Extended Abstracts of the 22nd (1990 International) Conference on Solid State Devices and Materials, Sendai, 1990, pp. 561-564 D-4-6

60 GHz High Relaxation Oscillation Frequency in Quantum Well Lasers

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Abstract

60GHz extremely high relaxation oscillation frequency is successfully achieved in quantum well lasers through a repetitive optical gain-switching method, demonstrating the superior performance of the quantum well laser as an ultrafast optoelectronic device. This high relaxation oscillation frequency is due to the high photon density as well as the enhanced differential gain properties in two dimensional carrier systems. The relation of the frequency characteristics between the gain-switching operation and the small signal modulation scheme is theoretically discussed.

1. Introduction

For the purpose of ultrafast optical communication systems and optical information processing systems, high-speed performance of semiconductor lasers such as high repetition rate short pulse generation and high frequency modulation is highly expected. It is well known that quantum well (QW) lasers have superior properties as to the high frequency modulation and short pulse generation due to the high differential gain property , which is enhanced by a factor of four compared to conventional double hetero-structure lasers, in two dimensional carrier systems [1) 2)]. In fact, an extremely short optical pulse as narrow as 1.3psec is achieved in multi-quantum well (MQW) lasers by a gain switching method [3)]. In this paper, we report extremely high relaxation oscillation frequency up to 60GHz achieved in the quantum well lasers which is driven by a repetitive optical gain-switching method using dye laser pulses. The relation between the frequency characteristics of the gain-switching operation and that of the direct modulation is also theoretically discussed.

2. Relaxation Oscillation Characteristics

Relaxation oscillation frequency f_r is one of the key factor to limit the modulation band width of semiconductor lasers. It is well known that f_r is proportional to the square root of the photon density multiplied by the differential gain on the basis of a small signal analysis of conventional rate equations. In the measurement of the relaxation oscillation characteristics over 10GHz, the observation of the transient relaxation oscillation caused by the step current with fast rise time using a streak camera is often used [4) 5)] because the direct frequency response measurement using microwave modulators and high speed detectors is limited by the electrical parasitic elements present in packaged semiconductor lasers and the band width of the detection systems. Figures 1(a)~(c) are the time charts of the transient response of the photon density and the carrier density driven by the step current injection, showing the transient behaviors with the relaxation oscillations. In this case, the relaxation oscillation frequency f_r corresponds to the oscillation frequency which has converged after a few oscillations appear.

The time interval between the first two oscillations is longer than that given by f_r, as shown in Fig.1(b), because the strong first oscillation reduces the carrier density below the threshold and it takes additional time to recover the carrier density beyond threshold. In our experiment, we developed a new method to measure f_r from the first two oscillations. In this method, the injected carrier dynamics is controlled by the repetitive gain-switching method in order to compensate the recovery time, as illustrated by a dotted line in Fig.1(c).

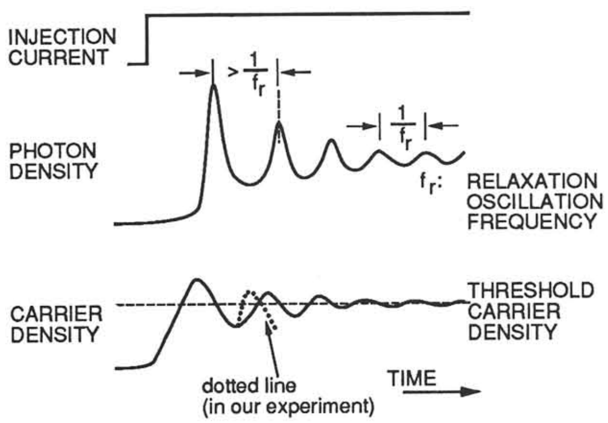

Fig.1: a) Time charts of injection current and transient response of b) photon density and c) carrier density

3. Experiment

In our experiment, we prepared a GaAs/AlGaAs MQW laser, which has ten 7nm wells separated by 10nm barriers, as illustrated in the inset in Fig.2. In order to measure the inherent high-speed characteristics of the MQW laser freely from the RC charging time, we adopted an optical pumping method, as illustrated in Fig.2. Two dye laser pulses (15psec, 700nm), one of which is delayed, pumped by a mode-locked Nd^{+}-YAG laser are used to excite and subsequently modulate the carrier density, as discused in Section 2. Temporal characteristics of modulated light output were measured by a streak camera whose time resolution is about 10psec. The first pumping pulse excites the carriers above the threshold condition by 10% of the threshold carrier density and the second pulse whose intensity is reduced by a neutral density filter to achieve the adequate intensity to compensate the decreased carriers is introduced just after the first oscillation. Figure 3 shows the time trace of the relaxation oscillation from the MQW laser measured by the streak camera. In this case, the time interval from the first oscillation to the second one is 16psec, which implies that the relaxation oscillation frequency reaches so high as 60GHz. This high relaxation oscillation frequency is attributed to the extremely high photon density as well as the enhanced differential gain properties in quantum wells.

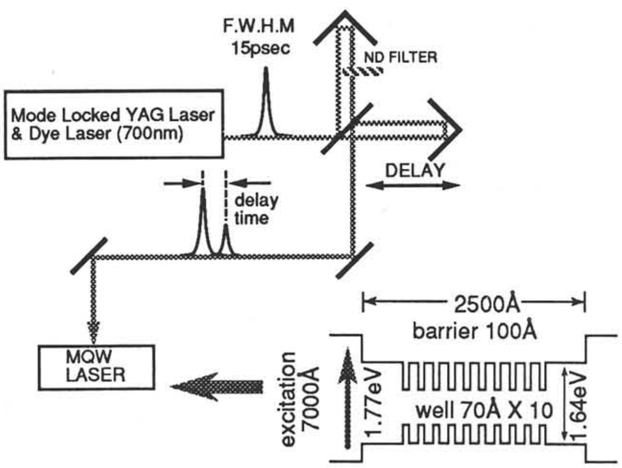

Fig.2: Schematic illustrations of the experimental configuration using picosecond dye laser pulses, and a GaAs/AlGaAs MQW laser used in this experiment

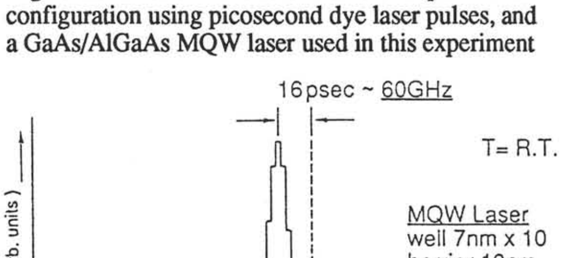

Fig.3: Temporal characteristics of modulated light output from a MQW laser measured by a streak camera

4. Discussion

The first relaxation oscillation by the step current injection is caused by the same mechanism with that of the short pulse generation in the gain switching method which utilizes the nonlinearity of I-L characteristics of semiconductor lasers around the threshold to produce shorter pulses than the excitation pulses. In fact, the peak intensity of the relaxation oscillation achieved in our experiment is high. It is because the excitation condition used in our experiment is similar to the gain switching method operating at extremely high repetition rate. It is well known that relaxation oscillation frequency is proportional to the square root of the photon density if modulation signal is relatively small compared to the bias current. However, the increase of modulation intensity reduces f_r [6]. In this section, we compare the frequency characteristics of the gain-switching operation with that of small signal modulation on the basis of conventional single mode rate equations in order to clarify the relation between the maximum operation frequency of the gain switching and the relaxation oscillation frequency.

Figures 4(a)~(d) show the time traces of the modulation current (dotted line) and the photon density (solid line) when average injection current is kept constant and the modulation frequency f_{mod} is varied, where the gain switching is realized by extremely large amplitude modulation: The amplitude of the signal current is the same with the bias current and the bias current is 50 times as high as the threshold current. Since the modulation frequencies are extremely high, pulse durations of the injection current are narrow enough to enable the picosecond pulse generation by the gain switching effect, as shown in Fig.4(a)~(c). With the increase of f_{mod}, the peak intensity of generated pulses begins to decrease and finally the gain switching is no longer realized, as shown in Fig.4(d).

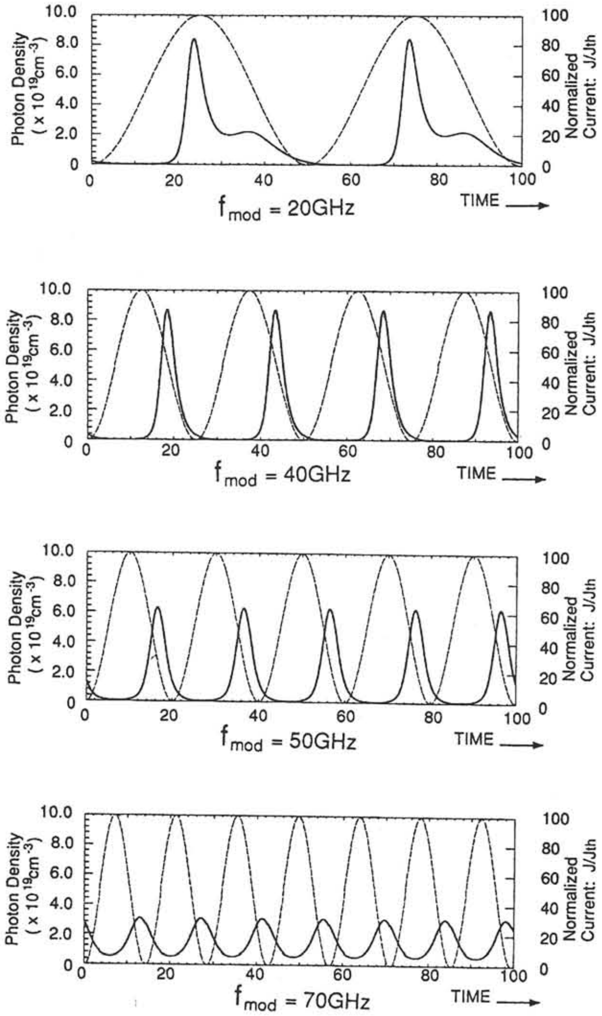

Fig.4: Time charts of modulation current and photon density at various modulation frequencies: (a) f_{mod}=20GHz, (b) 40GHz, (c) 50GHz, (d) 70GHz

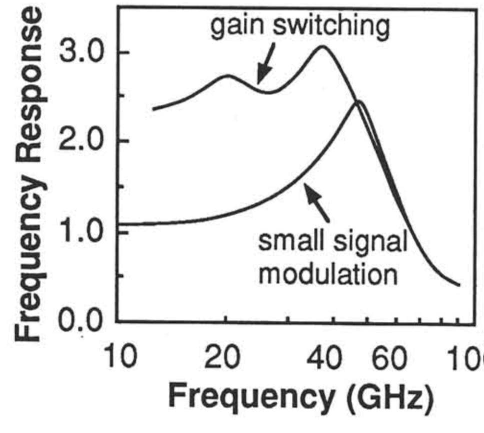

Fig.5: Frequency response of the gain switching operation and small signal modulation

Figure 5 shows the frequency response of the gain switching operation and the small signal modulation when the average injection current is the same. The horizontal axis is frequency and the vertical axis is the normalized frequency response $\delta(\varpi)$ which is defined by the normalized peak to peak output signal intensity by the average output intensity devided by the normalized peak to peak modulation signal current by the average signal current. As to the small signal modulation, $\delta(\varpi)$ corresponds to the conventional expression of frequency response and $\delta(\varpi)=1$ means the dc response. In small signal modulation, clear resonant peak owing to the relaxation oscillation appears. In the gain switching mode, on the other hand, the peak is broad and once modulation frequency goes over the resonant frequency of the small signal modulation, the gain switching condition can not be realized, as shown in Fig.4(c)(d), and the frequency response become the same curve with the small signal modulation. Figures.4(c)(d) and Fig.5 indicate that the maximum frequency of the gain switching, to which clear pulses can be generated, becomes just below the resonant frequency of the small signal modulation.

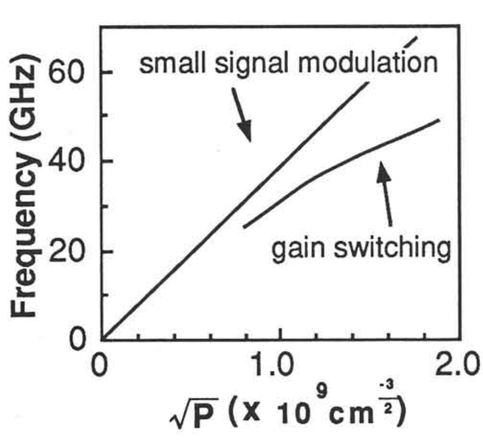

Fig.6: Resonant frequency of the gain switching operation and small signal modulation as a function of the square root of the averaged photon density

Figure 6 shows the resonance frequency of the small signal modulation and the maximum frequency of the gain switching operation as a function of the square root of the average photon density, indicating that upper limit of modulation band width of the gain switching operation is lower than that of the small signal modulation under the same photon density condition.

Since the modulation condition in our experiment is closer to the gain switching mode rather than the small signal operation, the measured f_r in our experiment is underestimated compared to the relaxation oscillation frequency which can be achieved under the same photon density.

5. Conclusion

In summary, extremely high relaxation oscillation frequency up to 60GHz is achieved in a quantum well laser, demonstrating the promising high speed properties of the quantum well lasers as the ultrafast optoelectronic devices. Theoretical analysis indicates that this high relaxation oscillation frequency results from the extremely high photon density owing to the strong excitation condition as well as the enhanced differential gain properties in the quantum wells.

[References]

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