Direct frequency measurement of the I₂-stabilized He–Ne 473-THz (633-nm) laser

D. A. Jennings, C. R. Pollock, R. E. Drullinger, K. M. Evenson, and J. S. Wells

Time and Frequency Division, National Bureau of Standards, Boulder, Colorado 80303

J. L. Hall

Quantum Physics Division, National Bureau of Standards, Boulder, Colorado 80303

H. P. Layer

Length and Mass Measurement and Standards Division, National Bureau of Standards, Washington, D.C. 20234

Received November 2, 1982

The absolute frequency of the 473-THz He–Ne laser (633 nm), stabilized on the g or i hyperfine component of the 127I₂ 11–5 R(127) transition, was measured by comparing its frequency with a known frequency synthesized by summing the radiation from three lasers in a He–Ne plasma. The three lasers were (1) the 88-THz CH₄-stabilized He–Ne laser (3.39 μm), (2) a 125-THz color-center laser (2.39 μm) with its frequency referenced to the R₁₁(26) laser, and (3) the 260-THz He–Ne laser (1.15 μm) referenced to an I₂-stabilized dye laser at 530 THz (576 nm). The measured frequencies are 473 612 340.492 and 473 612 214.789 MHz for the g and i hyperfine components, respectively, with a total uncertainty of 1.6 parts in 10¹⁰. The frequency of the i component adjusted to the operating conditions recommended by the Bureau International des Poids et Mesures is 473 612 214.830 ± 0.074 MHz.

The experimental arrangement is shown in Fig. 2. The He–Ne summing tube was 8 m long, 14 mm in diameter, and filled with a 10-to-1 ratio of 3He and 20Ne to the operating pressure of 40–60 Pa. The dc discharge current was 50 mA. The different laser radiations were coupled in and out by a quartz Brewster-angle prism. The 200-mW 260-THz laser (1.15 μm) had an 8-m-long, 9-mm-diameter discharge tube operating at 800 Pa with a 3He:20Ne ratio of 21:1. A resonant reflector consisting of a 99% reflective end mirror plus a partially transmitting metal film on a piezoelectric transducer (PZT) positioned 9 cm from the end mirror provided tuning and mode control. A fast PZT on the 50%-output coupler was used for the servo control.

The 260-THz laser was stabilized in the following...
The 473-THz frequency from the summing tube was combined on a beam splitter with 47 \( \mu \)W of radiation from a \(^3\text{He}-^{20}\text{Ne} 473-\text{THz} \) laser stabilized on the \( g \) or \( i \) hyperfine component of the \(^{127}\text{I}_2 11-5 \) \( R(127) \) transition. The rf beat between the two, detected by an avalanche photodiode, was used to frequency stabilize the color-center laser frequency.

The frequency reference in this measurement was the CH\(_4\) frequency at 88 THz. The value for CH\(_4\) was taken to be the average of the last four measurements of this transition\(^7\)–\(^8\) with an uncertainty of 1 part in 10\(^{10}\), or 9 kHz. The CO\(_2\) laser used to measure the color-center frequency was measured relative to the CH\(_4\)-stabilized laser, as was the CO\(_2\) laser used to measure the 260-THz frequency.\(^4\)

Table 1 shows the frequencies of the three lasers used, and their errors, and subsequently the frequency of the 473-THz laser. The errors are listed in two columns to separate the correlated error arising from the common CH\(_4\) basis for each of the three frequencies from the uncorrelated errors, such as counting and utilization of reference center for \( I_2 \). The correlated errors were added directly, and the uncorrelated errors were added in quadrature.

The \(^13\text{C}\)\(^{18}\text{O}_2 \) \( R(26) \) frequency used in the measurement of the color-center laser was 31287.036.4117 MHz with measurement errors of 1.3 kHz in addition to the 3-kHz uncertainty that is due to CH\(_4\). The color-center laser frequency at 2.39 \( \mu \)m was measured by comparing its frequency with the frequency synthesized from a

<table>
<thead>
<tr>
<th>Laser</th>
<th>Frequency (MHz)</th>
<th>Uncertainty (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH(_4), 88 THz</td>
<td>88376.181.609</td>
<td>0</td>
</tr>
<tr>
<td>Color center, 125 THz</td>
<td>125132.754.610(^a)</td>
<td>11</td>
</tr>
<tr>
<td>( I_2/2 ), 260 THz</td>
<td>260103.404.273</td>
<td>25</td>
</tr>
<tr>
<td>(^{127}\text{I}_2 11-5 ) ( R(127) ) ( g )</td>
<td>473612.340.492</td>
<td>47</td>
</tr>
<tr>
<td>(^{127}\text{I}_2 11-5 ) ( R(127) ) ( i )</td>
<td>473612.214.789(^c)</td>
<td>47</td>
</tr>
<tr>
<td>Total Uncertainty ([47.4^2 + (51.2^2 + (47.2)^2)]^{1/2} = 74 \text{ kHz})</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) Summed in quadrature.
\(^b\) As tuned for \( g \) component.
\(^c\) The Comité Consultatif pour la Définition du Mètre\(^1\) has recommended that the following conditions be realized when the \(^{127}\text{I}_2 \) molecule, transition 11-5, \( R(127) \), component \( i \) is used for intracavity stabilization of the 473-THz He-Ne laser: (1) \( I_2 \) cold-finger temperature of 18°C, (2) cavity standing-wave power of 40 mW, and (3) modulation peak-to-peak amplitude of 6 MHz. The He-Ne \( I_2 \)-stabilized laser used in this experiment had a standing-wave power of 13.4 mW, which gives a frequency correction of \(-37 \text{ kHz}\).\(^9\) The cold-finger temperature was 20°C, implying a frequency correction of \(+80 \text{ kHz}\).\(^9\) Therefore the \(^{127}\text{I}_2 11-5 \) \( R(127) \) frequency adjusted for the recommended operating conditions is 473612.214.830 \( \pm \) 0.074 MHz.
15-GHz klystron and four harmonics of the known frequency of the $^{13}\text{C}^{18}\text{O}_2$ $R_{11}(26)$ laser line. A MIM diode was used both to generate the harmonics and to mix the radiation. The resulting rf beat was amplified and displayed on a spectrum analyzer. This beat signal, typically with a 10–20-dB signal-to-noise ratio, was averaged for 30 sec and recorded for later analysis.

The $I_2$-stabilized 473-THz laser was similar to the one described previously. The frequency was stabilized on the $g$ or $i$ hyperfine component of $^{127}I_2$ 11-5 $R(127)$. The operating conditions were the following: $I_2$ cell at 20°C, modulation width 6 MHz, and 47-μW output power. The $g$ component has the better reproducibility, which is about 47 kHz, resulting in an uncertainty of 1 part in $10^{10}$. This uncertainty was added in quadrature to the other measurement uncertainties to give a final uncertainty of approximately 74 kHz, or 1.6 parts in $10^{10}$.

It is comforting to note that the frequency difference between the $g$ and $i$ hyperfine components in this measurement is 125.703 MHz, which compares well with recent frequency measurements in our laboratory between $g$ and $i$ of 125.694 MHz.

References

1. Report, Comité Consultatif pour la Définition du Mètre, 7th Session (Bureau International des Poids et Mesures, Sèvres, France, 1982).