



PROPOSED QWL GRATING COUPLER WITH InGaAsP AS A GRATING LAYER ADAMU YA'U ILYASU^{1*}, DR. GÖKHAN ÖZGÜR² AND RABIU ALIYU ABDULKADIR³

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ABSTRACT

This paper present the design of proposed quantum-well laser grating coupler with compound semiconductor that can generate it own input signal automatically from the fundamental guided mode without external human intervention. Grating coupler is an optical device which transfers beam of light energy into an optical waveguide. Several methods by using silicon and it oxide have been proposed to design such device, but the proposed structure is differ with conventional one, because it's can't generate it own input signal. So we design a quantum-well laser grating coupler different from traditional one by using compound semiconductors such as Indium Phosphate (InP), Indium Gallium Arsenide (InGaAs) and Indium Gallium Arsenide Phosphate (InGaAsP). The simulation is based on solving couple mode equations that describe the interaction of the guided modes, and was achieved by using an academic software cavity modeling framework CAMFR which work on frequency domain eigenmode expansion techniques. Finally proposed structure successfully generates a secondary peak at certain thickness which serves as input signal at grating level.

1.0 INTRODUCTION

It is important to study and investigate the function of some compound semiconductors in optics technology such as Indium Phosphate (InP), Indium Gallium Arsenide (InGaAs), and Indium Gallium Arsenide Phosphate (InGaAsP) and design quantum-well laser grating coupler which is capable of generating it's input signal. Silicon technology is very wide in the world but it has some limitations such as decrease in band gap energy with increase in temperature, fixed band gap [1]. In an ideal condition lasers are operated only in single mode form to produce narrow output spectrum, which was achieved by using frequency selective dielectric mirror at the cleaved surface of the semiconductor to get cleaned output spectrum in single mode, such devices include distributed Bragg reflector (DBR), and distributed feedback (DFB) [2].

2.0 THEORY

Lasers: are ideally operated only in single mode form to produce narrow output spectrum by using distributed Bragg reflector (DBR) or distributed feedback (DFB) [3]. DBR is a

waveguide structure made from materials with different refractive index and consist of corrugated section in one end whereby partial reflection of the wave interfere constructively to give reflected wave when wavelength is double the corrugated period, the operation principles of DBR is base on the coupling between forward and backward propagation field of the same mode in the grating waveguide, for any wavelength in which the constructive interference occurred, the wavelength is called Bragg wavelength [2]. If two waves satisfied the phase condition so Bragg law can be express as : $m = \frac{\lambda_B}{n} = 2\Lambda$, where m is the order of coupling, Λ is the grating period, λ_B is the Bragg wavelength and n is the refractive index of the materials. DFB is a laser structure in which the radiation is applied from the active region to the guiding layer along the whole cavity length in order to obtain optical gain, the principles of it operation is difference because the radiation is fed from active layer will be manipulate and fed to the guiding layer along the whole cavity length that

the whole cavity length so that corrugated medium will produce optical gain and constructive interference occurred at wavelength almost equal to the Bragg wavelength. The relationship between DFB wavelength and Bragg wavelength will be:

$\lambda_{DFB} = \lambda_B + \frac{\lambda}{2nL}$ where n is the effective index of the mode, L is the effective length of diffraction grating, λ_{DFB} is the DFB wavelength and λ_B is the Bragg wavelength [2].

Optical waveguide: is a structure with three layers (core, substrate and cladding) in which the propagation of light along the waveguide can be describe in terms of a set of guided electromagnetic waves called modes of a waveguide which is exchanging power if perturbation is applied to it and couple the light out to fiber [4].

Eigenmode Expansion: is a tool for solving Maxwell's equation which is use for calculating electromagnetic propagation based on local modes of the structure [5]. Refractive index of the layers that are not changing in z -direction and can be expressed as:

$$E(x, y, z) = e_m(x, y)e^{j\beta_n z} \quad (1)$$

For guided mode which is describe as lossless mode and radiation mode are associated with losses of optical power, the Maxwell's equation of such waveguide can be express in superposition of forward and backward propagating mode as:

$$E(x, y, z) = \sum_{k=1}^m (a_k e^{j\beta_k z} + b_k e^{-j\beta_k z}) E^k(x, y) \quad (2)$$

$$E(x, y, z) = \sum_{k=1}^m (a_k e^{j\beta_k z} - b_k e^{-j\beta_k z}) H_k(x, y) \quad (3)$$

Where a_k and b_k are forward and backward amplitude of the field profile respectively $E_x(x, y)$ and $H_x(x, y)$ are the modes of filed profile in x and y -direction respectively Equation (2) and (3) are the exact solution of Maxwell's equation with forward and backward propagation mode respectively which has direct relation with the incident, reflection and transmission of light in electromagnetic medium such as waveguide.

(a) Coupling into Fiber: The major problem of nanophotonics is the coupling light into or out of the waveguide by means of optical

fiber. This problem arises from mode mismatch of nanowire in nanometer and single mode fiber in microns. Some of the solution to this 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. The Bragg equation that describes the modes of operation for the grating at a particular coupling angle can be expressed as [6].

$$n_{eff} = n_{top} \sin(\theta_c) + m \frac{\lambda}{\Lambda} \quad (4)$$

Where n_{eff} is the effective index of the grating

n_{top} is the effective index of the material

θ_c is the coupling angle measured perpendicular to the surface

m is the diffraction mode

λ is the wavelength of the incident light

Λ is the grating period

(b) Perfectly Matched Layer (PML): Is an artificial and imaginary cladding thickness boundary that can absorb radiation travelling toward the walls without introducing any additional parasitic reflection regardless of wavelength, incidence angle or polarization of the incident light. The larger the imaginary components in absolute value of the thickness, the stronger the absorption [7].

(c) Optical Simulation: Modeling and simulation of optical devices is a model that describe Overall optical behavior of complex optical structure like vertical cavity surface emitting lasers and devices that incorporate crystals. Optical simulation can be use in different types of applications such as lens design, thin film design and physical optic simulation. Several methods can be applied for modeling optical devices such as finite difference time domain (FDTD), and eigenmode expansion method (EEM) e.t.c [8].

- (d) Cavity Modeling Framework (CAMFR): CAMFR is a fast flexible, full-vectorial Maxwell equation solver, it is powerful and easy to tackle general electromagnetic problems. Its main focus is the simulation of optical devices, lasers, light emitting diodes. Contrary to other traditional approaches like Finite-Difference Time-Domain (FDTD), CAMFR is not based on special discretisation of finite differences, but rather on frequency-domain eigenmodes in each z-invariant layer of the structure. Also it utilizes python language script to describe the structure to be simulated and perform calculation [9].
- (e) Silicon-on-Insulator (SOI): SOI emerges as the interesting platform for integrated nanophotonics due to the high refractive index difference between the silicon core and oxide cladding, but one of the drawbacks of the high index is the large mismatch in mode size and shape between the fundamental mode of SOI waveguide and mode of optical fiber. This problem can be resolved by using InP cladding with refractive index (3.1628) and InGaAsP material with refractive index 3.37 can act as a platform for integrated nanophotonic to reduce the problem of large mismatch in the mode.
- (f) Bragg Grating Coupler: Dielectric grating is widely used as directional couplers because it can be integrated with waveguide using planar photolithographic techniques to achieve high efficiency performance. A grating input/output coupler has a period on the order of optical wavelength and also

called second-order grating. The propagation constant of radiated beam and guided beam are related to the grating period and phase matching condition:

$$\beta_n \sin \theta_n = \beta + n \frac{2\pi}{\Lambda} \quad \text{and}$$

$\mu = N_{eff} \beta_0 - N_{eff} \frac{2\pi}{\Lambda}$, and radiated field varies as $\exp[i(\beta_n \sin \theta_n z + i\alpha - \omega t)]$. Where β_n is the propagation constant of the n -th order of the diffracted beam, Λ is the grating period, N_{eff} is the effective index of the refraction of the guided wave, β_0 is the unperturbed propagation constant in the waveguide, α is the radiated loss coefficient, and θ_n is the n -th order of the diffraction angle [11].

METHODOLOGY

Quantum – Well Laser Structure

Figure 3.1 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 phosphate material as bottom cladding, p-cladding layers of indium phosphate 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, also the structure is sandwiched in PML layers with 0.4 μm thickness. Table 3.1 summarizes the parameters of the QWL based on their index properties, assuming is a good cladding material at the surface while InP compound usually used inside the structure, also InGaAsP will serve as barrier or core due to its high refractive index.

Table 3.1 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

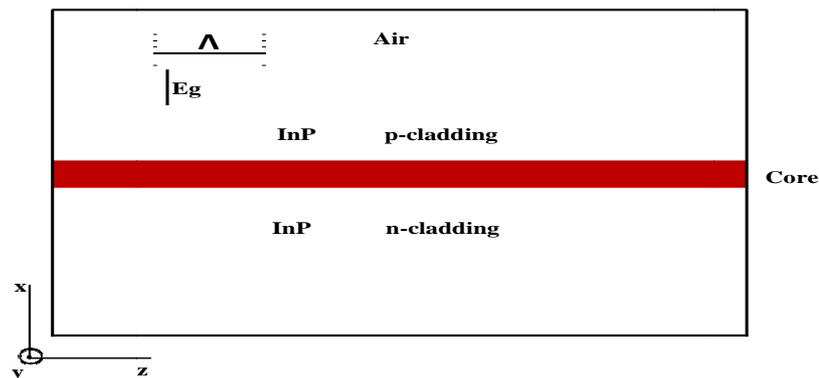


Figure 3.1 Quantum-Well Laser Structure

RESULTS

The main target is to design a quantum-well grating coupler structure which is capable of generating its own input signal. Quantum-well structure was simulated for TE polarization with

CAMFR software and obtained 3.0871 as effective index of the mode and optical field profile with highest peak point at position around 4 μm as shown in figure 4.1.

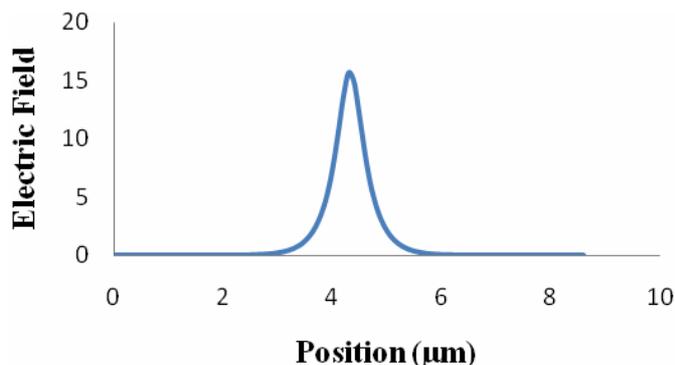


Figure 4.1 Optical Field for the Quantum-Well Laser Structure

To obtain the first order grating period (Λ_1) we simulated the structure for the reflectance versus grating period. The result was obtained when varying grating period from 0.1 μm to 0.3 μm. It was observed that, the maximum peak of reflectance occurred at a position around 0.243 μm along x-axis which indicates the first Bragg condition as shown in figure 4.2, since from the

Bragg law diffraction can occur only when $n\lambda = 2d\sin\theta = 2\Lambda_1$. Therefore the second Bragg is: $\Lambda_2 = 2\Lambda_1 = 2(0.243) = 0.486 \mu\text{m}$. So 0.486 μm was chosen as grating period for the simulation.

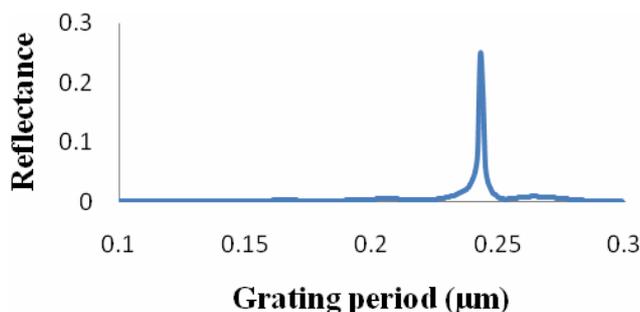


Figure 4.2 Reflectance versus Grating Period for Quantum-Well Laser

Also QWL structure was simulated for reflectance against wavelength to find the Bragg wavelength (λ_B). The result was obtained when varying wavelength from 1500 nm to 1600 nm. It was observed that, the maximum peak of reflectance occurred at

position around 1530 nm along x-axis which indicates the Bragg wavelength for the quantum-well laser structure as shown in figure 4.3. The result obtained for the Quantum-Well Laser structure is summarized in table 4.1.

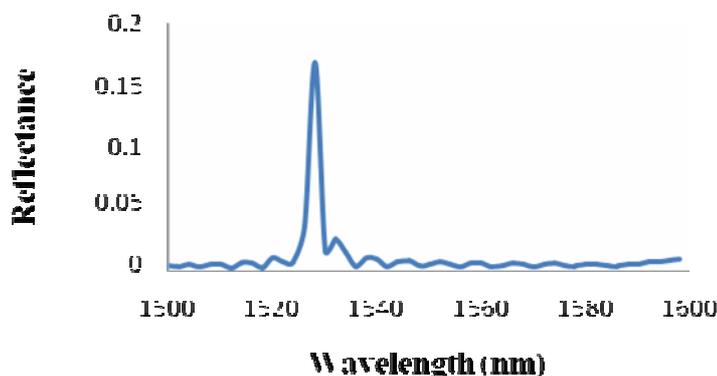


Figure 4.3 Reflectance Versus grating period for Quantum-Well Laser

Table 4.1 Quantum-Well Laser Simulation Result

Maximum field intensity unit	First Bragg period Λ_1 (μm)	Second Bragg Period Λ_2 (μm)	Bragg Wavelength λ_B (nm)
16.0	0.243	0.486	1530

The structure was divided into two sections top and bottom waveguide. The purpose is to simulate each section and get accurate parameters for the desired goal, Figure 4.4 represents the bottom waveguide of the quantum-well laser structure with top and

bottom cladding of indium phosphide. Table 4.2 contains the summary of parameters for the bottom waveguide. The result obtain was 3.1977 as effective index and optical field of the mode with maximum peak around $4.0 \mu\text{m}$ as shown in figure 4.5.

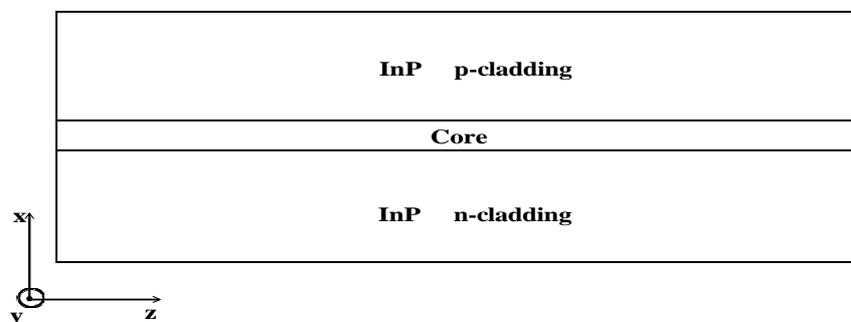


Figure 4.4 Bottom Waveguide

Table 4.2 Parameters for the Bottom Waveguide

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

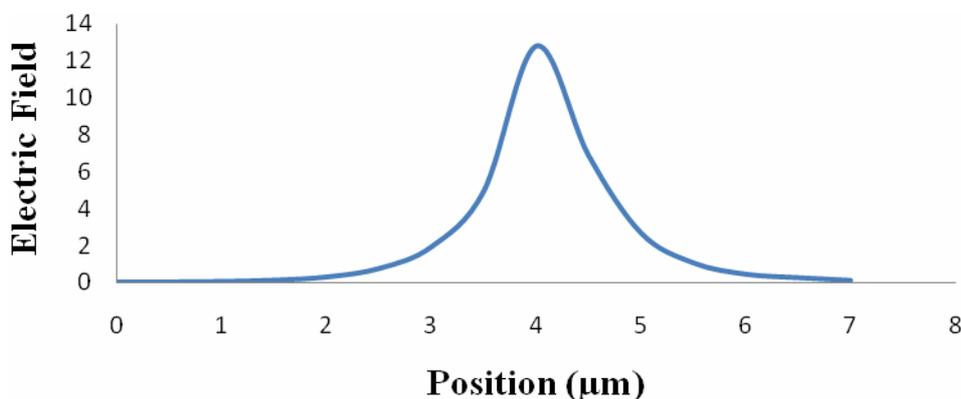


Figure 4.5 Optical Field for the Bottom Waveguide

To obtain the required thickness of the InGaAsP, the upper waveguide which comprise of p-cladding layer of indium phosphate material as bottom cladding, air as top cladding, and indium gallium arsenide Phosphate core as active layer as in figure 4.6. With the parameters in table 4.3, figure 4.6 was simulated and obtained the result when varying effective index and InGaAsP

thickness, the result from figure 4.7 shown that from the graph, the effective index of the top waveguide is approximately equal to that of bottom waveguide at position around $0.375 \mu\text{m}$, therefore instead of $0.05 \mu\text{m}$ InGaAsP thickness, we choose $0.375 \mu\text{m}$ as a thickness of InGaAsP for the simulation.

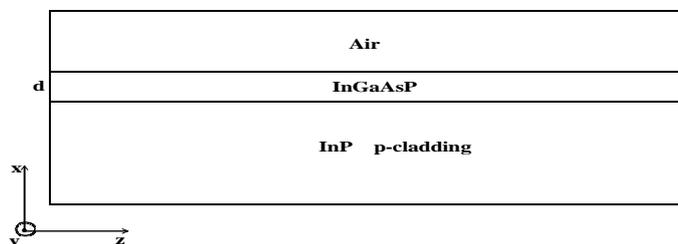


Figure 4.6 Top Waveguide

Table 4.3 Parameters for the Top Waveguide

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

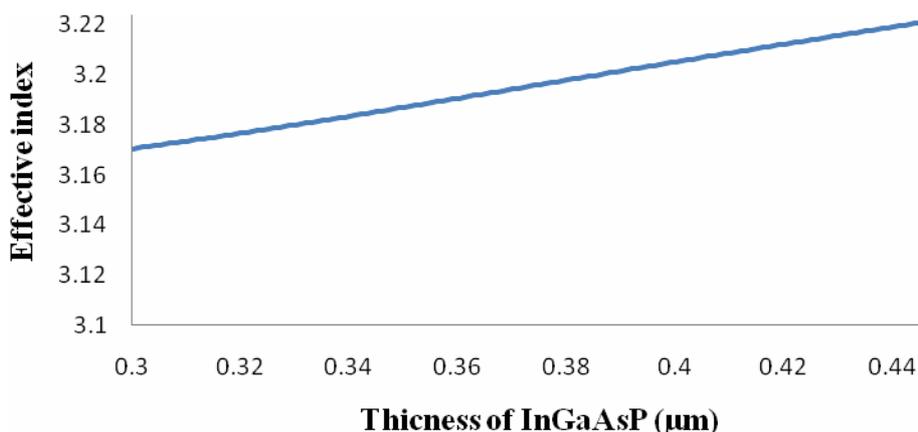


Figure 4.7 Index Variations for the Top Waveguide

Proposed Structure

To obtain the optical electric field of the proposed structure, top and bottom waveguide was combined with grating teeth at InGaAsP layer as shown in figure 4.8 and parameters in table 4.4 in order to obtain the generated input

Signal at the grating layer. It was successfully achieved that, the optical electric field of the proposed structure generated a secondary peak at position around 6.9 μm which serve as input signal of the grating coupler at InGaAsP layer as shown in figure 4.9.

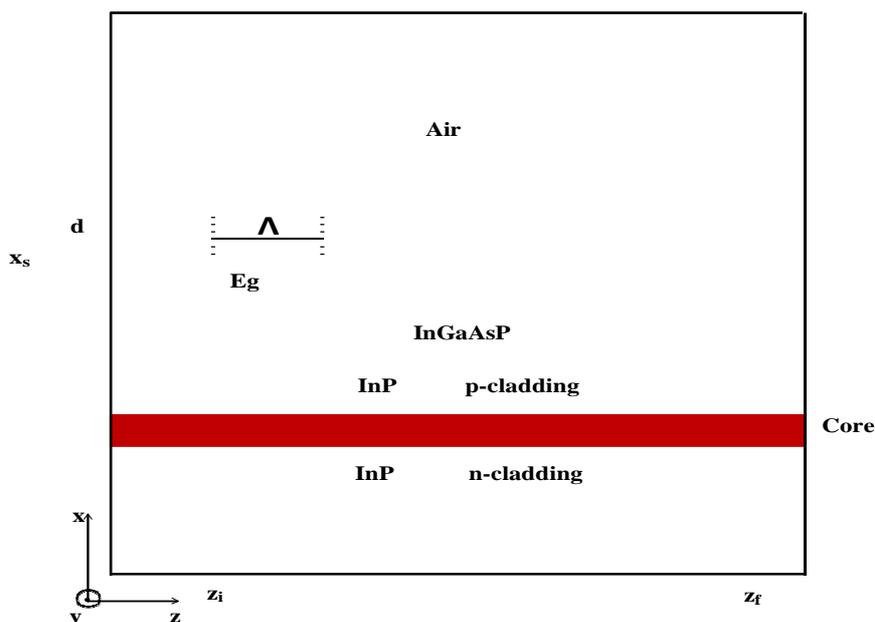


Figure 4.8 Complete Waveguide for the Proposed Structure

Table 4.4 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

It was successfully achieved that, the optical electric field for the proposed grating coupler generated a secondary peak at position around 6.9 μm which serve as input signal of the

grating coupler at InGaAsP layer as shown in figure 4.9.

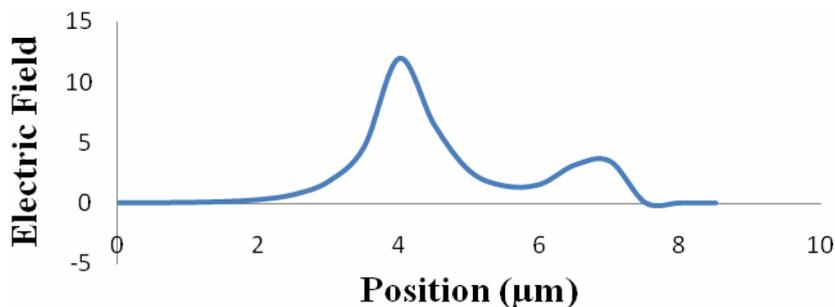


Figure 4.9 Optical Field for the Proposed Structure

For comparison the result obtained for second bragg condition and bragg wavelength for the proposed structure is similar with the one obtained from the initial quantum-well laser

structure, this indicate that the properties of the material still remain the same as shows in figure 4.10 and 4.11

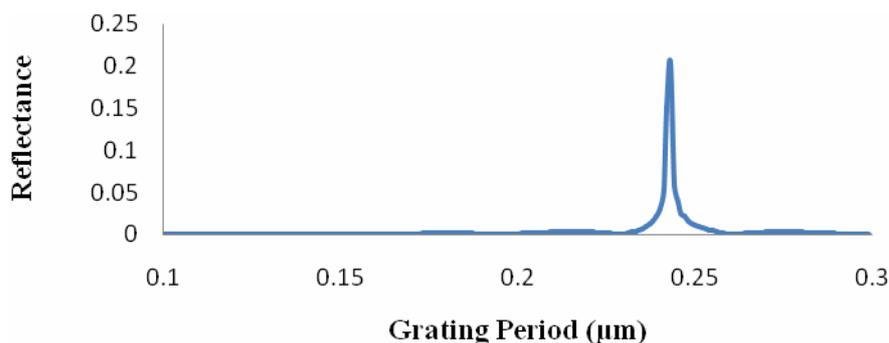


Figure 4.10 Reflectance Versus Grating Period for the Proposed Structure

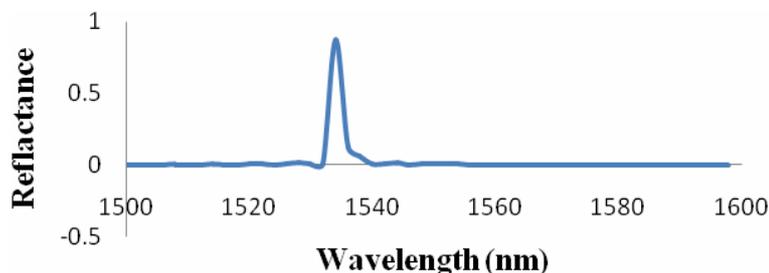


Figure 4.11 Reflectance Versus Wavelength for the Proposed Structure

4.2 Comparison of the Results

As observed from simulation results, the maximum field intensity for both structures occurred at position around 4.0 μm but

secondary peak was generated at position around 6.9 μm to serve as input signal at InGaAsP grating layer.

instead of sending it directly as in silicon or silicon oxide grating coupler, and other properties like effective index, bragg wavelength and second bragg condition remain

the same. Table 4.5 contains the summary of the result for both quantum-well laser and proposed structure.

Table 4.5 Comparison of Simulation Results

Structure	Effective index	Max field	$\Lambda_1(\mu\text{m})$	$\Lambda_2(\mu\text{m})$	$\lambda_B(\text{nm})$	Position of secondary peak (μm)
Quantum-well laser	3.1902	14.0	0.243	0.486	1530	NIL
Proposed Structure	3.1977	12.0	0.243	0.486	1530	6.0

4.0 Conclusion

In this paper we achieved in designing a special quantum-well laser grating coupler that can generate it own input signal form the fundamental mode at grating layer unlike traditional silicon-on-insulator grating coupler where by the input signal use to be send externally. Also it was achieved that, laser technology by using semiconductor now can overtake silicon technology to solve the problem of high index difference between silicon and it oxide. At the same time effect of

fundamental mode on the performance of the quantum-well laser grating structure was evaluated. The simulation with CAMFR software was achieved. It was recommended that further research by considering grating coupler parameters like grating period, Bragg wavelength, fill factor, number of mode in series expansion and cladding materials can be optimized to produce out coupled signal to optic fiber structure through grating layer.

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