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Comparison of 10 cm and 50 cm Long Iodine Cells in Iodine-Stabilized Diode Laser-Pumped Nd:YAG Laser at 532 nm

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Abstract: An iodine-stabilized diode laser-pumped Nd:YAG laser system at 532 nm was developed at the National Institute of Metrology of Thailand (NIMT) for the first time in Thailand. Two iodine cells with the lengths of 10 and 50 cm were used for the comparison of frequency stability of Nd:YAG laser. The experiment was set for phase modulation spectroscopy. The Nd:YAG laser was locked to the a10 component of the R(56)32-0 transition of iodine molecule. The variation of wavelength with time and the frequency stability were carried out at various iodine cell temperatures of 20, 10, 5, 1, -1, -3 and -5°C. The results from the frequency stability measurements showed that the lowest Allan standard deviation value of 6.643×10^{-10} was obtained at -5°C for 50 cm long iodine cell. From this Allan standard deviation value, it can be concluded that the iodine-stabilized diode laser-pumped Nd:YAG laser system at 532 nm developed in this study is acceptable to be used with a gauge block interferometer for the length calibration of the gauge block.

Keywords: Iodine-Stabilized, Diode Laser-Pumped Nd:YAG Laser, Frequency Stability, Doppler-Free Laser Spectroscopy

Introduction

Frequency-stabilized lasers have been widely used in many applications such as laser cooling and trapping of atoms, precision measurement, high-resolution spectroscopy and optical communications (Döringshoff *et al*., 2012; Tiwari *et al*., 2005; Nyholm *et al*., 2003).

Molecular iodine is presently used as the source of the frequency reference with reference frequencies at 532, 543, 612, 633 nm and others (Felder, 2005). These lines can be used as excellent frequency references for laser stabilization to a few parts in 10^{-9} or better (Edwards *et al*., 1996).

A set of selected transitions for iodine molecule at 532 nm that are included in the recommendation of the wavelength standards by the International Committee for Weights and Measures (CIPM) was reported by Quinn (2003). The a10 component of the R(56)32-0 transition with a frequency of 563.260223513 MHz and a wavelength of 532.245036 nm is recommended as the center line. Therefore, most works on the iodine-stabilized laser, the frequency and wavelength of the laser will be locked to the a10 component of the R(56) 32-0 transition.

However, the hyperfine interactions in molecular iodine have been studied extensively in the past three decades with increasing accuracy and resolution. The hyperfine splitting of iodine transition lines has been measured by Doppler-free laser spectroscopy with Ar^+ ion lasers, Kr^+ ion lasers, dye lasers and He-Ne lasers (Yoon *et al*., 2001; Lea *et al*., 2003). Recently, diode laser-pumped Nd:YAG lasers have been recognized as promising sources for high-resolution spectroscopy due to the high output intensity, narrow line-width and high absorption of green light in iodine. Hyperfine structures of the iodine transitions at 532 nm have been widely studied by many researchers (Arie and Byer, 1994; Eickhoff and Hall, 1995; Hong *et al*., 1998; Hong and Ishikawa, 2000; Rovera *et al*., 2002; Hong *et al.,* 2003; 2004).

For Doppler-free laser spectroscopy, various stabilization techniques have been used such as frequency modulation spectroscopy (Nyholm *et al*., 2003; Bjorklung, 1980), modulation transfer spectroscopy (Shirley, 1982; Robertsson *et al*., 2001; Snyder *et al*., 1980; Raj *et al*., 1980; Camy *et al*., 1982) and phase modulation spectroscopy (Cordiale *et al*., 2000; Schnatz and Mensing, 2001; Schenzle *et al*., 1982).

Science Publications

The National Institute of Metrology of Thailand (NIMT) was established in 1997 as a public agency under the supervision of Ministry of Science and Technology. The mission is to develop the national measurement standards to be recognized internationally and to disseminate the measuring accuracy to Thai community. The main works of NIMT are the calibration services. The NIMT provides the calibration services to the calibration laboratories and industrial sectors in order that their measuring equipment are traceable to the national and international standards. The calibration services provided are related to 7 metrology departments such as dimension, electrical and mechanical metrologies, etc.

At present, one commercial laser system available at NIMT is the iodine-stabilized He-Ne laser at 633 nm with a relative standard uncertainty of $\pm 2.5 \times 10^{-11}$ for an iodine cell cold finger temperature of 15°C (Quinn, 2003). This laser system is used as a primary standard for the calibration of wavelength of He-Ne laser. The other available laser system at NIMT is stabilized He-Ne laser at 633 nm with an uncertainty of $\pm 1 \times 10^{-9}$ which is used with a gauge block interferometer for the length calibration of the gauge block. However, at present, the iodine-stabilized diode laser-pumped Nd:YAG laser is not available at NIMT. Therefore, to improve the accuracy of the wavelength measurement it is necessary to have an iodine-stabilized Nd:YAG laser system.

In this study, the iodine-stabilized diode laser-pumped Nd:YAG laser system at 532 nm was developed at the National Institute of Metrology of Thailand (NIMT) for the first time in Thailand. The iodine cell lengths of 10 and 50 cm were used for the comparison in frequency stabilization. The fluctuation in wavelength and the frequency stability at different iodine cell temperatures of 20 (room temperature), 10, 5, 1, -1, -3 and -5°C were measured and determined.

Materials and Methods

Figure 1 shows the schematic of the experimental setup for iodine-stabilized diode laser-pumped Nd:YAG laser using phase-modulation saturation spectroscopy which is used to stabilize the frequency of a laser to the first-order Doppler-free saturated absorption line in an external absorber iodine cell. The diode laser-pumped Nd:YAG laser (Innolight GmbH, Prometheus) at 1064 nm with a PPKTP crystal to obtain the laser output at 532 nm (frequency 563 THz) and a power of 25 mW was used as a light source. The laser light was collimated by a convex lens and passed through the first half-wave plate to adjust the laser light intensity. The laser light was then passed to the first Polarizing Beam Splitter (PBS1) and divided into two orthogonally polarized beams, i.e., beam 1 and beam 2.

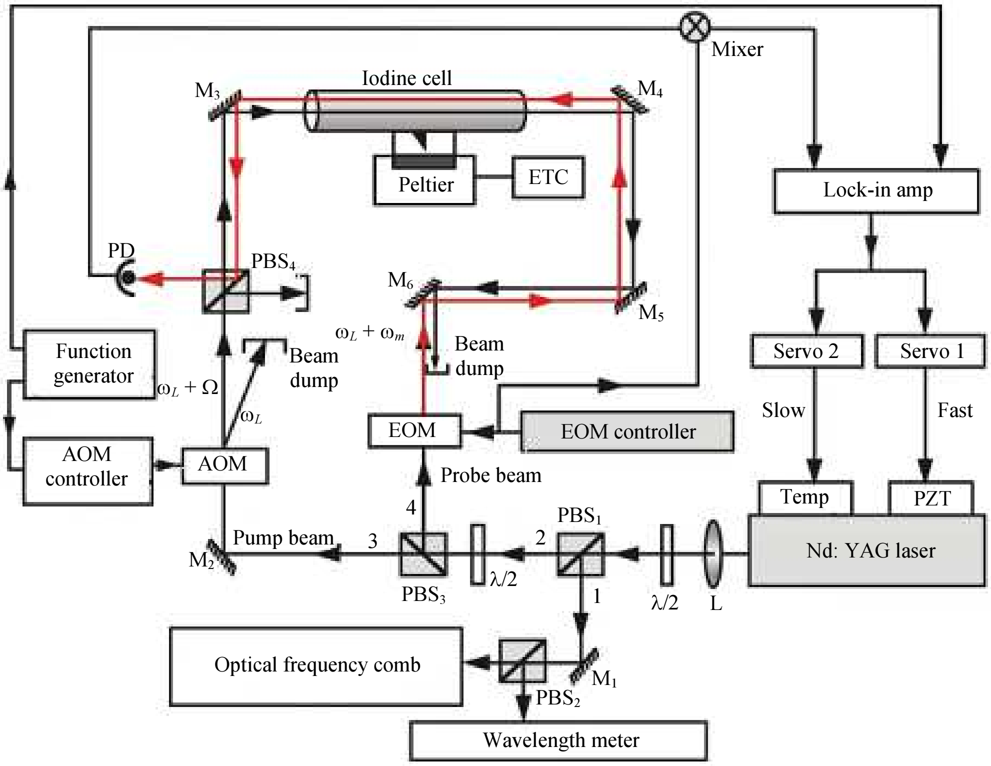

Fig. 1: Schematic of the experimental setup for iodine-stabilized diode laser-pumped Nd:YAG laser using phase modulation spectroscopy

The beam 1 was separated by the beam splitter 2 (PBS2) into two beams. One beam was passed to the wavelength meter (High Finesse, WS-7) for the wavelength measurement and other beam was passed to the optical frequency comb (Menlo Systems, FC1500) for the measurement of frequency stability of Nd:YAG laser.

The beam 2 was passed through the second half-wave plate for further adjustment of the laser light intensity. The laser light was split by the third Polarizing Beam Splitter (PBS_3) into pump beam 3 and probe beam 4. However, the intensity of the pump beam 3 was adjusted to be approximately double of that of the probe beam 4. Furthermore, the pump beam and the probe beam were overlapped and aligned accurately to provide counter-propagating beams within the iodine cell.

The pump beam 3 was reflected at the mirror M_2 and passed to the Acousto-Optic Modulator (AOM, Gooch and Housego). Then, the laser light frequency from 563 THz (ω_L) was shifted by 80 MHz(Ω) which acts as an optical isolator to prevent interferometric noise problems between the reflected pump beam and the probe beam. In addition, the AOM controller power was chopped by function generator at a frequency of 27.4 kHz in order to cancel a residual background arising from the Doppler broadened absorption and small residual amplitude modulation signals. It was passed through the beam splitter 4 (PBS_4). One beam was dumped and the other beam was passed through the iodine cell.

The probe beam 4 was phase modulated with angular frequency 5.2 MHz (ω_m) by the electro-optic modulator (EOM, Photonic Technology). The probe beam was reflected by mirrors M_6, M_5 and M_4 and passed through the iodine cell. Then, it was reflected by polarizing beam splitter (PBS_4) onto the photodiode (Thor Labs, PDA36A-EC).

If the laser frequency coincides with an iodine hyperfine transition, the modulation of the pump beam is transferred by the nonlinear response of the iodine molecules to the probe beam. Synchronous detection of the photodiode output at the modulation frequency yields Doppler-free saturation resonances as the laser is tuned through the iodine molecules spectrum. In practice, the dc signal is generated as the error signal due to the Doppler effect. The error signal is phase-sensitively demodulated (mixer) with the local oscillator signal which is used for the EOM modulation. The demodulated signal is electronically filtered, amplified by lock-in amplifier and it is referenced with the signal from function generator. The amplified signal is finally used to frequency lock the Nd:YAG laser to the laser lines. The signal was divided into a fast frequency control which was fed back to the Piezo-Electric Transducer (PZT) of Nd:YAG laser by servo controller 1 and a slow frequency control which was fed back to the laser crystal temperature controller by servo controller 2. For iodine molecules, there are many dominant hyperfine lines of iodine molecule at 532 nm. However, the line no. 1110 corresponding to R(56)32-0 transition, a10 component, frequency = 563.260223513 MHz, wavelength = 532.245036 nm is used as the reference line.

Therefore, in this study the frequency and wavelength of the Nd:YAG laser were locked to those of a10 component. In addition, two iodine cells with the lengths of 10 cm and 50 cm (Photonic Technology) were used in the iodine stabilized Nd:YAG laser system for the comparison of frequency stability of the Nd:YAG laser at 532 nm. The cold-finger temperature of the iodine cell was controlled by a peltier and Electronic Temperature Controller (ETC) at different temperatures of 20 (room temperature), 10, 5, 1, -1, -3 and -5°C. The variation of wavelength with time during one hour period was measured for each controlled iodine temperature.

Since it took about 10 min to measure a10 hyperfine component, the frequency stability of the frequency-stabilized Nd:YAG laser is also an important factor in the measurement results. The frequency stability of the frequency-stabilized Nd:YAG laser was calculated by recording the beat frequency between iodine-stabilized laser and the optical frequency comb. The beat frequency was measured using a high frequency counter with a 100 ms gate time and 600 data points in the time interval of 600 s. The average beat frequency was obtained and the Allan variance (σ^2) was determined from Equation 1:

$$\sigma^2(\tau) = \frac{1}{2v^2(N-1)} \sum_{i=1}^{N-1} \left(y_{i+1} - y_i\right)^2 \qquad (1)$$

Where:
τ = The time duration of each frequency measurement
v = The mean optical frequency
N = The number of measurements
y_i = The i^{th} frequency measurement

Results

The servo controller 1 was locked to the a10 component of the R(56)32-0 transition and at the Nd:YAG laser wavelength of 532.245036 nm. The iodine cell temperature was varied at different temperatures. The variation of wavelength with time during one hour period was carried out at different iodine cell temperatures of 20 (room temperature), 10, 5, 1, -1, -3 and -5°C. Figure 2 shows the variation of wavelength with time at room temperature for iodine cells with the lengths of 10 and 50 cm.

Figure 3 shows a typical variation of wavelength with time at -5°C for iodine cells with the lengths of 10 and 50 cm. The similar patterns of the variation of wavelength with time at another temperatures were also obtained, but they are not shown here. The maximum variation of wavelength ($\Delta\lambda_{\max}$) for iodine cells at all temperatures was determined and the results are given in Table 1.

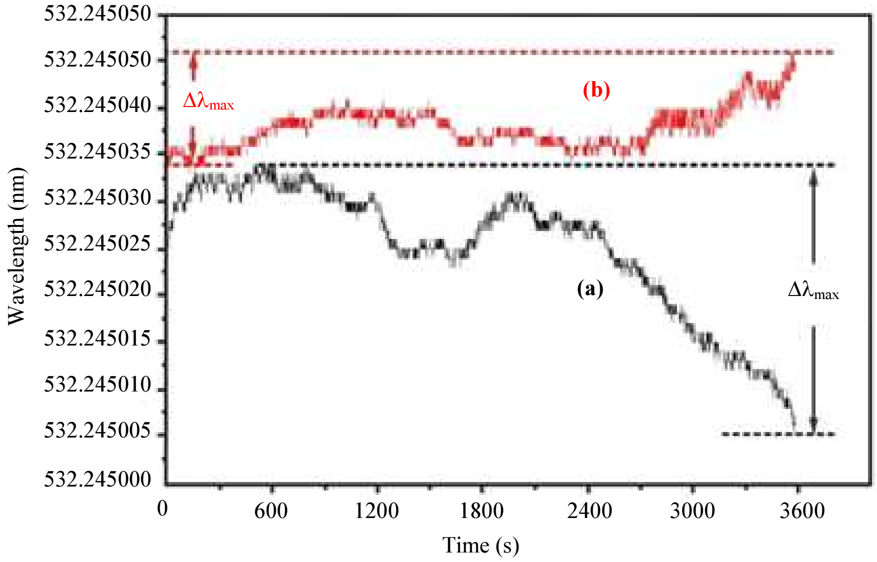

Fig. 2: Variation of wavelength with time at room temperature for: (a) 10 cm long and (b) 50 cm long iodine cells

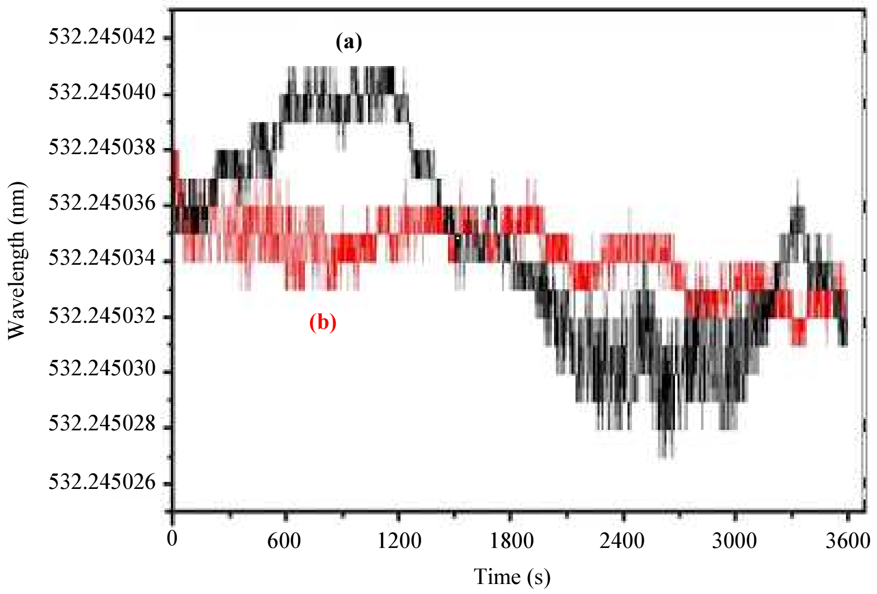

Fig. 3: Variation of wavelength with time at -5°C for: (a) 10 cm long and (b) 50 cm long iodine cells

Table 1: Maximum variations of wavelength ($\Delta\lambda_{max}$) at different iodine cell temperatures for 10 cm long and 50 cm long iodine cells

Iodine cell temperature (°C)	$\Delta\lambda_{max} \times 10^6$ (nm) 10 cm	50 cm
20	34	13
10	10	11
5	13	10
1	11	8
-1	9	9
-3	8	6
-5	10	4

The frequency stability of the Nd:YAG laser was calculated by recording the beat frequency between iodine stabilized laser and the optical frequency comb. The beat frequency was measured using a high frequency counter with a 100 ms gate time and 600 data points in the time interval of 600 s. The average beat frequency was obtained and the Allan standard deviation (σ) was determined according to Equation 1. Table 2 shows the Allan standard deviation at different iodine cell temperatures for both iodine cells and the plots are shown in Fig. 4.

From Fig. 4, it is clearly seen that the lowest standard deviation value is obtained at -5°C for both iodine cells.

Therefore, further measurements were carried out by varying measuring time from 1 to 128 s. Then, the Allan standard deviation was determined and the results are shown in Table 3 and the plots are shown in Fig. 5.

Discussion

From Fig. 2, it is seen that high fluctuation of wavelength is observed for both iodine cells at room temperature (20°C), especially for 10 cm long iodine cell. The maximum variation of wavelength ($\Delta\lambda_{max}$) was determined and the $\Delta\lambda_{max}$ values were found to be 34×10^{-6} and 13×10^{-6} nm for 10 cm long iodine cell and 50 cm long iodine cell, respectively.

Table 1 shows the maximum variation of wavelength at different iodine cell temperatures of 20, 10, 5, 1, -1, -3 and -5°C for 10 cm long iodine cell and 50 cm long iodine cell. It was observed that the $\Delta\lambda_{max}$ value tended to decrease as the iodine cell temperature was decreased for both iodine cells. The lowest $\Delta\lambda_{max}$ values of 10×10^{-6} and 4×10^{-6} nm were obtained at -5°C for 10 cm long iodine cell and 50 cm long iodine cell, respectively.

From the results of the frequency stability measurements as shown in Table 2 and Fig. 4, it was observed that the Allan standard deviation value (σ) tended to decrease as the iodine cell temperature was decreased for both iodine cells. The lowest σ values of 3.3161×10^{-9} and 0.6643×10^{-9} were obtained at -5°C for 10 cm long iodine cell and 50 cm long iodine cell, respectively. However, the iodine cell with 50 cm long gives the highest frequency stability at -5°C. The results of the frequency stability measurements are in good agreement with the fluctuation of wavelength measurements.

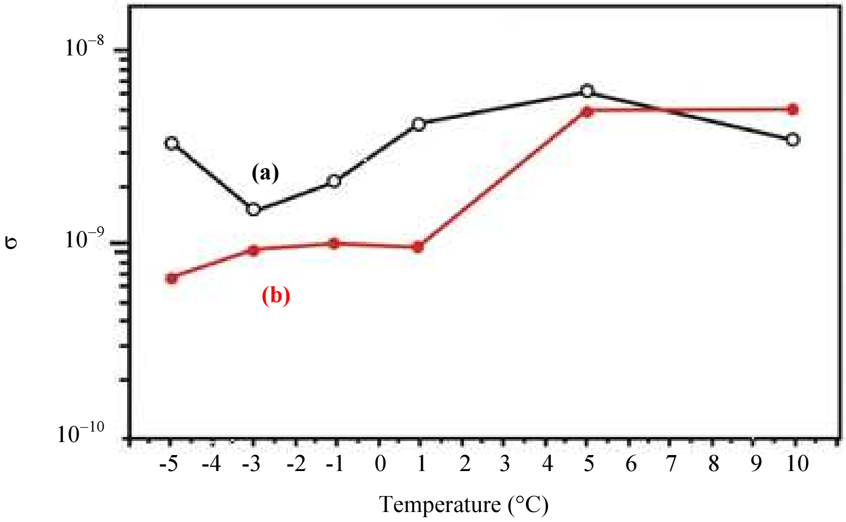

Fig. 4: Allan standard deviation as a function of the temperature for: (a) 10 cm long and (b) 50 cm long iodine cells

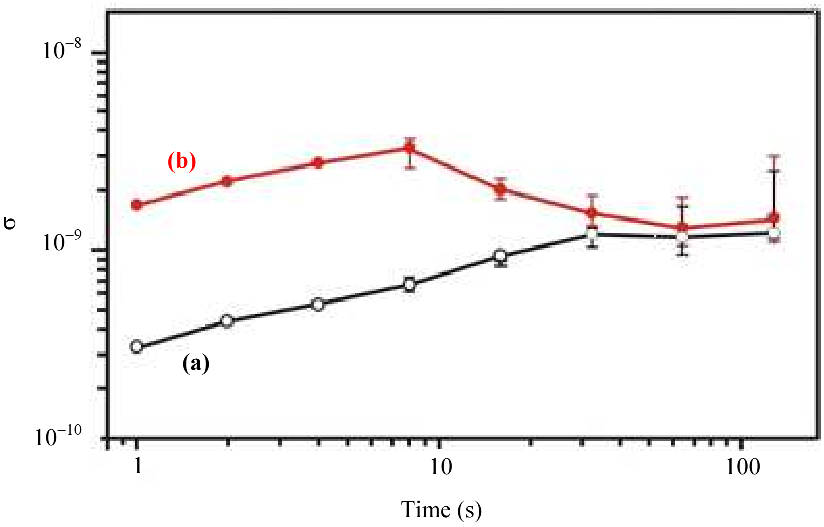

Fig. 5: Allan standard deviation as a function of the measuring time at -5°C for: (a) 10 cm long and (b) 50 cm long iodine cells

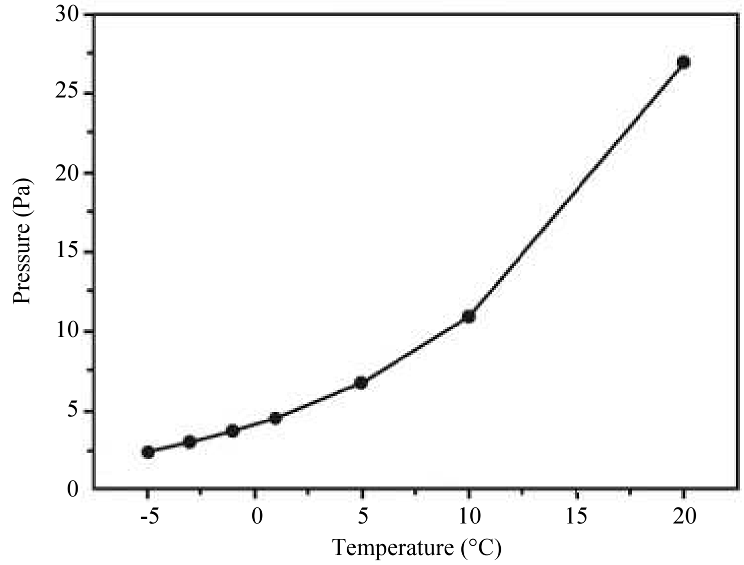

Fig. 6: Relationship between pressure and temperature of iodine

Table 2: Allan standard deviation determined at different iodine all temperatures

Iodine cell temperature (°C)	$\sigma \times 10^9$ 10 cm	50 cm
10	3.3852	4.8829
5	5.9726	4.8290
1	4.1761	0.9617
-1	2.0902	1.0097
-3	1.4681	0.9195
-5	3.3161	0.6643

Table 3: Allan standard deviation determined from measuring time of 1 to 128 s at -5°C for 10 cm long and 50 cm long iodine cells

Time (s)	$\sigma\times10^9$ 10 cm	50 cm
1	1.6921	0.3217
2	2.2236	0.4312
4	2.7795	0.5305
8	3.3161	0.6643
16	2.0289	0.9274
32	1.5339	1.2027
64	1.1619	1.2932
128	1.4502	1.2222

Table 4: Variation of pressure with iodine temperature

Temperature (°C)	Pressure (Pa)
-5	2.46
-3	3.03
-1	3.72
1	4.55
5	6.76
10	10.90
20	26.94

Table 3 and Fig. 5 show the standard deviation value (σ) for 10 cm long iodine cell and 50 cm long iodine cell at -5°C obtained from frequency stability measurements in the time interval of 1 s to 128 s. It is seen that the standard deviation value (σ) increases slowly from the 1st second to the 32nd second then it is almost constant from 32nd to 128th second for both iodine cells. However, the 50 cm long iodine gives more frequency stability than that of 10 cm long iodine cell. Therefore, it can be concluded that 50 cm long iodine cell at -5°C is suitable for the iodine-stabilized diode laser-pumped Nd:YAG laser at 532 nm.

It should be pointed out from Table 2 that, for 50 cm long iodine cell, the standard deviation value (σ) decreased from 4.8829×10^{-9} to 0.6643×10^{-9} as the iodine cell temperature was decreased from 10 to -5°C. It is clearly seen that the iodine cell temperature has strongly effect on the frequency stability of the iodine cell. This is due to the dependence of pressure in the iodine cell on the iodine cell temperature. Gillespie and Fraser (1936) measured the normal vapor pressure of iodine as a function of temperature in the chamber. The dependence of pressure on the iodine temperature is shown in Table 4 and the plots are shown in Fig. 6.

In this study, all the equipments were installed in the laboratory room with a controlled temperature of 20°C which is very high compared with the iodine cell temperature. Furthermore, the relative humidity in the room was about 50% which is rather high due to very high relative humidity in Thailand. These two parameters are believed to have the effects significantly on the frequency stability of the iodine-stabilized diode-pumped Nd:YAG laser system developed in this study. The lowest Allan standard deviation of 0.6643×10^{-9}

obtained at -5°C for 50 cm long iodine cell is quite high compared with previous values as reported in the literatures (Cordiale *et al*., 2000; Picard *et al*., 2003; Hong *et al*., 2003; 1998; Arie and Byer, 1994; Döringshoff *et al*., 2012; Rovera *et al*., 2002; Robertsson *et al*., 2001; Eickhoff and Hall, 1995; Bitou *et al*., 2003). Therefore, the developed iodine-stabilized diode laser-pumped Nd:YAG laser is not suitable to be used as a primary wavelength standard, However, the uncertainty of the iodine-stabilized laser system is acceptable to be used with a gauge block interferometer for the length calibration of the gauge block which is the main work of NIMT.

Conclusion

In this study, the iodine-stabilized diode laser-pumped Nd:YAG laser system at 532 nm was developed at the National Institute of Metrology of Thailand (NIMT) for the first time in Thailand. Two iodine cells with the lengths of 10 and 50 cm were used for the comparison of frequency stability. The experiment was set for phase modulation spectroscopy. The Nd:YAG laser was locked to the a10 component of the R(56)32-0 transition of iodine molecule. The variation of wavelength with time and the frequency stability were carried out at various iodine cell temperatures of 20, 10, 5, 1, -1, -3 and -5°C. The results from the frequency stability measurements showed that the lowest Allan standard deviation value of 6.643×10^{-10} was obtained at -5°C for 50 cm long iodine cell. From this Allan standard deviation value, it can be conclude that the iodine-stabilized diode laser-pumped Nd:YAG laser system at 532 nm developed in this study is acceptable to be used with a gauge block interferometer for the length calibration of the gauge block.

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Author's Contributions

Prayut Potirak: Carried out the experimental setup, collected all the measurement data and prepared the original manuscript.

Monludee Ranusawud: Provided all the equipments used in the experimental setup.

Pichet Limsuwan: Helped in writing the manuscript.

Prathan Buranasiri: Read and approved the manuscript.

Ethics

This article is original and contains unpublished material. It is confirmed that all authors have read and approved the manuscript and there are no ethical issues involved.

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