Chirp Control of Semiconductor Laser by Using Hybrid Modulation*

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SUMMARY Frequency chirp of a semiconductor laser is controlled by using hybrid modulation, which simultaneously modulates intra-cavity loss and injection current to the laser. The positive adiabatic chirp of injection-current modulation is compensated with the negative adiabatic chirp created by intra-cavity-loss modulation, which enhances the chromatic-dispersion tolerance of the laser. A proof-of-concept transmission experiment confirmed that the hybrid modulation laser has a larger dispersion tolerance than conventional directly modulated lasers due to the negative frequency chirp originating from intra-cavity-loss modulation.

key words: dispersion tolerance, frequency chirp, frequency response, semiconductor lasers

1. Introduction

A direct current modulation is the simplest modulation scheme to generate a high-speed optical signal by using semiconductor laser sources and is widely used for semiconductor lasers applied in optical data communication systems. Increasing the operation speed of directly current modulated lasers (DMLs) is one of the important targets to increase the transmission capacity of data communication systems for data centers to keep up with explosively increasing data traffic. A recent bandwidth-enhancement scheme of semiconductor lasers, which uses the photon-photon resonance (PPR) effect induced by the coupling between the lasing mode of the laser cavity and feedback light from an integrated external cavity, has recently been attracting attention for breaking through the limit of the modulation bandwidth of DMLs [1]–[4]. High-speed operation with a 40-Gbps non-return-to-zero (NRZ) signal has been achieved using a PPR-introduced DML with an external cavity [4]. To further enlarge the modulation bandwidth of the PPR-introduced DML, it is important to reduce the modulation-response degradation of the DML at a higher frequency region than the relaxation oscillation frequency. We previously proposed the hybrid modulation (HM) scheme, which simultaneously modulates the injection current and intra-cavity loss in a laser to modify the modulation-response degradation at a high-frequency region toward an ultra-high-speed semiconductor laser and demonstrated that our HM scheme can control the modulation response of a semiconductor laser [5]. Controlling an optical frequency chirp is also important for optical-signal generation because it determines the dispersion tolerance and transmission distance of optical signals for an optical fiber. The optical signal generated using a conventional directly modulated distributed feedback (DFB) laser has a positive frequency chirp, and its dispersion tolerance is limited to around 100 ps/nm for 10-Gbps NRZ-signal operation. Therefore, the transmission distance of the generated optical signal is limited to less than 10 km at a wavelength of 1550 nm [6]. To improve the dispersion tolerance and extend the transmission distance of DMLs, it is necessary to control the frequency chirp of the laser. There are several methods for controlling the frequency chirp in semiconductor lasers. A chirp-managed semiconductor laser (CML) was proposed to tailor the frequency chirp of a DML by applying a multi-cavity filter to narrow the lasing spectrum under modulation, and a dispersion tolerance of 4200 ps/nm for a 10-Gbps signal was demonstrated [7]. Another example is an FM-response-enhanced distributed Bragg reflector laser was used for 20-km standard single-mode fiber (SSMF) transmission under 40-Gbps signal operation [8]. For an electroabsorption (EA) modulator integrated with a DFB laser, the transient chirp of the DFB laser was cancelled out by that of the EA modulator by using a dual modulation scheme, in which the DFB laser is modulated with anti-phase signal compared to the EA modulator, and 180-km SSMF transmission of a 10-Gbps NRZ signal was confirmed [9]. We demonstrated that our HM scheme can enhance the dispersion tolerance for optical-fiber transmissions through numerical analysis of dynamic operation of an HM laser using rate equations [10]. Since our HM scheme can control the modulation response and extend the modulation bandwidth of PPR-introduced lasers, simultaneous control of the frequency chirp by using this scheme is attractive. In this study, we investigated the frequency chirp characteristics of the HM laser and confirmed negative chirp operation through numerical calculations and a proof-of-concept experiment.

2. Optical Frequency Chirp of Semiconductor Laser

The rate equations for a semiconductor laser are expressed as follows.
\[
\frac{dN}{dt} = \frac{I - N}{eV - \frac{\phi A_g}{\tau_e} (N - N_{th})}{1 + eS} S \quad (1)
\]
\[
\frac{dS}{dt} = \left[ \frac{\Gamma V_g A_g (N - N_{th})}{1 + eS} - \frac{1}{\tau_p} \right] S \quad (2)
\]
\[
\frac{d\phi}{dt} = \frac{\alpha N V_g A_g (N - N_{th})}{1 + eS} \quad (3)
\]
where \(N, S, \phi, I, e, V, \tau_e, \tau_p, \Gamma, V_g, A_g, N_{th}, \epsilon, \) and \(\alpha\) are carrier density, photon density, phase of light, injection current, electron charge, volume of DFB active section (2.2 \(\times\) \(10^{-17}\) m\(^3\)), carrier lifetime (0.8 ns), photon lifetime (2.0 ps), optical confinement factor of light into active region (0.05), group velocity of light (8.8 \(\times\) \(10^7\) m/s), differential gain coefficient (6.4 \(\times\) \(10^{-20}\) m\(^3\)), transparent carrier density (5.0 \(\times\) \(10^{24}\) m\(^{-3}\)), nonlinear gain coefficient (5.5 \(\times\) \(10^{-23}\) m\(^3\)), and linewidth enhancement factor (3.0), respectively. The typical values for InGaAsP multiple quantum well DFB lasers are used for parameters [11].

In our HM scheme, the injection current and intra-cavity loss 1/\(\tau_p\) are simultaneously modulated. From the rate equations, the optical frequency change \(\Delta \omega\) is approximately derived as follows when the term concerned with the photon lifetime is expressed as 1/\(\tau_p\) = 1/\(\tau_{p0}\) + \(\Delta(1/\tau_p)\), where 1/\(\tau_{p0}\) is a steady state value and \(\Delta(1/\tau_p)\) is a component arising from intra-cavity-loss modulation (ICLM).

\[
\Delta \omega \approx \frac{\alpha}{2} \left\{ \frac{1}{S} \frac{dS}{dt} + \frac{\epsilon}{\tau_{p0}} S + \Delta \left( \frac{1}{\tau_p} \right) \right\} \quad (4)
\]

The first term on the right side is known as a transient chirp component proportional to the differential of the photon density. The second term is known as an adiabatic chirp component proportional to the photon density. These two components determine the frequency chirp of conventional DMLs [12]. The third term appears due to ICLM with our HM scheme. When the third term has a negative value, the adiabatic chirp component can be compensated for. This indicates that the frequency chirp of the laser can be controlled by controlling the amount of ICLM. The optical fiber transmission characteristics can be improved when the adiabatic chirp is dominant (a range in which \(dS/dt)/S\) is not so large). Figure 1 shows a schematic of an HM laser. It has a DFB active section and ICLM section in the laser cavity. The ICLM section is composed of an EA waveguide, and its optical loss increases when an applied negative bias is increased. When in-phase electrical-modulation signals are applied to both sections, they lead to output-power modulations of the HM laser with the same sign. For example, both sections act to increase the laser-output power when modulation voltage increases (injection current increases and intra-cavity loss decreases). Under this condition, a negative value for \(\Delta(1/\tau_p)\) in Eq. (4) can be obtained and frequency chirp can be controlled. A semiconductor optical amplifier (SOA) section is also integrated in the laser cavity to compensate for the static loss of the ICLM section by applying a small DC to avoid the extra chirp caused by the gain-saturation effect at SOA [13]. The SOA section is treated as a simple gain material, and its contribution is included in the photon lifetime term. The facet of the SOA-section side is coated with a high-reflectivity (~80%) film; thus, the laser cavity of the HM laser is composed of the DFB, ICLM, and SOA sections.

### 3. Numerical Analyses

The time evolution of the photon density and lasing frequency change were calculated using the rate equations (Eqs. (1)–(3)). In the calculation, we used a relative modulation ratio \(\eta\) in dB defined as \(\eta = M_{ICLM}/M_C\) where \(M_{ICLM}\) and \(M_C\) are, respectively, the intensity-modulation sensitivities at 100 MHz for the ICLM and injection-current modulation [5], which represents the dominance of ICLM. When \(\eta\) is a large negative value, injection-current modulation is dominant. The \(\eta\) value does not affect the threshold current in the following calculations since the DC loss in the ICLM section and the DC current to the DFB section are kept constant.

Figures 2 (a) and 2 (b) show the time responses of photon density in the HM laser for various \(\eta\) when a falling (a) or rising (b) step signal was applied at \(t = 0\) ns. The optimum delay time \(\Delta t\) defined as a delay time of an injection-current modulation signal relative to that of an ICLM signal to minimize the relaxation-oscillation was kept at 20 ps [5]. The photon density sharply responded to each step signal with the reduced relaxation oscillation at \(\eta = -5\) dB. As \(\eta\) decreased, the response of photon density showed a delay and verges on conventional injection-current modulation.
characteristics. As shown in Fig. 2 (c), the positive transient and positive adiabatic chirps arose at $\eta = -20 \text{ dB}$ for the falling step signal. As $\eta$ increased, the positive transient chirp weakened and the adiabatic chirp changed from positive to negative due to ICLM. When the adiabatic chirp induced by ICLM was reasonably larger than that induced by injection-current modulation, the total chirp corresponded to a quasi-negative transient chirp with a negative adiabatic chirp, as seen at $\eta = -7 \text{ dB}$. A sign of these chirp characteristics invert for the rising step signal as shown in Fig. 2 (d). In this manner, our HM scheme controls the time responses of photon density and chirp.

Next, we investigated eye patterns calculated with 10-Gbps NRZ signals. A Bessel Thomson filter with a cutoff frequency of 7.5 GHz was taken into account to reject the unnecessary high frequency components. The calculation results of eye patterns at $\eta = -5$, $-7$, $-9$, and $-20 \text{ dB}$ under back-to-back condition and after 20-km SSMF transmission are shown in Fig. 3. As shown in Fig. 3 (a), a clear eye opening was confirmed under the back-to-back condition at $\eta = -5 \text{ dB}$, where a relative contribution of ICLM was strong and the ideal step response for the photon density was obtained. However, as shown in Fig. 3 (b) a large overshoot was observed at falling edge after the transmission because of the large negative adiabatic chirp induced by ICLM. Therefore, waveforms at $\eta = -5 \text{ dB}$ tended to be distorted after optical fiber transmissions. Although the waveform has slight overshoot, the distortion was suppressed at $\eta = -7 \text{ dB}$ (Fig. 3 (d)) compared to the condition at $\eta = -5 \text{ dB}$, where the negative adiabatic chirp generated by ICLM was less dominant. As shown in Fig. 3 (f) at $\eta = -9 \text{ dB}$, the overshoot of waveform after the transmission was further smaller than that at $\eta = -7 \text{ dB}$. However, leading edge of the eye pattern became gentle and extinction ratio degraded. At $\eta = -20 \text{ dB}$, where the injection-current modulation was dominant, central part of the eye patterns showed a dip after the transmission (Fig. 3 (h)) because of the positive adiabatic and positive transient chirps.

The relation between the extinction ratio of eye patterns and $\eta$ under back-to-back condition and after 20-km SSMF transmission is shown in Fig. 4. The maximum extinction ratio of 5.1 dB was obtained at $\eta = -4 \text{ dB}$ and an extinction ratio of 4.8 dB was maintained even after the transmission. It is worth mentioning that the extinction ratios after the transmission at the range from $\eta = -8$ to $-5 \text{ dB}$ were larger than the extinction ratios under back to back condition. This indicates that, under this condition, the HM laser has a negative chirp-operation condition with a chromatic dispersion tolerance of 340 ps/nm (17 ps/nm/km × 20 km) due to the negative adiabatic chirp arising from the ICLM applied with injection-current modulation. These calculation results indicate that our HM scheme controls relative contributions of transient and adiabatic chirps by tuning $\eta$ while maintaining the modified modulation response. Although simultaneous and arbitrary controls of both chirp and modulation bandwidth are difficult, the extinction ratio of eye pattern can be less degraded after 20-km SSMF transmission even when we use $\eta$ from $-8$ to $-5 \text{ dB}$ where the operation condition is optimum for obtaining the largest extinction ratio and wider modulation bandwidth.
4. Transmission Experiment

To confirm the frequency-chirp characteristics of the HM laser, we conducted a proof-of-concept experiment. We fabricated the HM laser having the same structure illustrated in Fig. 1. It consists of a 300-µm-long DFB active section, 150-µm-long ICLM section, and 50-µm-long SOA section. These sections have core regions of InGaAlAs quantum wells[14] and a ridge-waveguide structure buried in benzocyclobutene (BCB) to reduce the parasitic capacitance of the electrode pads. The waveguide width and thickness of the InGaAlAs multiple quantum well layer are respectively 2 and 0.17 µm. We estimated the pad capacitances of the DFB and ICLM sections to be 0.3 and 0.15 pF. A 45-ohm resistor was inserted in series for the pad of the DFB section, and a 50-ohm resistor in parallel for that of the ICLM section. The setup for the optical fiber transmission experiment is shown in Fig. 5. The electrical-modulation signal generated by a 10-Gbps pseudo random pattern generator was amplified then split using a power divider. The Δt between the two electrical-modulation signals was controlled by the two phase shifters. Attenuators were inserted into each path to control the ratio of the modulation depths of injection-current modulation and ICLM. The electrical-modulation signals were superimposed on DC bias by using bias-tees then applied to the DFB and ICLM sections. The DC bias current to the DFB section and DC bias voltage to the ICLM section were set to 90 mA (∼ 4.5Ith) and −1.82 V, respectively. The bias current to the SOA section was set to 5 mA to reduce its effect on frequency chirp. The eye patterns of the optical signal from the HM laser were monitored using a photo detector (f3dB ∼ 15 GHz), Bessel Thomson filter (f0 = 7.5 GHz), and digital oscilloscope. The Δt, AC modulation current to the DFB section, and AC modulation voltage to the ICLM section were set to 43 ps, 23.2 mA, and 0.56 V, respectively, which were determined to generate the clearest eye pattern before and after the 20-km SSMF transmission. The difference in Δt between the calculation and experiment may be due to the difference in the distance between the RF connectors and two modulation pads due to the mounting process of the laser to a high speed sub-assembly. Under the above conditions, dynamic single-mode operation was confirmed at a lasing wavelength of 1555.7 nm.

Figures 6 (a) and 6 (b) show the measured eye patterns for the DML and HM laser under the back-to-back condition. Data for the DML were obtained by modulating only the DFB section of the HM laser. A clear eye opening with a dynamic extinction ratio of 1.3 dB was observed in both cases. We note that the dynamic extinction ratio was limited by a saturation power (23 dBm) of RF amplifier used in the experiment. Figures 6 (c) and 6 (d) show the measured eye patterns after 20-km SSMF transmission for optical signals generated by the DML and HM laser. The eye patterns for the DML severely degraded after 20-km SSMF transmission. The eye patterns for the HM laser, on the other hand, showed clear or clearer eye openings, even after 20-km SSMF transmission, which is similar to the case calculated with η of −7 dB as shown in Figs. 3 (c) and (d). Although the extinction ratio of the eye patterns was limited by the experimental setup, the results indicate that the HM laser can control frequency chirp and enhance the dispersion tolerance for optical fiber transmissions.

5. Conclusion

Frequency chirps of a semiconductor laser were controlled with our HM scheme, which simultaneously modulates the injection current and intra-cavity loss of the semiconductor laser. The positive transient chirp dominant in conventional DMLs was found to be weakened due to ICLM, and negative chirp characteristics were obtained by tuning η. The proof-of-concept experiment confirmed that our HM scheme can control the frequency chirp of a semiconductor laser, and 20-km SSMF transmission was demonstrated at 10 Gbps, which cannot be explained by the characteristics of conventional DMLs.
References


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