Frequency stabilization of an external cavity diode laser to molecular iodine at 657.483 nm

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The saturation spectrum of the $P(84)$ 5–5 transition of $^{127}I_2$ at 657.483 nm is obtained with the third-harmonic demodulation method using an external cavity diode laser. The laser frequency is modulated by modulating the diode current instead of modulating the cavity length with a piezoelectric transducer (PZT). Current modulation allows a modulation frequency that is higher than PZT modulation. The signal-to-noise ratio of 1000 is better than previous results presented in the literature. The laser is frequency stabilized to the hyperfine component *o* of the $P(84)$ 5–5 transition with a frequency stability of better than 10 kHz (2.2×10^{-11} relative stability). © 2006 Optical Society of America

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1. Introduction

Molecular iodine has a broad spectrum of absorption lines from the near infrared to the dissociation limit at 499.5 nm. Its hyperfine structure (HFS) components have been studied extensively with high resolution and high precision. Such HFS components provide a dense spectrum of reference frequencies for frequency stabilization of lasers. Some are recommended as optical frequency–wavelength standards by the Consultative Committee for Length (CCL).[1]

The dominant optical frequency standard has been a He–Ne laser stabilized to iodine at 633 nm. Most member states of the Convention du Mètre have adopted such lasers as the national realization of the meter. A frequency uncertainty of ±10 kHz is regularly achieved.[1] However, the output power of a He–Ne laser is low, and He–Ne lasers are large in size and mechanically vulnerable. Thus there is growing interest in using diode lasers for frequency stabilization. For diode lasers, their smaller size, larger tuning range, higher power, and compactness make them an attractive source for stabilization.

Frequency stabilization of the external cavity diode laser (ECDL) to the iodine HFS components using an extra-cavity iodine cell has been extensively studied and reported at 633 nm,[2–5] 637 nm,[6,7] and 657 nm.[8] A portable laser frequency standard at 633 nm has been constructed by frequency stabilizing a miniaturized ECDL.[5] Its frequency stability matches that of iodine-stabilized He–Ne lasers at 633 nm. The best stability, 1×10^{-13}, is reached at an integration time of 4000 s. The systems in Refs. 2–8 use the traditional third-harmonic locking technique. The frequency modulation is achieved by modulating the cavity length of the ECDL using a piezoelectric transducer (PZT). This modulation scheme limits the modulation frequency to <10 kHz. The frequency of ECDL can also be modulated by modulating current through the diode. The current modulation allows a modulation frequency that is higher than PZT modulation for an ECDL. To reduce the noise, we chose to modulate the laser frequency by modulating the diode current instead of the cavity length by the PZT.

The reasons we chose a $P(84)$ 5–5 transition of $^{127}I_2$ at 657.483 nm for our study are as follows. First, the $^1S_0$–$^3P_1$ intercombination line of Ca at 657.459 nm has a linewidth that is much narrower than the HFS components of iodine. It is a useful reference for a precise optical frequency standard. Recently we have developed a novel Ca absorption cell and successfully observed its saturation absorption spectrum with a linewidth below 300 kHz.[9] To further investigate the high-resolution spectroscopy of Ca, we wanted to develop a stable diode laser system at 657 nm as a stable light source. Second, the diode laser at 657 nm has the characteristics of lower cost and a higher power than a diode laser at 633 nm. It is an attractive alternative for red diode laser systems locked to

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iodine. Therefore we decided to investigate the saturation spectrum of the hyperfine components of the $P(84)$ 5–5 transition of $^{127}I_2$ at 657.483 nm (~17 GHz away from the Ca transition) for frequency stabilization of our ECDL laser.

Previous works on this iodine transition are briefly reviewed here. In 1997, Kurosu and co-workers reported high-sensitive spectroscopy of the hyperfine components of the $P(84)$ 5–5 transition with a signal-to-noise ratio (SNR) of 500 at a 1 s time constant by means of a power-stabilized light from a diode laser spectrometer.[10] The power-stabilized laser system is a master–slave laser system whose intensity noise was reduced by feedback stabilization. Although they obtained good SNR, they did not stabilize the laser frequency to the hyperfine component. Later, Masuda and co-workers reported the first frequency stabilization of a diode laser to the hyperfine component *f* of the $P(84)$ 5–5 transition.[8] Their experimental setup is complex in that the iodine cell is placed inside an external resonant cavity to increase the signal. However, the SNR is low (~30 at a 1 s time constant) and the frequency stability is estimated to be 300 kHz.

In this paper we have obtained the third-harmonic demodulated saturation absorption signal of the hyperfine components of the $P(84)$ 5–5 transition with a SNR of 1000 at a 1 s time constant without using an external resonant cavity to increase the signal or without using power stabilization to reduce the intensity noise. Simply by using a longer iodine cell to increase the signal and higher modulation frequency by modulating the laser current to reduce the noise we can easily achieve this high SNR. We have locked the laser frequency to the hyperfine component *o* with a frequency stability of better than 10 kHz (2.2×10^{-11} relative stability). We have also determined the linewidth of the hyperfine components of the $P(84)$ 5–5 transition using the dependence of the peak amplitude of the third-derivative signal on the modulation width. The measured full width at half-maximum (FWHM) of the hyperfine component *o* is 7.5 MHz.

2. Experimental Setup

Our diode laser system is shown in Fig. 1. The ECDL is a commercial system from Environmental Optical Sensors, Incorporated. Its operation wavelength is at 657 nm. The ECDL is of the Littman–Metcalf design[11] and is composed of a laser diode, a diffraction grating, and a tuning mirror. The diode laser output is collimated and is incident on the grating at a grazing angle. Its first-order beam is diffracted toward the tuning mirror. The retroreflection off the mirror selects which wavelength is diffracted back into the diode laser. The output beam is the zero-order diffraction off the grating. The output power of the ECDL is 5.5 mW. The linewidth of the ECDL at free running is less than 1 MHz. Its frequency can be coarsely tuned by rotating the tuning mirror and finely tuned by applying a voltage to the PZT attached to the grating or changing the injection current of the laser diode. To reduce environmental noises affecting the ECDL stability, we put it into an aluminum box and pasted soundproof material onto the box. The soundproof material is a sound-absorbing foam material containing two lead septums separated by foam. To further reduce the vibration from the table, the aluminum box is placed on a layer of damping rubber.

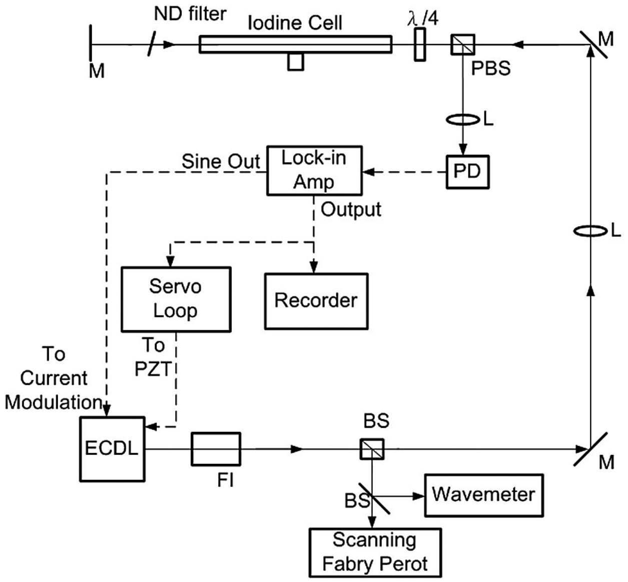

Fig. 1. Experimental setup. ECDL, external cavity diode laser; FI, Faraday isolator; BS, beam splitter; M, mirror; L, lens; PBS, polarizing beam splitter; λ/4, quarter wave plate; ND, filter-neutral density filter; PD, photodetector.

Before investigating the iodine spectrum we first study the amplitude modulation of our ECDL induced by PZT modulation and current modulation. The PZT modulation has a resonance at 1 kHz. The amplitude modulation is 0.42% at 30 MHz modulation width for a modulation frequency of less than 800 Hz. For current modulation the amplitude modulation is 0.5% at the same modulation width. We would like to emphasize that the amplitude modulation under current modulation is comparable to PZT modulation. Therefore we chose to modulate the laser frequency by current modulation.

The laser beam from the ECDL passes through a Faraday isolator (FI) to prevent the optical feedback effect, and then it is divided into two beams by a beam splitter (BS). The weaker beam is used to monitor the laser mode and wavelength in real time by a scanning Fabry–Perot interferometer and a wavemeter, respectively. The scanning Fabry–Perot interferometer has a free spectral range (FSR) of 1.5 GHz and a finesse of >200, and the wavemeter has an accuracy of 10^{-3} nm. The main beam is collimated to 2 mm in diameter by a lens (L) and then passes through a 60 cm iodine cell as a saturating beam with an optical power of approximately 3 mW. The intensity of the saturating beam is approximately 1 mW/mm^2. A fraction of the beam is then reflected back as a probe beam using a neutral density (ND) filter. A quarter waveplate ($\lambda/4$) and a polarizing beam splitter (PBS) are used to direct the probe beam to a photodetector (PD), and this also improves the optical isolation for the ECDL. The probe beam power entering the photodetector is 0.3 mW. The cold finger temperature of the iodine cell is normally stabilized to 15 °C, resulting in an iodine vapor pressure of approximately 17 Pa.

The Doppler-free saturation spectrum of the hyperfine components of the $P(84)$ 5–5 transition is observed and recorded with the conventional third-harmonic demodulation method by a lock-in amplifier. We modulate the ECDL frequency at 15.1 kHz by modulating the laser diode injection current using the sine output of the lock-in amplifier and scan its frequency by applying a triangular signal to the PZT of the ECDL. To stabilize the laser frequency, the third-harmonic output of the lock-in amplifier is fed into the laser PZT by a simple one-stage integral feedback control loop.

3. Results and Discussion

The third-derivative signal of the saturation spectrum of the hyperfine components of the $P(84)$ 5–5 transition is shown in Fig. 2(a), in which the modulation width is 11.66 MHz. The absorption line consists of 15 hyperfine components from *a* to *o*, distributed within 1 GHz. The observed spectrum shows a flat baseline with a negligible offset, which is important for absolute frequency stabilization. The isolated components *a*, *f*, and *o* are the best choices for frequency stabilization. The hyperfine components are obtained with a SNR of 1000 at a time constant of 1 s. Here the SNR is the peak-to-peak amplitude of the third-derivative signal divided by the noise level. The peak-to-peak amplitude of the third-derivative signal is 10 V and the noise level is 10 mV. The present SNR is mainly limited by the detection electronics. Using our diode laser system to gain a SNR of 1000 is relatively easy. The main reasons that we can obtain such a high SNR are a longer iodine cell and a higher modulation frequency as compared to those in Refs. 8 and 10. In our experiment, the iodine cell length is 60 cm as compared to 25 and 20 cm in Refs. 8 and 10, and the modulation frequency is 15.1 kHz as compared to 780 and 333 Hz in Refs. 8 and 10. A longer cell gives a higher signal, and a higher modulation frequency reduces the noise. We have observed the noise size of the third-harmonic demodulated signal with an oscilloscope and we find that noise decreases as we increase the modulation frequency. The higher modulation frequency reduces noise and improves SNR. Considering the limitation of the current driver of our ECDL, we chose a modulation frequency of 15.1 kHz instead of 34 kHz that was set by our lock-in amplifier. The signal amplitude versus the cold finger temperature shows a maximum at approximately 15 °C. Therefore in our study we keep the cold finger temperature at 15 °C.

In Fig. 2(a) the spectrum of the 15 hyperfine components from *a* to *o* shows a little asymmetry in their line shapes. It is an artifact due to the fast scan rate. The line shape is symmetric when using a slower scan rate. The line shape of the *o* component at a slow scan rate is shown in Fig. 2(b).

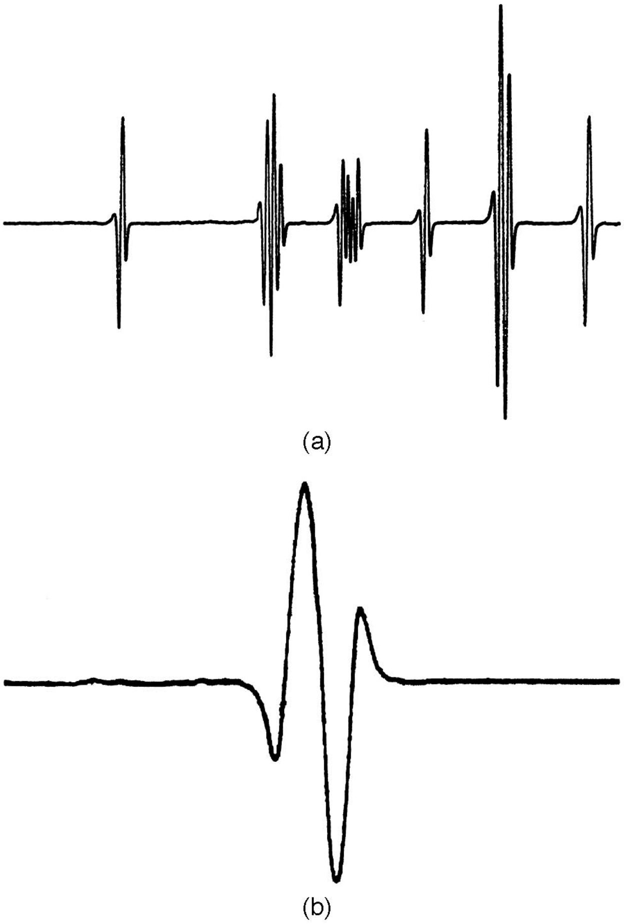

Fig. 2. (a) Third-derivative signal of the saturation spectrum of the hyperfine components of the $P(84)$ 5–5 transition. Here the time constant is 1 s. (b) The third-derivative signal of the *o* component using a slower scan rate.

To determine the linewidth of the HFS components one needs a precisely tunable laser system. Our ECDL does not satisfy this requirement. According to Nakazawa's analysis,[12] we investigate the amplitude of the third-derivative signal at various modulation widths and analyze the dependence between the signal amplitude and the modulation width using the result of Nakazawa's analysis. The amplitude of the third-derivative signal of HFS component *o* versus the modulation width is shown in Fig. 3, in which the experimental result is coordinated with the fitted theoretical curve. From the fitted theoretical curve, it indicates that the measured linewidth is 7.5 MHz for HFS component *o*. The standard error is better than 0.4 MHz (or 5%). By using this method, we have also determined the linewidth of the HFS components of *a* and *f*. Both have the same linewidth with a similar standard error. To verify the method described above we use another method to measure the linewidth for HFS components. According to Nakazawa's analysis, the frequency interval between the two side zero-

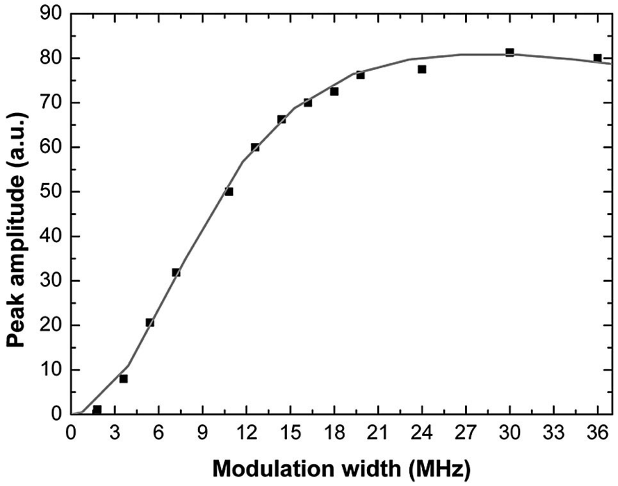

Fig. 3. Measured peak amplitude of the third-derivative signal as a function of modulation width (dotted points) and the theoretical fitted curve (solid curve). The fitted FWHM width is 7.5 ± 0.4 MHz.

cross points of the third-derivative signal is the linewidth when the modulation width is small.[12] The frequency interval between the two side zero-cross points of the third-derivative signal at 2 MHz modulation width is approximately 7.2 MHz. This indicates that the linewidth is approximately 7.2 MHz, which is consistent with the above result.

Nakazawa's analysis[12] also shows that, when the modulation width is 1.64 times the linewidth, the third-derivative signal obtains a maximum slope and enables the laser spectrometer system to obtain an optimal frequency stability. Under this optimal modulation, the third-derivative signal is fed into the laser PZT by a feedback control loop. Without a second identical laser system, we estimate the frequency stability from the error signal after locking by converting the error voltage to the frequency change. The frequency stability is estimated to be better than 10 kHz, corresponding to a relative value of 2.2×10^{-11}. The error signal is recorded by a chart recorder with a response time of slightly lower than 1 s. The SNR of 1000 at a 1 s time constant and a linewidth of 7.5 MHz implies that the optimum stability is $1.6 \times 10^{-11}\tau^{-1/2}$, assuming a white frequency fluctuation. Therefore the stability estimated from the error signal is quite reasonable. When the averaging time is 4000 s, the frequency stability is predicted to be 2.5×10^{-13}, which is not far from the stability of iodine-stabilized He–Ne lasers at 633 nm. Although the feedback loop is not optimized, our laser system obtains a good frequency stability. For comparison, Masuda and co-workers[8] reported the frequency stabilization of a diode laser to the hyperfine component f of the $P(84)$ 5–5 transition, and the stability they achieved was only 300 kHz.

4. Conclusions

We have developed a simple and compact diode laser stabilization system. HPS components of $P(84)$ 5–5 transition of molecular iodine ($^{127}I_2$) at 657.483 nm are observed with a SNR of 1000 at a 1 s time constant. Our system is less complex than the systems discussed in the previous literature.[8,10] The diode laser is frequency stabilized to the hyperfine component o of the saturated absorption signal. A frequency stability of better than 10 kHz is achieved. It is expected that the stability can be further improved by employing a higher modulation frequency and by optimizing the feedback loop.

In our system we modulate the frequency by current modulation instead of cavity length modulation by PZT, which was employed by others. Our results indicate that the amplitude modulation induced by current modulation is comparable to PZT modulation and the amplitude modulation-induced drift is negligible. We demonstrate that the SNR and stability can be increased by the current modulation since we can modulate the laser at a frequency that is higher than PZT modulation. Our scheme can be applied to ECDL at other wavelengths.

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