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Beat Signal Generation between Two Rubidium Absorption-Line-Stabilized Diode Lasers in GHz-Frequency Band

Tomoyuki Uehara[1, *], Shinya Maehara[2], Kohei Doi[3], Toshiya Nimonji[4], Takahiro Saito[5], Hideaki Arai[5], Takashi Sato[2], Yasuo Ohdaira[2], Shuichi Sakamoto[2], Masashi Ohkawa[2]

[1]Department of Communications Engineering, National Defense Academy of Japan, Yokosuka, Japan
[2]Faculty of Engineering, Niigata University, Niigata, Japan
[3]Faculty of Science, University of Toyama, Toyama, Japan
[4]YMP-Mundus Corporation, Osaka, Japan
[5]Graduate School of Science and Technology, Niigata University, Niigata, Japan

Abstract

A stable microwave source using frequency stabilized diode lasers was developed. The Doppler-free spectra of Rb atoms produced by saturated absorption spectroscopy were used to obtain highly-sensitive control signals and lock the frequency of diode lasers to it. The beat frequencies between two independently stabilized diode lasers were 1.2 GHz and 2.9 GHz. The fluctuations in beat frequencies were 40 kHz and 400 kHz respectively in the best stability.

Keywords

Frequency Stabilization, Diode Laser, Saturated Absorption Spectroscopy, Rubidium Absorption Line, Microwave

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1. Introduction

Diode lasers are compact, lightweight, inexpensive and durable. While they are now ubiquitous, they are still plagued by their frequencies' notorious sensitivity to changes in ambient temperature and injection current, so it is essential that their temperatures be controlled precisely, and that they are driven by a current-source that generates as little noise as possible. By performing such operations, we are able to precisely measure the spectral linewidth of several MHz close to the theoretical value and observe quantum noise [1]. Furthermore, it is reported that the spectral linewidth of diode lasers with the external resonator configuration can be narrowed to 200 Hz and even 1 Hz using internal references [2], [3]. On the other hand, stabilization of the center frequency of a diode laser has often been performed by locking the laser frequency to an external frequency reference, such as the absorption lines of atoms or molecules and stable Fabry-Perot cavity [4]–[11]. These techniques were established more than 30 years. But the high speed electronics for frequency stabilization or additional techniques [25] are used in many precise measurement fields. Because these basic techniques are improved both spectral purity and frequency stability, they are useful when applied to high-resolution spectroscopy or precision optical measurement [12]–[14]. Research in various fields, from fundamental scientific-, to industrial applications has tested frequencies ranging from microwave to THz wave. The standard method of generating a broadband microwave or THz wave pulse is to irradiate a semiconductor and a nonlinear optical crystal with a

* Corresponding author
E-mail address: Uehara@nda.ac.jp (T. Uehara)

femtosecond laser [15], [16]. There are also a number of methods for generating a monochromatic wave that allow us to ad- just frequency. One of these uses optical parametric generation [17] and difference frequency generation [18], by the nonlinear optical effect using a nanosecond laser. Another method uses a resonant tunneling diode oscillator [19], [20] and quantum cascade laser [21] to directly generate high frequency waves. Though they have the advantage of being compact due to their simple design, they are hindered by a lack of broad spectrum frequency tenability. In contrast, photo-mixers, which generate a beat frequency by superimposing two monochromatic laser beams, are able to generate a continuous high frequency wave with broad frequency tenability [22]. Recently, a tunable THz wave photo-mixer using a uni-traveling carrier-photodiode (UTC-PD) has been adopted by NTT, for use in spectroscopic remote gas-sensing applications [23]. However, a frequency- tunable THz source with high frequency stability and narrow linewidth is required, when applying it to continuous wave spectroscopy [24]. Uehara *et al* developed optical reference cavity stabilized lasers using a Fabry-Perot cavity and generated a stable microwave using fast PD [25]. This technique is sufficient for the purpose at first glance, because a lot of resonances are available in cavity and the differences between two resonant frequencies are relatively stable. But in this technique, they could not stabilize the absolute frequency of the beat note. So the absolute frequency drift of the beat note makes unlocked condition after the locking for some hours. In this cause, the absolute frequency stabilization of the beat note is needed.

In this paper, we propose that technology to enhance the coherence of the diode laser is applicable to the generation of a stable microwave which is frequency-controlled at room temperature. Due to the complexity and expense of optical comb-based THz wave generation, we are testing beat signals as potential substitutes for them. It is theoretically possible to generate a beat frequency of 7.1-THz from the two diode lasers that are respectively frequency- controlled to the D1 (377.5 THz) and D2 (384.6 THz) absorption lines of Rb atoms [7], [26]. In current stage, both diode lasers were stabilized to Rb D2 absorption lines, which are essentially immune to external variables as the external frequency reference. In addition, we are using saturated absorption spectroscopy [27], which can eliminate the effects of Doppler broadening in the absorption spectrum and improve the accuracy of control signal. As a result, we were able to measure beat frequencies of several GHz.

2. Principles of Frequency Stabilization

In this section, the locking scheme of frequency stabilization is introduced. Although it is written in basic books, it is important to introduce the basic characteristics of frequency stabilization.

2.1. Control Signal for Frequency Stabilization

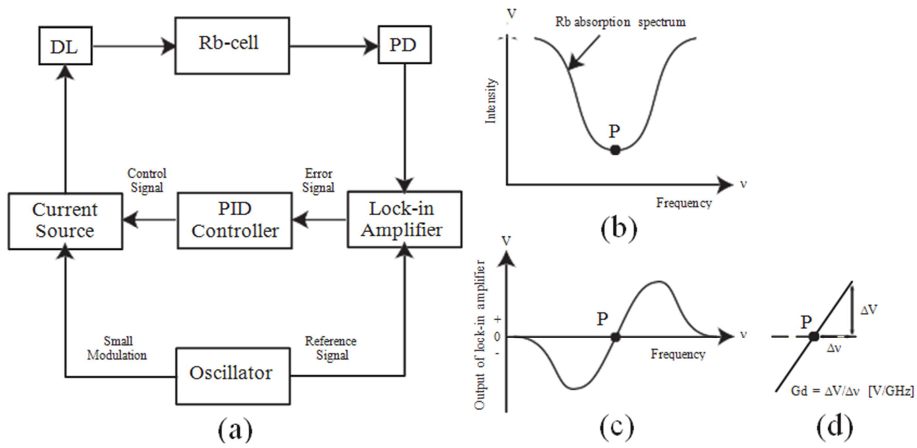

Fig. 1. Principle of stabilization. (a) Frequency stabilization system, (b) Absorption line profile of Rb, (c) First differential signal, (d) Stabilization point and G_d.

As the flow chart in Fig. 1(a) shows, we have stabilized the frequency of a diode laser operating at the frequency that is identical to the Rb-D2 absorption line. For purposes of frequency stabilization, the difference between the reference- and oscillation-frequencies needs to be measured, and fed back to the injection current. The laser beam, which has succeeded in passing through an Rb-cell without being absorbed by Rb atoms, is ultimately identified by a photo detector (PD) as a transmitted light signal. The curved line in Fig. 1(b) represents the transmitted intensity signal of the absorption profiles obtained by sweeping the laser injection current. Then, by applying minuscule modulations of the laser' injection current, and simultaneously detecting the transmitted light- and reference-signals, we obtain the output waveform of the first differential signal (Fig. 1(c)). When the laser' frequency deviates $\Delta\nu$ from stabilization point P, the control signal ΔV, which represents the difference between the reference- and oscillation-frequencies, can be obtained. We can stabilize the oscillation frequency of a diode laser, or lock its frequency at zero-output point P, by feeding the control signal back to the injection current. The frequency discrimination gain, G_d , is given by

$$G_d = \Delta V / \Delta_\nu \ \ (\mathrm{V/GHz}) \qquad (1)$$

where ΔV and $\Delta\nu$ represent changes surrounding stabilization point P (Fig. 1(d)). The higher G_d improves the reference frequency' S/N ratio.

2.2. Linear Absorption and Doppler-Free Saturated Absorption Spectrum

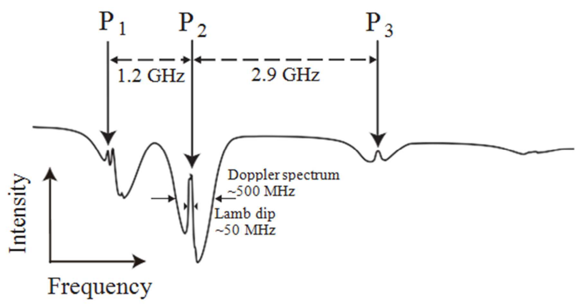

Fig. 2. Doppler-free signal output of the Rb-D2 absorption line.

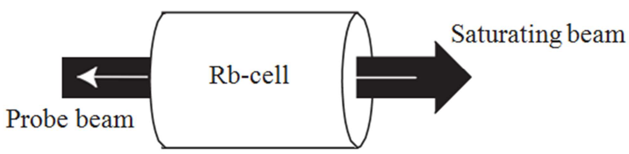

Fig. 3. Fundamental setup for the saturated absorption spectroscopy.

Using the Rb-D2 absorption line, we succeeded in stabilizing a diode laser operating at 780 nm. Rb, an alkaline metal, exists as a single atomic molecule, so its ab- sorption line' spectrum is simple in structure. Twelve absorption spectra of hyperfine structures are visible along the Rb-D2 line. Some are seen overlapping one another as the result of Doppler broadening. So in the end, four broad spectra remain (Fig. 2). When we need precise reference-frequencies using atomic absorption line, we apply a signal that is free of Doppler broadening; one that originates from the Doppler effect of moving atoms, and extends the absorption linewidth, thereby degrading the error signal used to observe the deviation of the laser frequency from its reference. Figure 3 depicts the fundamental setup used in saturated absorption spectroscopy (SAS), wherein a saturating beam, operating in conjunction with a probe beam used to observe the signal, is introduced to the Rb-cell from a direction opposite that of the probe beam. The two beams overlap within an Rb-cell. When atoms in a cell are excited by a saturating light and observed using a probe beam, we note a sharp dip, often referred to as a Lamb dip, and/or a cross-over resonance in the signal obtained, as shown in Fig. 2. Along the Rb-D2 absorption line, -shown as ravines having Doppler widths of 500 MHz, -these dips occur in close proximity to one another. Because the Lamb dip's resonance's spectrum-widths are roughly 50 MHz, we apply these signals to obtain improvements in G_d, which, in turn, enhances frequency stability.

3. Experimental Setup

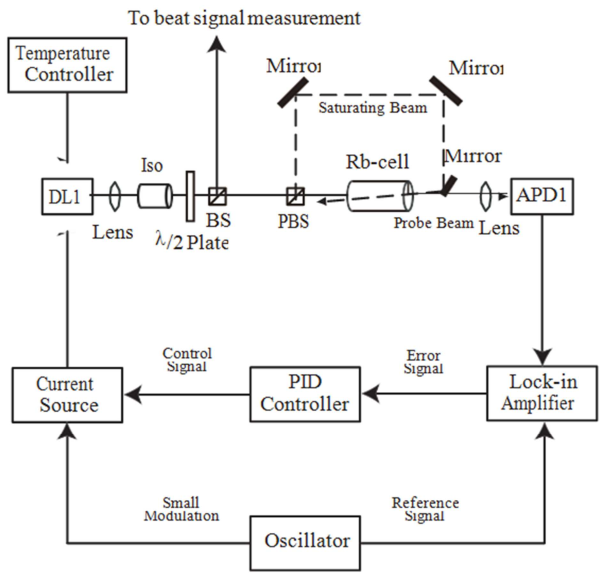

Fig. 4. SAS-based frequency stabilization system (Experimental setup 1).

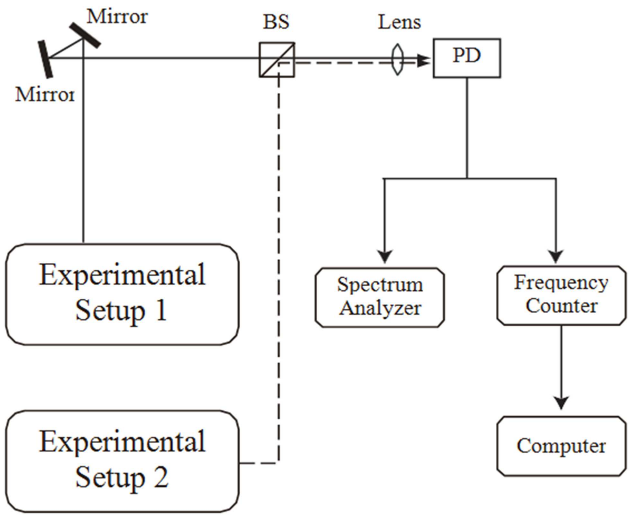

Fig. 5. Setup for beat signal measurement.

As illustrated in Fig. 4, our system employs a diode laser (Sanyo, DL-7140-201P), operating at 780 nm. Also, the temperature of diode laser is controlled within 0.002 K variations. The laser injection current is modulated by a small sinusoidal signal, while the beam, collimated by a specially-coated non-reflective lens, passes through an optical isolator (Iso) and a $\lambda/2$ plate, to be divided by a beam splitter (BS). It is further divided into saturating- and probe- beams, by a polarizing beam splitter (PBS). The saturating beam and the probe beam are introduced to the Rb-cell, such that they pass along almost the same optical axis from opposite directions. The probe beam is then detected by an avalanche photo diode 1 (APD1). The signal obtained at APD1 and the reference signals are detected simultaneously by a lock-in amplifier. The error-voltage signals acquired through the proportional (P), integral (I), and differential (D) circuits are fed back to the laser injection current as a control signal. Because the extremely high optical frequency prevents direct observation, we use the beat signal between frequency-stabilized diode lasers. Figure 5 illustrates the system used to obtain beat signals. By superimposing two laser beams, which have slightly different frequencies (ν_1 and ν_2) and detecting them by a photo detector (THORLABS, PDA8GSPD), we obtain the beat signal ($\nu_B = \nu_1 - \nu_2$). During the course of our study, direct optical- frequency measurements allowed us to use this beat signal to determine the relative frequencies of two independently- stabilized diode lasers.

4. Experimental Results and Discussion

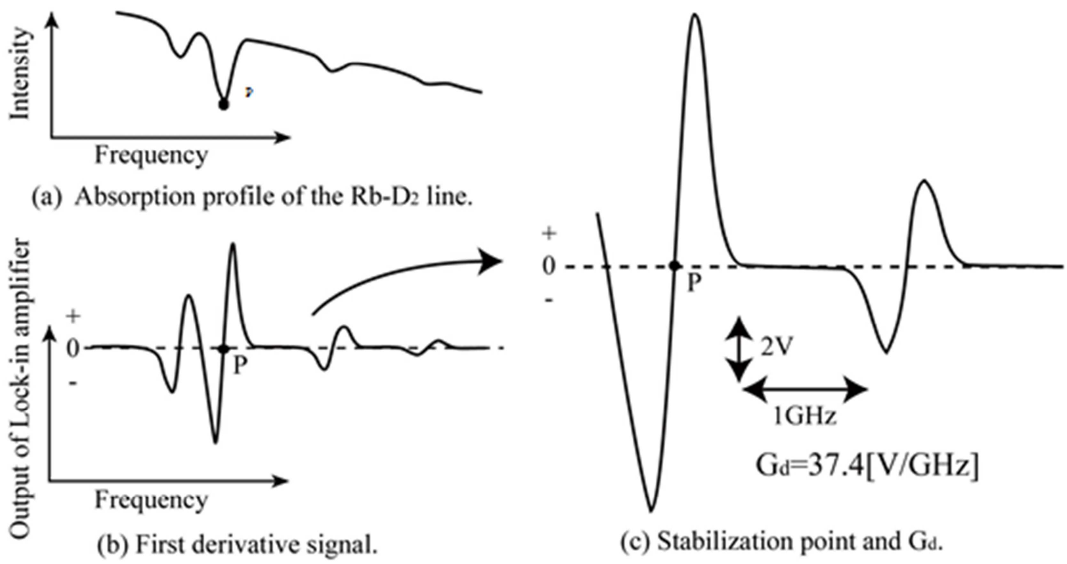

Fig. 6. Signal output of the Rb-D2 absorption line.

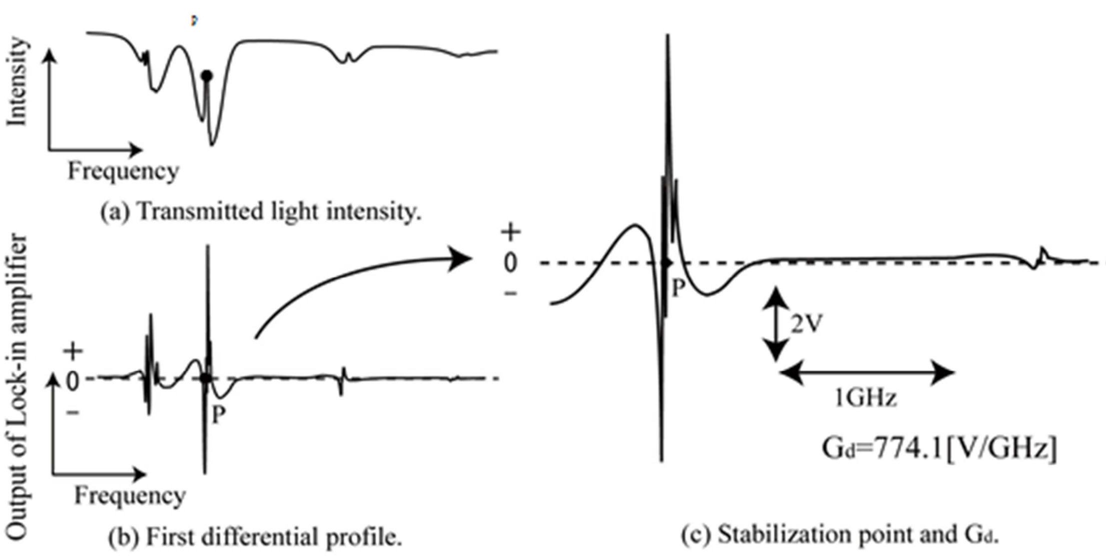

Fig. 7. Signal output of saturated absorption spectroscopy.

Figure 6 (a) and (b) represent the observed Rb-D2 absorption line and the output profiles of its first differential signals. Point P represents the stabilization point, where G_d=37.4 V/GHz (Fig. 6(c)). Because the Doppler-broadened spectrum decreases the value of G_d, we eliminated its influence entirely through the use of SAS. In so doing, we were able to ensure high, long-term frequency stability. In Fig. 7(c), G_d measured 774.1 V/GHz (roughly 20 times greater than the 37.4 V/GHz obtained in earlier attempts). In our experiments, we used beat signals to measure frequency fluctuations during free runs-, and the degree of stability obtained around the 1.2 GHz region. When detecting the beat signal in Fig. 5, one of the two laser frequencies is stabilized to P_1 or P_3 shown in Fig. 2, and the other is stabilized to P_2. Additionally, we measured the fluctuation of beat frequency around the 2.9 GHz region by combining stabilization points P_2 and P3. The frequency fluctuations of beat signals in 1.2 GHz and 2.9 GHz are shown in Fig. 8. In this figure, square root of the Allan variance × the beat frequency was used as the frequency fluctuation. The root Allan variance de pends on carrier frequency (i.e. laser frequency: 365 THz, microwave frequency: 1.2 GHz or 2.9 GHz). In order to avoid the confusion, we used the frequency fluctuation in Hz. The closed circles indicate frequency fluctuations in free-running lasers, while open circles and open triangles indicate frequency fluctuations of 1.2-GHz- and 2.9-GHz beat signals, respectively. It can be seen that the fluctuations of 1.2-GHz- and 2.9-GHz beat frequency are 40 kHz at averaging time of 30 s and 400 kHz at the averaging time of 0.3 s in the best. The frequency fluctuation of the beat signal becomes lower in any averaging time. Especially, open circles demonstrate greater stability than their closed counterparts, and we observed an improvement of almost two orders of magnitude at averaging time domain greater than 0.1 s. The frequency fluctuation was limited by signal to noise ratio in Rubidium absorption signals.

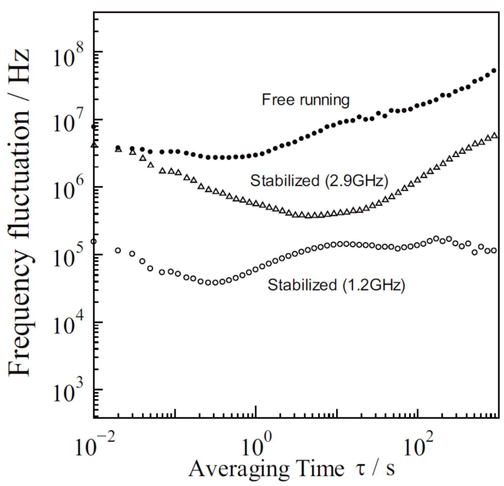

Fig. 8. Frequency fluctuation (1.2 GHz and 2.9 GHz).

5. Conclusion

Now that we have successfully observed the stable beat signals at 1.2 and 2.9 GHz, and we stabilized the beat frequencies with frequency fluctuation of 40 kHz and 400 kHz in the best stability. As future step, we will combine the systems which have cavity stabilized lasers and rubidium stabilized lasers. And we will generate a stable and tunable beat note in THz region.

Acknowledgments

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