.         | .....     |
| <b>Prof. Diao Abdel-Maguid Mohamed Khalil</b><br>Electronics Engineering and Electrical Communications<br>Faculty of Engineering, Ain Shams University. | .....     |
| <b>Prof. Ahmed Mohamed Attiya</b><br>Microwave Engineering Department, Electronics Research<br>Institute (ERI), Cairo, Egypt.                           | .....     |

# Statement

This thesis is submitted as a partial fulfilment of Master of Science in Electrical Engineering, Faculty of Engineering, Ain shams University.

The author carried out the work included in this thesis, and no part of it has been submitted for a degree or a qualification at any other scientific entity.

**Student name**

**Ahmed Shaker Abdeen Hassanen**

**Signature**

.....

# Researcher Data

|                                     |  |
|-------------------------------------|--|
| <b>Name</b>                         | : Ahmed Shaker Abdeen Hassanen                         |
| <b>Date of birth</b>                | : 15 September 1990                                    |
| <b>Place of birth</b>               | : Sharkia Governorate                                  |
| <b>Last academic degree</b>         | : Bachelor of Science                                  |
| <b>Field of specialization</b>      | : Electronics and communication                        |
| <b>University issued the degree</b> | : El-Shrouk Academy                                    |
| <b>Date of issued degree</b>        | : July 2012  |
| <b>Current job</b>                  | : Research Assistant at Electronics Research Institute |

# Thesis Summary

This thesis studies optical antennas in the IR range. Optical antennas have been studied based on two sections. The first section is studying Silicon-on-Insulator (SOI) grating coupler for coupling the light between an optical fiber and a strip waveguide at operating wavelength 1550 nm based on the available techniques of fabrication. However, the grating coupler has a drawback in the method of coupling as it depends on the incident angle of the light. Therefore, the second section of the thesis solves the problem mentioned above by studying the nanoantenna for coupling and sensing. Nanoantennas can be used for coupling the light, and the incident light, in this case, is perpendicular to the nanoantenna structure. Furthermore, different nanoantenna arrays structures have been studied to be operated at near-infrared (IR) and mid-IR, paving the way to be used as a compact sensor for condensed phase analytes or biomedical enzymes with high efficiency.

Finally, this thesis suggests a design of highly doped semiconductor nanoantenna array operating in the Mid-IR, which can be used for sensing condensed phase analytes. These analytes work as biomarkers to detect the enzymes in the blood and work as a biomedical sensor.

The thesis is divided into five chapters, as listed below:

## **Chapter 1:**

This chapter introduces a summary of the other chapters starting with the IR range applications and then briefly discusses the optical properties of the IR range materials, including the plasmonic material and the plasmonic effect. It will then briefly discuss the optical waveguides concentrating on the SOI waveguides and Gap-SPP waveguide as it will be discussed in chapters 3 and 4, respectively. Then a brief discussion about the classification of nanocouplers is introduced. Finally, it presents detail for each chapter.

## **Chapter 2:**

This chapter starts with a review of the nanoantenna. Based on chapter one, it discusses nanoantennas applications as a coupler with nanophotonic waveguides at the near IR range. Also, it presents a grating coupler review to illustrate the literature designs for SOI grating coupler to couple the nanophotonic waveguide with an optical fiber. Furthermore, the nanoantenna arrays review is presented too. Then it briefly discusses a literature review about decreasing the gap distance of the nanoantenna array.

## **Chapter 3:**

This chapter discusses the methodology for designing SOI grating coupler for input and output coupling between the nanophotonic waveguide and an optical fiber at an operating wavelength based on the available techniques of fabrication. This type of coupling technique depends on the angle of the incident light. Hence, the coupling efficiency between the nanophotonic waveguide and the optical fiber is discussed in detail. FDTD simulations of the design are included to clarify each parameter's effect to obtain the maximum coupling efficiency. These parameters, like the grating period, the thickness of the nanophotonic waveguide, the inclination angle of the optical fiber, and the grating width.

## **Chapter 4:**

This chapter is starting with designing a simple structure of dipole nanoantenna coupled with a nanophotonic waveguide. Then, it discusses different structures of nanoantenna arrays in the near IR-range by using gold metal. Next, studying a modification on those structures to be used as an efficient sensor to detect a minimal change of the surrounding medium. Furthermore, sensitivity analysis is proposed for each design. The second section of this chapter discusses an efficient, highly doped germanium nanoantenna array, which can be used as a sensor for condensed phase analytes operated at the Mid-IR range. The

incident light in this design is perpendicular to the nanoantenna array. The sensing technique in the aforementioned structure depends on the reflection, which can be used as a biomedical sensor.

## **Chapter 5:**

This chapter summarizes the outline of the thesis and discusses the recommendations and suggestions in future work.

Keywords: Nanoantenna, Plasmonics, Semiconductor nanoantenna, Sensing, Grating Coupler, Silicon photonics, Doped Ge, SOI.

# Acknowledgment

First of all, I am deeply grateful to Allah. Coming from the gratification of my supervisors whom their contribution has raised the quality of this thesis. They have always supported me and have given me enthusiasm for science. They have patiently guided me.

I would like to express the most profound appreciation to my committee chair, **Prof. Diaa Khalil**, for his advice and guidance, which has always been a source of inspiration and encouragement throughout the work, without his encouragement and careful supervision, this thesis would never have taken shape. I gratefully acknowledge the support and guidance from my work Electronics Research Institute, most particularly **Prof. Ahmed Attyia**, for his support, guidance, encouragement, and patience that he was ever ready to give me during the whole period that took me to complete this work. I am also grateful to **Prof. Mohamed Swillam** for his advice and guidance, besides paving the way for me to learn nanophotonics design.

Furthermore, I most grateful to my best friend and beloved wife, **Esraa**, for being extremely supportive and unboundedly patient while I was working on finishing this work. I also would like to thank my little daughter, **Ayla**, for giving me unlimited happiness and pleasure. Finally, I feel indebted to my family members for their continuous support and encouragement, especially my **parents**.

November 2020



# LIST OF CONTENTS

| Title  | Page No.  |
|--|-----------|
| <b>LIST OF CONTENTS</b> .....                          | <b>i</b>  |
| <b>LIST OF TABLES</b> .....                            | <b>iv</b> |
| <b>LIST OF FIGURES</b> .....                           | <b>v</b>  |
| <b>LIST OF ABBREVIATIONS</b> .....                     | <b>xi</b> |
| <b>Chapter (1): Introduction</b> .....                 | <b>1</b>  |
| 1.1 Motivation .....                                   | 1         |
| 1.2 Applications of Infrared .....                     | 2         |
| 1.2.1 Optical and IR Sensors.....                      | 6         |
| 1.3. Optical properties of the materials in IR.....    | 8         |
| 1.4 Optical waveguides .....                           | 16        |
| 1.4.1 SOI platform.....                                | 17        |
| 1.4.2 Plasmonic waveguides .....                       | 19        |
| 1.5 Nano couplers.....                                 | 20        |
| 1.5.1 Classifications of Nanocouplers .....            | 23        |
| 1.6 Organization of the thesis: .....                  | 24        |
| <b>Chapter (2): IR couplers and Nanoantennas</b> ..... | <b>26</b> |
| 2.1 Introduction .....                                 | 26        |
| 2.2 Nanoantenna .....                                  | 27        |
| 2.1.1 Nanoantenna applications .....                   | 28        |
| 2.3 Nano dipole antenna as coupler .....               | 33        |
| 2.4 Plasmonic array of nanoantennas .....              | 38        |
| 2.5 Grating Coupler .....                              | 40        |

|  |           |
|--|-----------|
| 2.5.1 The Challenge of coupling between silicon<br>nanophotonics and optical fibers..... | 41        |
| 2.5.2 Different structures of SOI Grating couplers.....                                  | 43        |
| 2.6 Survey on nanoantenna applications.....  | 49        |
| <b>Chapter 3: Design and Analysis of Different Grating<br/>Couplers.....</b>             | <b>56</b> |
| 3.1 Introduction .....   | 56        |
| 3.2 Design parameters .....  | 58        |
| 3.3 Review Discussion .....  | 60        |
| 3.4 The Design methodology of a grating coupler .....                                    | 65        |
| 3.5 Analytical design of the grating coupler .....                                       | 67        |
| 3.6 2D-FDTD Grating Coupler.....   | 69        |
| 3.7 Compact grating coupler.....   | 78        |
| 3.7.1 Optimization of the results for different thicknesses                              | 80        |
| 3.7.2 S parameters - 2D.....   | 80        |
| 3.7.3 Increasing the coupling efficiency:.....   | 82        |
| 3.8 3D-FDTD Grating Coupler.....   | 83        |
| 3.8.1 Studying taper section .....   | 84        |
| 3.8.1.1 Theory of taper section .....  | 85        |
| 3.8.2 Results of the compact grating coupler.....  | 88        |
| <b>Chapter (4): Nanoantenna .....</b>  | <b>90</b> |
| 4.1 Introduction .....   | 90        |
| 4.2 Gap-SPP.....   | 90        |

|   |            |
|---|------------|
| 4.3 Designing Nanoantenna as a coupler with plasmonic gap<br>WG .....       | 92         |
| 4.4 Nanoantenna Array in NIR range.....                                     | 99         |
| 4.4.1 Nanoantenna structures at .....                                       | 99         |
| 4.4.1.1 Ellipse nanoantenna array .....                                     | 104        |
| 4.4.1.2 Rectangular nanoantenna array .....                                 | 106        |
| 4.4.1.3 Circular nanoantenna array .....                                    | 108        |
| 4.4.1.4 Bow-tie nanoantenna array .....                                     | 110        |
| 4.4.2 Nanoantenna structure at.....   | 112        |
| 4.5 Nanoantenna in Mid-IR range .....                                       | 115        |
| 4.5.1 Highly doped semiconductors.....                                      | 116        |
| 4.5.2 Ellipse nanoantenna array .....                                       | 117        |
| 4.5.3 Interaction between the proposed nanoantenna and<br>biomolecules..... | 119        |
| 4.6 Conclusion .....  | 120        |
| <b>Chapter 5: Conclusion and suggestions for future<br/>work .....</b>      | <b>122</b> |
| 5.1 Conclusions .....   | 122        |
| 5.2 Future Work .....   | 123        |
| <b>References .....</b>   | <b>125</b> |

# LIST OF TABLES

| Table No.          | Title  | Page No. |
|--------------------|--|----------|
| <b>Table (1-1)</b> | Parameters of metals according to the Drude model, where the operating frequency of the interband transition represented by $\omega_{int}$ ..... | 12       |
| <b>Table (3-1)</b> | The geometry parameters of the grating coupler.....  | 77       |
| <b>Table (3-2)</b> | Optimized design of the grating coupler for different thicknesses.....   | 80       |
| <b>Table (4-1)</b> | Ellipse dimensions.....  | 118      |

# LIST OF FIGURES

| Figure No. | Title  | Page No. |
|------------|--|----------|
| Fig.1. 1   | Electromagnetic spectrum & IR region .....   | 2        |
| Fig.1. 2   | IR spectroscopy regions .....  | 4        |
| Fig.1. 3   | Classification of optical detection.....   | 4        |
| Fig.1. 4   | The absorbance of different gases in the MIR range .....   | 7        |
| Fig.1. 5   | SOI wafer that is commonly used in CMOS electronics. ....  | 18       |
| Fig.1. 6   | Types of waveguides which are commonly used in silicon photonics. ....   | 19       |
| Fig.1. 7   | SPP wave propagates at the interface between metal and dielectric .....  | 19       |
| Fig.1. 8   | Simple illustration of nano coupler as a funnel .....  | 21       |
| Fig.1. 9   | Transferring the light from dielectric WG (left) to plasmonic WG (right) .....   | 22       |
| Fig.1. 10  | Classification of nanocouplers .....   | 24       |
| Fig.2.1.   | DC equivalent circuit of the thermal nanoantenna. ....   | 28       |
| Fig.2.2    | Nanoantenna for sensing .....  | 29       |
| Fig.2.3    | Nanoantenna for wireless communications .....  | 30       |
| Fig.2.4    | Simple overview of NSOM for scanning single fluorescent molecule and comparison between the near field measurements in the optical range compared to the MHz to GHz range..... | 32       |
| Fig.2.5    | Nonlinear nanoantenna for generating spontaneous photon pairs .....  | 33       |
| Fig.2.6    | Geometry of dipole nanoantenna. ....   | 35       |
| Fig.2.7    | Input impedance of dipole nanoantenna. ....  | 37       |
| Fig.2.8    | Different structures of nanoantennas arrays for sensing .....  | 39       |
| Fig.2.9.   | The fabrication process of an array of nanoantenna is based on top to bottom fabrication process .....   | 40       |
| Fig.2.10   | Coupling the light between two optical fibers using uniform SOI grating coupler. ....  | 41       |

|   |    |
|---|----|
| Fig.2.11 The coupling scale differences.....  | 42 |
| Fig.2.12 Geometry of (a) Uniform grating coupler, (b) Non-uniform grating coupler and (c) Modified uniform grating coupler .....  | 44 |
| Fig.2.13 Comparison between the coupling efficiency of uniform and non-uniform grating structures.....  | 45 |
| Fig.2.14 Geometry of anisotropic grating structure. ....  | 46 |
| Fig.2.15 Directivity of (a) Uniform grating coupler, (b) Anisotropic grating coupler.....   | 46 |
| Fig.2.16 Coupling efficiency of a directive grating coupler .....   | 46 |
| Fig.2.17 Schematic diagram of SOI blazed GC .....   | 47 |
| Fig.2.18 Schematic diagram of the Slanted SOI WG. ....  | 48 |
| Fig.2.19 The effect of the reflectivity angle versus the slanted angle.   | 48 |
| Fig.2.20 (a) Schematic diagram of the near field measurement as a rectangular hole with dimensions $a_x$ and $a_y$ punctured in a gold thin film that is deposited over the GaP crystal layer. (b) FDTD simulations at resonance frequency 0.2 THz and the dimensions of the rectangle $a_x = 10\mu\text{m}$ and $a_y = 300\mu\text{m}$ ..... | 49 |
| Fig.2.21 The schematic diagram of the photoresist nanoantenna structure.....  | 50 |
| Fig.2.22 Electric field for an element of bow-tie nanoantenna array.  | 51 |
| Fig.2.23 (a) Schematic diagram of nanoantenna array, (b) Scanning Electron Microscope (SEM) for the structure at the nanogap region at the QD resonance wavelength for $L=8\mu\text{m}$ , $h=60\text{nm}$ , $G_x=20\text{nm}$ , $G_y=14\mu\text{m}$ and $L=8\mu\text{m}$ .....  | 52 |
| Fig.2.24 (a) The effect of changing the dimension of nanoantenna array on the transmittance, (b) illustrated representation of single layer QDs covering the nanogap region. (c) SEM image of the nanogap area covered with QDs illustrates the distribution of the field above the sensing area, (d) magnified QD layer .....                | 53 |
| Fig.2.25 Schematic diagram of a single nanoslit antenna, which is illuminated by a focused THz beam. (b) Adding adhesive tape that polarizes the nanogap pattern.....   | 54 |
| Fig.2.26 NIR transmission of nanoslit array at different dimensions of the gap. The first Fabry-Perot resonance at gap = 20nm and   |    |

|   |    |
|---|----|
| 10nm, While at gap=5nm and 2nm, indicate the second-order Fabry-Perot resonance .....   | 54 |
| Fig.2.27 2D FEM simulation for single nanoslit (a) Red squares represent the measured field enhancement at $f=0.3\text{THz}$ versus the gap width, while the blue triangles represent the modeling filed enhancement. (b) The amplitude of the electric field at 2nm width nanogap slit and thickness of gold around 150nm. ....  | 55 |
| Fig. 3.1 (a) 3D diagram of the grating coupler, (b) Cross-section diagram of the grating coupler .....  | 57 |
| Fig. 3.2 Silicon-On-Insulator SOI wafer cross-sectional view .....  | 58 |
| Fig. 3.3 The output of the grating coupler. (a) When the grating period matches with the optical wavelength inside the grating. $\frac{\lambda_0}{n_{\text{eff}}} = \Lambda$ . Besides, the output in the vertical direction is the first diffraction order, while the back reflection is the second diffraction order. (b) When the incident wavelength is smaller than the $\Lambda$ grating period $\frac{\lambda_0}{n_{\text{eff}}} < \Lambda$ , vertical output at a detuned angle thus no second order back reflection. The input of the light comes from the left on the waveguide. As shown in (b) is the best for coupling, as there are not any back reflections..... | 61 |
| Fig. 3.4. Bragg condition of the grating coupler (one-dimensional periodic structure). (a) grating coupler's periodicity, (b) Describes the diffraction components of the diffracted wave, (c) calculating the matched angle with a diffracted wave when the surrounding medium is air, (d) Represents the diffraction into the substrate to be matched with incident angle.....  | 63 |
| Fig. 3.5 Structure of a grating coupler .....   | 67 |
| Fig. 3.6 2D grating coupler to couple the light with a slap WG (with thickness 50nm).....   | 68 |
| Fig. 3.7. 2D simulations of the grating coupler, simulate an optical fiber mode source to inject the light into the waveguide. ....   | 70 |
| Fig. 3.8. The electric field versus length when injecting slab mode source. ....  | 71 |
| Fig. 3.9. Electric field intensity as a function of the wavelength and incident angle. ....   | 72 |