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MODELING AND SIMULATION OF OPTICAL GRATING SYSTEMS

by

Adamu Yau Iliyasu

August 2014
Kayseri, Turkey

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By

Adamu Yau Iliyasu

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APPROVAL PAGE

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ABSTRACT

Grating coupler is an optical device which transfers beam of light energy into or out of an optical waveguide. This transfer of energy is as a result of proper pitch on top of the waveguide structure. The critical parameters that contribute to the performance of grating structures includes etching depth, grating period, fill factor and wavelength. Coupling light out from the waveguide is an important issue in photonics, and different methods have been proposed to improve the efficiency of the out coupling from waveguides. In this thesis, we proposed a design of a quantum well-laser grating coupler structure different from a traditional one. Reflection and the light coupling out of the structure are analyzed with different grating periods and wavelengths to meet the Bragg conditions. The simulation of the proposed structure has been optimized using cavity modeling framework CAMFR software by varying wavelength and grating period. The efficiency of the out coupled light has been improved by a factor of six compared to a traditional grating design.

Key words: Grating coupler, Quantum-well laser, CAMFR, Distributed Bragg reflectors

OPTİK IZGARA SİSTEMLERİNİN MODELLENMESİ VE SİMÜLASYONU

Adamu Yau Iliyasu

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ÖZ

Optik ızgaralar, ışın enerjisinin optik dalga kılavuzlarının içine veya dışına aktarılmasında kullanılan optik aygıtlardır. Enerjini transferi, dalga kılavuzunun yüzeyine yerleştirilen uygun ızgara dişleri ile gerçekleştirilir. Izgaralardan oluşan bu aktarım veya bağdaştırıcı sisteminin kritik parametreleri ızgara derinliği, ızgara periyodu, dolgu faktörü ve dalga boyudur. Fotonik sistemlerde ışığın yapıdan çıkarılarak başka bir yapıya aktarılması önemli bir problemdir ve bu aktarımdaki verimliliğin artırılması için çeşitli yöntemler önerilmiştir. Bu tez çalışmasında, geleneksel bir kuantum-kuyusu lazer yapısında farklı olarak, yeni bir yapı önerilmiştir. Yansıma ve yapıdan çıkarılan ışık, Bragg şartını sağlamak üzere farklı ızgara periyotları ve dalga boylarında analiz edilmiştir. Önerilen yapının optimizasyonunda dalga boyu ve ızgara periyotları değiştirilerek CAMFR yazılımı kullanılmıştır. Geleneksel bir ızgara tasarımına kıyasla, yapıdan çıkarılan ışığın miktarında altı kat iyileşme gözlenmiştir.

Anahtar kelimeler: Optik ızgara bağdaştırıcı, Kuantum-kuyusu lazer, CAMFR, Dağıtılmış Bragg yansıtıcılar

Dedicated to my;

Late father, Mal. Adamu Iliyasu,

And entire members of our family

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SYMBOL/ABBREVIATION

VCSELs	Vertical Cavity Surface Emitting Lasers
BPM	Beam Propagation Method
EEM	Eigenmode Expansion Method
PICs	Photonic Integrated Circuits
InP	Indium Phosphide
GaAs	Gallium Arsenide
LNO_3	Lithium Niobite
CMOS	Complementary Metal Oxide Semiconductor
TE	Transverse Electric Field
TM	Transverse Magnetic Field
Λ	Grating Period
λ	Wavelength
θ_i	Incident Angle
θ_0	Diffractive Angle
λ_B	Bragg Wavelength
λ_{DFB}	DFB Wavelength
m	Grating Order

n_{eff}	Effective Index
DBRs	Distributed Bragg Reflectors
λ_0	Center Wavelength
β	Propagation Constant
a_k	Amplitude of the Forward Propagation Mode
b_k	Amplitude of the Backward Propagation Mode
E_k	Electric Field Profile
H_k	Magnetic Field Profile
H^*	Conjugate of Magnetic Field
Re	Real part of Complex Number
PEC	Perfect Electric Conductor
PMC	Perfect Magnetic Conductor
PML	Perfect Matched Layer
CMT	Couple Mode Theory
θ_c	Coupling Angle
η	Efficiency
z_0	Longitudinal Position of Fiber above Grating Coupler
CAMFR	Cavity Modeling Framework
LED	Light Emitting Diode
N	Number of Modes in Series Expansio

CHAPTER 1

INTRODUCTION

1.1 INTEGRATED PHOTONICS

Photonics is a branch of technology which deals with research and development in optical systems used in high speed communications, due to its high speed. Optical systems have started over taken some electrical systems in telecommunications, biomedical systems and military systems. Grating coupler is one of the optical devices invented in 1970's. Grating coupler can be use in many systems like optical integration, optical amplification, coupling light etc. The primary function of grating coupler is coupling light to photonic waveguides such as optical fibers. One of the major achievements in technology in twentieth century is the implementation of integrated circuits (ICs). ICs maybe electronic or optical in nature. Optical ICs used in many optical technology systems like wavelength division multiplexing (WDM) optical amplifiers. Photonics integrated circuits (PICs) is operated in single or hybrid form. Hybrid PICs is a combination of many optical devices in one system. Nowadays almost all photonic devices are operating with hybrid integrated system. Figure 1.1 is the simple structure of optical integrated circuit [1]. There are some set back with the operation of hybrid system such as optical, thermal and mechanical properties of the material and also packaging of sub-microns thickness materials cause some difficulties in the design. Optical integrated circuit has great advantage over electrical integrated circuit like expanded bandwidth, low-cost, expanded frequency. The main disadvantage with integrated optic circuit is the high cost of fabricating new technology [1].

The term "integrated photonics" is considered as fabrication and integration of different photonic components on a common planar substrate such as beam splitter and grating couplers. This system relates the waveguide technology and other displines such as: optoelectronic, electrooptics and quantum electronics. Figure 1.2 shows the relationships between waveguide technology and other fields [2]. For a perfect integration of photonic circuit there is need to consider wavelength scaling structure with high index contrast. This index contrast can be improved by keeping the waveguide in single mode and make the dimensions small. For example the wide index contrast between silicon (3.46) and air (1.0) is considered in semiconductor design. For design and simulation of photonic crystal slab, 2D periodic structures are used and the third vertical direction is used for confinement of light in the structure [3].

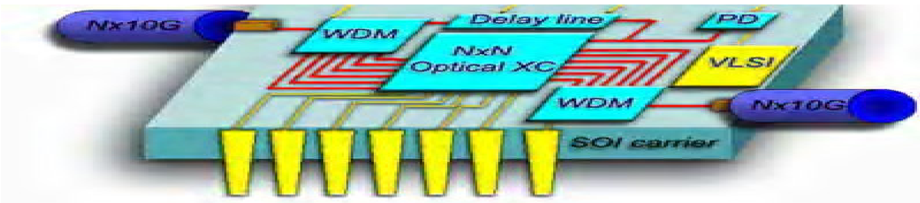


Figure 1.1 Optical Integrated Circuit [1]

Materials and substrates used in optical integrated circuit depend on the function of the circuit they are operating. The popular materials used in building optical component system include indium phosphide (InP), gallium arsenide (GaAs), lithium niobite ($LiNbO_3$), silicon (Si) and silica (SiO_2). Also materials are differ in terms their properties like refractive index, wavelength and area of application. Table 1.1 summarized the properties of some important material used in integrated circuit design.

Table 1.1 Optical component materials and their Properties

Chemical formulae	Refractive index	Operating wavelength (nm)	Active optical function	Passive optical function
InP	3.55	1310 or 1500	Modulation, detection, amplification	Switching, WDM
GaAs	3.15	1500	Local area network	-
$LiNbO_3$	2.1243	-	Optical modulation and mobile telephone	-
Si	3.42	1500	Optical and electronic integration	Array optical waveguide grating
SiO_2	1.5277	1500	-	Thermal protection, fiber

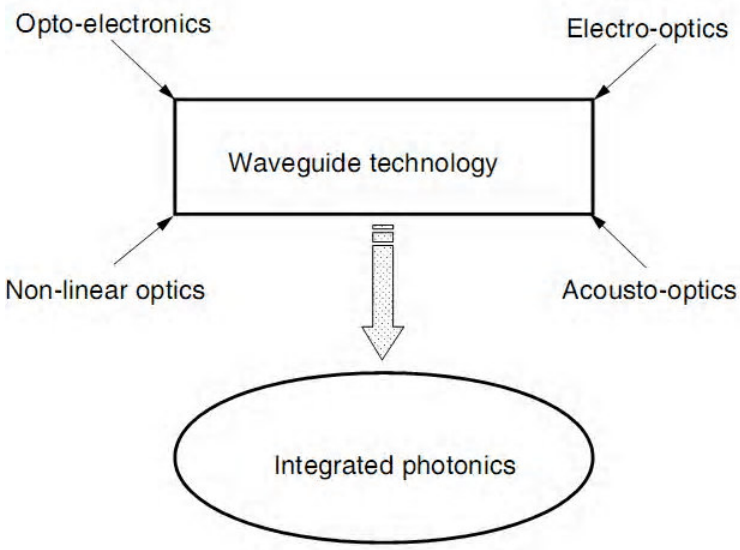


Figure 1.2 Integrated Photonics Chart [2]

1.2 MOTIVATION

The purpose of our research is to study and investigate the function of quantum–well laser structure and introduce a newly grating coupler for coupling light out from the grating structure to a photonic waveguide. A new grating coupler design has been proposed to improve the out coupling efficiency of the optical power of the structure which can be used to couple light from the waveguide into a fiber.

1.3 OPTICAL SIMULATION

Modeling and simulation of optical devices is a model that describes the overall optical behavior of complex optical structures like vertical cavity surface emitting lasers VCSELs and devices that incorporate crystals. For a long period of time simulation has been used as a toll for optical design to simulate problem that is not easy to solve in a laboratory [4]. Optical simulation can be use in different types of applications such as lens design, thin film design and physical optics simulation. Several methods can be applied for modeling optical devices, example beam propagation method (BPM), finite difference time domain (FDTD), and eigenmode expansion method (EEM) etc. In general simulation comprises of three steps: specification, evaluation and optimization. Specification includes, properties of the optical system example (field and focal length) while evaluation is a process of measuring the required specification and design is lastly modified to optimized its performance [4]. Many academic and commercial software are available for optical simulation, such as CAMFR, FIMPROP, FIMWAVE. Figure 1.3 is an example of a photonic crystal splitter which can be simulated with CAMFR and provide similar result in figure 1.4 to indicate behavior of electromagnetic wave in the structure.

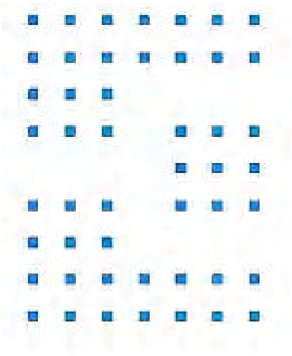


Figure 1.3 Photonic Crystal Splitter [5]

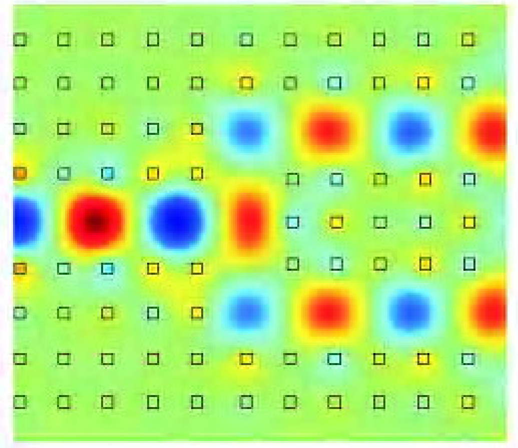


Figure 1.4 3dB Splitter in Index-guided Fiber [5]

1.4 OUTLINE OF THE THESIS

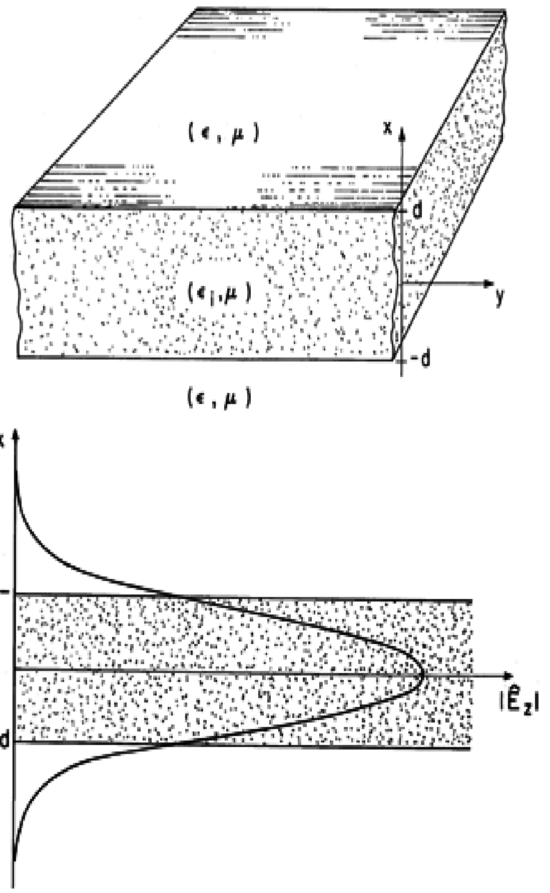
Chapter one has an introduction to integrated optics, motivation, optical simulations and outline of the thesis. In chapter two, we discuss about optical waveguides, optical grating systems, single frequency of semiconductor lasers, grating couplers, eigenmode expansion method and boundary conditions. Chapter three contents the discussion about the simulation software (CAMFR) and simulation. Chapter four discusses the simulation of a quantum–well structure and our proposed structure for obtaining second Bragg conditions. Chapter five covers the optimization of design parameters and simulation of quantum–well structure and the proposed. Finally, chapter six concludes and discusses the future work.

CHAPTER 2

BACKGROUND

2.1 OPTICAL WAVEGUIDES

Optical waveguide is a structure in which the propagation of light along the waveguide can be described in terms of a set of guided electromagnetic waves called modes of a waveguide. Each mode has it specific propagation constant. If periodic of perturbation is applied along the side of the waveguide mode, the mode has the ability to exchange it power, this phenomena is known as coupling. Typical waveguide consists of three main layers, core layer, substrate layer and cladding layer. The refractive index of the core has to be greater than refractive index of substrate and cladding for a light to be properly guided [6]. Figure 2.1 (a) shows the dielectric waveguide of thickness 2d and permittivity ε_1 surrounded by a dielectric of permittivity $\varepsilon < \varepsilon_1$ and (b) shows the transverse field for TE_0 mode on dielectric waveguide.



(a) (b)

Figure 2.1 (a) Dielectric Slab Waveguide, (b) Field Distribution of the Fundamental Mode [7]

Optical waveguides can be a 2D or 3D depending on the modes of operation. 2D optical waveguide is a waveguide in which light confinement occur as result of refractive index variation of the material that made up the structure along x-direction while in 3D optical waveguide the variation is always taken place in both x-direction and y-direction. The guided mode in optical waveguide maybe transverse electric (TE) or transverse magnetic (TM), this is because the waves propagates always along the single direction in a waveguide and also electric and magnetic field are always perpendicular to each other [8].

2.2 OPTICAL GRATINGS

Optical grating is a periodic structure with finite number of rectangular (sinusoidal, triangular) grating teeth at the top layer of the structure with the ability of collection of reflecting or transmitting light separated by a distance comparable to the wavelength . If the light is fed to the grating structure the diffraction takes place depending on the incident angle. This diffraction maybe zero order, first order, second order up to nth order diffraction. Optical grating can be of different types: transmission amplitude grating, (phase grating), reflection grating and (blazed grating) [9]. The operation principle is based on the interaction between normal incidents light on the structure with subwavelength. The transmitted light that passed through the grating can be varied by adjusting the shape and size of the grating structure. If the grating period is lower than the operating wavelength, all the diffracted optical energy of the incident light will enter zero order and cancel all high order diffraction. Figure 2.2 is diffraction grating structure describing the grating normal, incident light, reflected light and diffracted light with grating period d [10]. Figure 2.3 shows an example of grating structure with some physical parameters [11]. The Bragg equation in relation to the diffraction angle and grating period is express as

$$\Lambda \sin\theta_d = m\lambda \tag{2.6}$$

where Λ is the grating period

θ_d is the diffraction angle

m is the grating order and

λ is the wavelength

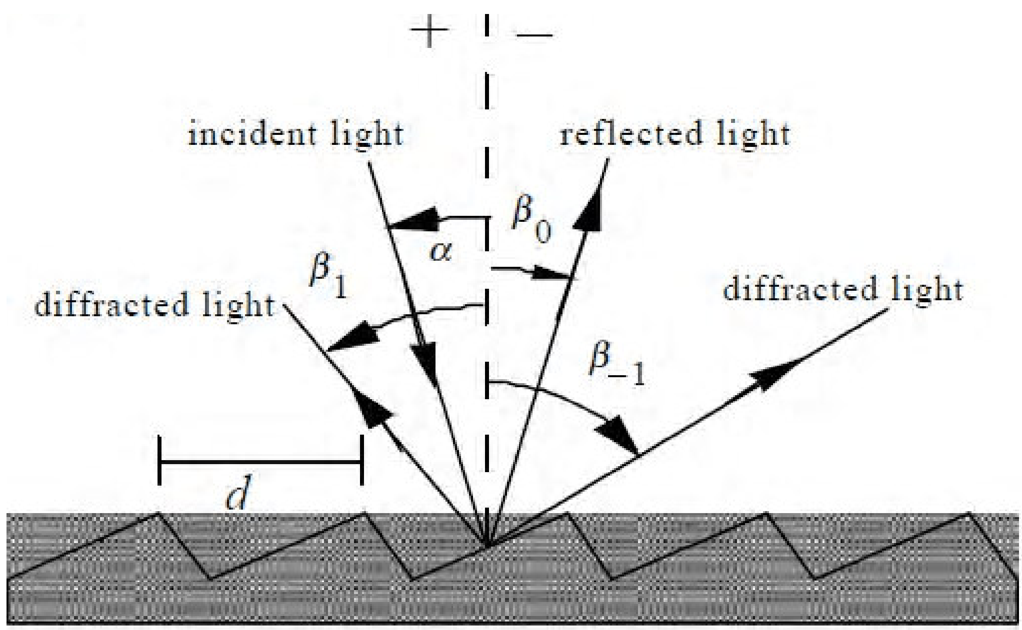


Figure 2.2 Diffraction Grating with Parameters [10]

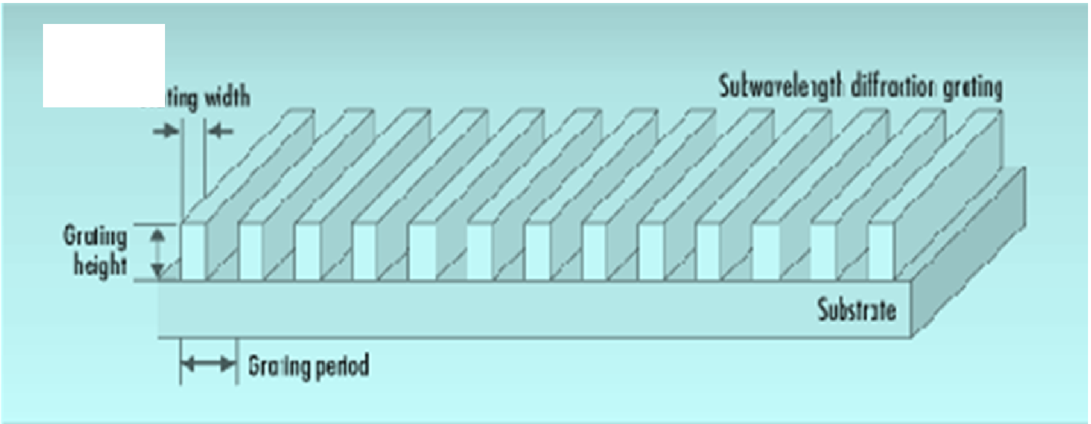


Figure 2.3 Subwavelength Grating Structure [11]

2.3 SINGLE FREQUENCY SEMICONDUCTORS LASERS

In an ideal condition lasers are operated only in single mode form to produce narrow output spectrum. This is achieved by using frequency selective dielectric mirror at the cleaved surface of the semiconductor in order to get cleaned output spectrum in single mode. We have many of them like distributed Bragg reflector (DBR), and distributed feedback (DFB) [12].

2.3.1 Distributed Bragg Reflectors (DBRs)

Distributed Bragg reflectors are waveguide structures that made from materials with different refractive index and consist of corrugated section in on e end whereby partial reflection of the wave interfere constructively to give reflected wave when wavelength is double the corrugation period. The Operation principles of DBRs is base on the coupling between forward and backward propagating field of the same mode in the grating waveguide [12], this process is shown in figure 2.4 [13], where the two waves can only interfere when corrugating period is multiple of wavelength, but for any wavelength in which the constructive interference occurred apart from the one mention above, that wavelength is called Bragg wavelength. If the two waves satisfied the phase condition so the Bragg law can be express as:

$$m\frac{\lambda_B}{n} = 2\Lambda \tag{2.7}$$

where m is the order of coupling

Λ is the grating period

λ_B is the Bragg wavelength

n is the refractive index

The condition necessary for achieving coupling in DBRs is the phase differences between the waves. If we assume the two waves to be M and Y the phase constant between the waves will be β_M and $-\beta_Y$ respectively, the phase difference between the two waves can be express as

$$\Delta\beta = \beta_M - \beta_Y \qquad (2.8)$$

If we assume the phase differences as $-\beta_M = \beta_Y = \beta$, therefore the phase difference will become

$$\Delta\beta = -2\beta \qquad (2.9)$$

And the phase mismatch condition between the two waves will be express as:

$$2\delta = -2\beta + mK \qquad (2.10)$$

The phase matching condition between the two waves will be satisfied when $2\delta = 0$. Then equation (2.10) becomes

$$\beta = \frac{mK}{2} \qquad (2.11)$$

Finally the grating period required to satisfies this phase matching condition between the waves is

$$\Lambda = \frac{m\pi}{\beta_B} \qquad (2.12)$$

where K is the coupling coefficient

$\Delta\beta$ is the change in phase constant

2δ is phase mismatch condition

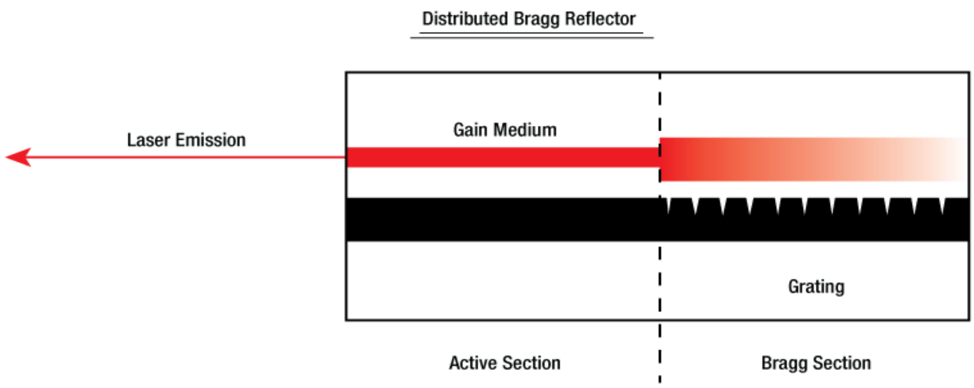


Figure 2.4 DBR laser principles [13]

2.3.2 Distributed Feedback (DFB)

Distributed feedback is a type laser structure which radiation is applied from the active region to the guiding layer along the whole cavity length in order to obtain optical gain. DFB provide an optical feedback to build up photons when radiation from the active layer spread to guiding layer. The principles of operation is different because here the radiation is fed from the active layer will be manipulate and fed to the guiding layer along the whole cavity length so that corrugated medium will produce optical gain and constructive interference occurred at wavelength almost equal to the Bragg wavelength. In a typical DFB structure the wave from the left direction moving in guiding layer experience partial reflections, this reflected wave are optically amplified by the medium to form the two waves which interfere or coupled at certain point and form standing wave [12]. This collision between left and right will only coherently coupled if their frequency is related to the corrugation period and the medium will change the wavelength which is differ from Bragg wavelength but they are symmetrically place about. The relationship between DFB wavelength and Bragg wavelength will be express as:

$$\lambda_{DFB} = \lambda_P + \frac{\lambda}{2nL} \tag{2.13}$$

where n is the effective index of the mode

L is the effective length of the diffraction grating

λ_{DFB} is the DFB wavelength

The two modes that separated with equal length within the range of Bragg wavelength which exist in a perfectly symmetry device as shown in figure 2.5 but in reality due to fabrication or a target goals, a symmetry is introduce and eliminate one of the two modes and leaves only one which lead to expression as:

$$m\frac{\lambda_B}{n} = 2\Lambda \qquad (2.14)$$

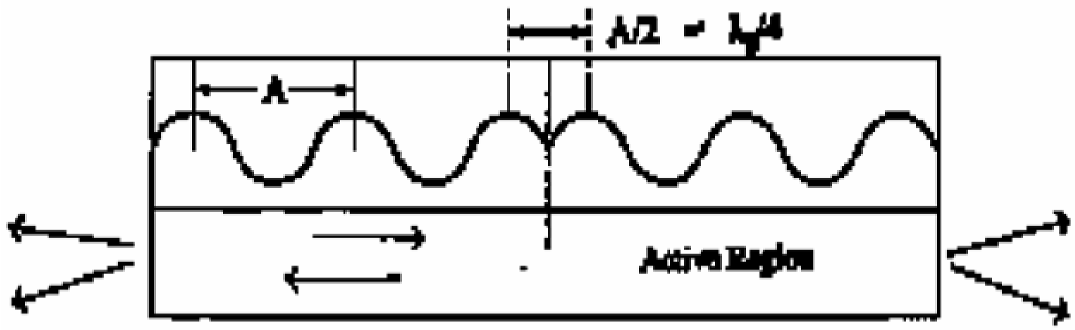


Figure 2.5 DFB laser structure [14]

2.4 FIBER BRAGG GRATINGS

Fiber Bragg grating are spectral filters based on principles of Bragg reflection. The principles of operation of fiber Bragg grating is when the light propagates by periodically alternating regions of higher and lower refractive index, it is partially reflected at each interface between those regions. If the pitch of the grating is properly designed then all partial reflected wave add up in phase and can grow to nearly 100% , for a specific wavelength even if the individual reflected wave are very small. But for other wavelengths, the waves that are out of phase the reflected wave end up cancelling each other which resulted in high transmission, as shown in figure 2.6. This condition for high reflection is known as Bragg condition [6].

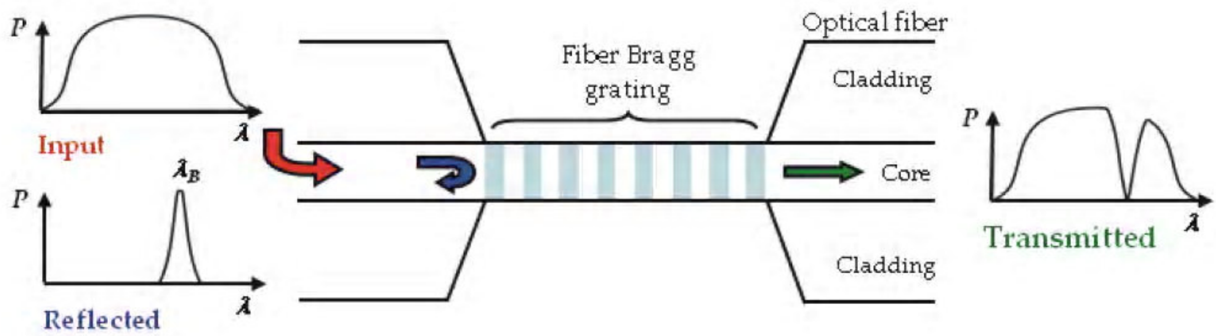


Figure 2.6 Fiber Bragg Gratings operation principles [15]

2.5 GRATING COUPLERS

Grating coupler is an optical structure which consists of number of rectangular, triangular, sinusoidal or parallelogram grating teeth [15]. Grating coupler can be classified into two types: reflection grating or short period grating in which coupling occurred between modes travelling in opposite direction and transmission grating or long period grating which coupling is between modes travelling in the same direction. The ability of grating coupler to couple the light vertically out-of-plane is when grating period is define as ratio of centre wavelength to the effective index of the modes. The basic operation principles of grating coupler is the ability to absorb signal from free space or release it to the free space [16]. But traditionally the escaped signal from grating coupler is non uniform in amplitude (asymmetrical beam), which is controlled by using apodized grating. Figure 2.7 is the simple structure of grating coupler with grating period, mode and propagation constant.

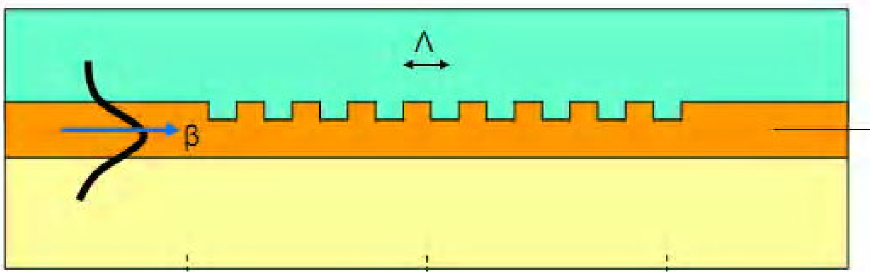


Figure 2.7 Simple Grating Coupler [17]

2.5.1 Coupling into Fiber

The major problem of nanophotonics is the coupling of light into or out of the nanophotonics waveguide by means of optical fiber. This problem arises from mode size mismatch of nanowire in nanometer and single mode fiber in microns. Some of the solution to this problem are lateral spot size conversion in an adiabatic taper plus out-of-plane coupling by diffraction with waveguide grating to the Gaussian mode profile of the fiber, refractive index contrast between the material and index matching layer material between the surface of the grating and fiber facet with refractive index equals to that of fiber core [19]. Figure 2.8 shows the comparison of mode field diameter between nanowire waveguide and standard optical fiber [19], and figure 2.9 shows the operation principle of the grating coupler and fiber [16].

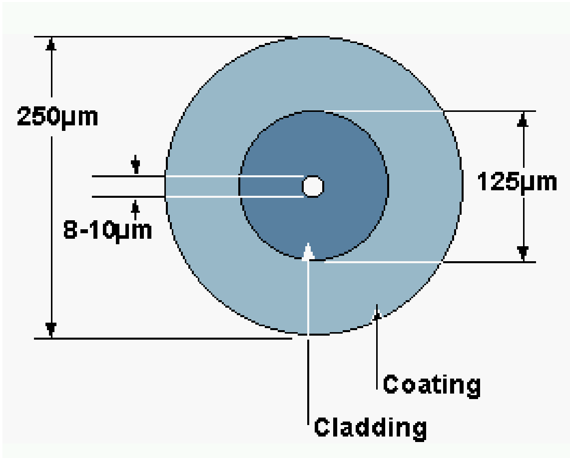


Figure 2.8 Nanowaveguide and fiber [18]

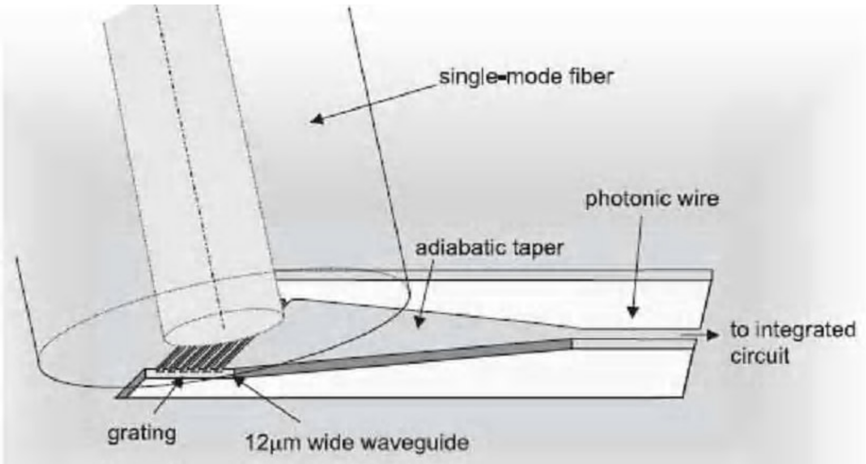


Figure 2.9 Operation Principle Grating Coupler [16]

The key component for the operation of grating coupler is Bragg condition. The Bragg equation that describes the modes of operation for the grating at a particular coupling angle can be express as [19]

$$n_{eff} = n_{top}\sin(\theta_c) + m\frac{\lambda}{\Lambda} \qquad (2.17)$$

where η_{eff} is the effective index of the grating

η_{top} is the effective of the material

θ_c is the coupling angle of the measured perpendicular to the surface

m is the diffraction mode

λ is the wavelength of the incident light

Λ is the grating period

Also the coupling efficiency between single mode fiber and grating coupler can be found by the quantity of outcoupled power from the grating structure to the Gaussian shaped fiber. If the width of the grating is perfectly pitch and the fiber is positioned at constant distance from the surface of the grating. The integral in equation (2.18) can be used to calculate the coupling efficiency. The efficiency of the outcoupled power from the grating to the fiber is equal to coupling efficiency from fiber to the grating structure [21].

$$\eta = \left| \iint E(x)E(y=z)Ae^{\frac{-(x-x_0)^2+(z-z_0)}{w_0^2}} e^{(jn\frac{2\pi}{\lambda}z\sin\theta_c} dxdz \right|^2 \tag{2.18}$$

where η is the coupling efficiency

A is the normalization of Gaussian beam

w is the beam diameter

2.5.2 Effect of Wavelength and Grating Period on Out Coupling

Uniform rectangular grating can be used to explain the effect of wavelength and grating period in a grating structure. In a uniform grating light can coupled out in a vertical form or almost vertical form. Vertical coupling can be achieved when the light is couple out at an angle $\theta = 0^0$ and grating period as the ratio of wavelength to the refractive (second order grating). Figure 2.10 shows the vertical coupling condition between waveguide and single mode fiber. But almost vertical coupling is achieved at a wavelength above or below the second order reflection peak in which the light is couple out at a small angle θ with respect to vertical direction, this grating method is called detuned grating. Detuned grating can be positive or negative, if grating period is larger and wavelength is small the grating is called positive detuned but if grating period is smaller and larger wavelength the grating type is negative detuned. Figure 2.11 (a) is negative detuning and (b) is positive detuning [21].

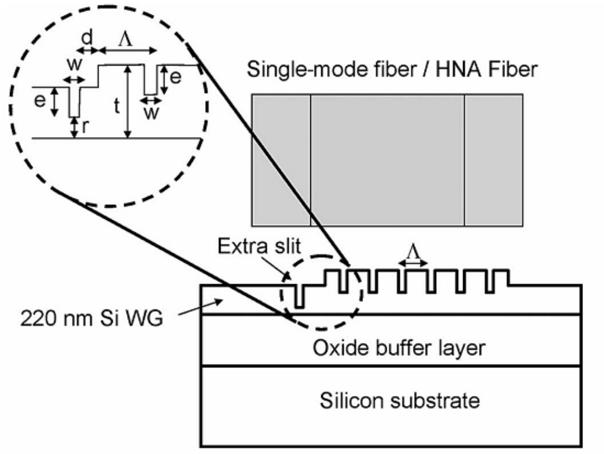
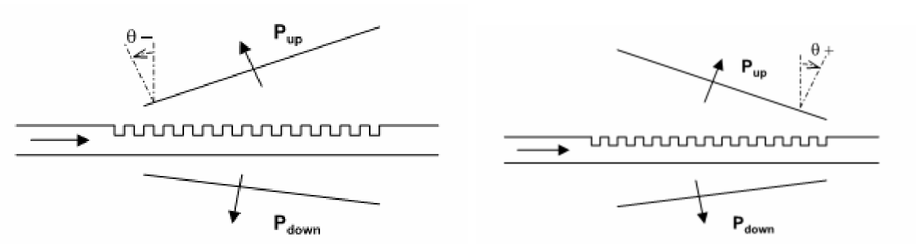


Figure 2.10 Vertical Coupling in Grating Couplers [22]



(a) (b)

Figure 2.11 (a) Negative Detuning, (b) Positive Detuning [21]

2.6 EIGENMODE EXPANSION METHOD

Eigenmode expansion method is a tools used for solving Maxwell's equation which is use for calculating electromagnetic propagation based on local modes of the structure and refractive index of the layers that are not change in z-direction. A waveguide structure that satisfied this condition can be express as [23]

$$E(x, y, z) = e_m(x, y)e^{i\beta_n z} \tag{2.19}$$

There are two modes that exist in a waveguide structure: guided mode which is described as lossless mode and radiation mode which is associated with losses of optical power. Therefore the Maxwell's equation of such waveguide is express in superposition of forward and backward propagating mode as:

$$E(x,y,z)=\sum_{k=1}^{m}\left(a_k e^{j\beta_k z}+b_k e^{-j\beta_k z}\right)E_k(x,y) \quad (2.20)$$

$$E(x,y,z)=\sum_{k=1}^{m}\left(a_k e^{j\beta_k z}-b_k e^{-j\beta_k z}\right)H_k(x,y) \quad (2.21)$$

where β is the propagation constant

a_k and b_k are forward and backward amplitudes, respectively, and

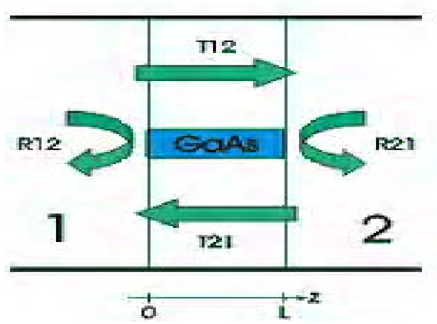
$E_k(x,y)$ and $H_k(x,y)$ are modes profiles.

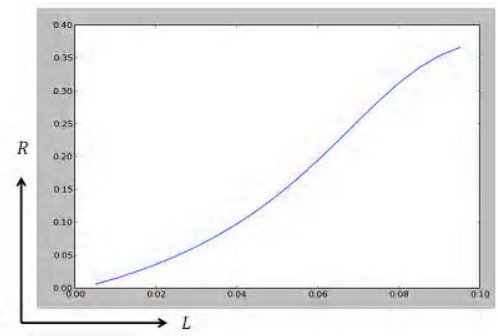
Equation (2.20) and (2.21) are the exact solution of Maxwell's equation with forward and backward propagation mode, respectively. The advantage of this two equation above is their bi-directional nature (i.e. which they can be applied when two waveguide are joined together). The equation are applied with the continuity condition for the field: the tangential electric field must be equal on each side of the interface, therefore the equation (2.20) and (2.21) becomes

$$\sum_{k=1}^{N}(a_k^{(+)}e^{i\beta_k z}-a_k^{(-)}e^{-i\beta_k z})=\sum_{k=1}^{N}b_k^{(+)}e^{i\beta_k z}-b_k^{(-)}e^{-i\beta_k z})E_{k.t}^{(b)}(x)$$

(2.2)

Figure 2.12 (a) shows the example of 2D waveguide structure simulated by eigenmode mode expansion method and (b) shows the result for the simulation.





(a) (b)

Figure 2.12 (a) 2D Waveguide Example Structure led by EEM, (b) Simulation Result [5]

2.6.1 Boundary Condition

Boundary condition is a process whereby artificial material included in a structure in order to avoid unwanted reflection which can cause wrong computation. The popular boundary conditions used are perfect electric and magnetic conductor (PEC/PMC) and perfect matched layers (PMLs). Figure 2.13 shows the example of an imaginary boundary condition of a waveguide sandwiched between two perfect conductors and PML layer and Table 2.1 summarizes some advantage and disadvantage of boundary conditions [23].

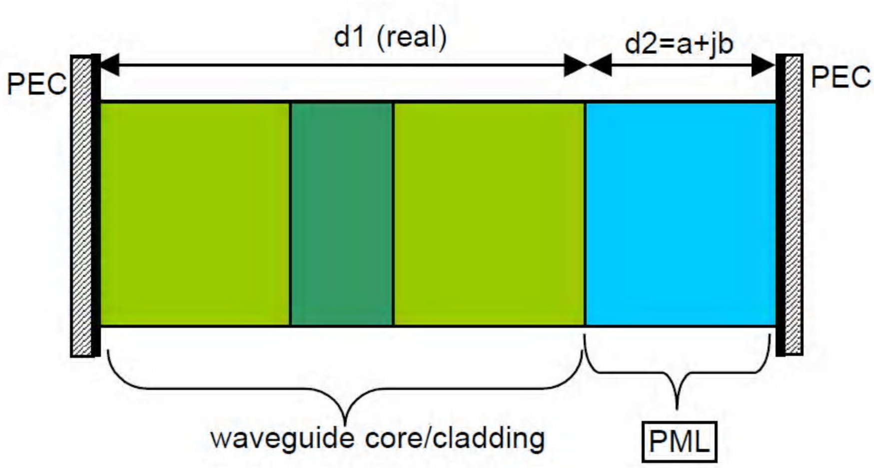


Figure 2.13 PML with imaginary thickness [23]

Table 2.1 Advantage and Disadvantage of PML

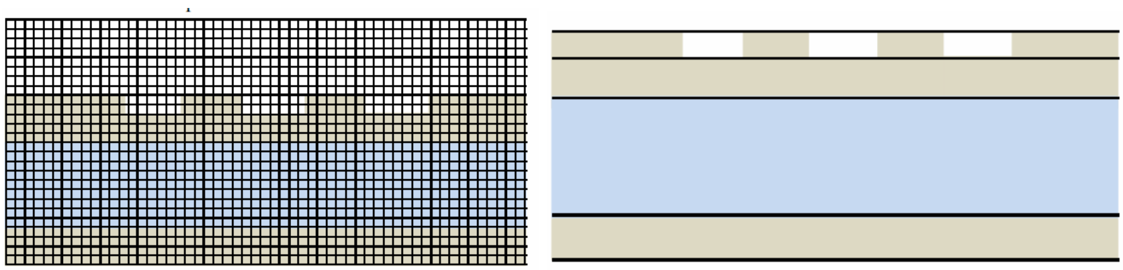
Advantages	Disadvantages
Exact solution can be obtain by adding more modes	Algorithm are complex
Is bi-directional	Not good for large cross sectional area structure
Solve for TE,TM and hybrid	Not easy to understand
Permit to build framework	

CHAPTER 3

SIMULATION PROCEDURES

3.1 CAMFR SOFTWARE

CAMFR is academic software developed by photonic group of information technology department of Ghent University, Belgium. The main function of the software is the simulation of optical devices like VCSEL, photonic crystals, light emitting diodes (LEDs) and general electromagnetic problems. CAMFR is function based on the principles of Eigenmode Expansion Method (EEM) in a structure with different layers in which refractive index does not change in z- direction unlike other traditional software which usually uses finite different time domain (FDTD). It is capable of calculating the fundamental mode, electric and magnetic field, reflectivity, transmissivity and field profile. It is currently applied in 2D Cartesian structure and 3D cylindrical symmetric structures [24]. Figure 3.1 shows the spatial discritization of grating coupler structure and (b) shows the eigenmode expansion grating coupler structure.



(a) (b)

Figure 3.1 (a) Spatial Discritization, (b) Eigenmode expansion [20]

CAMFR software utilizes python script in describing the structure to be simulated. Below is a sample code description for simulation a slab waveguide with CAMFR.

```
Slab = Slab( air(3) + InGaAs(1) + air(3) )

Slab.calc()

Slab.plot()
```

Outfile = (“my example”, ‘w’)

The code above defines a slab waveguide with InGaAs core of one micron thick and air cladding which are two microns thick. To represent structure with CAMFR notation, convention for the coordinate system must be considered, the x–axis lies in the vertical direction of the slab waveguide and start from the bottom wall of the structure. The whole waveguide is uniform in y- and z-directions. Figure 3.2 is a waveguide with arbitrary number of step index in the radial direction with GaAs as high index material and between air cladding sandwiched in a PML layers.

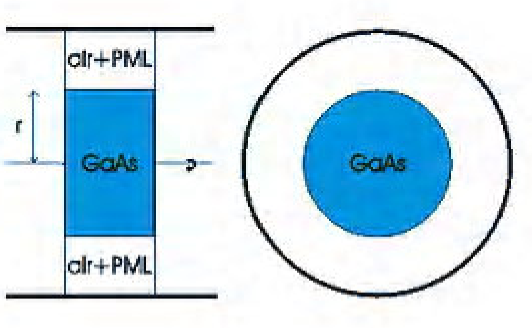
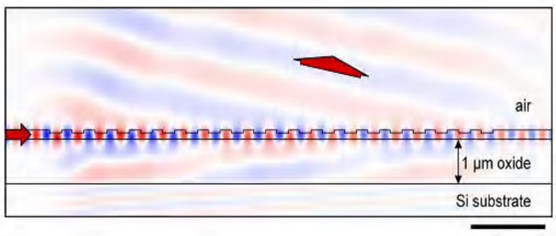
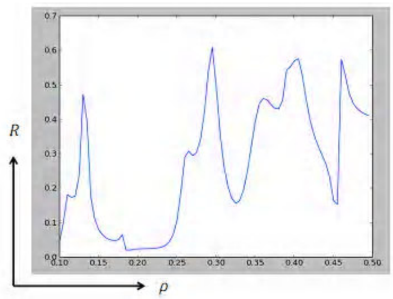


Figure 3.2 Simple Modeled Slab Waveguide [24]

Results of simulation by CAMFR can be displayed either in numerical form or graphical form. Figure 3.3 (a) indicates the sample of field propagation of the structure simulated by using CAMFR and (b) shows electric field propagation in the waveguide produced by software.





(a) (b)

Figure 3.3 (a) CAMFR Field Plot Sample Result, (b) CAMFR Graph Sample Result [3]

3.2 SIMPLE STRUCTURE EXAMPLE

Figure 3.4 is a simple quantum–well slab structure with n-cladding and p-cladding if indium phosphate and core of indium gallium arsenide with thickness d. We simulated this structure in order to show the basic concept of CAMFR. We calculated the effective index and electric field of the waveguide. The code used for the simulation is given in appendix A. Figure 3.5 shows the electric field of the structure.

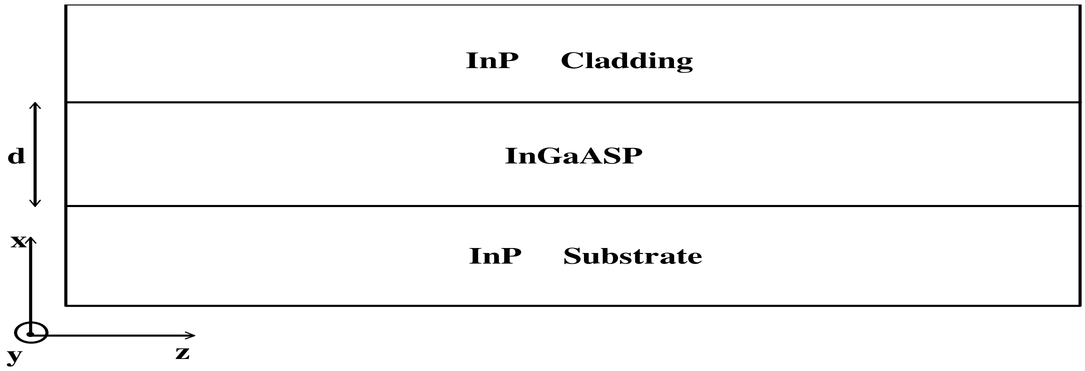


Figure 3.4 Simple Quantum–Well Slab Waveguide

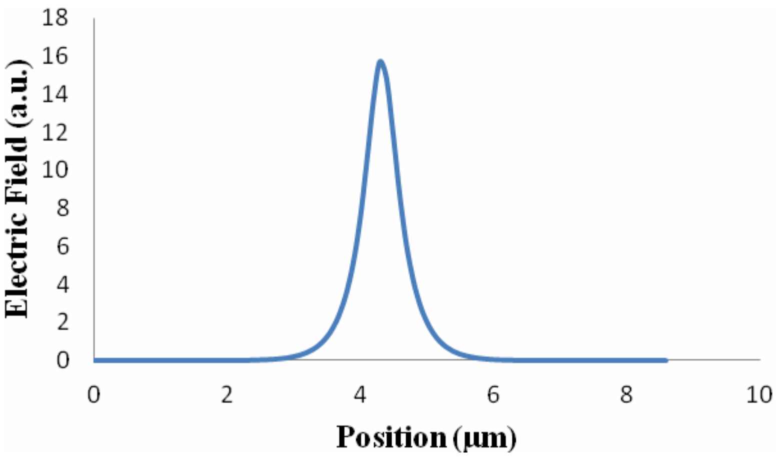


Figure 3.5 E-Field for Simple Example Structure

CHAPTER 4

PROPOSED STRUCTURES

4.1 QUANTUM– WELL LASER STRUCTURE

Figure 4.1 shows the structure and dimension of the layers for quantum well-laser (QWL) grating coupler. This structure is made from the n-cladding of indium phosphide material as bottom cladding, p-cladding layers of indium phosphide as grating layer, quantum-wells of indium gallium arsenide material as active layer with different refractive index and air cladding on top of the grating layer. We have assumed the number of period in the grating region to be twenty and also the structure is sandwiched in PML layers with 0.4 μm thickness. Table 4.1 summarizes the given parameters of the figure 4.1.

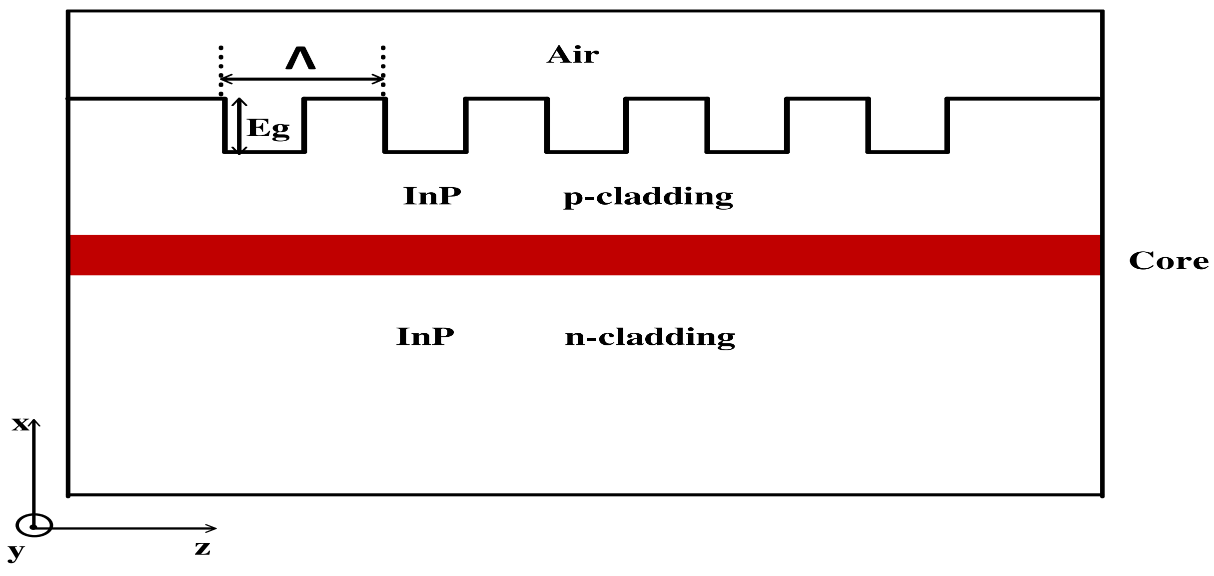


Figure 4.1 Quantum-Well Laser Structure

Table 4.1 QWL Structure parameters

Layers	Materials	Index	Thickness (µm)
Top cladding	Air	1.0	8.0
Grating	InP	3.1628	0.28
p-cladding	InP	3.1628	0.3
Barrier	InGaAsP	3.37	0.05
Four quantum wells	InGaAsP	3.46	0.01
Three barrier	InGaAsP	3.37	0.01
Barriers	InP	3.1628	0.05
n-substrate	InP	3.1628	4.0

4.1.1 Simulation Results

Quantum-well structure was simulated with CAMFR by with the parameters given in table 4.1 and the following simulation parameters: 1550 nm as center wavelength, twenty as number of modes in series expansion and twenty number of period in TE polarization. The simulation results obtained was 3.0871 as effective index of the mode and figure 4.2 shows the optical field profile of the mode.

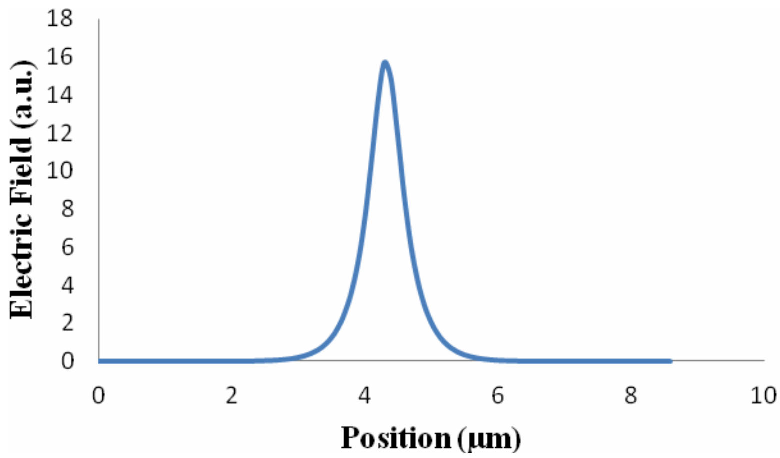


Figure 4.2 Optical Field for the Quantum-Well Laser Structure

To obtain the first order grating period (Λ_1) we simulated the structure for the reflectance $|r|^2 = R$ and grating period. The result was obtained by varying grating period from 0.1 µm to 0.3 µm using the parameters in table 4.1 and the following simulation parameters: 1550 nm as center wavelength, twenty as number of periods is twenty and twenty as number of modes in series expansion in TE polarization. The maximum peak of reflectance was occurred at a position around 0.243 µm. This value indicates the first Bragg condition; therefore the second Bragg is 0.486 µm.

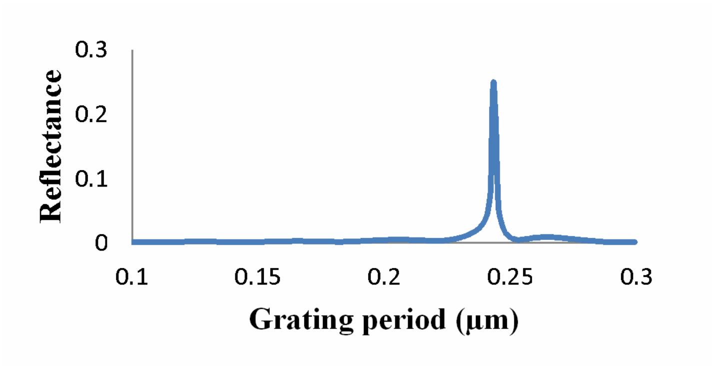


Figure 4.3 Reflectance versus Grating Period for Quantum-Well Laser

Also we simulated reflectance wavelength for finding the Bragg wavelength (λ_B). Figure 4.3 shows the simulation result obtained for reflectance against wavelength. This result was obtained when we varied wavelength from 1500 nm to 1600 nm with the following simulation parameters: 1550 nm as center wavelength, 0.486 µm for grating period, twenty as number of periods and twenty as number of modes in series expansion in TE polarization together with the parameters given in table 4.1. The maximum value of reflectance was occurred at position around 1530 nm in the x-axis which indicates the Bragg wavelength for the quantum-well laser structure as shown in figure 4.4.

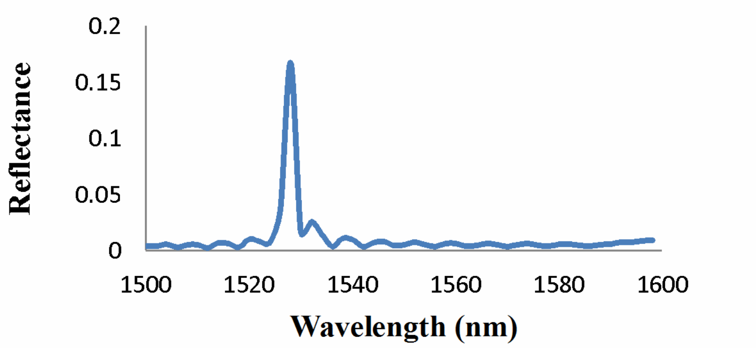


Figure 4.4 Reflectance versus Grating Period for Quantum-Well Laser

As we can see from simulation results above, the first order grating period is 0.243 µm and also Bragg wavelength is 1530 nm. Therefore the second Bragg grating for the quantum-well laser grating coupler structure is 0.486 µm for the design simulation. Table 4.2 shows the summary of the quantum-well laser grating coupler simulation results.

Table 4.2 Quantum-Well Laser Simulation Result

First Bragg period Λ_1 (μm)	Second Bragg Period Λ_2 (μm)	Bragg Wavelength λ_B (nm)
0.243	0.486	1530

.

4.2 PROPOSED STRUCTURE

Figure 4.5 shows the structure and dimension of layers of the proposed quantum well-laser grating coupler. The structure is made from the n-cladding of indium phosphide material as bottom cladding layer, p-cladding of indium phosphide material as cladding layer below the grating layer and also quantum wells layers of indium gallium arsenide material as active layer with different refractive index. The grating layer here is made from indium gallium arsenide phosphate material and air cladding on top of the grating layer, the number of period in the grating region is twenty, the structure is sandwiched between PML layers of thickness 0.4 μm each. Table 4.3 contains the parameters of the structure.

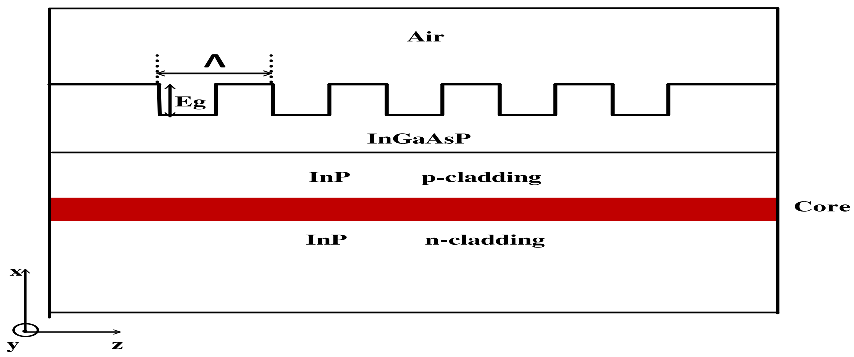


Figure 4.5 Proposed Structure

Table 4.3 Proposed Structure Parameters

Layers	Materials	Index	Thickness (μm)
Top cladding	Air	1.0	-
Gratings	InGaAsP	3.372	0.028
Resonant Layer	InGaAsP	3.372	0.350
p-cladding	InP	3.1628	2.55
Barrier	InGaAsP	3.37	0.05
Four quantum well	InGaAsP	3.46	0.01
Three barriers	InGaAsP	3.37	0.01
Barrier	InGaAsP	3.37	0.05
n-substrate	InP	3.1628	-

4.2.1 Simulation Results

We divided the structure into two sections: top and bottom waveguide. The purpose of dividing the structure is to simulate each section separately and get accurate parameters for the design simulation. Figure 4.6 represents the bottom waveguide of the proposed structure with top and bottom cladding of indium phosphide. Table 4.4 contains the summary of simulation parameters for the bottom waveguide of the proposed structure. Using the parameters in table 4.4 and center wavelength of 1550 nm for TE modes, we simulated the structure and obtained that, the effective index of the bottom waveguide of the proposed structure as 3.1977. Figure 4.7 is the optical field of the mode for the bottom waveguide of the proposed structure.

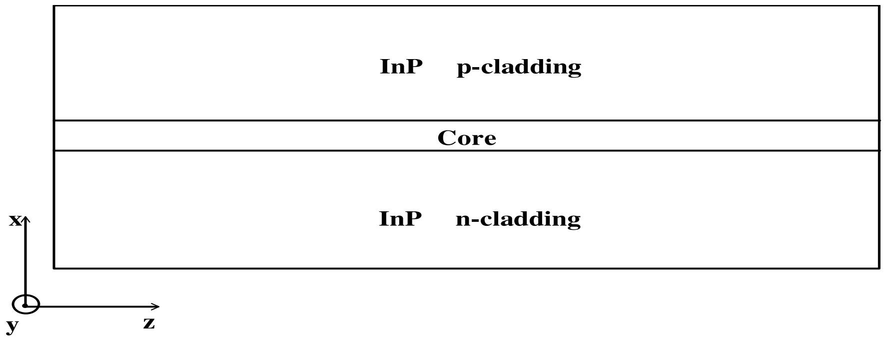


Figure 4.6 Bottom Waveguide of the Proposed Structure

Table 4.4 Parameters for the Bottom Waveguide of the Proposed Structure

Layers	Materials	Index	Thickness (μm)
p-cladding	InP	3.1628	4.0
Barrier	InGaAsP	3.37	0.05
Four quantum well	InGaAsP	3.46	0.01
Three barriers	InGaAsP	3.37	0.01
Barrier	InGaAsP	3.37	0.05
n-cladding	InP	3.1628	4.0

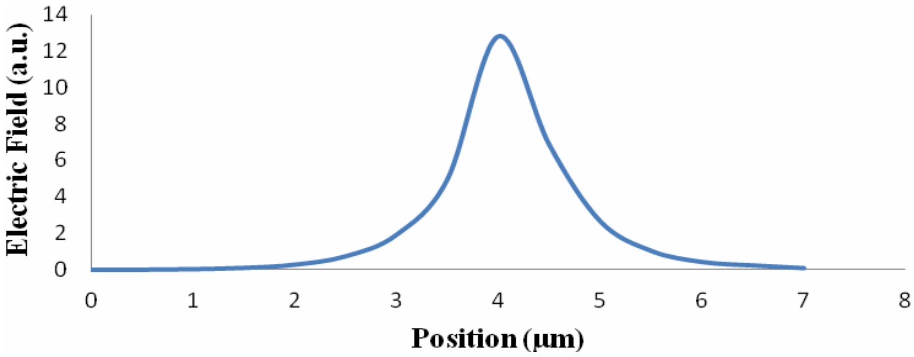


Figure 4.7 Optical Field for the Bottom Waveguide of Proposed Structure

We also simulated top waveguide of the proposed structure in order to obtain the required thickness of the InGaAsP. The upper waveguide is comprised of p-cladding layer of indium phosphide material as bottom cladding, air as top cladding, and indium gallium arsenide phosphate core layer as seen from figure 4.8. Using the parameters in table 4.5 and 1550 nm as center wavelength in TE polarization, we simulated the structure and observed from figure 4.9 that effective index of the top waveguide is approximately equal to that of bottom waveguide at thickness around 0.375 µm of the mode of the top waveguide is almost equal to the effective index of the bottom waveguide which is 3.19 µm. Therefore, we choose thickness of InGaAsP as 0.375 µm for the simulation.

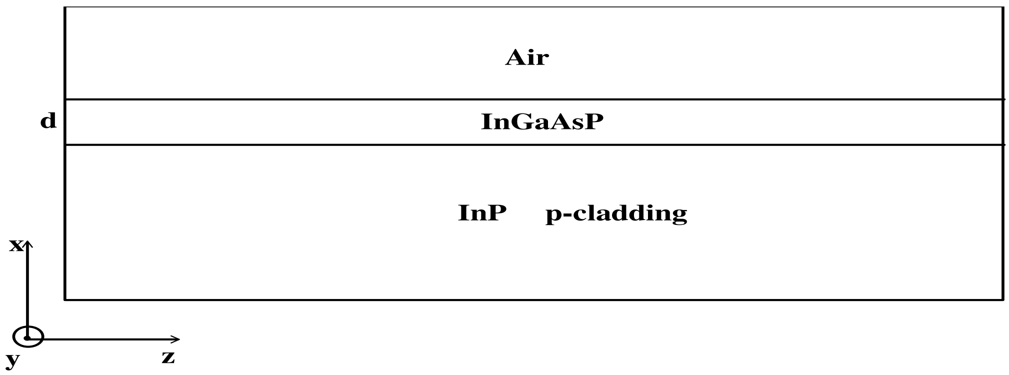


Figure 4.8 Top Waveguide of the Proposed Structure

Table 4.5 Parameters for the top Waveguide of the Proposed structure

Layers	Materials	Index	Thickness (µm)
Top-cladding	Air	1.0	2.0
Barrier	InGaAsP	3.37	0.05
p-cladding	InP	3.1628	4.0

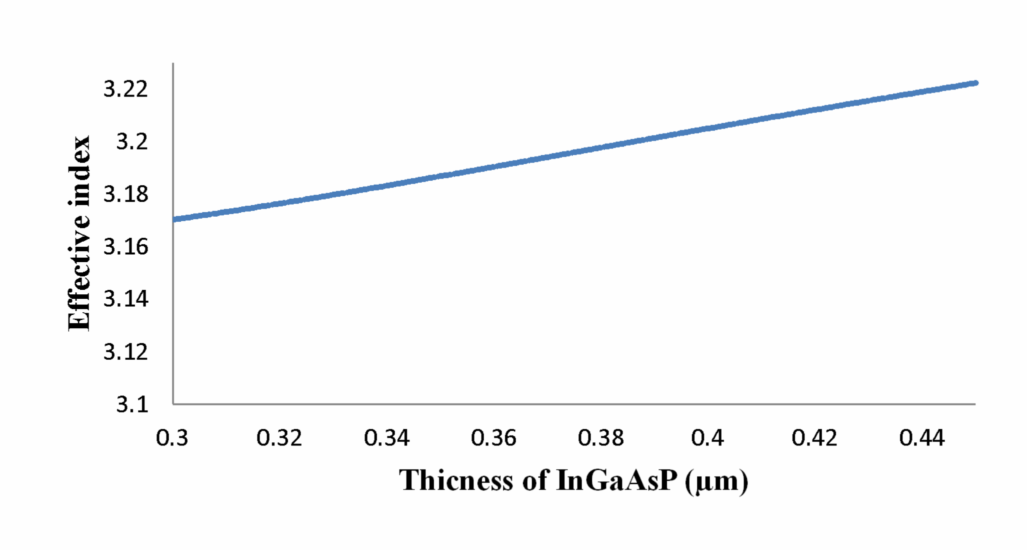


Figure 4.9 Index Variations for the Top Waveguide of the Proposed Structure

To obtain the optical electric field of the proposed structure, we combined the top and bottom waveguide. Figure 4.10 is the waveguide of the proposed structure. The structure was simulated with the following simulation parameters: 1550 nm as center wavelength, twenty as number of mode in series expansion in TE and parameters given in table 4.6. For the simulation of top waveguide of the structure we obtained that the effective index of the bottom waveguide is almost equal to the effective index of the top waveguide at thickness of 0.375 µm InGaAsP. Therefore we choose 0.375 µm as thickness of InGaAsP for the simulation. We simulate the structure by varying the vertical position of the structure from 0.0 µm to 8.75 µm by using parameters in table 4.6 and center wavelength of 1550 nm for TE mode. The thickness of InGaAsP used is 0.375 as obtained from the simulation of figure 4.8. It was observed that, the optical electric field of the proposed structure has a secondary peak in InGaAsP layer as seen in figure 4.11.

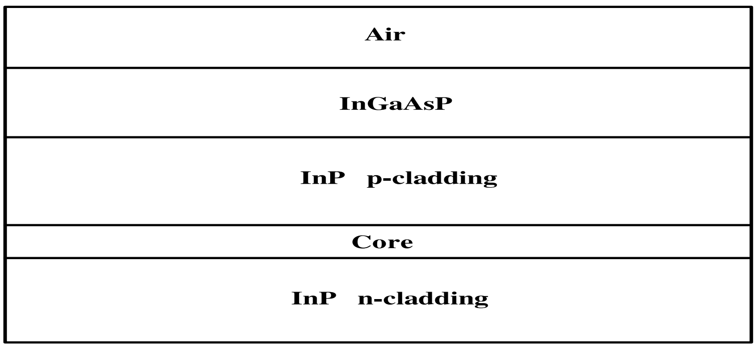


Figure 4.10 Complete Waveguide for the Proposed Structure

Table 4.6 Parameters for the Complete Waveguide of the Proposed Structure

Layers	Materials	Index	Thickness (µm)
Top cladding	Air	1.0	2.0
p-cladding	InP	3.1628	4.0
Barrier	InGaAsP	3.37	0.05
Four quantum well	InGaAsP	3.46	0.01
Three barriers	InGaAsP	3.37	0.01
Barrier	InGaAsP	3.37	0.05
n-cladding	InP	3.1628	4.0

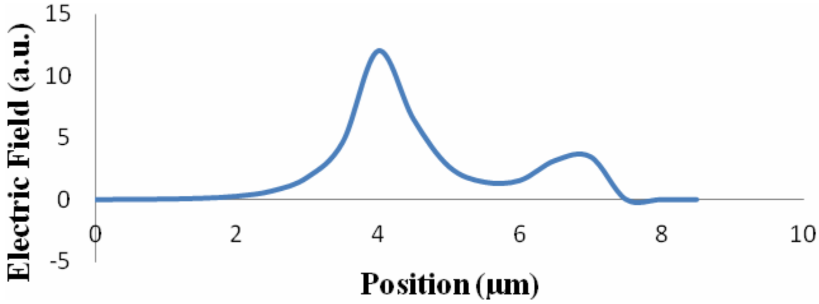


Figure 4.11 Optical Field for the Proposed Structure

Figure 4.12 shows the simulation result obtained for reflectance against grating period for the proposed quantum-well laser grating structure. This result was obtained when grating period was varied from 0.1 µm to 0.3 µm with the following simulation parameters: 1550 nm as center wavelength, twenty as number of periods, twenty as number of modes in series expansion, 0.375 µm as thickness of InGaAsP in TE polarization and parameters given in table 4.3. It was observed that the maximum reflection occurred at position around 0.243 µm which indicates the first order Bragg condition. Therefore the second order Bragg condition is twice of the first order which is 0.486 µm for the quantum-well laser structure.

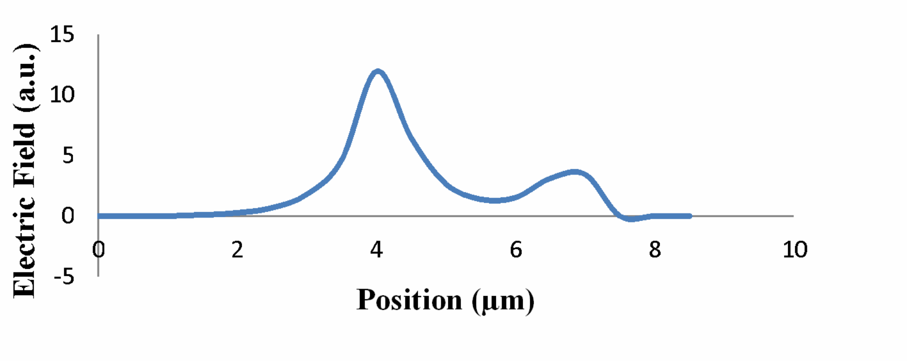


Figure 4.12 Reflectance versus Grating Period for the Proposed Structure

Figure 4.13 shows the simulation result obtained for reflectance against wavelength for the proposed quantum-well laser grating structure. This result was obtained when wavelength was varied from 1500 nm to 1600 µm with the following simulation parameters: 0.486 µm as grating period, 1550 nm as center wavelength, twenty as number of period, twenty as number of modes in series expansion, 0.375 µm as thickness of InGaAsP in TE polarization mode and parameters given in table 4.3. It was observed that the maximum reflection occurred at position around 1530 nm which indicates position of Bragg wavelength condition, which is the second order Bragg for the proposed quantum-well laser grating coupler structure.

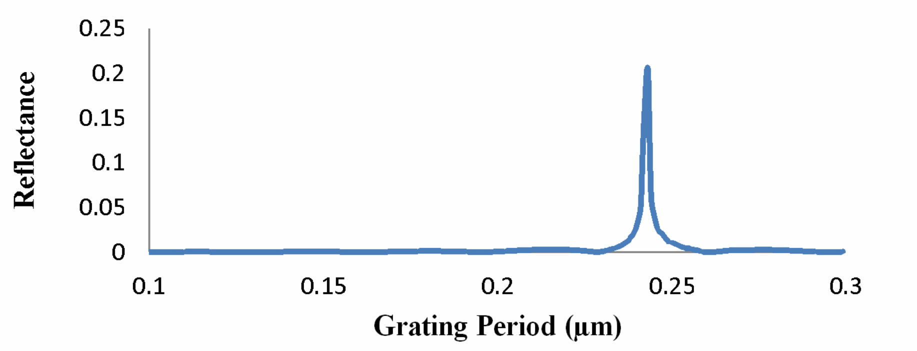


Figure 4.13 Reflectance versus Wavelength for the Proposed Structure

As we can see from simulation results above, first order grating period is 0.234 µm and also Bragg wavelength is1530 nm. Therefore the second Bragg grating for the proposed grating coupler structure is 0.486 µm for the design simulation. Table 4.7 shows the summary of the proposed structure simulation result.

Table 4.7 Proposed Structure Simulation Results

First Bragg period Λ_1 (µm)	Second Bragg Period Λ_2 (µm)	Bragg Wavelength λ_B (nm)	Effective Index
0.243	0.486	1530	3.19

Table 4.8 contains the summary of the results obtained for the simulation of both quantum-well structure and proposed structure for comparison. It has been observed that almost all the values are equal, therefore in conclusion both structures can be simulated with the same parameters and obtain the out coupled power and compare the percentage of the coupled power produced by each structure.

Table 4.8 Comparison of Simulation Results

Structure	Effective index	First Bragg period Λ_1 (µm)	Second Bragg period Λ_2 (µm)	Bragg wavelength λ_B (nm)
Quantum-well laser	3.1902	0.243	0.486	1530
Proposed Structure	3.1977	0.243	0.486	1530

CHAPTER 5

OPTIMIZATION OF THE STRUCTURES AND DISCUSSIONS

5.1 OPTIMIZATION OF PARAMETERS

In the previous chapter we simulate both quantum–well laser structure and proposed structure and obtained the effective index, electric field and effect of reflectance against grating period and wavelength in order to find the point for the highest peak of reflection which indicate the first Bragg condition and Bragg wavelength. The main target is to design a grating coupler structure with higher percentage of out coupled power that couple out from the structure. Many parameters are considered when designing grating structure. Some of the parameters considered are air thickness, etching depth, wavelength, grating period, fill factor and perfect matched layers. To obtain more efficient grating structure there are some parameters that are carefully chosen. These include thickness of PML layers and distance between the surface of the structure and the boundary (i.e. air thickness). Also fill factor which is defined as the ratio of width of the grating to grating period is an important parameter for determining center wavelength. To calculate out coupled power, we consider a certain position above the grating surface in vertical x-direction, and integrate the electric optical power (which is proportional to the multiplication of the electric field and the conjugate of the magnetic field). From figure 5.1 we consider x_s as value of x at the surface of the grating, $x_s + d$ is the position for calculating out coupled power above the grating surface. The area for integrating out coupled power along the longitudinal position has lower limit of z_i and the upper limit of z_f. Equation 5.1 represents the formula for calculating out coupled power above the grating surface.

$$outcoupledpower = \mathrm{Re}\int_{z_i}^{z_f} E \times H^* dz \qquad (5.1)$$

where E is electric field and H is conjugate of magnetic field.

In our design we consider figure 5.1 as proposed structure for the simulation and used the parameters given in table 4.3. We also choose one hundred and thirty as number of modes in series expansion, 1.0 µm as PML thicknesses, and 1.5 µm as height above the grating surface for calculating out coupled power. To determine air thickness and etching depth, we use the parameters in Table 5.1 for the simulation. The simulation was done using CAMFR software and the code used for the simulation is given in appendix B.

Table 5.1 Selected Parameters for the Simulation Design

Number of modes (N)	PML layer (µm)	Height above from the grating surface (d) µm
130	1.0	10.085

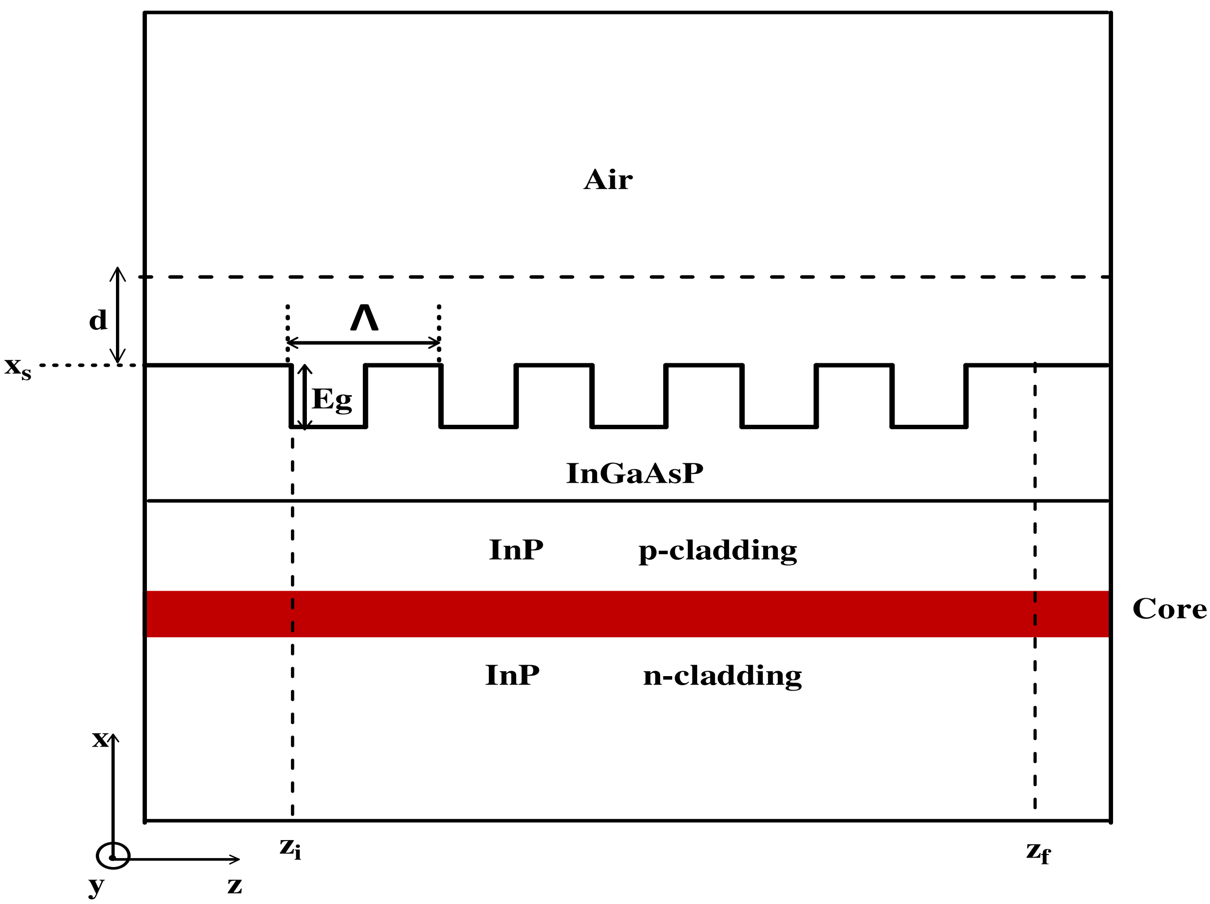


Figure 5.1 Proposed Structure for the Simulations

5.1.1 Air Thickness Consideration

We have simulated figure 5.1 by changing thickness of the air above the grating in order to get the right value of the air thickness for the simulation. We varied the air thickness from 7.0 µm to 17.0 µm and used the parameters given in table 4.3 and 5.1 for TE polarization mode. It has been observed that the outcoupled power shows almost no variation from 10 µm to 17 µm. Therefore we choose the optimized value of air thickness for the simulations within this range.

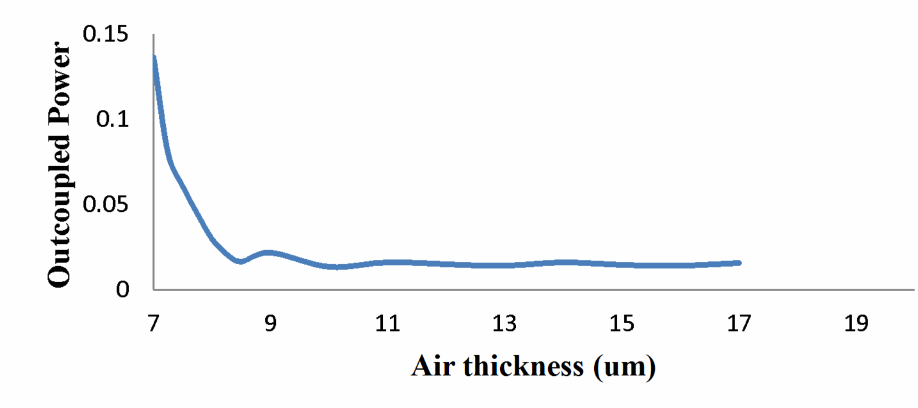


Figure 5.2 Optical Outcoupled power Versus Air Thickness

5.2.2 Etching Depth Consideration

We simulate both structures by varying the etching depth and select the value of etching depth with maximum outcoupled power as optimized value for the simulation. We varied the etching depth for both structures from 0.028 µm to 0.28 µm and used the parameters given in table 4.3 and 5.1 for TE polarization mode. It has been observed that in figure 5.3 the maximum value for the outcoupled power was obtained at etching depth around 0.168 µm for proposed structure. Therefore we choose 0.168 µm as optimized value of etching depth for the simulation.

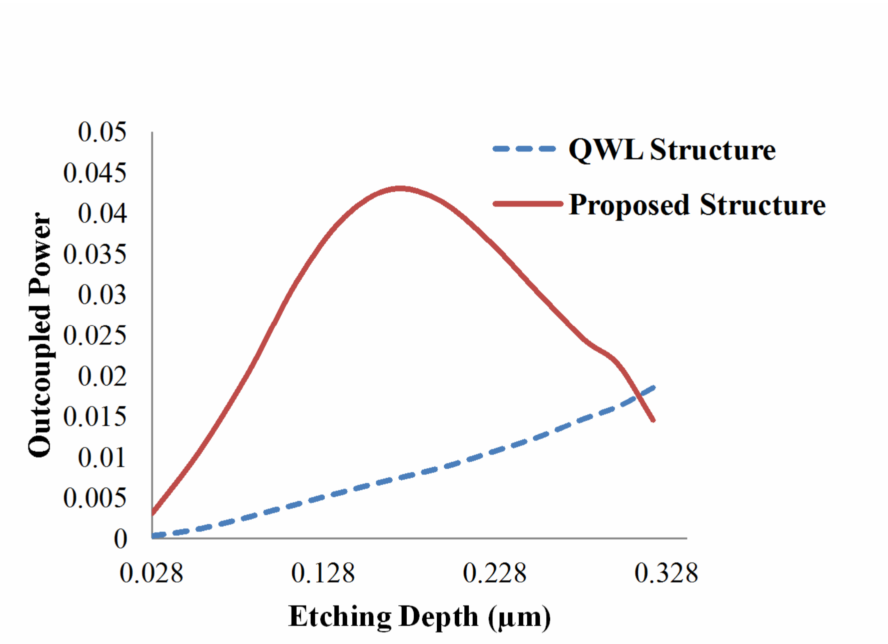


Figure 5.3 Outcoupled Power versus Etching Depth

5.2 EFFECT OF WAVELENGTH

After determining two simulation parameters which are air thickness and etching depth, we simulate both structures by varying wavelength. The parameters for the simulation are summarized in table 5. 2.

Table 5.2 Parameters for Simulation

Parameters	Air thickness (µm)	Etching depth (µm)	Grating period (µm)	Number of modes	PML Thickness (µm)	Fill factor	Polarization
Values	15.0	0.168	0.486	130	1.0	0.5	TE

With optimized parameters the wavelength of operation has been varied to calculate the outcoupled power and simulate for both structures. Figure 5.4 shows the effect of wavelength varied from the 1500 nm to 1600 nm with an increment of 10 nm. It has been shown that quantum-well structure produces less than 1% of outcoupled power from the structure while the proposed structure produces around 5% of outcoupled power from the structure around 1530 nm wavelength.

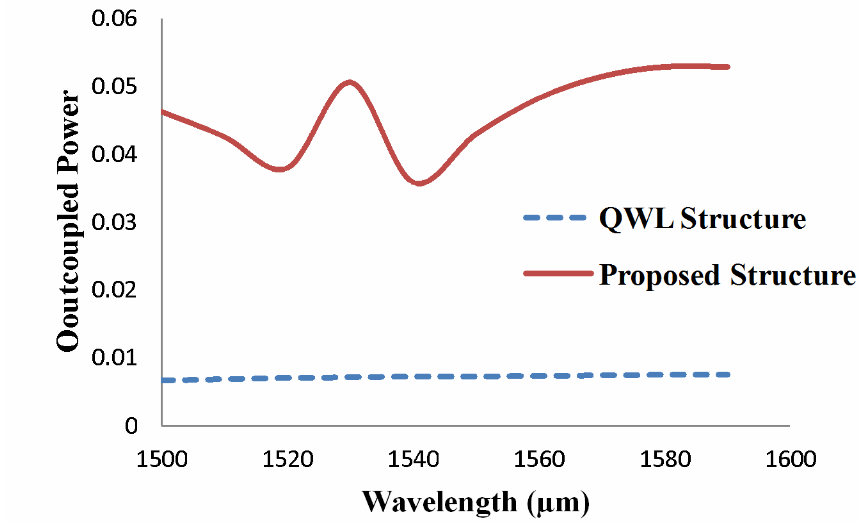


Figure 5.4 Outcoupled Power versus Wavelength

5.3 EFFECT OF GRATING PERIOD

Also with optimized parameters the grating period was varied to calculate the outcoupled power for both structures. The grating period was from 0.38 µm to 0.58 µm with increments of 0.02 µm and air thickness of 15 µm. Figure 5.5 shows that quantum-well structure yields 0.8% outcoupled power from the structure while the proposed structure results in 5% of outcoupled power from the structure.

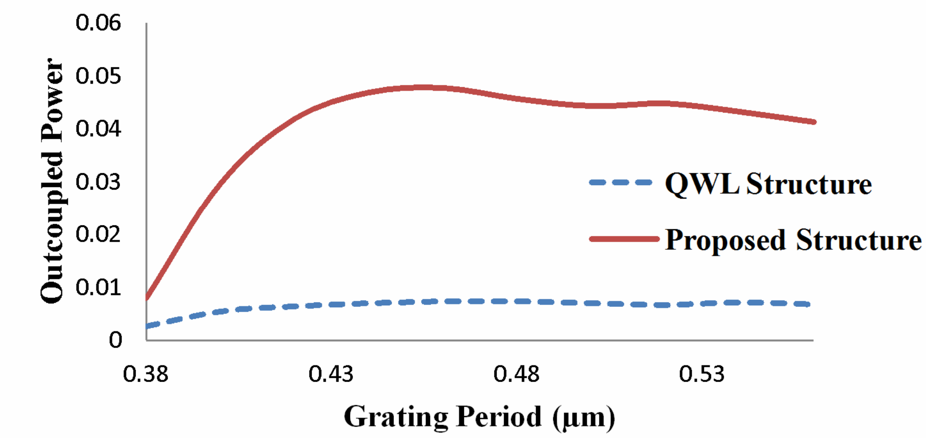
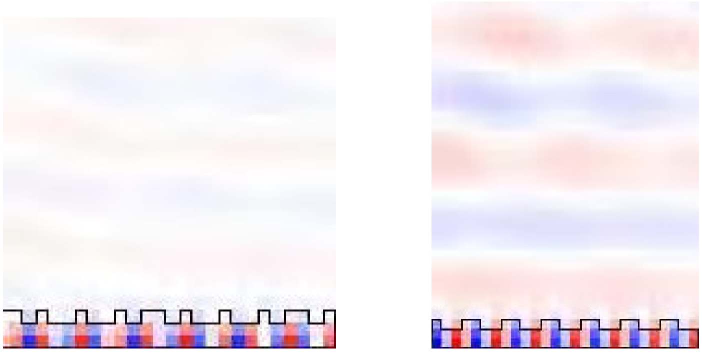


Figure 5.5 Outcoupled Power versus Grating Period

Figure 5.6 (a) show the field plot of quantum–well laser structure which indicates the propagation of field in grating structure. When light is incident in a grating structure some percentage will transmit and some will reflect; the remaining power will out couple up and down due to grating structure. Figure 5.6 (b) shows the field plot of proposed structure which indicates the propagation of field in grating structure. It has been observed the intensity of the propagation of the field in figure 5.6 (b) is more than for that in figure 5.6 (a) which indicates that the proposed structure has high percentage of outcoupled power.



(a) **(b)**

Figure 5.6 (a) Quantum-Well Laser Field (b) Proposed Structure Field Plot

5. 4 RESULTS AND DISCUSSION

First we simulated both structures for outcoupled power by optimizing air thickness and etching depth. With these optimized values we simulate the structures for outcoupled power against the wavelength and grating period. It was observed that 5.1% of outcoupled power was achieved at a wavelength around 1530 nm when varying wavelength from 1500 nm to 1600, we also varied grating period from 0.38 µm to 0.58 µm and the outcoupled power is almost 5.0% for the proposed structure. From the simulation results shown in table 5.5 by using the same parameters the outcoupled power obtained from the proposed structure is almost six times more than the outcoupled power produced from the quantum-well structure

Table 5.5 Summary of Simulation Results

Parameters	Air thickness (mµ)	Etching depth (µm)	Grating period (µm)	Center wavelength (µm)	Outcoupled Power at 1530 nm wavelength	Outcoupled power at 0.48 µm grating period
Quantum – well laser structure	15.0	0.168	0.486	1.55	0.79%	0.8%
Propose structure	15.0	0.168	0.486	1.55	5.0%	5.1%

CHAPTER 6

CONCLUSION

This thesis presents a systematic analysis on a quantum-well laser structure to serve as a grating coupler with capability of coupling optical power out from the structure. The analysis is performed by computer simulation using software which is based on eigenmode expansion method.

The out coupled light power which occurs at the surface of a grating coupler is studied by different characteristics of grating coupler structure parameters such as wavelength, grating period, an etching depth. A high index material of InGaAsP has been introduced as a grating layer in a quantum-well laser structure. The proposed structure with InGaAsP as grating layer has been simulated and it shows a mode with a secondary peak in the InGaAsP layer, while the mode of the quantum-well structure decays exponentially at the both cladding layers. The effect of grating period and wavelength on the performance of the grating structure has been evaluated by simulating the structures using CAMFR software. After optimizing the simulation parameters such as grating period and etching depth, the out coupled optical power achieved from the proposed structure with a high index layer of InGaAsP is almost six times more than the out coupled light power produced from a similar quantum-well laser structure. The simulated structure can be used to couple light into a waveguide from an optical fiber or vice versa. As for future work, the grating structure has to be fabricated and further optimization of the structure should be carried out to achieve efficient coupling experimentally.

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APPENDIX A

SIMULATION EXAMPLE CODE

```
#!/usr/bin/env python

#####################################################################
#
#simulation example for calculating effective index and field
#intensity for simple slab
#
#####################################################################

from camfr import *

set_lambda(1.55)
set_N(20)
set_polarisation(TE)

# Define materials.
InP = Material(3.16)
InGaAs1  = Material(3.20)
InGaAs2  = Material(3.30)
InGaAs3  = Material(3.40)
InGaAs  = Material(3.55)

#Define thickness
```

```
InPST = 4.0

InGaAs1T = 0.1

InGaAs2T = 0.1

InGaAs3T = 0.1

InGaAsT = 0.05

InPCT = 4.0


# Define waveguide.

#for x in arange(0.0, 8.65, 0.1):

waveguide =
Slab(InP(InPST)+InGaAs1(InGaAs1T)+InGaAs2(InGaAs2T)+InGaAs3(InGaAs3T)+In
GaAs  + \


(InGaAsT)+InGaAs3(InGaAs3T)+InGaAs2(InGaAs2T)+InGaAs1(InGaAs1T)+InP(InP
CT))


waveguide.calc()


# Print out some waveguide characteristics.

print x, waveguide.mode(0).n_eff().real

print x, abs(waveguide.mode(0).field(Coord(x, 0, 0)).E2().real)

waveguide.plot()
```

APPENDIX B

DESIGN SIMULATION CODE

```
# -*- coding: cp1252 -*-
############################################################################
#Simulate 1D grating made on InGaAsP material. This simulation is 2D.
# It willcalculate the reflection and powerup of the
# light coupling structure on 2D basis.The calculation is based
# on 2D cross section along the vertical
# direction.
############################################################################
from camfr import *
from numpy import *
# Set parameters.
set_lambda(1.5)
set_N(130)
set_polarisation(TE)
set_chunk_tracing(0)
set_degenerate(0)
set_orthogonal(False)

# Create materials
```

```
InP = Material(3.1628)
InGaAsPqw = Material(3.46)
InGaAsPbar = Material(3.37)
InGaAsPg = Material(3.372)
air = Material(1)

outfile = open("TESTING_.out", 'w')

# Define our own parameters
InPnCT = 4
InPpCT = 2.55
InGaAsPqwT = 0.01
InGaAsPb1T = 0.05
InGaAsPb2T = 0.01
InGaAsPgT = 0.365
airT = 10.0
ff = 0.5

set_lower_PML(-1.0)
set_upper_PML(-1.0)


period = 0.486
Eg = 0.168
no_of_periods = 20

    # looping
```

```
for P in arange(1390, 1400, 10):
    set_lambda(P/1000.0)


    # Define slabs
    waveguide =
Slab(InP(InPnCT)+InGaAsPbar(InGaAsPb1T)+InGaAsPqw(InGaAsPqwT)+InGaAsPbar(InGaAsPb2T)+InGaAsPqw(InGaAsPqwT)+InGaAsPbar(InGaAsPb2T)+InGaAsPqw(InGaAsPqwT)+InGaAsPbar(InGaAsPb2T)+InGaAsPqw(InGaAsPqwT)+InGaAsPbar(InGaAsPb1T)+InP(InPpCT)+InGaAsPg(InGaAsPgT)+air(airT))
    etched =
Slab(InP(InPnCT)+InGaAsPbar(InGaAsPb1T)+InGaAsPqw(InGaAsPqwT)+InGaAsPbar(InGaAsPb2T)+InGaAsPqw(InGaAsPqwT)+InGaAsPbar(InGaAsPb2T)+InGaAsPqw(InGaAsPqwT)+InGaAsPbar(InGaAsPb2T)+InGaAsPqw(InGaAsPqwT)+InGaAsPbar(InGaAsPb1T)+InP(InPpCT)+InGaAsPg(InGaAsPgT-Eg)+air(airT+Eg))
    # define stack
    stack = Stack(waveguide(1.0) + (no_of_periods)*(etched(period*(1.0-ff)) +
waveguide(period*ff)) + waveguide(1.0))
    # find the guided mode


    waveguide.calc()
    guided = 0
    inc = zeros(N())
    niguided = 1
    for t in range(0,6):
        if abs(waveguide.mode(t).n_eff().imag) < niguided:
            guided = t
            niguided = abs(waveguide.mode(t).n_eff().imag)


   # set input for calculating fields


        inc = zeros(N())
```

```
        inc[guided] = 1
        stack.set_inc_field(inc)


        stack.calc()
        x = 8.585
        R = abs(stack.R12(guided,guided))
        T = abs(stack.T12(guided,guided))
        up=stack.lateral_S_flux(x+1)
        down=stack.lateral_S_flux(x-1)
        powerup = 0.0 + 0.0*1j


    for z in arange(1.0, 1+20*period, 0.01):
        powerup+=
0.01*stack.field(Coord(x,0,z)).E2()*conjugate(stack.field(Coord(x,0,z)).Hz())
    stack.plot()
    print period, P, powerup.real
    print x, waveguide.mode(0).field(Coord(x, 0, 0)).E2().real
    outfile.flush()



    #free_tmps()
outfile.close()
```