THz wave generation using frequency stabilized laser diodes

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ABSTRACT

A laser diode (LD) has been used in many areas, such as optical communication systems. However, its oscillation frequency changes, with variations in ambient temperature and injection current, so its frequency stabilization is of vital importance. In these situations, Rb saturated absorption spectroscopy is the method of choice. We use the beat signal, both for the purpose of evaluating frequency stability between two independently stabilized LDs, and for generating THz waves. This work shows a basic experiment using our beat signal observation, by high-speed photodetector. In addition, we have also used a frequency-stabilized etalon, to improve frequency selectivity.

Keywords: laser diode, oscillation frequency, stabilization, Rb absorption line, generation of THz wave

1. INTRODUCTION

A laser diode (LD) is compact, lightweight, inexpensive and durable, so it has been used in many areas, such as optical communications systems. However, its oscillation frequency varies by the changes of its ambient temperature and injection current, so its frequency stabilization is important in the applications, which require oscillation frequency stability. We have used the Rb D_2 absorption lines (780.02 nm), which is basically immune to external variables, as the external frequency reference and the direct modulation method, where we apply weak injection-current modulation to a laser diode. However, because of the Doppler effect, absorption linewidth broadens, -negatively impacting control-signal accuracy. Therefore, we are using the saturated absorption spectroscopy, which can eliminate the effects of Doppler broadening in the absorption spectrum. In this system, the frequency stability evaluated by the square root of the Allan variance σ (2, τ) has reached 10^{-13}.

One of many fields in which frequency-stabilized LDs have seen wider application, is in the area of laser interferometer. When we observe the relative velocity changes of two artificial satellites flying in identical low-altitude trajectories, we can measure the fluctuations of the mass distribution of groundwater and rising sea level caused by global warming through changes in the earth's gravitational field. The square root of the Allan variance σ (2, τ) is used as a measure of the LD's frequency stability and the value less than 10^{-13} is required from the scientific requirement.

The beat signal between two LDs denotes the difference between the frequencies of two laser beams, which are superimposed and detected on the same photo detector. When we have two frequency stabilized LDs, we can get the frequency stabilized beat signal between these two LDs. Because it is difficult to measure optical frequencies directly, we often measure the beat signal, to evaluate the stability of the laser oscillation frequency. This method is applicable to generation of THz waves, if we have access to an extremely fast photo detector. Because THz wave technology is expected to replace X-rays, in such areas as food- and medical safety inspections, we believe the beat signal between the frequency stabilized LDs is a very good candidate of the coherent and stable THz generator.

Optical comb light sources are believed to be of sufficient strength and stability, for use as THz wave sources, but, their considerable cost, and physical bulk do present their own set of problem. Our system, which uses saturated absorption spectroscopy, achieves comparable results, at lower cost.

2. PRINCIPLES OF FREQUENCY STABILIZATION

2.1 Control signal extraction

As the flowchart in Fig. 1(a) shows, we have achieved optimum frequency-stability in a laser diode operating at approximately 780 nm, a frequency that is identical to that of the Rb-D_2 absorption line. For purposes of frequency

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stabilization, the difference between the reference and laser-oscillation frequencies needs to be measured, and fed back to the injection current. The laser beam, which has succeeded in passing through either an etalon or an Rb-cell without being absorbed by Rb atoms, is ultimately identified by an avalanche photo diode (APD) 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's injection current, and simultaneously detecting the transmitted light- and reference-signals, we obtain the output waveform of the first derivative signal illustrated in Fig. 1(c). When the laser's 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 laser diode (LD), 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

$$G_d = \frac{\Delta V}{\Delta \nu} \text{ [V/GHz]} \tag{1}$$

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

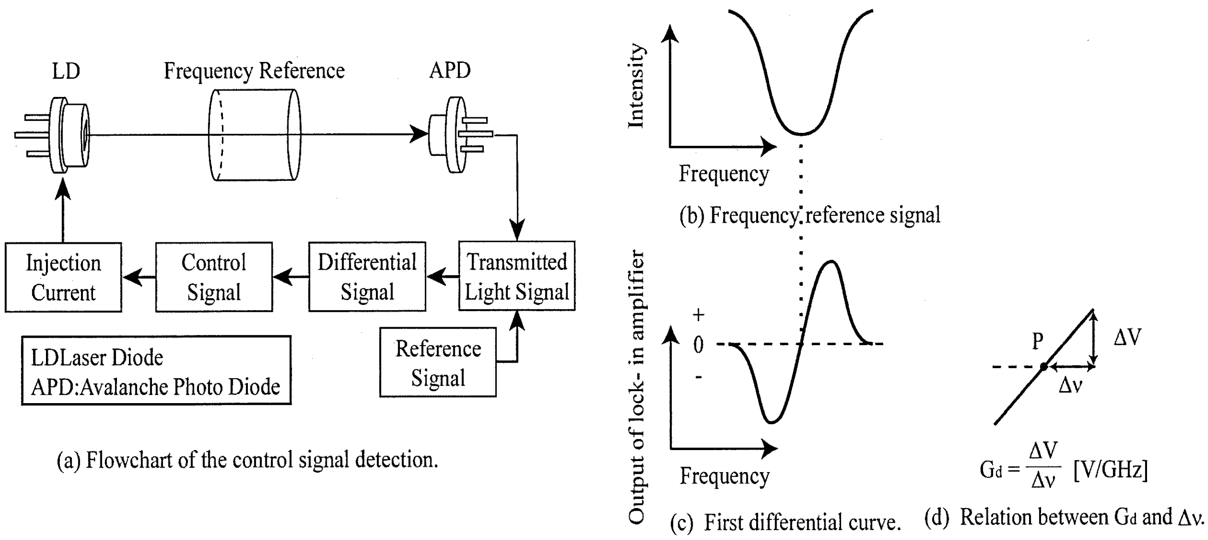

Fig 1 Principle of stabilization

2.2 Frequency references

2.2.1 Atomic absorption lines

The absorption lines of cesium (Cs) and rubidium (Rb) are well within the oscillation frequencies of LDs[2, 3, 6], and maintain their stability over extended periods. Using the Rb-D_2 absorption line, we succeeded in stabilizing a LD at 780 nm. Rb, an alkaline metal, exists as a single atomic molecule, so its absorption line's spectrum is simple in structure. Twelve absorption spectra of hyperfine structures are visible along the Rb-D_2 line. Some are seen overlapping one another, as the result of Doppler broadening. So in the end, four broad spectra remain (Fig. 2(a)).

Figures 2(b) and (c) represent the output profiles of the Rb-D_2 absorption lines' first derivative signals. Point P represents the stabilization point, where G_d=37.4 V/GHz. Because the Doppler-broadened spectrum decreases the value of G_d, we eliminated its influence entirely, through the use of saturated absorption spectroscopy[3, 4, 8, 9].

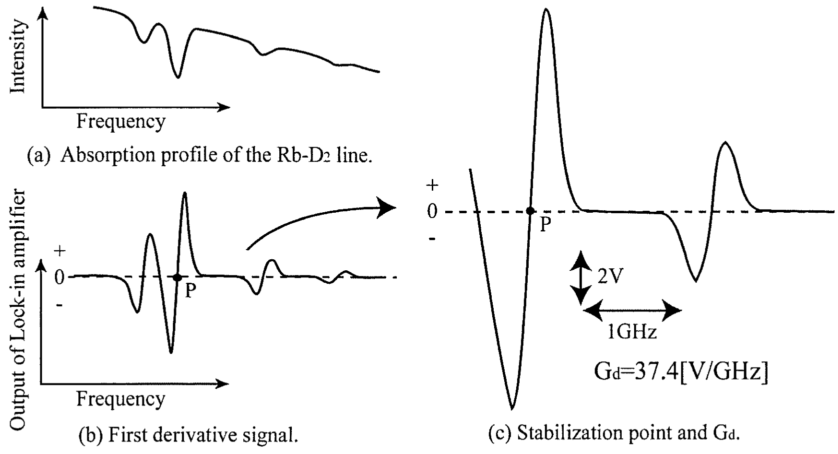

Fig. 2 Signal output of the Rb-D_2 absorption spectroscopy

2.2.2 Saturated absorption spectroscopy (SAS)

When we want to obtain precise reference-frequencies from atomic absorption lines, we must use a signal that is free from Doppler broadening[4]; one which 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 the reference frequency. Figure 3 represents the fundamental setup for this process, 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.

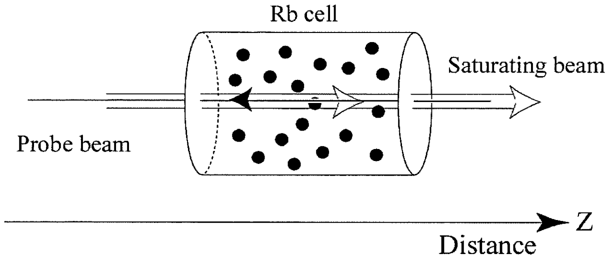

Fig. 3 Fundamental setup for the saturated absorption spectroscopy

These two beams overlap, within the Rb-cell. When atoms in an Rb-cell are excited by the "saturating beam" and observed using the 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. 4(a). Figure 4(b) then represents the output profile of the first derivative signal. Along the Rb-D_2 absorption line, -shown as ravines having Doppler widths of 500 MHz at room temperature, -these dips occur in close proximity to one another. Because the Lamb dip's- and the cross-over resonance's- spectrum widths are roughly 50 MHz, we apply these signals to obtain improvements in G_d, which, in turn, enhances frequency stability. If saturated absorption spectroscopy is used, the waveform shown in Figs. 4(a) and (b) can be obtained. At point P in Fig. 4(c), G_d was 774.1 V/GHz (about 20 times larger than the former value; 37.4 V/GHz). Using this method, we can obtain high, long-term frequency stability.

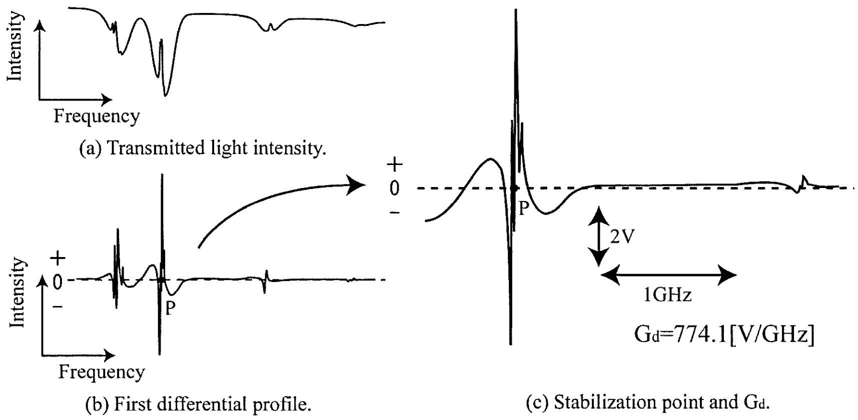

Fig. 4 Signal output of the saturated absorption spectroscopy

3. APPLICATION TO THz WAVE GENERATION USING A BEAT NOTE

Because the optical frequency is too high to observe it directly, we used the beat signal between the frequency stabilized LDs and measured their stability. This beat signal can be applied to THz wave generation, if we can use the extremely high-speed photo detector.

3.1 Applications using the Beat note

Figure 5 illustrates the system used to obtain a beat signal. By superimposing two laser beams, which have slightly different frequencies (f_1 and f_2) and detecting them by a photo detector (PD), we can obtain the beat signal, i.e., the difference frequency (f_B=f_1-f_2). This technique is referred to as optical heterodyning. In our study, because it is difficult to directly measure optical frequency, we used this beat signal for evaluating the relative frequency between two independently stabilized LDs, i.e., the stability of our stabilized LD.

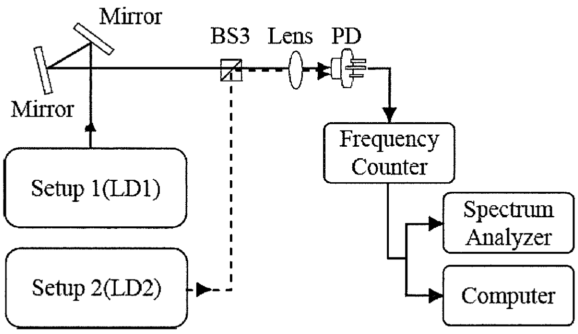

Fig.5 Setup for beat signal measurement

3.2 Generation of THz radiations

Because THz wave generation by optical comb generator is complex and expensive, we are trying to use the beat signal.

3.3 Frequency stability using a beat signal

Figure 6 shows the observed "free running" frequency stability when we set the beat signal at 200 MHz, 700MHz, and 900 MHz. We can see there are no extreme variations in Fig. 6, so we can expect that the stability does not change significantly in the selection of the beat signal frequency.

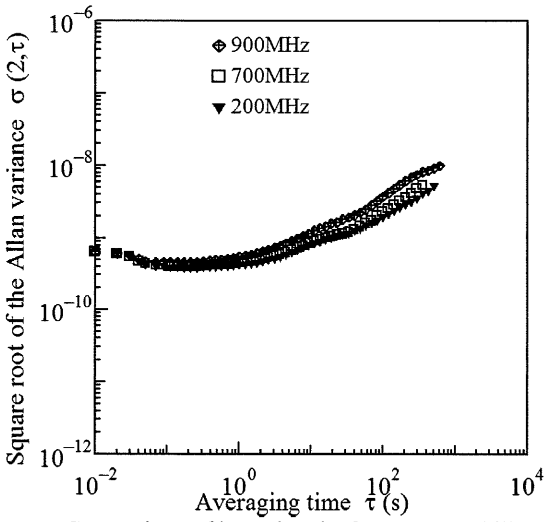

Fig.6 Comparison of beat signals' frequency stability

4. EXPERIMENTS AND RESULTS

4.1 Frequency stabilization in a 1.2-GHz beat note

In this experiment, we used the beat note between two stabilized LDs and the fast photo detector (up to 8 GHz) for generating GHz wave, and then we stabilized its frequency using our stabilization system. This means we can generate the stabilized GHz waves in our experimental setup.

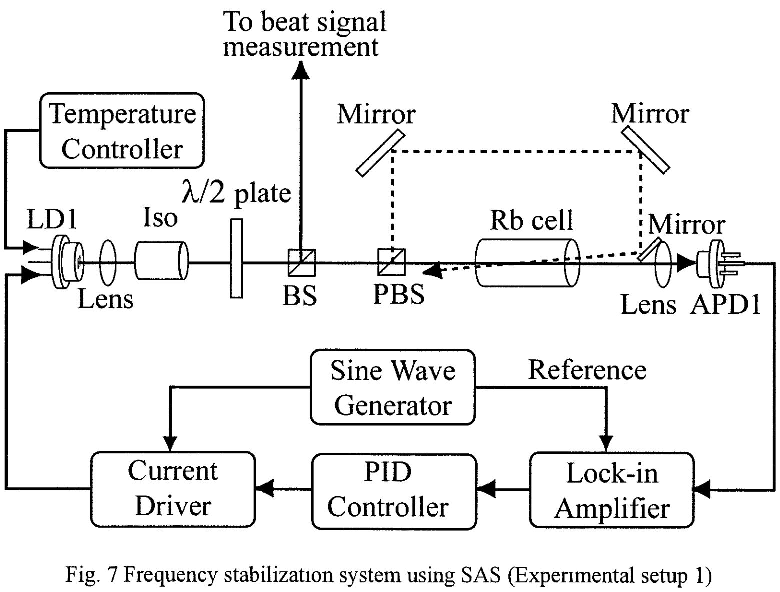

Fig. 7 Frequency stabilization system using SAS (Experimental setup 1)

Figure 7 shows our experimental setup, which is based on the principles of saturated absorption spectroscopy. Specifically, it consists of a laser diode (Sanyo Inc.'s DL-7140-201P), operating at 780 nm at room temperature, ±0.001 K variation. The laser injection current is modulated by a small sinusoidal signal (50 mV, 2 kHz). The laser beam, collimated by a specially coated, non-reflective lens, passes through an optical isolator and λ/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 the same optical axis from opposite directions. The probe beam is then detected by an avalanche photo diode (APD1). The signal obtained at APD 1 is synchronously detected by lock-in amplifiers with the sine wave reference signal. 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.

In our experiments we used the square root of the Allan variance of the beat signals as a measure of frequency fluctuation or stability, during free running and "our stabilization result" around 1.2 GHz region.

Test results regarding the frequency stability of a 1.2-GHz beat signal are shown in Fig. 8. The symbols ● and ○ mean "Free running" and "Stabilized", respectively. In the "Free running" experiment, only LD1 is stabilized and LD2 is in a "Free running" state, where we controlled only its temperature.

"○" shows better stability or less variation compared with the result given, by ●. We observed an improvement of almost two orders of magnitude in the square root of the Allan variance $\sigma(2,\tau)$ at $\tau > 0.1$ sec. We believe that it is relatively easy to increase beat note frequency up to 10 GHz or 100 GHz.

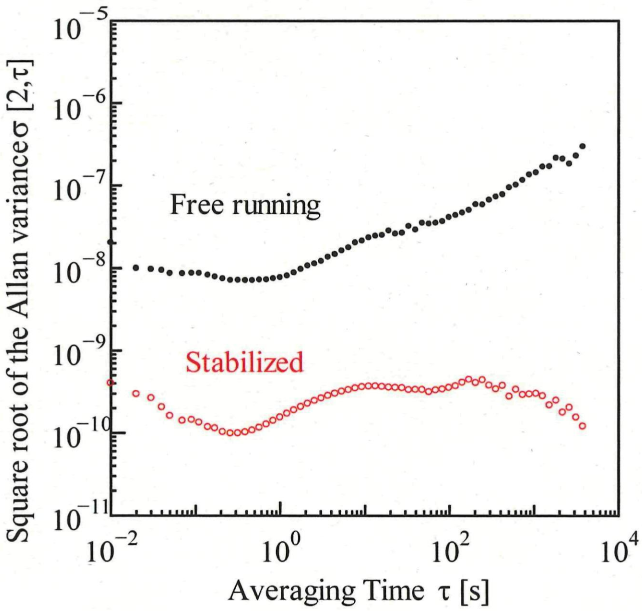

Fig. 8 Frequency stability

4.2 Frequency stabilization using an etalon in a 1.2-GHz beat note

Frequency selection is possible for the frequency stabilization using the Rb absorption lines. However, their frequencies do not shift, so the beat signal is un-tunable in this instance. If tunable, stabilized GHz and/or THz frequency signals are required, we will use a frequency-stabilized etalon. Figure 9 shows the experimental system using frequency-stabilized etalon.

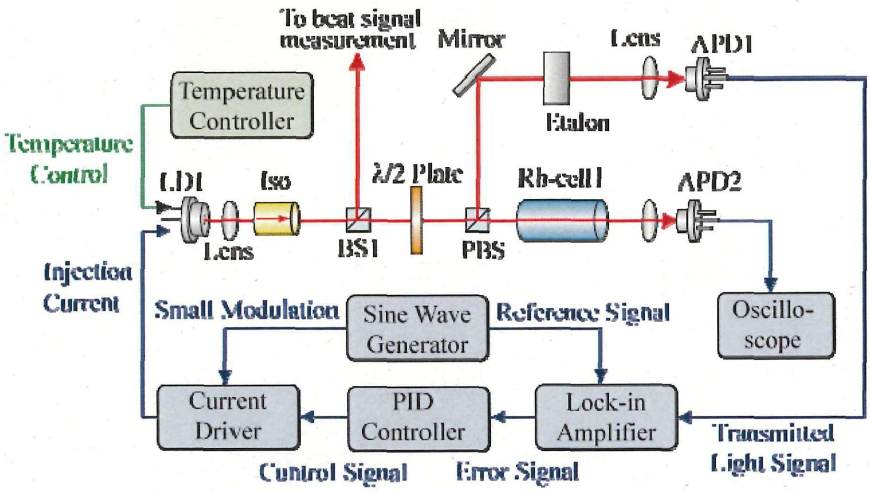

Fig. 9 Experimental system using frequency-stabilized etalon

Figure 10 shows stabilities observed during etalon-controlled- and free running, at higher than 2 GHz beat signal frequency. Temperature variations appear to negatively impact Etalon-stabilized frequency, long-term.

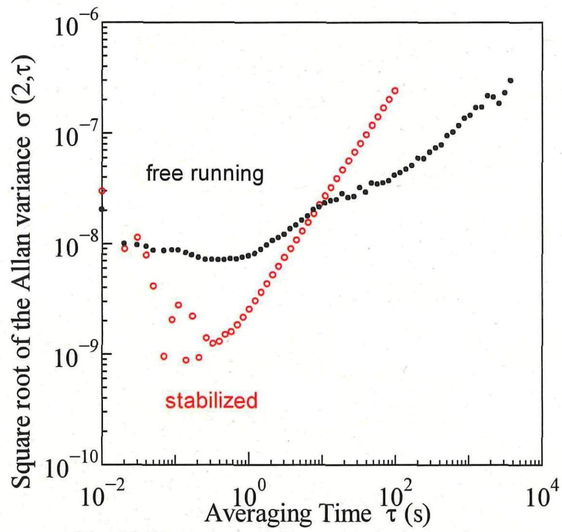

Fig. 10 frequency stabilization using an etalon

5. CONCLUSION

Now that we have successfully observed beat-notes higher than 1 GHz, we believe that we can stabilize the beat signals at even higher frequencies, so we can evaluate the stability of this higher beat signal frequency when we use the wider range frequency counter. Thus, it shows possibility of applying our system to a microwave generator.

We would like to use both D1 (794.76 nm) and D2 (780.02 nm) absorption lines of the Rb atom as frequency references, and observe the beat-note, to generate THz waves.

We stabilized the LD frequency using the etalon as a frequency reference at 2 GHz frequency regions, but the square root of the Allan variance was degraded compared with a free running from 10 sec or longer averaging time. We believe this is because the ambient temperature affected the etalon's reference frequency. There are residual temperature changes in our laboratory, so the etalon's reference frequency itself changed. We will control the ambient and the etalon temperatures in our next experiment and then generate the GHz and THz waves.

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