Comparison of I$_2$-stabilised He - Ne lasers: II
Leslie Pendrill
Ove Poulsen
P S Ramanujam
Harald Simonsen

COMPARISON OF I₂-STABILISED He-Ne LASERS:II

SP REPORT 1990:40
Weights & Measures
Borås, Sweden 1990
Abstract

Comparison of I₂-stabilised He-Ne lasers: II.

Leslie Pendrill, Ove Poulsen¹, P S Ramanujam² and Harald Simonsen¹

¹ Århus University, Institute of Physics, DK-8000 ÅRHUS C, Denmark
² Danish Institute of Fundamental Metrology, Bygning 322, Lundtoftevej 100, DK-2800 LYNGBY, Denmark

Three iodine-stabilised He-Ne lasers (wavelength 0.633 µm) have been compared in frequency in a triangular comparison scheme during 1988/89 at:

i) Århus University, Institute of Physics, Denmark,
ii) Danish Institute of Fundamental Metrology, and
iii) Swedish National Testing & Research Institute, Borås, Sweden.

The designs of the lasers were such that the lasers should satisfy the requirements specified by the International Conference for Weights & Measures (CGPM) in connection with the present definition of the unit of length, one metre. Two of the lasers have been constructed with the intention of replacing the present national standards of length in Denmark and Sweden, at present the former prototype bar in Pt-Ir, with optical frequency standards. One of the Danish lasers now belonging to DFM has been compared previously by Århus at the Physikalisch-Technische Bundesanstalt in December 1987. The aim of the present comparison was to assess the relative performance of the laser systems as a preliminary to performing a more formal comparison of such lasers at an international standards level. The report gives full details of the comparison procedure, including some construction details of the lasers of importance in determining system performance, and the results of a systematic investigation of power-dependent frequency shifts.

KEYWORDS: Laser, metre, He-Ne, iodine, length standard, laser standard, Denmark, Sweden

SP
RAPPORT 1990:40
ISBN 91-7848-246-1
ISSN 0284-5172
BORÅS 1990

SWEDISH NATIONAL TESTING AND RESEARCH INSTITUTE
SP REPORT 1990:40
Postal address:
P.O.Box 857, S-501 15 BORÅS
Sweden
Telephone Int + 46 33 - 16 50 00
Telefax Int + 46 33 - 13 55 02
Telex 36252 Testing S
CONTENTS

Acknowledgements 3

1 Introduction 4

2 Description of lasers 5
   2.1 Lasers DK1 and DK3 5
   2.1.1 Mechanical construction 5
   2.1.2 Electronic control system 5
   2.2 Laser SP1 5
   2.2.1 Mechanical construction 6
   2.2.2 Electronic control system 6

3 Measurement procedure 6
   3.1 Practical Realization of Metre definition: standard conditions 6
   3.2 Heterodyne spectroscopy 7

4 Comparison results 7
   4.1 Influence of iodine cell 8
   4.1.1 Iodine cells in lasers DK1 and DK3 8
   4.1.2 Iodine cell in laser SP1 8
   4.2 Influence of misalignment of laser cavity 9

5 Final frequency comparison. Conclusion & discussion 10
   5.1 Summary of Nordic comparison 10
   5.2 Comparison with Physikalisch-Technische Bundesanstalt, Braunschweig, West Germany 11

References 12
Acknowledgements

The authors would like to thank their colleagues in laser metrology, in particular Dr Jürgen Helmcke, of Physikalisch-Technische Bundesanstalt, West Germany, and Dr Howard Layer, National Institute for Standards and Technology, Washington D.C., USA, who have been constant sources of inspiration in the development of frequency-stabilised lasers.

The authors are grateful to their respective laboratories - SP (Swedish National Testing and Research Institute); the Physics Institute, Århus University; and the Danish Institute of Fundamental Metrology - for providing support and the laboratory facilities which have made this work possible.
1 INTRODUCTION

Amongst the lasers named in a list of recommended light sources for a practical realisation of the unit of length /1/, by far the most popular choice has been the He-Ne laser, wavelength 633 nm, stabilised in frequency to saturated absorption features in 12712 /2,3/.

The majority of such lasers developed at various laboratories over the world are constructed in largely similar ways, with for example, an intracavity iodine cell, and locking electronics based on phase-sensitive detection at three times the modulation frequency.

In recent years, world-wide intercomparisons /4,5/ of such lasers have confirmed the reproducibility quoted in the definition of the metre in 1983 /1/, that is an estimated relative uncertainty of \( \pm 1 \times 10^{-9} \). Differences in optical frequency amongst the lasers were characterised by a standard deviation of \( \pm 23 \) kHz (5 parts in \( 10^{11} \)) with a range of \( \pm 40 \) kHz /5/. Such differences may be attributable to different cavity configurations or differences associated with the various choices of electronic circuits for the frequency control.

Three iodine-stabilised He-Ne lasers (wavelength 0.633 \( \mu m \)) have been compared in frequency in a triangular comparison scheme during 1988/89 at:

i) Århus University, Institute of Physics, Denmark,
ii) Danish Institute of Fundamental Metrology, and
iii) Swedish National Testing Institute, Borås, Sweden.

The designs of the lasers were such that the lasers should satisfy the requirements specified by the International Conference for Weights & Measures (CGPM) in connection with the present definition of the unit of length, one metre. Two of the lasers have been constructed with the intention of replacing the present national standard of length in Denmark and Sweden, at present the former prototype bar in Pt-Ir, with optical frequency standards. One of the Danish lasers now belonging to DFM has been compared previously by Århus at the Physikalisch-Technische Bundesanstalt in December 1987.

The aim of the present comparison was to assess the relative performance of the laser systems as a preliminary to performing a more formal comparison of such lasers at an international standards level.

The report gives full details of the comparison procedure, including some construction details of the lasers of importance in determining system performance, and the results of a systematic investigation of power-dependent frequency shifts.
2 DESCRIPTION OF LASERS

2.1 Lasers DK1 and DK3

The I₂-stabilised He-Ne lasers, denoted DK1 and DK3, have been built at Århus University. One of the lasers (DK1) now belonging to DFM has been compared previously by Århus at the Physikalisch-Technische Bundesanstalt in December 1987.

2.1.1 Mechanical construction

Three super-invar bars, cavity length 37 cm.

High reflector, R₂ = 60 cm, transmission 0,9%, next to iodine cell. Laser light transmitted by this mirror is detected for frequency-control system. The mirror is mounted on a PZT tube for modulation of the cavity length.

Output coupler, R₁ = 200 cm, transmission 2,6%, next to plasma tube. The mirror is mounted on PZT tube for servo control of cavity length.

Iodine cells made and filled with 127I₂ at the Physikalisch-Technische Bundesanstalt, with number PTB (4/86) - DK1 and (5/86) - DK3.

2.1.2 Electronic control system

Plasma tube Melles Griot 05 LHB 290, with 05 LPM 340-3 power supply.

"3rd harmonic locking", modulation frequency 3,55 kHz (DK1) / 2,8 kHz (DK3)

PZT tube, diameter 6,4 mm, wall thickness 0,6 mm, extension 0,907 nm/V.

Photodetection filter, DK3: centre frequency 8,4 kHz, 3 dB bandwidth 2 kHz, gain ratio (3f:f) 70 dB. DK1, a 4th-order Butterworth filter with Q > 5.

Lock-in detector (PAR or own), square-wave reference.

Integrator, time constant 0,33 sec.

High-voltage PZT driver amplifier, voltage swing 0 - 1 kV, with a servo unity gain at about 1 kHz.

2.2 Laser SP1

The I₂-stabilised He-Ne laser, denoted by SP1, has been constructed at SP (Swedish National Testing & Research Institute, Borås) with the intention of replacing the present Swedish national standard of length, at present the former prototype bar in Pt-Ir, no. 29, from 1889, with an optical frequency standard. The laser and accompanying frequency-control electronics are largely similar to a laser system developed by Dr Howard Layer, at the National Institute for Standards and Technology, Gaithersburg, USA /3/. A detailed description of the laser SP1 may be found in /6/.
2.2.1 Mechanical construction

The laser cavity, length ca 39 cm defined by four super-invar bars, is bounded by two mirrors:

High reflector (Spectra Physics G3801-012), $R_2 = \infty$, reflectance > 99%, diameter 7.75 mm, closest iodine cell. The mirror is mounted on a PZT cylinder for modulation of cavity length.

Output coupler (Spectra Physics G3818-006), $R_1 = 60$ cm, transmission 0.9% at 0.63 μm. A few percent of laser light is detected for frequency-control system. The mirror is mounted on a PZT cylinder for DC control (including sweep and servo) of cavity length.

Iodine cell made and filled with $127\text{I}_2$ at Bureau International des Poids et Mesures (BIPM), with number cuve 43c (June 1985).

2.2.2 Electronic control system

Plasma tube Melles Griot 05 LHB 290, with Laser Drive Inc., model 314S-1 power supply.

"3rd harmonic locking". Modulation frequency 2.5 kHz. PZT cylinder, outer diameter 12.7 mm, wall thickness 0.8 mm, length 6.4 mm, extension -1.4 nm/V.

Photodetection filter, centre frequency 7.5 kHz, 3-dB bandwidth 1 kHz, gain ratio (3f/f) > 70 dB

Lock-in detector Burr-Brown 4213, with specified full power bandwidth of 320 kHz and output offset voltage of ±50 mV. Sine-wave reference.

Integrator consists of a double integrator, time constants 0.45 Hz and 100 Hz. High-voltage PZT driver amplifier, voltage swing of ca 400 V, Servo unity-gain frequency is ca 1 kHz, and gain at 0.01 Hz is ca 150 dB.

3 MEASUREMENT PROCEDURE

3.1 Practical Realization of Metre definition: standard conditions

Recommendation 1 (CI-1983) of the Comité International des Poids et Mesures (CIPM) in the Document on the Realization of the Definition of the Metre /1/ includes a List of Recommended Radiations, 1983. It is recommended that one way of realizing the metre is by means of one of the radiations in this list, whose stated wavelength in vacuum, or whose stated frequency, can be used with uncertainty shown, provided that the given specifications and accepted good practice are followed. In the list, the values of the frequency $f$ and of the wavelength $\lambda$ should be related exactly by the relation $\lambda f = c$, with $c = 299 792 458$ m/s but the values of $\lambda$ are rounded.
Amongst the list of radiations of lasers stabilized by saturated absorption is:

1.3 Absorbing molecule 127I₂, transition 11-5, R(127), component i.

The values \( f = 473\,612\,214.8\, \text{MHz} \)
\( \lambda = 632\,991\,398.1\, \text{nm} \)

with an estimated overall uncertainty of \( \pm 1 \times 10^{-9} \) [which results from an estimated relative standard deviation of \( 3.4 \times 10^{-10} \)] apply to the radiation of a stabilized He-Ne laser containing an iodine cell, subject to the conditions:

- cell-wall temperature between 16 °C and 50 °C with a cold-finger temperature of 15 °C ± 1 °C
- one-way intracavity beam power 15 mW ± 10 mW
- frequency modulation amplitude, peak to peak, 6 MHz ± 1 MHz.

3.2 Heterodyne spectroscopy

The difference in optical frequencies of the two lasers compared here was measured by heterodyne spectroscopy.

The heterodyne signal, registered by a fast photodetector, from the beating of two light electric fields of form \( E_1 \cos(\omega_1 t + \phi_1) \) and \( E_2 \cos(\omega_2 t + \phi_2) \), is given by:

\[
E_1^2[1 + \cos^2(\omega_1 t + \phi_1)] + E_2^2[1 + \cos^2(\omega_2 t + \phi_2)] + 2E_1E_2[\cos((\omega_1-\omega_2) t + \phi_1-\phi_2) + \cos((\omega_1+\omega_2) t + \phi_1+\phi_2)]
\]

The frequency difference, \( \omega_1 - \omega_2 \), typically some tens of megahertz, was measured with a frequency counter (MARCONI Instruments, 20 GHz µwave counter 2440). The spectrum of the rf signal was also displayed on an ANRITSU MS710A Spectrum Analyser.

To ensure reliable frequency counting, some care was taken to ensure that the counter received a signal of sufficient amplitude and signal-to-noise ratio. The beat signal was observed to be 35 dBm above a noise floor of -60 dBm. The frequency counter used here required an input signal of amplitude -15 dBm in the frequency range 5 - 100 MHz. The beat signal was therefore amplified 14 dBm, to an amplitude of -11 dBm, before being sent to the counter.

4 COMPARISON RESULTS

The three iodine-stabilised He-Ne lasers (wavelength 0.633 µm) have been compared in frequency in a triangular comparison scheme during 1988/89 at:

i) Århus University, Institute of Physics, Denmark, 881214 DK3:SP1
ii) Danish Institute of Fundamental Metrology 890201 DK1:DK3, and
iii) Swedish National Testing Institute, Borås, Sweden 890330 DK1:SP1.
An initial report on comparison i) has been published /8/.

A set of frequency difference measurements were performed, forming a matrix of frequency differences /7/ between the lasers when these were locked in frequency in turn to each of the four iodine absorption lines, conventionally labelled d, e, f, and g. The iodine components h, i, j were also observed, but the lasers DK1 and DK3 operated in two longitudinal cavity modes in the vicinity of these components because of the relatively high gain of these lasers.

A \( \tau = 10 \) s gate time was chosen for the frequency counter. Table 1 gives the results (and, in parentheses, the standard deviation). \( \Delta v \) is the frequency of laser 1 minus the frequency of laser 2.

### Table 1 Frequency differences for He-Ne lasers DK1, DK3 and SP1 (in MHz).

<table>
<thead>
<tr>
<th>Date</th>
<th>Laser 1 Intracavity power (mW)</th>
<th>Laser 2 Intracavity power(mW)</th>
<th>( \Delta v ) (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1988-12-14</td>
<td>DK3 17</td>
<td>SP1 6.7</td>
<td>-30 (10)</td>
</tr>
<tr>
<td>1989-02-01</td>
<td>DK1 14,7</td>
<td>DK3 13,3</td>
<td>+24 (15)</td>
</tr>
<tr>
<td>1989-03-30</td>
<td>DK1 18,7</td>
<td>SP1 10,5</td>
<td>+6 (15)</td>
</tr>
</tbody>
</table>

That the triangle of frequency difference measurements given in Table 1 do not sum to zero gives an indication of systematic uncertainties. Some investigations of these are given in the next section.

#### 4.1 Influence of iodine cell

##### 4.1.1 Iodine cells in lasers DK1 and DK3

Iodine cells made and filled with 127\( \text{I}_2 \) at the Physikalisch-Technische Bundesanstalt, with numbers PTB (4/86) (DK1) and PTB (5/86) (DK3).

##### 4.1.2 Iodine cell in laser SP1

In connection with the filling of the iodine cell BIPM 'cuve 43c' (at present installed in laser SP1) at the BIPM in Paris in June 1985, measurements were made of frequency differences between two of BIPM's lasers of well-known performance, one of which contained this cell. As a result, a systematic frequency difference of -36.4 kHz \( \pm 0.8 \) kHz on the frequency of a laser locked using this cell was noted /6/.
4.2 Influence of misalignment of laser cavity

Frequency difference measurements were performed when the two lasers were optimised for maximum laser power through alignment of the cavity mirrors.

Each laser was then deliberately misaligned, successively in the horizontal and vertical mirror alignments, while the other laser remained optimised. Measurements were made at each adjustment. The results are given in Table 4 (horiz. and vert. indicate misalignment on the horizontal and vertical adjustments while the other adjustment is optimum).

**Table 4** Frequency difference dependence on cavity alignment and associated intra-cavity power (ICP) variation

<table>
<thead>
<tr>
<th>Laser</th>
<th>$\frac{\delta v}{\delta \text{ICP}}$ (kHz/mW)</th>
<th>Intracavity power (ICP) range (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP1</td>
<td>-5,8 (horiz.)</td>
<td>$2,0 &lt; \text{ICP} &lt; 5,6$</td>
</tr>
<tr>
<td>DK3</td>
<td>+0,8 (horiz.)</td>
<td>$1,9 &lt; \text{ICP} &lt; 13,9$</td>
</tr>
<tr>
<td>DK3</td>
<td>+1,2 (vert.)</td>
<td>$4,6 &lt; \text{ICP} &lt; 13,9$</td>
</tr>
<tr>
<td>DK1</td>
<td>+6,9 (horiz.)</td>
<td>$3,5 &lt; \text{ICP} &lt; 11,5$</td>
</tr>
</tbody>
</table>

In figure 1 is shown the variation of the frequency difference $v(\text{DK1}) - v(\text{SP1})$ (in kHz) versus the intracavity power (in mW) of laser DK1 for various degrees of cavity misalignment. The frequency of laser SP1 was corrected at each measurement to a corresponding intracavity power of 12 mW throughout, using the power dependence coefficient given in Table 4.

A linear least-squares fit to the data yielded:

$$v(\text{DK1}) - v(\text{SP1}) = -123,6 + 6,9 \times \text{ICP (DK1)}$$

(kHz) (kHz) (mW)
Figure 1. Variation of frequency difference $n(DK1) - n(SP1)$ versus intracavity power of laser DK1 for various degrees of cavity misalignment.
5 FINAL FREQUENCY COMPARISON. CONCLUSIONS & DISCUSSION

5.1 Summary of Nordic comparison

Table 5 Summary of Nordic comparison

<table>
<thead>
<tr>
<th>Date</th>
<th>Laser 1</th>
<th>Intracavity power (mW)</th>
<th>Laser 2</th>
<th>Intracavity power (mW)</th>
<th>Δv (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1988-12-14</td>
<td>DK3</td>
<td>17</td>
<td>SP1</td>
<td>6,7</td>
<td>-30 (10)</td>
</tr>
<tr>
<td>1989-02-01</td>
<td>DK1</td>
<td>17</td>
<td>DK3</td>
<td>17</td>
<td>+38 (15)</td>
</tr>
<tr>
<td>1989-03-30</td>
<td>SP1</td>
<td>12</td>
<td>DK1</td>
<td>17</td>
<td>+6 (15)</td>
</tr>
</tbody>
</table>

Σ = +14 (15) kHz

A principal source of uncertainty in the measurements stems from the intensity-dependent frequency shifts. As is known from other comparisons /4/, large frequency shifts on cavity misalignment (typically 4 kHz/mW) are not uncommon.

Shifts in laser frequency when the iodine cell is rotated have also been reported /4/, but generally less than those on misalignment.

In a large, recent international comparison of such lasers /5/, power shifts in the range +1.4 kHz/mW to -6 kHz/mW were observed for the different lasers.

It is difficult in the present comparison to be certain in exactly which cavity alignment each laser was at each measurement, that is whether the output power obtained on a particular occasion was determined by a cavity mirror misalignment or by some other effect, such as rotation of the iodine cell or simply unclean mirrors and/or cell windows.
5.2 Comparison with Physikalisch-Technische Bundesanstalt, Braunschweig, West Germany

A comparison, 1987-12-04, between laser DK1 and PTB laser '03/86', at the Physikalisch-Technische Bundesanstalt, in Braunschweig, West Germany, gave

\[ v(\text{DK1}) - v(\text{03/86}) = -41 \text{ kHz} \]

where laser DK1 had an intracavity power of 20 mW. Using the intensity-dependence coefficients given in Table 4, one obtains

\[ v(\text{DK1}) = v(\text{03/86}) - 62 \text{ kHz}; \quad \text{ICP(DK1)} = 17 \text{ mW} \]

\[ v(\text{DK3}) = v(\text{03/86}) - 100 (15) \text{ kHz}; \quad \text{ICP(DK3)} = 17 \text{ mW} \]

\[ v(\text{SP1}) = v(\text{03/86}) - 56 (15) \text{ kHz}; \quad \text{ICP(SP1)} = 12 \text{ mW} \]

Further, the known frequency shift associated with the iodine cell '43c' in laser SP1 of -36.4 (0.8) kHz (section 4.1.2), can be used to give

\[ v(\text{SP1}) = v(\text{03/86}) - 20 (15) \text{ kHz}; \quad \text{ICP(SP1)} = 12 \text{ mW} \]
References


7. F Bayer-Helms, J-M Chartier, J Helmcke, A J Wallard, PTB-Bericht Me-17, 139-46 (1977)
