지연 광전궤환이 가해진 레이저 다이오드에서의 자기발진, 쌍안정성 및 혼돈

Self-pulsing, Bistablilty, and Chaos in a Laser Diode with Delayed Optoelectronic Feedback

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ABSTRACT

We observe experimentally self-pulsing, subharmonic generation, spectral bistability, and chaos in a stable laser diode with delayed optoelectronic feedback. The laser diode emits 200 ps optical pulses with 1.1 GHz repetition rate in the self-pulsing region. The bistable region critically depends on the closed loop gain of the system. We also explain observed experimental result.

Effects of optoelectronic feedback on the dynamics of the laser diode have attracted considerable attention[1-5]. The optoelectronic feedack narrows optical pulses emitted from self-pulsed laser diodes[1]. Delayed feedback is also employed to generate optical short pulses[2]. Recently, it is shown that the stable laser diode with negative optoelectronic feedback generates picosecond optical pulses[3]. There also exist several types of optical bistable devices in the laser diode with positive optoelectronic feedback[4-6]. Advance of the optoelectronic integrated circuit technology offers a possibility of monolithic integration of these devices. However, the systematic understaning of optoelectronic feedback effects on the dynamics of laser diode is not clear at this time. In this Paper we report self-puling, subharmonic generation, bistability, quasiperiodicty, and chaos in a stable laser diode with delayed optoelectronic feedback. The laser diode emits 200 ps optical pulses with 1.1 GHz repetition rate in the self-pulsing region. The bistable region critically depends on the closed loop gain of the system. We also explain observed experimental results.

To understand the effects of optoelectronic feedback on the laser diode we modeled our system that consists of a laser diode, a photodiode, and an amplifier by using a rate equation formulation[3]. The model for more general feeback networks are given in ref. 7. Generally, there exist self-pulsing in the laser diode with negative optoelectronic feedback[3,7], while optical bistability and optical multistability are possible in the laser diode with positive feedback[4-6]. For the delayed feedback, there exist self-pulsing, spectral bistability, and chaos, as will be shown here. Stability of the system can be determined by the gain condition and the phase condition[7]. The gain condition gives the required closed loop gain for oscillation and the phase condition gives the oscillation frequency. Since the laser diode has a resonance peak at the small signal resonance frequency, the required gain of the feedback amplifier is minimum at the resonance frequency.

The phase condition is satisfied at a single frequency if the feedback network has a sufficiently short delay time. With increase of the delay time, one number of frequencies that satisfy the phase condition increases. Thus this system shows a rich dynamics provided the bandwidth of the feedback network is sufficiently wide. We study these features experimentally.

Our experimental system that consists of a laser diode, a photodiode, and an amplifier. The optical output from the laser diode is detected by the photodiode and the photodiode current is negatively fed to the laser diode after amplification, i.e. the feedback current reduces the injection current. The experimental set-up is shown in Fig. 1. The optoelectronic feedback amplifier is designed by using an amplified photodiode (Antel Model ARX-SP) and an MMIC amplifier (Advantec Model MSA-0485). The 3 dB bandwidth of the designed feedback network is 300 MHz-1.7GHz, and the total delay time in the feedback pass is 1 ns. Threshold current of the used laser diode (Hitachi Model HLP 1400) is 57 mA. The measured resonance frequency of the laser diode is 4.9 $\times\sqrt{I_b/I_{th}-1}$ GHz, where I_b is the bias current and I_{th} the threshold current. The optical output of the laser diode detected by a high speed photodiode (Ortel Model PD050-OM) is observed by using a sampling oscilloscope and a RF spectrum analyzer.

Experiment is performed by varying the bias current of the laser diode. Modulation characteristics of the laser diode depend on its bias current. We show the evolution of the observed intensity spectrum with increase of the bias current in Fig. 2. The bias current of the amplifier is fixed at 18.2 mA (the closed loop gain is about 0.33). The system is stable if the bias current of the laser diode is less than 58.4 mA where the laser diode shows a noise spectrum peaked at $f = f_1$. The oscillation frequency f_1 increases as the bias current increases. As we increase the bias current, the amplitude of the spectrum f_1 grows, and it accompanies noise precursor[8] of the first subharmonic component as shown in Fig. 2(b). As we increase the bias current, the amplitude of subharmonics grows rapidly, while f_1 oscillation maintains slow growth rate. At the bias current of 59.5 mA the subharmonic component and the fundamental component have equal amplitude. As we increase the bias current, the amplitude of the subharmonics starts to decrease, since the resonance frequency of the laser diode approaches to f_1, It disappears at I_b=60.6 mA and the laser diode shows self-pulsing at a single frequency f_1. The typical pulse width is about 200 ps and the repetition rate is tuned from 1050 MHz to 1150 MHz as we increase of the bias current from 60.6 mA to 63.5mA. We show the intensity spectrum and its waveform in Fig. 2 (d) and (e). At I_b = 63.5 mA, the intensity spectrum changes abruptly to the spectrum shown in Fig. 2 (f). It shows quasiperiodic state with two fundamental frequencies, f_0 and f_1, and the other spectrum are beats of the f_0 and f_1. Here we note that the resonance frequency of the laser diode is about f_0+f_1. As we increase the bias current, the optical output becomes chaotic as shown in Fig. 2 (g). This sequence may be regarded as two-frequency route to chaos. Further increase of the bias current brings about locked states of f_0 and f_1. If we open the feedback loop, the system becomes stable, and the output spectrum shows a noise spectrum peaked about $f=f_0+f_1$. Further increase of the bias current brings about a noise spectrum peaked at the resonance frequency of the laser diode with the broadened noise peaks at f_0 and at f_1. Increase of the required closed loop gain for oscillation with increase of the laser bias current explains disappearance of oscillation at f_0 and at f_1.

We increase the bias current of the amplifier to 22.8 mA (the closed loop gain is about 0.34) and observe optical output. With increase of the bias current, the amplifier gain increases, while bandwidth of the feedback network decreases slightly. The system is stable when the bias current is lower than 57.8 mA. With increase of the bias current oscillation start at f_0 and its amplitude grows. We show observed spectrum in Fig. 3 (a). Here, we can see components of spectrum f_0, $2f_0$, $3f_0$, and a noise precursor of f_1. As increase of the bias current, oscillation frequencies of the spectra f_0 and the spectra f_1 increase. Also the spectral width of the f_1 broadened as shown in Fig. 3 (b). The amplitude of the f_0 component decreases with increase of the bias current and the intensity spectrum shows single spectrum at f_1 when bias current higher than 59.6 mA. This spectrum changes abruptly at I_b = 61.6 mA to stable f_0 oscillation. If we decrease the bias current f_0 oscillation maintained until I_b = 60.2 mA. In other words the laser diode shows bistable characteristics between I_b = 60.2 mA and I_b = 61.6 mA. The stable states are f_0 oscillation and f_1 oscillation. We show observed bistable states in Fig. 3 (c)-(f).

We also perform experiments by changing as the bias current of the amplifier, i.e., change of the closed loop gain. The bias current of the diode laser is fixed at I_b = 64.4 mA where the intensity spectrum shows chaotic behavior as shown in Fig. 2 (g). When the bias current of the amplifier is decreased, the system show quasiperiodic state with fundamental frequencies of f_0 and f_1. Further decrease of the bias current brings about noise spectrum that have sharpened peak at the resonance frequency of the optoelectronic feedback. If we increase the amplifier bias current, the laser diode shows stable f_0 oscillation like Fig. 3 (e) through the oscillation spectrum like Fig. 2 (f).

Similar behaviors are also observed by changing the coupling efficiency of the laser diode output to the photodiode.

Observed experimental results may be explained by the following argument. If the bias current of the laser diode is close to the threshold current, the system shows only stable self-pulsing with a single spectrum. The oscillation frequency is close to the resonance frequency of the laser diode. With increase of the bias current, the resonance frequency increases and the system has many spectra that satisfy the phase condition. And at a certain bias current of I_c, there exist two spectrum that have equal closed loop gain of c_1A_c for oscillation, and the resonance frequency of the laser diode is located within these two spectra. We show corresponding gain and phase condition in Fig. 4. If $I_b < I_c$ than the spectra with the lower frequency has a smaller required closed loop gain. Otherwise, the higher frequency spectrum has a smaller required closed loop gain. Since the delay time of the system is about 1 ns and the resonance frequency of the laser diode is about 1 GHz at $I_b = I_c$, there exist one spectra that satisfies phase condition near one over three of the resonance frequency. When the closed loop gain is sufficiently larger than c_1A_{ct}, the system usually shows self-pulsing with fundamental frequency that is the lowest frequency satisfying the phase condition with the lowest frequency. If the closed loop gain of c_1A adjust at a certain range (i.e. it is larger than c_1A_{ct} and smaller than the required closed loop gain for the spectra with the lowest oscillation frequency), the system shows bistable state between two different oscillation state. One is the oscillation with frequency about the resonance frequency of the laser diode (See Fig. 3 (c)). The other is the oscillation where the lowest frequency that satisfies the phase condition. Waveform of this state is shown in Fig. 3 (f). If we decrease the closed loop gain, there is no bistable region and the system shows a sequence of oscillation shown in Fig. 2. The observe bistability is similar to that in two mode laser[9].

In conclusion, we observe experimentally self-pulsing, subharmonic generation, spectral bistability, and chaos in a stable laser diode with the delayed optoelectronic feedback. We also explain the observed experimental results.

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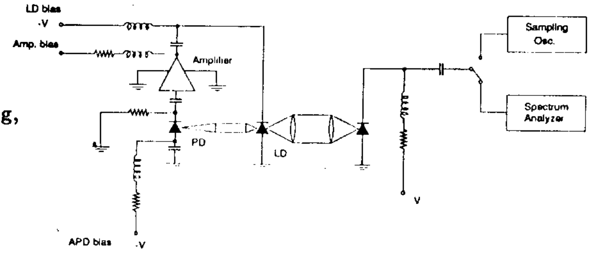
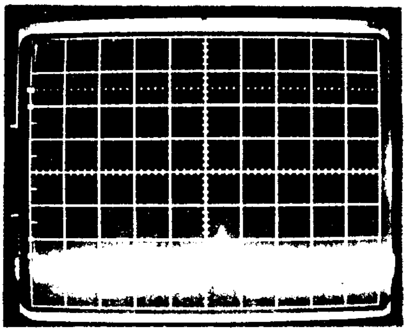
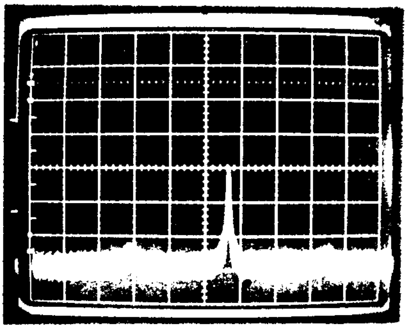


Fig. 1. Experimental setup.

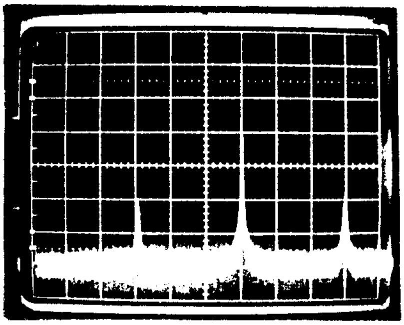


(a) I_b=58.4

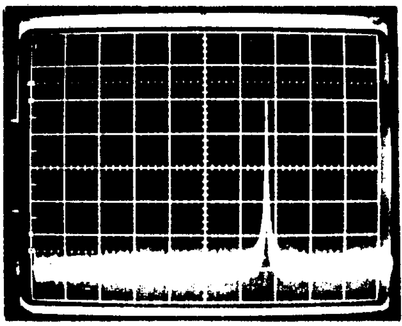
10dB



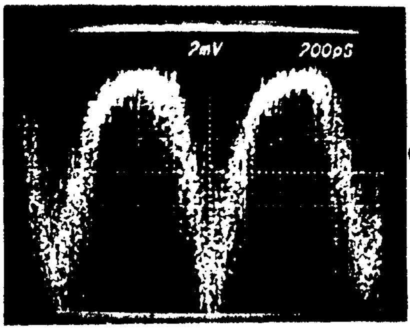
(b) I_b=59



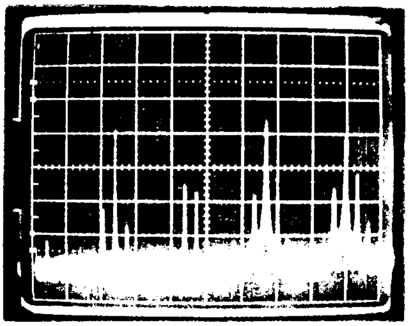
(c) I_b=60



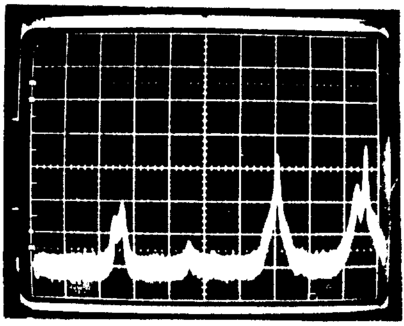
(d) I_b= 63



(e) I_b=64

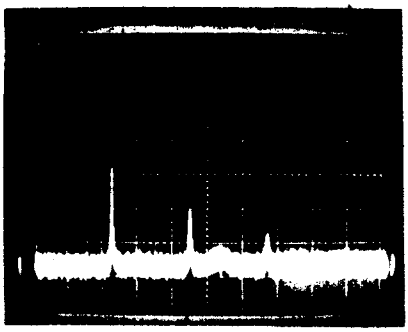


(f) I_b= 63



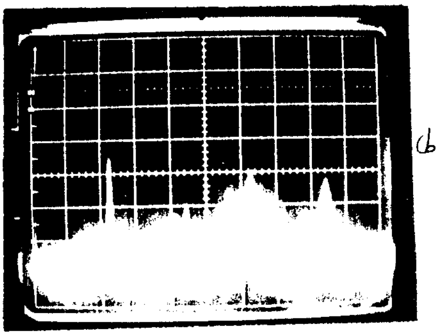
(g) I_b=64.4

Fig. 2. Observed optical output spcetrum and waveform with amplifier bias current of 18.2 mA.

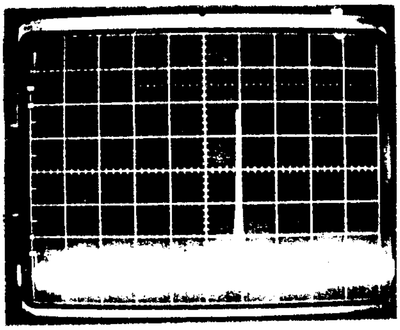


(a) I_b= 58.3

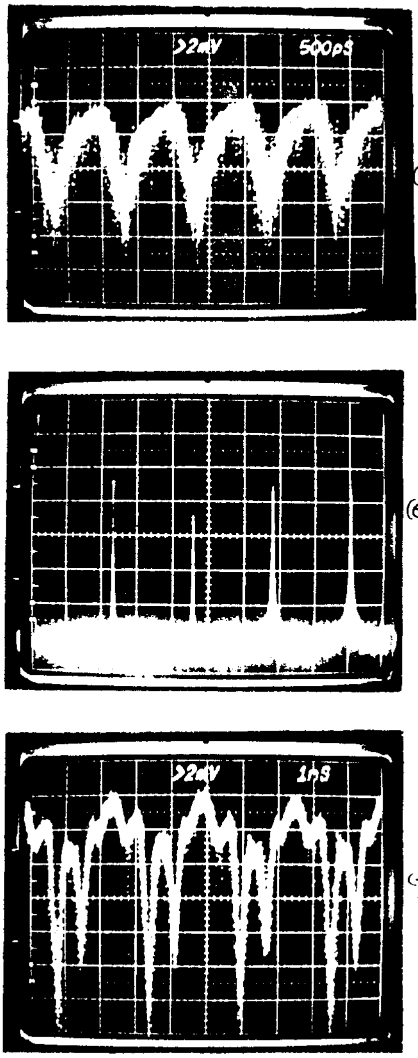
10 dB



(b) I_b=59.5



(c) I_b=60.7



(d) I_b=60.7

(e) I_b=60.7

(f) I_b=60.7

Fig. 3. Observed optical output spcetrum and waveform with amplifier bias current of 22.8 mA.

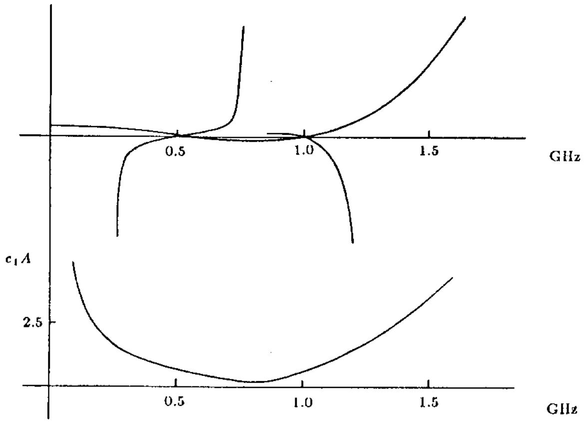


Fig. 4. Gain condition and phase condition for negative feedback with parameters $s_o = 0.0526$ ($I_b = 58.5$ mA), $T = 2000$. Bandwidth of the feedback network is 0.336 - 1.46 [GHz].