Appl. Phys. B 82, 25–29 (2006)
DOI: 10.1007/s00340-005-2003-2

Applied Physics B
Lasers and Optics

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Ultraviolet diode laser system based on the resonant optical feedback method with the capability of fast continuous sweep

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Received: 19 July 2005/Revised version: 2 September 2005
Published online: 4 November 2005 •

ABSTRACT An ultraviolet laser diode system stabilized to an external Fabry–Perot cavity by using the resonant optical feedback method is described. Both wide continuous sweep with fast response and drift compensation for long term operation are realized simultaneously by performing feedforward control along with feedback control of the system parameters. By utilizing the capability of synchronized sweep realized by the feedforward control, the modulation of the output frequency, due to dither for lock-in feedback control of the system parameters, is almost perfectly canceled. The method described here is useful for developing diode laser systems for practical use with such features as small short term fluctuation, long-term operability and fast continuous sweep.

PACS 42.55.Px; 42.60.By; 32.80.Pj

1 Introduction

Semiconductor lasers are extensively used in wide range of practical applications as well as in fundamental studies including atomic physics experiments, due mainly to their compactness and reliability [1]. Their limited stand-alone characteristics in tunability and short term stability can be improved by using the extended cavity configuration [2]. Such a laser system may fulfill the requirements in many spectroscopic applications, while in more demanding applications, including ion cooling experiments that exploit Raman transitions [3] or electromagnetically induced transparency [4], further improvement in the frequency characteristics is desirable. Better frequency characteristics may be obtained by combining resonant optical feedback or electronic feedback to the extended cavity configuration.

Electronic feedback to the injection current [5, 6] is one of the most straightforward methods to narrow the linewidth of a semiconductor laser. Wide-bandwidth electronic control can be realized by using a control circuit such as a bias-tee which is directly attached to the laser head, while such implementation of modulation capability increases the danger of exposing the laser chip to external surge voltages. This may be a serious problem especially when using immature semiconductor lasers, including ultraviolet diode lasers, which are relatively vulnerable to surge voltages.

On the other hand, the resonant optical feedback method [7–9], which is based on optical feedback from an external high-finesse resonator, enables linewidth reduction by more than a few orders with a simple setup, and do not require elaborate electronic circuits. In addition, by combining this method with electronic feedback to the injection current with modest bandwidth, even narrower linewidth can be obtained.

In a diode laser system based on the resonant optical feedback method, the output frequency is mainly determined by the resonance frequency of the external cavity (abbreviated to the external cavity resonance frequency). It also depends on the distance between the laser and the external cavity (abbreviated to the path length) or the resonance frequency of the laser cavity. These parameters are usually chosen at the optimum condition that gives the maximum linewidth reduction by resonant optical feedback. In many cases, especially when a sweep of the output frequency over a wide range is not necessary, only the path length is automatically controlled so that the transmission of the external cavity keeps the maximum value, whereas the laser cavity resonance frequency is manually adjusted to coincide with the external cavity resonance frequency. The control of the path length is usually done by applying a small modulation (dither) to it and performing lock-in detection in the external cavity transmission signal, which gives an error signal that is then used for feedback control of the path length. We briefly call this $1f$ lock-in feedback control in the followings.

On the other hand, in the cases where wide frequency sweep or long term operation is necessary, also the laser cavity resonance frequency has to be controlled so that it remains equal to the external cavity resonance frequency. For this purpose, a method that can be integrated with $1f$ lock-in feedback control mentioned above has been proposed and demonstrated by Ohshima et al. [10]. In the method, transmission curves are taken by applying sinusoidal modulation of the path length, in a similar way to the $1f$ lock-in feedback control scheme written above. Then the asymmetry of the transmission curves, which reflects the deviation of the laser cavity resonance frequency from the optimum value, is sensed by performing lock-in detection with the frequency-tripled modulation signal, and is used as an error signal for feedback control ($3f$ lock-in feedback control). Thus, the laser

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cavity resonance frequency follows the external cavity resonance frequency even if the latter changes considerably during a frequency sweep or in a long term operation. Hayasaka has reported wide continuous sweep of an ultraviolet extended cavity diode laser with resonant optical feedback, by performing feedback control with the $3f$ lock-in signal [11].

By performing such $3f$ lock-in feedback control, wide continuous frequency sweep is achieved, while the response of frequency sweep is limited by the time constant for lock-in detection. In addition, modulation of the output frequency cannot be neglected. Such modulation of the output frequency is observed even if only $1f$ lock-in feedback control is operated. However, in the case of $3f$ lock-in feedback control, a relatively large modulation amplitude is required in order to obtain a $3f$ lock-in signal with sufficient quality, hence such modulation of the output frequency may be more significant in the case.

In this paper we report on the demonstration of a scheme for control of the two main parameters in the resonant optical feedback system (the laser cavity frequency and the path length) in which feedforward control of the two parameters is also performed along with feedback control of them. The scheme enables both wide continuous sweep with fast response and drift compensation for long term operation at the same time. By utilizing the capability of synchronized sweep realized by the feedforward control, even cancelling of the output frequency modulation, due to the dither (small modulation) of the path length that is essential in lock-in feedback control, is possible and is demonstrated here. An ultraviolet diode laser in the extended cavity configuration is chosen as the light source to be controlled. The scheme enables us to develop really practical light source systems using the resonant optical feedback method.

2 Principles

In [9], Laurent et al. describes the equation that determines the center output frequency of the resonant optical feedback system, denoted as ω.

$$\omega_{\mathrm{N}} = \omega + \frac{\kappa}{2t_{\mathrm{d}}} \frac{\sin[\omega(\tau_{\mathrm{d}}+\tau_{\mathrm{p}})+\theta] - r^4 \sin[\omega(\tau_{\mathrm{d}}-\tau_{\mathrm{p}})+\theta]}{1+F^2\sin^2\omega\tau_{\mathrm{p}}}. \tag{1}$$

Here, t_{d} is the laser cavity round-trip time, and $\omega_{\mathrm{N}} \equiv 2k\pi/t_{\mathrm{d}}$ (k integer) is the laser cavity resonance frequency. κ is a dimensionless coefficient defined as $\kappa = (1+\alpha^2)^{1/2}\beta^{1/2}2F_{\mathrm{cfp}}/(1+r^2)F_{\mathrm{d}}$, where α is the phase-amplitude coupling factor of the diode laser, and β is the power mode coupling factor that represents the coupling efficiency of the diode laser output to the external cavity. F_{cfp} and F_{d} are the values of finesse for the external cavity and the laser cavity, respectively. r is the amplitude reflection factor of the two mirrors of the external cavity. $\tau_{\mathrm{d}} = 2L_{\mathrm{d}}/c$, $\tau_{\mathrm{p}} = 2L_{\mathrm{p}}/c$ are the round-trip time between the laser and the external cavity and that of the external cavity, respectively, where L_{d}, L_{p}, c are the path length, the length of the external cavity and the speed of light, respectively. θ is a constant that depends on α, and $F = 2F_{\mathrm{cfp}}/\pi$.

The linewidth reduction by resonant optical feedback depends on the slope factor $P = \mathrm{d}\omega_{\mathrm{N}}/\mathrm{d}\omega$. A linear dependence of the linewidth on P^{-1} is reported [9]. It can be confirmed[1] that in the case of fixed τ_{p} and $r \sim 1$ (a high finesse external cavity) P takes the maximum value of $P \sim 1+\kappa(\tau_{\mathrm{p}}/t_{\mathrm{d}})$ near the points in the $\omega - \tau_{\mathrm{d}}$ plane that satisfies the two conditions $\omega\tau_{\mathrm{d}}+\theta = 2k'\pi$ and $\omega\tau_{\mathrm{p}} = 2k''\pi$ (k', k'' integer). At these points, ω_{N} and ω coincides with the external cavity resonance frequency $\omega_{\mathrm{c}} = 2k''\pi/\tau_{\mathrm{p}}$. These facts being considered, in $1f$ lock-in feedback control, at first ω_{N} is manually set to coincide with ω_{c}. Then τ_{d} is stabilized by using the lock-in technique to the point that gives the maximum transmission of the external cavity. At that point $\omega = \omega_{\mathrm{c}}$ and P takes the maximum value, hence the largest linewidth reduction is obtained.

On the other hand, in operations for relatively long period where the drift of ω_{N} can not be neglected, the difference between ω_{N} and ω_{c} may also be detected and then zeroed by using the 3rd derivative of the transmission curve at the peak, which reflects the asymmetry of the curve around that point ($3f$ lock-in feedback control) [10].

In the case where sweep of the output frequency is necessary, both the path length and the laser cavity resonance frequency have to be varied by appropriate amounts in synchronization with the variation of the external cavity resonance frequency. Synchronized control of the three parameters is explained quantitatively in the following way. If the following transformation is applied to (1), the resulting equation is identical to the original equation:

$$\begin{aligned} &\tau_{\mathrm{p}} \to \tau_{\mathrm{p}}(1+\xi)^{-1}, \qquad \tau_{\mathrm{d}} \to \tau_{\mathrm{d}}(1+\xi)^{-1}, \\ &t_{\mathrm{d}} \to t_{\mathrm{d}}(1+\xi)^{-1}, \qquad [\omega_{\mathrm{N}} \to \omega_{\mathrm{N}}(1+\xi)], \\ &\omega \to \omega(1+\xi), \end{aligned} \tag{2}$$

where ξ is a dimensionless quantity that satisfies $|\xi| \ll 1$. This transformation corresponds to an operation that changes all the relevant quantities in the dimension of length (the three round-trip optical length $c\tau_{\mathrm{p}}$, $c\tau_{\mathrm{d}}$, ct_{d} and the output wavelength $\lambda \equiv 2\pi c/\omega$) by the same proportion $(1+\xi)^{-1}$. In other words, the transformation merely expands or shrinks the whole system very slightly. After such a change of parameters the resonant optical feedback system is kept in the equivalent condition, while the output frequency is shifted by $\omega\xi$ (synchronized sweep).

Although the combined $1f$ and $3f$ lock-in feedback control scheme mentioned above can be used to realize such synchronized sweep in an "adiabatic" manner by varying ω_{N} sufficiently slowly compared with the lock-in time constant, it is more straightforwardly realized with predesigned variation in the two parameters τ_{d} and ω_{N} in synchronization with the variation of τ_{p} (feedforward control), since the appropriate

[1] In the limit of $r \to 1$, P is written explicitly as follows as a function of ω and τ_{d}, by using $X \equiv \omega\tau_{\mathrm{d}}+\theta$, $Y \equiv \omega\tau_{\mathrm{p}}$: $P = 1+\kappa\,[(\tau_{\mathrm{p}}/t_{\mathrm{d}})\cos X\cos Y\,(1-F^2\sin^2 Y) - (\tau_{\mathrm{d}}/t_{\mathrm{d}})\sin X\sin Y(1+F^2\sin^2 Y)]\;/(1+F^2\sin^2 Y)^2$. Here τ_{p} is assumed to be fixed, and t_{d} is considered to be a dependent variable determined by (1). When either $X = 2k'\pi$ or $Y = 2k''\pi$ (k', k'' integer) is satisfied, P becomes approximately a function of only $\cos Y$ or $\cos X$, respectively. (t_{d} dependence is neglected since for optical frequencies k', k'' are very large.) This assures that $\partial P/\partial Y = \partial P/\partial X = 0$ (and therefore $\partial P/\partial\omega = \partial P/\partial\tau_{\mathrm{d}} = 0$) at $(X, Y) = (2k'\pi, 2k''\pi)$ (k', k'' integer), and thus implies that P takes the maximum value of $1+\kappa(\tau_{\mathrm{p}}/t_{\mathrm{d}})$ at those points. If r is not equal to 1, but is close to, the situation changes very little, which can be confirmed numerically.

amounts of change in the two parameters for a given change in τ_p is known in advance. In our scheme, synchronized sweep is realized with such feedforward control of the two parameters. In addition, $1f$ and $3f$ lock-in feedback control is simultaneously operated to compensate drift due to environmental changes. Since feedforward control of the system parameters complying with (2) keeps the system in the equivalent conditions, $1f$ and $3f$ lock-in feedback control are not disturbed even if they are operated simultaneously.

To verify that feedforward control complying with (2) can be operated independently of the lock-in feedback control scheme, we needs to check only that transformations given by (2) do not alter the external cavity transmission signal for a given arbitrary set of initial values of the system parameters. This may be accepted by reminding readers that the lock-in signals are derived from the external cavity transmission signal by varying one of the system parameters such as the path length. For a fixed value of the external cavity finesse, the transmission of the external cavity depends only on the ratio of the detuning $\omega - \omega_c$ to the external cavity mode spacing τ_p^{-1}. This ratio, equal to $\omega\tau_p - 2k''\pi$, is not altered by application of transformations described by (2). Therefore it is obvious that the lock-in feedback control scheme is not disturbed by feedforward control complying with (2).

3 Experimental setup

Figure 1 shows the experimental setup for the resonant optical feedback system, where an ultraviolet diode laser (Nichia NLHV3000A) in the extended cavity configuration is used as the light source [11, 12]. The wavelength of the laser is set at 397 nm by adjusting the angle of the diffraction grating in the extended cavity configuration. As for the external cavity for resonant optical feedback, a homemade confocal Fabry–Perot cavity (length ~ 0.1 m, free spectral range ~ 1500 MHz, finesse ~ 300) is used. The distance between the laser and the CFP cavity is about 300 mm. The CFP cavity axis is tilted against the incident beam by ~ 0.5 degree to prevent the directly reflected beam from returning to the laser diode chip.

The path length between the laser and the CFP cavity is modulated by a sinusoidal function with the frequency $f \sim 85$ Hz, by using a piezo transducer attached to the coupling mirror for the external cavity. The sinusoidal function is sent also to the reference input of the lock-in amplifier for $1f$ lock-in feedback control (LIA1). In addition, the signal is fed to a three-times multiplier, whose output is then sent to the other lock-in amplifier for $3f$ lock-in feedback control (LIA2).

The transmission of the external cavity is detected with a photodetector and sent to both LIAs. The output of LIA1 is sent to a PI (proportional-integral) controller, whose output is then added with the modulation signal for the path length control; thereby, the feedback loop for $1f$ lock-in feedback control is closed. The output of LIA2 is sent to another PI controller, and its output is fed to the piezo transducer for the cavity length of the extended cavity laser to perform $3f$ lock-in feedback control. This output is properly attenuated and applied also to the modulation input of the diode laser current

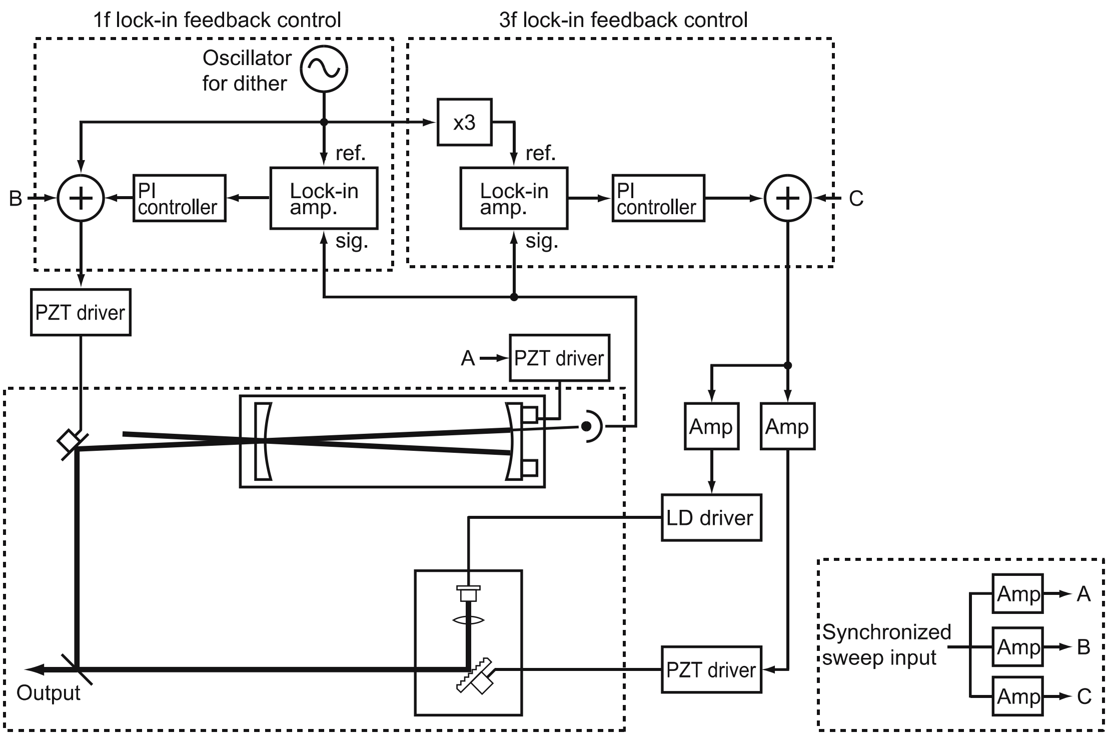

FIGURE 1 Experimental setup for feedback and feedforward control of the resonant optical feedback system. The optical section is shown in the *lower left box*, in which an ultraviolet extended cavity diode laser is narrowed by resonant optical feedback from an external Fabry–Perot cavity. In the *upper left* and *upper right box*, the sections for $1f$ and $3f$ lock-in feedback control of the system parameters are shown, respectively. In the *lower right box*, the section for generation of the control signals used in synchronized sweep of the system output frequency is shown. The signal A is used to control the external cavity length, and the signals B and C are used for feedforward control of the path length and the laser cavity resonance frequency, respectively

controller, in order to keep the mode frequency of the original diode laser cavity close to that of the extended cavity.

Furthermore, the synchronized sweep is performed by controlling those two piezo transducers (B, C in the figure) in synchronization with the sweep of the external cavity length (A). These three control signals is generated from the output of a function generator, by dividing it and amplifying each signal with the appropriate gain. The appropriate gains are estimated in advance by considering the characteristics of the piezo transducers used, and are further optimized while the system is in operation by choosing the values that give the widest continuous sweep range.

4 Performance of the resonant optical feedback system

4.1 *Short term fluctuation*

In order to roughly quantify the effect of linewidth reduction by resonant optical feedback, we have determined short term fluctuation of the developed system in a simple manner using the transmission of another Fabry–Perot cavity. A part of the ultraviolet diode laser system output is directed into a Fabry–Perot cavity, and its transmission is monitored with a detector. The frequency of the laser is set at one of the half-maximum points of the transmission curve, where the slope of the curve is steepest. By use of the slope of the cavity transmission curve the frequency excursion of the laser is converted into voltage fluctuation and can be detected electrically. If the bandwidth of the cavity is sufficiently large, this voltage fluctuation is directly related to the frequency fluctuation of the system output.

The cavity used here is a confocal cavity with the free-spectral range of 750 MHz and the finesse of ~ 14. The fluctuation (2σ) measured in the way described above is $\sim$30 kHz in 5 ms. On the other hand, the fluctuation without resonant optical feedback observed in the same way is 2 MHz in 5 ms. Hence, reduction of the frequency fluctuation by more than 60 is achieved.

4.2 *Continuous long term operation*

The capability of the system to be operated continuously in long terms is also investigated. Here, the external cavity length is fixed, while the feedback phase and the laser cavity length is controlled by negative feedback with $1f$ and $3f$ lock-in signals. Under such a condition, the duration for which the frequency of the laser output is locked to the external cavity resonance frequency by resonant optical feedback is measured.

The continuous operation duration of the laser system measured in that way is ~ 40 minutes. The reason that the system has ceased to operate continuously in the measurement is not clear, although we suppose that this is not the problem of the resonant optical feedback system but of the extended cavity laser itself. For such a relatively long duration, continuous operation of the extended cavity laser can be interrupted. The laser diode chip that we have used in the ECDL system is an ultraviolet laser diode without anti-reflection coating on the front facet, hence the discrepancy between the external cavity resonance frequency and the internal cavity resonance frequency, which may be caused by the drift of the ambient temperature, can lead to interruption of the single mode operation. Better temperature stabilization or performing anti-reflection coating on the facet might help to increase the continuous operation time.

4.3 *Synchronized sweep*

To perform synchronized sweep of the system output frequency, the gain values for three parameters should be adjusted to the appropriate values in advance. According to (2), the three round-trip optical path lengths $c\tau_{\mathrm{p}}$, $c\tau_{\mathrm{d}}$ and ct_{d} should be changed by the same proportion $(1+\xi)^{-1}$. Considering this and the characteristics of the piezo transducers used, the gain values can be roughly estimated, and with small modification to these values the optimum ones may be found.

Thus optimization for continuous sweep is performed, and a continuous sweep range of ~ 5.6 GHz is obtained. As for sweep speed, 0.5 GHz/s is realized. In our case, the sweep range is in fact limited by the output voltage range of the piezo amplifier for control of the path length; hence, an even larger sweep range may be realized by using higher voltages.

5 Result of dither cancellation

In the resonant optical feedback method, a small modulation (usually called dither) in a system parameter such as the path length is usually applied to detect deviation from the optimum condition. This dither may cause modulation in the output frequency. Especially in the case that $3f$ lock-in feedback control is performed, this dither have to be relatively large and can be a problem in practical situations.

This modulation can be eliminated by using another external reference cavity to detect the frequency excursion, and by performing negative feedback to one of the system parameters. Alternatively, the modulation may also be eliminated by feedforward control of one of the system parameters, that is, by applying a modulation with the same frequency, the appropriate amplitude and sign that cancels the original modulation to one of the system parameters. However, such treatments not only make the system more complicated, but may also disturb the feedback control scheme, since in those cases control signals with exactly the same frequency as the lock-in modulation frequency is applied to the system parameters, which may result in modification of the lock-in signal.

Here, we try to cancel the modulation due to a dither by performing feedforward control of not only one of the system parameters but all the three parameters, τ_{p}, τ_{d} and ω_{N}. As previously mentioned, synchronized parameter change according to (2) does not modify the lock-in signals at all but only shifts the output frequency. Therefore, when a synchronized sweep that exactly cancels the modulation due to a dither is performed, the lock-in feedback control is not affected, while the modulation of the output frequency is eliminated. In this case, dither of the system parameters is indeed performed. However, with respect to the output frequency its effects are cancelled and not visible. In our setup, this dither cancellation can be simply done by feeding the dither control signal amplified with an appropriate gain to the synchronized sweep input shown in Fig. 1.

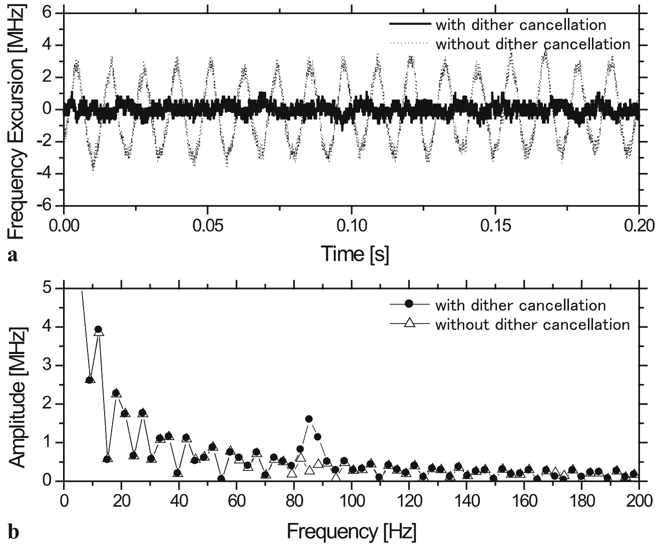

FIGURE 2 (**a**) Frequency excursion of the output of the resonant optical feedback system when dither cancellation is performed (*solid line*) or not (*dotted line*). (**b**) Fast-Fourier transformed results of the frequency excursion data. A peak near 85 Hz corresponding to modulation by dither exists in the result taken without dither cancellation, while it is completely absent in the result with dither cancellation

It is noted that, as previously mentioned, the synchronized sweep itself is realized with feedforward control, that is, control of τ_d and ω_N in accordance with variation of τ_p that keeps $\omega\tau_d + \theta - 2k'\pi$ and $\omega\tau_p - 2k''\pi$ constant. On the other hand, dither cancellation described above is also a type of feedforward control in which synchronized sweep is performed in accordance with the dither to keep the output frequency constant. Hence in this case two different types of feedforward control are implemented at the same time in a cascaded configuration, and they work cooperatively to be operated as one implementation of feedforward control, which cancels the modulation arising from the feedback control scheme without affecting its activity.

In the method described here, an external reference such as a Fabry–Perot cavity is necessary in the initial calibration procedure, since the required gain can be roughly estimated in advance but not exactly. However, once this initial calibration procedure is done, stand-alone operation of the system without an external reference may be possible. Even the atomic system itself, over which spectroscopy is to be performed by using the laser system, may be used for the calibration procedure.

Related to this subject, Schnier et al. [13] describes a scheme to detect the difference between ω and ω_c and to compensate it by changing the path length. Our scheme differs from that work in that both the two parameters, the path length and the laser cavity resonance frequency, are controlled to optimize linewidth reduction, as is the case in Ohshima et al. [10].

Figure 2 is the result of dither cancellation. The dotted line in Fig. 2a is the result taken without dither cancellation. In this case, modulation of about 5 MHz (peak-to-peak) is observed. On the other hand, by performing dither cancellation, the modulation is completely eliminated (the solid line). To further investigate the effect of dither cancellation, Fourier transformation of the above two results is performed. The results are shown in Fig. 2b. The peak corresponding to modulation by dither that can be seen in the result without dither cancellation is completely absent in the result with dither cancellation. From this, we can infer that the modulation due to dither is reduced by more than 20 dB by performing dither cancellation.

6 Conclusion

In conclusion, an ultraviolet diode laser system based on the resonant optical feedback method is developed. The principal system parameters are controlled by feedback control and feedforward control so as to enable both fast continuous sweep and drift compensation at the same time. Even the unavoidable frequency modulation due to the path length dither is almost perfectly cancelled by utilizing the capability of feedforward control. The scheme described here can be used to develop practical diode laser systems with better performance than in the widely used extended cavity diode laser systems. This scheme may also be combined with such a configuration as is described by Wicht et al. [14], in which the extended cavity configuration and the external cavity configuration is integrated so that a compact and robust design is possible.

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