Direct frequency measurement of the I_2-stabilized He–Ne 473-THz (633-nm) laser

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The absolute frequency of the 473-THz He–Ne laser (633 nm), stabilized on the *g* or *i* hyperfine component of the $^{127}I_2$ 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 CH_4-stabilized He–Ne laser (3.39 μm), (2) a 125-THz color-center laser (2.39 μm) with its frequency referenced to the $R_{II}(26)$ $^{13}C^{18}O_2$ laser, and (3) the 260-THz He–Ne laser (1.15 μm) referenced to an I_2-stabilized dye laser at 520 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 10^{10}. 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 absolute frequency of the He–Ne 633-nm I_2-stabilized laser is of considerable interest, especially now with the pending redefinition of the meter.[1] We describe here the first reported direct frequency measurement of this laser with an increase in accuracy of 30 over wavelength measurements that are limited by the Kr length standard to an uncertainty of 4 parts in 10^9.[2] A scheme for synthesizing the 473-THz (633-nm) frequency of the visible He–Ne laser was first proposed and demonstrated by Klementyev *et al.*[3] In this synthesis scheme, as shown in Fig. 1, the 473-THz radiation is generated by the resonant mixing of the three measurable frequencies of a cascade He–Ne laser oscillating simultaneously on the 88-THz (3.39-μm), 125-THz (2.39-μm), and 260-THz (1.15-μm) lines. The sum frequency at 473 THz is radiated by coherent polarization on the $3s_2$–$2p_4$ transition in Ne, which results from the nonlinear interaction of the three radiation fields resonant with three cascade transitions connecting the same two atomic levels.

Our first attempts to use this synthesis scheme for frequency metrology were unsuccessful because the required low discharge pressure (60 Pa) for simultaneous oscillation of all three laser transitions did not permit high-power and single-frequency operation. The solution to this problem was to use a separate laser for each required frequency and to mix them in a separate low-pressure He–Ne gain cell. In what follows, we describe the synthesis and measurement details of the 473-THz frequency.

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 ^{3}He and ^{20}Ne 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 ^{3}He:^{20}Ne 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

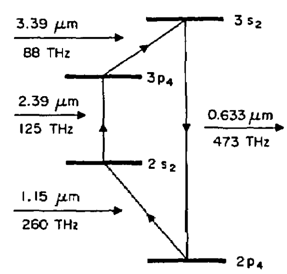

Fig. 1. Partial energy-level diagram of Ne showing the relevant levels for the sum-frequency mixing.

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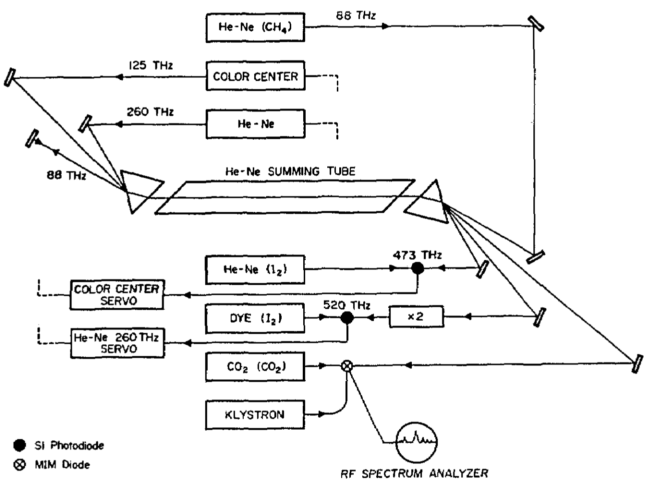

Fig. 2. Block diagram of the experimental setup for the sum-frequency mixing and the frequency measurement of the I_2-stabilized 473-THz laser.

manner. The output, after it passed through the He–Ne plasma summing tube, was focused and sent through a 25-mm-long temperature-tuned (185°C) 90° phase-matched $LiNbO_3$ frequency-doubling crystal. Radiation at 520 THz with approximately 50 μW of power was generated. A dye-laser frequency locked to the o hyperfine component of the $^{127}I_2$ 17-1 $P(62)$ transition, also at 520 THz, was used as the frequency reference.[4] The 260-THz laser was frequency locked by its second harmonic to the 520-THz dye laser.

The 88-THz frequency was generated by a 28-cm-long He–Ne laser frequency-offset locked to another 88-THz laser stabilized to the saturated absorption in CH_4. The usable output of 100 μW at 88 THz was first amplified by sending the radiation through the He–Ne summing tube in a direction opposite the 260-THz radiation in order to increase its power to about 8 mW and then retroreflected to provide the 88-THz radiation for summing. The return beam was isolated from the oscillator system by two 30-dB YIG Faraday isolators.

Sufficient power at 125 THz could not be obtained in a single mode from the $3p_4$–$2s_2$ transition in Ne, so the output from a stabilized color-center ring laser[4] was tuned to the appropriate frequency and used for mixing. This laser provided about 50 mW of power. After being sent through the summing tube, the 125-THz radiation was focused onto a W–Ni metal–insulator–metal (MIM) diode for the measurement of its frequency, which is described below.

To summarize the experimental details, radiation at 88, 125, and 260 THz with powers of 8, 50, and 200 mW, respectively, was sent into the He–Ne summing tube. The excited Ne atoms summed these radiations to give radiation at 473 THz with a power of 50 nW. No attempt was made to mode match the beams; however, the constraint of traveling through the 8-m tube without wall bounces forced the beams to be mode similar. Mixing could be verified by blocking any one of the three input beams, which immediately caused the generated red light to disappear.

The 473-THz frequency from the summing tube was combined on a beam splitter with 47 μW of radiation from a ^3He–^{20}Ne 473-THz laser stabilized on the g or i hyperfine component of the $^{127}I_2$ 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[5–8] 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 realization of line center for I_2. The correlated errors were added directly, and the uncorrelated errors were added in quadrature.

The $^{13}C^{18}O_2$ $R_{II}(26)$ frequency used in the measurement of the color-center laser was 31 287 036.4117 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 μm was measured by comparing its frequency with the frequency synthesized from a

Table 1. Frequency and Error Budget for the 473-THz Measurement

Laser	Frequency (MHz)	Measurement Uncertainty (kHz)	CH_4 Uncertainty (kHz)
CH_4, 88 THz	88 376 181.609	0	9
Color center, 125 THz	125 132 754.610[a]	11	12
I_2/2, 260 THz	260 103 404.273	25	30
		27.4[b]	51
$^{127}I_2$ 11-5 $R(127)g$	473 612 340.492	47	
$^{127}I_2$ 11-5 $R(127)i$	473 612 214.789[c]	47	
Total Uncertainty $[(27.4)^2 + (51)^2 + (47)^2]^{1/2} = 74$ kHz			

[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 $^{127}I_2$ 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 15°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 kHz.[9] The cold-finger temperature was 20°C, implying a frequency correction of +80 kHz.[10] Therefore the $^{127}I_2$ 11-5 $R(127)i$ frequency adjusted for the recommended operating conditions is 473 612 214.830 ± 0.074 MHz.

15-GHz klystron and four harmonics of the known frequency of the $^{13}C^{18}O_2$ $R_{II}(26)$ 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.[11] 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.

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