Dynamics of Semiconductor Lasers with Optical Feedback from Photorefractive Phase Conjugate Mirror

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The dynamics of semiconductor lasers with photorefractive phase conjugate optical feedback are experimentally studied. Photorefractive fringes considered here are rather static compared with time fluctuations of laser output power. Therefore, it is expected that a semiconductor laser with photorefractive feedback shows similar dynamics to those with conventional optical feedback. We examine relaxation oscillation and external cavity modes in the presence of photorefractive phase conjugate feedback. It is proved that the dynamics of photorefractive phase conjugate feedback are fundamentally the same as those of conventional optical feedback.

Key words: semiconductor laser, photorefractive optical feedback, instability, chaos

1. Introduction

The dynamics of semiconductor lasers with optical feedback has drawn the attention of many researchers as an excellent model for chaotic nonlinear systems, and has been the subject of experimental and theoretical works during the past two decades. The laser output power shows unstable and chaotic behavior due to external optical feedback. Relaxation oscillation of the semiconductor laser and external cavity mode are important in the dynamics. With increase of external reflectivity, the laser output shows periodic oscillation with a frequency near the relaxation oscillation, and then it evolves into quasi-periodic oscillations with a mixed state of relaxation and external mode frequencies. The dynamics is also affected by changes of the injection current and the external cavity length. Stability and instability of the laser output power depending on these system parameters have also been investigated. The studies are important not only for fundamental physics but also for applications. These studies have shown that laser output power under chaotic oscillation can be stabilized and the noise induced by the irregular fluctuations can be suppressed.

In the meantime, much attention has also been devoted to the dynamics of semiconductor lasers with phase conjugate optical feedback. Most of these studies were theoretical, and a fast response phase conjugate mirror, such as a nonlinear optical medium with a third order polarization, was assumed and the time dependent phase of the reflected light expected to be faithfully inverted to that of the input field. Photorefractive medium together with a light source from a semiconductor laser is used in many applications in photorefractive phase conjugate optics, such as photorefractive interferometers and optical information processing systems. Though a spatially reversed wavefront is generated both from photorefractive and third order nonlinear polarization mirrors, the time response of a medium in photorefractive phase conjugation is usually much slower (typically, from milliseconds to seconds) than that in third order polarization. The time scale of the laser dynamics of feedback induced instability is on the order of nano-seconds, which is dominated by the time scale of the relaxation oscillation. Therefore, the assumption of fast response of medium cannot be applied for the dynamics of semiconductor laser with such photorefractive phase conjugate feedback. A very fast formation of photorefractive grating in a BaTiO3 crystal of less than nano-seconds was reported, but the phenomenon was transient. Other fast time response photorefractive effect in a semiconductor material is also known, but here we restrict ourselves to photorefractive feedback effects with slow time response. A slow response of photorefractive medium as a feedback mirror is thought to results in the same dynamics as those those in conventional mirror feedback.

In this paper, we experimentally investigated the dynamics of semiconductor lasers with photorefractive feedback both for self-pumped and four wave mixing phase conjugations. We studied the frequency at which the laser output power evolves into period-one oscillation and compared it with that of conventional feedback. The excited frequency in period-one oscillation is very close to that of the relaxation oscillation for the solitary laser. Therefore, in the following, we call this frequency relaxation oscillation frequency in the presence of optical feedback. We also investigated the lowest excited frequency of the laser output power spectrum in quasi-periodic states which is induced by the external cavity mode. The results show that the dynamics both for self-pumped and four wave mixing phase conjugate feedbacks is the same as those of conventional optical feedback, though the external cavity length is not defined by the separation between the laser exit face and the photorefractive mirror but by the loop of the pump beam.
2. Experiments and Discussion

2.1 Self-Pumped Phase Conjugation

The experimental setup of a semiconductor laser with self-pumped photorefractive feedback is shown in Fig. 1. The semiconductor laser used was a single mode MQW (multi quantum well) laser diode (Mitsubishi ML1413R) which radiated a visible light with a wavelength of 680 nm and a maximum power of 50 mW. The threshold current was $I_{th}=36 \text{ mA}$ at the temperature of 25°C. The temperature of the laser was stabilized by an automatic temperature control circuit. The laser light emitted was collimated and separated into two beams by a beam splitter (BS). One of the beams was directed to a photorefractive medium as a focusing beam through a variable attenuator (VA) and fed back to the laser cavity. The photorefractive medium used was a Cerium-doped BaTiO$_3$ crystal. The crystal was mounted on a motor-driven movable stage by which the external mirror position was varied. A conventional mirror was also used to compare the results with those of the phase conjugate feedback. The other beam was used to measure spectra of the laser output power by a Fabry-Perot interferometer (free spectral range of 10 GHz) and a RF (radio frequency) spectrum analyzer (spectral band width of 6.5 GHz). Spectra were measured after slowly varying laser output power became stable enough to form a grating in the crystal (~ 60 seconds).

Figure 2 shows some examples of measured spectra for the photorefractive phase conjugate feedback. The injection current and the external cavity length were selected to be $I=1.7I_{th}$ and $L=32 \text{ cm}$, respectively. For no external feedback, the laser oscillates in almost a single mode as shown in Fig. 2(a). A small peak at 2.7 GHz in the RF spectrum corresponds to the relaxation oscillation frequency for the solitary laser. With increase of the photorefractive reflectivity, the laser output power shows periodic oscillation due to the excitation of the relaxation oscillation mode in Fig. 2(b). In this state, the laser output power has a non-vanishing excited frequency which is close to the relaxation oscillation frequency of the solitary laser. Here the intensity reflectivity is an estimated one from the increment of the average power detected by the monitor photodiode installed in the laser diode package and may not be exactly equal to the intensity fraction actually fed back to the laser active region. With a further increase in reflectivity (Fig. 2(c)), the external mode frequency merges in the spectrum and shows a mixed state of the relaxation oscillation and external mode frequencies and their higher harmonics. Figure 2(c) corresponds to a quasi-periodic state of the laser oscillation. Finally, for larger reflectivity, the coherence of the laser output is completely destroyed (see optical spectrum in Fig. 2(d)) and the noise level is greatly enhanced. The laser output is expected to be chaotic and corresponds to the coherence collapse state. The time scale of the laser output power fluctuations (typically around nano-seconds) is very short compared with the response of photorefractive crystal fringe formation. Since the spectrum observed in Fig. 2(d) is rather stable in time, the photorefractive medium acts like a static grating once a photorefractive grating is formed in the crystal.

Figure 3 shows the variations of the relaxation oscillation frequency against the external mirror position at onset of periodic oscillation (Fig. 2(b)). The injection current was fixed to be $I=1.7I_{th}$. The intensity reflectivity at which period-one oscillation due to undamped relax-
Fig. 3. Relaxation oscillation frequency dependence on the crystal position.

Fig. 4. Length calculated from the lowest frequency in quasi-periodic oscillations for the mirror position. Black and white circles are for self-pumped photorefractive phase conjugate and conventional mirrors, respectively.

Fig. 5. Dependence of the relaxation oscillation frequency on the injection current in self-pumped photorefractive phase conjugation geometry. Black and white circles are for self-pumped photorefractive phase conjugate and conventional mirrors, respectively.

Relaxation oscillation occurs depends on the position of the feedback mirror. As discussed later, the total feedback length of light in this configuration is equal to the loop of the beam reflected at the corner of the crystal. The horizontal axis is the mirror position for a certain offset and the vertical axis is the relaxation oscillation frequency. In the presence of optical feedback, the relaxation oscillation frequency decreases with increase in external cavity length, jumps up at a certain external cavity position, and then repeats the same process for increase of the external cavity length. This can be explained by the mode competition between the linear modes around the relaxation oscillation frequency. This frequency for the external cavity length has a periodic structure and the period is equal to the length corresponding to that calculated from the relaxation oscillation frequency for the solitary laser (2.73 GHz corresponding to \( L = 5.5 \) cm). The result in Fig. 3 agrees well with that obtained for conventional mirror feedback.\(^{13,27}\)

In quasi-periodic oscillation such as shown in the RF spectrum in Fig. 2(c), the external cavity mode is excited as a non-vanishing oscillation. It has been proved\(^ {27}\) that the lowest excited frequency or, equivalently, the frequency separation between successive peak frequencies in the laser spectrum is originated from the external mode, though the observed lowest frequency and the frequency calculated from the external cavity length are not always exactly coincident with each other. The lowest frequency in quasi-periodic oscillation for variation of the external cavity length is experimentally obtained and shown in Fig. 4. The injection current was fixed at \( I = 1.7I_\text{th} \). The intensity reflectivity at which quasi-periodic oscillation occurs also depends on the position of the feedback mirror. The horizontal axis is the mirror position for a certain offset and the vertical axis \( L_{\text{ep}} \) is the length calculated from the lowest frequency. Black circles are the results of the self-pumped phase conjugate feedback and white ones are those of the conventional mirror. The solid and broken lines are the interpolations for the data of the photorefractive and conventional mirrors, respectively. These data completely coincide with correction of the optical path difference due to the refractive index of the photorefractive crystal and other optical components.

Figure 5 shows the dependence of the relaxation oscillation frequency on the square root of the injection current. Black and white circles are the results for the phase conjugate and conventional mirrors, respectively. The external cavity length was \( L = 23 \) cm. For a solitary laser, the relaxation oscillation frequency is known to linearly increase with increase of the output power (being proportional to the square root of the injection current). In a feedback case, the frequency is also proportional to the square root of the injection current, but periodic jumps occur in the \( L-I \) characteristics. The jump shown in Fig. 5 is also explained by the external mode alternation for increase of the injection current as discussed in Fig. 3. Namely, the relaxation oscillation frequency at a certain external mode is pulled and switched by the next external mode with increase of the injection current. The amount of the frequency jump 0.65 GHz is well consistent with the frequency calculated from the external cav-
ity mode (the external cavity length of $L=23$ cm). Good coincidence in the data between the photorefractive and conventional mirrors is found. Thus it is concluded that the fundamental dynamics of photorefractive feedback related to relaxation oscillation and the external mode transition are the same as those for conventional optical feedback. Only the difference from conventional optical feedback is the automatic feedback of the spatial wavefront through a photorefractive mirror without any adjustment of optical components in the system.

2.2 Four Wave Mixing

The dynamics of a semiconductor laser with photorefractive phase conjugate feedback were also studied for a four wave mixing geometry. The experimental setup is shown in Fig. 6. The same laser diode and photorefractive crystal as for the self-pumped phase conjugate feedback were used. It is expected from the self-pumped phase conjugate experiment that the photorefractive crystal behaves only as a static grating for fast fluctuations of the laser output power. At the onset of period-one oscillation, the relaxation oscillation frequency was examined for variation of the mirror position $M_2$ (Fig. 7). The injection current was set at $I=2.2I_0$ (80 mA), the pump power was 10 mW, and the ratio of the signal to the pump was approximately $1/10$. The horizontal axis is the mirror position for a certain offset and the vertical axis is the relaxation oscillation frequency. The periodic structure for variation of the external cavity length is the same as in the previous experiment and the period is also equal to the length corresponding to the relaxation oscillation frequency of the solitary laser. The result of Fig. 7 agrees well with those for self-pumped photorefractive and conventional mirrors.

We changed the position of the photorefractive crystal and measured the relaxation oscillation frequency. Two different optical paths were investigated, however, the total lengths of the expected feedback loops of the pump beam diffracted by the crystal back to the laser were set to be the same. Figure 8 shows the results. The pump power was also around 10 mW and the ratio of the signal to the pump was approximately $1/10$. The distances between the laser facet and the photorefractive crystal were 33.9 (black circles) and 30.2 (white circles) cm, and the total lengths of the pump beams reflected by the mirror $M_2$ and diffracted back to the laser through the photorefractive crystal were 112.4 cm. The two data are coincident with each other. Jumps appearing in Fig. 8 are also explained by the alternation of the external cavity mode as discussed in Fig. 5. The average frequency jump is 0.26 GHz and the corresponding length is 115 cm. This means that the feedback loop to the laser cavity originates from the pump beam.

In Fig. 8, the difference between the positions of the photorefractive mirror was only 3.7 cm. Since the diffraction efficiency in the crystal is not only dependent on the incidence angles between the pump and signal beams but also on the coherence length of the laser, it is not easy to obtain stable periodic oscillation of the laser output power when the path difference between the pump and signal beams increases. Therefore it is not easy to plot the relation between the lowest excited frequency and the external cavity length as shown in Fig. 4. Instead, to examine such a plot, we observed spectra of quasi-periodic oscillations for two different lengths of the pump beam. We here define the lengths of the feedback beams. The first one (loop 1) is the length of the pump beam reflected by the mirror $M_2$ and diffracted back to the laser through the photorefractive crystal. The second (loop 2) is the
length of the signal beam diffracted by the phase conjugate crystal, reflected by the mirror M2 and again diffracted at the crystal back to the laser cavity. In Fig. 9(a), the total length of loops 1 and 2 was 116.3 and 102.0 cm, respectively. The injection current was 2.2Ith and the pump and signal powers in front of the crystal were 7 and 10 mW, respectively. The fundamental frequency excited due to the external mode is 0.23 GHz in Fig. 9(a) which is close to the frequency corresponding to the total length of the pump beam. Figure 9(b) shows an example of spectra for a large path difference. The total length of loops 1 and 2 was 178.8 and 102.0 cm, respectively. The injection current was also 2.2Ith and the pump and signal powers in front of the crystal were 6 and 10 mW, respectively. The fundamental frequency excited due to the external mode is 0.16 GHz in Fig. 9(b) which is very close to the frequency corresponding to the total length of the pump beam. Therefore, it is concluded that the feedback loop in the photorefractive feedback is the total length of the pump beam.

2.3 Discussion

In the photorefractive phase conjugation configuration considered here, the grating formed in a crystal is considered to be static compared with fast time fluctuations of the laser output power. However, if a phase conjugate medium responds very quickly as in a Kerr medium, the dynamic behaviors of semiconductor laser with phase conjugate feedback are much different from those with conventional optical feedback. The conventional and fast response phase conjugate mirrors were compared by the present authors based on the laser rate equations and also their linear stability analysis.27 In the theoretical analysis for fast response phase conjugate feedback, the time dependent phase of the field is reversed due to the fast response compared with fluctuations of the laser output power. The main difference between conventional and fast response phase conjugate mirror feedback is the phase locking phenomenon. The phase for fast response phase conjugate feedback has a unique solution and is locked at a certain value, while that for conventional feedback has multiple solutions and linearly changes with time.

In the following, we discuss the difference between phase conjugate feedback with fast and slow time responses and explain that the dynamics in a semiconductor laser with slow time response phase conjugate feedback are fundamentally the same as those for conventional mirror feedback. For example, for fast response phase conjugate feedback, a periodic structure with relaxation oscillation frequency similar to that shown in Figs. 3 and 7 is observed, but the external cavity length is always defined by the distance between laser exit face and phase conjugate mirror. Furthermore, jump positions of the frequency for change of the external cavity length are located alternately to those of conventional mirror feedback.27 Similarly, the positions of frequency jumps with increase of the injection current are also located alternately to those for conventional mirror feedback as shown in Figs. 5 and 8.27 Another difference is the behaviors of the lowest frequency. In conventional optical feedback, the lowest frequency excited in quasi-periodic oscillation is linearly proportional to the frequency calculated from the external cavity mode. On the other hand, the lowest frequency for fast response phase conjugate feedback undulates with a period equal to the relaxation oscillation frequency for change of the external cavity length, and its value is much less than the frequency calculated from the external cavity length.27 These results together with the experimental results obtained here support that the dynamics of slow response photorefractive optical feedback in a semiconductor laser are almost the same as conventional optical feedback except for the generation of a spatial phase conjugate wave by the crystal.

3. Conclusions

We have experimentally studied the dynamics of a semiconductor laser with photorefractive phase conjugate feedback. When time scales between response of photorefractive medium and laser output fluctuations differ greatly, the grating formed in the medium can be considered as a static one. Once a grating is formed in a photorefractive crystal, the dynamics is only governed by the total feedback loop of the pump beam. As a result, the dynamics is almost the same as that for conventional mirror feedback except for the generation of a
spatial phase conjugate wave. The dynamics is different from those for a fast response phase conjugate mirror as in a Kerr medium. Within the the time range of the measurement in the current experiments, the phenomena observed were rather stationary in a statistical sense. Therefore, a photorefractive mirror with slow time response may be a good medium as a feedback reflector for positive use of optical feedback effects since it functions as an automatic feedback reflector without any adjustment for optical components in the system. The reflection fraction of the feedback beam can be easily controlled by changing the pump ratio.

We have also discussed the difference of the dynamics between fast and slow time response phase conjugate feedback. No experiment on fast response phase conjugate feedbacks has previously been done. Feedback induced instability in semiconductor lasers with phase conjugate mirror can be examined by using a material exhibiting third order polarization nonlinearity. Such experiments may also be possible using semiconductor materials with fast time response photorefractive effect.35) It is not easy to perform experimental investigations of a semiconductor laser with fast response phase conjugate feedback, but experiments and comparison with slow time response phase conjugate feedback are expected to be accomplished in the future studies.

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References