THE STUDY OF IODINE CELL FOR STABILIZATION OF Nd:YAG LASER AT 532 nm

PRAYUT POTIRAK

A THESIS SUMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY IN APPLIED PHYSICS
FACULTY OF SCIENCE
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การศึกษาไอโอดีนเซลล์สำหรับการเสถียรของนีโอดีเมียมแย๊กเลเซอร์ที่ความยาวคลื่น 532 นาโนเมตร

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ประยุทธ โพธิลักษณ์

PRAYUT POTIRAK

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาดุษฎีบัณฑิต

สาขาวิชา ฟิสิกส์ประยุกต์

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หัวข้อวิทยานิพนธ์ การศึกษาไอโอดีนเซลล์สำหรับการเสถียรของนีโอดีเมียมแย๊กเลเซอร์ที่ความยาวคลื่น 532 นาโนเมตร
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บทคัดย่อ

วิทยานิพนธ์นี้มีจุดประสงค์คือ (1) ศึกษาคุณสมบัติการกระตุ้นของเลเซอร์ไดโอดกับผลึกนีโอดีเมียมแย็กที่ช่วงความยาวคลื่น 532 นาโนเมตร และ (2) ทำให้แสงเลเซอร์นั้นเกิดความสเถียรเป็นมาตรฐานที่ช่วงความยาวคลื่น 532.245036 นาโนเมตร ซึ่งได้มีการใช้หลอดไอโอดีนเซลล์ที่มีความยาว 2 ขนาด คือ 10 และ 50 เซนติเมตร ได้มีการใช้วิธีเฟสมอดูเลชั่น แอบซอฟชั่น สเปคโตสโคปีเพื่อให้ความยาวคลื่นนั้นความเสถียร ประกอบไปด้วยอะคูสโตออปติกมอดูลเลเตอร์ อิเลคโตออปติกมอดูลเลเตอร์ แผ่นเพลเทียร์หลอดไอโอดีนเซลล์ แหล่งจ่ายไฟ ระบบควบคุมในการล็อค และตัวควบคุมอุณหภูมิด้วยอิเลคทรอนิค

คำสำคัญ : นีโอดีเมียมแย็กเลเซอร์, เฟส มอดูเลชั่น แอบซอฟชั่น สเปคโตสโคปี, หลอดไอโอดีนเซลล์

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ABSTRACT

The aims of this dissertation are: (1) to study the characteristics of diode-pumped Nd:YAG laser at 532 nm and (2) to stabilize the laser light at a standard wavelength of 532.245036 nm using iodine cells with two tube lengths of 10 and 50 cm. The method used for the stabilization of wavelength was the Phase-modulation saturation spectroscopy. It consists of acousto-optic modulator (AOM), electro-optic modulator (EOM), Peltier, iodine cell, power supply, servo controller and temperature controller.

Keywords : Nd:YAG laser, Phase-modulation saturation spectroscopy, Iodine cell

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Chapter 1

INTRODUCTION

1.1 Study background

In the field of metrology, the working standards related to length have been established on the basis of a fundamental constant which will be applicable in any circumstances with no significant change in the level of uncertainty [1, 2]. This constant used is the speed of light, denoted by c. Astronomers have traditionally referred to length in terms of the time taken for light to cover a particular distance. The value of c can then be applied in converting the measurement to units more commonly used for distance. The principle applies in reverse whereby it is possible to express any distance in terms of the time taken by light to complete that distance. The meter can therefore be defined in terms of a unit of time once the speed of light has been ascertained. The speed of lights was determined and given a fixed value in 1983, which allowed the definition of a meter to be given as indicated [1]: One meter is the distance which light travels in a vacuum during the period of 1/299 792 458 of a second.

Having established this definition, there were three practical applications of the concept which could be used to measure the meter which were proposed by the Comité International des Poids et Mesures (CIPM) which is the authoritative body with responsibility for standardizing the measurement of lengths [1]. The first approach advises the use of a frequency stabilized laser to determine the meter via precision spectroscopy. *Mise en Pratique* [3] is the text in which the relevant wavelengths are presented, along with the medium which is to be used in determining achievable standards. For a physical object to be accurately formed to represent a meter it is necessary to use the precisely known value of Lambda of the optical frequency reference in order to determine how many wavelengths will be equivalent to the desired object length with the assistance of an interferometer [4]. Using such a technique the accuracy of the measurement of length will be dependent upon laser frequency, with the accuracy of the latter being in proportion to the accuracy of the former. It is therefore vital to minimize the uncertainty in the laser frequency to ensure that the length measurement is more accurate.

The problem typically encountered is the fact that free running lasers have a frequency stability which exhibits uncertainty levels greater than 10^{-6} (or 100 MHz). This level of uncertainty is clearly unsuitable when seeking accuracy in measurements [5]. One approach to address this issue is to tie the laser output frequency to the center frequency of assorted atomic and molecular species, but the uncertainty still undergoes only minimal improvement due to the effect of Doppler broadening which simultaneously raises the resonance width by up to 1,000 times.

For this reason, a saturated absorption technique should be employed in order to create a resonant spectral line which is not influenced by the Doppler effect and is thereby able to generate accuracy in excess of 1 part in 10^9 [5]. Given this degree of accuracy, it then becomes feasible to make a comparison between theoretical values for the resonance frequencies of different species and the measured frequencies obtained through the stabilized laser technique. When this process is complete, it generates a value for the laser output frequency along with a known level of accuracy. However, one further issue is that lasers are polychromatic, which comprises the frequency reference stability. This stability is then further affected by the influence of temperature changes or vibrations close to the laser [4, 6, 7]. To address these problems and achieve a suitably accurate definition of a meter it is necessary to implement a number of stabilization methods which fix the laser to predetermined atomic or molecular frequency references. Should such techniques prove capable of generating an accurate frequency reference which would gain broad acceptance, it can then be proposed for application to determine the appropriate national or international standards.

1.1 Standards of measurement

Within the field of metrology, the *Mise en Pratique* serves as the source of the recommendations for length standards whose realization would provide the appropriate legal standard. Various standards have been developed on the basis of these recommendations, making clear the extent of the freedom provided in terms of the regulation of how a standard may be established. A majority of laboratories face significant constraints, whether financial, or involving limitations to available resources or expertise, and because of this, it can be anticipated that the standards applied will become relatively diverse and their accuracy might vary notably. For this reason, this study makes use throughout of molecular iodine $^{127}I_2$ for the frequency reference.

Certain parties have emphasized the creation of standards capable of high levels of accuracy in measuring the frequency of a resonant line, with 1 part in 10 serving as a typical target. This can be accomplished through the modulation of the light which leaves the stabilized laser system, but the approach is not effective in measuring length. Although a high degree of accuracy can be achieved, the influence of environmental factors can be rather strong, ensuring that the systems cannot remained locked for long periods of time. These systems are most commonly used when it is necessary to measure fundamental parameters or when other primary and secondary lasers need to have their accuracy verified.

In Colorado, USA, various systems have been created by the JILA group. Among these are the practice of using femtosecond lasers to generate a link between microwave and optical measures, or building a cartographical representation of the gravity field of the planet. One further option is to find ways to make use of supremely accurate time clocks [2, 8].

1.2.1 Thailand's primary standards

The National Institute of Metrology of Thailand (NIMT) developed the country's most accurate primary standard to date using a 633 nm He-Ne frequency-stabilized intra-cavity laser which is fixed to a molecular iodine transition. The accuracy achieved was in the range of 1 part in 10^{10} [9, 10]. This standard was formulated using specifications which would guarantee the effective utilization of its accuracy.

There were several drawbacks associated with this standard resulting from the complexity involved as well as the [5, 10]. For this reason, dimensional measurements rely on the use of secondary standards, with the accuracy undergoing confirmation using the primary standard as a reference. This technique is unavoidable since there are no photo-detectors capable of measuring an optical frequency. In order to evaluate an optical frequency which is not known, it is compared to a known frequency in the shape of a primary standard, and the difference between frequencies can be established using a heterodyne beat. The main drawback with such an approach is that it is necessary to make frequent recalibration checks against the primary standard, thus adding to the cost of the process overall [5]. In cases where the primary standard exhibits a high degree of accuracy, it would be typical for the secondary standard accuracy to exceed 1 part in 10^8 [5]. This permits 100 mm objects to be measured with uncertainty approaching 1 nm [5].

A 532 nm Nd:YAG laser system was also created by NIMT to serve as a primary standard complementing the 633 nm de-facto standard [11]. This Nd:YAG system now appears likely to be acknowledged as the main practical realization of the meter and has accordingly attracted the attention of the major measurement institutions in a number of countries [11-17]. Its appeal lies in the strength of its output intensity allied to the narrow line-width and the high degree of absorption of green light in iodine. This 532 nm laser exhibited accuracy measured at just a few parts in 10^{13} [11].

Progress has been made regarding the Nd:YAG system through the ability to finally address the various issues which restrict the reference accuracy. The Bureau International des Poids et Mesures (BIPM) along with other national bodies have therefore concluded that the Nd:YAG laser has the potential to serve as the basis for a stable, portable, and cost-effective primary standard [3, 17, 18].

This 532 nm laser offers a gain curve which comprises at least ten ro-vibrational levels in iodine [17], allowing locking by the frequency stabilized laser. Iodine has strong and narrow absorption lines in the spectrum's green areas [18, 19] creating an excellent frequency reference. The narrow lines provide the iodine-stabilized Nd:YAG 532 nm laser with a much higher frequency stability than the iodine-stabilized 633 nm He-Ne laser; the difference is around two orders of magnitude greater than the latter laser which has been considered the standard for the past two decades [20]. It is thus unsurprising that researchers have developed an interest in the applications of this Nd:YAG laser in the field of metrology.

The short-term frequency stability of monolithic Nd:YAG lasers is naturally much better than that of gas laser systems [21]. However, the long-term frequency stability was the feature which required improvement if the Nd:YAG laser was to find useful applications in metrology and spectroscopy [21]. The key advantages of the system include the low intrinsic frequency, compact dimensions, low intensity noise, greater power, and ability to generate to output wavelengths at the same time. Also beneficial were the comparatively large tuning ranges in the spectrum of iodine close to 532 nm [22] along with the long lifetimes or short line-widths [17, 19].

While the systems discussed have exhibited high degrees of accuracy, the stabilization process comprises procedural aspects which should be further investigated to acquire a deeper understanding of the nuances.

1.2 Motivation for the research

The Ministry of Science and Technology created the National Institute of Metrology of Thailand (NIMT) in 1997, with the aim of developing national measurement standards toward the target of international recognition. The result was also to be made available to Thailand’s own scientific community. NIMT was given responsibility for calibration services provided both to calibration laboratories and industry to ensure that the country’s measuring tools would work in accordance with international standards. There are seven metrology departments for which calibration services are provided by NIMT in total.

NIMT currently has one available system using the iodine-stabilized He-Ne laser at 633 nm. It serves as the primary standard used in calibrating the wavelength for the He-Ne laser and has a relative standard uncertainty of $\pm$ 2.1 x 10^{-11} m in the case of an iodine cell cold finger temperature of 15°C. NIMT can also offer a stabilized He-Ne laser at 633 nm. Its application requires the use of a gauge block interferometer in order to calibrate the length of the gauge block. The iodine-stabilized diode laser-pumped Nd:YAG laser is currently not yet provided by NIMT, and so the best potential means to enhance the wavelength measurement accuracy would be to introduce an iodine-stabilized Nd:YAG laser system.

This research seeks to develop an iodine-stabilized diode laser-pumped Nd:YAG laser at 532 nm. Comparison of the frequency stabilization can be accomplished through the use of iodine cell lengths of 10 cm and 50 cm. During the course of this study it was therefore necessary to determine the variation in wavelength and also frequency stability at varying iodine cell temperatures. The temperatures used in this study for this purpose were 20°C, 10°C, 5°C, 1°C, -1°C, -3°C, and -5°C.

1.4 Objectives of the study

1) To study the characteristics of diode-pumped Nd:YAG laser,

2) To use the iodine cell for frequency stabilization of Nd:YAG laser system at various temperatures.

1.5 Scope of the study

In order to achieve the objectives, this study wavelength, when is various power (currents) and temperature crystal of Nd:YAG laser and design state for iodine cell. The scope of thesis is as follows:

1) Review previous research articles related to Iodine stabilized of the Nd:YAG laser with different methods and Applications.

2) Study theory of diode pumped Nd:YAG laser and the Second Harmonic which is generated as green laser with wavelength at 532 nm.

3) Design and develop state of Iodine stabilize system for generating standard wavelength of green light laser at 532 nm.

1.6 Expected results

1) Important physical meaning; i.e., Second Harmonic Generation (SHG) and Spectroscopy molecules of iodine cell will be clearly understood.

2) The investigation of the effects on wavelength of various parameters such as currents of laser diode, temperature of Nd:YAG crystal and temperature of PPKTP crystal.

3) Effects of temperature, this applied on the iodine cell for frequency stabilization will be acknowledged.

1.7 Overview of thesis

The thesis is structure in five main parts. First part interludes a general overview about the introduction of thesis. Second part describes the research on the overview of the principle for used the construction of the iodine stabilized Nd:YAG laser at 532 nm. Third part is related to the research methodology and device characterization. Fourth part the experimental results and finally overview of the result and discussion. The more detailed below is described the content each chapter:

Chapter 1 Introduction,

Chapter 2 Overview of the principle for used the construction of the iodine stabilized Nd:YAG laser at 532 nm,

Chapter 3 Research methodology and device characterization,

Chapter 4 Experimental results,

Chapter 5 Results and discussion.

.

Chapter 2
Principles

2.1 Literature review

Frequency maintained lasers have been applied in many fields of research. They are use in cooling and tracking of atom/molecule, precise calibration, mixing frequency spectroscopy and optical communications [19, 45, 46].

Molecular iodine is presently used as the source of the frequency reference with reference frequencies at 532, 543, 612, 633 nm and others [3]. They are used as a good frequency testimonial for balance of laser to some portions such as in nm or smaller [46].

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 Mesures (CIPM) was reported by Quinn (2003) [25]. The a_{10} composition of R(56) 32-0 transition with a frequency of 563.2602233513 MHz and a wavelength of 532.24036 nm is recommended as the center line. Therefore, most works on the iodine-stabilized laser, the frequency and wavelength of the laser will be limited to the a_{10} composition of the R(56) 32-0 transition line.

However, hyperfine interactions in iodine molecules were studied widely in the past three decades with improving accuracy and resolution. The hyperfine splitting of iodine transition lines is detected by Doppler-free laser spectroscopy with Ar^+ ion lasers, Kr^+ ion lasers, dye lasers, and He-Ne lasers [47] Currently, diode laser-pumped Nd:YAG lasers are introduced as a good candidates for high precision spectroscopy because of the big outcome of intensity, unbroaden line width and big absorption of green light in iodine. Hyperfine structures of the iodine transitions at 532 nm have been widely studied by many researchers [49, 50, 51, 52, 53, 54, 55].

For Doppler-free laser spectroscopy, various stabilization techniques have been used such as frequency modulation spectroscopy [29, 37, 56, 57, 58] and phase modulation spectroscopy [44, 59, 60].

2.2 Saturated absorption spectroscopy

The ways to preserve the frequency of the laser to atom/molecule of any saturated medium are considered as Saturated Absorption Spectroscopy so called SAS. The main idea under the saturable absorption is displayed in Figure 2.1.

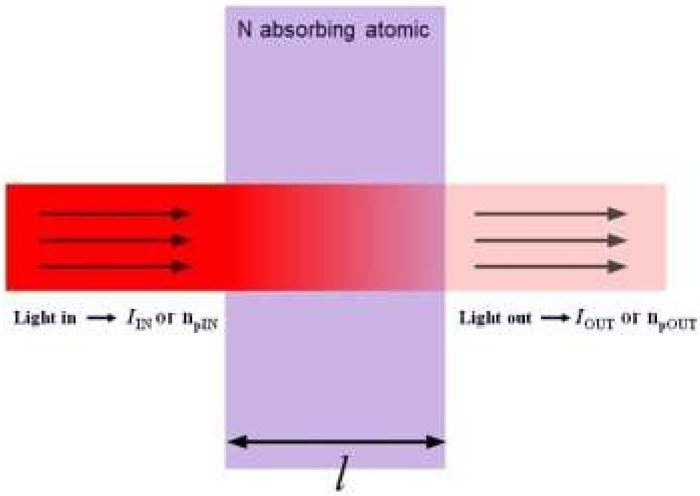


Figure 2.1 The principle of saturable one via the absorption of laser beam **by a saturation medium.**

After the light beam strikes into the saturation or absorption media, it will behaves a decrease in the photon numbers because of absorption at the frequency of resonance. In usual absorption, the law from the Beer and Lambert law is allowed holds when the intensity of the light beam as a function photon numbers existed) behaves an exponential reduction for a propagation distance of length (l) and pressure (p) as written in Eqs. 2.1 and 2.2

$$I_{OUT} = I_{IN} e^{-\alpha l p} \qquad (2.1)$$

$$\frac{n_{pOUT}}{n_{pIN}} = e^{-\alpha lp} \qquad (2.2)$$

where n_{pOUT} and n_{pIN} are the photon numbers at the input and output faces of the absorption media, respectively. As well, α represents the absorption coefficient and more described in Chapter 2. At resonance frequency, if there is one atom absorbed by another one photon therefore the lost of photon numbers because of the absorption is written as shown in Eq. 2.3

$$\Delta n = n_{pIN} - n_{pOUT} \qquad (2.3)$$

If I_{IN} and therefore n_{pIN} , is enhanced at a certain level when $\Delta n = N$. here N represents the total photon numbers supposing one frequency of resonance). At this level, all existing atoms in the media will be absorbed by a photon. Consequently, there is no further light is absorbed or this means that the saturation is achieved. At saturation level, some more enhancement in I_{IN} might result in a nonlinear increase for I_{OUT} as shown in Figure 2.2.

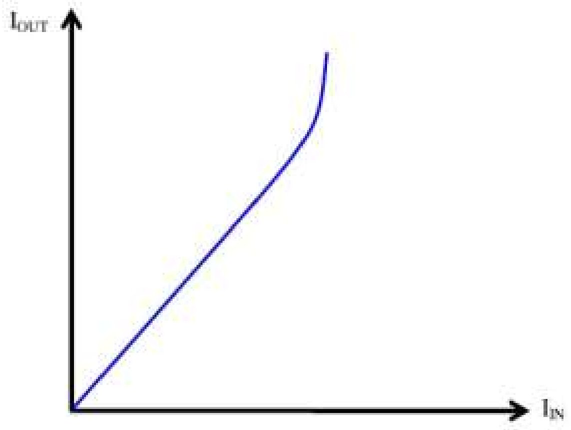


Figure 2.2 The alter in the exit intensity when the atoms are saturated.

The practical generation of SAS signals and the outcome of measurement in a frequency testimonial is further explained in some more detail.

2.2.1 Practical generation of SAS signals

Most practical of SAS concerns with the 2 counter propagation optical light paths when it goes through the absorption media. When a string saturates the light in order to saturate the transition and a comparatively poor beam, it is called the probe beam, this is used to detect the final characteristics [4,7]. These characteristics are suggested by the CIPM, with the comments for the wavelengths and any molecules which tend to offer a good practical standardization [1].

The molecule of our interests is concerned with iodine or $^{127}I_2$ with specified frequencies at 532 nm, 543 nm, 633 nm and other [3]. They are selected because of the general application and laser system available at these wavelength regimes, its more spectra of unbroaden absorption lines in the visible and the convenience of managing the pressure-induce shifts and unnarrowing with an adjustment in temperature, since the iodine molecule is not so light weight and hence its speed is quite slow at ambient temperature [26].

SAS is applied to solve the problem the results of broadening of Doppler effect [4,6,7] that at ambient temperature still enhances the line width of the testimonial and then the frequency deviation by about three-fold of magnitude if it is tested and compared with some spectroscopy approaches.

The deviation of frequency is considered as a relative detection. It is relied on the line width of the transition. And it is then depended upon the broadening effect. A ten order reduction in the line width is going to will make a functional decrease in the frequency fluctuation. Saturated absorption methods are lock the laser in order to make absorption line of Doppler-free to be more narrow therefore developing the frequency precision to be greater than 1 part in 10^9 [27].

Absorption saturation generates only a bit alter in absorption (even when it is very small as 0.01%). Then it is needed to make a corporation with any modulation method in order to increase the signal. And it might allow for the characteristics of the frequency testimonial to be detected [7]. There are nowadays 3 modulation spectroscopy approached that they are in generally concerned [7]: intra-cavity absorption and frequency modulation as well as modulation transfer spectroscopes. Individual method is explained as follows.

2.2.1.1 Intra-cavity systems

The cell including the saturation medium in the gas state is normally applied to investigate and detect the saturation absorption characteristic. Intra-cavity saturated absorption spectroscopy is carried out by putting a cell inside the cavity of laser. The big intensity of the light beam in the laser cavity permit a more bigger signal to be received from the profile of the absorption when it is related to a system of the external cell [4,5,28].

The laser frequency can modulated and the non-linear effect between the laser radiation and the absorption media modulates any light intensity transmitted by the medium property that is total light emission will demodulated [7].

This results in a reduction ability of the stabilization of laser system from offering a stable frequency testimonial applied to create the precise length detection because of the variation of the behavior of the frequency. Nevertheless, this method is suitable for stabilisation laser systems where they are created as the optical frequency testimonials as suggested for the detection of molecule/atom transitions to a high precision of greater than 1 part in 10^{11}.

2.2.1.2 Frequency modulation spectroscopy

Frequency Modulation spectroscopy (FMS) sometimes is called the optical heterodyne spectroscopy. It concerns with the frequency or phase modulating the individual probe beam. It is used to measure the difference of the absorption happed by individual side-band when it is traversed into the saturation medium [7, 28, 29]. A format for FMS is the same as that it is used for MTS, except for the saturating beam can be detected by the photodetector in place of the beam probe. There is a benefit of use of FMS compared to the intra-cavity method. That is, it is allowed for a greater decrease in technical noise provided by the photo detector [28, 30]. This is because of the big modulation frequencies applied in the specific conditions of a few noise restriction of detection of the signal and decrease in the noise of its amplitude [4, 7 ,28, 30]. Sensitive investigation of the a few changes in the intensity of the beam with towards a quantum limitation of sensitivity and it is done not so easy because of fluctuation power of the laser [31]. This effect can solved by adjusting the modulation frequency in specific range in between 100 up tp to 1000 MHz [30, 31] that it will transfer the detection of the signal frequency next to the maximum frequency of any fluctuations power of the laser that they are specifically introduced [31].

The modulation of the probe beam is carried out with an Electro-optic (EOM) an Acousto-optic Modulator (AOM) out of cavity of the laser. This arrangement allows the light for coming out of the laser to be un-modulated [5, 7, 9, 10, 32] Therefore it is provided a known frequency that we can use it for measurement of the length.

FMS is dependent of the phase-sensitive detection [4] where is limits the frequency action of the detection system to a narrow frequency range approximately 20 kHz via the application of the lock-in mode of the amplifier or double balance mixer lock in order to get the resonant frequency and cut out of any spurious movements because of the noise.

Some other benefit has a results in the application of the low frequency of the detection that is introduced as the two-tone spectroscopy [33]. This method is very close to other approaches applied in the microwave [34] and infrared spectroscopy [35] called tone-burst modulation. The two-tone method can solve the problem of some drawback that it is faced by FMS users when they are unable to apply a photo-sensitive detector with a bandwidth equals to the modulation applied [33].

To solve this aspect, low-frequency detection is produced by modulating at the same time for the output of laser together with the 2 different frequencies [33]. The outcome characteristic of the saturating probe is that of 2 side-band for individual side-band that it will have generally been produced with a single frequency.

The difference between the frequency compositions leads to the detection frequency that it is much lesser than individual single frequency offered. This hence is allowed us for the benefits of high-modulation frequencies in which they are introduced in FMS to be concerned within a lower modulation frequency region.

A frequency stabilisation system that it has the saturation media in the cavity of laser, or that is modulated for the laser, or it is used for the frequency modulation spectroscopy method, are going get struggle with a background deviation from Doppler. This depends on the gain-frequency profile of the laser [34]. Herein it is not so easy to get the precise detection of the zero-crossing of the resonant line without introducing a certain level of deviation that it is specified by the slope of the curve from the background. For these modulation laser systems, it is not possible to move out the whole curve from background. The best ways to do is to avoid the background at the phase-locking amplifier when the signal is investigated.

2.2.1.3 Modulation transfer spectroscopy

Modulation transfer spectroscopy (MTS) is considered as recently form of saturation absorption stabilization that it will perform a big application for use in offering the optical frequency testimonials for length metrology [5, 7, 9, 10, 32, 37]. The reason is that because of its capability to offer saturation absorption signals with better signal to noise ratios (SNR) that any background can be removed. The method is different from FMS because the saturation beam can be modulated [5, 7, 9, 10, 32] while the probe is not modulated. The reaction between the probe an a counter-propagation saturation beam in the absorbed medium is going to distribute the modulation side-bands to the probe beam through the process of non-linear effcet [37] as seen in Fig. 2.3.

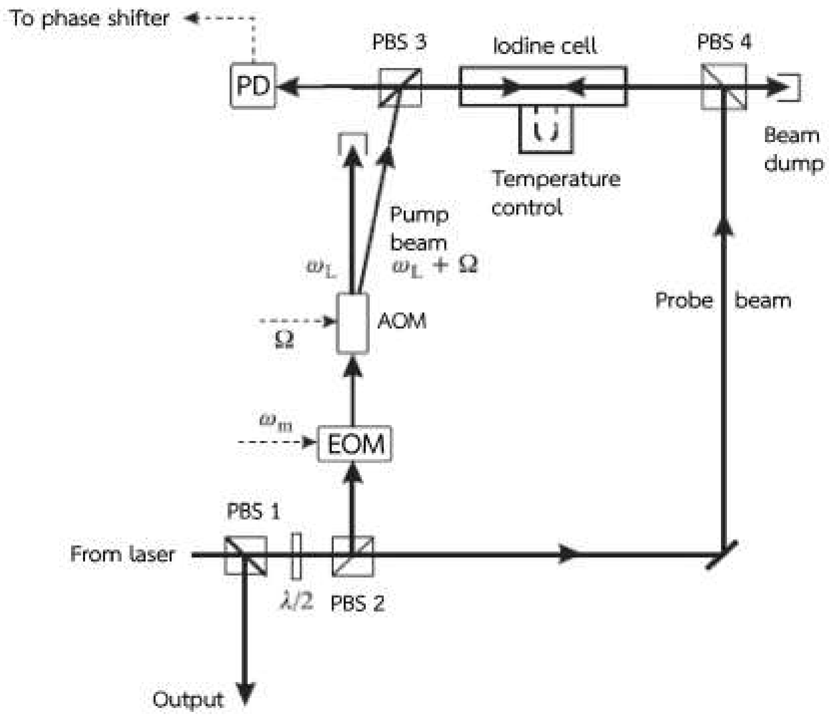


Figure 2.3 Optical set up of an iodine stabilization frequency double Nd:YAG laser at 532 nm by using the approach of modulation-transfer. EOM, AOM, PBS ,PD represent Electro-Optical Modulator, Acousto-Optical Modulator; Polarising Beam Splitter and Photodetector, respectively. Optics are marked with the solid and dashed lines.

The transfer of the modulation can move out the background effect of the Doppler that it is normally observed in FMS therefore offering a signal including a flat background and a discrimination of signal for stabilisied frequency.

The BIPM and a lot of national measurement laboratories presently often bring MTS in the design of a stabilization of laser system as one part of practical primary standardization [17]. Advancement of the MTS approach to obtain a few uncertainties of frequency is strongly dependent of the laser system when it is used in practical ways.

The free operation frequency noise behavior of individual laser seems to be differed since it is the sensitivity in which that individual laser performs to surrounding perturbations. Then MTS system optimization for a 633 nm He-Ne laser might not operation well enough for a 532 nm Nd:YAG laser. Herein, a methodology might be more advance. This might allows us to created MTS system which it can get optimization to stabilization of the frequency of laser of selection to the saturation absorption behavior of iodine molecule.

2.2.1.4 Phase-modulation saturation spectroscopy

Phase-modulation spectroscopy [38, 39] is normally applied for stabilization of the frequency of laser to the first-order Doppler free saturation absorption features outside of the cell of absorber [40, 41, 42, 43, 44,]. The technique is very close to the technique as called Pound-Dever-Hall. Considering the optical set up as shown in Fig. 2.4 we will see the iodine stabilisation laser when it has the exchangeable part of the output of a laser can be splitter out by a help of a half-wave plate and a polarization beam splitter PBS1. The same sum (at PBS 2) permits us to produce a probe and a counter-propagating pump in order to react with the molecule iodine within the absorber cell.

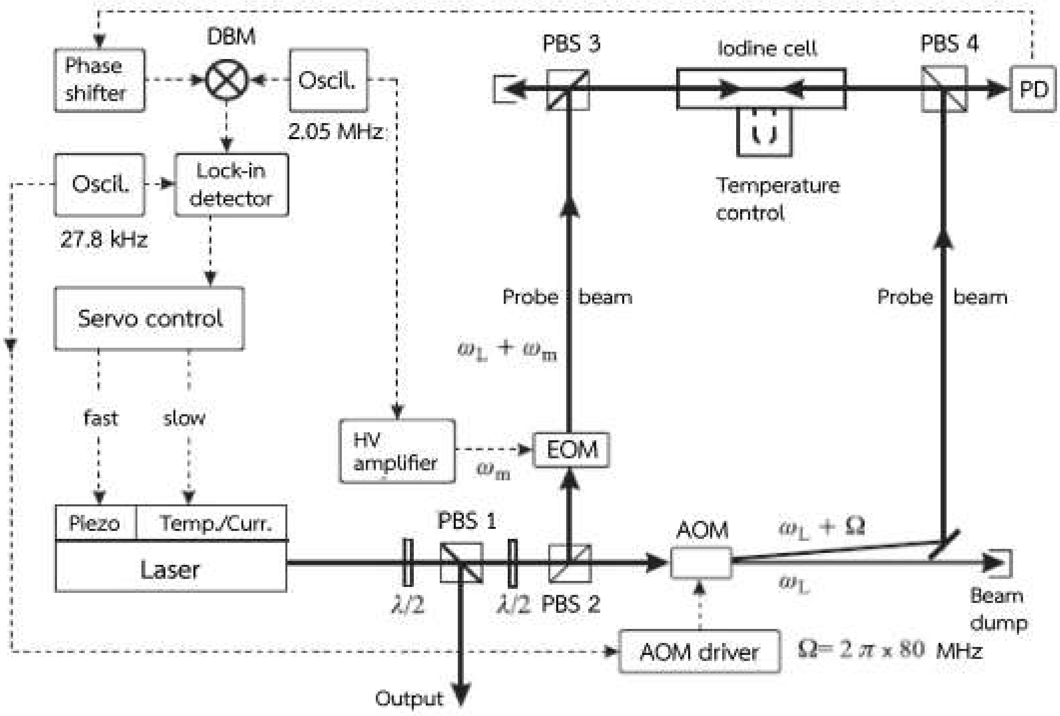


Figure 2.4 Optical set up of an iodine stabilization frequency double Nd:YAG laser at 532 nm using the technique of phase modulation. EOM: Electro-Optical Modulator; AOM: Acousto-Optical Modulator; PBS: Polarising Beam Splitter; PD: Photodetector. Optical and electrical paths are shown as solid and dashed lines.

The technique is normally good as the modulation frequency is selected to a level that is bigger enough to approach the shot noise limitation of the detection not to be effected by main low-frequency) technical noise from the laser. The precise to that the laser is able to be locked to the center of an absorption feature, nevertheless, it is effected by some offset in the error signal detected.

2.3 Diode laser-pumped Nd:YAG laser

Relevant aspects of semiconductor laser diodes are discussed in this section. There are advantages of the use of diode lasers. That is, it is possible to obtain a line width lower than 1 MHz, that is more suitable for precise of spectroscopy detections. They are cost effective, simple in construction, tune able over a wide wavelength range i.e. 15-20 nm and frequency can be modulated properly and quickly. The diode lasers have a continuous wave output with large electrical to optical performance (around 35%). In this section the construction, working principle and characteristics of the laser diode is described in more detail. Due to this, the laser is tune able over a range of 15-20 nm. Altering the injection current is possible to adjust the refraction index of the active part that may alter the laser frequency since the optical path length inside the optical cavity is altered. As the laser diode functions to be similar to a cavity, constructive interference might be only happened at particular wavelengths; then the wavelength of the laser is adjusted by altering the current of injection.

Temperature can have some effect on the optical path length of the optical cavity and the gain feature for semiconductors. The temperature relation of these two variable seems to be different. It leads to un-continuities in the profile of wavelength with respect to the temperature. Figure 2.5 displays the Wavelength at 532 nm of the Nd:YAG laser change with laser crystal temperature with the different current of laser diode by fixing PPKTP crystal temperature of output power at 1.750 mW applying in experiments done at the National Institute of Metrology of Thailand.

The output wavelength of laser alters not to quick with altering temperature at the quick current. However, once the temperature or current approaches to at a particular number, the laser tend to jumping from one longitudinal mode of the cavity to another one. Then output wavelength of the laser with respect to the temperature (or current) can be considered as a staircase. The slope of the individual stage is the adjusting in one cavity mode and the hops between individual stage is related to jumping from one mode to other mode so called mode jump or hop as well.

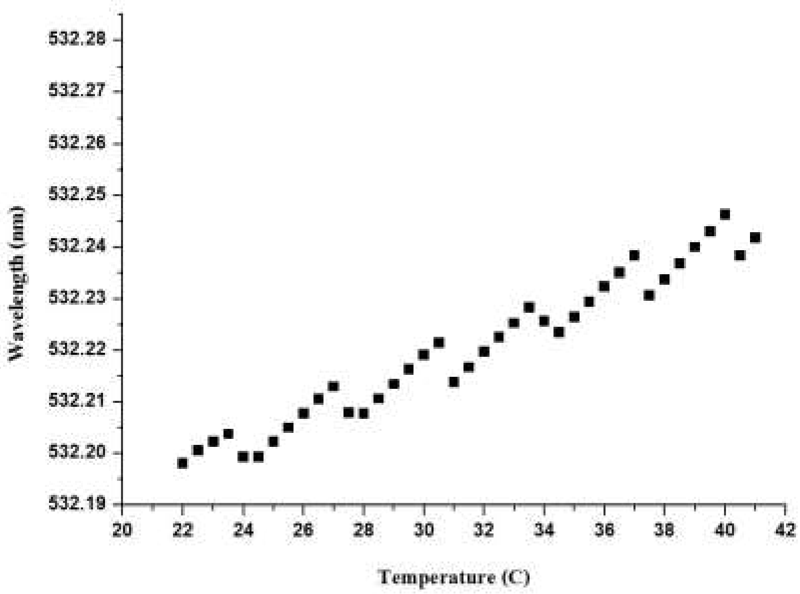


Figure 2.5 Wavelength at 532 nm of the Nd:YAG laser changes with laser crystal temperature at the different currents from the laser diode by fixing with PPKTP crystal temperature

2.4 Frequency stability and tuning for the diode lasers

To detect the frequency of the m^{th} longitudinal mode the phase shifts happening at the laser facets should be carefully considered further. The facet at the rear side of the diode laser should be coated as a pair mirrors with the high reflectivity and the laser feature is defined as the standing wave with a node at the facet. This is certainly wrong for the other facet that it uses as the output coupler with a specific coefficient of reflection of $R \approx 35$ %. There is therefore a phase shift ϕ of the wave inside the cavity reflected from the output facet that should equal to an additional optical path length in Eqs. 2.4 and 2.5.

$$m\lambda = 2n(\nu)L + \varphi\frac{\lambda}{2\pi} = m\frac{c}{\nu} \tag{2.4}$$

or

$$\nu_m = \frac{mc}{2n(\nu)L + \frac{\varphi.c}{2\pi\nu}} \tag{2.5}$$

Therefore, the frequency ν of the wave emitted is dependent of the number *m* of the longitudinal modes, under the phase shift ϕ because the reflection effect, on the length *L* = *L*(*T*) of the laser crystal and on the refraction index *n*. Considering some small deviations of these parameters we tend to mention according to Eq. 2.6.

$$\frac{\Delta\nu}{\nu} = \frac{\Delta mFSR}{\nu} - \frac{\Delta\varphi FSR}{2\pi\nu} - \frac{\Delta L}{L} - \frac{\Delta n}{n} \tag{2.6}$$

where the free spectral range FSR can be written according to Eq. 2.7.

$$FSR = \Delta\nu(2\pi) = \frac{c}{2nL(1 + \frac{\nu}{n}.\frac{dn}{d\nu})} \tag{2.7}$$

The first attribution is possible to lead to mode hops of approximately 100 GHz. The phase ϕ in the second term of is possible to changed at a certain level by coupling back a part of the emitted light from the diode laser. This influence is applied also for the frequency stabilised diode lasers. The last two attributions are dependent of the temperature of the laser. For a less variations from temperature the length *L*(*T*) of the laser diode is seemed to be changed in the linear trend together with the temperature corresponding to coefficients of thermal expansion

(CTE). The refraction index *n* might affect the laser frequency in a complex way as it might change with the frequency *v*, temperature *T*, the injection current *I* and the laser power *P* ($n = n(v, T, I, P)$). Temperature deviations results in the refraction index through the different influence. Generally, increasing the temperature of a laser diode can enhance its wavelength if the monotonic fluctuation is obstructed by uncontinuity hops as seen in Fig. 2.6.

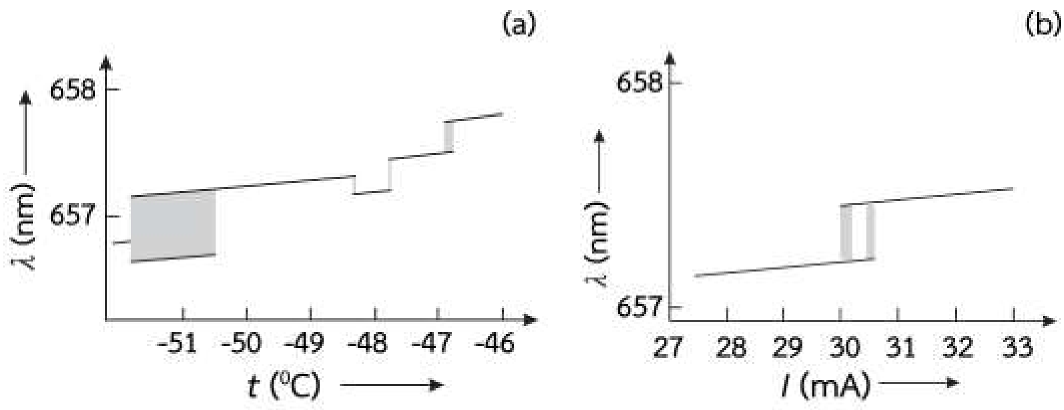


Figure 2.6. (a) Adjusting the wavelength of a InGaAlP laser diode by temperature. The grey zones represent the areass of multi-mode operation. (b) Adjusting the wavelength of a InGaAlP laser diode with injected current. The grey zones show the areas of multi-mode operation.

There are actually some ways to get the quick frequency modulation or frequency control of diode lasers which we can avoid the problem of the phase delays and amplitude modulation together with modulation of the bias current for instance by suing the intra-cavity electro-optic modulator [6] or the injection of “control light” [7]. When the wavelength of the control laser diode is adjusted very close to the transparency zone of the laser diode to be managed, i.e. to a wavelength in between the two zones of absorbed and stimulated emission, the refraction index of the laser at the management is modulated without amplitude modulation.

2.5 Acousto-optic modulator

Acousto-optic modulators relied on materials, for instance $PbMoO_4$ or TeO_2 are characterized by a specifically high speed v of the sound waves in the materials, that they are excited by a piezoelectric transducer for example as seen in Fig. 2.7. The sound wave of wavelength $\Lambda = 2\pi v/\omega_{sound}$ tend to modulate the density and, then, the refractive index n of the material. A laser beam moving throughout the media can be diffracted by the periodic modulation of the refractive index that is very similar to the optical grating effect.

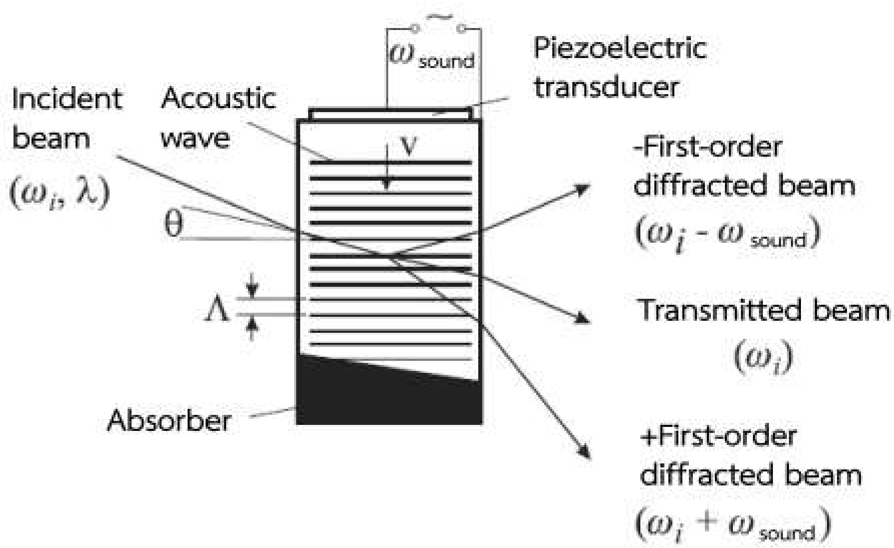


Figure 2.7 Acousto-optic modulator of the light wave is diffracted by a modulation of the refractive index introduced by a ultrasonic sound wave of angular frequency ω_{sound}

Generally, there is a huge difference when the light wave is deflected by a thin or thick gratings due to $\lambda \times l > \Lambda^2$ here l indicates the thickness of the grating.

Then, the acousto-optic modulator is possible to apply as a phase shifter for the diffracted light wave.

2.6 Electro-optic modulator

In specific crystals there is a possibility to adjust the propagation properties of electromagnetic radiation by applying the electric field in a several methods (see e.g. [39]). IF we consider a birefringent crystal just like $(NH_4)H_2PO_4$ (ADP), $LiTaO_3$, $LiNbO_3$, etc., cut and they tend to be used in such a way that the optical axis of the crystal is perpendicular to the direction of incident beam of the laser as seen in Fig. 2.8.

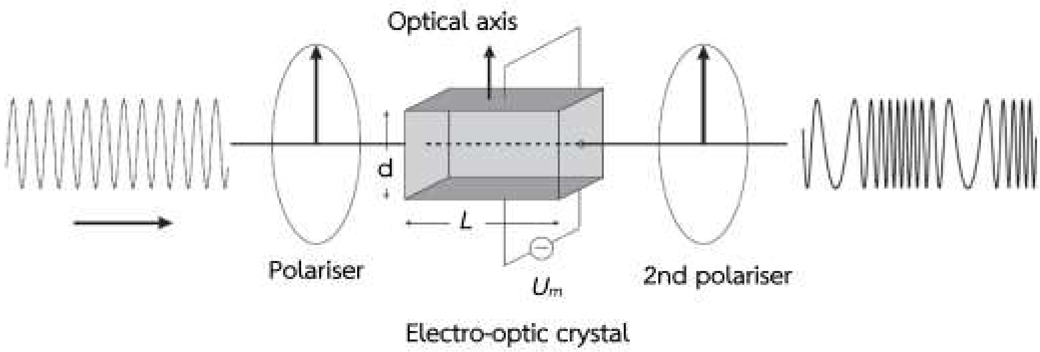


Figure 2.8 Electro-optic crystal performed as a transverse phase modulator.

If an electric field is used in the electro-optic media the center of charge of the binding electrons may be displaced as a function of the ionic cores. The resultant polarization of the material results in a change of the refractive index. The anisotropic action of the crystal to an applied electric field generally must to be explained by a tensor.

In a different organization, the electro-optic modulator is possible to use to obtain the quick amplitude modulation of the light beam, this is similar to a Pockets cell. Considering a linearly polarization laser beam normally to a crystal whose fast (slow) axis is now tilted by 45° with respect to the polarization direction of the laser beam as seen in Figure 2.9. In this set up the different velocities of the two partial waves of different polarizations leads to the phase shift between the two waves after the crystal relying on the voltage that it is applied to the this crystal. According to the results of the polarization of the input beam a phase difference of 0° and 180° results in linearly polarized light together with the polarization axes being parallel and perpendicular, respectively. A phase difference of 90° and 270° results in circularly polarized light and all other phase differences lead to in elliptically polarized light.

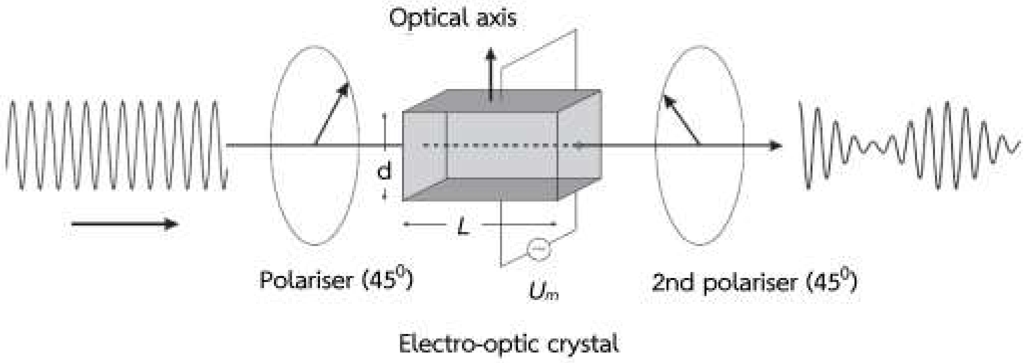


Figure 2.9 Electro-optic crystal performed as a transverse amplitude modulator.

All the electro-optic modulators carried out as amplitude modulators, and acousto-optic modulators are normally applied as a "noise eater" to avoid the problem of the fluctuations of the laser power. In such an set up of part of the transmitted laser power is split off and directed onto a photodiode. The difference between the photo current and the reference current of a constant current source is considered as an error signal for an electronic servo system that it is served as the electro-optic modulator as a servo element to maintain the constant laser power.

2.7 Optical frequency combs

Up to the turn of the century where a frequency stabilization laser was fitted onto a suitable frequency reference, the centre frequency are unable to measure properly and have to interfere by the robust theoretical model. Ever, the recent advancement of optical frequency combs (OFC) it has allowed for the direct investigation of optical frequencies that it is profound effects on frequency standards and on metrology. Herein a general point of view of OFCs is described with some more details and their influence can be found somewhere [23].

The OFC is considered as a femto-second mode-locked laser system that it is ability of bridging the divide between microwave frequencies, the highest frequencies detecable with electronic devices, and optical frequencies. Consequently the detection is possible to made of optical frequencies anywhere in the visible part of the spectrum from 400 to 1200 nm with uncertainties of smaller 1 part in 10 [13, 17-20, 23, 24]. These systems are successes to detect a variety spectral properties of resonant features as well as detect the outcome frequencies of current national primary standards to a big precise [12, 20].

However some disadvantages are still existed for the use of the frequency comb. The optical frequency combs are specifically quite complex for the laser system needed the one having big experience to arrange and carry out and as a result is overly not so cheap for the practical uses such as length measurement. Furthermore the uncertainty of a femtosecond (fs) comb is particularly restricted with the frequency uncertainty of the microwave source applied to stabilising the fs comb [24].

In order to use benefit of its capability to develop the realization of the metre the BIPM is possible set up a femtosecond laser comb for absolute optical frequency measurements, providing a precise of 6 parts in 10^{15} (about 3 Hz) [24] or about 3 folds of magnitude much more precise than previously use in the past. With the perceived potential that these systems have in length (and time [24]) metrology the BIPM encourages to use for all national metrology institutes and other laboratories to obtain the highest achievable precise and to find out a simple ways of method and improvement so as to urge the widespread application [3, 25].

2.7.1 Measuring optical frequencies

The outcome of the laser is sequentially pulses that they are essentially copies of the same pulse separated by the round trip time. These pulses nevertheless are not identical to each other as the pulse envelope propagates with group velocity whilst the carrier wave propagates with its phase velocity.

Consequently, the carrier shifts as a function of the pulse envelop after individual round trip by the phase angle. This resultant spectrum includes of a comb of laser modes that they are separated by the pulse repetition frequency as shown in Figure 2.10.

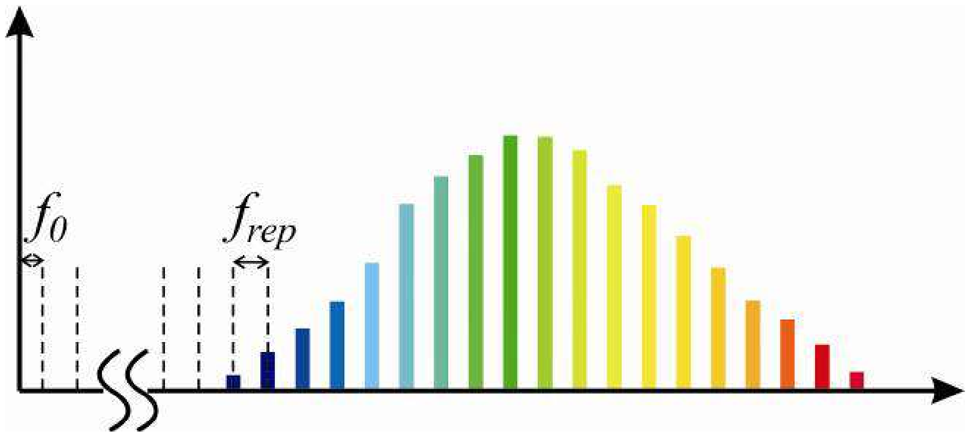


Figure 2.10 Profile of the optical frequency comb

To approach the stabilization of the frequency comb, the comb spacing and the comb offset are considered to be stabilization. Two phase locked loops for locking the repetitive rate and offset frequency to a RF standard transfer the precise and stability between the radio frequency and the optical domain. Frequency counters without dead time are applied to detect the beat signals with CW laser and to arrange well the phase locked loops for cycle slips. An oscilloscope and spectrum analyzers are also applied for observation.

The wavelength center optical frequency comb is provide at 1560 nm with spectral width of 200 nm. Coherent radiation in the UV-vis region is introduced by second harmonic generation (SHG). Spectral broadening because of the self phase modulation through the intensity dependent index of refraction in an optical fiber is applied to enhance the width of the frequency combs to 600 nm. Consequentlly, the spectrum of the optical frequency comb shows the visible thing and wavelength range is from 400 to 1000 nm as seen in Figure 2.11.

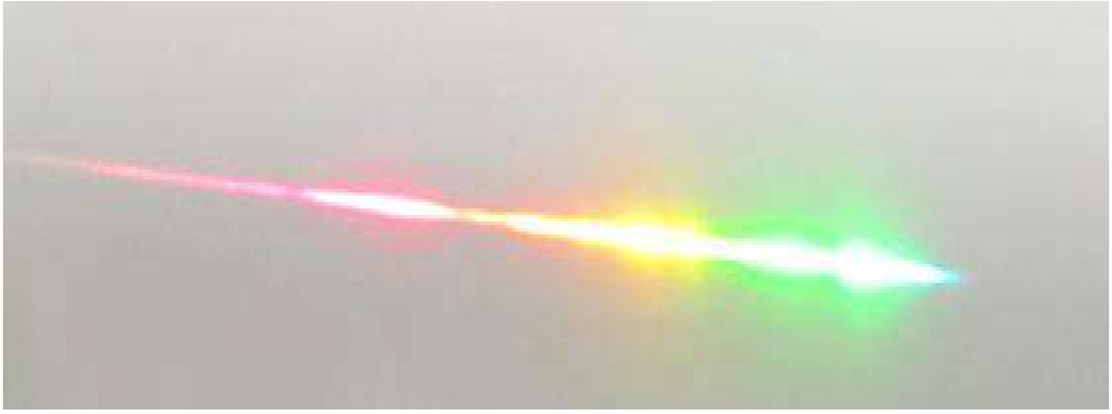


Figure 2.11 Spectrum of the optical comb

Frequency of the CW laser can be detected by frequency measuring method as well as wavelength method. Frequency measuring one is restriced by the accuracy of the fundamental standard, as a result, is better one about a some order of magnitude. Herein we apply the beat frequency one to detect the frequency of the cw laser. Principle of the beat frequency method is to detect the frequency difference between the cw laser and the optical frequency comb. As the optical frequency comb includes thousands of frequency modes, the beat signal observed by the photodiode consisted of thousands of frequency as well. By using a band-pass filter, only beat frequency between cw laser and the optical frequency comb of mode number that it has frequency close to the cw laser need be counted and detected. Figure 2.12 displays the arrangement of the beat frequency optical setup.

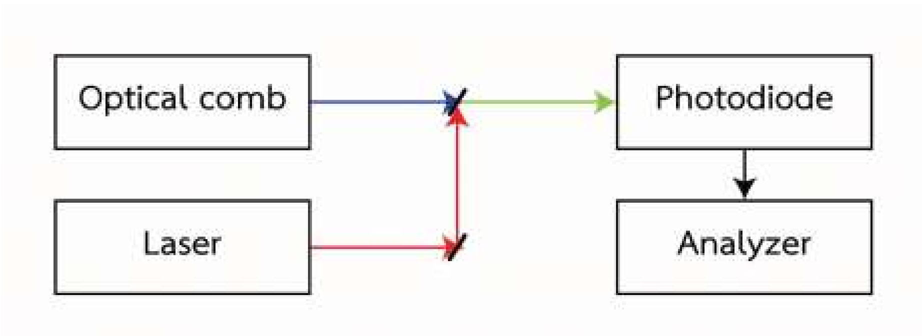


Figure 2.12 Frequency optical set-up

Frequency of the cw laser is written as (2.8)

$$f_{cw} = n \cdot f_{rep} \pm 2 f_0 \pm f_{beat} \tag{2.8}$$

here *fcw* denotes the frequency of the cw laser, *n* means the mode order, f_{rep} represents the repetitive rate of the frequency comb, f_0 indicates the offset frequency of the frequency comb and f_{beat} shows the measured beat note between the cw laser and the nearest adjacent comb mode.

2.8 The $^{127}I_2$ hyperfine structure near 532 nm

The dispersion signal of a hyperfine line is possible to feed back into the piezoelectric transducer frequency actuator of the laser via a servo controller, nearly locking the laser frequency to the hyperfine line of the iodine. We have seens the eight relatively strong rovibrational transitions within the tuning range of the doubled laser (18 787-18 789 cm-'). Using vibrational band head energies and rotational constants, we have set the vibrational and rotational numbers for these lines as seen in Table 1. The line numbers and measured frequencies are selected by Ref. 1. It is noted that lines 1109 and 1111 each includes two rovibrational transitions. Several additional transitions between the 1 and 2 vibrational levels in the X state to vibrational levels 35-42 in the B state fall within the tuning range of the laser. We see about the hyperfine structure of some of them, however detailed detection were made only on the strong iodine lines (Table 1), coming from the lowest vibrational level in the X state.

Table 2.1: $^{127}I_2$ absorption features under the tuning range of the frequency-doubled Nd:YAG Laser

Line	Measured (cm-1)	Assignment
1106	18787.1285	P(119)35-0
1107	18787.2800	R(56)33-0
1108	18787.3389	R(106)34-0

1109	18787.8042	R(136)36-0
1110	18788.3371	R(56)32-0
1111	18788.4454	P(103)34-0

Absolute frequency of the other transitions concerning those adopted as suggested and frequency intervals between transitions and hyperfine components. In the (table 2.2), u_c indicates the estimated combined standard uncertainty. All transition in molecular iodine refer to the B-X system.

Table 2.2: Transition wavelength of iodine molecular saturated absorption line R(56) 32-0 and wavelength

An	R(56)32-0	Frequency (MHz)	Wavelength (nm)
a1	-571.5420	563259651.971	532.245576176
a2	-311.8440	563259911.669	532.245330778
a5	-260.1760	563259963.337	532.245281955
a6	-170.0640	563260053.449	532.245196804
a7	-154.5480	563260068.965	532.245182143
a8	-131.9160	563260091.597	532.245160757
a9	-116.1990	563260107.314	532.245145905
a10	0.0000	563260223.513	532.245036105
a11	126.5130	563260350.026	532.244916558
a12	131.2120	563260354.725	532.244912118
a13	154.4880	563260378.001	532.244890123
a14	160.6650	563260384.178	532.244884287
a15	286.4120	563260509.925	532.244765464

The frequency modulation (FM) saturated absorption spectra of the iodine lines shown in Figure 2.13.

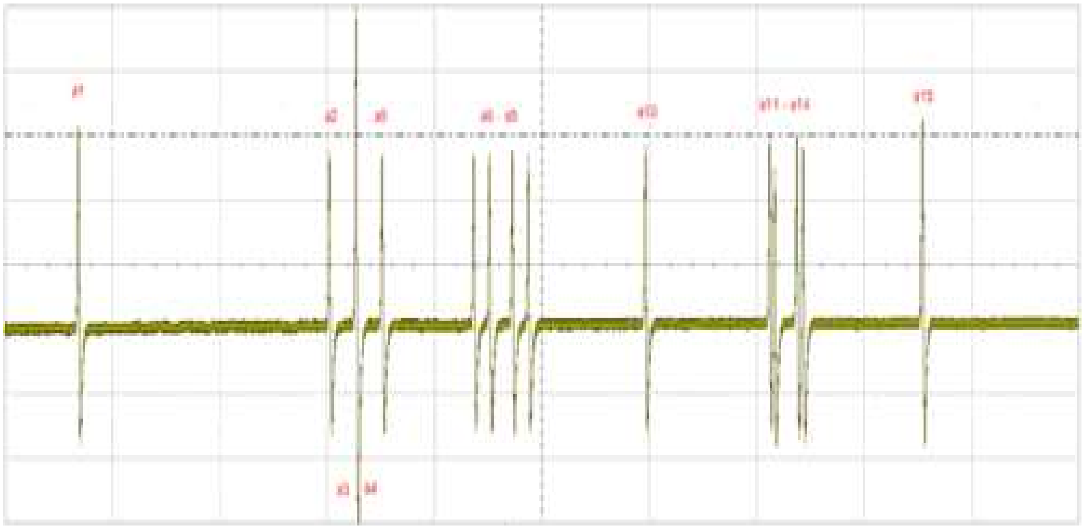


Figure 2.13. FM saturated absorption spectrum of R(56)32-0. The inset is an expanded scan of the a, line.

Chapter 3
Research Methodology

3.1 Equipment

3.1.1 Nd:YAG laser

A commercial diode laser-pumped Nd:YAG laser manufactred by Innolight Gmbh, Germany, model Prometheus 50 NE as shown in Figure 3.1.

Figure 3.1 Diode laser-pumped Nd:YAG laser

3.1.2 Wavelength meter

The wavelength meter (High Finesse, WS-7) with a large spectral range for high speed measurement of laser. This can be operated with very low light intensity coupled through optical multi-mode fiber as shown in Figure 3.2.

Figure 3.2 Wavelength meter

3.1.3 Power meter

The power meter (Gentec-Eo, Tuner) is a numerical and digital needle LCD display laser power monitor. It is fitted with a 77 x 58 mm LCD display that displays 17.5 mm digits. The power meter is ideally used to deal with thermal detector (thermopile) and optical detector. The thermal detector can be used to measure the laser power up to a maximum power of 100 mW as shown in Figure 3.3.

Figure 3.3 Power Meter

3.1.4 Iodine cell

Two iodine cells with the lengths of 10 cm and 50 cm purchased from Photonic Technology were used in this study as shown in Figure 3.4.

Figure 3.4 Iodine cells with the lengths of 10 cm and 50 cm

3.1.5 Photo detector

The photo detector (Thorlabs, PDA36A) were used for measuring CW light sources as shown in Figure 3.5.

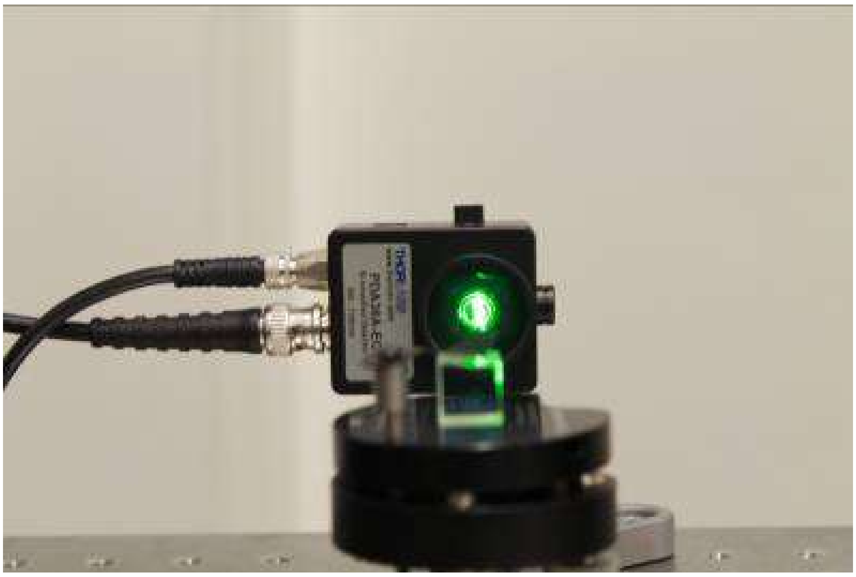


Figure 3.5 Photo detector amplified

3.1.6 Electro-Optical Modulator (EOM)

The electro-optical modulator (Photonic Technology, EOM-02-6-U) used in this work is designed with a resonant frequency of 6 MHz for low-voltage modulation at this frequency is shown in Figure 3.6.

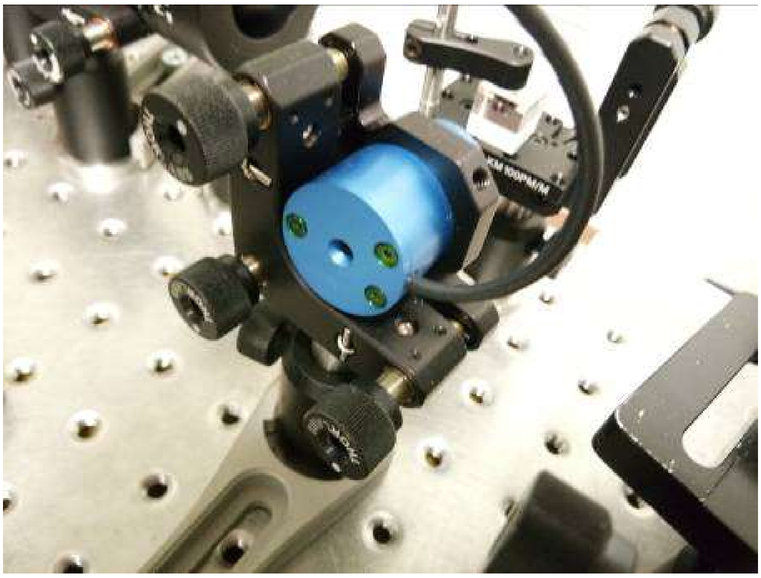


Figure 3.6 Electro-Optical Modulation

3.1.7 Acousto-optic modulator (AOM)

A compact acousto-optic modulator (Gooch & Housego, I-FS080-3S2C-3-GH33) as shown in Figure 3.7.

Figure 3.7 Acousto-optic modulator

3.1.8 Servo Controller

High-speed servo controller (New Focus, LB1005) was used for signal control for required to stabilize the intensity and frequency of many laser systems is shown in Figure 3.8.

Figure 3.8 Servo controller

3.1.9 Digital Lock-In Amplifiers

Figure 3.9 shows the lock-in amplifiers (Stanfords, SR810 DSP) was used in this work for lock frequency signal.

Figure 3.9 Digital lock-in amplifier

3.1.10 Optical frequency combs

Optical frequency comb at NIMT is manufactured by MenloSystems, model FC1500. The optical frequency synthesizer is shown in Figure 3.10.

Figure 3.10 Optical comb system

3.1.11 Function generator

Two function generators (Tektronix, AFG 3021B and AFG 3022B) as shown in Figure 3.11.

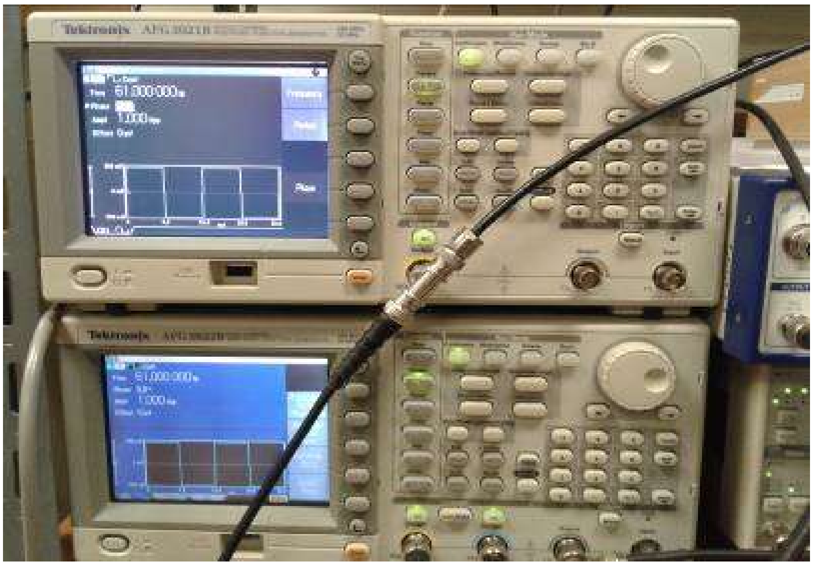


Figure 3.11 Function generator

3.1.12 Thermometer

A low-cost high-accuracy digital thermometer (Heart Scientific, model 1502A) as shown in Figure 3.12.

Figure 3.12 Thermometer

3.1.13 Power Supply

The power supply (Tektronix, PWS2326) designed with wide current and voltage ranges was used for peltier operating as shown in Figure 3.13.

Figure 3.13 Power supply

3.1.14 Oscilloscope

The oscilloscpoe (LeCroy, WaveRunner 604zi) features 400 MHz - 4 GHz of bandwidth, 40 GS/s sampling rate was used for signal detection. Figure 3.14.

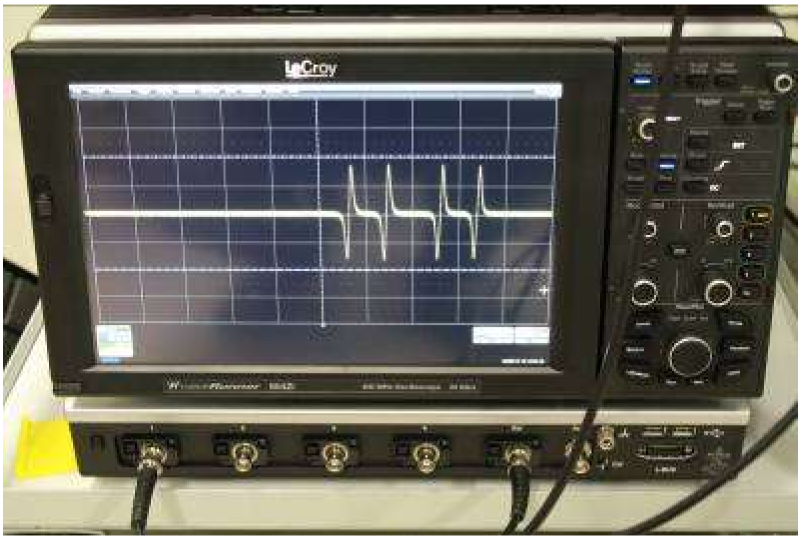


Figure 3.14 Oscilloscope

3.2 Study the characteristic of diode laser pumped-Nd:YAG laser

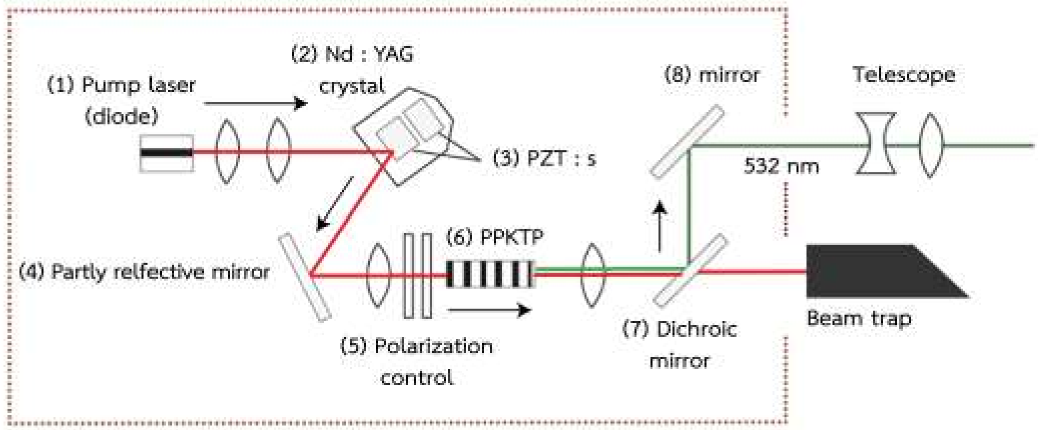


Figure 3.15 Schematic diagram of diode laser pumped-Nd:YAG laser

Figure 3.15 shows the experimental setup of the diode laser pumped-Nd:YAG laser. The laser system used in this work is a commercial frequency doubling Nd:YAG laser (Innolight, Prometheus 50 NE), emitting 100 mW of power at 532 nm and > 500 mW of power at 1064 nm. A partly reflective mirror was inserted for reducing the high intensity of laser beam at 1064 nm generated from Nd:YAG crystal. To get rid of the transmitted light, a noise eater circuit was used. Then, the reflected infrared laser beam was focused on a nonlinear PPKTP crystal to generate the second harmonic wavelength at 532 nm. The 1064 nm and 532 nm beams were separated by dichroic mirrors and the 1064 nm beam was terminated by a beam trap.

3.2.1 Laser output power measurements

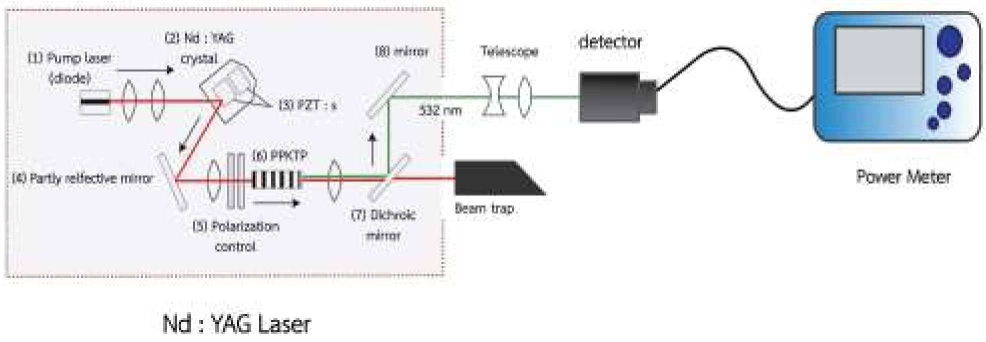


Figure 3.16 Schematic diagram for measuring laser output power at 532 nm.

Figure 3.16 shows the schematic diagram for the measurement of the laser output power. The output powers of laser beam at 532 nm were measured using a laser power meter by varying diode laser current from 1.0 to 1.8 A with different Nd:YAG crystal temperatures of 22, 26, 30, 32, and 34 ^{0}C and PPKTP crystal temperature was fixed at 34 ^{0}C. From the first measurement, the optimum Nd:YAG crystal temperature that yields the maximum laser output power is obtained. It was found that the maximum power is obtained at Nd:YAG crystal temperature of 30°C. Then, the laser output power measurements were repeated at different PPKTP crystal temperatures of 22, 26, 30, 32, and 34 ^{0}C and the Nd:YAG crystal temperature was fixed at 30 ^{0}C.

3.2.2 Wavelength measurements

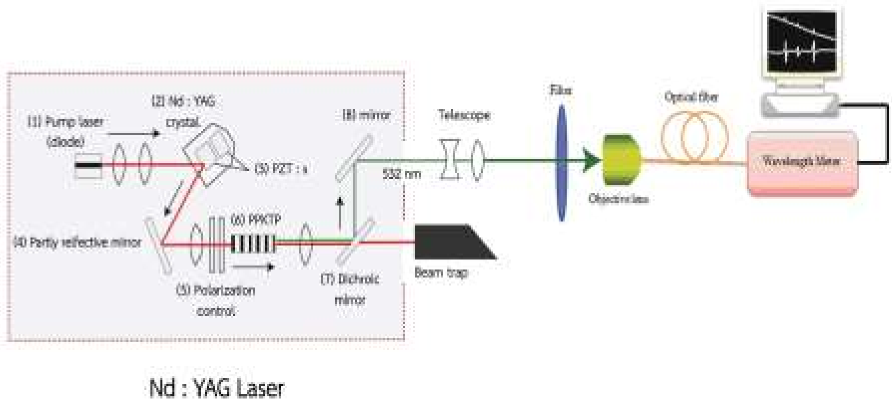


Figure 3.17 Schematic diagram for measuring laser beam at a wavelength of 532 nm.

Figure 3.17 shows the schematic diagram for the measurement of the wavelength. The wavelength of laser beam was measured by a wavelength meter which connected to a computer fordata processing. A filter was put between the objective lens and the laser head to attenuate the intensity of laser light. The wavelength at 532 nm of doubled frequency Nd:YAG or green laser beam was measured at various laser currents from 0.90 to 1.85 A and different Nd:YAG crystal temperatures of 22, 26, 30, 32 and 34 °C with a fixed PPKTP crystal temperature at 34 °C.

3.3 Iodine stabilized diode laser-pumped Nd:YAG laser at 532 nm

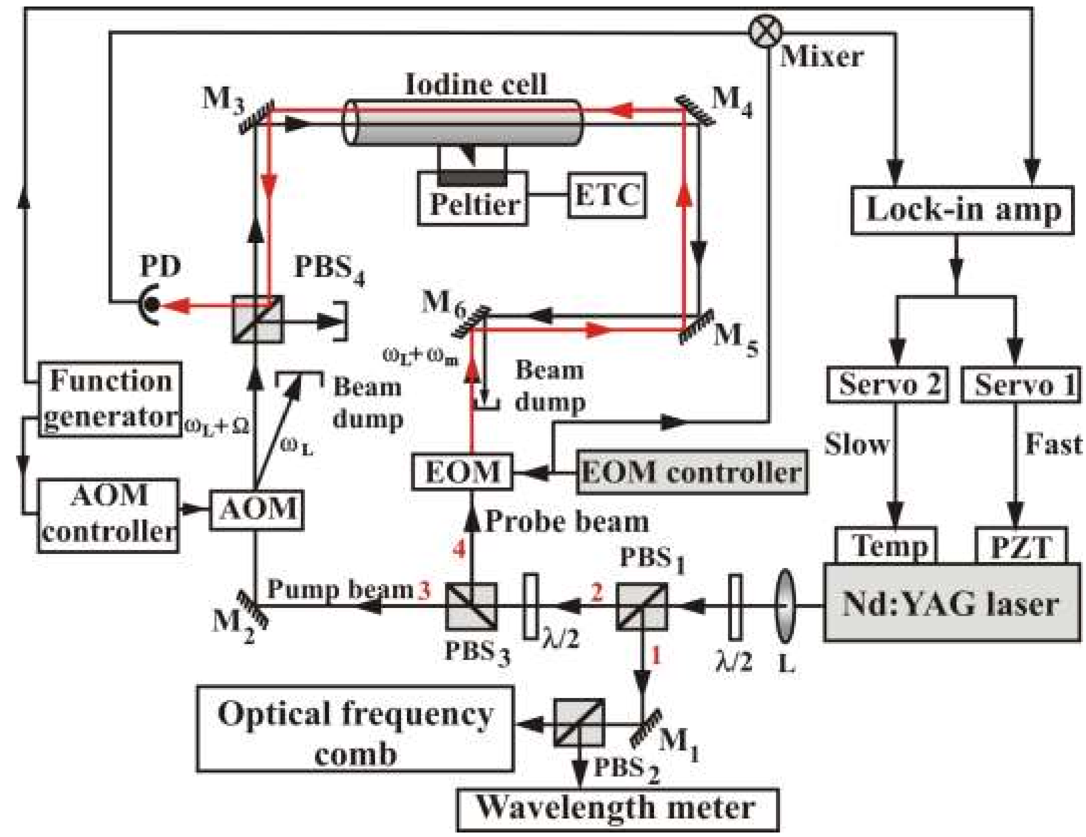


Figure. 3.18 Schematic of the experimental setup for iodine-stabilized diode laser-pumped Nd:YAG laser using phase modulation spectroscopy.

Figure 3.18 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 (PBS_1) and divided into two orthogonally polarized beams, i.e. beam 1 and beam 2.

The beam 1 was separated by the beam splitter 2 (PBS_2) 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 & 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, a_{10} component, frequency = 563.260223513 MHz, wavelength = 532.245036 nm is used as the reference line.

Therefore, in this work the frequency and wavelength of the Nd:YAG laser were locked to those of a_{10} 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^{o}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 a_{10} 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 Eq. (1).

$$\sigma^2(\tau) = \frac{1}{2\nu^2(N-1)}\sum_{i=1}^{N-1}(y_{i+1} - y_i)^2 \qquad (4.1)$$

where τ is the time duration of each frequency measurement, ν is the mean optical frequency, N is the number of measurements and y_i is the i^{th} frequency measurement.

Chapter 4

Results and Discussion

4.1 Results on laser output power measurements

The laser output powers of 532 nm laser beam were measured at various laser currents from 1.0 to 1.8 A and different Nd:YAG crystal temperatures of 22, 26, 30, 32 and 34 ^{o}C with a fixed PPKTP crystal temperature at 34 ^{o}C. The results are shown in Table 4.1

Table 4.1: Laser output power at 532 nm at various laser currents from 1.0 to 1.8 A and different Nd:YAG crystal temperatures with a fixed PPKTP crystal temperature at 34 ^{o}C.

Laser current (A)	Laser output power (mW)				
	Nd:YAG crystal temperature (^{o}C)				
	22	26	30	32	34
1.0	0.490	0.611	0.671	0.882	0.773
1.2	2.679	4.220	6.252	8.601	8.172
1.4	17.280	27.200	22.290	24.450	24.560
1.6	31.470	37.990	41.530	41.640	39.660
1.8	55.630	60.380	60.720	59.100	57.280

The relationship between laser output power and laser current at different Nd:YAG crystal temperatures is shown in Figure. 4.1

It can be seen from Figure 4.1 that at a low laser current from 1.0 to 1.2 A the laser output power increased slowly. Then, it increased rapidly from 1.2 to 1.8 A. It is observed that at Nd:YAG crystal temperature 30 ^{o}C the laser output power increased linearly with increasing laser current and reached a maximum power of 60.720 mW at 1.8 A.

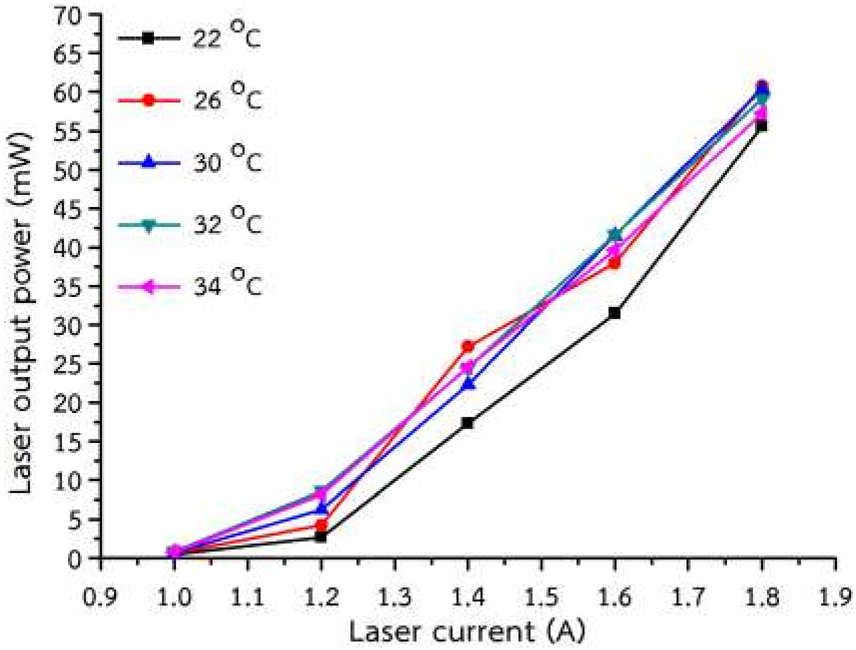


Figure 4.1 Relationship between laser output power and laser current at Nd:YAG crystal temperatures of 22, 26, 30, 32 and 34 °C

The results obtained from the laser output power measurements show that the optimum Nd:YAG crystal temperature that yields the maximum power is 30 °C. Further measurements were carried out by fixing Nd:YAG crystal temperature at 30 °C and PPKTP crystal temperature was varied from 22 to 34 °C. The results on the laser output power measurements are shown in Table 4.2.

Table 4.2: Laser output power at 532 nm and various laser currents from 1.0 to 1.8 A with different PPKTP crystal temperatures and fixed Nd:YAG laser crystal temperature at 30 °C.

Laser current (A)	Laser output power (mW)				
	PPKTP crystal temperature (°C)				
	22	26	30	32	34
1.0	0.542	0.565	0.968	1.789	0.918
1.2	0.892	0.962	1.529	4.962	6.442
1.4	1.139	1.155	1.377	5.890	22.570

1.6	1.363	1.441	1.587	5.240	41.690
1.8	1.652	1.861	2.404	8.857	60.770

The relationship between laser output power and laser current at different PPKTP crystal temperature is shown in Figure 4.2.

It is seen from Figure 4.2 that at a low laser current from 1.0 to 1.2 A. The laser output power increased slowly and almost constant throughout the varied laser current range for PPKTP crystal temperatures of 22, 26, 30 and 32 °C. However, the PPKTP at 34 °C showed rapid increase linearly of the laser output power from about 1 mW upto a maximum power of 60.770 mW at a laser current of 1.8 A. therefore, it can be concluded that the optimum operating temperatures for laser diode pumped-Nd:YAG laser are 30 °C and 34 °C for Nd:YAG crystal and PPKTP crystal, respectively.

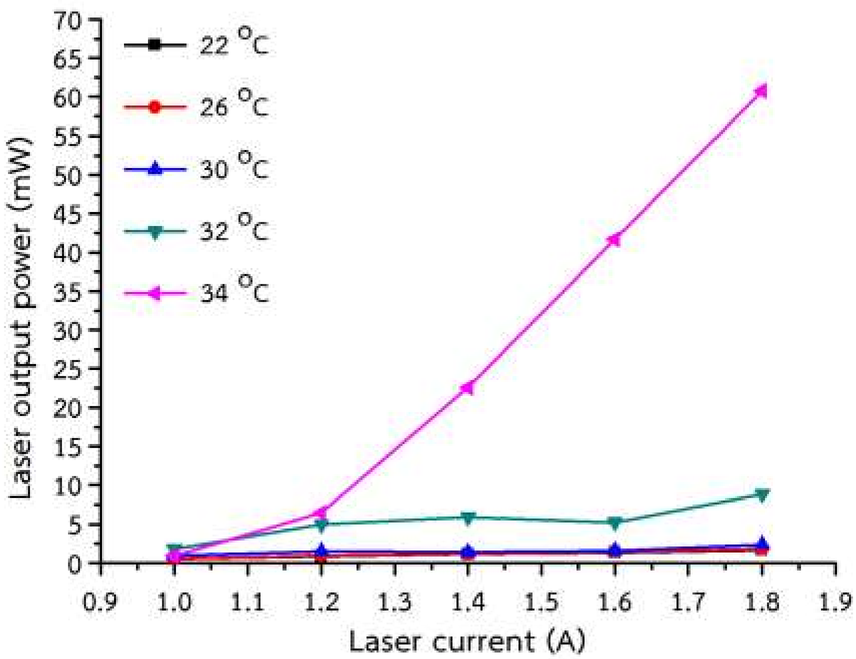


Figure 4.2 Relationship between laser output power and laser current at PPKTP crystal temperatures of 22, 26, 30, 32 and 34 °C

4.2 Results on wavelength measurements

The wavelengths of doubled frequency Nd:YAG or green laser beam were measured at various laser currents from 0.90 to 1.85 A and different Nd:YAG crystal temperatures of 22, 26, 30, 32 and 34 °C with a fixed PPKTP crystal temperature at 34 °C the results are shown in Table 4.3.

Table 4.3: Wavelength measurements at 532 nm at various laser currents from 0.90 to 1.85 A and different Nd:YAG crystal temperatures and fixed PPKTP crystal temperature at 34 °C

Laser current (A)	Wavelength (nm)				
	Nd:YAG crystal temperature (°C)				
	22	25	30	35	40
0.90	532.172490	532.178680	532.195540	532.202450	532.211660
0.95	532.184650	532.189810	532.196020	532.202990	532.222910
1.00	532.184250	532.190350	532.196450	532.214230	532.223310
1.05	532.184650	532.190720	532.207600	532.214700	532.234470
1.10	532.195800	532.201860	532.207960	532.225840	532.234800
1.15	532.196200	532.202190	532.219060	532.226190	532.245920
1.20	532.196570	532.213280	532.219360	532.237340	532.246240
1.25	532.207670	532.213550	532.225100	532.237680	532.246540
1.30	532.207940	532.213800	532.230720	532.238050	532.257640
1.35	532.208250	532.224940	532.231050	532.249170	532.258060
1.40	532.219380	532.225290	532.231420	532.249540	532.258450
1.45	532.219780	532.225690	532.242070	532.249990	532.258860
1.50	532.220230	532.226080	532.243010	532.250420	532.259310

1.55	532.220620	532.226460	532.243420	532.250850	532.270460
1.60	532.221010	532.226880	532.243830	532.251280	532.270870
1.65	532.221410	532.232620	532.244200	532.251710	532.271260
1.70	532.229500	532.238410	532.244580	532.258510	532.271630
1.75	532.232940	532.238800	532.254020	532.263240	532.272040
1.80	532.233340	532.239210	532.254130	532.263670	532.272440
1.85	532.233680	532.239540	532.254930	532.263980	532.272790

The variation of wavelength with laser current at different Nd:YAG crystal temperatures is shown in Figure 4.3.

For iodine molecules, there are many dominant hyperfine line of iodine molecule at 532 nm. However, the line number 1110 corresponding to R(56) 32-0 transition, a10 component, frequency = 563.260223513 THz and wavelength = 532.245036 nm was used as the reference line. From Figure 4.3, it can be observed that only at Nd:YAG crystal temperature of 30 ^{o}C give stable wavelength close to the reference wavelength value of 532.245036 nm. Furthermore, the optimum laser current is in the range 1.45 to 1.70 A

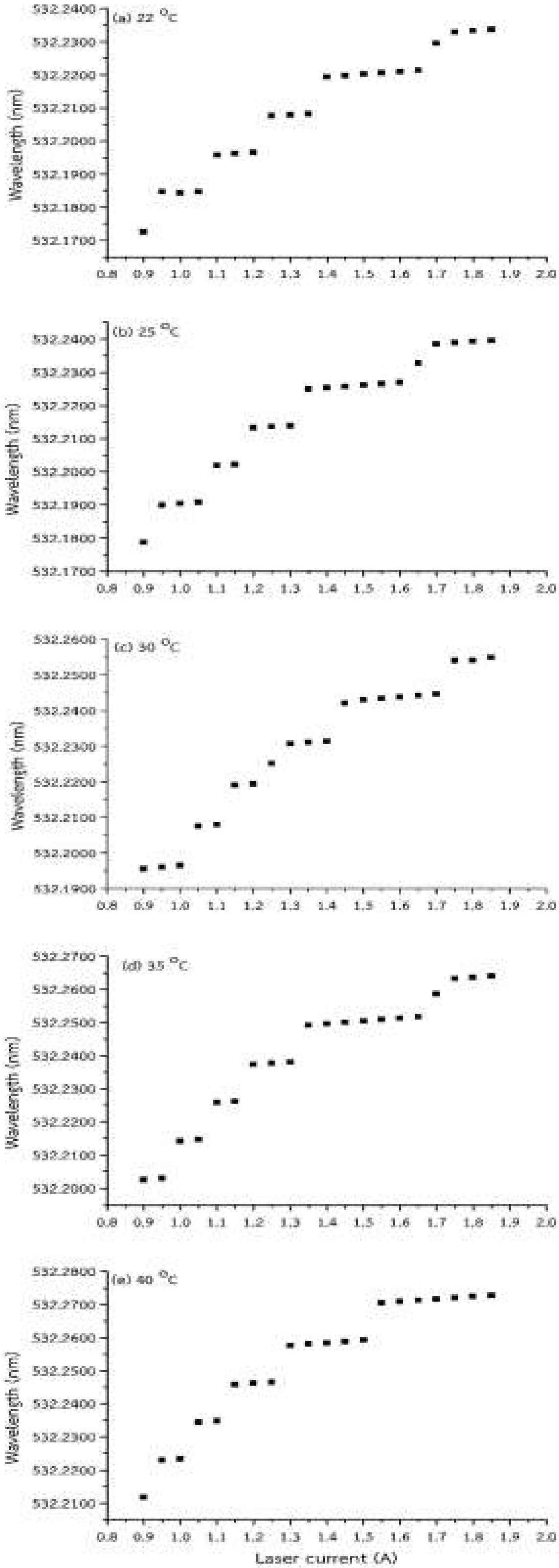

(a) 22 °C
(b) 25 °C
(c) 30 °C
(d) 35 °C
(e) 40 °C
Wavelength (nm)
Laser current (A)
0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0

Figure 4.3 Variation of wavelength with laser current at Nd:YAG crystal temperatures of: (a) 22, (b) 25, (c) 30, (d) 35 and (e) 40 °C

4.3 Effects of laser crystal temperature on laser output wavelength

The change of laser output wavelength at 532 nm was investigated by varying the temperature of Nd:YAG crystal from 22 to 41 °C at a step of 0.50 °C and the laser currents were set at 1.15, 1.50 and 1.85 A while the PPKTP crystal temperature was fixed at 34 °C. The results are shown in Table 4.4 and the variation of wavelength as a function of Nd:YAG crystal temperature is shown in Figure 4.4.

Table 4.4: Temperature dependence of laser output wavelength on Nd:YAG crystal temperature at different laser currents of 1.15, 1.50 and 1.85 A.

Nd:YAG crystal temperature (°C)	Laser output wavelength (nm)		
	Laser current (A)		
	1.15	1.50	1.85
22.00	532.1980210	532.2204710	532.2335570
22.50	532.2005640	532.2232310	532.2364980
23.00	532.2022470	532.2257910	532.2387340
23.50	532.2037090	532.2285640	532.2315100
24.00	532.1992750	532.2250000	532.2344010
24.50	532.1992850	532.2232770	532.2370900
25.00	532.2022340	532.2260520	532.2398430
25.50	532.2049600	532.2288290	532.2426010
26.00	532.2077050	532.2315740	532.2453760
26.50	532.2105080	532.2342550	532.2374720
27.00	532.2129380	532.2369970	532.2402830
27.50	532.2078110	532.2289120	532.2428450
28.00	532.2076740	532.2317290	532.2456080
28.50	532.2105700	532.2344350	532.2484960
29.00	532.2134030	532.2371600	532.2513150
29.50	532.2162360	532.2399000	532.2540720
30.00	532.2190540	532.2431230	532.2461080

30.50	532.2214660	532.2392400	532.2482280
31.00	532.2137370	532.2379890	532.2513880
31.50	532.2166450	532.2408260	532.2543840
32.00	532.2196870	532.2436640	532.2572840
32.50	532.2225470	532.2466070	532.2602000
33.00	532.2252440	532.2494960	532.2513840
33.50	532.2282900	532.2523100	532.2553320
34.00	532.2256780	532.2444320	532.2582380
34.50	532.2234680	532.2474020	532.2611750
35.00	532.2264510	532.2503860	532.2641200
35.50	532.2293710	532.2532850	532.2671220
36.00	532.2323780	532.2562900	532.2648080
36.50	532.2349840	532.2593290	532.2623180
37.00	532.2382870	532.2517150	532.2652970
37.50	532.2305890	532.2545160	532.2682820
38.00	532.2336820	532.2578190	532.2714410
38.50	532.2367330	532.2609310	532.2740630
39.00	532.2399380	532.2639630	532.2748470
39.50	532.2430130	532.2670970	532.2698930
40.00	532.2462320	532.2595430	532.2731100
40.50	532.2383490	532.2627320	532.2763280
41.00	532.2417810	532.2659870	532.2795590

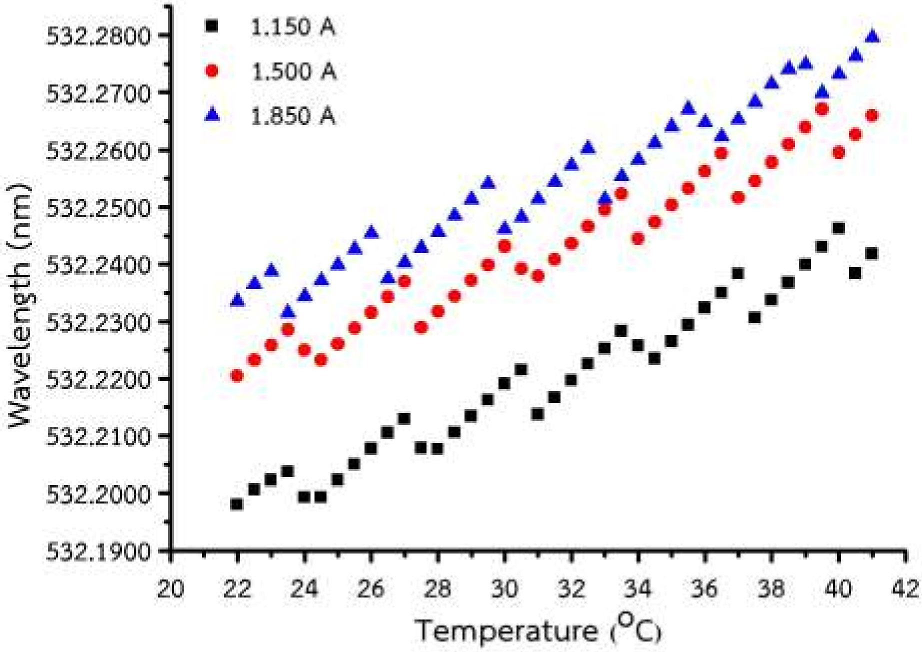


Figure 4.4 Variation of laser output wavelength as a function of Nd:YAG crystal temperature

It is seen from Fig. 4.4 that the wavelength increased and decreased alternatively as the Nd:YAG crystal temperature was increased. Furthermore, at some temperature ranges the wavelength was remained constant. This phenomena is called mode jump.

4.4 Results on iodine-stabilized diode laser-pumped Nd:YAG laser at 532 nm

From Figure 3.18, 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 4.5 shows the variation of wavelength with time at room temperature for iodine cells with the lengths of 10 and 50 cm.

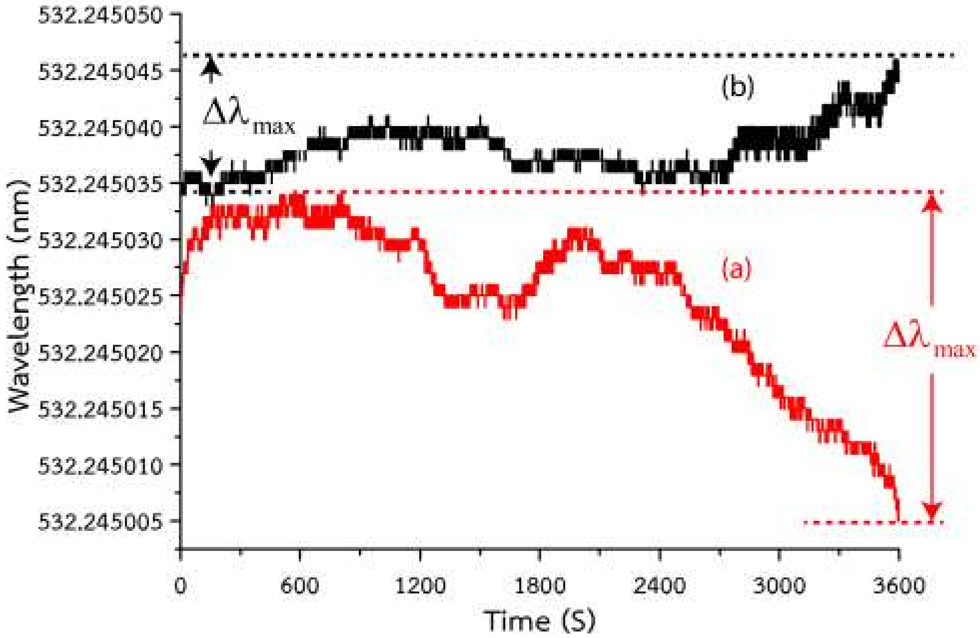


Figure 4.5 Variation of wavelength with time at room temperature for: (a) 10 cm long and (b) 50 cm long iodine cells.

From Figure 4.5, it is seen that high fluctuation of wavelength is observed for both iodine cells at room temperature (20^{o}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 x 10^{-6} and 13 x 10^{-6} nm for 10 cm long iodine cell and 50 cm long iodine cell, respectively.

Figure 4.6 shows a typical variation of wavelength with time at -5^{o}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 4.5.

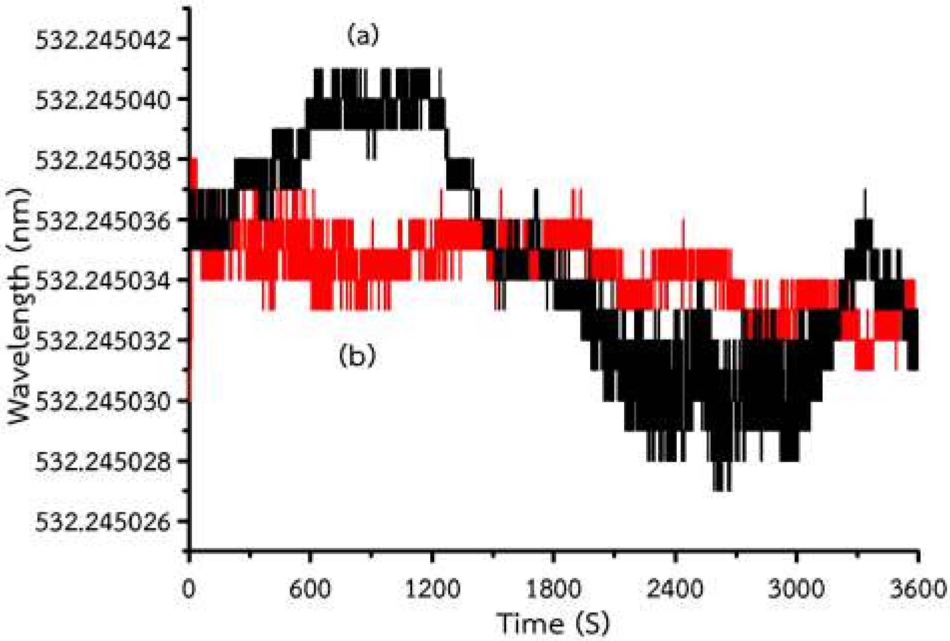


Figure 4.6 Variation of wavelength with time at -5 C^{o} for:(a) 10 cm long and (b) 50 cm long iodine cells.

Table 4.5: Maximum variations of wavelength ($\Delta\lambda_{max}$) at different iodine cell temperatures for 10 cm long and 50 cm long iodine cells.

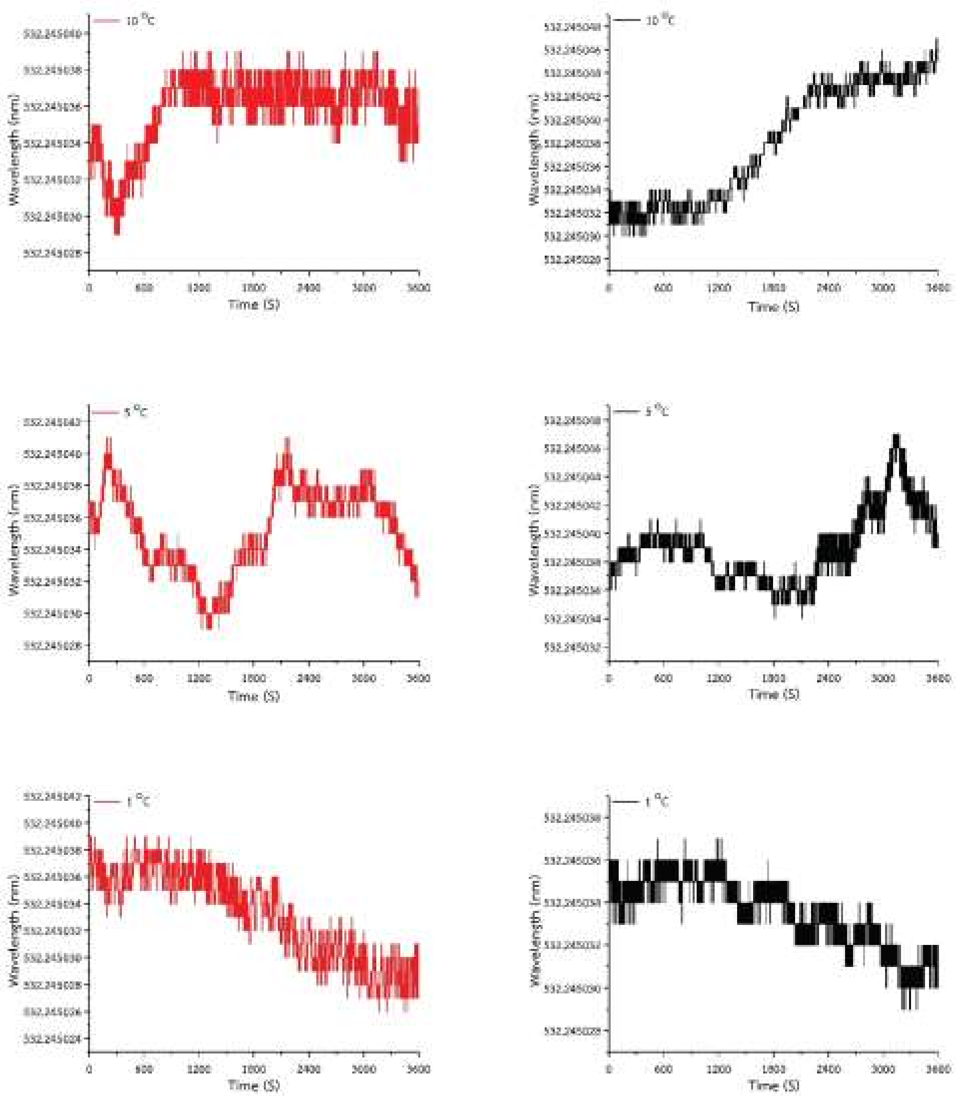
Iodine cell temperature (°C)	$\Delta\lambda_{max}$ x10^{6} (nm)	
	10 cm	50 cm

20	34	13
10	10	11
5	13	10
1	11	8
-1	9	9
-3	8	6
-5	10	4

Table 4.5 shows the maximum variation of wavelength at different iodine cell temperatures of 20, 10, 5, 1, -1, -3 and -5 ^{o}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 x 10^{-6} and 4 x 10^{-6} nm were obtained at -5 ^{o}C for 10 cm long iodine cell and 50 cm long iodine cell, respectively.

Figure 4.7 shows the variation of wavelength with time at iodine cell temperatures of 10, 5, 1, -1, -3 and -5 °C for iodine cell with the lengths of 10 and 50 cm.

(a) (b)



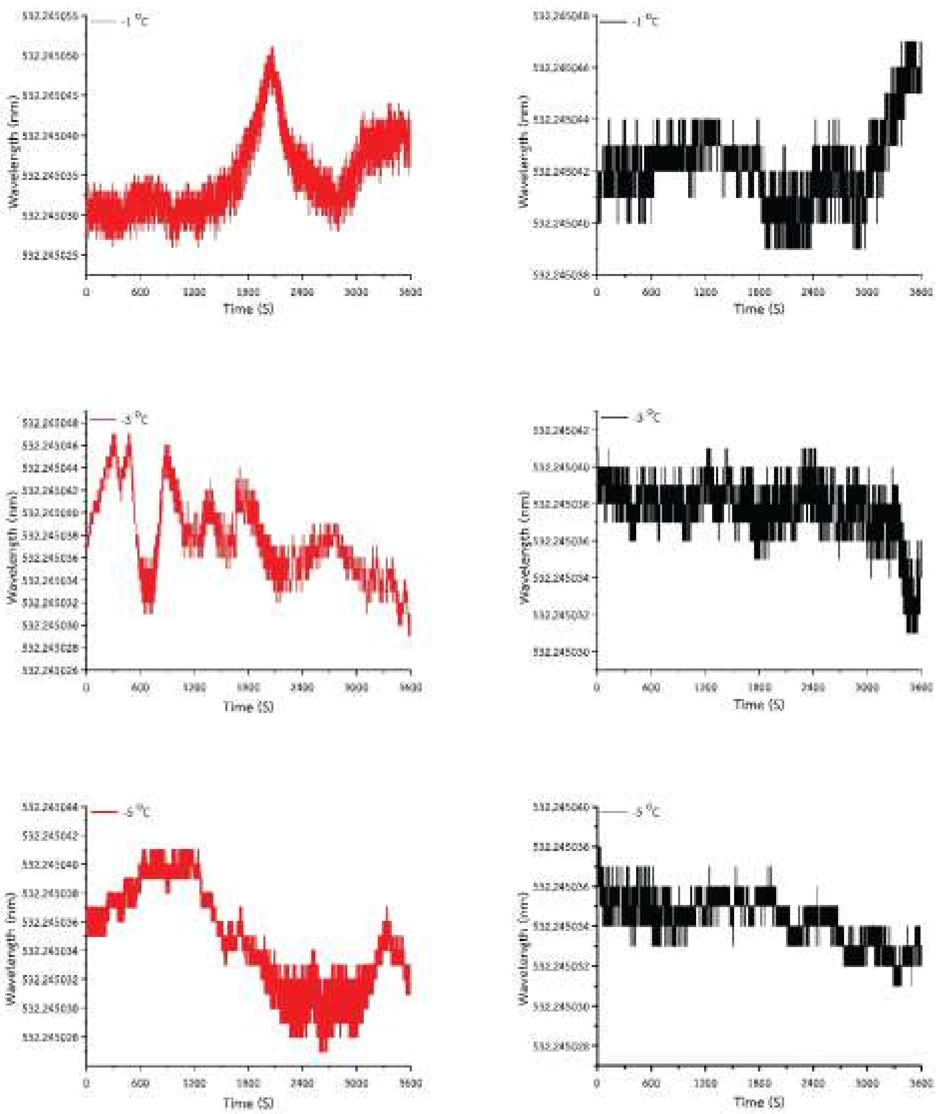


Figure 4.7 Variation of wavelength with time during one hour period was carried out at different iodine cell temperatures of 10, 5, 1, -1, -3 and -5 °C for iodine cell with the lengths of: (a) 10 and (b) 50 cm.

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 Eq.

(1). Table 4.6 shows the Allan standard deviation at different iodine cell temperatures for both iodine cells and the plots are shown in Figure 4.8.

Table 4.6: 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

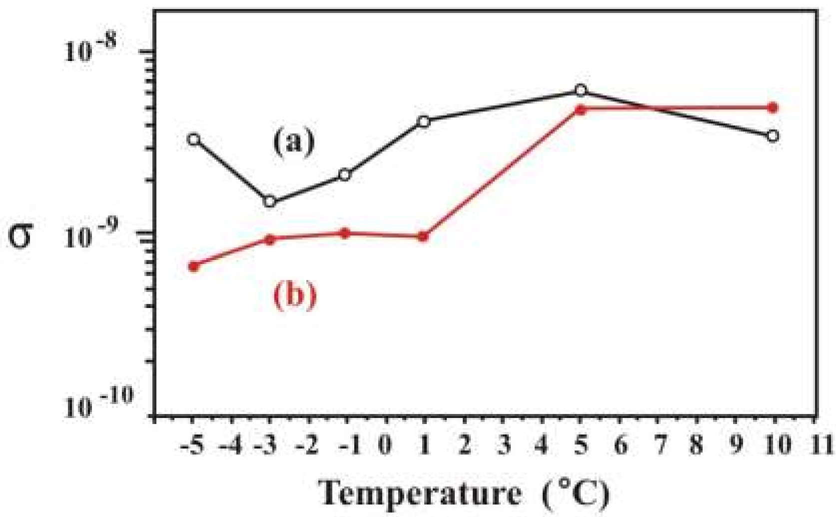


Figure 4.8 Allan standard deviation as a function of the temperature for: (a) 10 cm long and (b) 50 cm long iodine cells.

From the results of the frequency stability measurements as shown in Table 4.6 and Figure 4.8 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 x 10^{-9} and 0.6643 x 10^{-9} were obtained at -5 ^{o}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^{o}C. The results of the frequency stability measurements are in good agreement with the fluctuation of wavelength measurements.

From Figure. 4.8, it is clearly seen that the lowest standard deviation value is obtained at -5^{o}C for both iodine cells. Therefore, further measurements were carried out by varying measuring time from 1 s to 128 s. Then, the Allan standard deviation was determined and the results are shown in Table 4.7 and the plots are shown in Figure 4.9.

Table 4.7: Allan standard deviation determined from measuring time of 1 to 128 s at -5^{o}C for 10 cm long and 50 cm long iodine cells.

Time (s)	σ x 10^{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

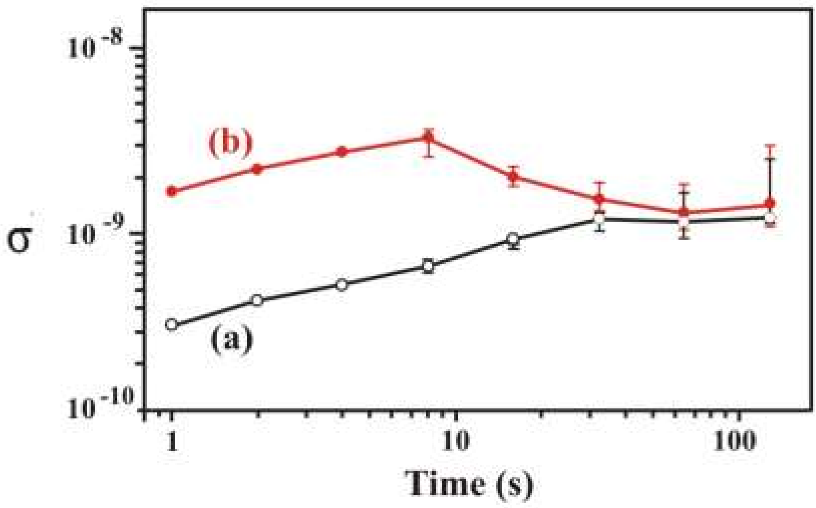


Figure 4.9 Allan standard deviation as a function of the measuring time at -5 C^{o} for: (a) 10 cm long and (b) 50 cm long iodine cells.

Table 4.7 and Figure 4.9 show the standard deviation value (σ) for 10 cm long iodine cell and 50 cm long iodine cell at -5^{o}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^{o}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^{o}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 4.8 and the plots are shown in Figure 4.10.

Table 4.8: Variation of pressure with iodine temperature.

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

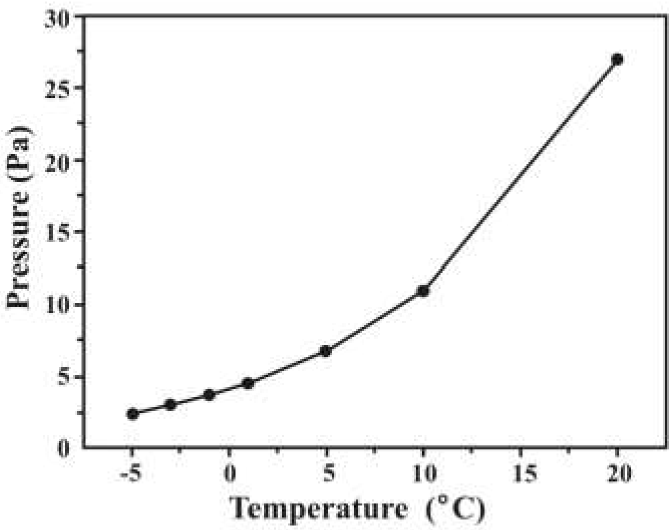


Figure 4.10 Relationship between pressure and temperature of iodine.

In this work, 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 work. The lowest Allan standard deviation of 0.6643 x 10^{-9} obtained at -5°C for 50 cm long iodine cell is quite high compared with previous values as reported in the literatures [17, 22, 44, 45, 50, 51, 53, 54, 56, 61]. 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.

Chapter 5
Conclusion

The objectives of this study are: (1) To study the characteristics of diode laser pumped-Nd:YAG laser, and (2) To use the iodine cell for frequency stabilization of Nd:YAG laser system at various temperatures.

The diode laser pumped-Nd:YAG laser used in this work is a commercial frequency doubling Nd:YAG laser (Innolight, Prometheus 50 NE), emitting 100 mW of power at 532 nm and > 500 mW of power at 1064 nm. The wavelength of pump diode laser is 708 nm. The second harmonic generation (SHG) crystal is potassium titanyl phosphate (PPKTP).

5.1 Conclusions on characteristics study

The measurements of characteristics of diode laser-pumped Nd:YAG laser include the measurement of the laser output power 532 nm and the wavelength measurement at 532 nm.

The output powers of laser beam at 532 nm were measured using a laser power meter by varying diode laser current from 1.0 to 1.8 A with different Nd:YAG crystal temperatures of 22, 26, 30, 32, and 34 ^{0}C and PPKTP crystal temperature was fixed at 34 ^{0}C. From the first measurement, the optimum Nd:YAG crystal temperature that yields the maximum laser output power is obtained. It was found that the maximum power id obtained at Nd:YAG crystal temperature of 30°C. Then, the laser output power measurements were repeated at different PPKTP crystal temperatures of 22, 26, 30, 32, and 34 ^{0}C and the Nd:YAG crystal temperature was fixed at 30 ^{0}C.

The results obtained from the laser output power measurements show that the optimum Nd:YAG crystal temperature that yields the maximum power is 30 ^{o}C. Further measurements were carried out by fixing Nd:YAG crystal temperature at 30 ^{o}C and PPKTP crystal temperature was varied from 22 to 34 ^{o}C.

The relationship between laser output power and laser current at different PPKTP crystal temperature was determined. It was found that at a low laser current from 1.0 to 1.2 A. The laser output power increased slowly and almost constant throughout the varied laser current range for PPKTP crystal temperatures of 22, 26, 30 and 32 ^{o}C. However, the PPKTP at 34 ^{o}C showed rapid increase linearly of the laser output power from about 1 mW upto a maximum power of 60.770 mW at a laser current of 1.8 A. therefore, it can be concluded that the optimum operating temperatures for laser diode pumped-Nd:YAG laser are 30 ^{o}C and 34 ^{o}C for Nd:YAG crystal and PPKTP crystal, respectively.

The wavelength of laser beam was measured by a wavelength meter which connected to a computer for data processing. A filter was put between the objective lens and the laser head to attenuate the intensity of laser light. The wavelength at 532 nm of doubled frequency Nd:YAG or green laser beam was measured at various laser currents from 0.90 to 1.85 A and different Nd:YAG crystal temperatures of 22, 26, 30, 32 and 34 ^{o}C with a fixed PPKTP crystal temperature at 34 ^{o}C.

For iodine molecules, there are many dominant hyperfine line of iodine molecule at 532 nm. However, the line number 1110 corresponding to R(56) 32-0 transition, a10 component, frequency = 563.260223513 THz and wavelength = 532.245036 nm was used as the reference line.

The variation of wavelength with laser current at different Nd:YAG crystal temperatures was carried out. It was found that only at Nd:YAG crystal temperature of 30 ^{o}C give stable wavelength close to the reference wavelength value of 532.245036 nm. Furthermore, the optimum laser current is in the range 1.45 to 1.70 A. In addition, it was found that the wavelength increased and decreased alternatively as the Nd:YAG crystal temperature was increased. Furthermore, at some temperature ranges the wavelength was remained constant. This phenomena is called mode jump.

5.2 Conclusions on iodine-stabilized diode laser-pumped Nd:YAG laser at 532 nm

In this work, 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^{o}C were measured and determined.

The servo controller 1 was locked to the a_{10} 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 ^{o}C. The variation of wavelength with time at room temperature for iodine cells with the lengths of 10 and 50 cm shows that high fluctuation of wavelength is observed for both iodine cells at room temperature (20^{o}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 x 10^{-6} and 13 x 10^{-6} nm for 10 cm long iodine cell and 50 cm long iodine cell, respectively.

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 x 10^{-6} and 4 x 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, 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 x 10^{-9} and 0.6643 x 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.

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 was calculated. It is seen that the standard deviation value (σ) increases slowly from the 1^{st} second to the 32^{nd} second then it is almost constant from 32^{nd} to 128^{th} 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 for 50 cm long iodine cell, the standard deviation value (σ) decreased from 4.8829 x 10^{-9} to 0.6643 x 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.

Finally, 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 work. 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. 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.

References

[1] J. Helmcke, "Realization of the metre by frequency-stabilized laser", Meas. Sci. Technol. vol. 14, 1187-1199, (2003).

[2] John L. Hall, "Optical frequency measurement: 40 years of technology revolutions", IEEE Journal on selected topic in quantum electronics, vol. 6, no. 6, 1136-1144, (2000).

[3] R. Felder, "Practical realizatio of the definition of the metre, including recommended radiations of other optical frequency standards (2003)", Metrologai, vol. 42, no. 4, 5-323, (2005).

[4] W. Demtroder,. Laser spectroscopy - Basic concepts and instrumentation, Fourth Edition (2008).

[5] E. Jaatinen and N. Brown, "A simple external iodine stabilizer applied to 633 nm, 612 nm and 543 nm He-Ne lasers", Metrologai, vol. 32, 95-101, (1995).

[6] A. Thorne, U. Litzen and S. Johansson, Spectrophysics: Principles and Applications, (1999).

[7] E. Jaatinen and J.-M. Chartier, "Possible influence of residual amplitude modulation when using modulation transfer with iodine transitions at 543 nm", Metrologia, vol. 35, 75-81, (1998).

[8] JILA, JILA website: http://jilawww.colorado.edu/, webmater@jila.colorado.edu, (2006).

[9] E. Jaatinen and N. Brown, "Sequential frequency locking of three He-Ne lasers with one external iodine stabilizer", Metrologai, vol. 34, 309-312, (1997).

[10] E. Jaatinen and N. Brown, "Stabilised Helium-Neon lasers for measurement of Gauge block", Australian Optical Society News, vol. 12, no. 2, 25-28, (1998).

[11] E. Jaatinen, "NML's 532 nm Primary wavelength standard", CSIRO Telecommunications & Industrial Physics Technology Measurement, (2001).

References (cont.)

[12] Y. Zhang, J. Ishikawa and F.L. Hong, "Accurate frequency atlas of molecular iodine near 532 nm measured by an optical frequency comb generator", Optics Communications, no. 200, 209-215, (2004).

[13] A. Y. Nevaky, et al., "A Nd:YAG laser with short-term frequency stability at the Hertz-lrvrl", Optics Communications, no. 210, 91-100, (2002).

[14] M. V. Okhapkin, et al., "Tunable single-frequency didoe-pumped Nd:YAG ring laser at 1064/532 nm for optical frequecny standard applications", Optics Communications, no. 203, 359-362, (2002).

[15] F. L. Hong and J. Ishikawa, "Hyperfine structures of the R(122)35-0 and P(84)33-0 transitions of $^{127}I_2$ near 532 nm", Optics Communications, no. 183, 101-108, (2000).

[16] A. Y. Nevaky, et al., :Frequency comparison and absolute frequency measurement of I2-stabilized lasers at 532 nm", Optics Communications, no. 192, 263-272, (2001).

[17] S. Picard, et al., "Results from international comparisons at the BIPM providing a World-wide reference network of $^{127}I_2$ stabilized frequency-doubled Nd:YAG lasers",

IEEE Transactions on Instrumentation and Measurement, vol. 52, no. 2, 236-239, (2003).

[18] F. L. Hong, et al., "Frequency comparison of $^{127}I_2$ stabilized Nd:YAG lasers", IEEE Transactions on Instrumentation and Measurement, vol. 48, no. 2, 532-536, (1999).

[19] K. Nyholm, et al., "Frequency stabilization of a diode-pumped Nd:YAG laser at 532 nm to iodine by using Third-Harmonic technique", IEEE Transactions on Instrumentation and Measurement, vol. 52, no. 2, 284-287, (2003).

[20] F. L. Hong, et al., "Comparison of independent optical frequency measurements using a portable iodine-stabilized Nd:YAG laser", IEEE Transactions on Instrumentation and Measurement, vol. 52, no. 2, 240-244, (2003).

References (cont.)

[21] P. Laporla, et al., "Amplitude and frequency stabilized solid-state lasers in the near infrared", Journal of Physics D: Applied Physics, on. 34, 2396-2407, (2001).

[22] A. Arie and R.L. Byer, "Laser heterrodyne spectroscopy of $^{127}I_2$ hyperfine structure near 532 nm", Journal of the Optical Society of America B, Vol. 10, on. 11, 1990-1997, (1993).

[23] J. L. Hall and J. Ye, "Optical frequency standards and measurement", IEEE Transactions on Instrumentation and Measurement, vol. 52, no. 2, 227-231, (2003).

[24] L. S. Ma, et al., "The BIPM laser standards at633 nm and 532 nm simultaneously linked to the SI second using a femtosecond laser in an optical clock configuration", IEEE Transactions on Instrumentation and Measurement, Vol. 52, no. 2, 232-235, (2003).

[25] T. J. Quinn, "Practical realization of the definition of the metre, including recommended radiations of other optical frequency standards (2001)", Metrologia, vol. 40. no. 2, 33-103, (2001).

[26] A. Brillet and P. Cerez, "Laser frequency stabilisation by saturated absorption", Journal de Physique, vol. A2, on. 8, 73-82, (1981).

[27] E. Jaatinen, "Origin of pressure induced frequency shifts in optical frequency reference laser- a description", QUT-School of Physical Science, (2003).

[28] U. Brand, "Frequency stabilisation of a HeNe laser at 534.5 nm wavelength using frequency-modulation spectroscopy", Optics Communications vol. 100, 361-373, (1993).

[29] G. Camy, C. J. Borde and M. Ducloy, "Heterodyne saturation spectroscopy through frequency modulation of the saturating beam", Optics Communications vol. 41, on. 5, 325-330, (1982).

[30] M. D. Levenson, W. F. Moerner and D. E. Horne, " FM spectroscopy detection of stimulated Raman gain", Optics Letters, vol. 8, on. 2, 108-110, (1983).

References (cont.)

[31] G. C. Bjorklund and et. al., " Frequency modulation (FM) spectroscopy", Applied Physics B, vol. 32, 145-152, (1983).

[32] E. Jaatinen and N. Brown, "Primary wavelength standards for direct measurement of gauge blocks", Proceedings of SPIE conference, vol. 3477, 18-24, (1998).

[33] G. R. Janik, C. B. Carlislee and T. F. Gallagher, "Two-tine frequency-modulation spectroscopy", Journal of the Optical Society of America B, vol. 3, on. 8, 1070-1074, (1986).

[34] A. J. Wallard, "Frequency stabilisatioin of the helium-neon laser by saturated sbsorption in iodine vapor", Physics E: Scientific Instruments, vol. 5, 926-930, (1972).

[35] C. S. Gudeman and et. al., "Tone-burst modulated color-center laser spectroscopy", Optics Letters, vol. 8, 310, (1983).

[36] A. N. Dharamsi, " A theory of modulation spectroscopy with appilcations of higher harmonic detection", Journal of Physics D: Applied Physics, vol. 29, 540-549, (1996).

[37] J. H. Shirley, "Modulation transfer processes in optical heterodyne saturation spectroscopy", Optics Letters, vol. 7, on. 11, 537-539, (1982).

[38] Gary C. Bjorklund., "Frequency-modulation spectroscopy: a new method for measuring weak absorptions and dispersions", Optics Letters, vol. 5, 15-17, (1980).

[39] Ma Long-Sheng and J. L. HALL, IEEE Journal of Quantum Electronic, vol. 26, no. 11, (1990).

[40] Ady Arie and Robert L. Byer., "Laser heterodyne spectroscopy of $^{127}I_2$ hyperfine structure near 532 nm", J. Opt. Soc. Am. B, vol.10, no. 11, 1990-1997, (1993).

[41] Mark L. Eickkhoff and J. L. Hall., "Optical frequency standard at 532 nm", IEEE Transactions on Instrumentation and Measurement, vol. 44, no. 2, 155-158, (1995).

References (cont.)

[42] A. Yu. Nevsky, R. Holzwarth, J. Reichert, Th. Udem, T.W. Hansch, J. von Zanthier, H. Walther, H. Schnatz, F. Riehle, P.V. Pokasov, M.N. Skvortsov and S.N. Bagayev., "Frequency comparison and absolute frequency measurement of I2-stabilized lasers at 532 nm", Optics Communications, vol. 192, 263-272, (2001).

[43] Jun Ye, Long Sheng Ma and John L. Hall., "Ultrastable optical frequency reference at 1.064 micrometer using a C_2HD molecular overtone transition", IEEE Transactions on Instrumentation and Measurement, vol. 46, 178-182, (1997).

[44] P. Cordiale, G. Galzerano and H. Schnatz., "International comparison of two iodine-stabilized frequency-doubled Nd:YAG lasers at λ=532 nm", Metrologia, vol. 37, 177-182, (2000).

[45] K. Doringshoff, M. Reggentin, E.V. Kovalchuk, M. Nagei, A. Keetman, T. Schuldt, C. Braxmaier and A. Peters., "Iodine based optical frequency reference with 10^{-15} stability", IEEE, 419-421, (2012).

[46] V.B. Tiwari, .R. Mishra, H.S. Rawat, S. Singh. S.P. Ram and S.C. Mehendale, "Laser frequency stabilization and large detuning by Doppler-free dichroic lock technique: Application to atom cooling", Pramana-Journal of physics, vol. 65, no. 30, 403-411, (2005).

[47] C.S. Edward, G.P. Barwood, P. Gill, F. Rodriguez-Llorente and W.R.C. Rowley, " Frequency-stabilised didoe lasers in the visible region using Doppler-free iodine spectra", Optics Communications, vol. 132, no. 1-2, 94-100, (1996).

[48] S.N. Lea, W.R.C. Rowley, H.S. Margolis, G.P. Barwood, G. Huang, P. Gill, J.M. Chartier and R.S. Windeler, "Absolute frequency measurements of 633 nm iodine-stabilized helium-neon lasers", Metrologia, vol. 40, no. 84-88, (2003).

[49] A. Arie and R.L. Byer, "Absolute Frequency Stabilization of Diode-Pumped Nd:YAG Lasers", Laser Physics, vol. 4, no. 2, 387-391, (1994)

[50] M.L. Eickhoff and J.L. Hall, "Optical frequency standard at 532 nm", Ieee Transactions on Instrumentation and Measurement, vol. 44, no.2, 155-158, (1995).

References (cont.)

[51] F.L. Hong, J. Ishikawa, T.H. Yoon, L.S. Ma, J. Ye and J.L. Hall, " A portable 1_2-stabilized Nd:YAG laser for wavelength standards at 532 nm and 1064 nm", Proceeding of SPIE, vol. 3477, 1-10, 1998.

[52] F.L. Hong and J. Ishikawa, " Hyperfine structures of the R(122)35-0 and P(84)33-0 transitions of $^{127}I_2$ near 532 nm", Optics Communications, vol. 183, no. 1-4, 101-108, (2000).

[53] G.D. Rovera, F. Ducos, J.J. Zondy, O. Acef, J.P. Wallerand, J.C. Knight and P.St.J. Russeil, " Absolute frequency measurement of an I_2 stabilized Nd:YAG optical frequency standard", Measurement science and technology, vol. 13, 918-922, (2002).

[54] F.L. Hong, J. Ishikawa, K. Sugiyama, A. Onae, H. Matsumoto, J. Ye and J.L. Hall, " Comparison of independent optical frequency measurements using a portable iodine-stabilized Nd:YAG laser", Ieee Transactions on Instrumentation and Measurement, vol. 52, no. 2, 240-244, (2003).

[55] F.L. Hong, ., S. Diddams, R. Guo, Z.Y. Bi, A. Onae, H. Inaba, J. Ishikawa, K Okumura, D. Katsuragi, J. Hirata, T. Shimizu, T. Kurusu, Y. Koga and H. Matsumoto, " Frequency measurements and hyperfine structure of R(85)33-0 transition of molecular iodine with a femtosecond optical comb", the Journal of the Optical Society of America B, vol. 21, no. 1, 88-95, (2004).

[56] L. Robertsson, L.S. Ma and S. Picard, " Improved iodine-stabilized Nd:YAG lasers Proceeding", of SPIE, vol. 4269, 268-271, (2001).

[57] J.J. Snyder, R.K. Raj, D. Bloch and M. Ducloy, " High-sensitivity nonlinear spectroscopy using a frequency-offset pump", Optics letters, vol. 5, no. 4, 163-165, (1980).

[58] R.K. Raj, D. Bloch, J.J. Snyder, G. Camy and M. Ducloy, " High-frequency optically heterodyned saturation spectroscopy via resonant degenerate four-wave mixing ", Physical review letters, vol. 44, no. 19, 1251-1254, (1980).

References (cont.)

[59] H. Schnatz and F. Mensing, " Iodine-stabilized frequency-doubled Nd:YAG lasers at λ=532 nm; design and performance", Proceeding of SPIE, vol. 4269, 239-247, (2001).

[60] A. Schenzle, R.G. Devoe and R.G. Brewer, " Phase-modulation laser spectroscopy", Physical Review A, vol. 25, no. 5, 2606-2621, (1982).

[61] Y. Bitou, K. Sasaki, S. Iwasaki and F.L. Hong, "Compact I_2-stabilized frequency-doubled Nd:YAG laser for long gauge block interferometer", Journal of applied physics, vol. 42, no. 5A, 28667-2871, (2003).

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Investigation of the characteristic of the Nd:YAG laser for standard wavelength in metrology

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Keywords: Nd:YAG laser, second harmonic, stabilized laser

Abstract. This research studied characteristics of the Nd:YAG laser with second harmonic generation (SHG) at 532 nm. It can be develop as a standard wavelength according to the recommendation made by the Comite′ International des Poids et Measures (CIPM). This study investigates various parameters that effect wavelength and laser power of the Nd:YAG laser such as injection current of diode laser, temperature of Nd:YAG crystal and second harmonic generator crystal. Its wavelength can be tuned in the range of standard wavelength at 532.24503 nm with 10^{-7} of stability.

Introduction

In recent years, using the absorption of energy levels at a_{10} from R(56)32-0 of Iodine spectrum ($^{127}I_2$) wavelength 532.2450361 nm, the standard wavelength at 532 nm has been developed by the International Committee for Weights and Measures, (CIPM) for using in metrology [1-3]. Due to its compact size, diode-laser-pumped frequency doubled Nd:YAG laser has been interested for using in this work. Then, It is important to study all parameters, i.e. laser diode current, laser crystal temperature, and doubling crystal temperature, for operating this laser [4-5].

Experimental Setup

The experimental setup was shown in Fig. 1. The laser system used in this work is a commercial frequency doubling Nd:YAG laser (Innolight Prometheus 50 NE), emitting 100 mW of power at 532 nm and > 500 mW of power at 1064 nm. A partly reflective mirror has been inserted for reducing the high intensity laser beam at 1064 nm generated from Nd:YAG crystal. To get rid of the transmitted light, a noise eater circuit has been used. Then, the reflected infrared beam has been focused into a nonlinear PPKTP crystal to generate the second harmonic wavelength at 532 nm. The 1064 nm and 532 nm output light source were separated inside the laser using dichroic mirrors and the 1064 nm output light source is terminated using a beam trap [6].

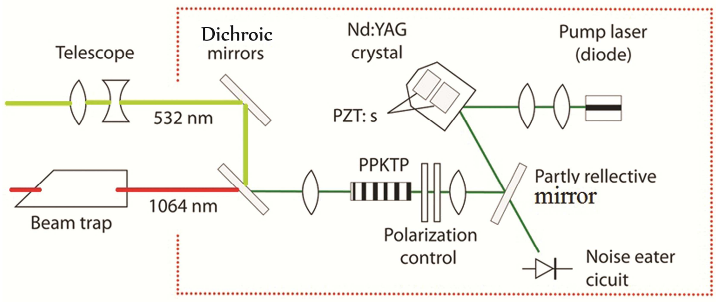

Fig. 1. Schematic diagram of the frequency doubling Nd:YAG laser.

The output beam (at 532 nm) power has been measured by a laser power meter (Tuner laser power mater model Tuner) when varying diode laser current from 0.700 to 1.850 A with different laser crystal temperatures (22, 26, 30, 32, and 34 ^{0}C) by fixing PPKTP crystal temperature at 34 ^{0}C. Then the experiment has been repeated by varying the PPKTP crystal temperatures (22, 26, 30, 32, and 34 ^{0}C) and fixing the laser crystal temperature at 30 ^{0}C as shown in Fig. 2 (a).

Next, the output wavelength has been measured by using a wavelength meter (High Finesse type WS-7) with connect to a computer for processing the data. A filter has been put between the objective lens and the laser head to attenuate the output power light. The experiment has been done by fixing temperature of PPKTP crystal at 34 ^{0}C, and different the laser diode current at 1.150 A, 1.500 A, and 1.850 A with varying laser crystal temperatures from 22 ^{0}C to 41 ^{0}C. Furthermore, the experiment has been done by fixing the PPKTP crystal temperature at 34 ^{0}C, with different laser crystal temperatures at 22, 25, 30, 35, and 40 ^{0}C and varying laser diode current from 0.900 A to 1.850 A as show in Fig. 2 (b).

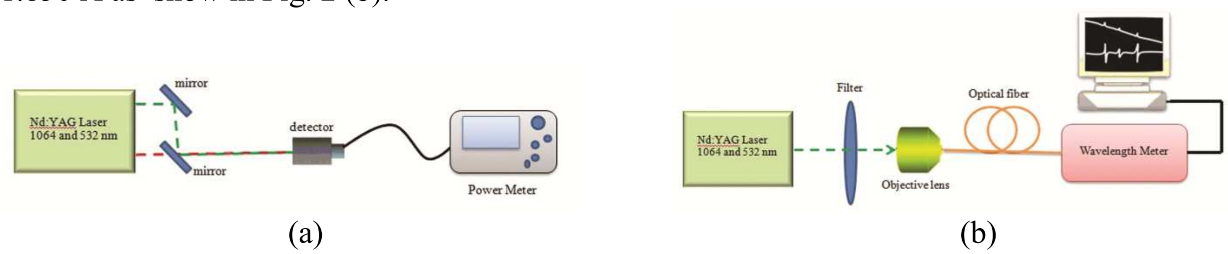

Fig. 2. Schematic diagrams of the experimental setup. (a) Shown the Nd:YAG laser for measuring laser power when varies the optical parameters. (b) Shown the Nd:YAG laser for measuring the output wavelength when varies the input wavelength range.

Results and Discussion

The efficiency of Nd:YAG laser is depended on the laser diode currents and laser crystal temperature of output power laser. The Fig. 3 shows the characteristics of the output power laser varying of laser diode currents with increasing of laser diode currents under different laser crystal temperatures when the temperature of PPKTP crystal has been fixed at 34 ^{0}C. Furthermore, A maximum continuous wave (CW) output power is equal to 95.130 mW at current of the diode laser be 1.850 A with laser crystal temperatures at 30 ^{0}C. The variations of all plots at different crystal temperatures are linear and the output powers at different diode laser currents are almost the same.

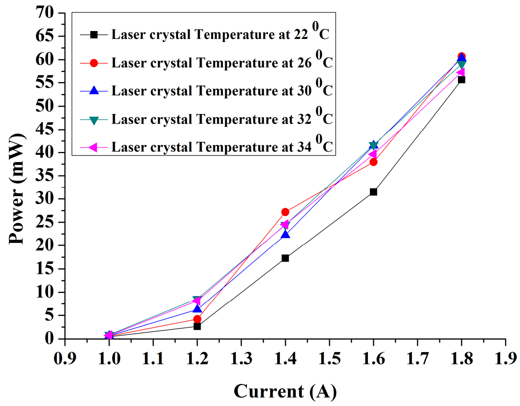

Fig. 3. Output power of the Nd:YAG laser with varying of the pumping laser diode currents under different laser crystal temperature by fixed PPKTP crystal temperature at 34 ^{0}C.

The Fig. 4 shows the plot of output powers with varying laser diode currents at different PPKTP crystal temperatures with fix laser crystal temperature at 30 ^{0}C. When the PPKTP crystal power is equal to 34 ^{0}C, the output powers have been increased with large slope with varying laser diode current. Furthermore, at the laser diode current be 1.850 A the maximum power is equal to 93.600 mW.

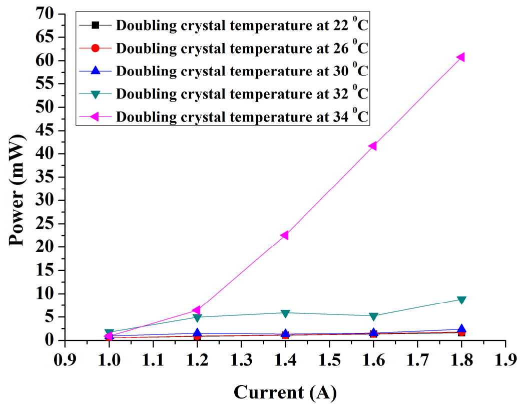

Fig. 4. Output power of Nd:YAG laser with varying of the pumping laser diode currents under different PPKTP crystal temperature by fixed laser crystal temperature at 30 ^{0}C.

The variation of wavelength of laser diode radiation with increase of laser crystal temperature under different laser diode currents has shown in Fig. 5. With fixing PPKTP crystal temperature at 34 ^{0}C, the output wavelength has been increased with temperature of laser crystal at different laser diode currents. The output wavelengths have been increased with laser diode current. With all different laser diode current, the mode-hops have been founded at some laser crystal temperatures as shown in Fig. 5. The changing rate of wavelength with temperature is approximately equal to 0.07 nm/^{0}C.

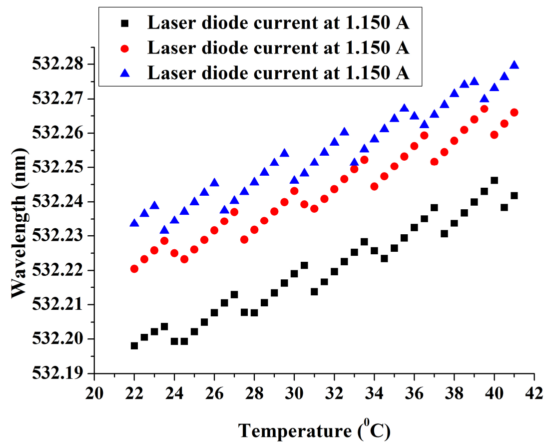

Fig. 5. Wavelength of the Nd:YAG laser variation with laser crystal temperature under different laser diode currents by fixed PPKTP crystal temperature at 34 ^{0}C.

At every laser crystal temperature, the wavelength has been increased with the laser diode current as step function with fixing PPKTP crystal temperature at 34 ^{0}C as shown in Fig 6.

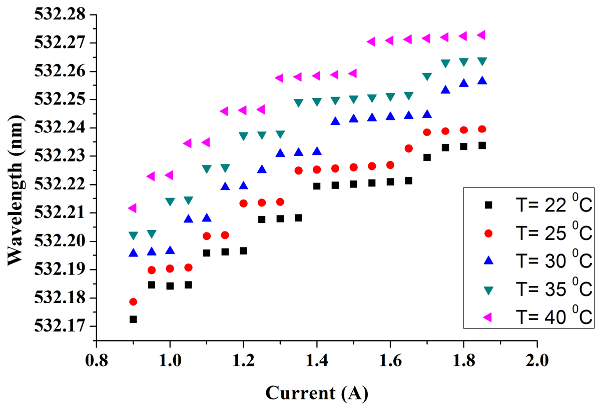

Fig. 6. Wavelength of laser diode variation laser diode currents under different laser crystal temperature by fixed doubling crystal temperature at 34 ^{0}C.

Conclusion

In this paper, various parameters that effect wavelength and laser power of the SHG Nd:YAG laser such as injection current of diode laser, temperature of Nd:YAG crystal and second harmonic generator crystal have been investigated. The maximum output laser power is approximately equal to 94.000 mW when the laser diode current is 1.850 A. The mode-hops of output wavelength have been observed when the laser crystal temperature has been varied. The output wavelength has been increased as step function with the varied laser diode current.

Reference

[1] T.J. Quinn, Metrologia. 40 (2003) 103-133.
[2] F.L. Hong, J. Ishikawa, Z.Y. Bi, J. Zhang, K. Seta, A. Onae, J. Yoda, H. Matsumoto, IEEE. T. Instrum. Meas. 50 (2001) 486-489.
[3] S. Taccheo, P. Laporta, S. Longhi, C. Svelto, IEEE. Photonic. Tech. L. 7 (1995) 989-991.
[4] D.L. Yu, D.Y. Tang, Opt. Laser. Technol. 35 (2003) 37-42.
[5] Z. Sun, R. Li, Y. Bi, C. Hu, Y. Kong, G. Wang, H. Zhang, Z. Xu, Opt. Laser. Technol. 37 (2005) 163-166.
[6] K. Nyholm, M. Merimaa, T. Ahola, A. Lassila, IEEE. T. Instrum. Meas. 52 (2003) 284-287.

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Original Research Paper

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).

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 $\pm 2.5\times10^{-11}$ 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 $\pm 1\times10^{-9}$ 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.

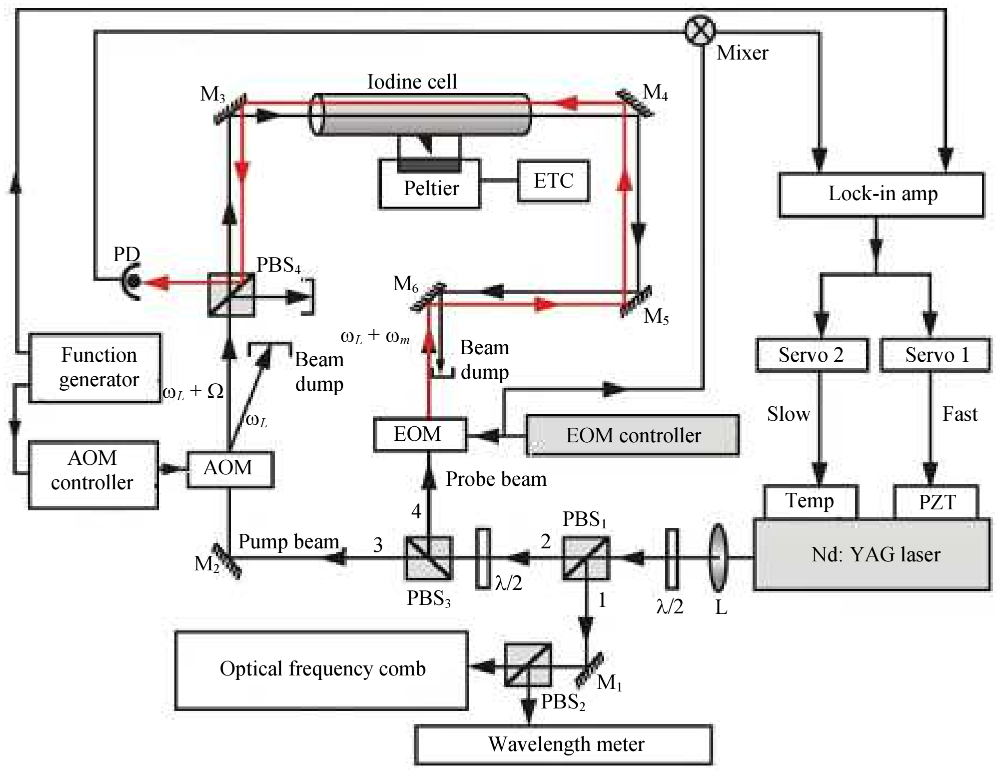

Fig. 1: Schematic of the experimental setup for iodine-stabilized diode laser-pumped Nd:YAG laser using phase modulation spectroscopy

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:

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

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.

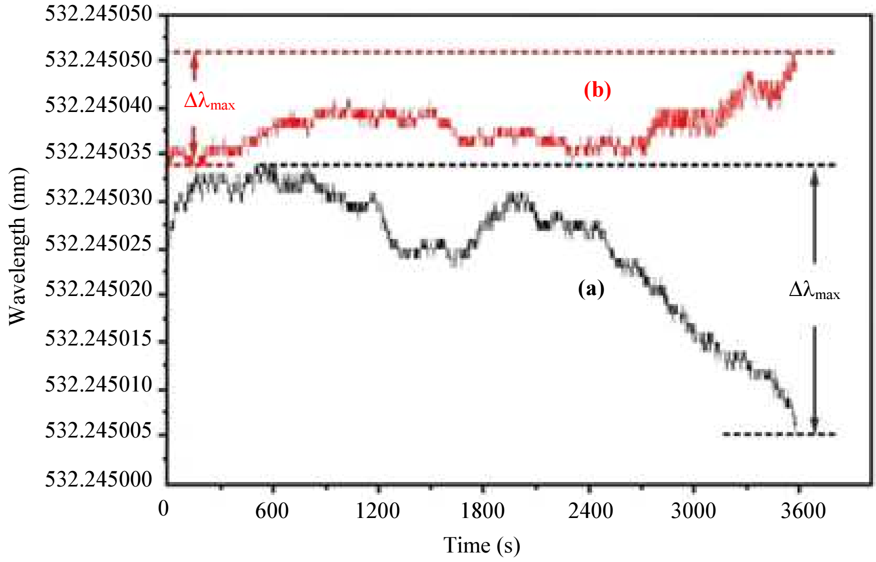

Fig. 2: Variation of wavelength with time at room temperature for: (a) 10 cm long and (b) 50 cm long iodine cells

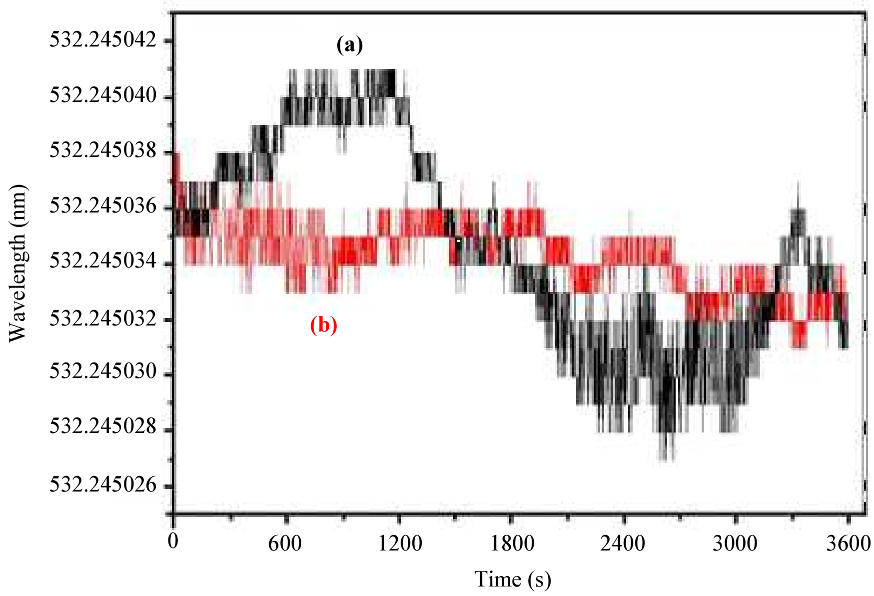

Fig. 3: Variation of wavelength with time at -5°C for: (a) 10 cm long and (b) 50 cm long iodine cells

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.

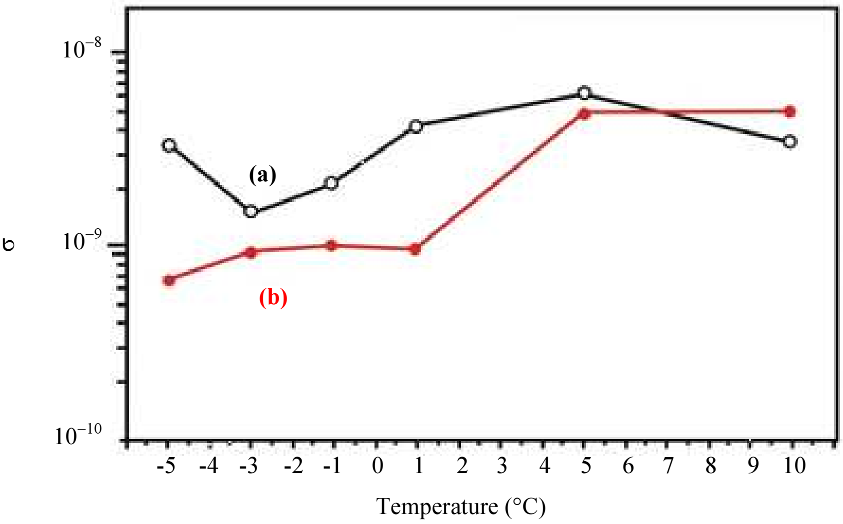

Fig. 4: Allan standard deviation as a function of the temperature for: (a) 10 cm long and (b) 50 cm long iodine cells

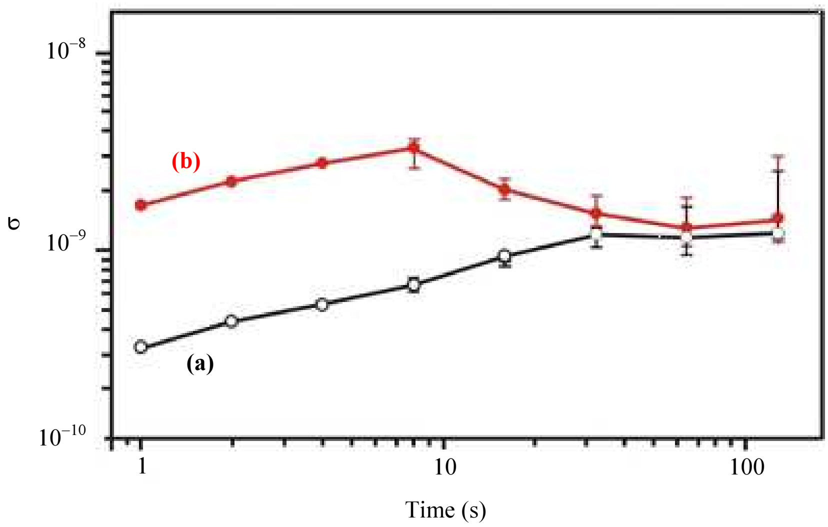

Fig. 5: Allan standard deviation as a function of the measuring time at -5°C for: (a) 10 cm long and (b) 50 cm long iodine cells

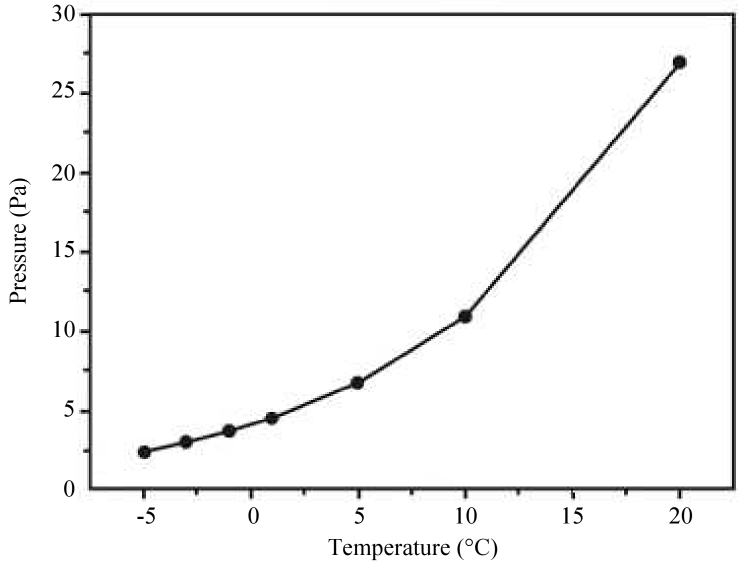

Fig. 6: Relationship between pressure and temperature of iodine

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)	$\sigma \times 10^9$ 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.

References

Arie, A. and R.L. Byer, 1994. Absolute frequency stabilization of diode-pumped Nd:YAG lasers. Laser Phys., 4: 387-391.

Bjorklung, G.C., 1980. Frequency-modulation spectroscopy: A new method for measuring weak absorptions and dispersions. Opt. Lett., 5: 15-17. DOI: 10.1364/OL.5.000015

Bitou, Y., K. Sasaki, S. Iwasaki and F.L. Hong, 2003. Compact I2-stabilized frequency-Doubled Nd:YAG laser for long gauge block interferometer. Japanese J. Applied Phys., 42: 2867-2871. DOI: 10.1143/JJAP.42.2867

Camy, G., C.J. Borde and M. Ducloy, 1982. Heterodyne saturation spectroscopy through frequency modulation of the saturating beam. Opt. Commun., 41: 325-330. DOI: 10.1016/0030-4018(82)90406-0

Cordiale, P., G. Galzerano and H. Schnatz, 2000. International comparison of two iodine-stabilized frequency-doubled Nd:YAG lasers at λ = 532 nm. Metrologia, 37: 177-182. DOI: 10.1088/0026-1394/37/2/11

Döringshoff, K., M. Reggentin, E.V. Kovalchuk, M. Nagei and A. Keetman *et al*., 2012. Iodine based optical frequency reference with 10^{-15} stability. Proceedings of the European Frequency and Time Forum, Apr. 23-27, IEEE Xplore Press, Gothenburg, Sweden, pp: 419-421. DOI: 10.1109/EFTF.2012.6502415

Edwards, C.S., G.P. Barwood, P. Gill, F. Rodriguez-Llorente and W.R.C. Rowley, 1996. Frequency-stabilised diode lasers in the visible region using Doppler-free iodine spectra. Opt. Commun., 132: 94-100. DOI: 10.1016/0030-4018(96)00316-1

Eickhoff, M.L. and J.L. Hall, 1995. Optical frequency standard at 532 nm. IEEE Trans. Instrument. Measurement, 44: 155-158. DOI: 10.1109/19.377797

Gillespie, L.J. and L.H.D. Fraser, 1936. The normal vapor pressure of crystalline iodine. J. Am. Chem. Society, 58: 2260-2263. DOI: 10.1021/ja01302a050

Felder, R., 2005. Practical realization of the definition of the metre, including recommended radiations of other optical frequency standards (2003). Metrologia, 42: 323-325. DOI: 10.1088/0026-1394/42/4/018

Hong, F.L. and J. Ishikawa, 2000. Hyperfine structures of the R(122)35-0 and P(84)33-0 transitions of 127I2 near 532 nm. Opt. Commun., 183: 101-108. DOI: 10.1016/S0030-4018(00)00870-1

Hong, F.L., S. Diddams, R. Guo, Z.Y. Bi and A. Onae *et al*., 2004. Frequency measurements and hyperfine structure of R(85)33-0 transition of molecular iodine with a femtosecond optical comb. J. Opt. Society Am. B, 21: 88-95. DOI: 10.1364/JOSAB.21.000088

Hong, F.L., J. Ishikawa, T.H. Yoon, L.S. Ma and J. Ye *et al*., 1998. A portable 12-stabilized Nd:YAG laser for wavelength standards at 532 nm and 1064 nm. Proc. SPIE, 3477: 1-10. DOI: 10.117/12.323092

Hong, F.L., J. Ishikawa, K. Sugiyama, A. Onae and H. Matsumoto *et al*., 2003. Comparison of independent optical frequency measurements using a portable iodine-stabilized Nd:YAG laser. IEEE Trans. Instrument. Measurement, 52: 240-244. DOI: 10.1109/TIM.2003.811676

Lea, S.N., W.R.C. Rowley, H.S. Margolis, G.P. Barwood and G. Huang *et al*., 2003. Absolute frequency measurements of 633 nm iodine-stabilized helium-neon lasers. Metrologia, 40: 84-88. DOI: 10.1088/0026-1394/40/2/313

Picard, S., L. Robertsson, L.S. Ma, K. Nyholm and M. Merimaa *et al*., 2003. Comparison of 127I2-stabilized frequency-doubled Nd:YAG laser at the Bureau International des Poids et Mesures. Applied Opt., 42: 1019-1028. DOI: 10.1364/AO.42.001019

Nyholm, K., M. Merimaa, T. Ahola and A. Lassila. 2003. Frequency stabilization of a diode-pumped Nd:YAG laser at 532 nm to Iodine by using third-harmonic technique. IEEE Trans. Instrumentat. Measurement, 52: 284-287. DOI: 10.1109/TIM.2003.811679

Quinn, T.J., 2003. Practical realization of the definition of the meter, including recommended radiations of other optical frequency standards (2001). Metrologia, 40: 103-133. DOI: 10.1088/0026-1394/40/2/316

Yoon, T.H., A. Marian, J.L. Hall and J. Ye, 2001. Phase-coherent multilevel two-photon transitions in cold Rb atoms: Ultrahigh-resolution spectroscopy via frequency-stabilized femtosecond laser. Phys. Rev., 63: 011402(1)-011402(4). DOI: 10.1103/PhysRevA.63.011402

Rovera, G.D., F. Ducos, J.J. Zondy, O. Acef and J.P. Wallerand *et al*., 2002. Absolute frequency measurement of an I2 stabilized Nd:YAG optical frequency standard. Measurement Sci. Technol., 13: 918-922. DOI: 10.1088/0957-0233/13/6/313

Robertsson, L., L.S. Ma and S. Picard, 2001. Improved iodine-stabilized Nd:YAG lasers. Proc. SPIE, 4269: 268-271. DOI: 10.1117/12.424482

Raj, R.K., D. Bloch, J.J. Snyder, G. Camy and M. Ducloy, 1980. High-frequency optically heterodyned saturation spectroscopy via resonant degenerate four-wave mixing. Phys. Rev. Lett., 44: 1251-1254. DOI: 10.1103/PhysRevLett.44.1251

Shirley, J.H., 1982. Modulation transfer processes in optical heterodyne saturation spectroscopy. Opt. Lett., 7: 537-539. DOI: 10.1364/OL.7.000537

Snyder, J.J., R.K. Raj, D. Bloch and M. Ducloy, 1980. High-sensitivity nonlinear spectroscopy using a frequency-offset pump. Opt. Lett., 5: 163-165. DOI: 10.1364/OL.5.000163

Schnatz, H. and F. Mensing, 2001. Iodine-stabilized frequency-doubled Nd:YAG lasers at λ = 532 nm; design and performance. Proc. SPIE, 4269: 239-247. DOI: 10.1117/12.424477

Schenzle, A., R.G. Devoe and R.G. Brewer, 1982. Phase-modulation laser spectroscopy. Phys. Rev. A, 25: 2606-2621. DOI: 10.1103/PhysRevA.25.2606

Tiwari, V.B., S.R. Mishra, H.S. Rawat, S. Singh and S.P. Ram *et al*., 2005. Laser frequency stabilization and large detuning by Doppler-free dichroic lock technique: Application to atom cooling. Pramana - J. Phys., 65: 403-411. DOI: 10.1007/BF02704199