Extension of absolute-frequency measurements to the visible: frequencies of ten hyperfine components of iodine

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Direct-frequency measurements have been extended into the visible region of the electromagnetic spectrum. The visible frequencies were synthesized by generating the second harmonic of the recently measured 260-THz ^{20}Ne, 1.15-µm laser with a $LiNbO_3$ crystal. The absolute frequencies of ten hyperfine components of $^{127}I_2$ near 520 THz are reported.

There is at present considerable interest in the possibility of defining the units of time and length in terms of the frequency and wavelength of a single atomic or molecular transition, with the numerical relation between them fixed by a defined value for the velocity of light. For such a system to be practical it is essential that frequency-measurement techniques be extended to bridge the spectral range from the microwave region (where the second is defined) to the visible region (where the meter is defined). To this end we have measured the frequencies of ten iodine hyperfine components at 520 THz ($\lambda = 0.576$ µm) by comparison with the known frequency of a Lamb-dip stabilized pure ^{20}Ne laser (the NBS laser) at 260 THz ($\lambda = 1.15$ µm). The yellow-green light at 520 THz, generated (in the NRC laser) by doubling of 260-THz radiation from a He–Ne discharge, was servo-locked to individual hyperfine components of $^{127}I_2$ observed in saturated absorption, and their frequencies were determined simply by measurement of the beat frequencies of the two radiations at 260 THz.

The NBS laser had a 13-cm-long by 1.5-mm-diameter capillary. A hot cathode discharge in pure ^{20}Ne at a pressure of 33 Pa produced about 80 µW of single-frequency output. The frequency was stabilized to the center of the Lamp dip by an electronic servo system, which adjusted the mean cavity length so as to null the amplitude modulation of the output power produced by a 100-Hz cavity-length modulation (first-harmonic locking). The optical frequency modulation was approximately 10 MHz peak-to-peak. The mirrors were carefully adjusted to produce a symmetrical Lamb dip, and several repetitions of the mirror adjustment procedure showed a reproducibility of the Lamb-dip center frequency of approximately ±0.1 MHz. The total pressure shift in the ^{20}Ne laser is well under 0.1 MHz.[1] The frequency of this laser has been determined to be $f_{\mathrm{Ne}} = 260\,103\,264 \pm 30$ MHz by comparing its radiation with that synthesized from a 197-THz (1.5-µm) He–Ne and two CO_2 lasers.[2]

The 520-THz radiation was produced by the composite cavity NRC laser, shown in Fig. 1.[3] Radiation at 260 THz is generated in the He–^{20}Ne discharge in arm AB with about 100 µW transmitted through mirror A. Arm CB is closely coupled to AB by reflectance at

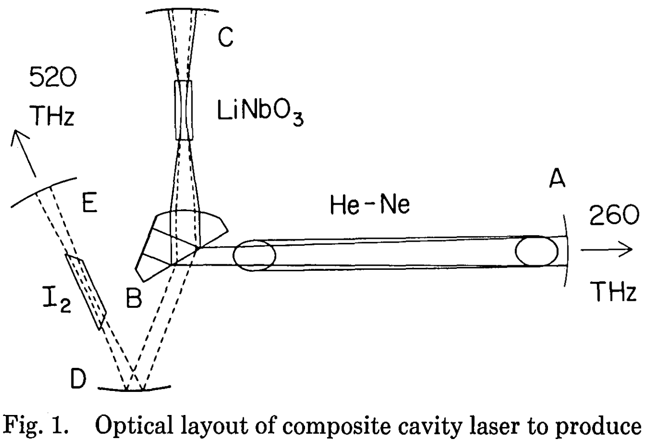

Fig. 1. Optical layout of composite cavity laser to produce saturated absorption in I_2 at twice the He–Ne frequency of 260 THz (1.15 µm).

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the prism surface at B and acts as a Fox–Smith mode selector to force single-frequency operation even though AB is about 1 m long. The curved prism surface provides optimum concentration of the infrared radiation in the nonlinear crystal of lithium niobate maintained at the phase-matching temperature for doubling 260 THz (173°C). About 10 μW of the doubled radiation left the prism toward D when mirror E was blocked: when cavity CBDE was resonated, the one-way internal power was approximately 500 μW at 520 THz. Electronic servos driving piezoelectric transducers on mirrors C and E keep the three arms in resonance, AB and CB in the infrared and CBDE in the visible. The frequency can be tuned about 2.5 GHz at 520 THz by driving mirrors A, C, and E in synchronism.

There is a substantial overlap of the doubled radiation and the strong $P(62)$ line in the 17-1 band of $^{127}I_2$. Fifteen hyperfine components (labeled a to o in order of decreasing frequency) are expected in this line, and ten of these (f to o) were observed in saturated absorption within the laser tuning range. The lowest frequency component, o, is well separated from the others and provides by far the best signal-to-noise ratio because the background absorption from the other iodine components is relatively small and because it occurs near the peak of the laser output power. The components had a full width at half-height of 2 MHz for an iodine pressure of 4 Pa. With 2-MHz frequency modulation (at 1.8 kHz), the laser could be servo-locked to the zero crossing of the amplitude modulation at 5.4 kHz that occurs at the center of each component (third-harmonic locking). The infrared laser was locked in turn to each hyperfine component for the frequency measurements described below and thus was at half the frequency of the hyperfine line.

The frequency measurements were done simply by combining the 260-THz beams from the two lasers on a high-speed photodiode. The beat frequency was displayed on a spectrum analyzer and measured with an adjustable marker oscillator and counter. The frequency, f_α, of the α-component is given by

$$f_\alpha = 2[f_{\mathrm{Ne}} + (f_\alpha/2 - f_{\mathrm{Ne}})].$$

Six determinations of the frequency difference between the o component and the Lamb dip were made with a readjustment of the mirrors of the NBS laser for symmetrical Lamb dip between each one. The standard deviation of six such settings was about 0.1 MHz. Systematic errors due to asymmetry of the modulation envelope were estimated to be less than about 1% of the 45-MHz full width of the Lamb dip. Other sources of error were significantly less than this. The mean value is

$$f_o/2 - f_{\mathrm{Ne}} = 154.3 \text{ MHz},$$

and the estimated 1-σ error is 0.5 MHz. The frequency of the o component of the $P(62)$-line, 17-1 band of $^{127}I_2$ is thus

$$f_o = 2[f_{\mathrm{Ne}} + (f_o/2 - f_{\mathrm{Ne}})] = 520\ 206\ 837 \pm 60 \text{ MHz}.$$

A preliminary measurement of the wavelength of this component gave $\lambda = 576\ 294\ 758 \pm 6$ fm,[4] from which we calculate $f_o = c/\lambda = 520\ 206\ 811 \pm 6$ MHz.[5] The agreement between the above values for the frequency is satisfactorily within the error limits. In addition, the laser was locked to each of the components (n to f) and the beat frequencies between $f_\alpha/2$ and f_{Ne} were measured. The results are shown in Table 1. The uncertainty in each of these beat frequencies is also 0.5 MHz.

Table 1. Differences between the $^{127}I_2$, 17-1, $P(62)$ Hyperfine Components, α, and the Second-Harmonic of the Lamb-Dip Stabilized ^{20}Ne, 1.15-μm Laser

Hyperfine Component, α	$f_\alpha - 2f_{\mathrm{Ne}}$ (MHz)
o	308.6 (1.0)
n	584.1
m	595.9
l	602.1
k	615.2
j	727.3
i	738.7
h	747.3
g	760.6
f	888.0

This extension of absolute-frequency measurements to the visible paves the way for highly accurate measurements in this portion of the electromagnetic spectrum. The rather large error limit on f_α is due to the free-running 197-THz He–Ne laser used in the measurement of the Lamb-dip stabilized ^{20}Ne, 1.15-μm laser. In view of the reproducibility of this Lamb-dip stabilized laser, an improved determination of its frequency, f_{Ne}, can be combined with the above value of $f_\alpha - 2f_{\mathrm{Ne}}$ to decrease the uncertainty of these iodine frequencies by about 2 orders of magnitude.

References

1. J. L. Hall, IEEE J. Quantum Electron. **QE-4,** 638 (1968).
2. D. A. Jennings, F. R. Petersen, and K. M. Evenson, Opt. Lett. 4, 129 (1979).
3. A paper giving full details of this laser is in preparation by G. R. Hanes.
4. The authors wish to thank K. H. Hart of NRC, Ottawa, for this wavelength value.
5. Using the value c = 299 792 458 m/sec recommended in BIPM, Comptes Rendus des Seances de la Conf. Gen. des Poids et Mesures, 15th, p. 103, 1975.