Analysis of Optical Gain of Intersubband Optically Pumped Mid-infrared Laser in Homogeneous Magnetic Field

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Abstract. Optically pumped mid-infrared intersubband lasers in magnetic field are considered. The rate equation model is set up to include electron scattering with acoustic and polar optical phonons in the magnetic field. A strongly non-monotonic gain vs. field dependence is found, with gain peaks occurring at fields which bring appropriate states into resonance with optical phonons, opening additional relaxation paths. These peaks exceed the gain achievable in the structure under zero-field conditions.

INTRODUCTION

Intersubband semiconductor lasers have been introduced in the 90s for creating laser beam with better qualities than ordinary semiconductor lasers. Among intersubband SC lasers the ones with electron injection as a pump are the most popular ones, but these type of laser has a huge fault, they are quite difficult to produce. In a response to this a new type of intersubband SC lasers have been proposed with the different pump, such as optically pumped intersubband lasers which radiate in mid-infrared domain which is in present days very interesting for industry and technology. Though, this type of laser has to use other laser for the pump, their big side is a great simplification of laser fabrication and design, and this is the main reason for develop of this type of laser.

The reason for putting this type of laser in HMF (homogeneous magnetic field) is to attain the discrete energy levels instead of energy subband. With discrete levels the optical gain is going higher for some magnitudes of HMF then without it, and in the same time the laser beam monochromatic and coherency is a lot better then without HMF. To attain discrete energy levels without MF the 3D quantum structure would be needed, the quantum dot (QD) laser. The manufacture of QD laser is a lot more difficult then even quantum cascade laser. The laser structure for optically pumped lasers suggested by [5] we shall simulate in HMF.

THEORETICAL CONSIDERATION

The structure considered here has been proposed by [5], and it is based on GaAs-AlGaAs hetero-junction. This structure is periodical and it consists out of highly asymmetrical coupled quantum wells and barrier 20 nm wide. Asymmetrical coupled quantum well (ACQW) is consisting out of two GaAs wells 7.8 nm and 4.9nm wide, and AlGaAs barrier 1.7 nm wide in between. Here, in this structure, there are 3 subbands, lower subband is ground state, and upper two are excited states. Energy deference between the bottom of first excited and ground subband is in resonance with energy of polar optical phonon (36 meV). Optical pumping is being preformed between ground and second excited subband using CO$_2$ laser. To attain population inversion necessary for lasing it is needed fast liberation of electrons in first excited subband, because lasing is being preformed between second and first excited state. The liberation of electrons from first excited subband is being preformed by nonradiative emission of phonons. Output photons have energy which is lower then the energy of input photons, causing the shift of laser spectrum to the higher wavelengths (mid-infrared domain).
In magnetic field there are now discrete levels and those levels could be very close to each other, especially for the small fields, and not just for small fields even for the larger fields difference between levels could be very small for the Landau levels which are coming from different subbands. All this is leading to conclusion that acoustical phonons mustn’t be excluded in magnetic field in this case. The transition rate for this type of interaction we shall calculate using expression from [6].

The modified expression from [6] for transition rate has in its final result delta function, because in delta function argument there is no phonon wave vector and that is the reason why delta function went through integral. The delta function in the final result is a major problem here, because no calculation can be done it is necessary to substitute delta function with appropriate function which could be calculated. Therefore delta function in this paper we shall modify with Gaussian:

$$\rho_i(E_i) = \frac{1}{\sigma \sqrt{2 \pi}} e^{-\frac{(E_i-E_{io})^2}{2\sigma^2}}$$

energy spreading for the initial level, it is the same for the final level, so in the end we have:

$$D = \frac{1}{\sigma 2\sqrt{\pi}} e^{-\frac{(E_{io}-E_{fo}-E_{lo})^2}{4\sigma^2}}, \quad (2)$$

$\sigma$ is standard deviation for Gaussian. The standard deviation in Gaussian is taken differently for different types of transition. If a transition is taking place between levels of the same subband and different Landau number the standard deviation is given as $\sigma = \sigma_o \sqrt{B}, \quad \sigma_o = 1 meV / \sqrt{T}$, for transitions between levels with the same Landau number and different subbands standard deviation is equal to $\Gamma$ a width of Lorentzian, Lorentzian is yet another approximation of delta function, and at the end if transition is taking place between levels from different subbands and with different Landau numbers standard deviation is equal to geometric figure mean of two approaches for standard deviation mentioned above. This approach for $\sigma$ has given results which are close to the experimental results. The final expression for computing transition rates for electron-optical phonon interaction in magnetic field is very easy to get with putting expression (2) instead delta function in expression from [6] for transition rate of electron-optical phonon in bulk material.

According to equation (3.84) in Picrek PhD Thesis the electron-acoustical phonon matrix element in magnetic field for phonon emission is given and using that expression we’ve gotten the expression for electron-acoustical phonon interaction in magnetic field:

$$W_{ij} = \frac{\Xi^2 (E_i - E_f)^2}{\pi \rho v_s^4 \hbar^3} [n(E_i - E_f) + 1] \int_{0}^{q_{ij}^{max}} \left| G_{ij} (q_x) \right|^2 \left| F(q_x, v_i, v_f) \right|^2 dq_x,$$

where, $\rho$ is density, $v_s$ is speed of acoustical phonons, $Q$ is phonon wave vector, $\Omega$ is a volume. $W_{ij}Q$ is acoustical phonon energy. $q_0$ is: $q_0 = \sqrt{\frac{(E_f - E_{io})^2}{\hbar v_s} - q_z^2}, \quad q_{z\max} = \frac{E_f - E_{io}}{\hbar v_s}$. The expression (10) is good for $E_i \geq E_f$, and if it is $E_f \geq E_i$ then $W_{ij}=0$.

As mentioned before in magnetic field we have discrete levels and it is very important to say that we shall ignore every level which is above level (3,0), for example (3,1), (3,2) etc., because optical pumping is being performed between levels (1,0) and (3,0) so levels which are above level (3,0) have only thermal electron population which is again very small at temperature of 77K (laser is need to be cooled). Nevertheless, rate equations have to be solved for each level below the level (3,0). Of course, the number of levels and the number of rate equations depends out of magnitude of magnetic field. In rate equations we have $P$ and $P$ is pumping rate which expression is given in [1] and [3]. 2D thermal electron concentration in magnetic field is given as:
The expression for determine optical gain in HMF is expression for optical gain which is given in [1] and [3], the only difference is in 2D electron concentration which is now determined out of the new rate equations in magnetic field. Where \( n_2 \) is 2D electron concentration which is the sum of all 2D concentration of the levels with prime quantum number 2 ( (2,0), (2,1), etc.), and \( n_3 \) are levels with prime number 3 ( (3,0), (3,1), etc.).

\[
\bar{\eta}_{i,j} = \frac{eB}{\pi\hbar} \frac{1}{m_e} \frac{m_e}{m_i}(1 + \frac{E_i - E_f}{kT}) + 1 \tag{4}
\]

NUMERICAL RESULTS AND DISCUSSION

Numerical calculations were performed for the structure parameters \( a=7.8 \text{ nm}; d_1=9.5 \text{ nm}; d_2=14.4 \text{ nm}; \) and the Al mole fraction in the AlGaAs equal to 0.22. The material parameters used in calculation are: \( m_b=0.0853m_0 \) in the barrier and \( m_w=0.067m_0 \) in the well, \( m_0 \) is the free electron mass, the refraction index for GaAs is \( n=3.3 \); surface doping density \( N_d=10^{15} \text{ m}^{-2} \), the barrier height \( U_0=217.5 \text{ meV} \); optical phonon energy \( E_{LO}=36 \text{ meV} \); optical pump power \( S_{in}=10^{10} \text{ W/m}^2 \); the Lorentzian width at 77K is \( \Gamma=4.25\text{meV} \); static and high-frequency permittivities of GaAs \( \varepsilon_s = 12.4 \) and \( \varepsilon_{ss} = 10.6 \); \( \Xi=6.7-1.2x \text{ eV} = 6.436\text{eV} \) (for \( x=0.22 \)); \( \rho=5.3174 \times 10^3 \text{ kg/m}^3 \); \( v_s=4.7 \times 10^3 \text{ m/s} \). The energies of (1,0), (2,0) and (3,0) states in the structure are \( E_1=38.85 \text{ meV} \), \( E_2=76.3 \text{ meV} \), \( E_3=164.34 \text{ meV} \), respectively.

The calculated optical gain vs. field dependence for the structure is given in Fig.1. In discussing the gain vs. the magnetic field dependence one should first note that level (2,0) is in optical phonon resonance with (1,0), independent on the magnetic field strength, because their Landau indices are equal, i.e. this resonance is set by proper choice of the structure configuration itself. Therefore, this relaxation path is always fast, and the behaviour of gain with magnetic field then depends on relative alignment of other pairs of states, having different Landau indices, because their field-tunable spacings and wave functions influence the scattering rates, and therefore the overall electron distribution. Pumping is also being preformed between levels (1,1) and (3,1), (1,2) and (3,2), etc. The maximum Landau number for the level with prime quantum number 3 is obtained by finding out energy difference between (3,0) and (3, lmax), that energy difference should be less then 30 meV, which is quite enough for the temperature of (77 K).

In range of HMF between 0T and 19T, there is more then just one final pumping level, at B=19T maximum Landau number for levels with prime quantum number 3 is 0, because energy for level (3,1) exceeds 30 meV. In this magnetic field range we have several final pumping levels which results multiple pumping transitions ((1,0) on (3,0), (1,1) on (3,1), etc.), and this sustain a large population inversion by filling levels (3,..). With increase of magnetic field the number of final pumping levels is declining, which then causes then reduces population inversion and we have optical gain decrease in general, local gain peaks are caused by variations in (3,...) transition rates. It is important to say that gain curve between 0T and 1T, and around 1T could be inaccurate due to replacement of Delta function by expression (2).

At larger magnetic fields then 18T even if there is no more multiple final pumping levels just level (3,0) the spacing between levels (1,0) and (1,1) increases and comes in resonance with optical phonon energy, which strongly increases the transition rate between the two and empties the (1,1) level. The increased population of level (1,0) makes pumping more efficient, and eventually results in a strong gain peak at 21 T. With further increase of the magnetic field the (1,1)-(0,0) spacing goes out of resonance with optical phonons, state (1,1) again retains a large fraction of electrons, and the gain decreases.

With further increase of the magnetic field, level (1,1) is now coming to optical phonon resonance with level (2,0) (and the level (1,1) comes above (2,0) ). When this happens a high population of level (1,0) occurs, leading to pronounced population inversion and the gain peak at 41 T. This peak is lower than the peak at 21 T, however, because the level (2,0) again retains a larger electron density, which decreases the gain.
CONCLUSION

We have modeled optically pumped mid-infrared intersubband semiconductor laser in magnetic field, by including the acoustic and optical phonon scattering processes in the rate equation model. A strongly non-monotonic dependence of the optical gain on magnetic field strength is found, with very prominent peaks at fields which bring pairs of relevant states in resonance with optical phonon energy, thereby opening fast relaxation paths. The particular structure considered here has peaks of optical gain, at very small fields, at 21T and at 41T, the peaks at very low fields are almost three times as high as the peak at 41T, and about four times larger than the gain at zero magnetic field. Further improvements might be possible by using the quantum well profile optimization methods developed previously [10-16].

REFERENCES