Analysis of Nonlinear Optical Effects in Monolithically Integrated FM-Mode-Locked Semiconductor Laser Diodes

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Abstract *Simulation shows that asymmetric nonlinear optical gain causing the mode instability of mode-locked lasers can be compensated by phase modulation. Mode stabilization was confirmed experimentally using monolithically integrated FM-mode-locked semiconductor laser diodes.*

Introduction

Mode-locked semiconductor laser diodes are compact short pulse light sources with repetition rates of 10 to 160GHz, which are indispensable for future ultra-fast OTDM systems and optical signal processing systems because of their compactness and mode stability[1]. The increase of output power is required. When repetition rates increases, the problem of gain saturation becomes serious, because average output power increases to keep the energy of a single pulse and the cavity length of mode-locked lasers becomes shorter than that of lasers with low repetition rates. In addition, the nonlinear optical effects such as cross phase modulation (XPM), cross gain modulation(XGM), and four-wave mixing (FWM) between modes cannot be ignored in the high power range.

For the increase of output power from mode-locked semiconductor lasers, the reduction of internal optical loss, the supression of the nonlinear optical effects by low optical confinement waveguide[2], and the control of nonlinear optical effects are effective methods. The control of nonlinear effects is, however, not sufficiently discussed.

In this work, we discuss the nonlinear optical effects in mode-locked semiconductor lasers. The numerical simulation in frequency domain was used. The effect of asymmetric nonlinear gain on the mode locked condition is discussed. It is shown that phase modulation is an effective method to surpress the asymetric nonlinear gain. Experiments shows the spectrum width is broadened by the phase modulation in spite of the asymetric nonlinear gain in a monolithically integrated FM-mode-locked semiconductor laser diode.

Simulation

The propagation of optical pulses in a mode-locked laser was simulated in the frequency domain. The frequency dependence of nonlinear gain[3] in the active layers can be easily considered by this method.

The .procedure of the simulation is as follows.

1. The shape and the repetition rates of output pulses are assumed.
2. By the Fourier transformation, the frequency components of the output pulses are calculated.
3. The special optical profile of each frequency component in the cavity is calculated under the assumption of the uniform threshold gain.
4. The frequency components of carrier density pulsation are calculated using the calculated using the frequency components of the optical profile in the cavity.
5. The nonlinear optical gain for each optical frequency component is calculated using the convolution of the frequency components of the carrier density pulsation and the optical profile.
6. New gain spectrum is calculated to compensate the nonlinear optical gain as main optical frequency components composing optical pulses keep the lasing condition.
7. The special optical profile of each frequency component is re-calculated using the new gain spectrum and the nonlinear gain.

The nonlinear optical effects between the modes such as XPM, XGM, and FWM by carrier density pulsation effects are considered by the convolution in the procedure 5.

The cavity length of 1010 μm was adjusted to the reputation rate of 43GHz. Phase modulation region with the length of 100 μm was set to one side of facets. Output pulse width was assumed to 2ps. Average output power were changed from 50mW to 250mW. The cases with and without phase modulation were calculated. The initial threshold gain was calculated by the CW lasing condition. The nonlinear optical susceptibilities were given by Ref. 3.

Fig. 1 shows the calculated nonlinear gain for detuning from the center of optical oscillation frequency. The broken lines show the case without phase modulation. When output power increases from 50mW to 250mW, the gain decreases due to the gain depletion. In addition, the gain in higher frequency region is more suppressed due to asymmetric nonlinear gain. This asymmetric nonlinear gain causes the mode instability of mode-locked oscillation because the low frequency components of optical pulses are enhanced but the high frequency components are suppressed, even if gain depletion is compensated by the increase of the carrier density.

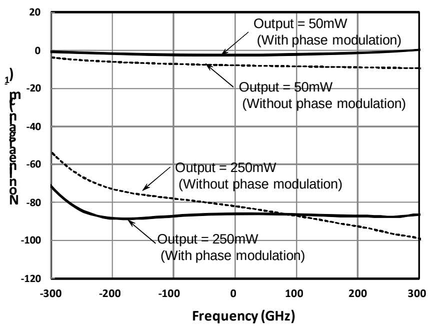

Fig. 1: Nonlinear gain in a mode-locked laser.

As the asymmetric nonlinear gain is due to the interference between the spectral hole-burning effect and the carrier density pulsation effect, it can be compensated by the refractive index modulation, in order word, the phase modulation.

The solid lines in Fig. 1 show nonlinear gain with the phase modulation. The tilt due to the asymmetric nonlinear gain is suppressed. As the remnant symmetric gain depletion can be compensated by the increase of the carrier density, mode-locked oscillation is stabilized by the phase modulation, in which beats between modes have anti-phase compared with the phase of the modulation.

These results mean FM mode-locking with phase modulation is effective for increasing optical output power, not only because of the internal loss reduction compared with conventional AM mode-locking using a saturable absorber, but also because of the suppression of mode instability caused by asymmetric nonlinear gain in high output power operation.

Experiment

The Experimental setup of an FM mode-locked laser is shown in Fig. 2a). An SOA monolithically integrated with phase modulation region was used as a gain medium. The length of gain region and phase modulation region are 700 μm and 400 μm, respectively. The laser cavity consisted of high-reflective-coating facet of gain region and an external grating mirror coupled with anti-reflective-coating facet of the modulation phase region. The band-gap of core in the phase modulation region is transparent

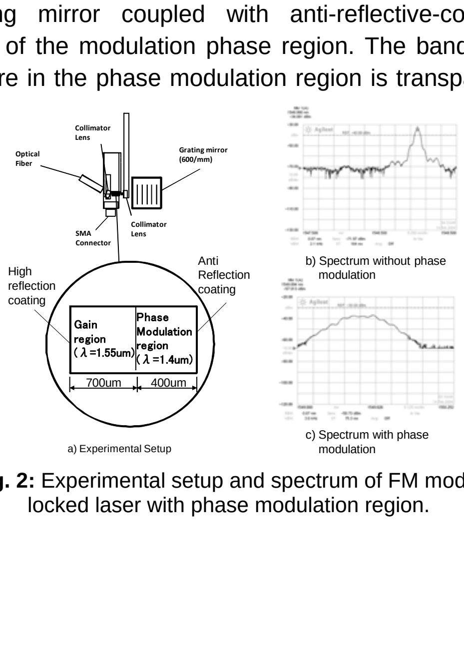

Fig. 2: Experimental setup and spectrum of FM mode-locked laser with phase modulation region.

for light with1.5 μm wavelength. The lasing threshold was around 25 mA when the electric current in the phase modulation region was 0 mA. The electric power and the frequency of the modulation were 17 dBm and 445MHz, respectively. The external cavity frequency was adjusted to 10.25 GHz, which was 23 times of the modulation frequency. The spectrum from the rear facet of the SOA was observed by an optical spectrum analyzer.

The spectrum with and wthout the phase modulation was shown in Fig. 2 b). By the phase modulation, stable multi-mode operation is obtained. The asymetric nonlinear gain was estimated from the ASE power difference between long and short wavelength region of outside of the lasing modes. Pulse width was also estimated from the spectrum bandwidth. The relation between the asymetric nonlinear gain and the spectrum width is shown in Fig 3. The current was fixed to 300mA and lasing wavelength was changed by the angle of the grating mirror. The offset currents in phase modulation region were controled as the spectral bandwidth becomes maximum. For shorter wavelength, the spectrum band width becomes wider, which means mode-locked oscillation becomes stable in spite of the increase of the asymmetric nonlinear gain.

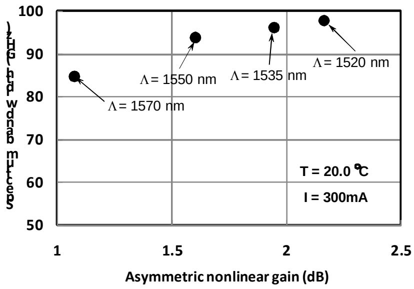

Fig. 3: Spectrum bandwidth from a mode-locked laser.

Conclusions

We discuss the nonlinear optical effects in mode locked laser diodes. Numerical simulation shows that asymmetric nonlinear optical gain causing mode instability can be compensated by phase modulation. FM mode-locking with phase modulation is effective for increasing optical output power. Experimental results support the result of simulation.

Acknowledgement

We wish to thank Dr. Morito and Mr. Takabayashi in Fujitsu Laboratories Ltd. for preparing SOAs for experiments.

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