Below-band-gap Linear and Nonlinear-optics Waveguiding Characteristics of a Weakly Index-guided Semiconductor Laser

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ABSTRACT

We report the reduced linear-optics waveguiding efficiency for the signals around 1560 nm as the injection current of a GaAs/AlGaAs multiple quantum well laser diode (lasing wavelength at 840 nm) with a ridge-loading waveguide configuration increased. The decreased waveguide transmission and the more expanded mode profile indicated the variation of the effective refractive index distribution in the lateral dimension with injection current. The variation was partially due to carrier diffusion into the regions outside the ridge. Also, enhancements of two-photon and three-photon absorption coefficients with injected carrier density at 1560 nm in the same laser diode device were observed. The results were obtained by calibrating 130 fsec laser transmission data through the laser diode. Such enhancements were mainly attributed to the existence of hole states in the first heavy-hole subband during carrier injection. With the hole states, two-photon absorption in the TE polarization finds the other transition path for a higher transition rate. Such hole states are not so effective to the two-photon transition in the TM polarization.

Keywords: waveguide, effective refractive index, two-photon absorption, nonlinear optics

1. INTRODUCTION

Waveguides are key structures for various optoelectronics devices. The confinement factor and attenuation constant of an optoelectronics waveguide can influence the operation efficiency of such a device. For instance, the waveguiding efficiency or confinement factor of a semiconductor laser or optical amplifier is an important factor for improving the gain constant. Waveguiding behaviors of such an active device are strongly related to its active region carrier density, which significantly controls its refractive index variation. It is usually believed that the refractive index decreases with increasing carrier density [1-4]. This trend leads to the positive value of the linewidth enhancement factor. Because the refractive index decreases monotonically from a local maximum near the resonance wavelength as wavelength increases, unless other resonance processes occur. It is natural to expect a lower material refractive index below the band gap when a larger current is injected onto the material. In a ridge-loading laser diode, the injection of current onto the top of the ridge is expected to diffuse into the regions outside the ridge-loading area. Based on the refractive index dependence on carrier density described above, such a carrier diffusion process may result in waveguide index profile variation and hence waveguiding property changes. Such changes may occur for wavelengths near and below band gap. In this paper, we report the observation of decreasing waveguiding efficiency with increasing injection current below band gap in a GaAs/AlGaAs multiple quantum well laser of a ridge-loading waveguide configuration.

Multi-photon processes are important tools for spectroscopy research. Through a two-photon process, electrons can be excited to an energy state of opposite parity to the initial state such that a one-photon forbidden state can be observed [5,6]. Multi-photon processes are also useful for all-optical switching applications. In particular, two-photon transition can induce Kerr-like, ultrafast nonlinear refractive index variation, which has been considered for power-dependent switching and modulation operations, self-limiting and laser passive mode locking. For practical applications, semiconductors have been considered for devices based on multi-photon processes because of their high multi-photon absorption coefficients and mature device process techniques. Among them, GaAs/AlGaAs multiple quantum well (MQW) structures have been widely studied for two-photon induced nonlinear refractive index variation near half the band gap, which is in the optical fiber communication wavelength range. It has been experimentally shown that the effective nonlinear refractive index near half the band gap of a typical GaAs/AlGaAs MQW waveguide can be as large as $2 \times 10^{-13} \text{ cm}^2/\text{W}$, which is about 1000 times that of silica fiber. Also, strongly birefringent optical nonlinearity, induced by two-photon absorption, has been observed. In this letter, we report the novel phenomena of the enhancement of two-photon and three-photon processes in a GaAs/AlGaAs quantum well laser structure due to carrier injection. These multi-photon absorption coefficients increase with injection

current.

2. EXPERIMENTAL RESULTS – LINEAR OPTICS

The fabrication of the device is based on a GaAs/AlGaAs quantum well structure. Between the 1.5- μm p- and n-type $\text{Al}_{0.4}\text{Ga}_{0.6}\text{As}$ cladding, the five GaAs/ $\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}$ quantum wells, with 6.5 nm well width and 20 nm barrier width, were sandwiched by the 100 nm i- $\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}$ separate confinement layer on each side. Laser diodes were fabricated with ridge-loading waveguides of 4 μm in ridge width and 1- μm etching depth on the 1.5- μm thick p-type cladding layer. The device length was 500 μm . Current was injected from the top of the ridge of a fabricated laser diode. Near-field mode profiles of the laser waveguide was monitored with an out-coupling objective (40 X) and an IR camera. The threshold injection current is about 75 mA. We end-fire coupled a cw laser at 1560 nm of very narrow linewidth, which was from an external-cavity, tunable semiconductor, into the fabricated GaAs/AlGaAs laser diode. The output light near 840 nm from the laser diode was removed with a low-pass color filter when the transmitted 1560 nm signal was to be monitored.

Without input of 1560 nm, 3-D near-field mode patterns of 840 nm signal were recorded with various injection current levels of 30, 60, 80 and 100 mA. In Fig. 1, we plot the line scans around the absolute intensity peak in the (a) horizontal and (b) vertical directions. One can see that in both directions the intensity distributions become more centralized as injection current increases. This trend is attributed to the dominance of stimulated emission over spontaneous emission when the injection current is approaching to the threshold value. Stimulated emission results in higher directivity when compared with spontaneous emission. After the threshold condition is reached, the further decrease of profile width might be related to the clamp of carrier density in the waveguiding region and carrier density increase outside the region due to increased leaked carriers. Hence, the refractive index of the guiding region is fixed and that outside is reduced, resulting in stronger signal confinement. Such a phenomenon is more prominent in the horizontal direction.

With the input power at 2.46 mW (the end-fire coupling efficiency is estimated to be lower than 1 %), we recorded the near-field mode patterns of 1560 nm signal transmission with 0, 40, 60 and 100 mA injection currents. The trend can be better understood with the lateral line scan results shown in Fig. 2. Figure 3 shows the variations of 1560-nm signal transmission power of the (a) TE and (b) TM polarization with injection current at various input power levels. In either TE or TM case, output power decreases with injection current. The output power level saturates when the injection current is larger than 75 mA (threshold condition). The saturation trend indicates that the variations of waveguiding behaviors are strongly related to carrier density in the device because the carrier density in the active region becomes clamped when a laser reaches the threshold condition. From the results above, one can see the decreasing guiding efficiency of the laser diode waveguide for the signal at about half the band gap as the injection current increases. The lower transmission in the situation of a higher injection current can be due to the process of free carrier absorption of 1560 nm signal. However, the changed waveguide mode profile reveals that the refractive index distribution, at least in the lateral dimension, is varied as the injection current is increased. This phenomenon can be attributed to the decreased effective refractive index in the regions under the waveguide ridge as carrier density increases (before the threshold condition). Although the effective refractive index outside the ridge region may also be decreased due to carrier diffusion, the gradient of lateral refractive index distribution becomes shallower. In this situation, waveguide mode profile spreads outward and the confinement factor is reduced. Therefore, the more extended evanescent field results in higher waveguide loss due to the perturbations in the waveguide cladding regions. Such a variation in the refractive index distribution would saturate as the carrier density is clamped at the threshold condition.

3. EXPERIMENTAL RESULTS – NONLINEAR OPTICS

A mode-locked fiber laser was used to provide 48 MHz, 130 fsec pulses at 1560 nm. The pulses are almost transform-limited. With various input power and current injection levels, output powers were recorded. The input power level and polarization were controlled with a half-wave plate and a polarizer. Before recording, a low-band-pass optical filter was used to remove the photon contribution of 840 nm. An infrared camera was used to assist end-fire coupling of ultra-short fiber laser into the waveguide of the semiconductor laser. The end-fire coupling efficiency was estimated between 0.4 and 0.6 % based on a sequence of linear optics studies of the laser diode waveguide.

The symbols in Fig. 4 depict the variations of TE-polarized output power at several injection current levels with TE-polarized input. The continuous curves represent the results of simulations. The decreasing power with increasing injection current can be clearly seen. Also, the curve bending clearly indicates the effects of multi-photon processes. As to be shown later, the curve bending includes the effects of two-photon and three-photon transitions. Figure 5 shows the variations of the two-photon absorption coefficients, β , as functions of injection current. The results were calibrated by using the method of inverse transmission. Note that the input intensities used for calibration were obtained by multiplying the power values in the horizontal axis of Fig. 5 by the estimated end-fire coupling efficiency. Although no anti-reflection coating at either end facet of the waveguide was prepared, it has been estimated that the multiple reflection effects are negligible. Calibration for β values was conducted with the data points of low and medium input power levels, before three-photon

absorption became significant, i.e., with injection current smaller than 25 mW. From Fig. 5, one can see that the β values of both polarization are in the ranges between 2 and 5 cm/GW, which are quite consistent with what reported near half the band gap of a GaAs/AlGaAs QW waveguide. Also, the generally higher β values in the TE polarization, compared with the TM polarization, are also observed in Fig. 5. Note that β in the TE polarization increases faster with injection current, compared with the TM polarization.

Figure 6 shows the variations of three-photon absorption coefficients, γ , as functions of injection current for the two polarization components. They were calibrated by numerically solving the equation of intensity evolution in the waveguide for fitting the output power curves in Fig.1. The equation gives

$$\frac{\partial I}{\partial z} = -\alpha I - \beta I^2 - \gamma I^3$$

In the fitting process, α and β values were used. The γ values were obtained by optimizing the fitting curves, as shown with the continuous lines in Figs. 1 and 2. Note that with the end-fire waveguide coupling efficiency outside the range between 0.4 and 0.6, reasonable γ values cannot be obtained. As shown in Fig. 6, the order of magnitude of the calibrated γ values is the same as previously reported in a passive AlGaAs waveguide structure. Although with certain variations, the values in the TE and TM polarization are about the same. Both increase with injection current.

The enhancement of two-photon absorption in the TE polarization shown in Fig. 5 can be interpreted as follows. With current injection, exciton structures are essentially destroyed. However, the missing electron states created in H1 subband provide a path for two-photon absorption for TE photons. The two arrows show the successive photon transitions to complete a two-photon process. With the hole states in H1 created by injection current, two-photon transition through the aforementioned path can be quite strong. Hence, the two-photon absorption coefficient was increased with injection current. For TM photons, because the electron occupation in the L1 subband is less affected by injection current, the increase of the corresponding two-photon absorption coefficient is smaller. The process of three-photon transition is much more complicated than two-photon transition. Hence, it is difficult to provide a clear interpretation for its enhancement with injection current. However, it is believed that such enhancement is still related to the existence of hole states in H1 subband and possible in L1 subband when the injection current is high. Intra-band multiple-photon absorption is another possible path to enhance those coefficients (indicated with the two arrows on the right-hand side) because plenty carriers exist with carrier injection.

4. CONCLUSIONS

In summary, we have reported the decreasing waveguiding efficiency for the signal about one half the band gap as the injection current of an GaAs/AlGaAs multiple quantum well laser diode with a ridge-loading waveguide configuration was increased. This trend was opposite to that of the lasing signal (at 840 nm) of the device. With the signal at 1560 nm, the decreased waveguide transmission and the more expanded mode profile indicated that the effective refractive index distribution in the lateral dimension was varied with injection current. The decreased material refractive indices in both regions under and outside the waveguide ridge resulted in refractive index distributions of weaker guiding. This trend stopped when the laser threshold condition was reached. Also, we have reported the enhancements of two-photon and three-photon absorption coefficients with injected carrier density in a GaAs/AlGaAs quantum well structure. Such enhancements are mainly attributed to the existence of hole states in the valence subbands with carrier injection. Other causes may exist in such a complicated laser diode system.

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Fig. 1 Line scan intensity distributions of 840 nm signal in the (a) horizontal and (b) vertical directions.

Fig. 2 Line scan intensity distributions of 1560 nm signal in the (a) horizontal and (b) vertical directions.

Fig. 3 Output power variations with injection current for the 1560 nm signal in the (a) TE and (b) TM polarization at several input power levels.

Fig. 4 Output power vs. input power in the TE polarization for various injection current levels with symbols for experimental data and continuous curves for simulation results.

Fig. 5 Calibrated two-photon absorption coefficients, β , for both TE and TM polarization.

Fig. 6 Calibrated two-photon absorption coefficients, γ , for both TE and TM polarization.