An Enhanced Simulative Study on SWIRGs of $In_{0.68}Al_{0.08}Ga_{0.24}As/InP$ Lasing Nanoscale Heterostructure

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Abstract

The foremost emphasis of this foundational research letter has been given on analytical investigation of an enhanced simulative study on shortwave infrared gains (SWIRGs) of $In_{0.68}Al_{0.08}Ga_{0.24}As/InP$ lasing nanoscale heterostructure for fiber optic cable communication applications under transverse electric and magnetic bi-modes at 300K. In the starting of this work, taking into account recent and emerging computational technology, an enhanced and improved effective mass theory for single and multi-sub-bands has been utilized to enumerate the appropriate SWIR gain parameters as well as electrons-holes (Es-Hs) levels of quasi-Fermi energies. Under advanced simulation, first of all, the salient computational performances of Es-Hs levels of quasi-Fermi sub-band energies versus injected carriers (10^{18} cm^{-3}) at 300K have been analysed simulatively. Next, electric and magnetic transverse bi-modes induced several spectral performances of SWIR-gain with wavelengths of photons have also been investigated analytically. In spite of this, the prominent performances of SWIR-differential gain ($10^{-16}cm^2$) with injected carriers (10^{18} cm^{-3}) under transverse electric and magnetic bi-modes at 300K have been analyzed dominantly. Throughout the results, the peak intensities of SWIR-gain are achieved at wavelengths 1330 nm and 1550 nm corresponding to two crests of SWIR-spectra respectively under transverse bi-modes. Consequently, this emitted SWIR light gain by $In_{0.68}Al_{0.08}Ga_{0.24}As/InP$ heterogeneous nanostructure of wavelengths ~ 1330 nm and 1550 nm can be substantially utilized in the applications of fiber optic cable communications in the transmission of SWIR-signals through the modern process of total internal reflection with minimal attenuations of SWIR-signals (in dB × km^{-1}) owing to lowest fiber dispersions and fiber absorptions.

Keywords: Es-Hs quasi-Fermi sub-band energy levels, SWIR-gain, SWIR-differential gain, SWIR-loss, Transverse bi-modes.
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Introduction

In today's advanced research, there have been observed so many differences between homogeneous and heterogeneous junctions based on nanoscale structures. As it has been known that a homogeneous structure has been formed when two materials of equal band gap interact while a heterogeneous structure has been formed when two materials of different band gap interact with each other. In taking into consideration emerging nanotechnology, for the applications of SI- telecommunication systems, an InAlGaAs heterogeneous junction nanostructure [1-9] has been investigated by researchers for emission of SI radiations. The various optoelectronic characteristics like modal confinement parameter, intensity of modal infrared gain, intensity of infrared gain [10-12] have been investigated in emerging research fields. In this research work various SWIRGs of $In_{0.68}Al_{0.08}Ga_{0.24}As$ /InP heterogeneous nanostructure at room temperature under transverse bi-modes have been simulated analytically. In order to enumerate the various SWIR-gain parameters as well as energies of Es-Hs quasi-Fermi levels an advanced effective mass theory of single and multi-sub band has been applied. Electric and magnetic transverse bi-modes induced several spectral performances of SWIR-gain with wavelengths of photons have also been investigated analytically. In spite of this, the prominent performances of SWIR-differential gain in ($10^{-16}cm^2$) with injected carriers (in 10^{18} cm^{-3}) under transverse electric and magnetic bi-modes at 300K have been analysed dominantly.

Heterostructure Details and Theoretical Method

In this simulative work, there has been proposed a heterogeneous nanostructure of five SNLs (Step-index Nanoscale Layers). This nanostructure has been simulated such that, one NQL (Nanoscale Quantum-well Layer) has

Table1: Layer-compositions and layer-parameters of $In_{0.68}Al_{0.08}Ga_{0.24}As$ /InP heterostructure.

SNLs	% x,y of ($In_{1-x-y}Al_yGa_xAs$)	Width(nm)	Wave-length (nm)	BOE (eV)
NCL (C.B.)	00%, 45%	10.00	08451	0.2574
NBL (C.B.)	34%, 27%	05.00	10472	0.1753
NQL	24%, 08%	06.00	15783	0.0734
NBL (V.B.)	34%, 27%	05.00	10472	- 0.1753
NCL (V.B.)	00%, 45%	10.00	08451	-0.2574

been sandwiched between two NBLs (Nanoscale Barrier Layers), and after that it has been covered by two NCLs (Nanoscale Cladding Layers) and after that the whole system has been grown simulatively on an InP base (substrate) layer. Layer-compositions, layer-parameters and Band offset energy (BOE) for conduction and valence bands of $In_{0.68}Al_{0.08}Ga_{0.24}As$/InP nanoscale structure have been exhibited in table 1.

An expression of Infrared gain amplification coefficient [13] as a function of photon's energies has been given by the following mathematical relationship.

$$G(\hbar\omega) = \frac{q^2\hbar 2\pi}{2n_{eff}(\hbar\omega)m_0^2\varepsilon_0 c} \times \left[1 - exp\left(\frac{\hbar\omega - \Delta f}{k_b T}\right)\right] \times \sum_{nc,nv} \frac{|M_b|^2 f_c f_v}{4\pi^2 L_W} \times \frac{(\hbar\pi\tau)dk_x dk_y}{\pi(\{\hbar\omega_{nc}+\hbar\omega_{nv}+\hbar\omega_{sg}\}-\hbar\omega)^2+(\hbar\pi\tau)^2}$$

Here- $\hbar\omega$ = Photonic energy, $\hbar$ = reduced Planck constant, ω = angular frequency, q = charge of electron, n_{eff} = effective refractive index, m_0 = mass of electron, ε_0 = permittivity of free space, c = speed of light, Δf = energy separation between quasi-Fermi levels, k_b = Boltzmann constant, M_b = bulk momentum matrix, f_c, f_v = conduction and valence band fermi functions. L_W= width of quantum well layer, k_x, k_y = wave vectors, τ = photon life time.

The differential form of infrared gain coefficient has been defined as differential gain coefficient [14-23] expressed by the following equation.

$$G'(\hbar\omega) = \frac{dG(\hbar\omega)}{dN} = \frac{8\pi^2 m_r \hbar\omega}{c\varepsilon h^3 L_w} \times \int_{E'}^{\infty} |M_b|^2 \times \left(\frac{df_c(\hbar\omega)}{dN} - \frac{df_v(\hbar\omega)}{dN}\right) \times L(\hbar\omega')d\hbar\omega'.$$

Here - $G'(\hbar\omega)$ = differential shortwave infrared gain, $\frac{dG(\hbar\omega)}{dN}$ = derivative of shortwave infrared gain with respect to carrier density, $L(\hbar\omega')$ = line shape function, $|M_b|^2$ = squared bulk momentum matrix element, m_r = reduced mass, h = Planck constant, $\frac{df_c(\hbar\omega)}{dN}$ = differential quasi fermi function for conduction band with respect to carrier density, $\frac{df_v(\hbar\omega)}{dN}$ = = differential quasi fermi function for valence band with respect to carrier density, ε = electric permittivity, c = speed of light.

Simulative Results and Discussions

An increment in infrared light per unit initial value of it at per unit length of propagating infrared light can be defined as infrared gain parameter. In fig. 1 the transverse bi-modes spectral performances of intensity of SWIR-gain with wavelengths of photons have been shown by blue right (y) and blue top (x) axes. As it has been shown in black spectra that the corresponding to two crests at lasing photon's wavelengths ~ 1330 nm and 1550 nm, the peak values of SWIR-gain have been achieved by the simulation results in transverse electric mode-TE, while in transverse magnetic mode-TM, only single peak of SWIR has been achieved at 1330 nm, it is presented by blue graph. By fig. 1, it has also been shown the energies behaviours of quasi-Fermi levels of Es and Hs with densities of injection carriers by black left (y) and black bottom (x) axes. Although the curves of Es and Hs have been shown by black and red colours respectively.

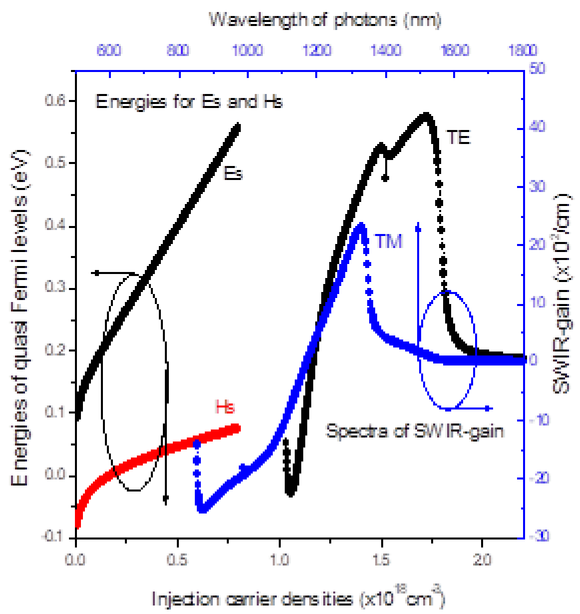

Figure 1: Transverse electric (TE) and transverse magnetic (TM) bi-modes induced spectral performances of SWIR-gain

(Shortwave infrared gain) with wavelength (nm) and levels of Es (electrons in conduction bands) and Hs (holes in valence bands) for quasi-Fermi energy sub-bands with injection carrier densities (cm^{-3}) at 300K.

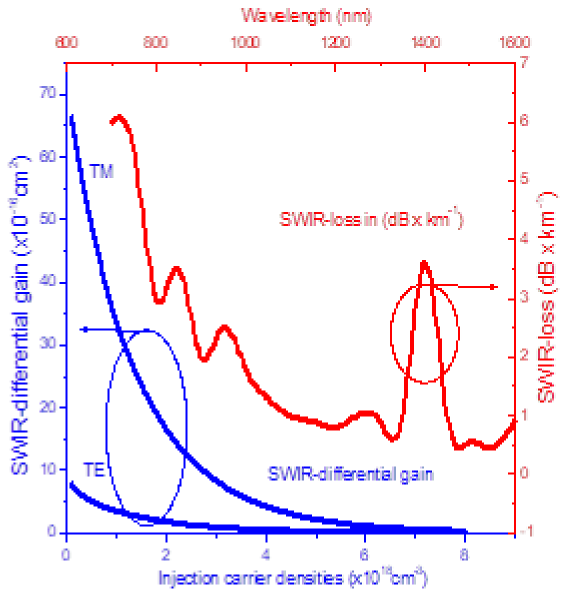

Figure 2: Simulative performances of transverse electric (TE) and transverse magnetic (TM) SWIR-differential gain (shortwave infrared differential gain in cm^2) with injected carrier concentration in cm^{-3} and SWIR-loss (shortwave infrared loss in per cm) with wavelength in nm at 300K.

As it has been observed by black and red graphs of Es and Hs that the energy separation between Es and Hs quasi-Fermi sub-bands levels enhances as an increase in injected carriers. Further, the transverse bi-modes performances of intensity of SWIR-differential gain with densities of injection carriers by left (y) and bottom (x) axes in blue colour have been graphically simulated in fig.2. Further, in fig.2 both blue curves show the inverse behaviours of differential values of SWIR-gain with densities of injection carriers. Although, in transverse mode-TM the value of SWIR-differential gain has been achieved higher than that of transverse mode-TE. Further, fig. 2 also exhibits the behaviours of SWIR-loss (in dB × km^{-1}) with wavelengths (nm) by right (y) and top (x) axes in red colour. As it has been observed by the SWIR-loss spectrum that the SWIR-loss has been found negligible at the wavelengths ~ 1330 nm and 1550 nm in the comparison of 1400 nm. Thus 1330 nm and 1550 nm wavelength's achieved SWIR-light have been largely utilized in emerging and recent applications of fiber optic cable communications in the transmission of SWIR-signals through the modern process of total internal reflection with microscopic attenuations of SWIR-signals (in dB × km^{-1}) owing to minor fiber dispersions and minor fiber absorptions.

Conclusions

At room temperature (300K), under transverse electric and magnetic bi-modes, the cardinal aim of this proposed research work has been to study of investigation on an advanced simulation of SWIRGs of $In_{0.68}Al_{0.08}Ga_{0.24}As/InP$ heterogeneous nanoscale structure. In order to enumerate the various SI-parameters as well as energies of Es-Hs quasi-Fermi levels an improved effective mass theory single and multi-sub-bands has been applied analytically. In the advanced simulations throughout the results, the peak values of SWIR-gain have been found corresponding to two crests at the photon's wavelengths ~ 1330 nm and 1550 nm. This emitted SWIR-light gain has been largely used in the applications of nanoscale fiber optic cable-based SWIR-signal communications through the process of total internal reflection with microscopic SWIR attenuation of shortwave infrared signals (in dB× km^{-1}) owing to minor fiber absorption and dispersions.

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