Effect of frequency modulation amplitude on Iodine stabilized He-Ne Laser, at λ ≈ 633nm

M. Amer and F. Abdel Aziz

National institute for standards, Giza, Egypt.

The frequency-variation shifts of a He-Ne Laser stabilized by saturated absorption of iodine $^{127}I_2$ arising from the modulation amplitude were determined. Modulation depths of the range 4 to 8 MHz_{p-p} were chosen. At the recommended operating temperature of 15 °C for the iodine cell, the linear coefficients have been determined from a sets of matrix measurements for individual components d, f, g, h, i, j in the range of modulation amplitude for test laser.

1. Introduction:

According to the new definition of the meter, a physical quantity (length) is defined by means of another (frequency) through a relationship involving an universal constant (speed of light). The consequence is that the wavelength of a radiation could be evaluated through measuring its frequency. This procedure has been accomplished by international metrological laboratories leading to the value presently recommended by CCDM for frequency of stabilized lasers [1].

He-Ne lasers stabilizes by saturated absorption in an interactivity cell filled with iodine using the third derivative detection technique [2], are now acknowledged as a relative short term stability of the order of 10^{-12} and reproducibility of better than 10^{-11}[3]. The NIS stabilized laser utilizes an intra cavity iodine cell and single Brewoster window laser tube in conjunction with third harmonic lock-in detection to stabilize the laser wavelength to one of the fourteen hyperfine components of a vibrational-rotational transitions of molecular iodine. Factors which can influence the determination of the correct center frequency of the hyperfine components are cell pressure, modulation amplitude, intracavity laser power, the temperature of the wall of the iodine cell, the cavity geometry and the effects of electronics. It is important to study the effect of the these parameters on the reproducibility of each national He-Ne lasers stabilized on I_2 and compared with the other international organization to confirm the suitability of these lasers as international standards of wave length

The frequency stabilized of I_2 stabilized He-Ne lasers is based on locking the laser frequency to the center of an absorbing line of I_2 Fig(1) shows typical power output of third derivatives spectra for I_2 stabilized He-Ne- laser at $\lambda \approx 633$ nm.

The group of components d, e, f, and g full conveniently near the center of the single frequency tuning range of the laser and it is by reference to one component of this group that the laser is usually stabilized. However, the other components are also suitable for stabilization, Fig(1).

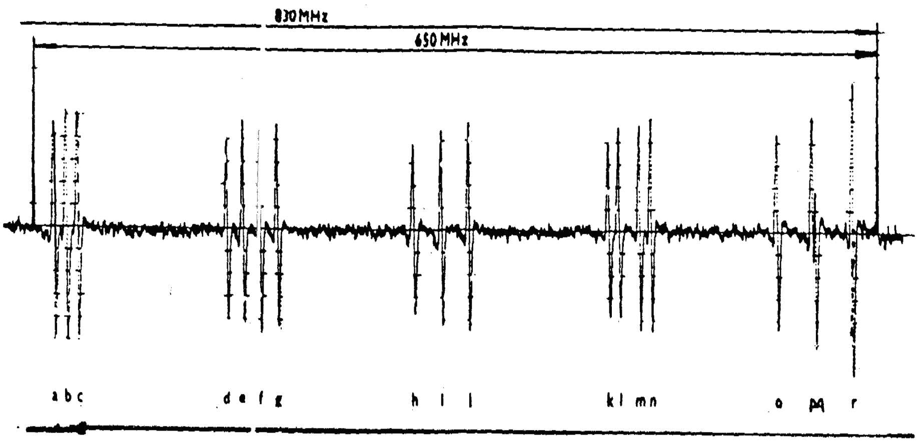


Fig (1): Spectrum of R(127) 11-5 absorption line, observed by the third harmonic derivatives.

A series of reports describing the results of a series of grouped laser comparison from national laboratories undertaken by Bureau international des Poids et Mesures (BIPM) at the request of the comite consultatif pour la Définition du Métre (CCDM, now consultative committee for length, CCL) during the period 1993-1995 [8-11].

Among the parameters that are normally controlled in iodine stabilized laser and influence the determination of the correct center frequency of the hyperfine components, is the frequency modulation amplitude. This means that, there is a fundamental frequency shift combined with the modulation amplitude shift due to the third harmonic locking as long as the absorption line profile is assymmetric. In this work we study the effect of frequency modulation amplitude on Iodine stabilized He-Ne laser.

2. Theory of measurement:

The most convenient means for studying and verifying the effect of frequency modulation amplitude on stabilized lasers is by heterodyne (beat frequency) methods [4]. The optical heterodyne method is used expensively in laser physics to compare the frequencies of laser sources. This method takes advantage of readily available electronic test equipments, and is capable of producing very accurate results. Unlike wavelength comparison using interference methods, optical heterodyne measurements are proceeded in air without the need to make index of refraction corrections.

An optical heterodyne signal is generated by combining the output beams of two lasers onto the active area of a fast photodetector. If the photodetector has sufficient bandwidth, the electrical output will represents the frequency difference between the two lasers. This occurs because a photodiode response to the square of the electric field (i.e. the intensity) of the incident light. If the time-varying part of the electric field of a constant-amplitude, single-frequency laser is represented by $E_1(t)=E_1\cos\omega_1 t$

The response of the photodetector can be written as:

$$
\begin{aligned}
I(t) &\propto E^2_1(t)\\
&= \tfrac{1}{2} E^2_1[1+\cos(2\omega_1 t)]\\
&\approx \tfrac{1}{2} E^2_1 \text{ as } \omega_1 \rightarrow \infty
\end{aligned}
$$

The high oscillatory term has been dropped since ω_1 is much larger than the detector bandwidth, leaving only a dc term.

If a second laser field, $E_2(t)$, is overlapped with the first, the response of the photodiode to the field $E(t)= E_1(t)+E_2(t)$ is given by

$$
\begin{aligned}
I(t) &\propto E^2(t)\\
&= [E_1\cos\omega_1 t + E_2\cos\omega_2 t]^2\\
&= \tfrac{1}{2}[E^2_1+E^2_2+E^2_1\cos(2\omega_1 t) + E^2_2\cos(2\omega_2 t)]\\
&\qquad +E_1 E_2(\cos(\omega_1+\omega_2)t + \cos(\omega_1-\omega_2)t)
\end{aligned}
$$

$$
I(t) \approx 1/2[E^2_1+E^2_2] + E_1 E_2\cos(\omega_1-\omega_2)t \qquad \text{as } \omega_1, \omega_2 \rightarrow \infty
$$

3. Experimental Work:

A block diagram of the experimental setup used in this work for heterofyne measurements is shown in Fig. (2). An avalanche photodiode model 1601 –New Focus with band width 1 GHz was used as a detector, frequency counter model HP53181A with frequency range up to 3 GHz was used for frequency measurement and FR-spectrum analyzer model HP8594E for beat note signal adjustment.

In this work, two iodine stabilized lasers with autolocking circuity for quick and unambiguous acquisition of a selected peak at different iodine with hyperfine components (d, e, f, g, h, i, j) were used. The lasers are provided with an electronic system that stabilizes their frequency to control zero-crossing of odd harmonic of the hyperfine structure (HFS) components of the R(127) 11-5 transition of iodine molecule by the conventional method [5]using the third harmonic method. The first laser used as a reference laser (ν_{ref}) and the second laser used as a test laser (ν). Both lasers are model 100 Iodine stabilized He-Ne laser produce by Winters elector-Optics, Inc. These lasers function as a primary wavelength standard. Therefore, the lasers requires no calibration in order to realize its full accuracy.

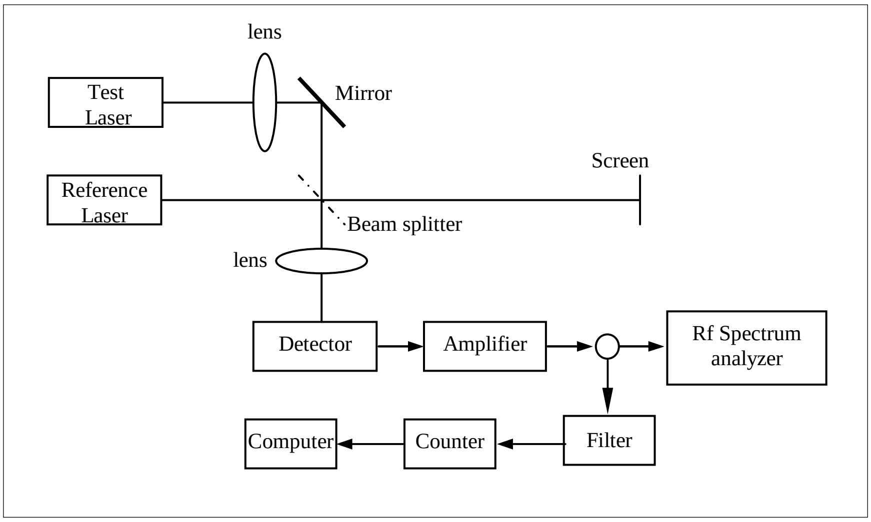


Fig. (2): The main components of a typical system for heterodyne measurements.

The short term stability of the laser cavity length is achieved by using a massive invar for the main laser cavity spacer. The parameters for the reference laser was adjusted to the value recommended by CIPM [6] where the iodine pressure was kept at 17.4 Pa (15 ± 0.2°C) and its amplitude modulation was 6.0±0.1 MHz_{p-p} at 1172 Hz and the temperature of the laser cavity spacer was kept around 29±1°C [7] and the one-way intracavity beam power was kept around 10±0.5 mW.

The parameters for the test laser was adjusted to the value recommended by CIPM [6] and the same as the reference laser except the frequency modulation amplitude. The modulation width was varied from 4 MHz to 8MHz with step 1MHz using a potentiometer located in the wave generator part at the electronics board and was measured using the spectrum analyzer.

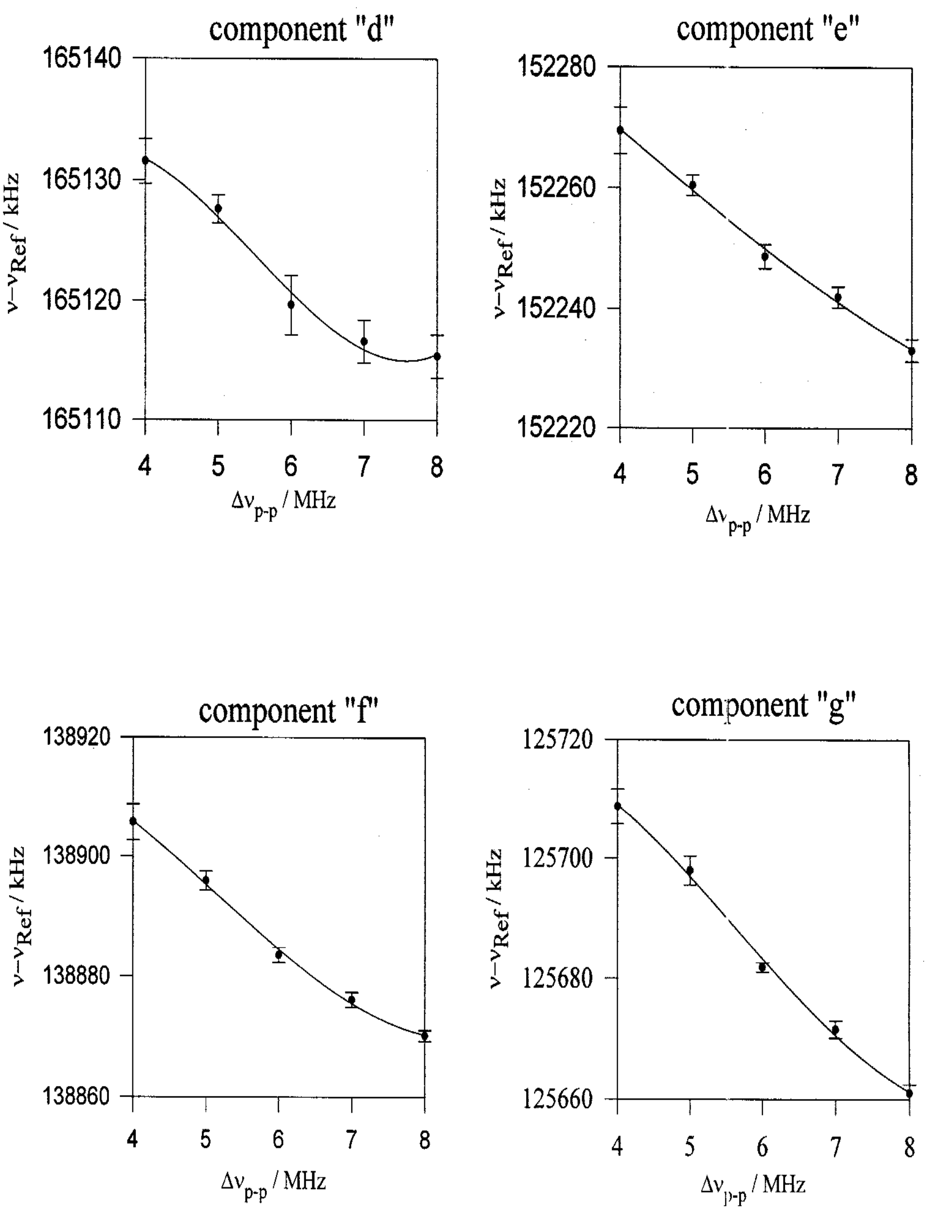
4. Results:

Along the experiment, sets of measurements for the frequency difference ($\nu-\nu_{Ref}$) was taken for each value of frequency modulation amplitude. Each set of measurement was performed using the reference laser locked to hyperfine component (i) or (f) as a reference while the frequency of the test laser locked at hyperfine component (d, e, f, g) or (h, i, j) respectively. Ten measurements, each with a measuring time 10 s, were taken for every component, then the mean value and the standard deviation has been evaluated.

Figs.(3 & 4) show the frequency shift at different frequency modulation amplitude for different hyperfine component (d, e, f, g, h, i, j). All components show nearly the same behavior. Fig. (3) shows that ($\nu-\nu_{Ref}$) are positive values for d, e, f and g components i.e. the frequency of the test laser is higher than the frequency of the reference one for these components. Fig. (4) show that ($\nu-\nu_{Ref}$) are negative values for h, i and j components i.e. the frequency of the test is less than that of the reference laser for these components.

Analyzing the obtained experimental values, a 2nd and 3rd degree polynomial approximation were adjusted to the experimental values and the mean values were taken, and its derivative at working point were evaluated.

This derivative was taken to represent the frequency-variation factor [2]. The obtained results are summarized in Table (1).


component "d"
165140
165130
165120
165110
ν−ν_Ref / kHz
4 5 6 7 8
Δν_p-p / MHz
component "e"
152280
152260
152240
152220
ν−ν_Ref / kHz
4 5 6 7 8
Δν_p-p / MHz
component "f"
138920
138900
138880
138860
ν−ν_Ref / kHz
4 5 6 7 8
Δν_p-p / MHz
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4 5 6 7 8
Δν_p-p / MHz

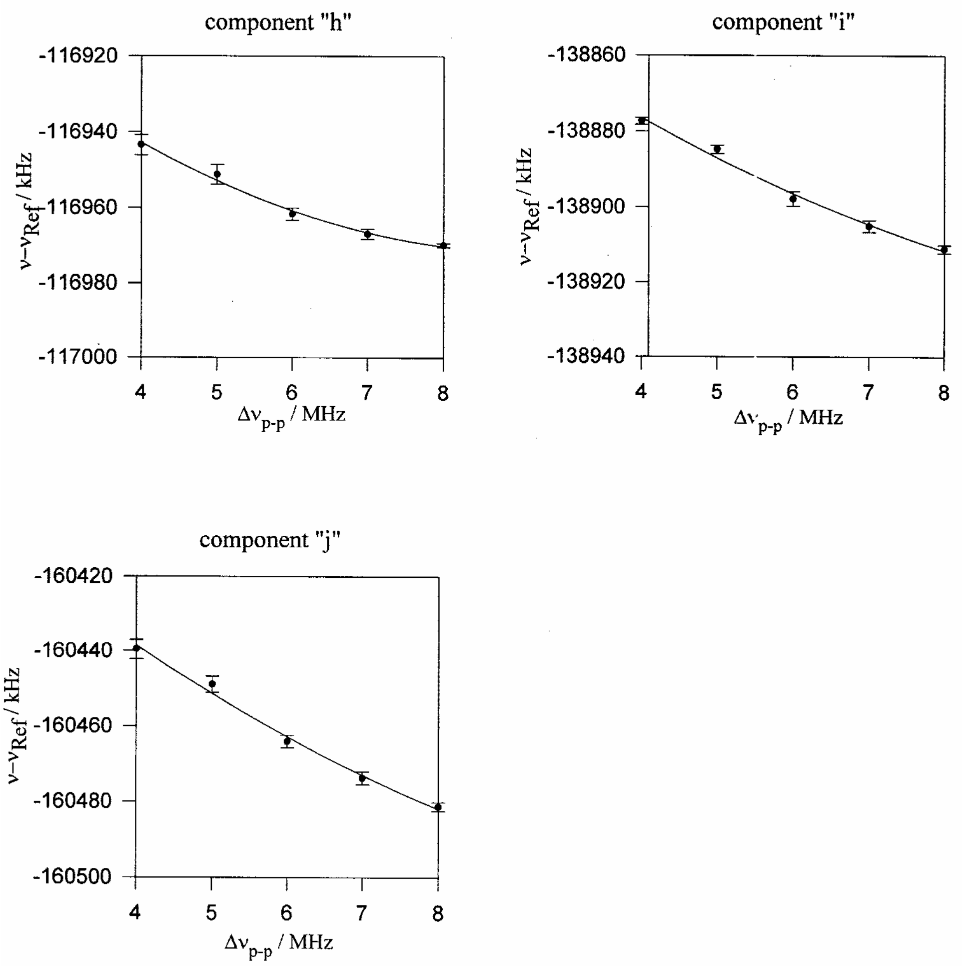

Table (1): Influence of frequency modulation amplitude on frequency of laser components.

Hyperfine Component	$(\partial \nu / \partial(\Delta\nu_{p\text{-}p}))$ (*kHz/MHz*)
D	-5,33 ±0,85
E	-9,28 ±0,01
F	-9,62 ±0,32
G	-12,33 ±0,15
H	-7,24 ±0,43
I	-10,84 ±1,17
J	-11,78 ±0,93

However in fact the effect of change in modulation width on frequency shift should be taken into consideration when comparing the frequencies of two primary standard lasers or calibrating a secondary standard lasers and / or to estimate the calibration uncertainties.

The effect of modulation amplitude on the d, e, f, g components of transition 11-5, R(127) of $^{127}I_2$ was determined by (9, 10, 11) and tabulated in tables (2, 3 and 4). Where $\Delta f/f\omega$ is the modulation width factor, L is the slope of a linear fit to the data points and s the estimated standard uncertainty of one measurement.

Table (2): Effect of modulation amplitude on the d, e, f, g components of transition 11-5, R(127) of $^{127}I_2$ as found by (9, 10, 11).

		L	S	L	S	L	S	L	S	L	S
$(\Delta f / f_\omega)$/ (kHz/MHz)*	d	-7.8		-10				-9.5		-8.3	0.5
	e	-9.6		-10				-10.5		-11.2	0.5
	f	-9.5		-10				-10.5		-12.2	0.5
	g	-10.5		-10				-11.5		-13.4	0.6
	average	-9.4		-10				-10.5		-11.3	
	s	1.1		0		-9.1		0.8		2.2	

Table (3): Effect of modulation amplitude on the d, e, f, g components of transition 11-5, R(127) of $^{127}I_2$ as found by (9, 10, 11).

		L	S	L	S	L	S	L	S	L	S
$(\Delta f / f_\omega)$/ (kHz/MHz)*	d	-7.0	1.0	-8.0	0.5	-6.4	1.5			-7.2	0.4
	e	-10.7	0.5	-10.4	0.3	-8.4	0.7			-10.2	0.1
	f	-8.9	0.5	-10.9	0.4	-9.0	0.9			-10.5	0.2
	g	-12.0	0.4	-12.5	0.3	-8.8	0.4			-11.3	0.3
	average	-9.6		-10.5		-8.2				-9.8	
	s	2.2		1.9		1.2				1.8	

Table (4): effect of modulation amplitude on the d, e, f, g components of transition 11-5, R(127) of $^{127}I_2$ as found by (9, 10, 11).

		L	S	L	S	L	S	L	S	L	S	L	S
$(\Delta f / f_\omega)$/ (kHz/MHz)*	D	-6.2	0.6	-15.5	1.4	-4.2	0.7	-4.6		-6.4	1.4	-8.3	0.5
	E	-10.7	0.3	-18.3	1.1	-10.2	0.4	-10.0		-9.2	0.4	-11.2	0.5
	F	-12.4	0.3	-20.1	1.3	-10.1	1.0	-9.9		-10.0	1.3	-12.2	0.5
	G	-15.0	0.5	-21.6	1.2	-14.1	0.4	-12.6		-9.3	0.6	-13.4	0.6
	average	-11.1		-18.9		-9.3		-9.3		-8.7		-11.3	
	S	3.7		2.6		3.4		3.4		1.6		2.2	

5. Conclusion:

He-Ne lasers stabilized by saturated absorption in iodine are one of the contemporary world primary standard of wavelength in the 633 nm region. The absolute accuracy of iodine stabilized laser is limited by normally controlled in iodine stabilized laser and can influence the determination of the correct center frequency of the hyperfine components is the frequency modulation amplitude. The effect of modulation amplitude on the d,e, f, g components of transition 11-s, R(127) of $^{127}I_2$: $\Delta f / f_\omega$ is the modulation width factor, L is the slope of a linear fit to the data points and s the estimated standard uncertainty of one measurement as found by (9, 10, 11) was tabulated in tables (2, 3, and 4).

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