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Experimental Observations of Dynamic Properties in External Cavity Semiconductor Laser with Multi-Mode Oscillation

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Experimental Observations of Dynamic Properties in External Cavity Semiconductor Laser with Multi-Mode Oscillation

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Contents

I. Introduction

Laser diodes with optical feedback attract considerable attention both as a physical model of nonlinear optical systems and from the application point of view. The stability and instability of laser diodes with optical feedback oscillating in a single mode have been widely investigated and various phenomena including chaos have been reported in single mode models.[1-4] Besides the intensity fluctuations in the light output of the laser, the external optical feedback also induces spectral instabilities including coherence collapse and mode hopping.[5,6] A multimode model has been assumed when performing feedback-induced noise control using high frequency injection current modulation in compound cavity laser diodes.[7] Recently, a method for adaptive mode selection has been proposed using the feedback-induced mode competitions among longitudinal modes of a Fabry-Perot laser diode.[8,9] For both of the above applications, it is strongly required that the feedback-induced dynamics of multimode laser diodes be experimentally clarified.

The purpose of this report is to report the results of an experimental investigation of mode hopping and high frequency modulation behavior of a compound cavity laser diode with multi-modes. The compound cavity laser diode oscillates in single-, two-, or multi-modes depending on the feedback and injection parameters. By analyzing the light output of a particular longitudinal mode using a monochrometer, the mode hopping of the compound cavity laser diode is observed and the mode dwelling time distribution is investigated. The low frequency fluctuations (LFF) are also observed. Though the LFF is usually observed in a compound cavity laser diode with single mode oscillation, it is also observed here in a multimode case in our experiment. The LFF induced by a high frequency modulation of injection current is also investigated.

II. Fundamental Properties

The experimental setup is shown in Fig. 1. The light source used in the experiment is a

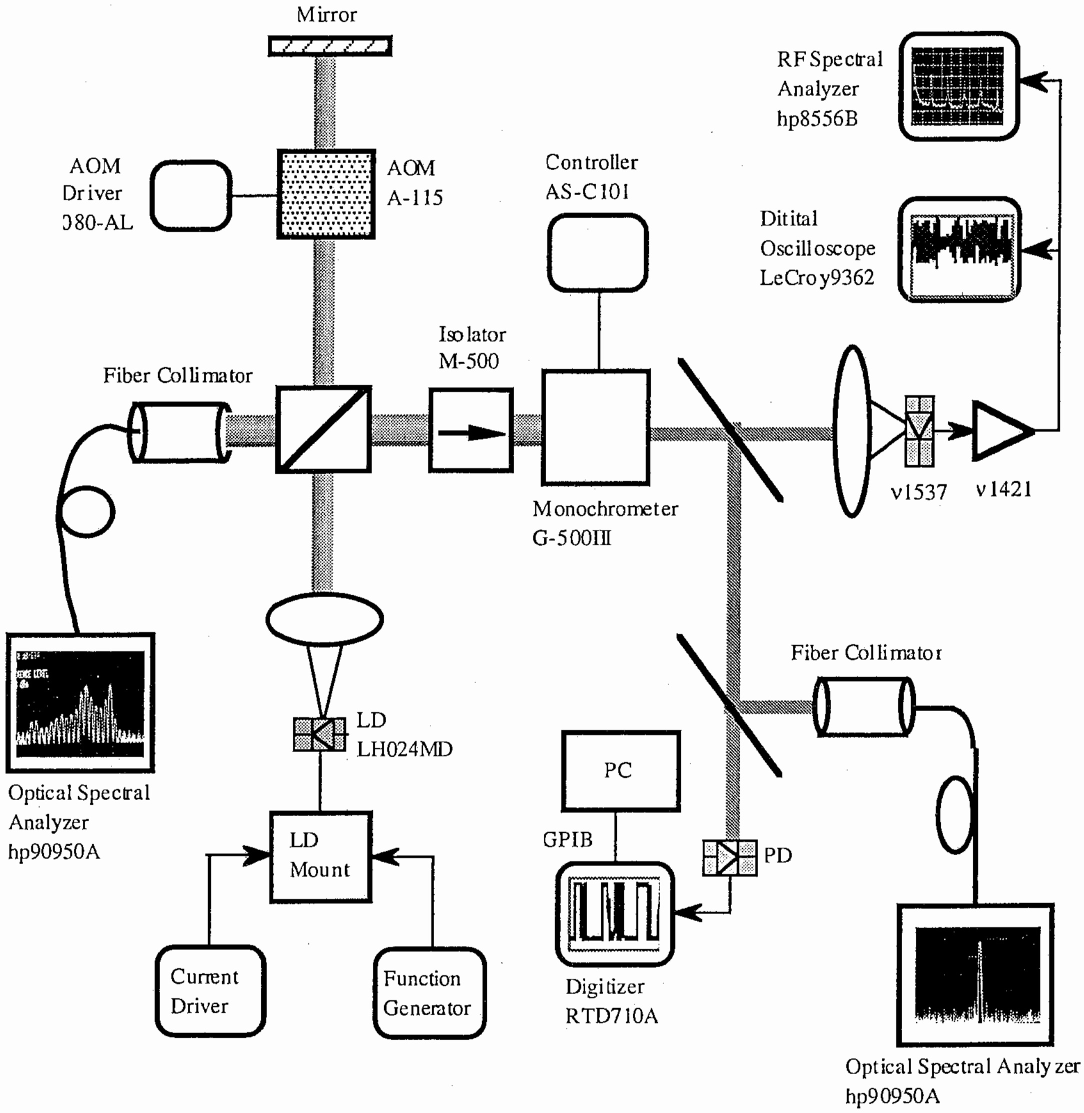


Fig. 1 Experimental setup.

single mode laser diode Sharp LT024MD with the maximum output power of 30mW at the wavelength of 785nm. The light output is collimated by a lens and the beam is divided with a beam splitter. The transmitted beam is reflected by an external mirror to the cavity of the laser diode. An acousto-optic modulator (AOM) is inserted in the feedback loop to adjust the feedback level. The reflected beam from the beam splitter is injected into a monochrometer (Nikon G-500III) through an optical isolator with the isolation of 30dB. The resolution of the monochrometer is about 0.02nm that is much smaller than the longitudinal wavelength separation of the laser which is about 0.3nm. With this monochrometer, we can select a particular longitudinal mode and observe the light output variations of that mode. The light output of the monochrometer is analyzed in three ways. The first one is to observe the optical spectrum using an optical spectrum analyzer (HP70950A). The second one is to analyze the fast time variations using a fast photo-diode detector (NewFocus 1537), a fast digital oscilloscope (LeCroy 9362), and a RF spectrum analyzer (HP8566B). Their bandwidths are respectively 6.5GHz, 750MHz, and 22GHz. The third step is to observe the dwelling time at the selected mode using a slow PIN photo-diode, a digitizer (Rtd710A), and a microcomputer through GPIB. The large memory of the digitizer enables us to observe the waveform from one milli-second to some ten seconds.

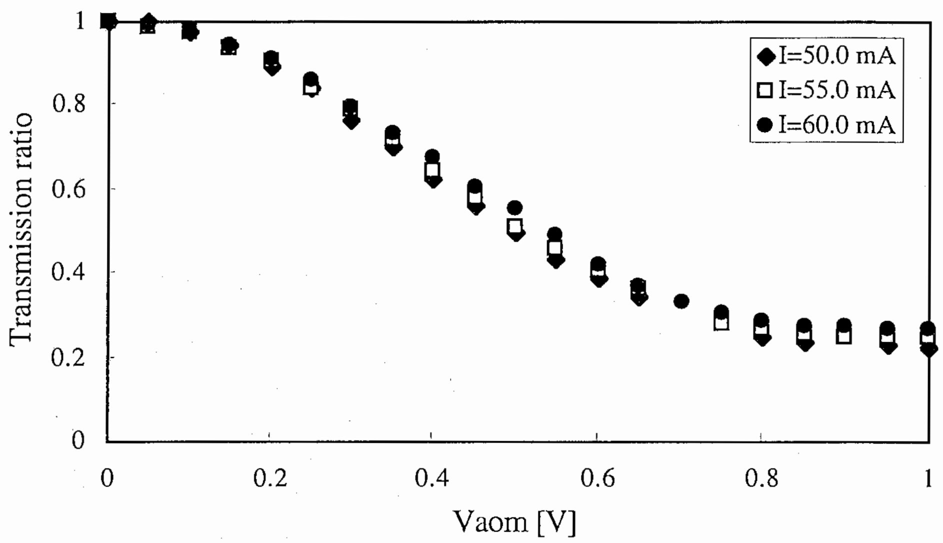


Fig. 2 Transmission ratio of the zeroth order diffraction beam versus applied voltage on AOM.

Instead of a conventional ND variable attenuator, an AOM is used to change the level of the feedback light in this experiment. This is performed by directing only the zeroth order diffraction beam into the laser cavity. Fig. 2 shows the transmission ratio of the zeroth order diffraction beam versus the applied voltage on the AOM. For the laser spectral width as narrow as several nanometers, we do not need to consider the dispersion of the transmitted beam induced by the AOM. Using the AOM, we can conveniently and quantitatively change the effective reflectivity of the feedback loop.

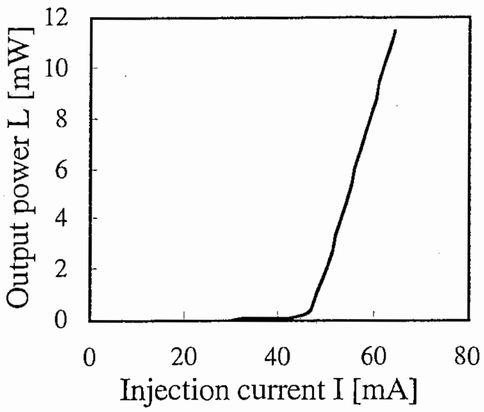


Fig. 3 Light-current characteristics of the solitary laser diode.

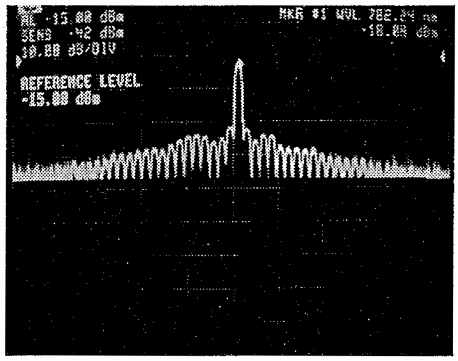


Fig. 4 Optical spectrum of the solitary laser diode.

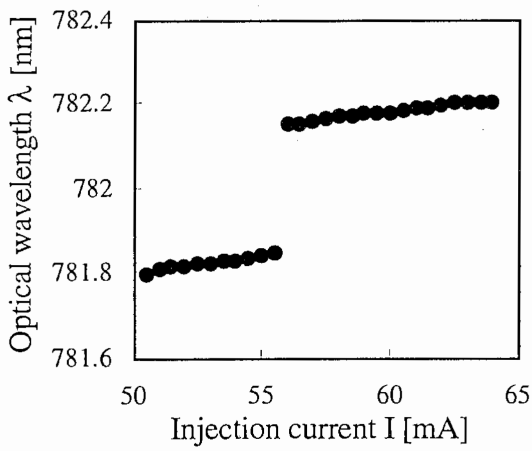


Fig. 5 Variation of the main wavelength versus bias injection current.

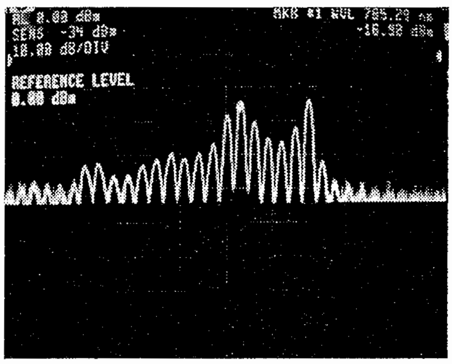
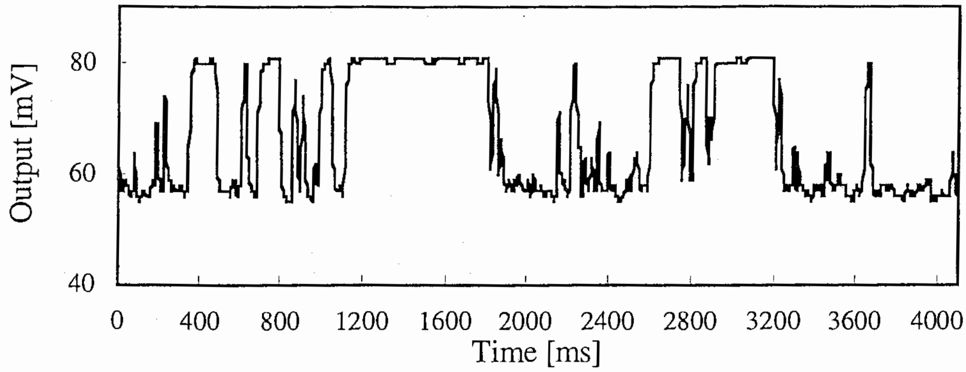


Fig. 6 Optical spectrum of laser with external optical feedback.

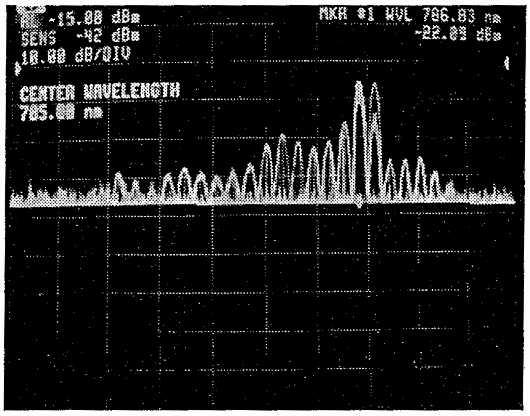
First, we investigate the fundamental characteristics of the solitary laser diode, i.e., the laser without the external optical feedback. Fig. 3 shows the relationship between the light output power and the injection current. The threshold current I_{th} is 46.9mA and the slope efficiency is 0.667mW/mA at the temperature of 22℃. Without the external optical feedback, the laser diode oscillates at a single mode when the injection current is set well above the threshold. Fig. 4 shows a typical optical spectrum for the solitary laser. When the injection current is varied the wavelength changes as shown in Fig. 5. Upon the increase of the injection current, the wavelength shows a continuous red-shift which is interrupted by sudden jumps corresponding to the mode hops. When the external feedback is introduced, the spectrum of the laser diode shows dramatic changes. Fig. 6 is the optical spectrum observed at a moderate feedback level. In this case, the laser oscillates in multi-mode and we can observe about 20 oscillation modes. Moreover, when the external feedback exists, the main wavelength also shifts considerably from the single mode wavelength of the solitary laser.

III. Observations of Mode Hopping

Mode hopping due to the external optical feedback is investigated. For very small external feedback, the laser stays stable and oscillates in a single mode, while it usually oscillates in multi-mode under moderate optical feedback. There also exists a single mode oscillation window at some moderate optical feedback region as shown later in Fig. 10. The mode number is dependent on the parameters such as the external cavity length and reflectivity, or the injection current.



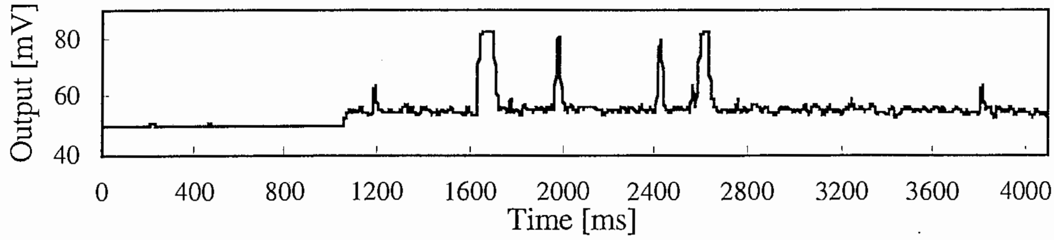
(a)



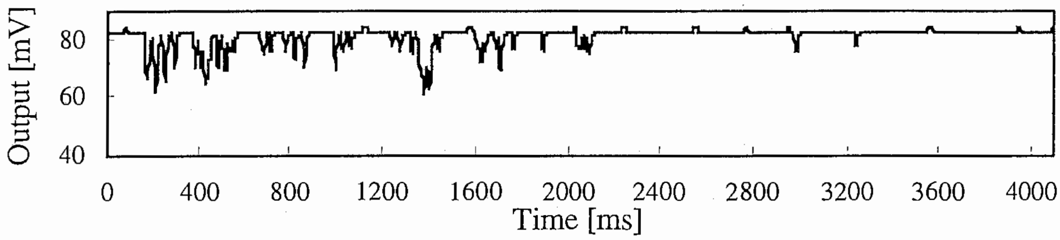
(b)

Fig. 7 (a) Waveform of light output of a particular mode and (b) Optical spectra recorded during the whole observation time of (a).

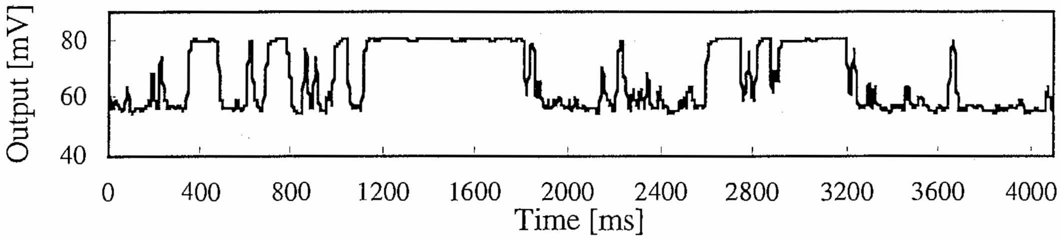
Figs. 7(a) and (b) depict the transient process of the laser output with the external optical feedback. Fig. 7(a) shows a time series of the light output of the monochrometer detected by the PIN photo-diode. Since the monochrometer is adjusted to pass only one longitudinal mode, the two states of the waveform correspond to two different longitudinal modes and one can recognize the mode hopping from the on-off process in the figure. The mode hopping is further verified in Fig. 7(b) which records the variation of the optical spectra during the whole observation time of Fig. 7(a). There



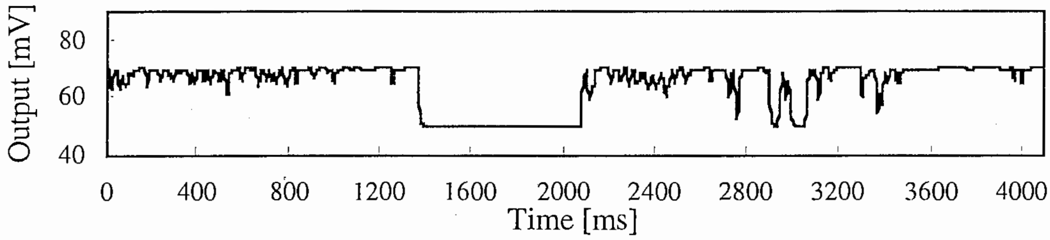
(a)



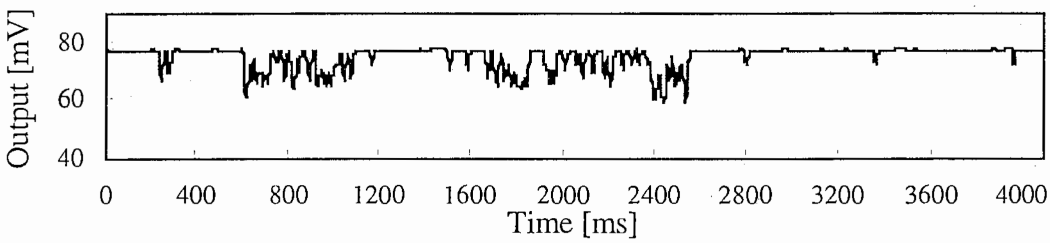
(b)



(c)



(d)



(e)

Fig.8 Time series of mode-hopping. (a) $I=1.28I_{th}$, (b) $I=1.28I_{th}$, (c) $I=1.28I_{th}$, (d) $I=1.20I_{th}$, (e) $I=1.10I_{th}$

are two main peaks in Fig. 7(b). The left peak corresponds to the lasing mode at the upper state of Fig. 7(a) while the right one corresponds to the lower state.

Fig. 8 shows some examples of time series of the laser output power with the slow detector. The selected wavelength by the monochrometer is λ=786.8nm at the external cavity length of about 33cm. In Figs. 8(a)-(c), the injection current is fixed at 60.0mA (I=1.28I_{th}), but the external reflectivity is changed by the tilt of the reflection mirror in this case. Therefore, we cannot give the quantitative fraction of the reflection in this case. The reflectivity is changed continuously along (a), (c), (b). In Fig. 8(a), the observed mode is rarely visited while in Fig. 8(b) this mode is nearly always the dominant mode of the laser. Fig. 8(c) shows a frequent mode hopping between the observed mode and some other modes. In Figs. 8(d) and (e), the external reflectivity is fixed at the same value as that in Fig. 8(a) but the injection current is varied from 1.28 I_{th} to (d) I=1.20 I_{th} and (e) I=1.10 I_{th}. The mode hopping rate is also dependent on the bias injection current as is seen from this figure.

IV. Mode Dwelling Time Distribution

The mode dwelling time is investigated here. The light output of the monochrometer is detected by the slow detector and the output signal is digitized using the digitizer (Rtd710A) with a sampling time of 500μs. With the large memory of the digitizer, we can obtain the data of 131,072 points with 10-bit resolution. At the injection current of I=54.0mA and the external cavity length of 33cm, the mode hoppings between wavelengths of 785.30 and 786.84nm for a range of V_{AOM} =0.27～0.43V and between 786.84 and 787.14nm for a range of 0.00～0.15V are examined. The laser output corresponding to the wavelength of λ=786.84nm is selected by the monochrometer and its mode dwelling time distribution is investigated by analyzing the time series of the output signal.

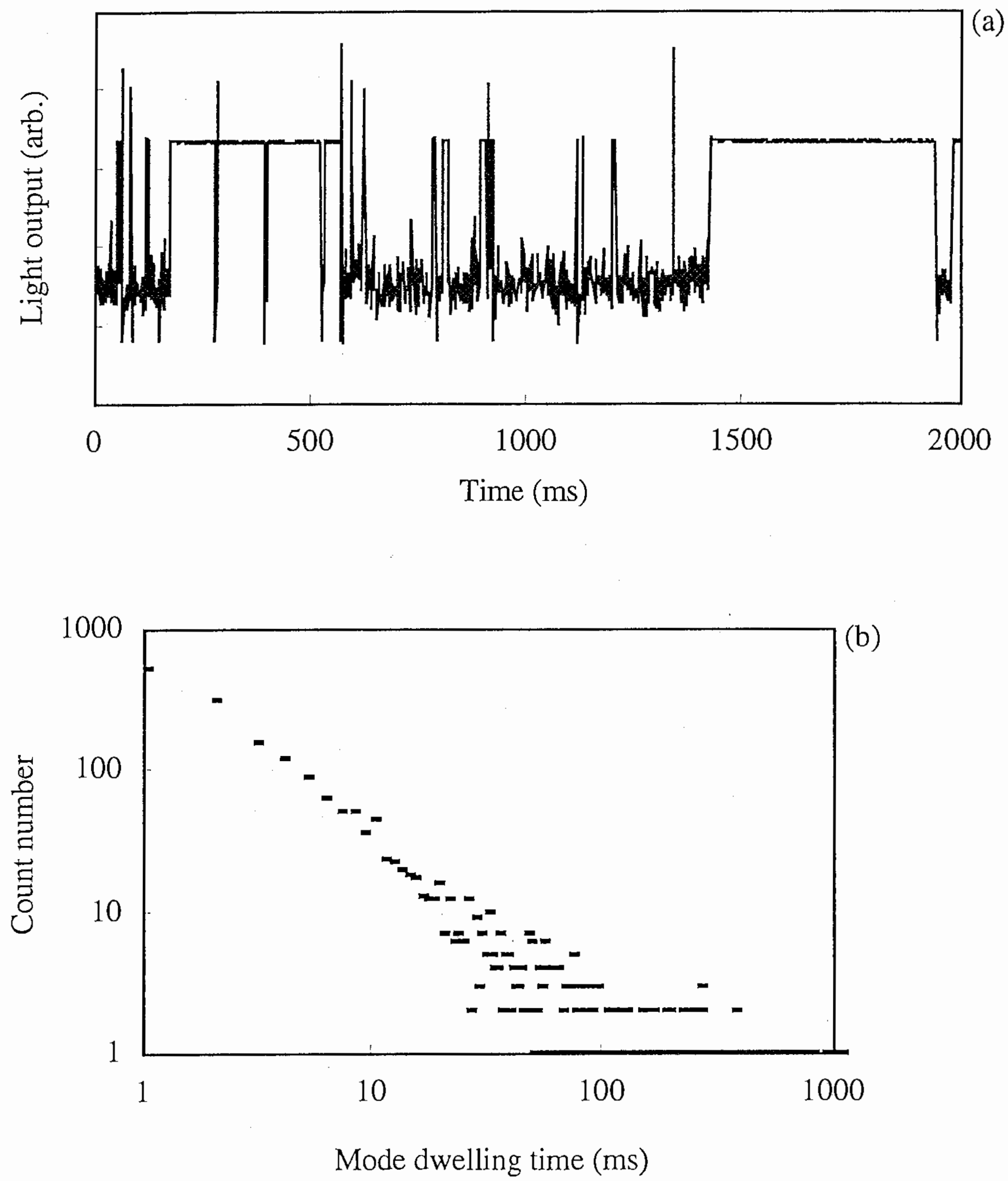


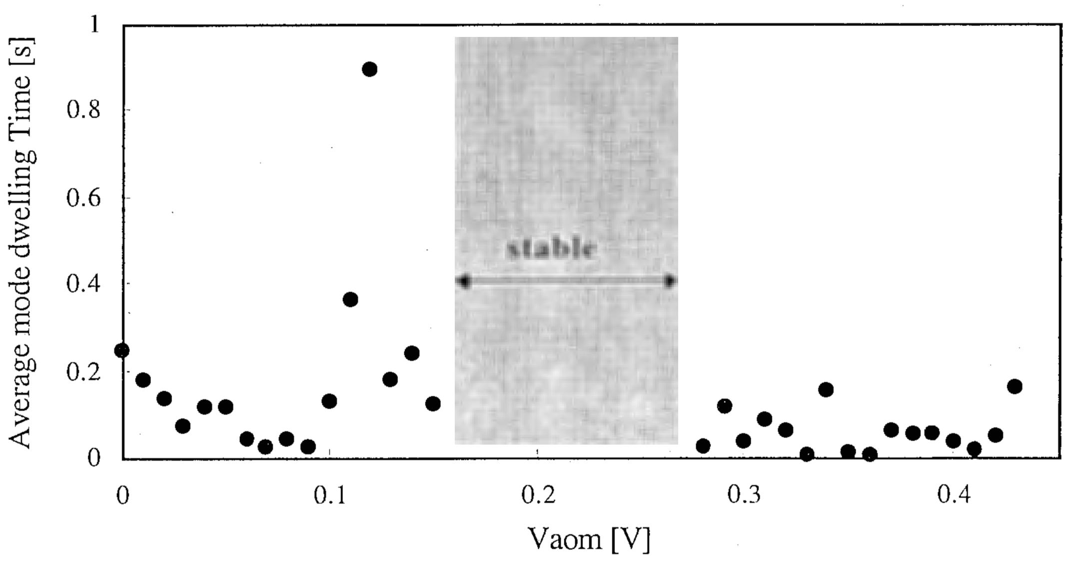
Fig. 9 (a) Time series and (b) mode dwelling time distribution of mode hopping. I=54.0mA, L_{ext}=33cm, and V_{AOM}=0.37V.

Fig. 9(a) shows the time series of the light output for the wavelength of λ =786.84nm. The dwelling time at the observed mode is calculated by putting a threshold level to Fig. 9(a) and counting the time length above the threshold. By counting the number of each dwelling event at the upper state and plotting it versus the dwelling time length, one can get a mode dwelling time distribution as shown in Fig. 9(b) in logarithmic scale. Obviously, there is a power-law scaling between the occurrence probability $P(l)$ for each dwelling event, which is proportional to the relative count number, and the dwelling time length l. It can be written as

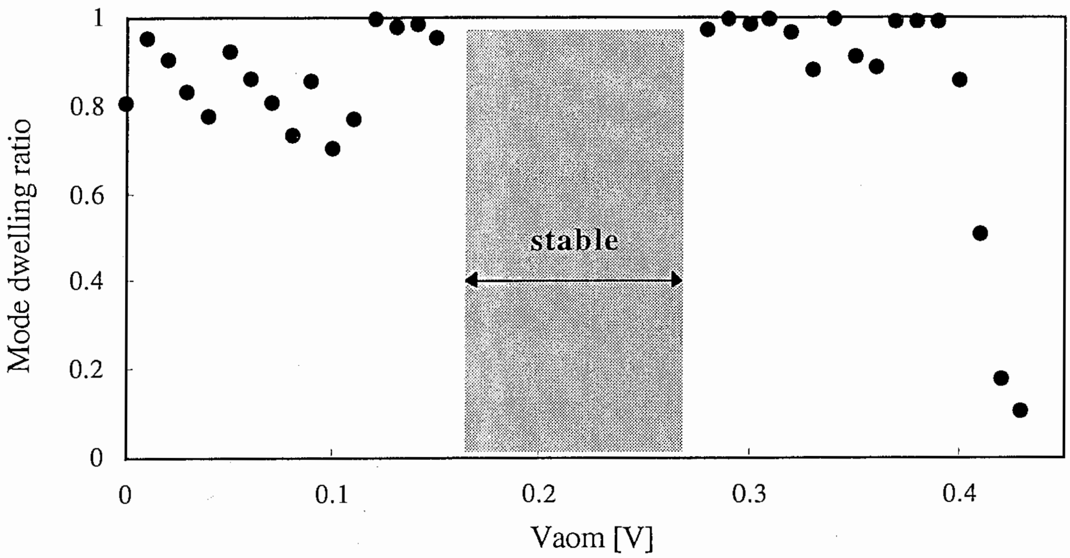
$$P(l) \propto l^{-\sigma} , \qquad (1)$$

where the exponent σ is about 1.3 in Fig. 7. In previous works, it has been suggested that the mode hopping in compound cavity laser diode is related to the Langevin noises.[6,9-11] The power-law scaling observed here also supports such suggestion.

Fig. 10 shows the average mode dwelling time and the main mode ratio as a function of the external reflectivity. The condition is the same as that in Fig. 9. The mode dwelling is defined as the ratio of time that the selected mode stays as the dominant



(a)



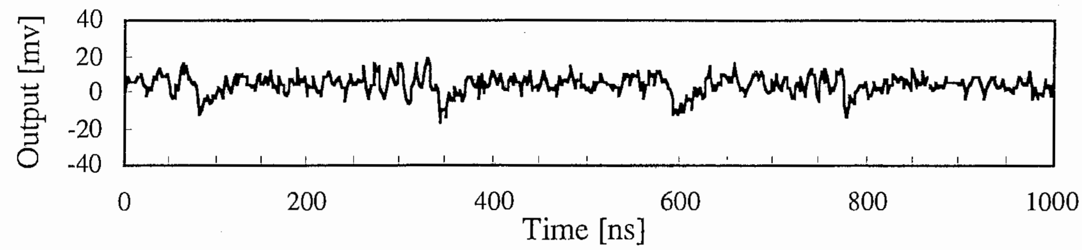
(b)

Fig. 10 (a) Average mode dwelling time and (b) main mode rate versus external reflectivity. The word "stable" in the graph means laser is at a single mode.

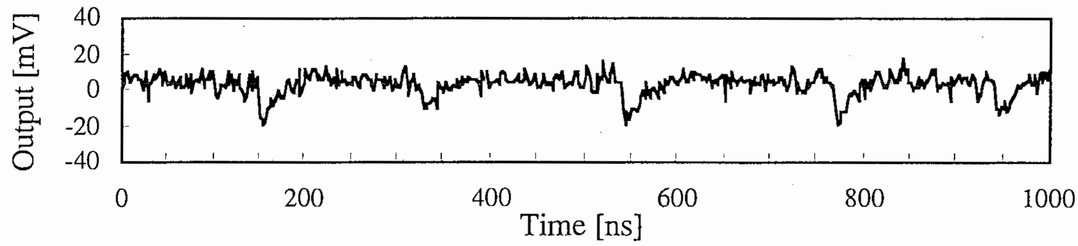
mode. As mentioned previously, there exists a single mode oscillation window for a certain external reflectivity. This window is indicated by the hatched area in the figure. Since the sampling time for this experiment is 500μs, switching faster than 500μs cannot be detected in this setup. But in this case, this sampling rate is chosen by considering the occurrence frequency of the mode hopping. The fast mode hopping characteristics among possible modes have not been well understood yet, so we should take into consideration the faster mode hopping in further investigations.

V. Low Frequency Fluctuations

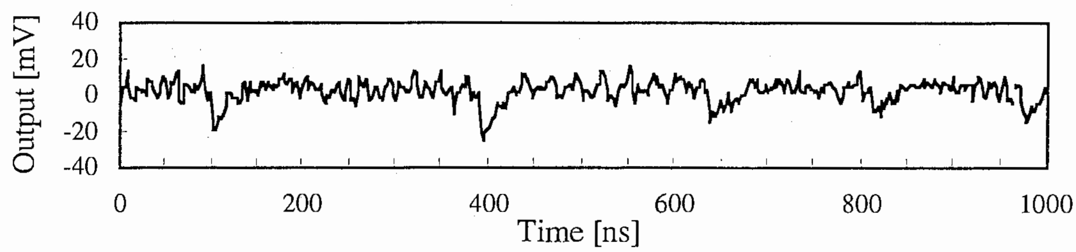
The phenomenon that the laser output shows irregular power drops is known as a low frequency fluctuation (LFF). Here the word "low frequency" means that the frequency of such fluctuations is much lower than (less than one tenth of) both the relaxation frequency and the external cavity frequency of the compound cavity laser diode. The as one of the typical effects in a laser diode with the external optical feedback. The order of the frequency of the LFF is from 1MHz to 100MHz depending on the system parameter values. The LFF is usually observed in lasers with a single mode oscillation. However, it is also observed here in a multi-mode case.



(a)



(b)



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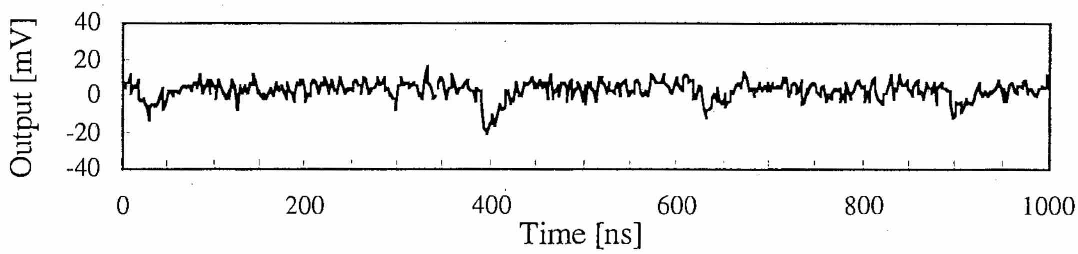

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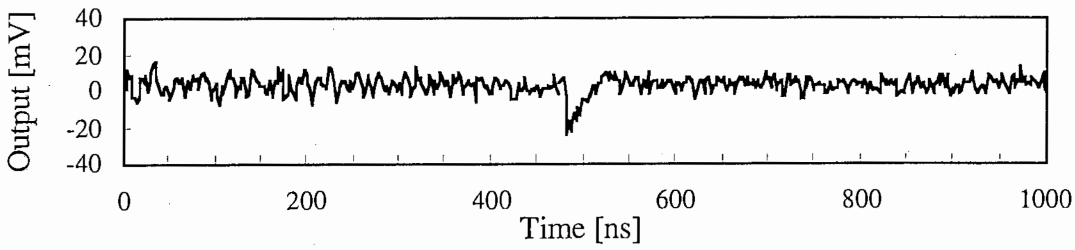
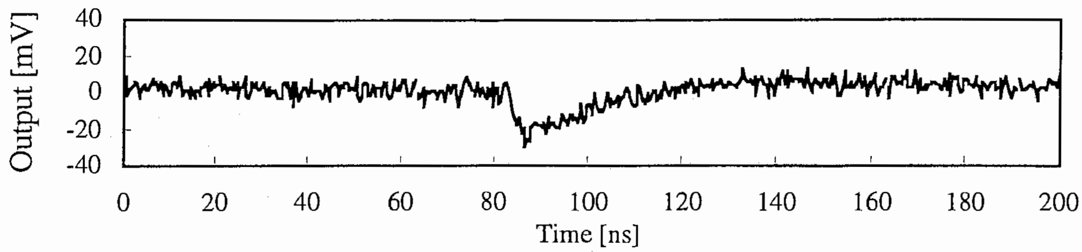


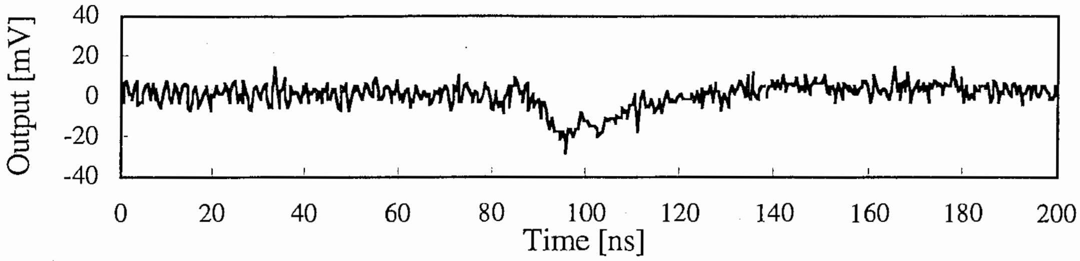
(e)

Fig. 11 Time series of LFF. Powermeter values are compatible with those in Fig. 8(a)-(e).

Fig. 11 shows some examples of the observed LFF waveforms using the high speed digital oscilloscope with the fast detector. Unlike waveforms of mode hopping in last two sections where the DC level of the signal directly corresponds to the light intensity of the observed mode, here only the fluctuations (AC signal with zero mean) of the light output is detected. The parameter values for the observation condition from Figs. 11(a) to 11(e) are coincident with those in Fig. 8, respectively. The change of the external reflectivity seems to have little effect on the frequency of the power drops as shown in Figs. 11(a)-11(c), but the amplitude of the power drop increases as the increase of the external reflectivity. On the other hand, the frequency of the power drop is considerably affected by the variations of the injection current as shown in Figs. 11(c)-11(e). It seems that the occurrence of the LFF is proportional to the injection current. Fig. 12 shows extended time series of the power drops corresponding to Fig. 11(e). Though the condition is the same both for Figs. 12(a) and (b), different waveforms of the power drops were observed. The time response of the power drops are different from each other between Figs. 12(a) and (b). The LFF has not been completely understood yet and the result here implies complex dynamics of the power drops in the laser diode with optical feedback.



(a)



(b)

Fig. 12 Time series of LFF in extended time scale corresponds to Fig. 11(e).

VI. High Frequency Modulation Phenomena

Several interesting phenomena are observed by the modulation of the injection current of the compound cavity laser diode. First we determine the external cavity frequency as a basis for the modulation frequency. The external cavity frequency can be determined from the spacing between the adjacent spectral peaks in the RF spectrum. As an example of effects of the modulation on the dynamics of the laser diode, we here investigate the influences of the modulation frequency on the light output dynamics. In particular, we investigate how the laser output behaves when the modulation frequency is close to the external cavity frequency.

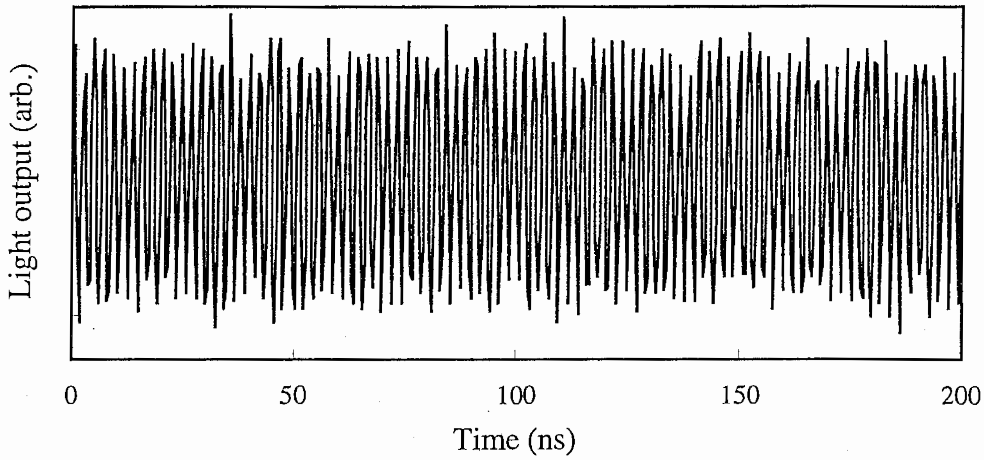


Fig. 13 Time series of laser output with high frequency modulation.

Fig. 13 shows the time series of the laser output modulated by the frequency of f_m=455MHz which is very close to the external cavity frequency f_{ext}=450MHz. The bias injection current is I=55.0mA and the depth of the modulation is 5dBm relative to the bias injection current. At the case $f_m \sim f_{ext}$, the output waveform of the laser synchronizes with the modulation signal as shown in Fig. 13. When the detuning between f_m and f_{ext} is extended, we observe the LFF in the output waveform of the laser diode. Fig. 14 shows some examples of such results. The frequency of the LFF increases with the increase of the detuning as shown in the figure. The LFF is observed for a comparatively small frequency detuning, say about several ten MHz. Fig. 15 shows the frequency of the LFF as a function of the modulation frequency. For the case $f_m < f_{ext}$, the frequency of the LFF tends to be locked to a certain value within some frequency detuning range and jumps to a new step when the modulation frequency is further decreased. On the other hand, for $f_m > f_{ext}$, the LFF frequency is linearly proportional to the detuning frequency with a slope of about 4/5. These two interesting features have not been completely understood at present and further study is necessary.

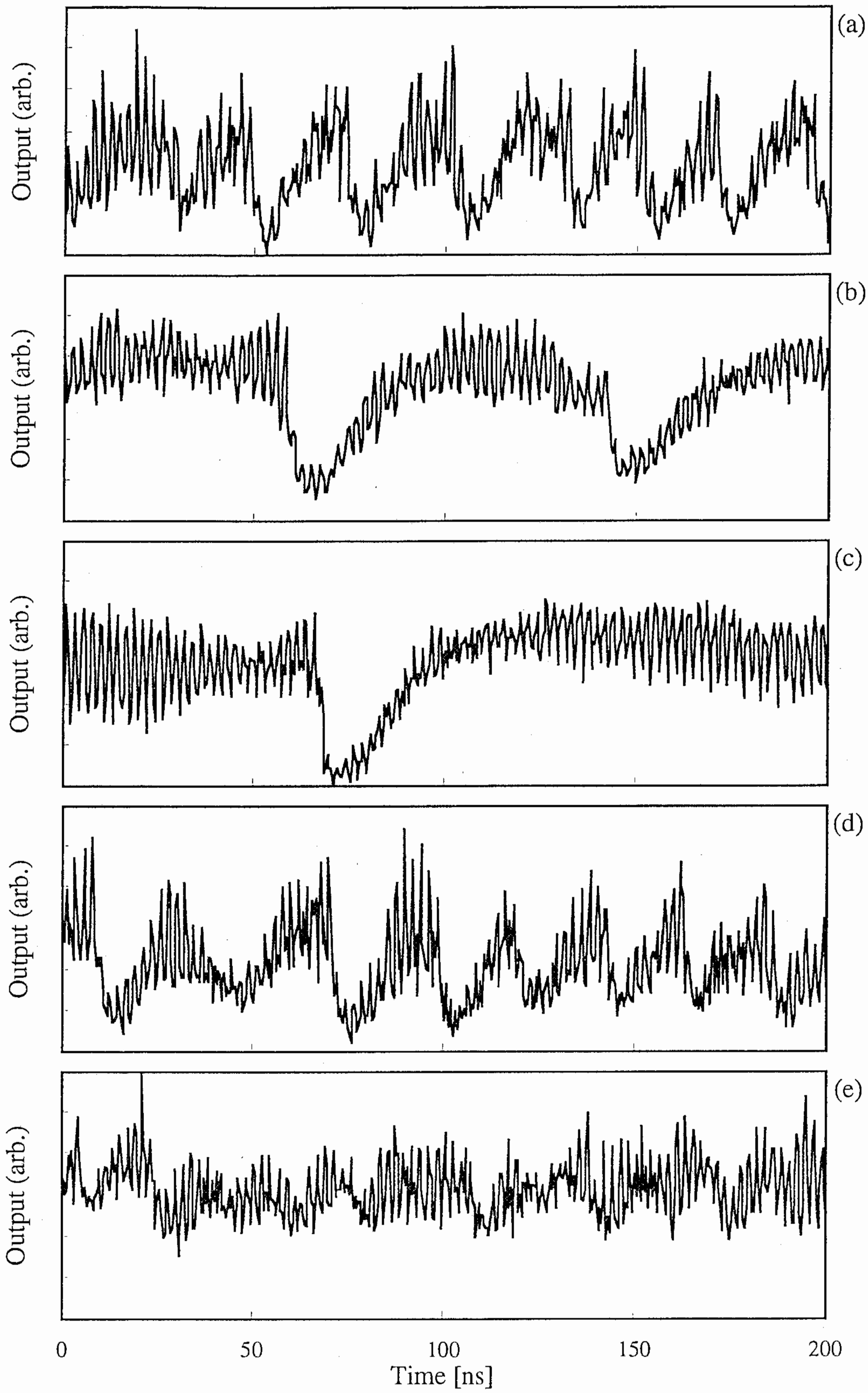


Fig. 14 Time series of laser output for various modulation frequencies. Modulation

frequencies are (a) 360, (b) 430, (c) 460, (d) 500, and (e) 540MHz.

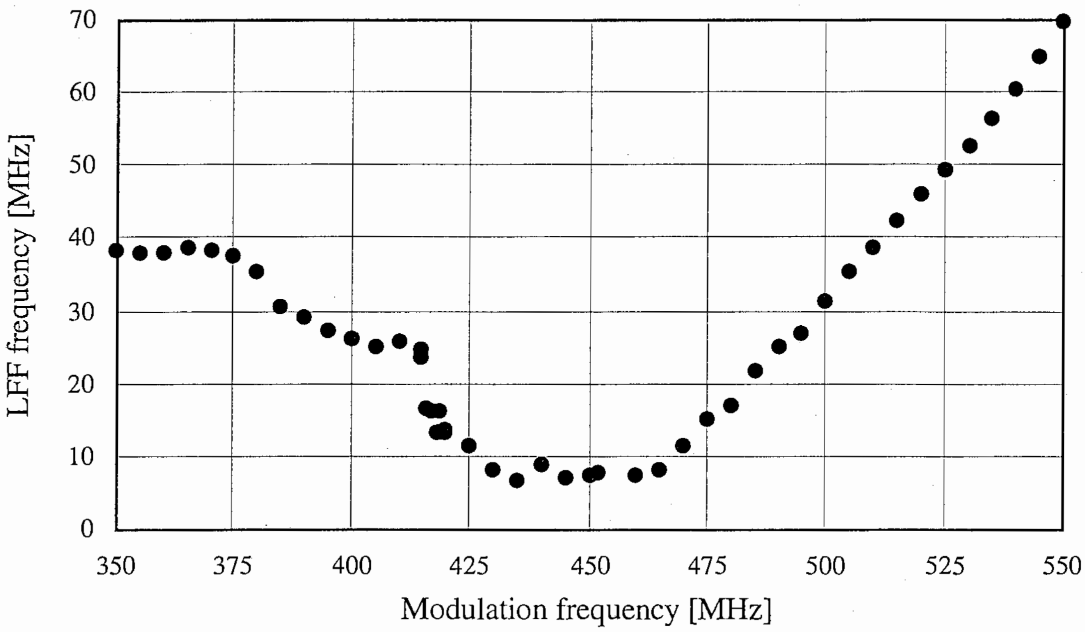


Fig. 15 Correspondence between the LFF Frequency and the modulation frequency. The external cavity frequency is 450MHz.

VII. Conclusion

We have studied the dynamic behaviors of a compound cavity laser diode with a multi-mode oscillation. The mode hopping and mode dwelling time distribution have been investigated for different parameters. In particular, it was found that when the laser is in mode hopping state, the probability of the laser dwelling at one longitudinal mode decreases as a power function of the dwelling time. Low frequency fluctuations were also observed in the compound cavity laser with and without high frequency injection modulation. When the modulation frequency is slightly lower than the external cavity frequency, the frequency of the LFF tends to be locked to certain discrete levels. On the other hand, when the modulation frequency exceeds the external cavity frequency, the LFF frequency is linearly proportional to the detuning frequency with a slope of about 4/5. By directly observing the light output of a particular longitudinal mode, this experiment demonstrated convincing results of mode hopping dynamics in a multimode laser diode with optical feedback. The obtained mode dwelling time distribution and mode dwelling ratio are not only worthy of further theoretical study but also work as a preliminary guidance for performing mode selections in millisecond time scales. It should be worthwhile to investigate mode hopping dynamics in fast time scales and compare the results with the present experiment. Further works are also needed to reveal features of LFF in multimode laser diodes and the relation between the LFF frequency and the detuning between modulation and external cavity frequencies.

Acknowledgment

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