Wide-Bandwidth and High-Sensitivity Measurement Technique of Intrinsic Modulation Response of Semiconductor Lasers

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***Abstract*—We propose and demonstrate a measurement technique of the intrinsic modulation responses of semiconductor lasers with high sensitivity in a wide modulation frequency range. The technique is based on the two-tone optical modulation and lock-in detection of an optical spectrum having modulation sidebands. The measured modulation response of a conventional 1.55-μm distributed feedback laser indicates that the lock-in detection improves the signal-to-noise ratio by 22 dB. This significant improvement allows measurement of the modulation response up to 75 GHz even though the 3-dB bandwidth of the distributed feedback laser is only 11 GHz. Our technique is suitable for evaluation of the intrinsic modulation response of wide-bandwidth semiconductor lasers free from device parasitic effects.**

***Index Terms*—Semiconductor laser, modulation response, coherent optical spectrum analyzer, lock-in detection.**

I. Introduction

The role of directly modulated lasers (DMLs) is becoming more important in recent years. A DML is a cost-effective laser source for data communications and has shown promise for coping with the huge amount of traffic in data centers [1], [2]. There are many reports on the modulation response of DMLs in both edge-emitting lasers and vertical-cavity surface-emitting lasers (VCSELs) [3], [4], [5], [6], [7], [8], [9], [10], [11]. The standard evaluation technique of the modulation response in semiconductor lasers is based on the electrical modulation of the injection current, as semiconductor lasers are operated by electrical signals in most cases. At the same time, there is a growing interest in photonic computing and chaotic photonic systems [12], [13], [14], [15], which exploit the wide intrinsic modulation bandwidth of semiconductor lasers and do not necessarily require their direct electrical modulation. For these applications, the intrinsic modulation response, which is not hidden by the frequency response of the electrode pads and experimental setup, is informative. Measurement of the intrinsic modulation response is also informative for DMLs exploiting the photon-photon resonance effect, which is included in the more recent high-speed DMLs [16], [17], [18], [19], [20], [21]. Usage of the photon-photon resonance effect causes a second resonance peak in the response and can extend the modulation bandwidth, but it requires rather complicated optimization of the device structure and operation conditions. The measurement of the intrinsic modulation response is thus helpful in terms of concentrating on the optimization for the photon-photon resonance free from electrical frequency characteristics. Moreover, extraction of the electrical frequency characteristics becomes possible with the help of a conventional vector network analyzer.

The optical modulation of semiconductor lasers driven by a DC current above a certain lasing threshold can be conducted by injecting a sinusoidally amplitude-modulated light for exciting additional carriers [22], [23]. The modulation response can be measured after optical-to-electrical conversion of the modulated output light from a semiconductor laser under test. It is typical to use an electrical spectrum analyzer with its center frequency set to the same frequency as the modulation signal. However, the bandwidth of the electrical spectrum analyzer becomes a limiting factor for measuring wide-bandwidth semiconductor lasers. To circumvent this problem, an optical spectrum analyzer that measures the response sensitivity as the intensity of modulation sidebands can be used [24], [25], but it tends to be less sensitive compared to the electrical spectrum analyzer due to the low stray light rejection ratio of the optical spectrum analyzer.

An optical two-tone that generates an intensity-modulated signal light can be used for exciting carriers in a semiconductor laser under test. Generally, there are two methods for generating the optical two-tone. One is based on an external modulator such as a Mach-Zehnder modulator [25]. This method is useful for easily obtaining a precise modulation frequency. However, its achievable modulation frequency is limited by numerous factors such as the modulator, signal generator, and coaxial cables. The other method is to use two free-running laser sources having slightly separated wavelengths. This method is simpler to conduct than the former and its modulation bandwidth can easily exceed 100 GHz without the limitation of the electrical bandwidth of components, but it suffers from lower accuracy in the modulation frequency with the megahertz range.

In regard to the wide-bandwidth measurement of the modulation response of semiconductor lasers, the combination of

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an optical spectrum analyzer and optical two-tone generation using two free-running laser sources is suitable. However, an additional attempt is necessary to improve the sensitivity of modulation response. In this article, we demonstrate such an attempt to achieve both wide bandwidth and high sensitivity for the measurement of modulation response. The key is a lock-in detection of the optical spectrum that includes modulation sidebands generated by an envelope-modulated optical two-tone having a constant power. Measured modulation responses reveal that the lock-in detection improves the signal-to-noise ratio by 22 dB, indicating that our technique is useful for the optical characterization of the intrinsic modulation response of semiconductor lasers with high sensitivity in a wide modulation frequency range.

II. Principle

A. Modulation Responses in Semiconductor Lasers

We briefly describe the modulation responses in semiconductor lasers that can be characterized in the spectral domain. The electric field of a single-mode semiconductor laser under sinusoidal modulation of the injection current can be expressed as [24], [26]

$$E(t) = E_0\sqrt{1+m\cos\left(2\pi f_m t\right)}\cdot e^{j\{2\pi f_0 t+\beta\sin(2\pi f_m t+\theta)\}}, \tag{1}$$

where E_0 is the electric field amplitude, m is the amplitude modulation index, β is the frequency modulation index, f_m is the modulation frequency, f_0 is the optical carrier frequency, and θ is the phase difference between the amplitude and frequency modulations. Under a small signal modulation in which $m << 1$ is held, the optical power of the pth-order sideband can be expressed as [24]

$$H_p = I_0 J_p^2(\beta)\left(1 - p\frac{m}{\beta}\sin\theta\right), \tag{2}$$

where I_0 is the power of the optical carrier component and J_p is the pth-order Bessel function of the first kind. The optical power of the first-order sidebands at higher (H_{+1}) and lower (H_{-1}) frequencies relative to the optical carrier component (H_0) can be expressed as

$$\frac{H_{\pm1}}{H_0} = \frac{J_1^2(\beta)}{J_0^2(\beta)}\left(1 \mp \frac{m}{\beta}\sin\theta\right), \tag{3}$$

where J_0 and J_1 are the zeroth- and first-order Bessel functions of the first kind. Under the assumption that $\beta << 1$ and $J_1{}^2(\beta)/J_0{}^2(\beta) \approx 0.25\beta^2$, β and m can be given by [24]

$$\beta \approx \sqrt{\frac{2\left(H_{+1}+H_{-1}\right)}{H_0}}, \tag{4}$$

$$m = \frac{2\beta}{\alpha\sqrt{1+\left(f_g/f_m\right)^2}}, \tag{5}$$

where α is the linewidth enhancement factor and f_g is the characteristic frequency that represents the boundary of the contribution between the transient and adiabatic chirps, which is expressed as $f_g = \kappa P/2\pi\tau_p$. Here, κ is the gain compression coefficient, P is the optical output power of the semiconductor laser, and τ_p is the photon lifetime.

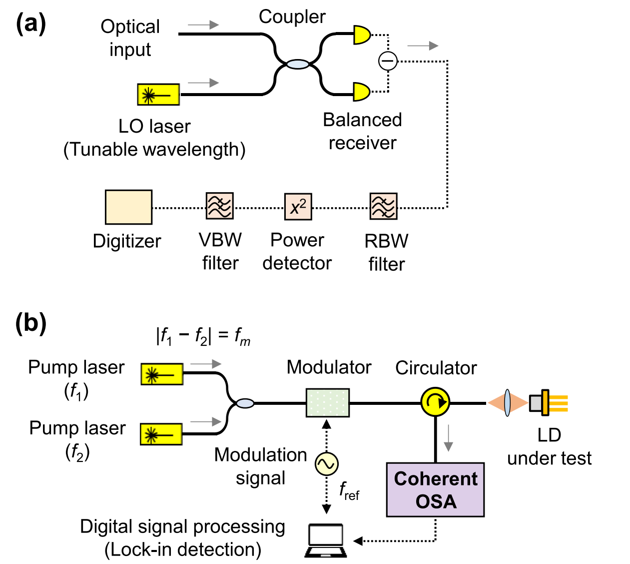

Fig. 1. (a) Basic configuration of coherent OSA. (b) Schematic of wide-bandwidth and high-sensitivity measurement system of intrinsic modulation response of LD.

From (4), β can be obtained from the optical power of the first-order sidebands in a measured optical spectrum, and m can then be obtained by using (5). The frequency dependence of the amplitude modulation response obtained from m is the same as β when f_m is much higher than f_g, while there is a non-negligible difference in the responses of m and β at low modulation frequencies below f_g. Note that a value of α is not necessary for obtaining a relative modulation response of semiconductor laser normalized by the response at the lowest modulation frequency.

B. Optical Modulation and Detection of Responses

As discussed in the previous subsection, an amplitude modulation response can be evaluated from optical spectra by using an optical spectrum analyzer (OSA). Conventional grating-based OSA is convenient for evaluating optical spectra in a wide wavelength (frequency) range, but it generally has a poor frequency resolution of > 1 GHz and a poor stray light rejection ratio. In contrast, a coherent OSA in which the optical spectrum is measured by a photo-mixing technique with a local oscillator (LO) laser is advantageous for obtaining a high frequency resolution in the megahertz range [27], [28], [29]. As shown in Fig. 1(a), in a coherent OSA, an optical beat signal generated by mixing the optical input and LO laser is detected by a balanced receiver. The electrical beat signal is then filtered by a resolution bandwidth (RBW) filter and converted into a slowly varying signal by using a power detector. After passing a video bandwidth (VBW) filter, the signal is converted from analog to digital using a digitizer. We used the coherent OSA to exploit its high frequency resolution.

There is an earlier study on a coherent OSA with lock-in detection to improve the signal-to-noise ratio (SNR) of spectra

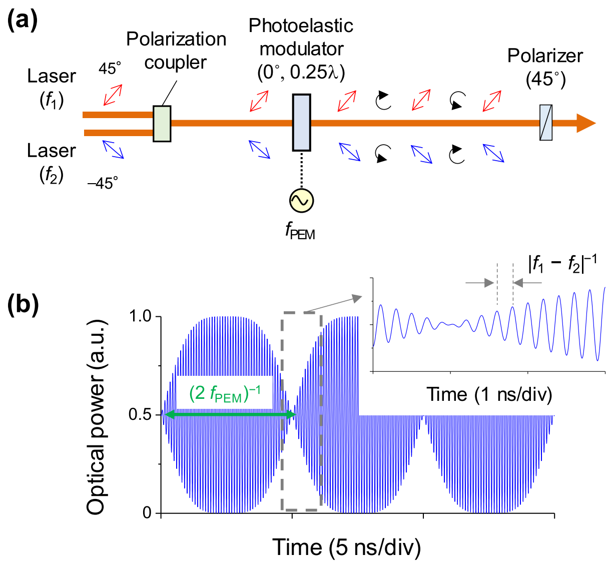

Fig. 2. (a) Configuration for envelope-modulated optical two-tone generation. (b) Time evolution of simulated optical beat signal. Inset shows enlarged view within dashed rectangular frame.

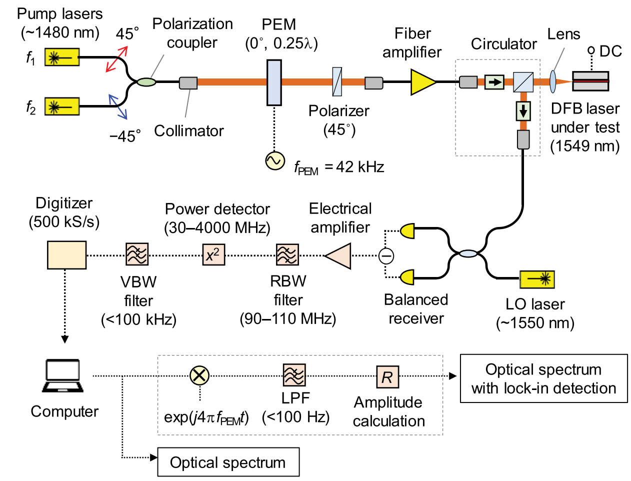

Fig. 3. Experimental setup and signal processing for wide-bandwidth and high-sensitivity measurement of intrinsic modulation responses of DFB laser.

by suppressing noises such as thermal noise of the photo receiver. In [30], output light of the LO laser was modulated by an optical chopper. However, as shown in Fig. 1(b), mixed light from two frequency-detuned pump lasers should be modulated in our case because the pump-induced change of a laser diode (LD) under test includes information on the modulation response. A straightforward choice for an additional modulator for the lock-in detection would be to use an optical intensity modulator such as an optical chopper. However, low-frequency intensity modulation of the kilohertz range induces non-negligible frequency modulation of the LD under test because of the thermal effect [31]. Optical frequency change due to this frequency modulation exceeds a few gigahertz, which is much higher than the typical RBW of coherent OSA, and it results in spurious signals. Therefore, the frequency modulation of the LD induced by the additional modulator should be low enough to not obscure the lock-in detection signals.

C. Generation of Envelope-Modulated Optical Two-Tone

We developed a technique for the envelope-modulated optical two-tone generation used in the lock-in detection that suppresses the low-frequency frequency modulation of an LD under test. A schematic of its configuration is shown in Fig. 2(a). Two pump lasers with a frequency detuning corresponding to the modulation frequency (f_m) and orthogonal linear polarizations of each other (45° and −45°) are combined by using a polarization coupler. The combined light is modulated by using a photoelastic modulator (PEM) with a fast axis of 0°, retardation amplitude of 0.25 λ, and modulation frequency of f_{PEM}. This modulation leads to differential polarization modulation for the two pump lasers. The modulated light passes through a polarizer with an axis of 45°. The x- and y-polarization electric field components (E_x and E_y) under such modulation can be expressed with the Jones matrix formalism, as

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}\begin{bmatrix} 1 & 0 \\ 0 & e^{j\frac{\pi}{2}\sin(2\pi f_{PEM}t)} \end{bmatrix} \cdot \left(\frac{E_1}{\sqrt{2}}\begin{bmatrix} 1 \\ 1 \end{bmatrix} + \frac{E_2}{\sqrt{2}}\begin{bmatrix} 1 \\ -1 \end{bmatrix}\right), \quad (6)$$

where $E_1 = A\cdot\exp(j2\pi f_1 t)$ and $E_2 = B\cdot\exp\{j(2\pi f_2 t + \phi_0)\}$, and ϕ_0 is the phase difference between E_1 and E_2. The resulting power for the optical excitation (I_{pump}) is expressed as $I_{\mathrm{pump}} = |E_x|^2 + |E_y|^2$.

A simulated result of I_{pump} with A and B of $2^{-1/2}$, f_{PEM} of 100 MHz, $|f_1 - f_2|$ of 10 GHz, and ϕ_0 of 0.5π is shown in Fig. 2(b). We can see here that the high-frequency modulation component corresponds to $|f_1 - f_2|$ and the envelope modulation occurs at a frequency of $2 f_{\mathrm{PEM}}$. (Note that this value of f_{PEM} is unrealistic for a commercial PEM; it was only utilized here for proof of concept to save computational effort with a coarse time step.) We confirmed that the above process can generate the envelope-modulated optical two-tone with a constant power that is suitable for the lock-in detection of modulation responses. Two intensity modulators which are operated under the push-pull modulation condition can also be used instead of the PEM for generating the envelope-modulated optical two-tone.

III. Measurement of Modulation Response

A. Experimental Setup

The experimental setup for the modulation response measurement is shown in Fig. 3. The two pump lasers were distributed feedback (DFB) lasers operated at around 1480 nm, and the detuning frequency between them was controlled by temperature. For the envelope-modulated optical two-tone generation, we used a configuration similar to the one in Fig. 2(a) with the f_{PEM} of 42 kHz. A DFB laser having an InGaAsP multiple-quantum-well active region was used for the measurement of modulation responses. It was operated at 1549 nm with a bias current of 40 mA, which is 2.5 times higher than the threshold current of 15.8 mA. The output power was 3 dBm under the condition. A free-space optical circulator was used to avoid any instabilities of the DFB laser under test due to weak light reflections at distant locations. The total optical power of the pump lasers injected into the DFB laser under test was estimated to be ~6 dBm at the lens position and it was absorbed in the active region without direct coherent coupling with the lasing mode because of the large wavelength separation of ~70 nm. Moreover the pump wavelength is transparent in the barrier and separate confinement heterostructures with a 1.3-μm band gap wavelength of the DFB laser under test.These conditions correspond to a relatively strong optical pumping within the small-signal modulation regime.

The LO laser was a DFB laser operated at around 1549 nm. Frequency tuning of the LO laser was conducted by temperature control with a frequency step of 7.5 MHz. The beat signal detected using a balanced receiver was amplified and then filtered using a RBW filter. The filter's passband determined an achievable spectral resolution of ~220 MHz. A power detector converted the beat signals while passing the slowly varying signal with a frequency of 2 f_{PEM}. Digitized signals were processed in a computer to obtain the optical spectrum with the lock-in detection at a reference frequency of 2 f_{PEM} as well as a conventional optical spectrum of the coherent OSA. The in-phase and quadrature-phase components of the signal were extracted by multiplying $\exp(j4\pi f_{\mathrm{PEM}} t)$, and then an infinite impulse response low pass filter with a cutoff frequency of 100 Hz was applied to them. The amplitude component was calculated from root sum square of filtered values of the in-phase and quadrature-phase components. Finally, an averaged signal with the Hanning window was calculated for each frequency step. These calculations were coded with MATLAB and LabVIEW.

A typical beat signal of the envelope-modulated optical two-tone with $|f_1 - f_2|$ of 1.47 GHz measured using a photodiode and an oscilloscope is shown in Fig. 4(a). We can see here that the envelope modulation was repeated at 2 f_{PEM} (84 kHz, corresponding to 11.9-μs interval), and a high frequency component of 1.47 GHz corresponding to the modulation frequency for the DFB laser under test was included. The extinction ratio of the modulation was 10 dB. However, we presume that the actual value of the extinction ratio is higher than because there are non-negligible noises of the oscilloscope in Fig. 4(a), which means that residual amplitude modulation of the envelope-modulated optical two-tone was successfully suppressed.

The linewidth of the beat note spectrum is basically determined by the spectral linewidth of each pump laser (~2 MHz in specification). As shown in Fig. 4(b), a narrow beat note spectrum was confirmed by calculating the Fourier transform of the beat signal in Fig. 4(a). The spectral shape was reasonably fitted by the Lorentzian curve with a full-width at half-maximum of 1.0 MHz. The additional spectral broadening with a width of ~100 MHz was attributed to the temperature variation of the pump lasers. This broadening is acceptable when we measure modulation responses higher than 100 MHz.

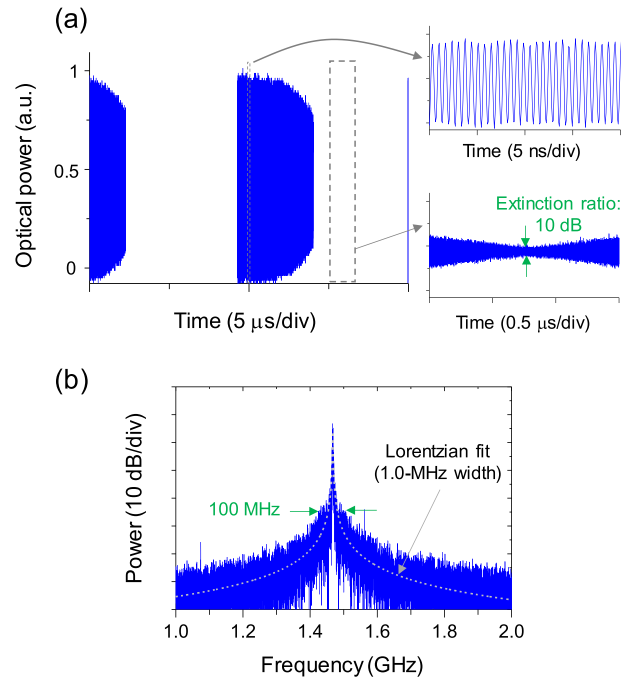

Fig. 4. (a) Time evolution of measured optical beat signal with $|f_1 - f_2|$ of 1.47 GHz. Insets show enlarged views within dashed rectangular frames. (b) Beat note spectrum calculated from signal in Fig. 4(a). Dashed curve indicates fitted Lorentzian function wit 1.0-MHz width.

B. Optical Spectra

Typical measured optical spectra without and with the lock-in detection are respectively shown in Fig. 5(a) and (b). We can see here that sidebands shifted when the modulation frequency varied for both cases, and better clarity of the sidebands was confirmed with the lock-in detection. A detailed comparison of the spectra at the modulation frequency of 3.1 GHz without and with the lock-in detection is provided in Fig. 5(c). An optical spectrum measured using a grating-based OSA (Advantest Q8384) with a frequency resolution of 1.3 GHz is also shown as a reference. We confirmed a significant noise reduction with the lock-in detection for the entire spectrum and its typical value was 23 dB at the relative frequency of around −20 GHz. This noise reduction allowed us to observe not only the first-order sidebands but also the second-order sidebands generated by the frequency modulation. The advantage of high frequency resolution and high sensitivity of the coherent OSA with the lock-in detection is obvious when the optical spectrum is compared to that with the grating-based OSA. The measured sidebands can be left-right asymmetric due to interference between the frequency and amplitude modulation components, so averaging the two sidebands is necessary (as indicated in (4)).

C. FM-AM Ratio

We evaluated the ratio of the FM (β) and AM (m) responses of the DFB laser prior to the measurement of the modulation responses. Although there is a method for separating the FM and AM components in optical spectra [32], we simply conducted

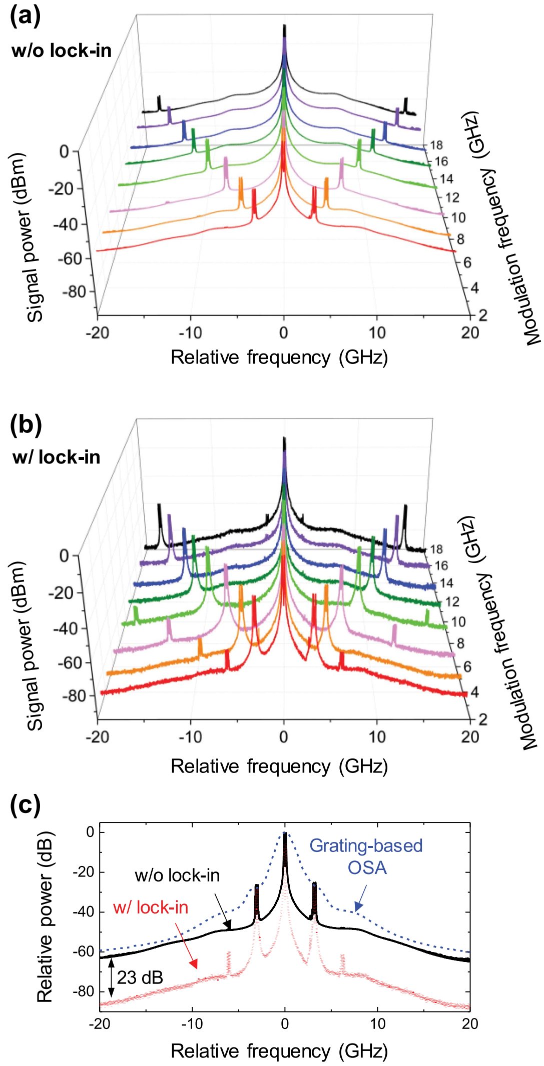

Fig. 5. Optical spectra under different modulation frequencies measured using coherent OSA (a) without lock-in detection and (b) with lock-in detection. (c) Comparison of measured optical spectra at 3.1-GHz modulation frequency without (solid black) and with (dotted red) lock-in detection. Optical spectrum measured using grating-based OSA (dashed blue) is included for reference.

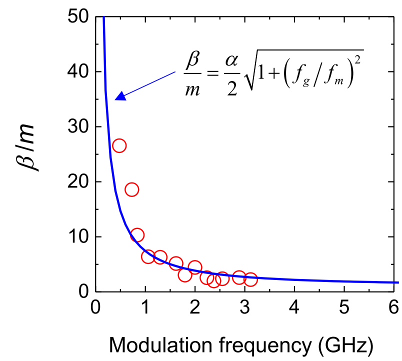

Fig. 6. (a) Measured FM-AM ratio of modulation responses. Solid curve indicates fitted and simulated data with α of 2.4 and f_g of 6.1 GHz.

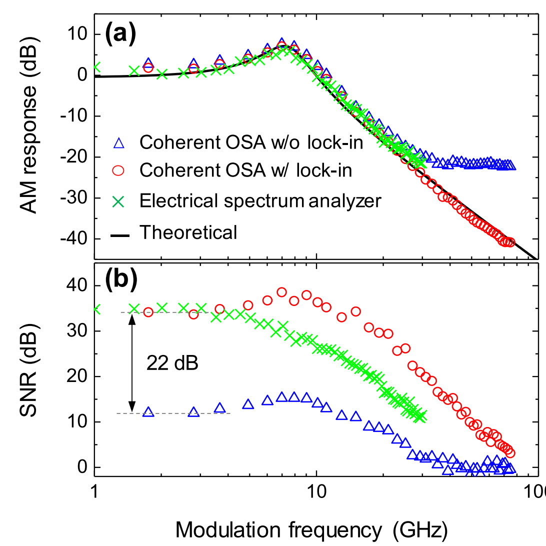

Fig. 7. (a) AM responses measured using coherent OSA without (triangles) and with (circles) lock-in detection, and using electrical spectrum analyzer (crosses). Theoretical response is indicated by solid curve. (b) SNR of modulation responses for coherent OSA without (triangles) and with (circles) lock-in detection, and electrical spectrum analyzer (crosses).

numerical fitting of (2) to measure the optical spectra at low modulation frequencies by taking into account the first- and second-order sidebands. The measured FM-AM ratio (β/m) at low modulation frequencies is shown in Fig. 6. By fitting a theoretical curve of β/m obtained from (5), we estimated reasonable parameter values: f_g of 6.1 GHz and α of 2.4. Hereafter, we use the f_g value to extract m from (5), while β is directly obtained from (4) for each modulation frequency.

D. Modulation Responses

Measured AM responses of the DFB laser using the coherent OSA without and with the lock-in detection are shown in Fig. 7(a). The response without the lock-in detection exhibited a saturation at around 30 GHz due to inadequate SNR, as shown in Fig. 7(b). Here, the SNR of a sideband is defined as the ratio between the average peak power of the first-order sidebands and noise floor. The lock-in detection improved the SNR by 22 dB and extended the measurable response frequency range up to 75 GHz even though the DFB laser has a 3-dB bandwidth of only 11 GHz. Also, as indicated by the solid curve in Fig. 7(a), the measured response with the lock-in detection was in reasonably good agreement with the theoretical curve of typical semiconductor lasers given by [33],

$$H(\omega) = \frac{\omega_r^2}{\sqrt{(\omega_r^2 - \omega^2)^2 + \omega^2\gamma^2}}, \quad (7)$$

where ω is the angular frequency of the modulation signal, ω_r is the resonance angular frequency, and γ is the damping factor. The parameter values we utilized were $\omega_r = 2\pi\times7.5$ GHz and $\gamma = 20\ \mathrm{GHz}^{-1}$. Fig. 7(a) also shows the AM response measured using a photodiode and an electrical spectrum analyzer up to 30 GHz in place of the coherent OSA. This response also agreed with the theoretical curve and thus supports the reasonability of the responses measured using the coherent OSA. A narrow RBW (3 MHz) of the electrical spectrum analyzer led to a maximum SNR of 35 dB, but the SNR gradually decreased due to relative intensity noise of the DFB laser under test. Although the coherent OSA had a relatively wide RBW (20 MHz), the lock-in detection helped to improve the SNR. These results demonstrate that our technique is suitable for the wide-bandwidth and high-sensitivity measurement of the intrinsic modulation response of semiconductor lasers. Although our technique is not suitable for accurately evaluating modulation responses in the megahertz range, combination use of an electrical spectrum analyzer is available for low modulation frequencies.

IV. Conclusion

We experimentally demonstrated a wide-bandwidth and high-sensitivity measurement technique for the intrinsic modulation response of semiconductor lasers. Envelope-modulated optical two-tone generation based on the polarization modulation of two free-running DFB lasers was used for optical pumping of an LD under test and lock-in detection of coherent OSA with high sensitivity. The modulation response of a typical DFB laser could be measured up to 75 GHz despite the 11-GHz bandwidth of the DFB laser thanks to improving the SNR by 22 dB. Since the measurable bandwidth for the laser under test is limited by the wavelength tuning range of the pump laser and the LO laser, measurable bandwidth of more than 200 GHz can be easily achieved at C-band. This technique is also useful as a tool for the optical measurement of VCSELs with only optical excitation as a wafer level test because optical excitation is usually weak compared to electrical excitation, which tends to cause a low SNR of modulation responses.

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References

[1] X. Zhou, R. Urata, and H. Liu, "Beyond 1 Tb/s intra-data center interconnect technology: IM-DD OR coherent?," *J. Lightw. Technol.*, vol. 38, no. 2, pp. 475–484, Jan. 2020.

[2] X. Pang et al., "200 Gbps/lane IM/DD technologies for short reach optical interconnects," *J. Lightw. Technol.*, vol. 38, no. 2, pp. 492–503, Jan. 2020.

[3] N. H. Zhu et al., "Directly modulated semiconductor lasers," *IEEE J. Sel. Topics Quantum Electron.*, vol. 24, no. 1, pp. 1–19, Jan./Feb. 2018.

[4] S. Yamaoka et al., "Directly modulated membrane lasers with 108 GHz bandwidth on a high-thermal-conductivity silicon carbide substrate," *Nature Photon.*, vol. 15, pp. 28–35, Jan. 2021.

[5] Y. Matsui, R. Schatz, D. Che, F. Khan, M. Kwakernaak, and T. Sudo, "Low-chirp isolator-free 65-GHz-bandwidth directly modulated lasers," *Nature Photon.*, vol. 15, pp. 59–63, Dec. 2021.

[6] S. Mieda, S. Shiratori, N. Yokota, W. Kobayashi, and H. Yasaka, "Intra-cavity loss modulation for ultrahigh-speed direct modulation lasers based on photon-photon resonance," *Appl. Phys. Exp.*, vol. 8, no. 8, Jul. 2015, Art. no. 082701.

[7] T. Tomiyasu et al., "20-Gbit/s direct modulation of GaInAsP/InP membrane distributed-reflector laser with energy cost of less than 100 fJ/bit," *Appl. Phys. Exp.*, vol. 11, no. 1, Dec. 2017, Art. no. 012704.

[8] R. Rosales, M. Zorn, and J. A. Lott, "30-GHz bandwidth with directly current-modulated 980-nm oxide-aperture VCSELs," *IEEE Photon. Technol. Lett.*, vol. 29, no. 23, pp. 2107–2110, Dec. 2017.

[9] S. T. M. Fryslie, M. P. T. Siriani, D. F. Siriani, M. T. Johnson, and K. D. Choquette, "37-GHz modulation via resonance tuning in single-mode coherent vertical-cavity laser arrays," *IEEE Photon. Technol. Lett.*, vol. 27, no. 4, pp. 415–418, Feb. 2015.

[10] H. Dalir and F. Koyama, "40 Gbps modulation of transverse coupled cavity VCSEL with push-pull modulation scheme," *Appl. Phys. Exp.*, vol. 7, no. 9, Aug. 2014, Art. no. 092701.

[11] N. Yokota, K. Nisaka, H. Yasaka, and K. Ikeda, "Spin polarization modulation for high-speed vertical-cavity surface-emitting lasers," *Appl. Phys. Lett.*, vol. 113, no. 17, Oct. 2018, Art. no. 171102.

[12] D. Brunner, M. C. Soriano, C. R. Mirasso, and I. Fischer, "Parallel photonic information processing at gigabyte per second data rates using transient states," *Nature Commun.*, vol. 4, Jan. 2013, Art. no. 1364.

[13] C. Huang et al., "Prospects and applications of photonic neural networks," *Adv. Phys.: X*, vol. 7, no. 1, Dec. 2022, Art. no. 1981155.

[14] G. D. VanWiggeren and R. Roy, "Communication with chaotic lasers," *Science*, vol. 279, pp. 1198–1200, Feb. 1998.

[15] A. Uchida et al., "Fast physical random bit generation with chaotic semiconductor lasers," *Nature Photon.*, vol. 2, pp. 728–732, Nov. 2008.

[16] A. A. Tager and B. B. Elenkrig, "Stability regimes and high-frequency modulation of laser diodes with short external cavity," *IEEE J. Quantum Electron.*, vol. 29, no. 12, pp. 2886–2890, Dec. 1993.

[17] P. Bardella, W. W. Chow, and I. Montrosset, "Design and analysis of enhanced modulation response in integrated coupled cavities DBR lasers using photon-photon resonance," *Photonics*, vol. 3, no. 1, Jan. 2016, Art. no. 4.

[18] S. Mieda, N. Yokota, W. Kobayashi, and H. Yasaka, "Ultra-wide-bandwidth optically controlled DFB laser with external cavity," *IEEE J. Quantum Electron.*, vol. 52, no. 6, Jun. 2016, Art no. 2200107.

[19] B. Hong, T. Kitano, T. Mori, H. Jiang, and K. Hamamoto, "Bandwidth enhancement scheme demonstration on direct modulation active-MMI laser diode using multiple photon photon resonance," *Appl. Phys. Lett.*, vol. 111, no. 22, Nov. 2017, Art. no. 221105.

[20] M. S. Al-Ghamdi, H. Dalir, A. Bakry, R. T. Chen, and M. Ahmed, "Regimes of bandwidth enhancement in coupled-cavity semiconductor laser using photon-photon resonance," *Japanese J. Appl. Phys.*, vol. 58, Oct. 2019, Art. no. 112003.

[21] D. Chen, Y. Liu, and Y. Yu, "Understanding the photon-photon resonance of DBR lasers using mode expansion method," *Opt. Quantum Electron.*, vol. 55, Nov. 2023, Art. no. 29.

[22] H. Yasaka, Y. Yoshikuni, and M. Watanabe, "Measurement of gain saturation coefficient of a DFB laser for lasing mode control by orthogonal polarization light," *IEEE J. Quantum Electron.*, vol. 27, no. 10, pp. 2248–2255, Oct. 1991.

[23] C. B. Su et al., "Characterization of the dynamics of semiconductor lasers using optical modulation," *IEEE J. Quantum Electron.*, vol. 28, no. 1, pp. 118–127, Jan. 1992.

[24] N. H. Zhu et al., "Estimation of frequency response of directly modulated lasers from optical spectra," *J. Phys. D: Appl. Phys.*, vol. 39, no. 21, pp. 4578–4581, Oct. 2006.

[25] M. Kanno, N. Yokota, and H. Yasaka, "Measurement of intrinsic modulation bandwidth of hybrid modulation laser," *IEEE Photon. Technol. Lett.*, vol. 32, no. 13, pp. 839–842, Jul. 2020.

[26] L. Bjerkan, A. Royset, L. Hafskjaer, and D. Myhre, "Measurement of laser parameters for simulation of high-speed fiberoptic systems," *J. Lightw. Technol.*, vol. 14, no. 5, pp. 839–850, May 1996.

[27] D. M. Baney, B. Szafraniec, and A. Motamedi, "Coherent optical spectrum analyzer," *IEEE Photon. Technol. Lett.*, vol. 14, no. 3, pp. 355–357, Mar. 2002.

[28] J. M. S. Domingo, J. Pelayo, F. Villuendas, C. D. Heras, and E. Pellejer, "Very high resolution optical spectrometry by stimulated Brillouin scattering," *IEEE Photon. Technol. Lett.*, vol. 17, no. 4, pp. 855–857, Apr. 2005.

[29] K. Feng et al., "An optoelectronic equivalent narrowband filter for high resolution optical spectrum analysis," *Sensors*, vol. 17, no. 2, Feb. 2017, Art. no. 348.

[30] M. O. van Deventer, C. M. de Blok, and C. Park, "High-dynamic-range heterodyne measurement of optical spectra," *Opt. Lett.*, vol. 16, no. 9, pp. 678–680, May 1991.

[31] S. Kobayashi, Y. Yamamoto, M. Ito, and T. Kimura, "Direct frequency modulation in AlGaAs semiconductor lasers," *IEEE Trans. Microw. Theory Tech.*, vol. 30, no. 4, pp. 428–441, Apr. 1982.

[32] T. Zhang, N. H. Zhu, B. H. Zhang, and X. Zhang, "Measurement of chirp parameter and modulation index of a semiconductor laser based on optical spectrum analysis," *IEEE Photon. Technol. Lett.*, vol. 19, no. 4, pp. 227–229, Feb. 2007.

[33] L. A. Coldren, S. W. Corzine, and M. L. Mašanović, *Diode Lasers and Photonic Integrated Circuits*. Hoboken, NJ, USA: Wiley, 2012, ch. 5, sec. 5.3, p. 266.