Numerical analysis of biased GaAs/AlGaAs intersubband Raman laser

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***Abstract*—We demonstrate the potential for tunable laser operation at mid-infrared wavelength by using biased GaAs/AlGaAs intersubband Raman laser (IRL). From the numerical analysis for time evolution of Stokes photons and electron populations based on non-equilibrium rate equations, it is shown that the IRL output wavelength varies from 14.3 to 11.7 µm by changing the bias from -50 to 0 kV/cm when pumping wavelength is assumed to be 9.1 µm. This indicates that IRL can work as a voltage-controlled frequency modulator.**

I. Introductory Remarks

INTERSUBBAND Raman laser (IRL) is an optically-pumped semiconductor laser making use of the stimulated intersubband Raman scattering in asymmetric coupled double quantum wells (ACDQWs). IRL consisting of n-type GaAs/AlGaAs ACDQWs achieved laser emission [1] at mid-infrared wavelength by optical pumping with a CO_2 laser.

Maung and Katayama [2] have proposed the intersubband (ISB) charge-density-excitation mechanism as the dominant process of resonant light scattering for the observed IRL, and have given a good theoretical fitting to the observed Raman lasing Stokes shift due to the coupled ISB plasmon-phonon modes (I^+ and I^-). Further in our previous work, the gain change of IRL in mid-infrared wavelength is predicted by applying a bias field perpendicular to the interface [3].

In present work, we simulate non-equilibrium characteristics of biased n-type GaAs/AlGaAs IRL based on the coupled rate equations [4, 5] to explore the possible tunability. The ISB electron scattering rates due to the confined LO phonons and interface optical phonon modes in ACDQWs are taken into account. During pumping period of the stimulated Raman process from sub-picosecond to a nanosecond, we evaluate the time variation of characteristics in IRL.

II. Theory

We solve coupled non-equilibrium rate equations for the Stokes photon, electron population and average transverse energy of electrons in two subbands self-consistently. Rate equations of Stokes photon density (N_{St}) can be written as

$$\frac{dN_{St}}{dt} = \frac{c}{\eta_s} G_R N_{St} - \frac{N_{St}}{\tau_c} \quad (1)$$

where c, η_s and τ_c are the velocity of light, refractive index for scattered laser frequency and cavity life time, respectively. The intersubband Raman gain G_R for single ACDQWs is written as

$$G_R = \frac{4\pi^3 c^2}{\omega_i \omega_s^2 \eta_s^2 a} \left\{ \frac{d^2\sigma}{d(\hbar\omega_s)\, d\Omega} \right\} (n_1 - n_2)\, I_{Pump}, \quad (2)$$

where ω_i (ω_s) is the frequency of pumping (Stokes) light, n_i is the electron population of subband i, and $I_{Pump} = N_{in}\hbar\omega_i c/\eta_i$ is the pumping intensity, respectively. The quantity $d^2\sigma/d\omega_s d\Omega$ denotes the differential cross section of Raman scattering [2].

In previous work [3], we have studied the maximum Raman gain by optimizing G_R in the presence of biased field, taking into account ISB absorption, assuming $n_1 >> n_2$. However, G_R should be determined in consistent way with n_1 and n_2, by looking at ISB electron dynamics under optical pumping. So we accord here to the time evolution scheme developed in ref. [4] by averaging of the Boltzmann's equation over possible in-plane (transverse) energy distribution. In this modeled scheme, we assume the Fermi distribution form for non-equilibrium electrons in subband, and explore the time variation of electron temperature T_i and quasi-Fermi energy E_{fi} in the Fermi distribution of subband i. The time variation of the 2D electron density n_i in subband (i = 1, 2) is determined by

$$\frac{dn_i}{dt} = \mp K' \frac{d^2\sigma}{d\omega_s\, d\Omega} (n_1 - n_2) N_{in} \left(N_{St} + 1\right) + \left(\frac{dn_i}{dt}\right)_{relax}, \quad (3)$$

where $-$ (+) corresponds to subband 1(2), $K' = 8\pi^3 c^4/\omega_s^2 \eta_s^3$ and $(dn_i/dt)_{relax}$ denotes relaxation rate of n_i due to both electron –confined LO phonon and electron-interface phonon scattering, taking into account the Fermi statistics [4,5].

III. Results and Discussions

In our modeled structure, the single ACDQWs consists of two GaAs wells separated by an intermediate $Al_{0.3}Ga_{0.7}As$ barrier. The composition is $Al_{0.3}Ga_{0.7}As$ 20 nm, GaAs 7.34 nm, $Al_{0.3}Ga_{0.7}As$ 1.13 nm, and GaAs 6.21 nm thick. The system is modulation doped so as resulting in a sheet carrier density of $3\times 10^{11}\,\mathrm{cm}^{-2}$. We assume the pumping wavelength λ_{in} = 9.1 µm, I_{Pump} = 300 kW/cm^2, τ_c = 9.56 × 10^{-11}s and the lattice temperature of T_L = 80 K. Our procedure for simulation of n_i and T_i is to assume an initial condition in the thermal equilibrium without optical pumping. Also, the scattering cross section is assumed to be constant during the period of simulation.

In Figs. 1(a) and 1(b) we depicted a time evolution of N_{St} and n_i by solving eqs. (1) and (3) for the biased electric field -40, -20, 0 and 20 kV/cm . It is seen in Fig. 1(a) that the steep increase of N_{St} appears in the time interval of several hundred of ps from the initial time for each bias, except for the case of 20kV/cm. This increase of N_{St} corresponds to the Raman lasing due to the stimulated resonant electronic light scattering. We present time evolution of n_1 and n_2 in Fig. 1(b). In response to the increases in N_{St}, n_1 (n_2) also exhibits a steep decrease (increase) according to the IRL mechanism.

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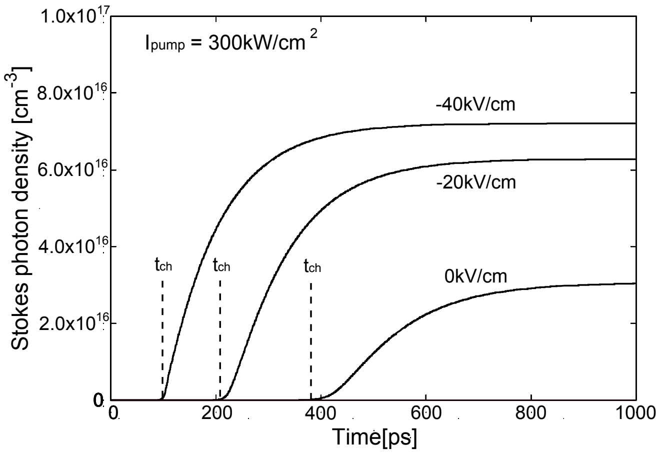

Fig. 1(a) Time evolution of Stokes photon density. For 20kV/cm, steep increase of N_{St} does not occur, so that we cannot see it in this scale.

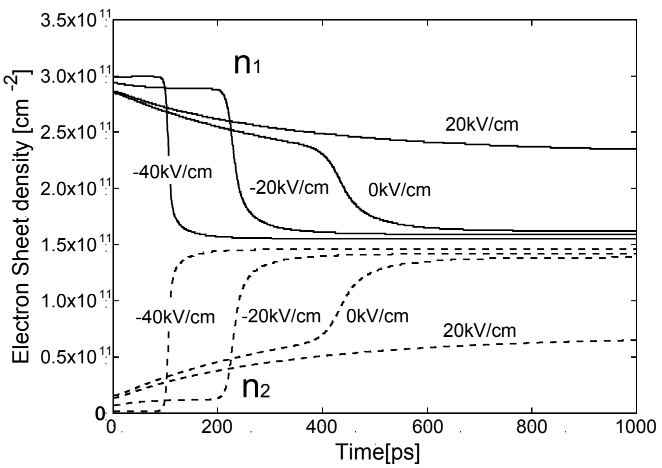

Fig. 1(b) Time evolution of electron sheet density (solid line : subband 1, dashed line : subband 2)

We point out one interesting feature of time evolution in n_1 (n_2) in Fig. 1(b). The feature is that n_1 (n_2) approaches a stationary value after a steep change of n_1 (n_2) occurs around a characteristic time t_{ch} (The location of t_{ch} is denoted by vertical dashed line for each electric field in Fig. 1(a)). Thus (n_1-n_2) tends to a constant stationary value in the limit of t~1ns. Similar drastic change with that of n_i near t_{ch} can also be seen in the time evolution of T_i and effective relaxation time of electron-phonon scattering.

In Fig. 2, the calculated Stokes photon density at ~1ns after pumping started is plotted by the cross from -50 to 50 kV/cm by solving eq. (1) and eq. (3), consistently. In that simulation, we estimated G_R from the maximum peak intensity of $d^2\sigma/d\omega_S d\Omega$ which corresponds to one of the coupled ISB plasmon-phonon modes (I^+ or I^-) at each bias field. So we plotted the maximum peak intensity of $d^2\sigma/d\omega_S d\Omega$ as a function of biased field in Fig. 2. So it is seen that an interchange of peak intensity from the lower coupled mode (I^-) to the upper one (I^+) takes place around -25 kV/cm as the electric field decreses from 0 to -50 kV/cm. As is seen in Fig. 1(a), the Stokes photon density at ~ 1 ns corresponds to the lasing photon density in a steady-state. So we judge from Fig. 2 that the IRL can lase if the maximum peak intensity of $d^2\sigma/d\omega_S d\Omega$ corresponding to (I^+ or I^-) is larger than a critical value at each bias field. It is also important that N_{St} is enhanced by applying negative bias.

In Fig. 3, the corresponding output wavelength versus bias is plotted by solid lines. The dashed corves indicate the non-lasing modes. For the evaluation of these wavelengths, we estimated the bias dependence of the coupled ISB plasmon-phonon modes (I^+ or I^-) [3]. We can see that the IRL output wavelength varies from 14.3 to 11.7 μm by changing the bias from -50 to 0 kV/cm for λ_{in} = 9.1 μm.

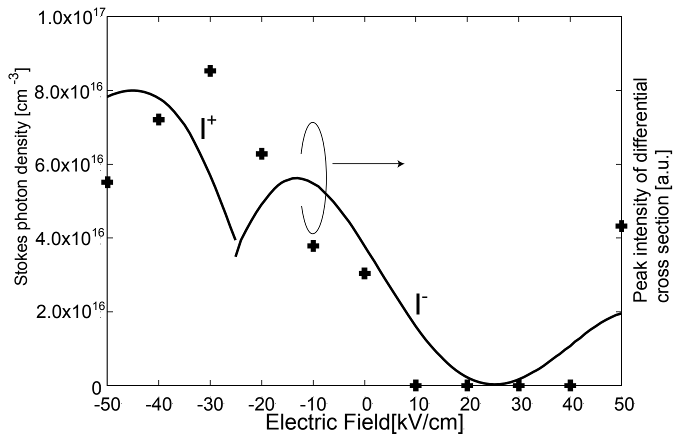

Fig. 2 Stokes photon density at 1 ns

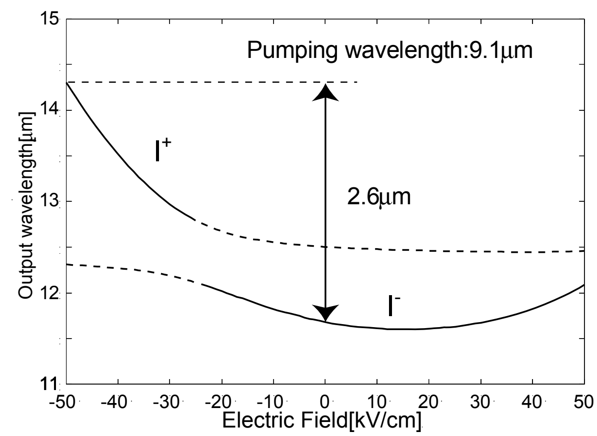

Fig. 3 Electric field dependence of IRL output wavelength

In conclusion, the biased GaAs/AlGaAs intersubband Raman laser (IRL) has been explored by numerical simulation. We have revealed the potential for tunable laser operation at mid-infrared wavelength. These results indicate that IRL can work as a voltage-controlled frequency modulator in mid-infrared region.

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