2-ps, 10-GHz mode-locked laser with semiconductor optical amp, ring cavity, and sinusoidally modulated light injection

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***Abstract*—In new optical pulse generator using delayed-interference-signal-wavelength-converter (DISC)-type all-optical gate, we injected sinusoidally modulated light to ring cavity. With this way, externally modulated laser oscillation and mode-locked pulse laser oscillation occurred. These generated pulse's widths and repetition frequencies are 27 ps, 10.5 GHz and 2.1 ps, 10.5 GHz, respectively.**

Keywords-mode-locking; all-optical; semiconductor optical amplifier (SOA); optical pulse generator

I. Introduction

Recent years, the demand for broadband network is increasing in the world. To support the demand, higher transfer speed, error-free, and large network capacity is necessary. As an effort to increase the capacity and transmission speed, one of the solutions is to combine wavelength division multiplexing (WDM) system with optical time division multiplexing (OTDM) system. High-repetition rates optical clock pulses are useful for ultrahigh-speed OTDM systems and all-optical signal processing [1,2].

One of the widely used schemes of high-repetition-rate optical clock-pulse generators is mode-locked laser diodes (MLLD) that used saturable absorber [3]. Another one is using Fabry-Perot optical resonator integrated with phase modulator [4]. Measured pulse width was calibrated to 2.1 ps and time bandwidth product was 0.22 assuming a Lorentzian pulse.

Another way to generate high repetition rates optical clock pulse that using DISC [5,6] has proposed and experimentally demonstrated since 2001[7.8]. This new scheme optical clock pulse generator (DISC-loop) has potential advantages (which MLLD's hardly have), such as tunabilities in pulse width, repetition frequency, and center wavelength.

During the intensive experimental studies done by Ryoichi Nakamoto, Hiroyuki Takeuchi, Takahiro Arai, et al. in the following more-than-one years in our research group, more than three input facets of SOA's inside our experimentally-fabricated generator were fatally degraded, one by one after long intervals. Because all of these degradations seemed to have occurred suddenly after our several-times several-hour-long standard characterization-research studies, we have speculated that a Q-switched high-energy optical pulse was unintentionally generated inside the cavity only once after many-hours experimental studies, and then fatally damaged the SOA's input facet.

In this work, for preventing the above-mentioned sudden facet degradations, we revise our mode-locked laser scheme as follows. Instead of injecting cw seed light, we inject sinusoidally modulated light into the ring cavity so that the mode-locked output pulse's repetition frequency is synchronized to the frequency of the externally modulated input light.

II. Oscillation Type in DISC-Loop

The new mode-locked laser scheme in this work, which is called disc-loop laser hereafter, is schematically shown in Fig. 1. It consists of a ring cavity, a continuous-wave (cw) light source, a DISC gate, quarter and half wavelength plates (Q's and H's), polarizers (P's), an erbium-doped fiber amplifier (EDFA), an energy-dividing Mach-Zenhder interferometer (ED-MZI), and a tunable delay. The DISC is composed of a SOA and MZI, and works as an all-optical polarization converter. What is newly installed in this scheme (with respect to the previous scheme [5]) is the part of input light into ring cavity. We use an electro-absorptive modulator (EAM) for sinusoidally modulating the cw light, before injecting it into the cavity.

We adjust the input ring cavity light's polarization to transverse electric (TE) mode, and apply gain by EDFA. That way we operate DISC-loop in oscillation state.

If injected light was cw light, injected DISC loop's type oscillation states are cw laser oscillation or mode-locked pulse laser oscillation. We increase loss at P by adjusting Q and H at feedback to SOA, to attenuate the intensity of cw laser oscillation wavelength. This way, we make the transition from cw laser oscillation state to mode-locked pulse laser oscillation state.

III. Externally Modulated Laser Oscillation and Mode-Locked Pulse Laser Oscillation

Externally modulated laser oscillation and mode-locked pulse laser oscillation DISC-loop type pulse generator scheme is shown in Fig. 1. Sinusoidally modulated light's repetition frequency is 10.5 GHz (Fig. 2). Its extinction ratio is 9 dB, and width is 36 ps, center wavelength is 1550 nm. Injected sinusoidally modulated light's intensity is 0 dBm. We used a bulk type SOA (InPhenix IPSAD1501), and injection current was 200 mA. Delay time of the calcite used in the experiment (Δt), is 2.3 ps. The injected light not only modulates the gain of SOA, but also modulates the intensity of the circulating amplified spontaneous emission (ASE). We adjust the ring cavity's length, and polarized light's direction to TE mode. This way, the polarizer device's loss is decreased and the externally modulated laser oscillation's intensity is increased.

We change the loop state from externally modulated laser oscillation state to mode-locked pulse laser oscillation state by adjusting polarized light's direction to transverse magnetic (TM) mode.

Shown in fig. 3 and 4 are the signal at DISC-loop output's autocorrelation trace and spectrum of the externally modulated laser oscillation and mode-locked pulse laser oscillation, respectively. The output pulses in externally modulated laser oscillation (Fig. 3) has extinction ratio of 7.2 dB, pulse width is 27 ps and repetition frequency is 10.5 GHz. The pulse component's center wavelengths are 1548.3 nm and 1551.8 nm, and these wavelengths are near MZI maximum transmittance wavelengths.

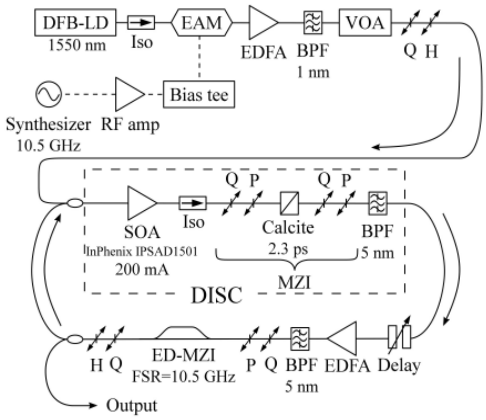
On the other side, the output pulse of the mode-locked pulse laser oscillation have these properties (Fig. 4): the extinction ratio is 13.8 dB, pulse width is 2.1 ps, repetition frequency is 10.5 GHz, and center wavelength is the same as the input modulated light's wavelength 1550 nm. The time-bandwidth product is 0.37 fitted with sech^2 shape, approximately matches to the Fourier-transform-limit.

When the state becomes the mode-locked pulse laser oscillation, time width narrowed and extinction ratio enlarged. However, we found some distortion in the mode-locked pulse laser oscillation (Fig. 4). We suspect that it is made by conversion process and currently under investigation.

IV. Conclusion

We propose the pulse generation by injecting sinusoidally modulated light to DISC-loop type pulse generator. Sinusoidally modulated light's repetition frequency is 10.5 GHz. As a result, when the feedback is TE mode, 27 ps, 10.5 GHz pulses are generated. At mode-locked pulse laser oscillation state, 2.1 ps, 10.5 GHz pulses are generated.

We proved that there is 2 modes occur from intensity-modulated input, which are mode-locked pulse laser oscillation and externally modulated laser oscillation instead of cw laser oscillation and mode-locked pulse laser oscillation. This oscillation method is expected to prevent high damaging energy generated by Q-switch. We aim higher repetition frequency pulse generation in the DISC-loop with this externally modulated laser oscillation method.



DFB-LD: Distributed Feedback Laser Diode, EAM: Electro Absorptive Modulator, EDFA: Erbium Doped Fiber Amplifier, VOA: Variable Optical Attenuator, SOA: Semiconductor Optical Amplifier, Iso: Isolator, MZI: Mach-Zenhder Interferometer, Q: Quarter wavelength plate, H: Half wavelength plate, P: Polarizer, BPF: Band Pass Filter, ED-MZI: Energy Divided MZI, FSR: Free Spectral Range

Figure 1. Forced and mode-locked pulse laser oscillation DISC-loop scheme

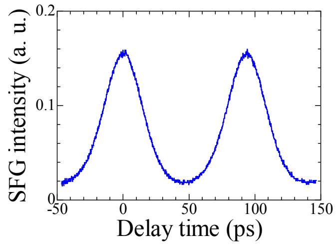


Figure 2. Injection of sinusoidally modulated light

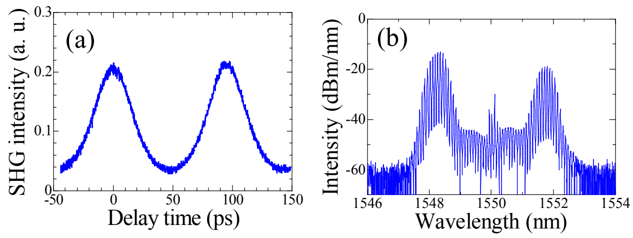


Figure 3. Output of TE mode feedback state
(externally modulated laser oscillation)
(a)Autocorrelation trace, (b)Optical spectrum

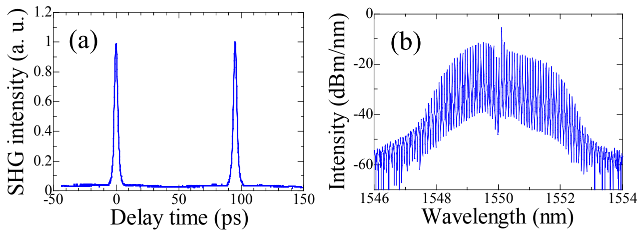


Figure 4. Output of TM mode feedback state
(mod-locked pulse laser oscillation)
(a)Autocorrelation, (b)Optical spectrum

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