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Frequency stabilization and measurements of 543 nm HeNe lasers

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Abstract. In this paper we report our investigations on the frequency stabilization and frequency measurements of 543 nm HeNe laser. It contains following four different works. (1) Using a metal laser tube we have built an iodine-stabilized 543 nm HeNe laser by the Frequency-Modulation (FM) spectroscopy. The signal-to-noise ratio of the hyperfine spectrum reached 2×10^{-12} at 1 s sampling time. (2) We have built a compact iodine-stabilized 543 nm HeNe laser system using the third-harmonic locking technique. Stability better than 1×10^{-12} for sampling time > 1 s is obtained. We also suggest the b_{10} line for the future recommendation. (3) We constructed the Lamb-dip stabilized He-^{20}Ne and He-^{22}Ne lasers and measured their frequency stability, reproducibility, and absolute frequencies. The results suggest that the Lamb-dip stabilized lasers are appropriate for secondary wavelength standards. We have also deduced the isotope shift of Ne atom at 543 nm. (4) We have developed two two-mode stabilized 543 nm HeNe lasers using the bang-bang control method. The Allan variance is 1×10^{-11} at 1 s sampling time.

Key words: frequency stabilization, frequency measurement, 543 nm HeNe laser, iodine stabilization, lamb-dip stabilization, two-mode stabilization

1. Introduction

Setting up length standard has fundamental importance in precision experiments and length metrology. In 1983, the meter was redefined as 1/299792458 of the distance of light traveling in the vacuum within 1 s (CIPM 1984). Therefore, the meter can be realized by the frequency-stabilized laser locked to a suitable atomic/molecular transition center. In 1992, the International Committee on Weights and Measures has adopted the iodine-stabilized 543 nm HeNe laser as a recommended wavelength standard (BIPM 1992).

The investigations of iodine-stabilized 543 nm HeNe laser system began right after the observation of the saturation spectrum of iodine hyperfine transitions in an external cell using an internal-mirror 543 nm HeNe laser in 1986 (Chartier *et al.* 1986). In 1989, Brand and Helmcke reported an iodine-stabilized system using the Frequency-Modulation (FM) spectroscopy (Brand and Helmcke 1989). In the mean time, Chartier *et al.* (1989) also successfully established two iodine-stabilized 543 nm HeNe laser systems using the third-harmonic locking technique (Chartier *et al.* 1989). They used metal laser tubes in their experiments. In 1990, Simonsen and Poulsen established an iodine-stabilized 543 nm HeNe laser system using the double differential method (Simonsen and Poulsen 1990). In 1993, Brand improved their iodine-stabilized HeNe laser system to 1×10^{-11} at 1 s sampling time. In 1994, we reported our iodine-stabilized lasers using the third-harmonic locking technique (Lin *et al.* 1994). The stability was $\sim 1 \times 10^{-12}$ at 1 s sampling time. Except Chartier *et al.* (1989), all the other researchers use the glass laser tubes in their systems.

In spite of its good stability, the most popular wavelength standard is not the iodine-stabilized 543 nm HeNe laser but iodine-stabilized 633 nm red HeNe laser. There are reasons for the unpopularity of the iodine-stabilized 543 nm laser system in most length standard laboratories: (1) The configurations of the above systems are quite complicated and only one international comparison has been performed up to now (Simonsen *et al.* 1995). (2) Corresponding secondary wavelength standards have not been fully investigated.

However, comparing with the iodine-stabilized 633 nm HeNe laser which has one iodine cell inside laser cavity, the iodine-stabilized 543 nm HeNe laser has the following advantages: (1) It has fewer problems of power broadening and gas lensing because the iodine cell is external to the laser cavity. Therefore, it should have better frequency reproducibility than the iodine-stabilized 633 nm HeNe laser theoretically (Hanes *et al.* 1973). (2) The internal-mirror 543 nm HeNe lasers is available commercially, the iodine-stabilized 543 nm laser is easier to maintain than the iodine-stabilized 633 nm laser. (3) Cavity modulation is not absolutely necessary for obtaining the locking error signal. Therefore, if one can construct simple and compact iodine-stabilized 543 nm HeNe laser systems, it can/will play important roles in general length standard laboratories.

In 1998, we demonstrated that iodine-stabilized 543 nm HeNe laser could be made compact (Cheng *et al.* 1998). In this paper, we report our investigations on the frequency stabilization and absolute frequency measurements of 543 nm HeNe laser. Firstly, we demonstrate that the iodine-stabilized 543 nm HeNe laser can be made compact no matter what technique (third-harmonic locking technique or FM spectroscopy) is used, and no matter what kind of laser tube (glass or metal) is used. Especially our iodine-stabilized laser using the third-harmonic locking technique shows high resolution and good stability. Secondly, we investigate the properties of the corresponding secondary wavelength standards: Lamb-dip stabilized He-^{20}Ne, He-^{22}Ne lasers, and two-mode stabilized lasers. For the Lamb-dip stabilized lasers, we measure their frequency stability, reproducibility, and absolute frequencies and we also deduce the isotope shift of Ne $3s_2 \rightarrow 2p_{10}$ transition. For two-mode stabilized lasers, we use the concept of bang-bang control to perform laser stabilization, and measure its Allan variance.

2. Iodine-stabilization using Frequency-Modulation (FM) spectroscopy

The Frequency-Modulation (FM) spectroscopy was developed in 1980 (Bjorklund 1980) and it has been widely used in high precision spectroscopy since then. Its advantages include: (1) The laser cavity is not modulated. (2) The modulation frequency can be high enough such that quantum-limited detection is possible.

The principle of FM spectroscopy is briefly described below. When a laser radiation is modulated by an electro-optic phase modulator (EOM), it produces two sidebands of equal amplitude. The high frequency sideband is in phase with the carrier, while the low frequency sideband is 180° out of phase with the carrier. After the modulated radiation passes through an absorption cell, the balance of the two sidebands in general will be destroyed except for the case that the carrier frequency is at the center of absorption transition. When the intensity of passed laser radiation is demodulated with the same frequency applied to the EOM, one will obtain a signal proportional to the unbalance between the sidebands. Therefore, the laser frequency can be stabilized to the corresponding atomic/molecular transition center using such an unbalanced signal. The detail principle of the FM spectroscopy could be found in Bjorklund *et al.* (1983).

The setup of our FM iodine-stabilized 543 nm HeNe laser system is similar to the arrangement in Brand (1993). Our schematic is shown in Fig. 1. A metal laser tube (PMS[1] model. LTGR0050) instead of glass laser tube is used. We control the laser cavity by wrapping a thin film heating tape on the laser tube. An acousto-optic modulator AOM (80 MHz carrier frequency) is placed in the pump beam with 40 kHz chopping frequency to eliminate the residual Doppler background. The AOM also prevents the optical feedback effect. The first downshift frequency beam is used as the pump beam; the probe beam is phase modulated by an EOM modulated at 5 MHz. We use an 120 cm long and a 6 cm long iodine cells in our experiment. The temperature of the cold finger is kept at −8°C for the long cell and 14°C for the short cell.

The obtained signal-to-noise ratio (S/N) vs. the iodine vapor pressure is shown in Fig. 2. The S/N increases rapidly with the vapor pressure and drops slowly after it reaches the optimal value. The cold finger temperature at the optimal S/N is −8 and 14°C for the 120 and 6-cm cell respectively. The obtained spectrum using the 120-cm long iodine cell can be found in Fig. 3. The S/N is 2×10^{-12} at 1 s sampling time, which is better than Brand (1993). For the 6-cm iodine-cell, few $\times 10^{-11}$ S/N at 1 s sampling time can be achieved at the optimal vapor pressure. Using only the thermal loop we are able to lock the laser frequency to the a_9 line and the stability is better than 1×10^{-10} judging from the fluctuation of the error signal.

[1] The PMS Electro-Optics, Inc. has changed its name to Research Electro-Optics, Inc.

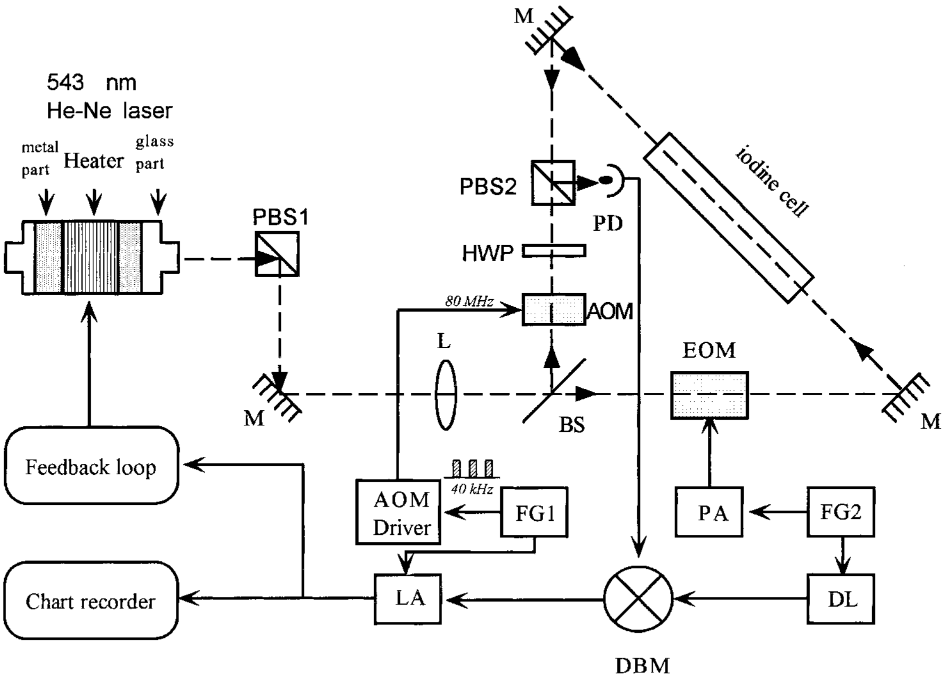


Fig. 1. Schematic diagram of our FM-stabilized laser system. PBS: polarizing beam splitter; M: mirror; AOM: acousto-optic modulator; EOM: electro-optic modulator; HWP: half-wave plate; L: lens; BS: beam splitter; PD: photo-diode; FG: function generator; PA: power amplifier; DL: delay line; LA: lock-in amplifier; DBM: double-balance mixer.

To sum up, we demonstrate the FM-spectroscopy of iodine using a metal laser tube, and we show that it could have good S/N both for both long (120 cm) and short (6 cm) iodine cells. It is possible to lock the laser frequency to a good stability using only the thermal loop. Notice that there are some weak lines in Fig. 3, part of them are identified as the crossover lines of R(12) 26-0 line in Cheng *et al.* (1998).

3. Compact iodine-stabilized 543 nm HeNe laser

Under limited laser power and at a constant vapor pressure, it is not advantageous to use a long absorption cell in saturation spectroscopy because the length of absorption cell will reduce the contrast in the saturation signal. In addition, there exists practical difficulty of obtaining good beam overlapping in the long absorption cell. For example, in Lin *et al.* (1994), the authors used an 120 cm iodine cell and about 200 μW single mode power while on the contrary, in Cheng *et al.* (1998), the authors used a 6 cm iodine cell and 70 μW single mode power, and the latter obtained better S/N and resolution under almost the same conditions.

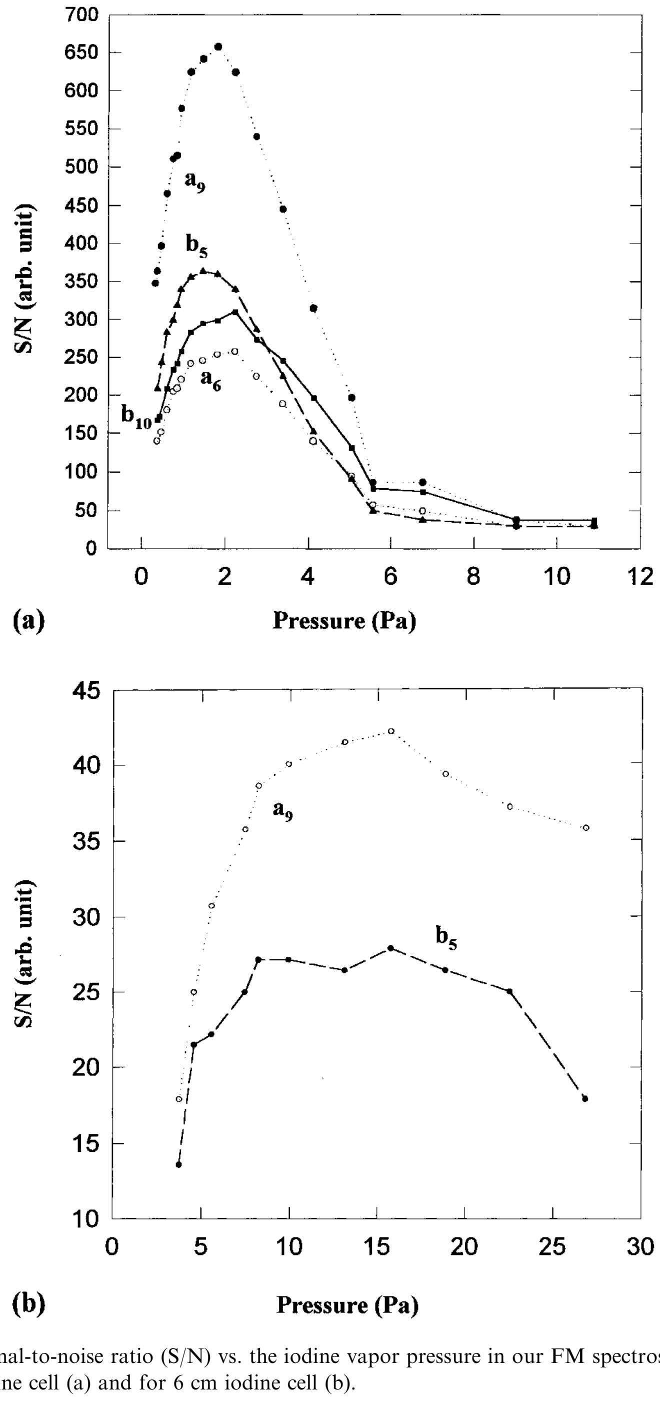


Fig. 2. The signal-to-noise ratio (S/N) vs. the iodine vapor pressure in our FM spectroscopy experiment for 120 cm iodine cell (a) and for 6 cm iodine cell (b).

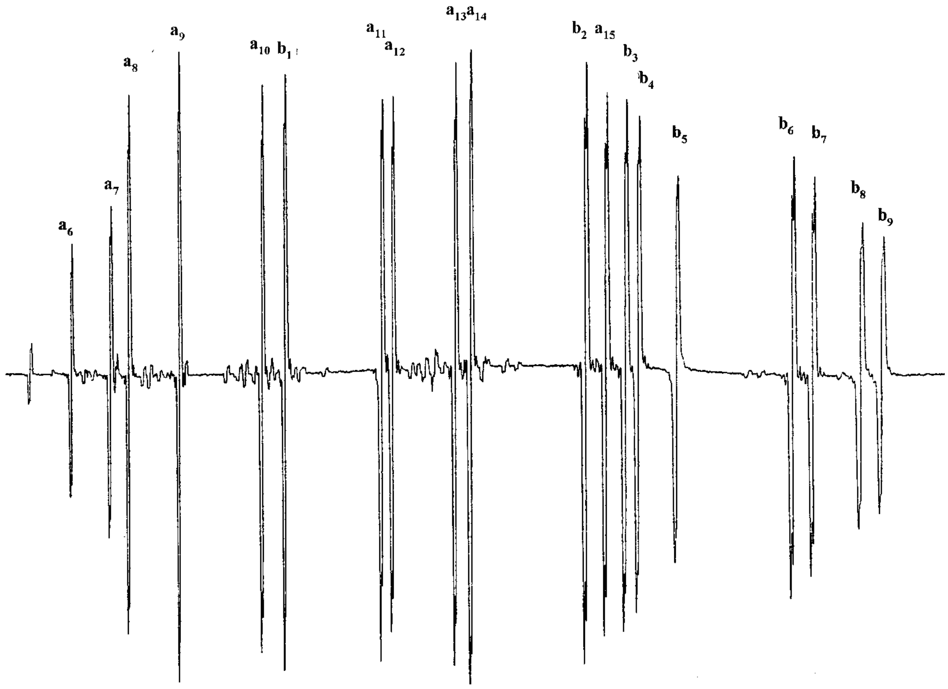
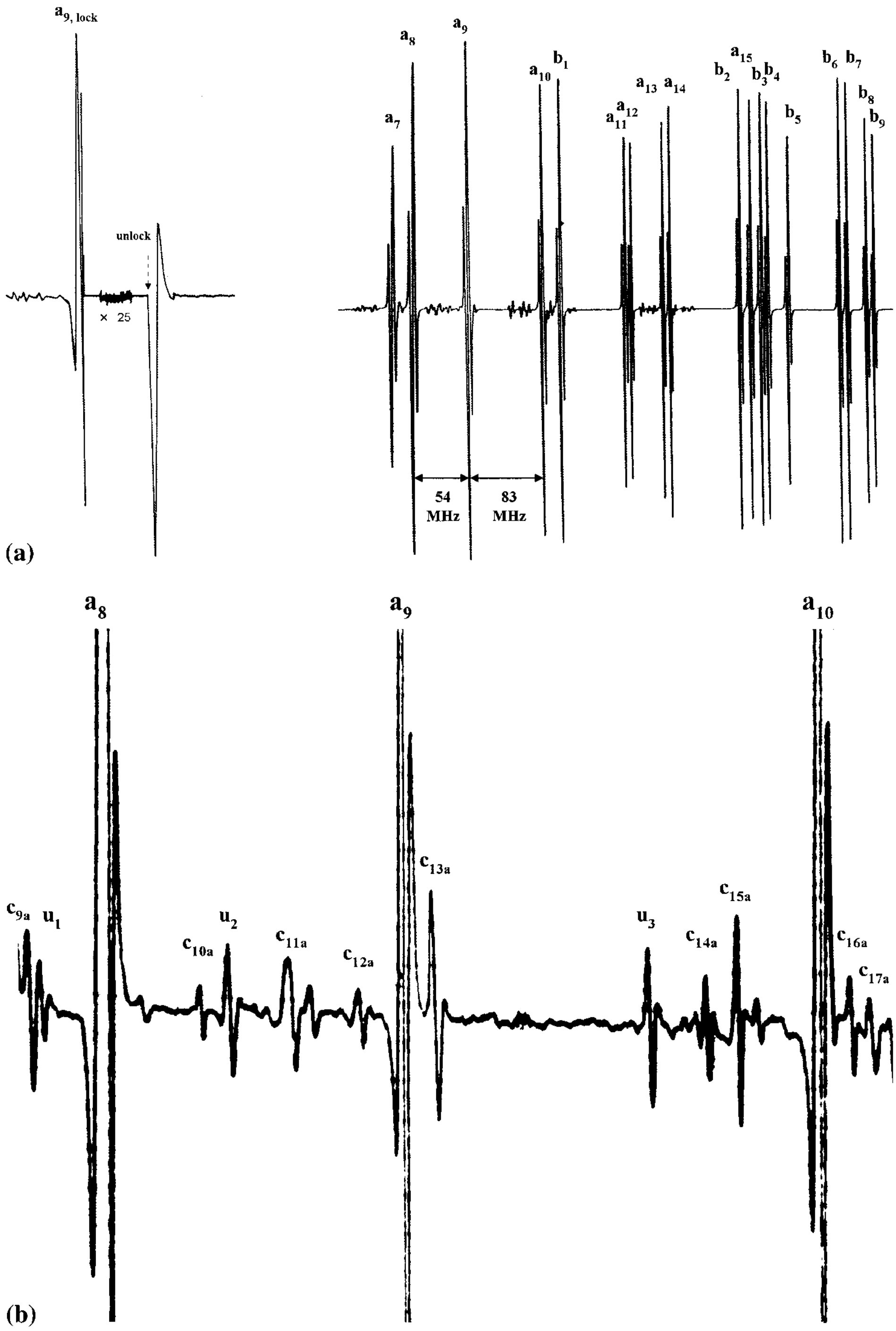


Fig. 3. FM hyperfine spectrum of the iodine at 543 nm. Here, the lock-in time constant is 100 ms and modulation frequency is 5 MHz. Note that there are weak lines among the main hyperfine lines. The frequency scale is not linear.

Our compact iodine-stabilized system has same arrangement as Cheng *et al.* (1998). We will briefly described the system here, and reader should refer to Cheng *et al.* (1998) for the details. The lasers used are model LGR-024-S or LGR-323 from Melles Griot Inc., USA. The main differences from Cheng *et al.* (1998) is that no alignment screws are needed for LGR323 laser and the wood box is not used. The output power is about 250 μW for LGR-323 laser. The cold finger is kept at 0°C which is the temperature recommended by CCDM (BIPM 1992). The hyperfine spectrum is obtained by the third-harmonic technique. The total implemented area can be less than 40×70 cm^2.

Figure 4(a) shows the hyperfine spectrum obtained by the LGR024-S laser. The saturation signal shows good S/N which is better than 8000 at 1-Hz bandwidth for a_9 component of the R(12) 26-0 line. Therefore, the noise-limited-stability of the laser system locked to this resonance would be better than 1×10^{-12} for integration time > 1 s. Using only the thermal loop, this laser system can be stabilized to the a_9 line for more than eight hours in an ordinary laboratory with noisy background and without temperature regulation. The minimum laser power for frequency-stabilizing to the main lines is about 40 μW. From Fig. 4(b), one can easily find that two crossover


a9, lock
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b8
b9
54 MHz
83 MHz
(a)
a8
a9
a10
c9a
u1
u2
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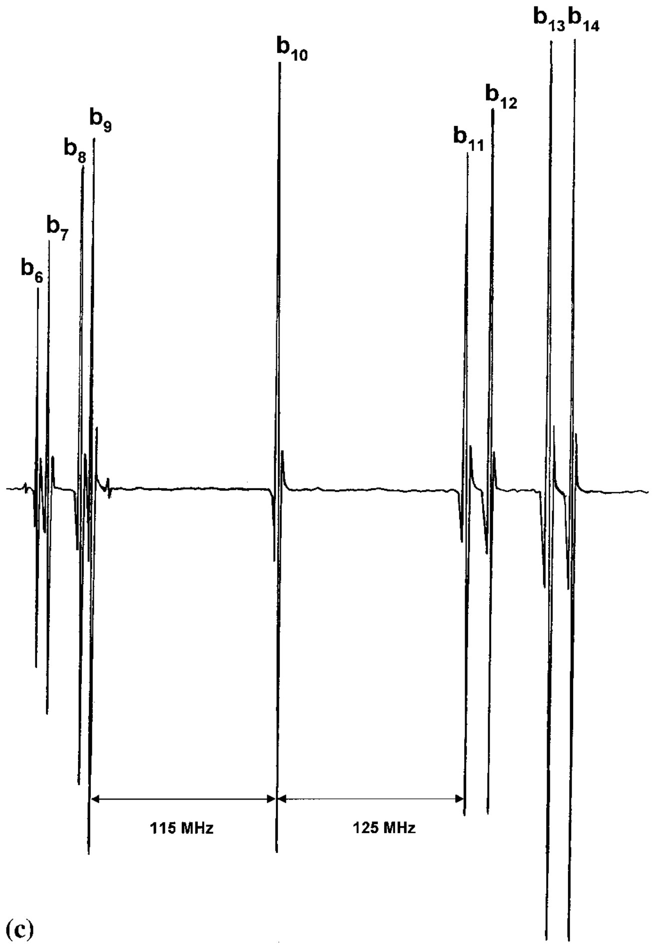
(b)

Fig. 4a,b



(c)

Fig. 4. (a) The hyperfine spectrum obtained by Melles Griot 05LGR024-S laser. The S/N of the a_9 line is ~8000 normalized to 1 Hz bandwidth. (b) The expanded view of the spectral range near a_9 line (the recommended wavelength standard). Two crossover resonances are found near the a_9 line. (c) The hyperfine spectrum obtained by Melles Griot 05LGR323 laser. The b_{10} line is far away from the neighboring main lines and crossover resonances.

resonances, namely, c_{12a} and c_{13a}, are very close to the a_9 component and they can cause a shift of the locked frequency of this recommended wavelength standard. Instead, the hyperfine component b_{10} of the R(106) 28-0 line, as shown in Fig. 4(c) (obtained by the LGR323 laser), is a better reference line since there is no neighboring main lines or crossover resonances. Recently we have studied the properties of the iodine-stabilized 543 nm laser locked to the b_{10} line and the results will be published elsewhere.

Comparing the spectrum obtained using the FM-spectroscopy (Fig. 3 in Section 2), the compact system presented here has the following advantages: (1) compact, (2) less residual amplitude modulation problems (Gehrtz *et al.*

1985), thus, less background problem, and (3) less modulation broadening, thus, higher resolution.

4. Lamb-dip stabilized 543 nm HeNe lasers

As early as 1963, the power saturation dip of a single mode gas laser, referred as 'Lamb-dip' nowdays, was theoretically predicted (Lamb 1963, 1964) and experimentally observed (Mcfarlane 1963). One can stabilize the laser frequency to the corresponding atomic transition center by taking the first derivative signal of the Lamb-dip as the error signal. Since the width of the Lamb-dip is much less than the Doppler width of laser gas, the Lamb-dip stabilized laser has good stability and it has been applied to some precision frequency/length measurements as the absolute frequency reference (Pescht *et al.* 1977; Buchia *et al.* 1981; Musturmota and Fujise 1989; Sasada 1991; Mio and Tsubono 1992).

As shown in Fig. 5, the arrangement of the Lamb-dip laser is quite simple. The lasers used are Melles Griot LGR024 and LGR024-S filled with ^{22}Ne and ^{20}Ne gas respectively. The laser frequency is modulated by a PZT glued on the laser tube. The modulation frequency is 32 kHz and the optical modulation depth is 16 MHz. The first derivative signal, used as the error signal to stabilize laser cavity, is obtained by first harmonic output of a lock-in-amplifier.

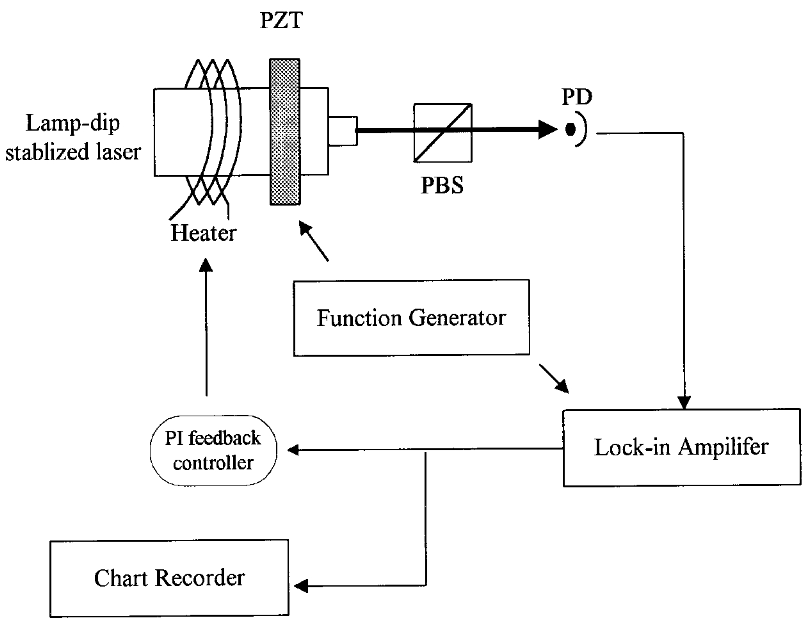


Fig. 5. Schematic diagram of the Limb-dip stabilized laser system.

Two internal-mirror Lamp-dip stabilized 543 nm HeNe lasers are constructed. They have 3.2×10^{-11} frequency stability, and less than 1 MHz reproducibility by comparing an iodine-stabilized 543 nm HeNe laser during fifteen days. By measuring the absolute frequencies of Lamb-dip stabilized lasers of different isotopes, we also deduce the isotope shift between ^{20}Ne and ^{22}Ne in $3s_2 \rightarrow 2p_{10}$ transition (Paschen notation). Our result is 1014 ± 5 MHz which is one order of magnitude better than Gerstenberger, Drobshoff, and Sheng's result (1998) in precision. Combining with the results of Kotlikov and Tokarev (1980), and Cordover, Jaseja, and Javan for Ne $3s_2 \rightarrow 2p_4$ 633 nm laser transition (Cardover *et al.* 1965), we obtain a specific-mass-shift (SMS) of −272 MHz for Ne 3s → 2p transition, and the large standard deviation (19 MHz) in the fitting suggests the J-dependence in SMS (Bauche and Keller 1971).

In conclusions, we have constructed two Lamb-dip stabilized 543 nm HeNe lasers and shown that they have good frequency stability and reproducibility. They can be used for secondary length standards in some applications.

5. Two-mode stabilized 543 nm HeNe laser using bang-bang control

The two-mode balanced method, which balances the power of two laser oscillation modes with mutually orthogonal polarization (Brand *et al.* 1989), is one of the most popular and convenient way to realize the secondary length standard.

Conventionally, feedback control is achieved by the PID (proportional, integral, and differential) loop and the optimal PID parameters depend on the transfer function of the laser system. In our two-mode stabilized 543 nm HeNe lasers, we use the bang-bang control to stabilize the laser frequency. The bang-bang control is the on-off control commonly used in the temperature control of water chiller. The realization of bang-bang control is by the circuit shown in Fig. 6. The difference of the power of the two orthogonal polarized modes, come from PD1 and PD2 in Fig. 6, is amplified by an AMP01 differential amplifier. The output of the AMP01 is sent into a comparator which is connected to a 7805 voltage regulator IC to control the current applied to the heating tape wrapped on the laser tube. When the comparator output is high then the heater is on, otherwise the heater is off.

Using our feedback loop, the two-mode stabilized laser shows an Allan variance of 1×10^{-11} at 1 s sampling time (shown in Fig. 7). The absolute frequency of the two-mode stabilized laser can be measured by beating against the iodine-stabilized HeNe laser.

Comparing with the Lamb-dip stabilized 543 nm HeNe laser, two-mode stabilized laser has the advantages of simpler arrangement and no modulation in the output frequency. However, its disadvantage is poorer frequency

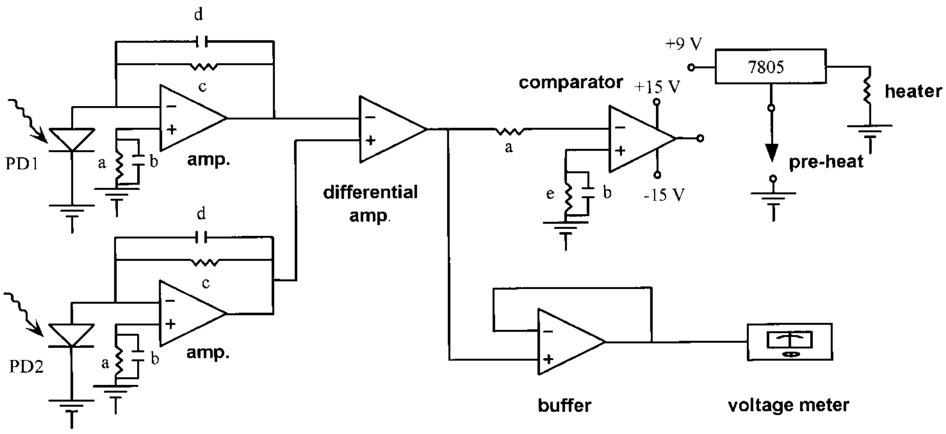


Fig. 6. The circuit of the bang-bang control. Here, a: 100 kΩ; b: 0.1 μF; c: 330 kΩ; d: 5 nF; e: 1 kΩ.

reproducibility. We investigate the reproducibility of both the Lamb-dip stabilized and two-mode stabilized lasers for fifteen days by comparing with an iodine-stabilized 543 nm HeNe laser. Less than 1 MHz frequency drift is found for the Lamb-dip stabilized laser while about 10 MHz drift is found for the two-mode stabilized laser.

6. Future work – frequency measurement of iodine-stabilized 543 nm HeNe laser

Measuring the absolute frequency of the iodine-stabilized 543 nm HeNe laser using the arrangement shown in Fig. 8 is now proceeding in our laboratory.

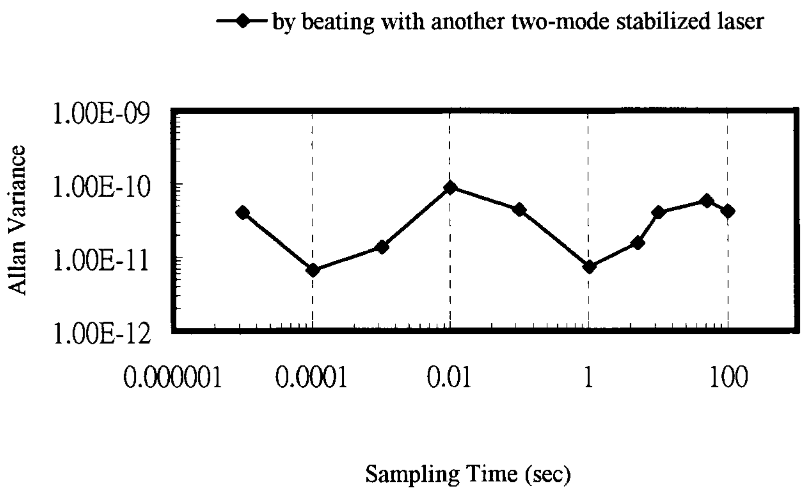


Fig. 7. Allan variance of the two-mode stabilized laser system.

The CO_2 laser is frequency-stabilized to 9P(38) line of CO_2 molecule using the saturated fluorescence. Its output is then frequency doubled by a $ZnGeP_2$ nonlinear crystal. For enhancing the SHG conversion efficiency, a bow-tie cavity is constructed to resonate the second harmonic radiation, and 15 mW second harmonic power is obtained with 10 W fundamental power. The iodine-stabilized 612 nm HeNe laser has a three-mirror cavity for selecting single mode with high power, and more than 5 mW single-mode power is achieved. The sum frequency generation of the iodine-stabilized 612 nm radiation (f_2 in Fig. 8) and the frequency-doubled CO_2 radiation ($2f_1$ in Fig. 8) by a PPLN (periodically-poled $LiNbO_3$) crystal produces a radiation whose frequency is about 24.7 GHz from the frequency of the iodine-stabilized 543 nm HeNe laser (f_3 in Fig. 8). This frequency gap can be measured by beating the sum frequency radiation against the third sideband of the 543 nm HeNe laser modulated by an 8.1 GHz electro-optical phase modulator. In order to reduce the width of the beat note, the 543 nm and 612 nm

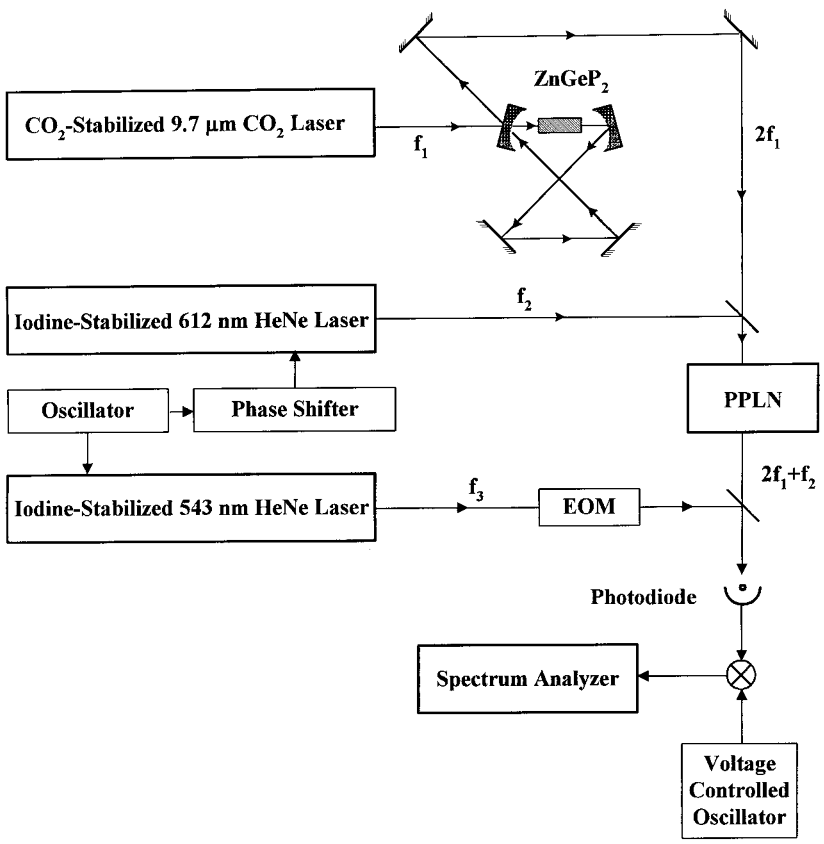


Fig. 8. Schematic diagram of the absolute frequency measurement of 543 nm iodine-stabilized HeNe laser. Here, EOM: electro-optic modulator; PPLN: periodically-poled $LiNbO_3$.

HeNe lasers are modulated at the same modulation frequency and their modulation depths and phases are adjusted properly to cancel the frequency modulation. In addition, a voltage controlled oscillator is used to eliminate the frequency modulation of the CO_2 laser. Up to now we have built the three frequency-stabilized lasers and have succeeded in frequency doubling of the CO_2 laser. At present we are integrating all the laser systems and working on the sum frequency generation.

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