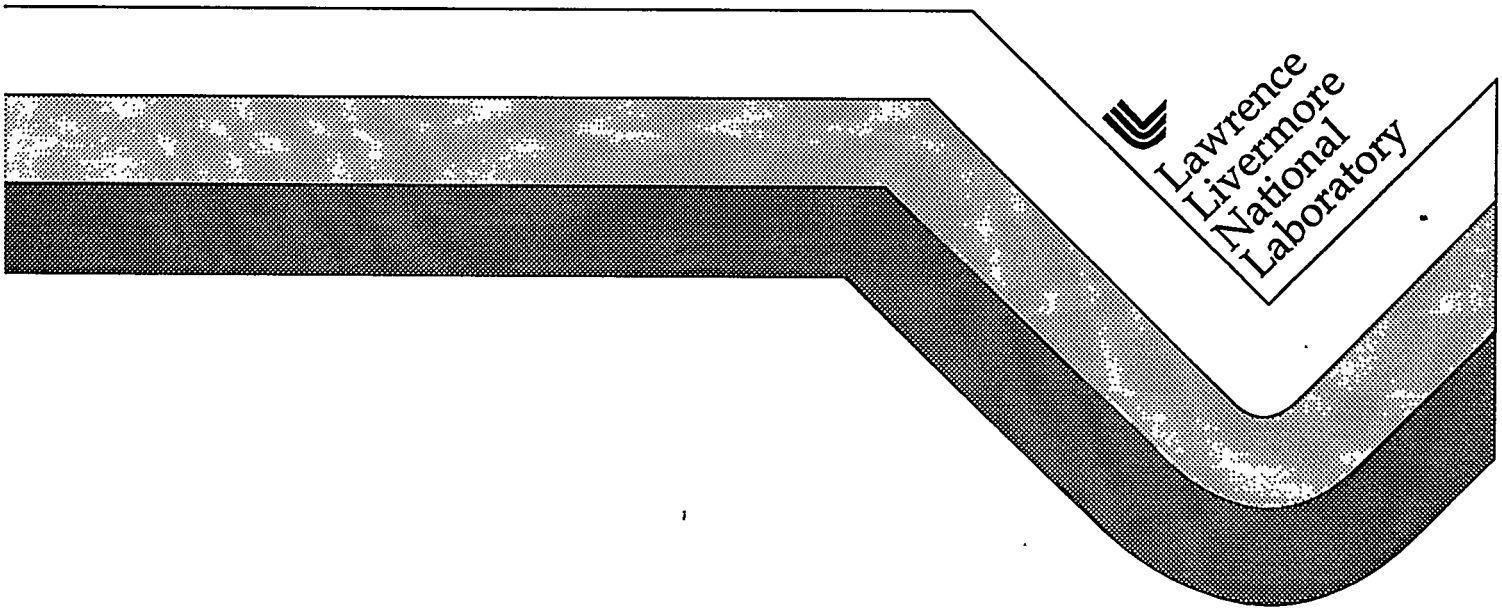
UCRL-CR-107777
S/C-923-003

Molecular Iodine Absolute Frequencies

C. J. Sansonetti

June 25, 1990



Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

MOLECULAR IODINE ABSOLUTE FREQUENCIES

Final Report

work performed under contract #923-003

for

Lawrence Livermore National Laboratory

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June 25, 1990

ABSTRACT

Fifty specified lines of $^{127}I_2$ have been studied by Doppler-free frequency modulation spectroscopy. For each line the classification of the molecular transition has been determined, the hyperfine components have been identified, and one well-resolved component has been selected for a precise determination of its absolute frequency. In three cases a nearby alternate line was selected for measurement because no well-resolved component was found for the specified line. Absolute frequency determinations were made with an estimated uncertainty of 1.1 MHz by locking a dye laser to the selected hyperfine component and measuring its wave number with a high-precision Fabry-Perot wavemeter. For each line results of the absolute measurement, the line classification, and a Doppler-free spectrum are given.

INTRODUCTION

Fifty specified lines of $^{127}I_2$ have been studied by the method of Doppler-free frequency modulation spectroscopy. For each line a Doppler-free scan has been made, the hyperfine components have been identified, the classification of the molecular transition has been determined, and the absolute frequency of one hyperfine component has been measured with an accuracy estimated to be ±1.1 MHz. In this report the results are presented along with a brief description of the experimental methods employed.

EXPERIMENTAL METHODS

The apparatus used to observe the Doppler-free spectra of I_2 lines by frequency modulation (FM) spectroscopy is essentially similar to that described by Hall, Hollberg, Baer, and Robinson.[1] The theory of FM spectroscopy including an analysis of the observed line shape is given by Bjorklund, Levenson, Lenth, and Ortiz.[2]

In our apparatus (Figure 1) a commercial ring dye laser operated with Rhodamine 6G, DCM, or Rhodamine 110 provides tunable single-frequency radiation with a line width of less than 1 MHz. The laser beam is split into a strong saturating beam and a weak probe that counterpropagate coaxially through the iodine cell. The beams in the cell are approximately collimated and about 2 mm in diameter. The frequency of the saturating beam is shifted upward by 72 MHz and its intensity is sinusoidally modulated at 85 kHz by an acousto-optic modulator. The frequency shift introduced by the AOM prevents optical feedback from the counterpropagating beams into the dye laser. A variable attenuator provides adjustment of the saturating beam intensity.

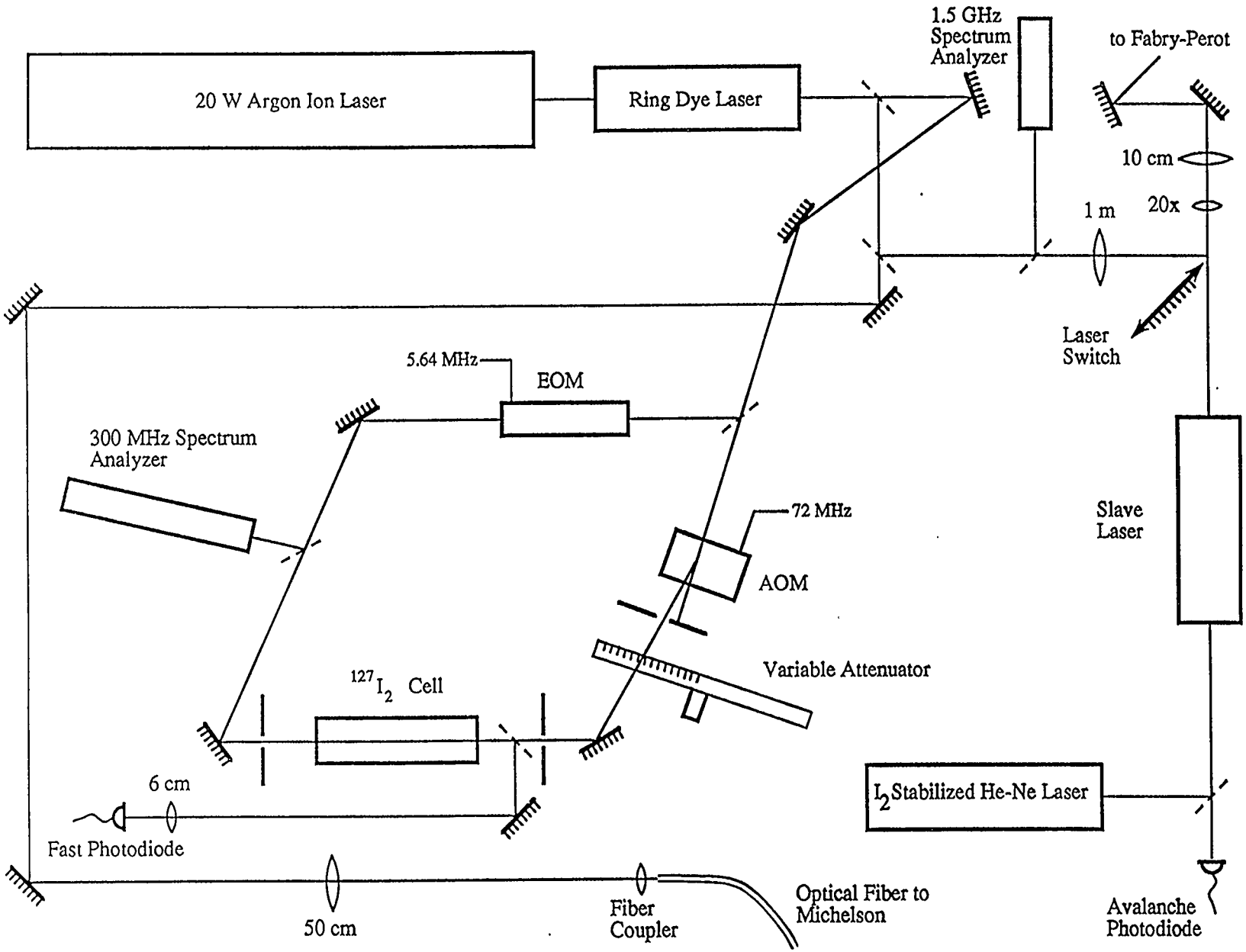

Figure 1. Experimental apparatus.

The probe beam passes through an electro-optic phase modulator that imposes sidebands at ±5.64 MHz from the laser center frequency. The EOM drive power is adjusted to put 10% of the total power in each sideband by observing the spectrum of the probe beam on a 300 MHz spectrum analyzer. As the laser frequency is scanned the sidebands probe the narrow saturated absorption resonance induced by the saturating beam. After passing through the iodine cell a portion of the probe beam intensity is picked off by a beam splitter and focused on a fast photodiode. The resulting signal is processed by a high pass filter, double balanced mixer, and lockin amplifier (Figure 2) to recover the derivative shaped FM resonance.[2] The phase of the local oscillator signal to the mixer is adjusted by a variable delay line to produce the best combination of FM signal and freedom from residual amplitude modulation induced noise.[3]

The iodine cell used in this work was constructed in the NIST optical shop and filled by Howard Layer of NIST. The methods used in preparing the cell were identical to those used for the cells in I_2-stabilized He-Ne lasers constructed at NIST.[4] Previous tests with such cells have shown that frequency shifts due to residual background gas pressure are less than 1 part in 10^{11}. The cell is 12 mm in diameter and 30 cm long with fused quartz Brewster windows and a small sidearm. For all observations reported here the cell and sidearm were operated at room temperature, typically 23±1°C. At this temperature the long cell and collinear beam geometry employed provided excellent signal to noise ratio even for transitions below 16,000 cm^{-1} for which heated cells are sometimes required.

Each of the specified I_2 lines was initially scanned to observe its hyperfine structure and identify a hyperfine component suitable for the

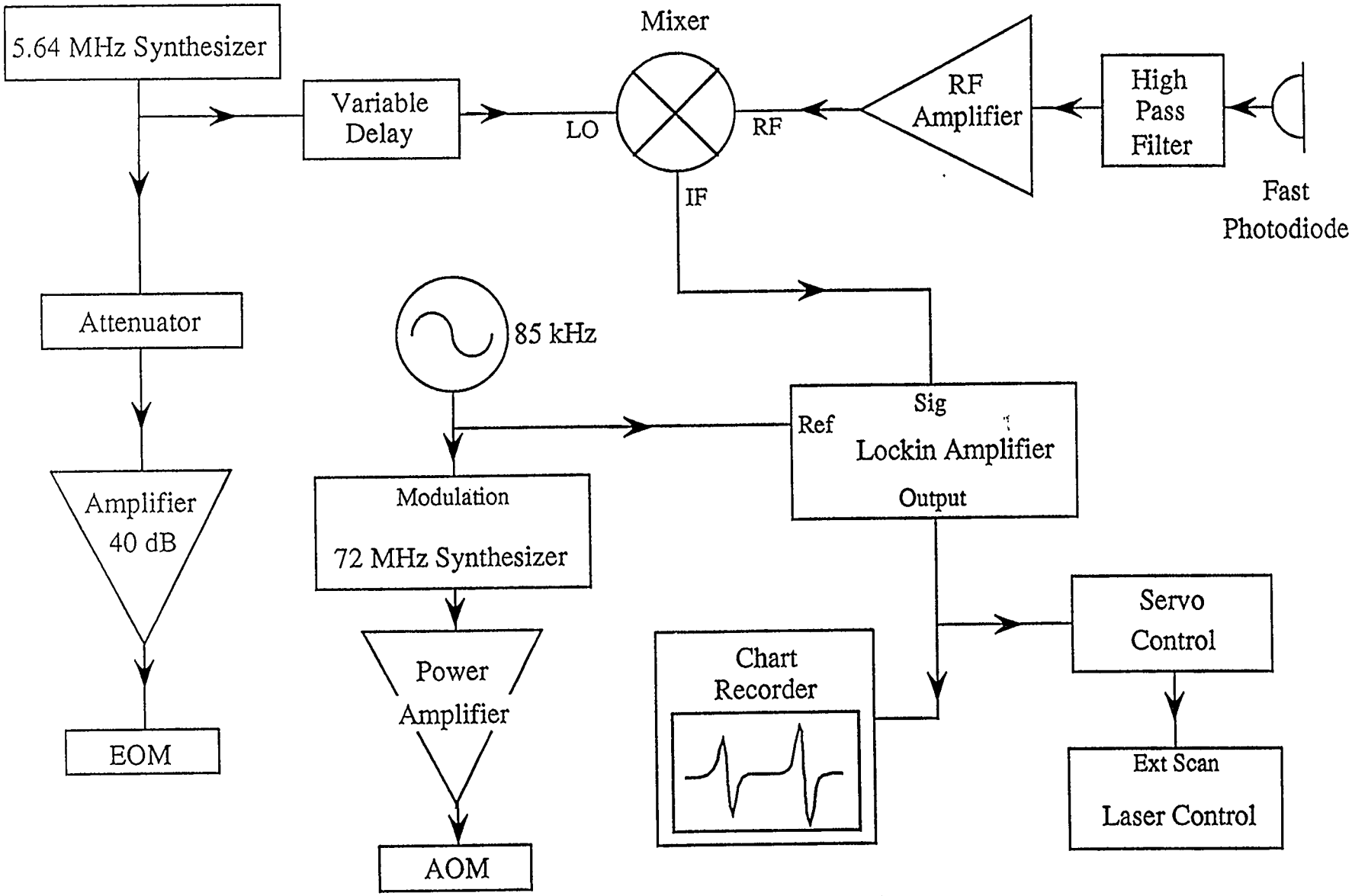

Figure 2. Electronic schematic for FM spectroscopy.

absolute frequency measurement. The laser was tuned to the line of interest by using a travelling Michelson wavemeter with an accuracy of about ±0.002 cm^{-1}. Typically a scan 0.045 cm^{-1} wide was made in a period of about 4 min. with a lockin time constant of 0.1 sec. The iodine hyperfine components observed had widths of about 4 to 6 MHz. After an appropriate hyperfine component was selected for the absolute measurement, the laser was servo-locked to the zero crossing of the FM signal. The servo-lock was implemented through the external scan input of the laser controller. It was able to maintain a stable lock for an indefinite period and was found not to increase or decrease the laser bandwidth.

The absolute frequency measurement of the dye laser locked to an I_2 line was made using the Fabry-Perot wavemeter developed in our laboratory. This instrument uses a plane plate Fabry-Perot interferometer to measure the wavelength of a tunable laser with respect to the I_2-stabilized He-Ne laser,[4] which is the best realization of the definition of the meter in the optical region. A brief description of the instrument is given in the paper included as Appendix A of this report. It has been shown to be relatively insensitive to systematic errors of alignment, and routinely produces results with an precision of better than 2 MHz.

To obtain the highest absolute accuracy from the Fabry-Perot wavemeter, its results must be corrected for the wavelength dependence of the phase shift that occurs when light is reflected from its aluminized plates. In previous work[5,6] this phase correction has been determined by measuring Doppler-free lines of I_2 in the region 15,233 - 17,352 cm^{-1} and of Te_2 in the region 19,917 - 21,221 cm^{-1} using several Fabry-Perot spacers of varying lengths.[7] Since the phase dispersion for aluminum coatings is known to be smoothly varying,[8] the

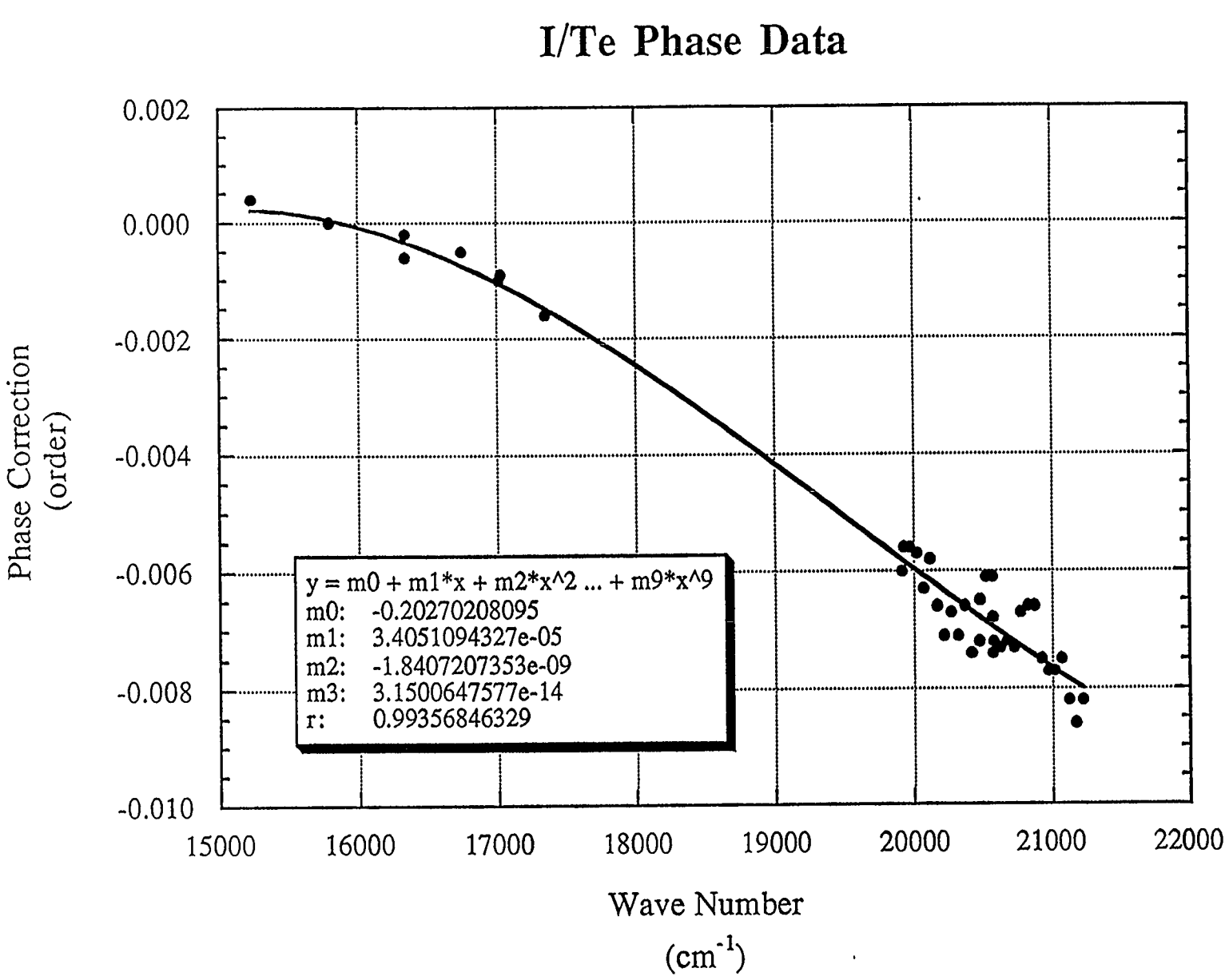

Figure 3. Phase correction applied to Fabry-Perot wavemeter results.

correction for this work was obtained by fitting a curve through these two sets of data as shown in Figure 3. Over the range of measurements reported here, the phase correction determined from this curve should be accurate to better than 0.0005 order.

RESULTS

Results for the I_2 lines observed in this work are collected in Table 1. The number in the leftmost column is the line number from the list of lines specified by LLNL for measurement. In a few instances it has been necessary to select alternate lines for measurement because no clearly resolved component of the specified line was observed. These alternate lines are flagged with an "A" (i.e. 23A). Two additional lines (15,233 and 17,352 cm^{-1}) were measured to verify the accuracy of the absolute measurements because they have been previously measured with high precision in other laboratories.[9-11]

Doppler-free scans of all lines studied are collected as Appendix B. On each chart the experimental parameters pertaining to that scan are noted. All identified hyperfine components are labeled. Primes are used to differentiate components of different ro-vibrational transitions. The hyperfine component measured is indicated with an arrow. Wave numbers given at the beginning and end of each scan are from the Michelson wavemeter. Since the scans are linear within 2%, they can be used to determine component spacings and line widths. The relative accuracy of these beginning and ending wave numbers should be ± 0.001 cm^{-1}. In some cases, however, they may not have been corrected for the index of refraction of ambient air. Their absolute accuracy is not specified.

The classifications reported in Table 1 are based on calculations of the transitions of the I_2 B-X band system made using Dunham parameters derived by

Table 1. Iodine Classifications and Wave Numbers

Line Number	Iodine Atlas Value (cm-1)	Classification	Component Measured	Number of Measurements	Average	Phase Correction (cm-1)	Final Value (cm-1)
	15233.3709	R 73(5-5)	i	2	15233.367430	0.000005	15233.367434
1	15278.5970	P110(6-5)	t	2	15278.574309	0.000005	15278.574313
2	15297.7331	P149(7-5)					
		P100(6-5)	t	2	15297.712479	0.000005	15297.712483
3	15379.2427	R 75(10-7)					
		R 41(6-5)	t	2	15379.221560	0.000004	15379.221564
4	15406.9571	P102(7-5)	t	2	15406.937551	0.000004	15406.937555
		R 50(10-7)					
5	15411.4115	R 94(5-4)	t	2	15411.389348	0.000004	15411.389352
6	15427.3290	P 77(5-4)	t	2	15427.306473	0.000004	15427.306477
7	15672.5397	P 65(7-4)	t	2	15672.517404	0.000002	15672.517406
8	15727.5450	R 22(9-5)	t	3	15727.518574	0.000002	15727.518576
		P 16(9-5)					
9	15807.2997	R 50(8-4)	t	2	15807.267685	0.000001	15807.267685
		P 44(8-4)					
		P115(9-4)					
		R 20(6-3)					
10	15846.4016	P 96(9-4)	t	2	15846.384989	0.000000	15846.384989
11	15856.9480	R 96(9-4)	t	2	15856.931275	0.000000	15856.931275
12	15886.5167	P 61(7-3)	t	2	15886.494960	0.000000	15886.494960
13	15954.0395	R146(11-4)					
		R 97(8-3)	t	2	15954.016996	-0.000001	15954.016995
14	15973.6555	R 91(10-4)	t	2	15973.631203	-0.000001	15973.631202
15	16038.2142	R 36(10-4)	t	2	16038.192687	-0.000002	16038.192684
16	16052.4503	R 97(7-2)					
		R103(9-3)	t	2	16052.429632	-0.000003	16052.429629
17	16172.3322	P 91(10-3)	t	2	16172.309259	-0.000005	16172.309254
18	16205.9667	R 78(12-4)					
		R 76(10-3)	t	2	16205.946035	-0.000005	16205.946029
19	16254.6570	P 17(10-3)	t	3	16254.623408	-0.000006	16254.623402
		P 26(12-4)					
20	16304.5209	P 76(11-3)	t	2	16304.499055	-0.000007	16304.499047
21A	16404.6488	P 78(10-2)	t	2	16404.626628	-0.000009	16404.626618
21	16404.7515	P128(11-2)					
		P 79(12-3)					
22	16424.4721	R 70(10-2)	t	3	16424.450544	-0.000010	16424.450534
23	16502.4381	P130(12-2)					
		P127(14-3)					

Line Number	Iodine Atlas Value (cm-1)	Classification	Component Measured	Number of Measurements	Average	Phase Correction (cm-1)	Final Value (cm-1)
23A	16502.8396	P 82(13-3) P 69(17-5)	t	2	16502.817090	-0.000011	16502.817078
24	16568.2788	P 27(11-2) unk	t	2	16568.255081	-0.000013	16568.255068
25	16638.0513	R 69(12-2) P117(13-2)	i	2	16638.049738	-0.000014	16638.049723
26	16780.8628	P 26(11-1) unk 21 comp	t	2	16780.840099	-0.000018	16780.840081
27	16806.6502	R 95(12-1) unk 21 comp	t	2	16806.627933	-0.000019	16806.627914
28	16875.1316	P106(13-1)	t	2	16875.109273	-0.000020	16875.109253
29	16917.3532	P 80(15-2)	t	2	16917.332084	-0.000022	16917.332062
30	17006.0671	R 97(14-1)	t	2	17006.044229	-0.000024	17006.044205
31	17038.4004	P 66(16-2)	t	2	17038.378880	-0.000025	17038.378855
32	17045.9683	R122(15-1) P 85(21-4)	t	2	17045.945484	-0.000025	17045.945459
33	17123.3318	P 73(17-2) P 31(21-4)	t	2	17123.310044	-0.000027	17123.310017
34	17157.4170	R 67(15-1)	t	2	17157.396940	-0.000028	17157.396912
35	17165.7490	unk P 56(15-1) P 64(13-0) R 69(13-0)					
35A	17166.0247	P108(16-1) P 67(32-4)	t	3	17166.002855	-0.000029	17166.002827
36	17205.8103	R140(15-0) P 98(14-0)	t	2	17205.788983	-0.000030	17205.788953
	17352.2507	P 62(17-1)	t	3	17352.231385	-0.000034	17352.231351
37	17380.8373	P 38(17-1)	t	2	17380.816968	-0.000035	17380.816933
38	17448.3840	R 42(20-2)	t	2	17448.363136	-0.000037	17448.363099
39	17461.2028	P 67(16-0)	t	2	17461.182268	-0.000038	17461.182230
40	17501.1426	P 70(29-5) R 38(16-0)	t	2	17501.121932	-0.000039	17501.121892
41	17521.7556	R 77(19-1)	t	2	17521.737692	-0.000040	17521.737652
42	17531.3994	P 67(19-1)	t	2	17531.384150	-0.000040	17531.384109
43	17578.6019	R 92(25-3) P 26(19-1)	i	2	17578.599511	-0.000042	17578.599469
44	17605.3313	P 23(17-0)	t	2	17605.308111	-0.000043	17605.308068

Table 1 cont.

Line Number	Iodine Atlas Value (cm-1)	Classification	Component Measured	Number of Measurements	Average	Phase Correction (cm-1)	Final Value (cm-1)
45	17668.6779	R 32(20-1)	t	2	17668.657257	-0.000045	17668.657212
46	17685.4186	R 46(18-0) unk	t	2	17685.398109	-0.000045	17685.398063
47	17704.6923	R 19(18-0)	t	2	17704.669118	-0.000046	17704.669072
48	17742.5229	P 68(19-0)	t	3	17742.501514	-0.000047	17742.501466
49	17811.1083	R 49(27-3) R 84(20-0)	t	3	17811.087555	-0.000050	17811.087505
50	17845.2328	P 28(22-1) R 32(22-1)	t	3	17845.202261	-0.000051	17845.202210

Gerstenkorn and Luc from their observation of the I_2 absorption spectrum by Fourier transform spectroscopy.[12] In general the I_2 spectrum is very dense with several transitions predicted within the Doppler profile of each line listed in the iodine atlas.[13] The classifications given are based on the line position, hyperfine structure, and expected intensity. A classification is listed if hyperfine components belonging to that transition were observed in the scan presented in Appendix B. It is possible that additional transitions that had no components within the scan contribute to the Doppler broadened line given in the iodine atlas.

In a few cases hyperfine components were observed that could not be identified with any predicted transition of the B-X band system. These may belong to some other band or to transitions with J higher than that for which the Dunham parameters are applicable. Where unidentified transitions were observed, the entry "unk" appears in the classification column with the number of hyperfine components if it could be determined.

For most lines it was possible to measure the "t" component of the hyperfine structure. Note that in this work the hyperfine components are designated as in Reference 14. In some published works this component is labeled "o" for fifteen component structures. In a few cases the "i" component was measured as noted in Table 1. In all cases the component can be readily identified by reference to the scans in Appendix B.

The absolute frequency for each line was measured at least twice on separate days to try to minimize any systematic alignment factors that might affect the results. Some lines were measured three times for consistency checks and diagnostic purposes. Each of these measurements is the average of 80 individual determinations from the Fabry-Perot wavemeter accumulated over a

period of about 2 min. The standard deviation of each set of 80 values is about 0.000004 cm^{-1} (0.13 MHz). Measurements taken on different days vary significantly more than this short term random variation. This indicates that the dominant errors in the Fabry-Perot wavemeter are systematic in nature. Previous experience shows that variations as large as 2 MHz from the average of a large number of measurements taken over many days are occasionally seen (less than 1% probability; see Appendix A, Figure 2). For the results reported in Table 1, no single measurement differed from the reported average by more than 0.7 MHz.

A number of contributions to the uncertainty of the absolute wave numbers reported can be identified. First, the dye laser is locked to the I_2 hyperfine component by a first derivative type lock. The lock point can be shifted from the actual center of the resonance by baseline shift in the FM signal or by line asymmetry. From our recorded line profiles we estimate that this effect does not exceed 5% of the line width, hence it may contribute 0.3 MHz to the uncertainty. Second, the directly measured laser wave number must be corrected for the frequency shift introduced in the saturating beam by the AOM. This amounts to increasing the measured value by one half the frequency shift. Since the AOM is driven by a high precision synthesizer, this correction contributes negligibly to the uncertainty. Third, there is the uncertainty of the wave number of the reference laser for the Fabry-Perot wavemeter. This laser is frequency-offset locked to an I_2 stabilized He-Ne laser with an uncertainty smaller than that of the wave number of the I_2 stabilized laser. Its uncertainty, about 30 kHz, is also negligible. Fourth, there is the daily systematic variation in the results of the Fabry-Perot wavemeter mentioned above. From previous tests the standard deviation of a

large ensemble of measurements of the same transition is about 0.5 MHz. Based on this, the three standard error uncertainty for the average of two measurements is about 1 MHz. Finally, there is the uncertainty in the phase correction applied to the Fabry-Perot results. At wavelengths close to the reference laser this correction is approximately zero and its uncertainty is negligible. For those lines most distant from the reference laser it does not exceed 0.0005 order or 0.4 MHz for the 218 mm Fabry-Perot spacer used in this work. Adding these sources of error in quadrature we obtain 1.1 MHz as an estimate of the uncertainty of our final results. Comparison of the two lines measured for verification of the absolute wave numbers with previous results is shown in Table 2. For both lines the current results fall within 1/3 MHz of the best values from other laboratories.

CONCLUSION

Work specified under contract #923-003 between Lawrence Livermore National Laboratory and the National Institute of Standards and Technology has been completed. All lines listed in Table 1 of the Description of Requested Work have been studied, and Doppler-free scans are included as Appendix B of this report. In three cases alternate lines within 0.5 cm^{-1} of the specified line have been selected for measurement because the original line was a blend. Scans of the alternate lines are also presented. Fifty iodine hyperfine components have been measured with an estimated absolute accuracy of ±1.1 MHz. Test measurements on two lines previously measured with high accuracy in other laboratories show agreement at the level of 1/3 MHz. This confirms the general accuracy of the methods employed.

Table 2. Comparisons with Previous Measurements

$^{127}I_2$ Line	This Experiment (cm^{-1})	Other measurements (cm^{-1})	Deviation (cm^{-1})
R 73(5-5) i	15233.367434(37)	15233.367443(40)[a]	0.000009
		15233.367429(42)[b]	-0.000005
P 62(17-1) t	17352.231351(37)	17352.231348(40)[a]	-0.000003
		17352.231340(11)[c]	-0.000011

[a] Reference 9.

[b] Reference 10.

[c] Reference 11 with uncertainty quoted as three standard deviations.

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APPENDIX A

Description of Fabry-Perot Wavemeter

PRECISE LASER WAVELENGTH MEASUREMENTS: WHAT CAN WE LEARN FROM CLASSICAL SPECTROSCOPY?

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ABSTRACT

The wavelengths of cw dye lasers are typically measured using Michelson wavemeters, but the absolute accuracy of such instruments is limited by their sensitivity to alignment of the laser beams. This systematic problem can be largely eliminated by diffusely scattering the beams and using classical spectroscopic methods to measure the wavelength. We have developed a laser wavemeter, based on a static Fabry-Perot interferometer, with an accuracy of a few parts in 10^9 and an update rate of about 2 Hz. The system is insensitive to the alignment and collimation of the incoming laser beams. The potential for a more precise wavemeter based on techniques of Fourier transform spectroscopy is also considered.

INTRODUCTION

Commercial single-frequency cw dye lasers have a linewidth of less than 1 MHz or a part in 10^9 of the optical frequency. Such lasers have been available for a decade, but there remains a need for a convenient method for measuring their wavelengths with accuracy comparable to the linewidth. Commercial wavemeters are limited to a part in 10^6, and the more precise wavemeters built in many laboratories do not consistently produce results better than a part in 10^8. Higher accuracy can be achieved by high-precision interferometric techniques[1] or direct frequency measurements,[2] but these techniques are not adapted to routine laboratory use.

MICHELSON WAVEMETERS

Over the last decade a variety of wavemeter designs have been reported (i.e. Refs. 3 - 9), but only variations of the Michelson wavemeter have seen wide use for precise measurements of cw lasers. A Michelson wavemeter of reasonable size can achieve a resolution of a part in 10^7 by using simple fringe counting. This can be improved to better than a part in 10^8 by multiplying the fringe frequency in a phase-locked loop.[4]

Although high precision Michelson wavemeters have been built in a number of laboratories, they have not achieved absolute accuracy comparable to their resolution. Some of their sources of uncertainty are quantifiable and can be controlled by appropriate design and laboratory practice. Among these are the uncertainties in the diffraction correction, the correction for the dispersion of

* Formerly National Bureau of Standards.

air, and the wavelength of the reference laser.

In contrast to these uncertainties which can be controlled to a part in 10^9, other less predictable sources of error can be identified. Laser amplitude instabilities characteristic of dye lasers can cause errors in the fringe counting and multiplication circuitry leading to a large scatter and systematic bias in the wavemeter results. This problem is readily detectable but may not be easy to eliminate. Not so easily detected are systematic errors due to misalignment of the laser beams. Two types of alignment error can be distinguished. First, the beams may not be aligned parallel to the motion of the travelling mirror. In some geometries this causes lateral shifts between the interfering beams at the fringe detector, and in any case it causes the beams to move about in the travelling retroreflector. These effects can cause phase errors in the observed fringes. Second, the unknown laser may not be aligned parallel to the reference beam. If the angle of inclination between the beams is θ, the relative error in the measured wavelength is $\theta^2/2$. To obtain a relative error smaller than a part in 10^9 the angle θ must be less than 4.5×10^{-5} rad. It is very difficult to maintain alignment at this level, and there is no readily observable condition that signals misalignment.

A good discussion of uncertainties in Michelson wavemeters has been given by Castelli et al.[10] in a report on tests of the high-resolution instrument at Kaiserslautern. With very careful alignment they were able to obtain a relative uncertainty of 5×10^{-9} in measurements of an argon ion laser. When a cw dye laser was substituted for the argon ion laser the relative uncertainty increased to 1×10^{-8}. And in routine use the authors estimated that a relative uncertainty of 3×10^{-8} could be expected.

In summary, the routine accuracy of Michelson wavemeters is limited mainly by the difficulty of maintaining proper alignment of the laser beams through the instrument. Misalignment is not readily detectable and may easily cause systematic errors far greater than the statistical spread of a series of independent measurements.

CLASSICAL METHODS

Classical methods for wavelength measurement are techniques developed to determine the wavelength of spectral features in an incoherent emission source. Such a source can be regarded as a spatially extended collection of independent point emitters each of which radiates isotropically. As a consequence, the illumination of a spectroscopic instrument can be determined by the aperture of the instrument rather than by the characteristics of the source.

The most precise classical wavelength measurements are made by using Fabry-Perot interferometry or Fourier transform spectroscopy. In careful experiments accuracy better than a part in 10^8 can be obtained. Typically the accuracy is limited not by the technique or instrumentation but rather by the spectral line width and limited coherence length of the source. Since lasers can readily overcome these source limitations, it is worthwhile to consider the application of classical methods to laser wavelength measurements.

FABRY-PEROT WAVEMETER

A complete discussion of precise wavelength measurements by Fabry-Perot interferometry has been given by Meissner.[11] Briefly, the interferometer is illuminated by an extended source and the transmitted light is imaged by an achromatic lens to form a pattern of concentric interference rings. For an evacuated interferometer

$$(P + \epsilon)\lambda = 2t \qquad (1)$$

where P is the integer and ϵ the fractional order of interference at the center of the fringe pattern, λ is the wavelength, and t is the spacer length. ϵ can be determined from the observed radii of the interference rings. Using Eq. 1 one can calculate the spacer length t from a standard line, and the wavelength of an unknown line can be determined by using the equation a second time. To use Eq. 1 it is necessary to know t accurately enough to determine the integer order for the standard line and the unknown wavelength accurately enough to determine the integer order for the unknown line. In practice the optical path difference in the interferometer is slightly wavelength dependent due to phase shifts on reflection from the aluminium coatings. To obtain the highest accuracy this phase shift must be determined and taken into account.

A schematic diagram of the Fabry-Perot wavemeter developed at the National Institute of Standards and Technology is shown in Fig. 1. It differs in design principles and accuracy from earlier Fabry-Perot based instruments.[8,10] The interferometer has a 218 mm Invar spacer. Its 10 cm fused quartz plates are flat to better than $\lambda/50$ and are coated with aluminum to 85% reflectivity.

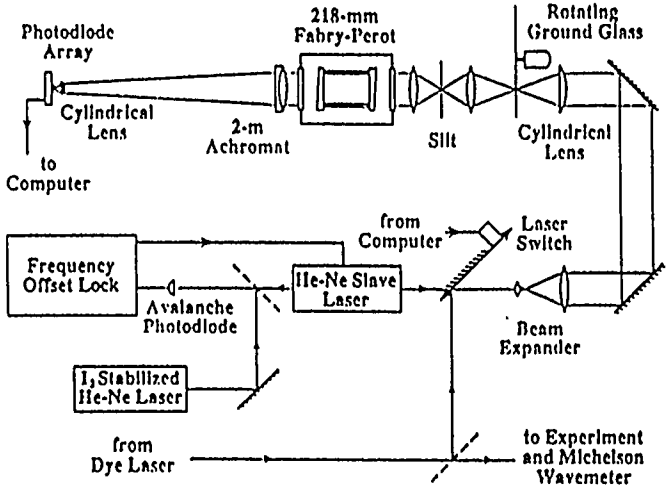

Figure 1. Schematic diagram of the Fabry-Perot wavemeter.

It is housed in a vacuum chamber at a pressure below 10 mTorr to eliminate the need for index-of-refraction corrections. The quartz plates are pressed against the spacer by springs whose tension can be adjusted from outside the vacuum housing to obtain parallelism of the plates.

The Fabry-Perot is illuminated by laser light scattered from a rotating ground glass plate. This emulates a classical source in that it is extended in space and each point on the ground glass scatters light into a solid angle large enough to fill the aperture of the instrument. The laser beam is expanded and imaged by a cylindrical lens as a line on the ground glass. The interferometer is mounted in collimated light, and the interference rings are projected by a 2-m achromat on a photodiode array of 1024 elements on 25 μm centers. A short focal length cylindrical lens just before the array increases its effective width from 25 to 200 μm. This optical system makes efficient use of the laser light and assures that all parts of the interferometer send light to all parts of the fringe pattern. In this way misalignment or imperfection in the plates broadens the fringes but does not distort the pattern.

In operation the interferometer is illuminated alternately by the dye laser and by a He-Ne reference laser which is used to determine the etalon length. This provides a continuous calibration of the system in terms of an internationally recognized standard and eliminates need for thermal stabilization of the apparatus. The reference laser is a single-mode He-Ne that is frequency-offset locked to an I_2 stabilized He-Ne. Use of a slave laser is required to provide sufficient power for the interferometer and to eliminate the frequency modulatation used to lock the I_2 stabilized laser.

Control and data reduction is provided by a minicomputer which selects the laser illuminating the interferometer and reads the fringe patterns from the photodiode array. Each pattern is analyzed to find the fractional order of interference at the center of the pattern, and the fractional order numbers are used to calculate t and the dye laser wavelength. The initial wavelength required to determine the integer order number is obtained from a low precision Michelson wavemeter. Once an initial value has been provided the Fabry-Perot wavemeter operates continously at a rate of about 2 Hz without additional input unless the stabilized dye laser is unlocked or is scanned more rapidly than 200 MHz/sec.

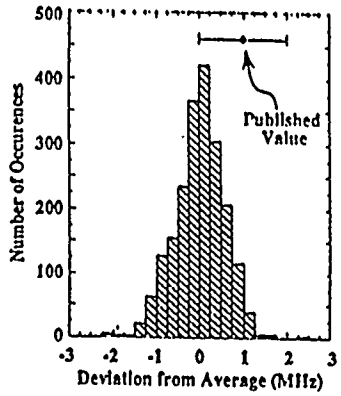

Figure 2. Distribution of wavemeter test results.

The performance of the Fabry-Perot wavemeter is shown in Fig. 2. A dye laser was locked to the $^{127}I_2$ R(66)13-2o transition and its wavelength was measured at intervals of one minute. More than 2000 measurements were accumulated over

nine days with full realignment of the instrument each day. The results fell in a narrow distribution with 93% of the individual values within 1 MHz of the mean. The average of all measurements is 1 MHz lower than the best literature value for the line[12] and agrees within the stated uncertainties. Additional measurements of many I_2 lines for which precise values have been reported indicate that an absolute accuracy better than 2 MHz is routinely obtained. Tests have shown that errors due to any plausible misadjustment of the apparatus or illumination are smaller than 1 MHz. The primary limitation of the system is its need for an initial wavelength with an accuracy of a few parts in 10^7 from another source.

FOURIER TRANSFORM WAVEMETER

The limitations of the Fabry-Perot wavemeter can be overcome by a wavemeter based on the techniques of Fourier transform spectroscopy. Such a wavemeter with an accuracy of a part in 10^7 has been described by Juntilla et al.[9] Here we will discuss the use of a high resolution Fourier spectrometer[13] as a wavemeter and estimate the accuracy it could obtain. The procedure described would take about 5 minutes per measurement, but an instrument designed for wavemeter use could operate much more rapidly.

Assume that the aperture of the Fourier spectrometer is illuminated simultaneously by diffusely scattered light from a dye laser and a reference laser whose wave number is accurately known. For a 0.1 mm aperture, errors due to finite aperture size would be negligible. A small aperture need not decrease the instrumental throughput since the intrinsic source brightness can be increased by focussing the lasers at the scatterer. One would first record and transform a short densely-sampled single-sided interferogram to obtain an initial dye laser wave number in an unaliased spectrum. A 5 mm optical path difference and 1550 Å sampling interval would yield a 32,000 cm^{-1} free spectral range with 1 cm^{-1} resolution from a 2^{15} point transform. This would be followed by a long sparsely-sampled double-sided scan to obtain high resolution in a highly aliased spectrum. A 5 m optical path difference with 155 μm step size would give 0.001 cm^{-1} resolution and 32 cm^{-1} free spectral range from a 2^{18} point transform. The results from the initial scan would be used in choosing the actual step size to ensure that the aliased spectra of the dye and reference laser would be well resolved. The high resolution spectrum would be interpolated in the vicinity of the lines and analyzed to determine dye and reference wave numbers based on the nominal interferogram step size. Finally a multiplicative correction to the wave number scale would be determined from the reference laser result and applied to obtain the wave number of the dye laser.

The accuracy obtainable can be estimated from the expression

$$\delta\sigma = \frac{FWHM}{n(S/N)}. \qquad (2)$$

Here FWHM=0.001 cm^{-1} is the width of the line, n=1 is the number of primary transform points on the profile, and (S/N) is the signal to noise ratio. With an instrument of this type $(S/N)>10^3$ is typical for a strong emission line in an unaliased spectrum of 10^6 points. For our case (S/N) is reduced by a factor of 4 because we are using only 64,000 interferogram points and by an additional factor of 32 because we are operating in an aliased spectrum of order 1000. Applying these factors we expect (S/N)>800 producing a random uncertainty in each of the laser wave numbers of 1.25×10^{-6} cm^{-1}. Using the reference laser wave number for absolute calibration eliminates systematic bias but increases the statistical uncertainty by 2 giving a final uncertainty of 1.75×10^{-6} cm^{-1} or a relative uncertainty of 9 parts in 10^{11} for visible light. This suggests that the ultimate accuracy of such a wavemeter might at this point be limited by the uncertainty of the reference laser.

CONCLUSIONS

Classical methods for wavelength measurements are readily adapted to laser sources and provide a level of accuracy that is not generally obtained by conventional wavemeters. The Fabry-Perot wavemeter developed at NIST gives rapid convenient wavelength measurements for cw dye lasers with an accuracy of a few parts in 10^9. The system is easy to adjust and insensitive to laser alignment, collimation, and amplitude instabilities. A Fourier transform wavemeter similar to existing Fourier spectrometers has potential to provide wavelength measurements with an accuracy limited only by the uncertainty of the I_2 stabilized He-Ne laser.

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