

Laser Fabrication by Using Photonic Crystal

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Abstract— This paper involves the calculation for composition of different layer used in laser structure and the simulation of cavity, formed by creating air columns in the InGaAsP medium, for square lattice. The aim of this project is to fabricate approximately zero threshold current lasers. This project involves FDTD simulation for optimizing dimension of the device, fabrication of laser structure and finally characterization of the device structure.

Index Terms—Photonic band gap, zero threshold current, FDTD simulator.

INTRODUCTION

Photonics crystals relate to photon as semiconductor materials are for electrons. Photonics crystal has a band structure that contains a photonics band gap due to the interaction of photons with a periodic potential, which is caused by the difference in refractive index in the structure. The main motivation to work in PBG materials are minimum loss through tight bend and easy tailoring of photonic crystal properties. Two-dimensional photonics crystal allows great miniaturization in the design of Photonics integrated circuits, which will reduce the cost of future optical communication system.

Photonics crystals are two and three dimensionally periodic structures with high refractive index contrast. The existence of a photonics band gap, a frequency range in which propagation of light is prevented in all directions, makes PBG structures very useful in applications where spatial localization of light is required.

When a point defect is created in a photonic crystal, it is possible for that defect to pull a light mode into the band gap. Because such a state is forbidden from propagating in the bulk crystal, it is trapped. The mode decays exponentially into the bulk. Such a point defect, or resonant cavity, can be utilized to produce many important effects. Application of resonant cavities can be applied to enhance the efficiency of lasers;

taking advantage of the fact that the density of states at the resonant frequency is very high (approaches a delta function).

Photonics band gap properties can be tailored by changing –

1. Lattice parameter of the crystal
2. Radius of pillars or holes
3. Refractive Index of the material

By changing the size or the shape of the defect, photonic band gap can be changed. By increasing the amount of dielectric in the defect, one can pull down higher-order modes. The defect was created by increasing the radius of the center rod.

This makes PBG material very useful for the application. Various scientific and engineering applications, such as control of spontaneous emission, zero-threshold lasing, sharp bending of light are expected by using the photonic band gap and the artificially introduced defect states and/or light-emitters.

The vertical-cavity surface-emitting laser is now recognized as a very important light source for local area networks. However, there is a limitation of available power, typically to less than a few mill watts for complete single longitudinal and lateral-modes.

To overcome this problem, a square photonic crystal lattice is used in the laser structure. The PBG containing N-type InP substrate is bonded with InGaAsP/InP by using wafer fusion technique. Active layers contain multiple quantum well and quantum barrier sandwiched between N and P type InP layer.

The photonic crystal enabled them to form a stable laser [1] cavity in which the crystal controlled the propagation of light in the X- and Y-directions, yielding a two-dimensional standing wave; the lattice points determine both the lasing wavelength and the beam pattern. Our aim is to design a new photonic crystal laser for telecommunications applications.

FDTD SIMULATION:

FDTD simulator is used (Finite difference Time difference) to study the interaction of electromagnetic fields with two-dimensional PBG structures. The FDTD [2-3] simulator is a full-wave solution to the vector Maxwell equations. It can incorporate complicated scatterers and materials such as the PBG structures with great flexibility. In this manner, the basic electromagnetic properties of the PBG structures can be determined over a broad bandwidth of frequencies in a single run. This allows a determination of the pass and stop bands of the PBG from an essentially impulse excitation of the PBG

structure. The response of the same structure at selected frequencies, such as the resulting electric field patterns, can then be evaluated in detail.

Since the TE mode is a favorable mode for air columns embedded in the dielectric medium so we are restricted to the TE polarization, which requires the E_y , H_x , and H_z field components. The associated FDTD equations are obtained with the standard staggered grid, leap-frog time integration scheme [4] and are given by the expressions-

$$H_x^{n+\frac{1}{2}}\left(i, k+\frac{1}{2}\right)=\frac{2\mu-\sigma_m\Delta t}{2\mu+\sigma_m\Delta t}H_x^{n-\frac{1}{2}}\left(i, k+\frac{1}{2}\right)+\frac{2\Delta t}{2\mu+\sigma_m\Delta t}\frac{1}{\Delta z}\left[E_y^n(i, k+1)-E_y^n(i, k)\right]$$

$$H_z^{n+\frac{1}{2}}\left(i+\frac{1}{2}, k\right)=\frac{2\mu-\sigma_m\Delta t}{2\mu+\sigma_m\Delta t}H_z^{n-\frac{1}{2}}\left(i+\frac{1}{2}, k\right)+\frac{2\Delta t}{2\mu+\sigma_m\Delta t}\frac{1}{\Delta x}\left[E_y^n(i+1, k)-E_y^n(i, k)\right]$$

$$E_y^{n+1}(i, k)=\frac{2\epsilon-\sigma_e\Delta t}{2\epsilon+\sigma_e\Delta t}E_y^n(i, k)-\frac{2\Delta t}{2\epsilon+\sigma_e\Delta t}J_y^{n+\frac{1}{2}}(i, k)+\frac{2\Delta t}{2\epsilon+\sigma_e\Delta t}\frac{1}{\Delta z}\left[H_x^{n+\frac{1}{2}}\left(i, k+\frac{1}{2}\right)-H_x^{n-\frac{1}{2}}\left(i, k-\frac{1}{2}\right)\right]-\frac{2\Delta t}{2\epsilon+\sigma_e\Delta t}\frac{1}{\Delta x}\left[H_z^{n+\frac{1}{2}}\left(i+\frac{1}{2}, k\right)-H_z^{n-\frac{1}{2}}\left(i-\frac{1}{2}, k\right)\right]$$

The superscript n labels the time steps while the indices i and k label.

- Where ϵ = dielectric constant of the medium
 μ = magnetic permeability of the medium
 σ_E = electrical conductivity of the medium
 σ_M = magnetic conductivity of the medium
 Δt = increment step for time
 Δx = increment step along x direction
 Δz = increment step along z direction

Selection of Design Parameter

The aim is fabricate photonic cavity laser for telecommunication wavelength i.e. 1.55 micron. Photonic cavity laser offers the benefit of low noise, due to compact size, and high spontaneous emission coupling factor of the micro cavity. Flexibility in geometry allows fine tuning of defect mode radiation pattern as well as emission wavelength. This device is also useful where crystal growth of high index contrast mirrors is limited such as long wavelength vertical cavity surface emitting laser or blue green GaN based device [5]. Various materials available for laser fabrication are listed below-

- GaInP $\lambda=670\text{nm}$ Visible band
- AlInP $\lambda=584\text{nm}$
- Ternary AlGaAs (0.75-0.87 μm)
- Quaternary InGaAsP (1.1-1.6 μm)
- II-VI direct band gap: Hg CdTe
- IV-VI direct band gap: PbSnTe ($\lambda=3-35\ \mu\text{m}$)

We choose InGaAsP/InP material for our structure due to the relatively long emission wavelength and low nonradiative

surface recombination rate [6-7] of this material. Low nonradiative recombination rate is required for high gain. After choosing the material of our laser structure, the composition of different component in quaternary is to be determined. The direct energy gap E_0 (eV) of the quaternary at room temperature is extrapolated from the ternary data and given by Moon et al [8].

$$E_0(x, y) = 1.35 + (0.758x + 0.642)x + (0.101y - 1.101)y - (0.28x - 0.109y + 0.159)xy$$

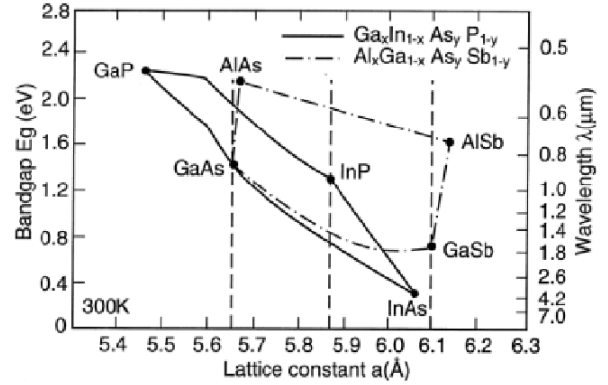


Fig (1). Bandgap vs. Lattice constant Curve

For a wavelength = 1.55 micron corresponding energy is 0.8eV, we choose our x and y value which satisfy the above equation.

Results are listed below-

x	y	Quaternary
0.1	0.59	In _{0.9} Ga _{0.1} As _{0.59} P _{0.41}
0.2	0.67	In _{0.8} Ga _{0.2} As _{0.67} P _{0.33}
0.3	0.76	In _{0.7} Ga _{0.3} As _{0.76} P _{0.24}
0.4	0.86	In _{0.6} Ga _{0.4} As _{0.86} P _{0.14}
0.5	0.96	In _{0.5} Ga _{0.5} As _{0.96} P _{0.04}

On the basis of these calculations composition of strained layer of InGaAsP, which act as a quantum well, is taken as x=0.53 and y= 0.99.

The critical layer thickness for InGaAsP layer is calculated by Matthews-Blakeslee [9] and People-Bean model [10].

According to Matthews-Blakeslee critical layer thickness is given by the expression-

$$d_c = \frac{b(1-\nu \cos^2 \theta)}{4\pi f(1+\nu) \cos \lambda} \left[\ln \left(\frac{d_c}{b} \right) + 1 \right]$$

Where b = burgers vector = $\frac{a_f}{\sqrt{2}}$

a_f is lattice parameter of InGaAsP film.

ν = Poisson ratio, and

$$f = \frac{a_f - a_s}{a_s} = \text{misfit parameter}$$

According to People Bean model critical layer thickness is given by the expression-

$$d_c = \frac{b(1-\nu)}{32\pi f^2(1+\nu)} \left[\ln \left(\frac{d_c}{b} \right) \right]$$

Design Structure:

P InP layer
Unstrained InGaAsP
Strained InGaAsP
Unstrained InGaAsP
Strained InGaAsP
Unstrained InGaAsP
N InP Substrate

Fig (2). Layer Structure for Laser Device

Multiple quantum well active layer is used between the N and P type InP layer. A square photonic crystal lattice is used in the laser structure. An unstrained layer of InGaAsP acts as quantum barrier and compressively strained layer of InGaAsP acts as quantum well. Compressive strained layer [11] of InGaAsP provides the following benefit

- Reduction of Auger recombination rate in device.
- Reduction of transparency carrier density in laser.

An unstrained layer of InGaAsP is lattice matched with InP substrate and for modeling and designing InGaAsP QWCs, it is important to know some fundamental properties of the material system InGaAsP such as lattice constant and band-gap as a function of composition. The lattice constant of the quaternary can be deduced from the well-known binary materials with the following values

$$a_0(\text{GaAs}) = 5.6533 \text{ \AA}$$

$$a_0(\text{InP}) = 5.8688 \text{ \AA}$$

$$a_0(\text{GaP}) = 5.4512 \text{ \AA}$$

Vegard's law, which states that the composition and lattice constant have a linear relationship, holds for the quaternary material system $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$ [12]. For any composition of $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$ this gives a lattice constant of

$$a_0(x, y) = 5.8688 - 0.4176x + 0.1896y + 0.0125xy$$

For the composition lattice-matched to the InP substrate, one obtains a relationship of the composition fractions given by

$$x = \frac{0.1896y}{0.4176 - 0.0125y}$$

For the unstrained layer of InGaAsP which act as a quantum barrier, composition of InGaAsP is taken as $x=0.47$ and $y=0.94$.

Simulation Result:

The PBG structure used in our investigation is a 10×9 square lattice of air columns each of which has an infinite length along the y-axis. These air columns are surrounded by InGaAsP with a relative permittivity of 11.56. The cavity structure is formed by removing one column of rods. This type of photonic structure favors TE mode while square lattice of dielectric columns embedded in air medium supports TM mode [13]. As the radius of air holes is increased, the TE mode gap frequency increases due to the reduction in effective dielectric index of the medium and gap frequency varies inversely to square root of the dielectric of the medium.

The aim is to design cavity for communication wavelength i.e. $1.55 \mu\text{m}$. A value of inter-hole spacing, a , and radius of holes, r , is to find out to get maximum output and least scattering, provided width of the wave-guide should be of the order of wavelength.

The steps taken in the computation are as follows -

1. Choose the wavelength for which cavity is to be designed.
2. Starting value of cell size, a , can be taken $a \approx \frac{\lambda}{2}$
3. $r = ma$ where $0 < m \leq 0.5$

With starting value of cell size $0.775 \mu\text{m}$, one can vary the radius of air columns in steps of $0.1 \mu\text{m}$ and next simulation can be performed for another value of cell size. With the choice of $\lambda = 1.55$ micron meter, one obtains $a = 1 \mu\text{m}$ and $r = 0.3 \mu\text{m}$ for the TE mode and $a = 1 \mu\text{m}$ and $r = 0.35 \mu\text{m}$ for the TM mode. We formed the cavity by removing 2 air columns in X direction and 2 along Z direction. This PBG structure is two dimensional by design.

We simulated for different set of cell size parameter with variation in radius of holes for TM mode and TE modes. Simulation Results are presented below.

For TE Mode: radius of air column = $0.3 \mu\text{m}$

Cavity size = 2×2

while figure (3) shows the variation of H_y for TM mode.

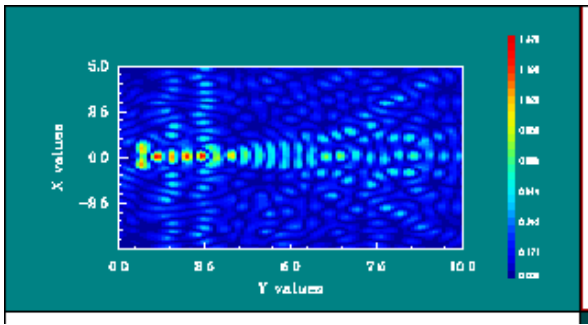


Fig (3). E_y component of field for TE mode
Refractive Index Profile:

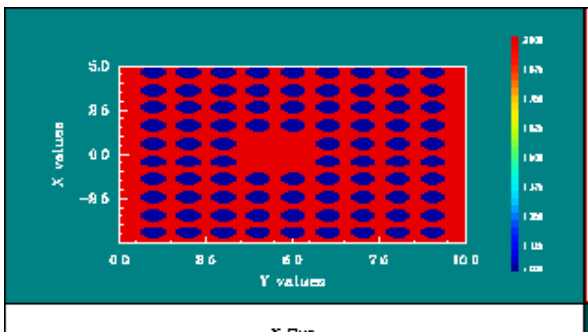


Fig (4). Refractive Index profile for TE mode

For TM Mode: Air column radius = $0.35 \mu\text{m}$
and cell size parameter = $1.0 \mu\text{m}$
Cavity size = 2×2 ;

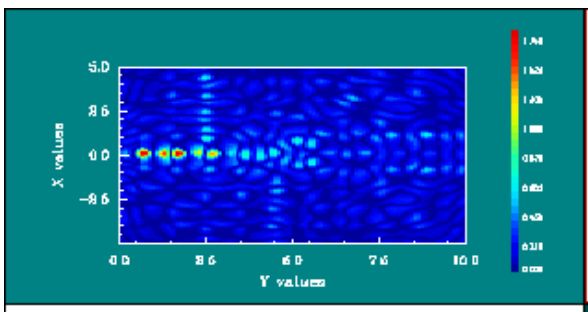


Fig (5). H_y component of field for TM mode

Discussion:

We have done simulation for different value of $r/a=0.1, 0.2, 0.3, 0.4$ and $0.5\mu\text{m}$ and observed that most of the energy is confined in the cavity for $r/a=0.3\mu\text{m}$ in case of transverse electric mode, which is favored for air columns surrounded by

dielectric medium. The fig (1) and fig (2) shows the variation of E_y and refractive index profile for TE mode respectively

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