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Iodine stabilised He–Ne Laser

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Abstract. A single mode He-Ne laser operating at 6328 Å is used with an iodine cell in the cavity to detect the absorption components of iodine falling within the gain curve of the laser line. Experimental details are given for locking the frequency of the laser line with one of the hyperfine components of the iodine absorption line, using a servo-control system. The system uses the technique of detecting the first and third harmonics of the modulation frequency.

Keywords. Frequency stabilisation; wavelength standard; He-Ne laser.

1. Introduction

A major improvement in the technique of stabilisation of the frequency of He-Ne lasers operating at 633 nm, took place after the experiment of Hanes and Dahlstrom (1969). They reported the coincidence of hyperfine components of R(127) line of 11-5 band of the $B^3\Pi^+_{0u} \leftarrow X^1\Sigma^+_{0g}$ electronic transition of iodine with that of 633 nm neon line of the He-Ne laser. Under the condition of saturated absorption, they observed 14 components of the iodine line, within the tuning range of the single frequency He-Ne laser. Due to very narrow width of about 4·5 MHz, they suggested using these components as fixed references on which the laser frequency might be stabilised.

Later, a number of laboratories (Chartier *et al* 1976) adopted this scheme and developed iodine stabilised He-Ne lasers as future international length or frequency standard. Recently, some of these laboratories have intercompared the frequencies of these lasers to estimate their reproducibility and stability. It is found that the reproducibility between two similar lasers operating under similar conditions of iodine temperature and modulation amplitude, is of the order of 2×10^{-11} and stability of the order of 5×10^{-12} for 10 sec integration time.

We report in this paper the work on development of the iodine stabilised He-Ne laser carried out in our laboratory. The main emphasis is on the experimental aspect of locking the laser frequency to one of the absorption features of iodine with the technique of detection of the first and third harmonics of the modulation frequency.

2. Principle

To build a frequency stabilised laser, one has to operate the laser in a single frequency mode, with an iodine absorption cell in the laser cavity. As the frequency of the laser is varied over the Doppler broadened gain curve of the laser line, saturated absorption peaks are observed in the power output of the laser. These peaks stand about 0·1 % higher than the background and can conveniently be detected by phase-sensitive detection technique. The laser frequency can be servo-locked to any one of these absorption components taking it as a reference. To do this, the deviations of the laser frequency from the reference frequency caused by any disturbance, are detected as an error signal and applied back through the servo-control system to retune the laser frequency to the reference.

The phase-sensitive detector output voltage as a function of laser frequency scanning, is the first derivative of the power output curve and shows the broad feature of power output with a superimposed structure due to iodine absorption component. However, it is difficult to identify the centre of each component and with conventional zero-seeking servo-control system, arbitrary off-sets of zero are necessary for stabilisation to a particular component. Of course, this zero off-set becomes redundant when an absorption component falls conveniently at the peak of the power output curve and provides the absorption feature at the zero crossing of the main curve.

However, the problem of identifying the centres of other absorption components may be overcome, using a technique which basically differentiates the power output curve successively thrice (Wallard 1972). This ensures an asymmetric discriminant shape and also eliminates the large background slope. The differentiation may be performed by detecting the third harmonic content of the fundamental modulation frequency in the power output of the laser. The third harmonic component represents the rate of change curvature of the iodine feature. Using one of the components as a reference and the deviation of the laser frequency from it as the error signal, allows the servo-control to lock the laser frequency at a point corresponding to the maximum rate of change of iodine absorption curve. This enables location of the centre of the absorption curve for locking the laser frequency to it.

3. Theory

According to theory, the minimum fractional spectral width of the output of a single mode laser is extremely small. For a low power gas laser in the visible region of the spectrum a typical value is $\simeq 10^{-15}$.

This extremely sharp frequency can be varied over the entire band-width of the Doppler broadened gain curve of the laser transition. This gain curve is denoted by $A(\nu, \nu_0)$ and is well approximated by the Gaussian profile, given by,

$$A(\nu, \nu_0) = A_0 \exp - [(\nu/\nu_0)/\triangle\nu_D]^2 \tag{1}$$

where ν_0 is the laser emission frequency at the centre of the line profile and $\triangle\nu_D$ is the full width at height A_0/e.

In the presence of an absorber, say iodine vapour in the cavity, this gain curve profile is slightly modified due to the appearance of saturated absorption peak at a frequency ν_p. The shape of this may be adequately represented by a Lorentzian function $B_p(\nu, \nu_p)$ such as,

$$B_p(\nu, \nu_p) = a^2 [a^2 + (\nu - \nu_p)^2]^{-1} \tag{2}$$

where α is the half-width at half-maximum of the peak. Thus, when the absorber saturates only weakly, the output of the laser power curve is quite well represented by the function $I(\nu, \nu_0, \nu_p)$ defined as (Cerez and Brillet 1977),

$$I(\nu, \nu_0, \nu_p) = A(\nu, \nu_p)\,[1 + k\,B_p(\nu, \nu_p)] \tag{3}$$

where k is the relative size of the absorption peak.

As the power curve represented by (3) is formed by a slowly varying background curve and the sharp absorption feature, the resulting intensity changes, when the laser frequency is modulated by a low frequency sinusoidal signal (ω), are to be analysed as two different cases (Hanes *et al* 1973).

Case 1: Let the slowly varying background power curve be denoted by $F(\nu)$. Then, with the modulation signal applied, the laser intensity is given by (Wallard 1972)

$$I = F(\nu + a \sin \omega t) \tag{4}$$

where a is the amplitude of modulation.

Expanding the expression as Taylor's series, and considering only the important term from the sum of the coefficients of sin $n\omega t$ we get the coefficient of sin $n\omega t$ as,

$$\frac{a^n F^n(\nu)}{2^{n-1}\, n!}$$

where $F^n(\nu)$ is the nth derivative of $F(\nu)$. This term approximately gives the amplitude of the phase-sensitive detector signal when the detection is carried out at nth harmonic of the modulation signal. As $F(\nu)$ is given by

$$A_0 \left\{\exp - \left(\frac{\nu - \nu_0}{\triangle \nu_D}\right)^2\right\},$$

we have the coefficient of sin $n\omega t$ proportional to $(a/\triangle\nu_D)^n$, a being much smaller than $\triangle\nu_D$ the higher order terms fall off very rapidly.

Case 2: In the neighbourhood of iodine absorption feature, the power curve is modified by the presence of inverted Lamb dip, which for not too large saturation may be represented by a Lorentzian profile given by (2). The harmonic content in this case has been analysed by Arndt (1965), and is applied to the case of iodine absorption component by Hanes *et al* (1973). They have shown that if the modulation amplitude bandwidth is of the order of Lorentzian semi-half-width w, the signal due to background falls off relatively to that from the narrow iodine component as $(w/\triangle\nu_D)^n$.

As this ratio is of the order of 100 for most of the iodine features falling within the gain curve of the 6328 Å He-Ne laser, detection at third harmonic, instead of first, gives a large reduction in the background signal.

4. Experimental details

The resonator structure is made from invar bars of length 450 mm and diameter 25 mm with mirror mounts on either side. The mirror mounts are provided with very fine adjustment screws to align the mirrors. The laser tube and the iodine cell are mounted on two independent adjustable holders which in turn are saddled on the two invar bars.

The concave mirrors used have radii of curvature of 1000 mm and transmission of 99·5 % and 99·8 %. One mirror is mounted on a pair of PZT tubes: one of which is used for modulation and the other one to scan and servo-control the laser cavity length.

The Brewster angle laser tube has an active length of 170 mm and the iodine cell length is 100 mm. The tube is filled with He-Ne mixture of 9:1 ratio at a pressure of 3 mm of Hg. A high voltage stabilised power supply which is modified to work as a constant current source (Herngvist 1969; Goldsbarough 1972) is used to run the laser. The ripple content of the power supply is less than 30 mV.

The laser tube shows the presence of regular and irregular oscillations in the power output at certain values of current (Wallard and Woods 1974). Hence, suitable current ranges are chosen such that the laser noise is minimum. A Fabry-Perot interferometer with 80 mm mirror spacing is used to check the single mode operation of the laser.

The phase lock amplifier for the first and third harmonic detection of the modulation frequency and other electronic units for servo-control system are made in the laboratory based on the circuits given by Shotton and Rowley (1975) and Wallard and Wilson (1974).

Figure 1 shows the block diagram of the experimental set-up. A modulation signal of 775 Hz (*f*) from an oscillator is applied to PZT No. 1. A saw-tooth scanning voltage from a cathode ray oscilloscope (CRO) or a function generator is also applied to PZT No. 2 through the high tension (HT) amplifier.

The changes in intensity due to the scanning are detected by the photo-multiplier tube (PMT) and are displayed on the CRO beam No. 2 or on a chart recorder channel

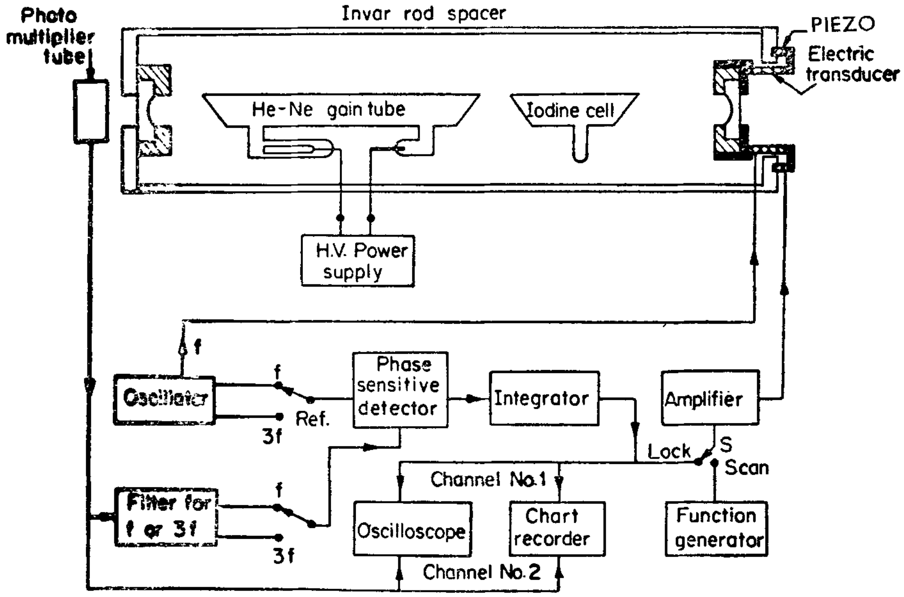

Figure 1. Block diagram of the experimental set-up.

No. 2. The same PMT output is fed to the phase-sensitive detector (psd) through narrow band filters for frequencies *f* or 3*f*. A reference signal of frequency *f* or 3*f* from the oscillator is also provided to the psd. The resulting psd output after passing through integrator is displayed on the beam No. 1 of the CRO or on the channel No. 1 of the chart recorder. Thus, we get the power output curve and also its first derivative or third derivative display.

As explained earlier, the laser frequency can be servo-locked to those frequencies where the first or third derivatives cross the zero. Usually, during the scan, the first derivative crosses the zero only once, while the third derivative crosses it at each peak of the absorption components. The servo-control is switched on by the switch *S* which changes the HT amplifier input from function generator to the integrator output at that moment during the scanning when the derivative of a particular component crosses zero.

5. Results and discussion

The upper trace of figure 2 shows the power output of the laser as a function of cavity tuning (intensity decreasing downward). The lower trace is the psd-integrator output and is the first derivative of the upper curve. It can be seen that the seven saturated absorption peaks of iodine j, i, h and g, f, e, d which are submerged in noise in the power output curve are revealed in this curve. The same seven absorption components recorded on a chart recorder are shown in figure 3.

By reducing the scanning amplitude only a small part of the gain curve can be scanned to get better details. Figure 4 shows the group of four absorption components g, f, e, d which fall conveniently near the centre of the single frequency tuning

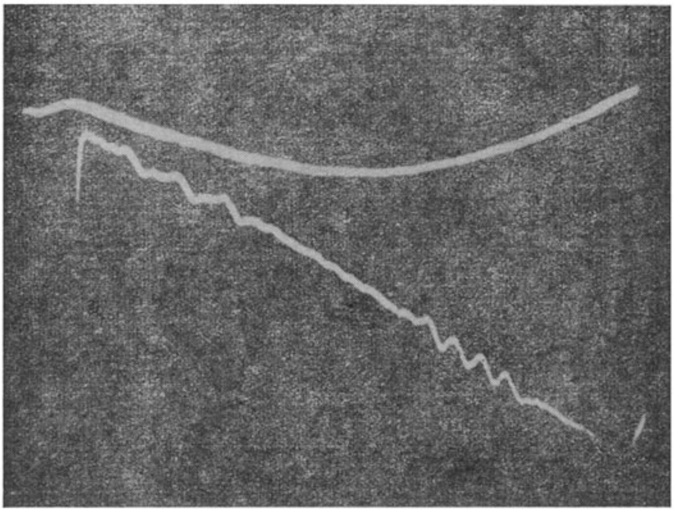

Figure 2. (Upper trace) Power output of the laser as a function of cavity tuning. (intensity increasing downward) (Lower trace) psd integrator output as a function of cavity tuning. (first derivative of the upper curve) Frequency increases from left to right. The three features at the top of the curve are the j, i, h, components and the lower four are g, f, e, d. The zero crossing is in the middle of the trace.

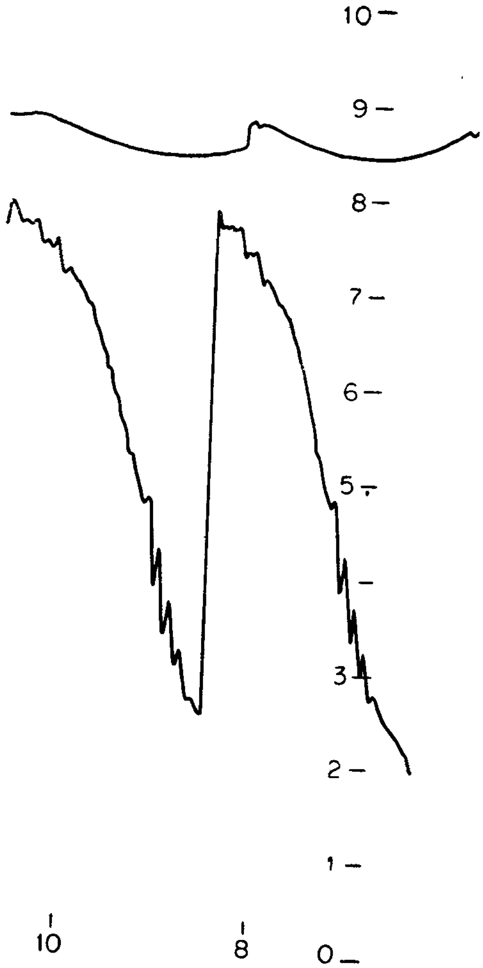

Figure 3. Same as figure 2 but on a chart-recorder showing a series of these curves.

range of the laser. The laser frequency can be stabilised with reference to one of these components. The same figure also gives the corresponding power output curve, with power increasing downward. (It may be noted that there is some lateral shift in the two traces for a simultaneous event.)

Figure 5 shows the power output and its first derivative for two scans of the laser cavity and also when the servo-lock is closed at the *f* component during the third scan. The duration of one scan is about 20 sec, and the duration of the power output record in locked condition is for 10 min.

No special precautions could be taken for the temperature control of the laser cavity and the I_2 cell, and its mechanical and acoustical isolation. The laser was mounted on a foam rubber cushioned table-top and the experiment was carried out in an isolated room. The slow decrease in power output of the laser as seen in the power output trace is due to the slow increase in iodine absorption with the rise in temperature.

The third harmonic detection technique was also used considering its advantages and figure 6 shows the result. The upper curve in figure 6 is the power output curve

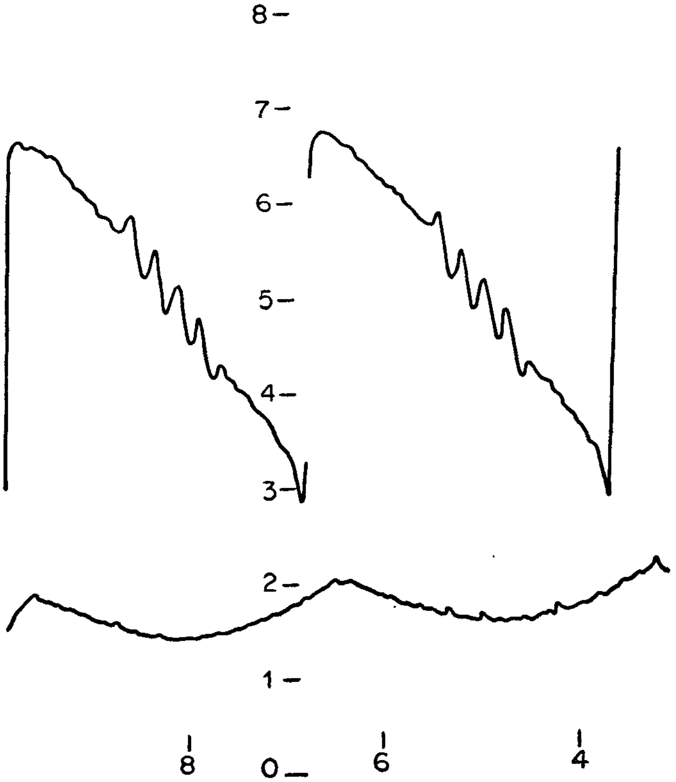

Figure 4. Curves showing the power output (intensity increasing downward) vs cavity tuning and its corresponding first derivative, showing only the four absorption features of iodine. The zero line for the power output curve is at the top of the figure and that for first derivative is at the centre.

(increasing downward) and the lower one is its third derivative. The same traces recorded on a chart recorder are depicted in figure 7. The zero-crossing for all the seven components can be clearly seen.

As the cavity length in this case is about 450 mm, the adjacent laser modes are spaced by about 300 MHz, while the frequency separation between *a* and *j* components is more than 300 MHz. Scanning of a wider range to get the other absorption components (*a*, *b* and *c*) is possible only in our next set-up where the cavity length is reduced to 350 mm.

The noise in the third derivative curve is partly due to a small 3rd harmonic content in the modulation signal (*f*) and also partly due to uncontrolled environmental conditions.

Work on the setting up of the two identical iodine stabilised lasers with a cavity length of 350 mm is now in progress. These lasers will be run under controlled environmental conditions and their stability and reproducibility will be determined by the usual beat frequency method.

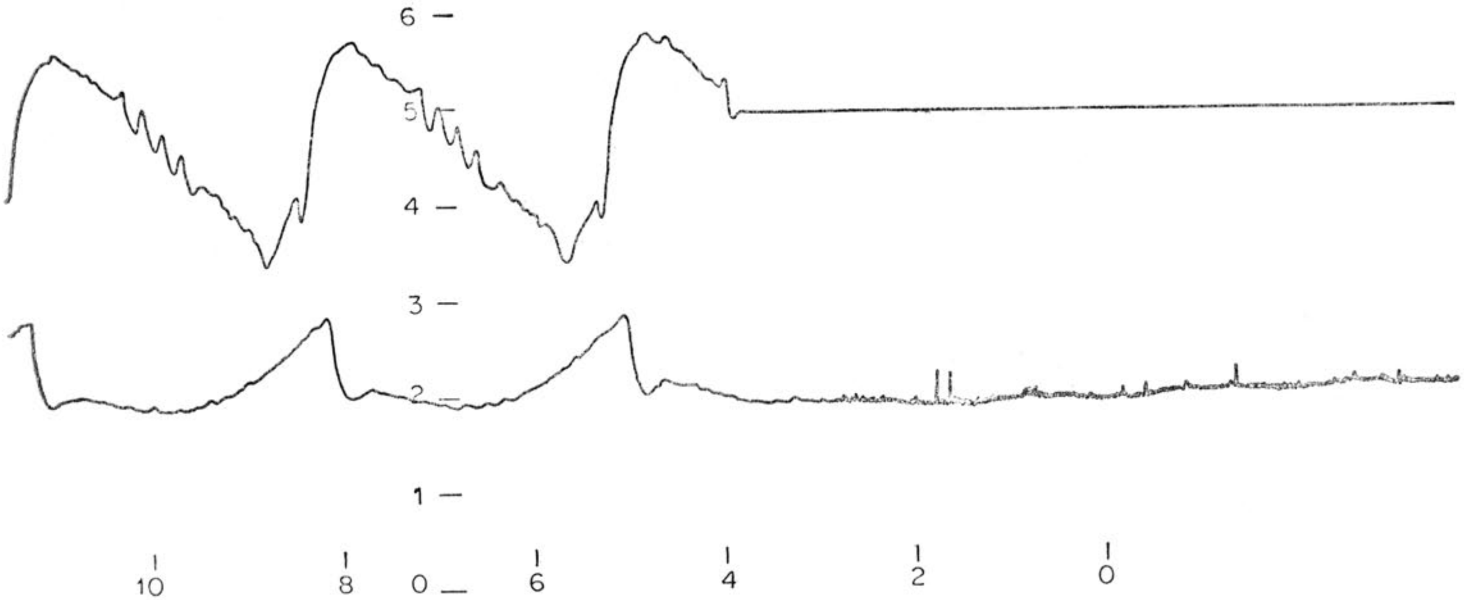

Figure 5. A series of curves, showing the power output and its first derivative for a few scans of the cavity and when the laser frequency is locked, to one of the absorption feature.

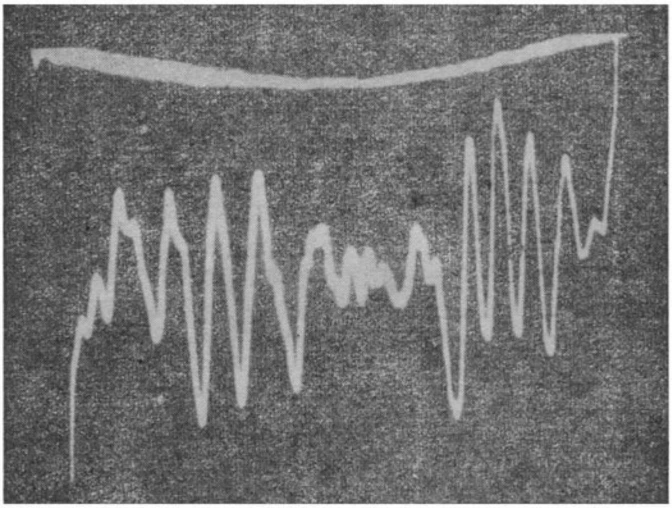

Figure 6. The upper trace shows the laser power output as a function of cavity tuning (intensity increasing downward) and the corresponding third derivative showing the seven absorption components of iodine line.

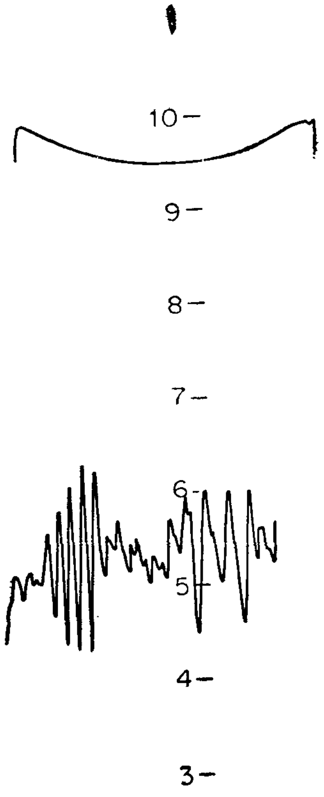

Figure 7. Same as figure 6 but recorded on a chart recorder. The order of the absorption features is reverse to that in figure 6.

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