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OPTICAL BISTABILITY IN ACTIVE DEVICES

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Abstract - Recent progress in the study of both absorptive and dispersive bistability in semiconductor lasers is reviewed. Inhomogeneously excited semiconductor lasers as an absorptive case and resonant type laser diode amplifiers as a dispersive case, are described.

1. Introduction

Recent progress in the study of both absorptive and dispersive bistability in laser diodes (LDs) is reviewed /1/. The most distinctive feature of bistable LDs is that they have optical gain. Optical gain results in advantages such as low switching optical power, high ON-OFF ratio, and large fan-out.

The first stage in the study of optical bistable LDs started in 1964 with the tandem-type LD proposed by Lasher /2/. Based upon the advanced semiconductor laser technology developed for optical fiber communications, the second stage of bistable LD study began in 1981 by Kawaguchi and Iwane /3/ and Harder et al. /3/. They reported remarkable bistable characteristics in InP/InGaAsP lasers and GaAs/AlGaAs lasers, respectively.

Since then, various types of bistable LDs have been reported as listed in Table 1. Bistability can be seen in ON-OFF of laser oscillation /2-4/, optical gain change in resonant type LD amplifiers /5/, polarization /6/, transverse mode /7,8/, lasing wavelength /9/ as well as locked and unlocked state in injection locking systems /10/. Details are described in Reference /11/.

Applications to photonic switching and optical fiber communications have already been investigated. Using tandem-type laser diodes as optical memories, an optical time-division switching system was developed by Suzuki et al. /12/. Webb has studied the use of a bistable LD amplifier as a clocked decision gate, and shown that all-optical regeneration using such a gate is feasible /13/.

2. Absorptive bistability

Inhomogeneously excited LDs such as tandem type LDs show bistability in the current-light output curve and optical input-output curve. This is because the region where a carrier is not injected acts as a saturable absorber.

Sometimes self-pulsing as well as bistability are present in tandem-type LDs. These depend on the carrier lifetime distribution along a laser cavity /14/. A

Table 1. Bistable semiconductor lasers

Switching	LD Structure	Principle	Characteristics	References
laser oscillation ON / OFF	inhomogeneous excitation e.g. tandem type (FP, DFB)	saturable absorption	proposal demonstration τ : sub-ns P : $< 1 \mu W$	Lasher Kawaguchi et al./Lau et al. Tomita et al. Suzuki et al.
gain	resonant type LD amplifier (FP, DFB)	nonlinear refractive index	proposal multiple bistability P : $< 1 \mu W$ 'NOT'(two inputs) 'NOT'(reflection)	Ohtsuka et al. Kawaguchi Adams et al. Kawaguchi Adams et al.
polarization	TM light injection	nonlinear gain / refractive index	τ : ON 200 ps OFF 430ps	Mori et al.
	TM/TE oscillation LD	temperature dependent gain		Chen et al.
tranverse mode	twin-stripe	mode-gain change	τ : < 250 ps P : $\sim$ sub-pJ	Maclean et al.
lasing wavelength	LD with external cavity	mode hopping		Glas et al.
locked /unlocked	injection locking	nonlinear refractive index		Kawaguchi

Fig. 1 - Threshold pump rates (full lines) and pulsation region (shaded region) vs. non-radiative carrier lifetime in region II. Figure shows a schematic diagram of the tandem-type laser structure used in the analysis.

electrode was divided into two parts along the laser cavity, and drive currents were injected separately into the divided parts as shown in Fig. 1. The case where the two parts of the active region were given different carrier recombination rates was considered using different non-radiative carrier lifetimes for each region. The threshold pump rate and output stability as a function of the nonradiative carrier lifetime in region 2, τ_{nr2} , are shown in Fig. 1. The solid lines indicate the threshold pump rates. When τ_{nr2} is longer than 2ns, the laser has two threshold pump rates, P_{th1} and P_{th2} , depending on the initial conditions. These bistable characteristics can be attributed to the fact that the active layer of region 2 acts as a saturable absorber. When the nonradiative carrier lifetime is shorter than 2ns, the laser has only one threshold pump rate. The shaded region represents the pulsation region in the figure. When the nonradiative carrier lifetime is shorter than 0.5ns, self-pulsation occurs over a

Fig. 2 - (a) Calculated output response of self-pulsating laser for sinusoidal current modulation. (i) Period 1, (ii) period 2, (iii) period 4, and (iv) chaotic.

(b) Observed output response. (i) period 2 and (ii) chaotic.

wide range from just above the laser threshold to a very high excitation level. Due to their nonlinearity, semiconductor lasers exhibit interesting characteristics when the current and carrier lifetime distribution are changed along the laser cavity.

One example of optical chaos in LDs is briefly discussed. We considered the laser which shows self-pulsation because the carrier lifetime of region 2 is short. Furthermore, the pump rate in region 1, is modulated by sinusoidal RF current superimposed on the DC bias current. This nonlinear laser system shows chaotic behavior through period-doubling bifurcations with increasing modulation frequency as seen in Fig. 2(a) /14/. At 1.54 GHz, the laser showed sustained pulse oscillation with the modulation frequency. The first subharmonic appeared at 1.75 GHz. At 1.81 GHz, period 4 oscillation was obtained. Furthermore, chaotic outputs were seen at above 2 GHz.

These characteristics were also observed in the experiment /15/. Experimental waveforms and spectra from a GaAlAs LD are shown in Fig. 2(b). By increasing the difference between the resonance frequency, f_R , and modulation frequency, f_m , period 2 and chaotic oscillation were observed.

When carrier lifetime is about the same over the whole laser cavity, tandem type LDs show bistable output characteristics. The InGaAsP distributed-feedback laser structure operating at 1.55 μm is shown in Fig. 3. The p-type electrode was divided into three parts, and the resistance between the p-type electrodes was within a few hundred Ω . Thus, the divided regions can be excited independently through the electrodes. If I_1 is set at zero or a low value, region 1 acts as a saturable absorber. It is then possible to obtain bistable characteristics in both the current-light output and optical input-output curves.

A typical measured current-light output curve is shown in Fig. 4(a). A noticeable hysteresis loop is seen in the curve. The current range of bistability decreases with increasing in the current injected into the saturable absorber. The current can optimize the bistable current range.

When the bias current is set at just below the turn-off threshold, the optical input-output curve exhibits bistability resulting from an injection of optical power into the saturable absorber as shown in Fig. 4(b). The bias current values are indicated by the closed circles (1) to (3) in Fig. 4(a). An increase in the bias current markedly increases the input optical power range of bistability. When the bias current is in the current range of bistability, the bistable laser

Fig. 3 - Structure of bistable DFB LD. I_1 set at a low value. Region 1 acts as a saturable absorber.

Fig. 4 - (a) Observed current-light output curve. (b) Observed optical input-output curve. The bias current values are indicated by the closed circles (1) to (3) in (a).

emits coherent light when input optical power is injected. The laser stays in an "ON state" even when the input optical power is reset at zero. This means that the bistable laser acts as an optical memory device.

Recently, a tunable optical-wavelength conversion device for photonic switching has been demonstrated using this same structure /16/ .

3. Dispersive bistability

A resonant type LD amplifier can act as a nonlinear Fabry-Perot interferometer, and shows bistability. This is because the active layer refractive index changes due to gain saturation by light injection.

Among the many types of bistable semiconductor lasers studied previously, only Fabry-Perot type LD amplifiers appear to have multiple bistability or multistability potential. In the LD amplifier, there are many constructive interference transmission peaks. If cavity Q stays constant, the device shows multistability for strong light input intensities. However, cavity Q decreases as the injected optical intensity is increased through gain saturation. Utilizing a long Fabry-Perot cavity LD amplifier, optical multiple bistability is demonstrated /17/ .

Let us consider the relationship between inputs and outputs for a resonant-type LD amplifier with two optical inputs /18/ .

Using two optical inputs, a NAND gate and a NOR gate can be obtained. The initial detuning of a signal beam is equal to π radian, that is, the signal beam wavelength coincides with the resonance wavelength of the LD amplifier when $P_{in1} = 0$. When P_{in1} is increased, carrier density decreases, causing the refractive index of the active layer to become larger. This results in the lowering of the

cavity resonance frequency. Therefore, bistable characteristics are observed in the $P_{in1} - P_{out1}$ curve. In the $P_{in1} - P_{out2}$ curve, reverse (clockwise) hysteresis is obtained as shown in Fig. 5(a)(i). On the other hand, when wavelength detuning of the signal beam from the resonance wavelength is greater than that of the control beam, normal (counterclockwise) hysteresis are observed in both the $P_{in1} - P_{out1}$ and the $P_{in1} - P_{out2}$ curves as shown in Fig. 5(a)(ii).

The experimental results are shown in Fig. 5(b). In Fig. 5(i), the signal beam detuning is estimated to be π radian from a comparison between the calculated and experimental results of the $P_{in1} - P_{out2}$ curve. By increasing the LD2 current, the wavelength of LD2 is shifted toward the longer wavelength side. In Fig. 5(ii), a 2.2 radian signal beam detuning state is observed. Therefore, normal (counterclockwise) hysteresis are observed in both the $P_{in1} - P_{out1}$ and the $P_{in1} - P_{out2}$ curves as shown in Fig. 5(ii). The experimental results agree well with the theoretical results shown previously.

High speed switching has been demonstrated employing modulation of an 800 Mbit/s pulse pattern [19]. In this experiment, the λ_2 input was kept constant, while the λ_1 input was directly modulated.

4. Future Prospects

Major remaining problems in bistable semiconductor lasers are the realization of two dimensional arrays and reduction in threshold current.

Three types of surface-emitting bistable lasers have been proposed. Vertical

Fig. 5 - (a) Calculated normalized output power P_{out1}/P_s and P_{out2}/P_s vs. input power $\eta P_{out1}/P_s$ for Fabry-Perot semiconductor-laser amplifier with two holding beams. (i) $\delta_2 = \pi$ and (ii) $\delta_2 = 2.2$. (b) Observed P_{out1} vs. P_{in1} and P_{out2} vs. P_{in1} curves. (i) $\delta_2 = \pi$ and (ii) $\delta_2 = 2.2$.

cavity-laser type optical logic and gate devices were proposed /20/. These devices include a saturable absorber in the vertical laser cavity. A surface emitting bistable LD using output coupling by second order grating of a distributed Bragg reflector /21/ as well as the laser with an integrated beam deflector /22/ have also been demonstrated. However, the threshold currents of these devices are more than 50 mA at present. To construct two dimensional arrays, the threshold currents have to be reduced.

Semiconductor lasers with threshold currents of less than 1 mA have been already reported. For example, a gallium-arsenide single-quantum-well, graded-index separate-confinement, buried-heterostructure laser has recently achieved a 0.55 mA threshold /23/. It is believed using advanced technologies such as the quantum confined effects, LDs with a much lower threshold current, 1 μ A threshold LDs, will be achieved /24/. In that case, construction of 1000x1000 two dimensional arrays may become possible in the future.

5. Summary

Recent progress in the study of absorptive and dispersive bistability in semiconductor lasers was reported. The bistable semiconductor lasers will be advantageous in the field of transmission and exchange, utilizing the merits of optical gain. When threshold currents are reduced further, two-dimensional arrays of bistable LDs will become important in optical information processing.

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