

Investigation of Optical Gain of Type-I and Type-II Nano heterostructure

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Abstract: This paper deals the investigation of optical gain characteristics of a single quantum well of material composition $InGa_{0.76}N_{0.24}$ (Type-I) sandwiched between the barriers of material composition GaN. The structure is grown on GaN substrate and $In_{0.53}Ga_{0.47}As$ (Type-II) sandwiched between the barriers of material composition $GaAs_{0.51}Sb_{0.49}$. The structure is grown on InP substrate. Apart from optical gain, we have also investigate energy band structure along with valance and conduction band envelope functions and the comparative picture of the two heterostructures (Type-I and Type-II) with in two polarization i.e Transverse electric(TE) and Transverse Magnetic(TM). The behavior of quasi Fermi levels for the valance and conduction band has also been investigated. For optical gain simulation, the heterostructure has been modeled with the help of six band k.p method. The 6×6 diagonalized K.p Hamiltonian has been solved to evaluate the light and heavy hole energies. For the injected carrier density of $15 \times 10^{12}/cm^2$, the optimized optical gain is found $\sim 30320.21/cm$ at wavelength $0.93 \mu m$ and $\sim 12327.21/cm$ at wavelength $1.85 \mu m$ for Type-I and Type-II heterostructures respectively.

Keywords: Optical Gain, Type-I and Type-II, TE and TM mode, Heterostructures

1. Introduction

In the area of Optoelectronics, semiconductor heterostructures play a important role. Since two decades, the III- V semiconductors based quantum well heterostructure have been widely used for lasing applications[1]. Lasing heterostructures offer the improved performance in the terms of long wavelength, High intense beam output and switching speed. Due to minimal inter-modal delay effects and minimal losses, heterostructures semiconductor are very important for optoelectronic device applications[2-3]. For obtaining lasing, quantum well structure is most effective approaches. However, high carrier density is required for homogeneous quantum wells, to invert their population before any stimulated emission process. In this paper we investigate the Optical Gain of Type-I heterostructure $InGaN/GaN$ and Type-II heterostructure $InGaAs/GaAsSb$ which is capable of better carrier and optical confinement. P.A.alvi et al. have calculated the optimized optical gain with in TE mode $9000/cm$ at corresponding lasing wavelength of $1.95 \mu m$ under very high pressure[4]. The modal gain and optical losses have been studied within TE and TM modes by Rashmi Yadav et al. She also reported that maximum gain is achieved at the lasing wavelength $1.40 \mu m$ and $1.25 \mu m$ in TE and TM mode respectively[6]. In Recent Research, H.K Nirmal have studied that the various lasing characteristics like refractive index, differential gain and antiguiding factor in relation with the photonic energy with in TE and TM mode[7]. Emanuele et al. reported that Deep-UV optical gain in $AlGaIn$ -Based Graded index separate confinement heterostructure. He designed a graded Index laser double heterostructure with $AlGaIn$ in active region to enhance the optical confinement of heterostructures[8]. In [9] Wei Guo have reported that stimulated emission and optical gain for 250 nm emission from an $AlGaIn$ heterostructure. Hongping Zhao et al. analyzed that improved gain media self consistently for Type-II $InGaIn$ heterostructure[10-11].

2. Device Structure

The proposed model have a Two heterostructures i.e Type-I heterostructure $InGaN/GaN$ and Type -II heterostructure $InGaAs/GaAsSb$. For Type-I $InGaN/GaN$ heterostructure, single quantum well of width 4 nm of ternary compound $InGaN$ sandwiched between the barrier layer of GaN of 6 nm . The whole heterostructure has been grown on the substrate of binary compound GaN. For Type-II $InGaAs/GaAsSb$ heterostructure, single quantum well of width 4 nm of ternary compound $InGaN$ sandwiched between the barrier layer of GaAsSb of 2 nm . The whole heterostructure has been grown on the substrate of binary compound InP. Optical gain or material gain is the important properties of lasing heterostructures which is explained in different polarization mode. $InGaAs/GaAsSb$ 'W' type lasers on substrate has been investigated in [13]. Chia-Hao Chang et al. investigated the optical gain for $InGaAs/GaAsSb$ quantum well heterostructure[14-16]. Recently, Balie Chen et al. have reported the optimized wavefunction overlap and transition wavelength for $InGaAs/GaAsSb$ type-II quantum well heterostructure [17]. For the calculation of discrete energy levels within the conduction band, the single band effective mass equation can be used as

$$-\frac{\hbar^2}{2m_c^*} \nabla^2 \Psi + V_c \Psi = E_c \Psi \quad (1)$$

where Ψ is the envelope function \hbar is plank's constant, m_c^* conduction effective mass, V_c potential of conduction band, E_c is conduction band electron energy level. For calculation of discrete energy levels (i.e conduction electron and light and heavy hole levels) with in the quantum well heterostructure we have used 6×6 Hamilton matrix.

$$H_{6 \times 6}(k) = \begin{pmatrix} H_{3 \times 3}^+ & 0 & \vec{0} \\ \vec{0} & H_{3 \times 3}^- & \vec{0} \end{pmatrix} \quad (2)$$

where $H_{3 \times 3}^+$ and $H_{3 \times 3}^-$ can be expanded as (2) with $U = +$ or $-$ represents upper and lower blocks.

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$$H_{3,3}^U = - \begin{pmatrix} P+Q - V_h(Z) & R(k) \pm iS(k) & \sqrt{2}R(k) \pm \frac{i}{\sqrt{2}}S(k) \\ R(k) \pm iS(k) & P - Q - V_h(Z) & \sqrt{2}Q \pm i\sqrt{\frac{3}{2}}S(k) \\ \sqrt{2}R(k) \pm \frac{i}{\sqrt{2}}S(k) & \sqrt{2}Q \mp i\sqrt{\frac{3}{2}}S(k) & P + \Delta_{so} - V_h(Z) \end{pmatrix} \quad (3)$$

In (2) $V_h(Z)$ represents the unstrained valence band edge, Δ_{so} represents the spin-orbit split-off energy. Also $P = P(k) + P(\epsilon)$ and $Q = Q(k) + Q(\epsilon)$ is expanded in equations (4) and (5), also, $S(k)$ and $R(k)$ are expanded in equation (6)

$$P(k) = \frac{\hbar^2}{2m_0} \gamma_1 (k_x^2 + k_y^2) \quad (4a)$$

$$P(\epsilon) = -a_v (\epsilon_{xx} + \epsilon_{yy} + \epsilon_{zz}) \quad (4b)$$

$$Q(k) = \frac{\hbar^2}{2m_0} \gamma_2 (k_x^2 - 2k_z^2) \quad (5a)$$

$$Q(\epsilon) = -\frac{b}{2} (\epsilon_{xx} + \epsilon_{yy} - 2\epsilon_{zz}) \quad (5b)$$

$$S(k) = \frac{\hbar^2}{2m_0} \sqrt{\frac{3}{2}} \gamma_3 \frac{\epsilon_{yz} + \gamma_3}{2} k_x^2 \quad (6a)$$

$$R(k) = \frac{\hbar^2}{2m_0} \sqrt{3} \gamma_3 k_x k_z \quad (6b)$$

For quantum well structures optical gain coefficient can be written as

$$G(E) = \frac{q^2 M_B^2}{E \epsilon_0 m_0^2 c h n_{eff} W}$$

$$\sum_{i,j} \int_{E_g}^{E_{gb}} m_{r,ij} C_{ij} A_{ij} (f_c - f_v) L(E - E') dE \quad (7)$$

Where E is the optical energy, q is the electron charge, n_{eff} the effective refractive index of the laser structure, w width of the quantum well, i and j the conduction band and valence band quantum numbers, C_{ij} is the spatial overlap factor, ϵ_0 permittivity, M_B^2 bulk momentum.

3. Results and Discussion

Fig 1 and fig 2 shows the wavefunction waveform for the Type-I and Type-II heterostructure respectively which shows the expected conduction and valence band alignment. To know the valence subbands energy level six band hamilton is used.

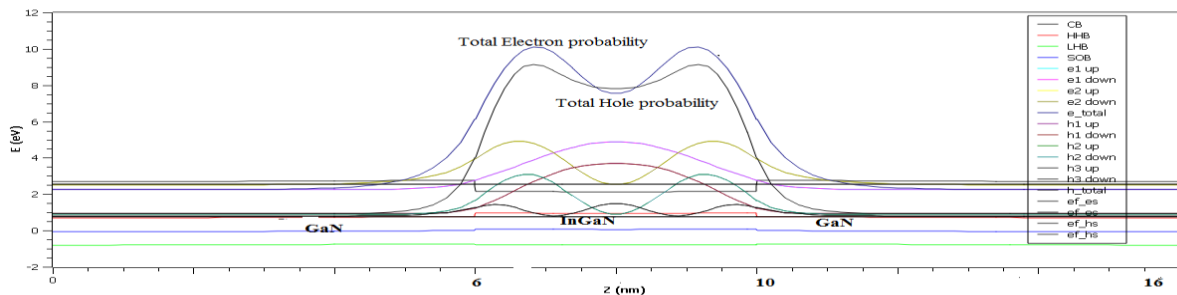


Figure 1: Wavefunction waveform for Type-I heterostructure InGaN/GaN

From the figure 1 it is clear that electron confinement at the quantum well is good as compared to hole confinement for type-I heterostructure.

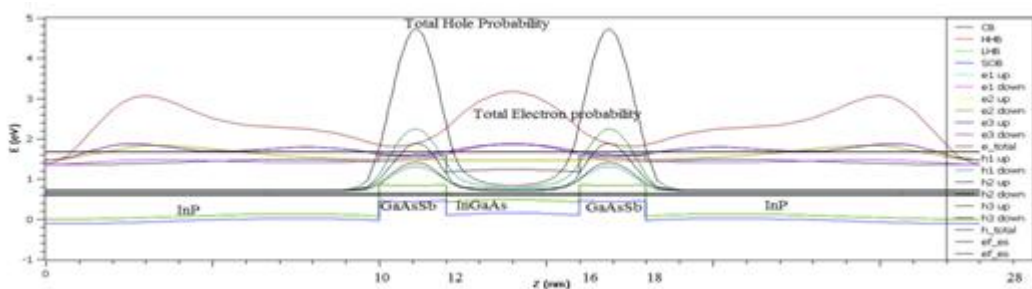


Figure 2: Wavefunction waveform for Type-II heterostructure InGaAs/GaAsSb

But figure 2 shows the hole confinement at quantum well is good as compared to electron confinement for type-II heterostructure.

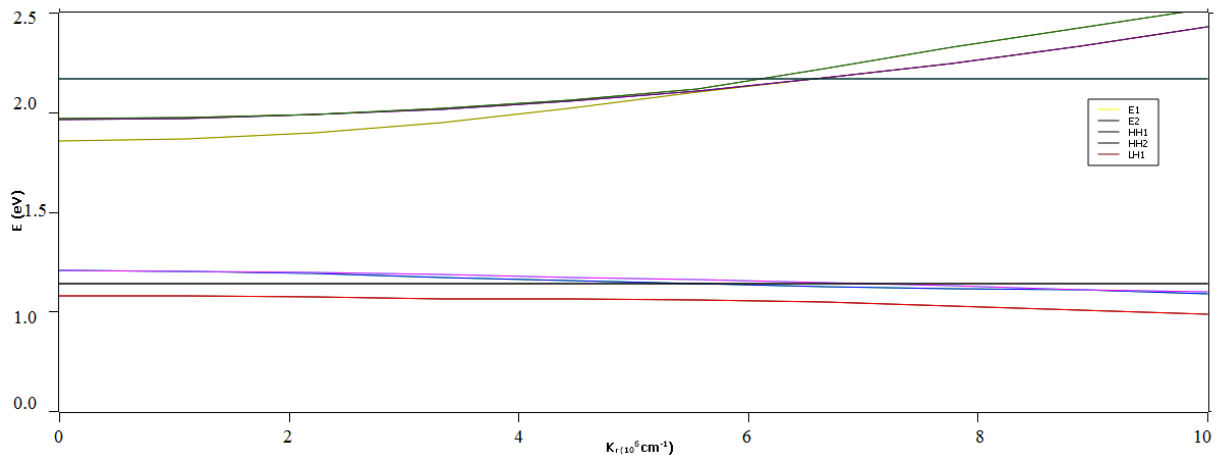


Figure 3: Conduction and valence band dispersion profiles for Type-I heterostructure InGaN/GaN at 300K

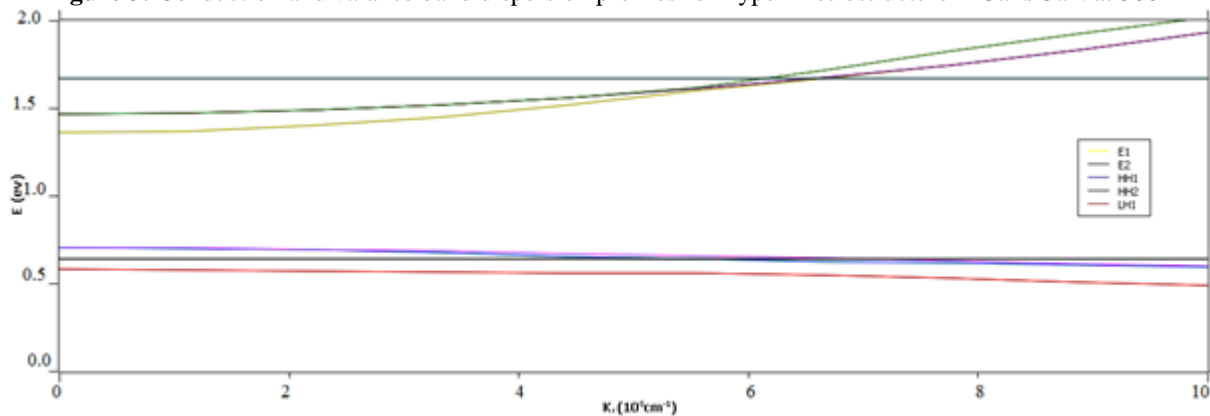


Figure 4: Conduction and valence band dispersion profiles for Type-II heterostructure InGaAs/GaAsSb at 300K
 TE mode

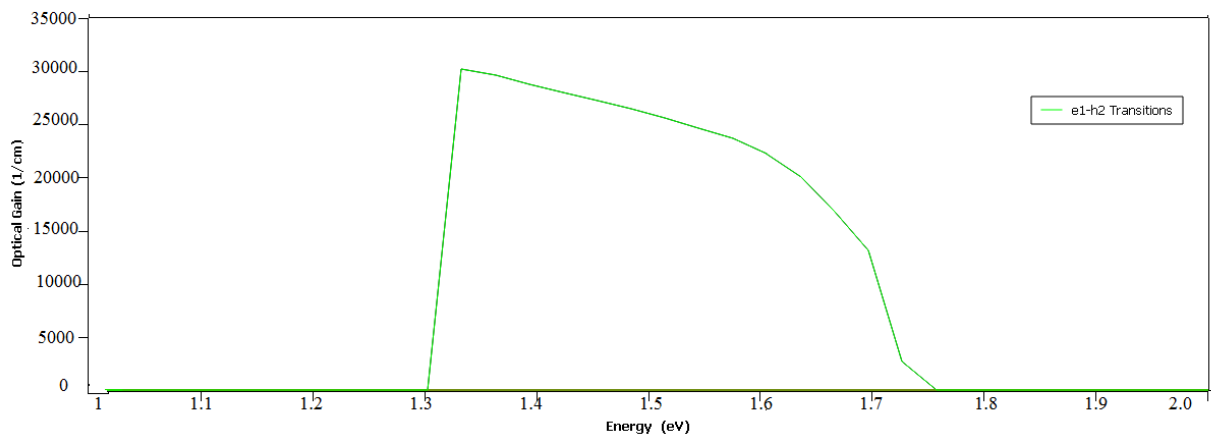


Figure 5: Optical gain as a function of photon energy for Type-I heterostructure InGaN/GaN at 300K

In TE mode for Type-I heterostructure InGa_{0.76}N_{0.24} the optical gain is found for e1-h1 transition is ~ 4.961/cm (not shown in waveform) at corresponding lasing wavelength 0.775μm, for e1-h2 transition is 30320.21 at corresponding

lasing wavelength 0.93μm. By observation it is found that the optical gain is negligible in e1-h1 transition as compared to e1-h2 transition.

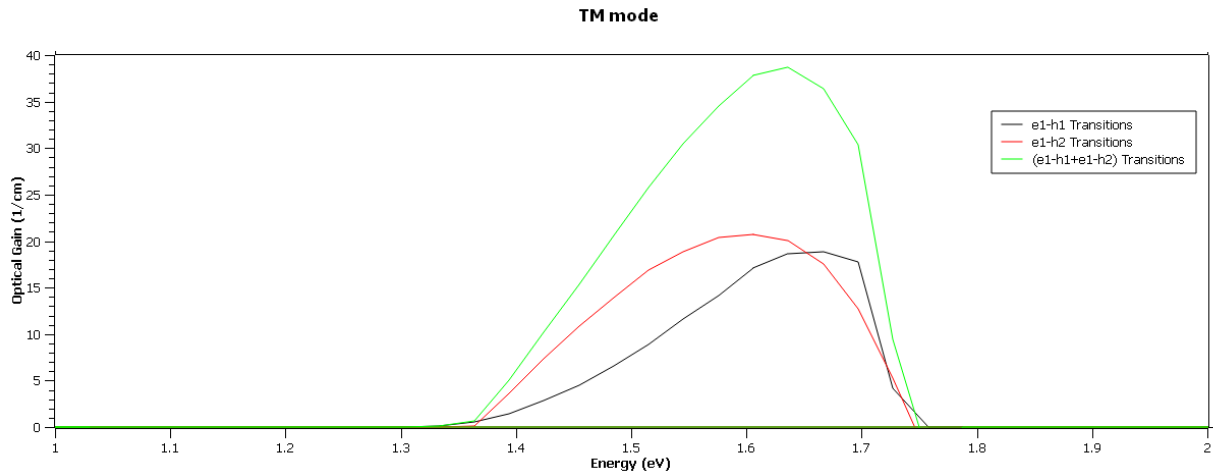


Figure 6: Optical gain as a function of photon energy for Type-I heterostructure InGaN/GaN at 300K

From figure 6 it is observed that the optical gain for Type-I InGaN/GaN heterostructures in TM mode is $\sim 18.8933/\text{cm}$ at corresponding lasing wavelength $0.74 \mu\text{m}$ for e1-h1 transition and $\sim 20.6839/\text{cm}$ at lasing wavelength $0.77 \mu\text{m}$ for e1-h2 transition. The total (e1-h1+e1-h2) optical gain is $\sim 38.6765/\text{cm}$ at corresponding wavelength $0.76 \mu\text{m}$. By observation it is clear that the maximum optical gain is found in TE mode for Type-I InGaN/GaN heterostructure.

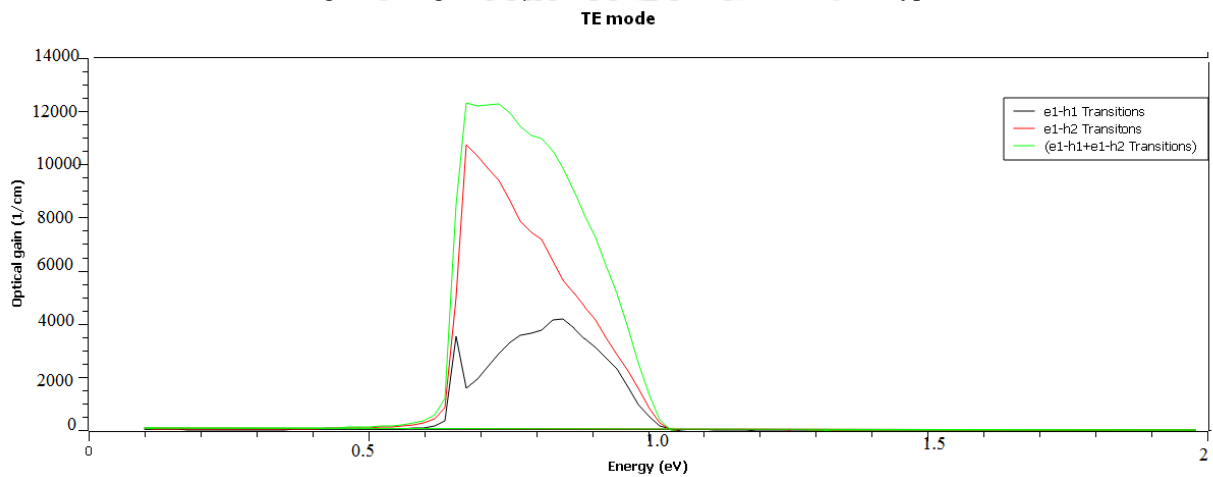


Figure 7: Optical gain as a function of photon energy for Type-II heterostructure InGaAs/GaAsSb at 300K

For Type-II heterostructure InGaAs/GaAsSb the optical gain is found $\sim 4193.308/\text{cm}$ at corresponding wavelength $1.47 \mu\text{m}$ (e1-h1 transition) and $\sim 10741.74/\text{cm}$ at corresponding wavelength $1.85 \mu\text{m}$ (e1-h2 transition). The total optical gain is $\sim 12327.2/\text{cm}$ at corresponding wavelength $1.85 \mu\text{m}$ (e1-h1+e1-h2 transition). From the figure it is concluded that the optical gain is less for e1-h1 transition as compared to e1-h2 transition.

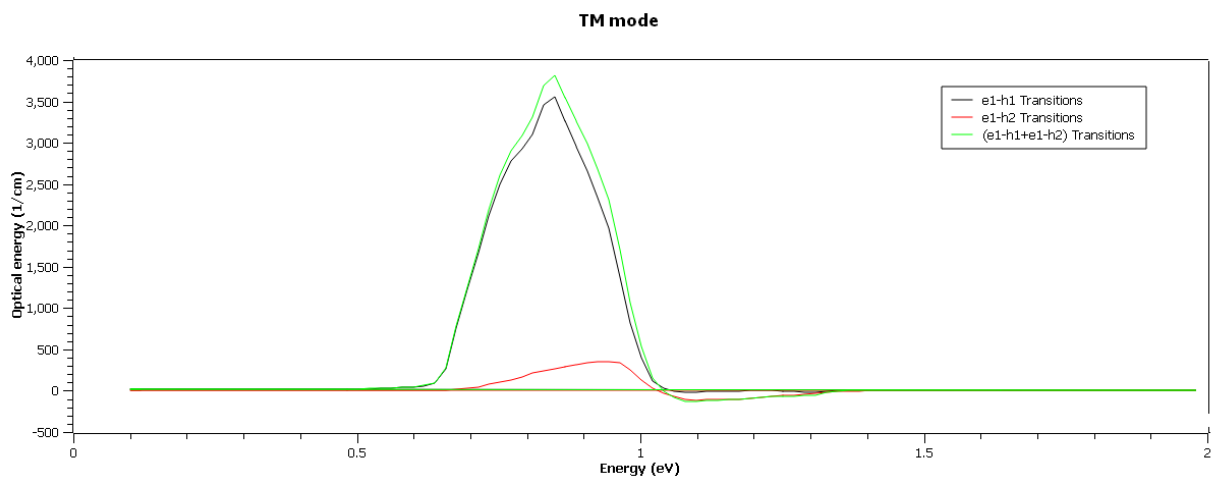


Figure 8: Optical gain as a function of photon energy for Type-II heterostructure InGaAs/GaAsSb at 300K

For e1-h1 transition (Type-II heterostructure InGaAs/GaAsSb) optical gain is found ~ 3555.16/cm at corresponding lasing wavelength 1.47 μm and for e1-h2 transition the optical gain is ~ 347.10/cm at corresponding lasing wavelength 1.34 μm . The total optical gain is found ~ 3819.18/cm at corresponding lasing wavelength 1.47 μm . From figure 7 it is clear that the maximum optical gain is achieved for e1-h1 transition. In TE mode type-II heterostructure the maximum optical gain is found for e1-h2 transition whereas in TM mode type-II heterostructure the maximum optical gain is found for e1-h1 transition which is the just reverse case from the TE mode.

4. Conclusions

We have investigated that Optical Gain of the two heterostructures i.e Type-I and Type-II heterostructures. For the type-I heterostructure maximum optical gain is found ~ 30320.21/cm at photonic energy 1.333eV within TE mode whereas in Type-II heterostructure maximum optical gain is found ~ 12327.21/cm at photonic energy 0.675eV within TE mode. On the behalf of comparative study of both the Type-I and Type-II heterostructures, it is suggested that Type-I heterostructures is better than type-II heterostructure due to its maximum optical gain.

By the investigation of both heterostructures Type-I and Type-II we found that maximum optical gain is obtained in Type-I heterostructure within TE mode.

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