

Fig. 1. (M. 3)

laser pumps a scintillation dye (PBD) to provide a background absorption continuum from 330 to 440 nm of 15-ns duration coincident with the pump to within 1 ns. Passing both beams through a magnesium oven ( $10^{15}$ - $10^{16}$  atoms  $\text{cm}^{-2}$ ) produces an absorption spectrum for the measurement of the peak absorption from the 'P' level ( $\lambda = 375$  nm). By employing a split dye laser cavity with two independent tuning elements, to produce simultaneously and colinearly the exciting and probing frequencies, the narrow-band resonance ( $\lambda = 297.3$  nm) can be photo-electrically measured.

Comparison of experimental and computed results will be given.

#### M.4 The Radiation Pressure of Laser Light (Invited), A. Ashkin, *Bell Telephone Laboratories Inc., Holmdel, N. J. 07733.*

Recent experiments on the radiation pressure of laser light will be reviewed. It will be shown that radiation pressure can exert forces sufficient to move small particles about freely in various media. Applications of these forces to particle separation, optical levitation, the micromanipulation of small particles, and isotope separation will be discussed. A short movie will be shown.

#### M.5 Precision Speed of Light Determination by Means of Simultaneous Absolute Frequency and Wavelength Measurements in the Infrared: A Progress Report of the Activities at M.I.T. (Invited), A. Javan, *Department of Physics, Massachusetts Institute of Technology, Cambridge, Mass.*

Beginning early in 1966, a long-term project was undertaken at M.I.T. with two separate but related ultimate objectives. The first was to devise the necessary technologies to extend the methods of microwave frequency synthesis and harmonic frequency mixing into the far infrared, infrared, and optical region, so that widely differing laser frequencies can be compared with a precision limited by their ultimate frequency stability. The second aim consisted of applying a long-arm scanning Michelson interferometer, together with an on-line computer, to compare the wavelengths of two lasers oscillating at widely different regions of the spectrum with an accuracy mainly limited by diffraction corrections. The emphasis was placed on the comparison of a stable visible helium-neon laser wavelength with that of lasers in the infrared or far infrared. (The latter project began most actively in early 1967 with the continued collaboration of F. Zernike, Perkin-Elmer Corporation.)

The major motivations in developing these technologies at M.I.T. have been their important potential spectroscopic applications utilizing narrow nonlinear infrared and optical resonances obtainable in a variety of ways. The speed of light determination is merely one by-product, important only in relating the units of time and length.

By now, the harmonic frequency synthesis and hence, absolute measurements can be done routinely at wavelengths as short as at least the near infrared. (See also discussions by K. Evenson at this conference.) Since the summer of 1970 when absolute frequency determination was done at M.I.T. in the five-micron region using a carbon monoxide laser, we have shifted emphasis back to the ten-micron range to obtain improved accuracy. Attempts are now made to determine precisely the frequencies and

wavelengths of the centers of narrow saturation resonances, obtained with the aid of a recent method, in the individual *P* and *R* branch transitions of carbon dioxide at a low gas pressure. At present, our methods appear to allow wavelength comparison to within one or two parts in one hundred million and frequency measurements (using a previously described phase-locked chain), to within an accuracy limited by the basic stability of the standard clock. The talk will summarize these activities and will give the latest results. A list of the students and colleagues who have made this work possible will also be presented.

#### M.6 The Speed of Light: Progress in the Measurement of the Frequency and Wavelength of the Methane-Stabilized He-Ne Laser at 3.39 $\mu\text{m}$ (Invited), R. L. Barger, J. D. Cupp, B. L. Danielson, G. W. Day, K. M. Evenson, J. L. Hall, D. G. McDonald, L. O. Mullen, F. R. Petersen, A. S. Risley, and J. S. Wells, *University of Colorado and NBS, Boulder, Colo.*

The synthesis of infrared frequencies to 88 THz has recently been accomplished.<sup>1</sup> The frequency of a CW helium-neon laser tuned to the methane absorption was measured at the National Bureau of Standards and found to be 88.376245(55) THz. A second round of experiments to increase the accuracy of this measurement is now well under way. The experimental part of the measurement of the wavelength has been completed, and continuing analysis of systematic errors is

<sup>1</sup> K. M. Evenson, G. W. Day, J. S. Wells, and L. O. Mullen, *Appl. Phys. Lett.*, Feb. 1, 1972.

TABLE I

$\nu_x$ (THz)	$\lambda_x$ (m)	Laser	1	$\nu_1$	$m$	$\nu_2$	$n$	$\nu_{kly}$
0.890760	337	HCN	0		0		12	0.0742
10.718073	28	H <sub>2</sub> O	12	0.8908	0		1	0.0289
32.176083	9.3	CO <sub>2</sub> (R10)	3	10.7181	0		-1	0.0199
29.447187	10.2	CO <sub>2</sub> (R30)	1	32.1761	-3	0.8908	1	0.0195
88.376245	3.39	He-Ne	3	29.4472	0		-1	0.0487

being made now. The accuracy of the frequency measurement should be good to a few parts of  $10^9$ , and the wavelength measurement should be good to the limits of the present length standard (about 1 part in  $10^8$ ). Thus the value of  $c$  obtained from these measurements will be a definitive value.

To compare an unknown laser frequency,  $\nu_x$ , with harmonics of one or two other lasers, one needs to satisfy the following:

$$\nu_x = l\nu_1 + m\nu_2 + n\nu_{kly} \pm \nu_{beat}.$$

The quantities  $\nu_1$  and  $\nu_2$  are basis laser frequencies, and  $l$ ,  $m$ , and  $n$  are harmonic numbers where  $m$  and  $n$  may be either positive or negative. Once  $\nu_x$  is determined, it serves as a basis laser frequency for the measurement of the next higher frequency laser. A chain of such lasers and klystrons extending down to a frequency standard gives an absolute value to the frequency of each laser. The lasers used in the first experiments were free running lasers, and each one was tuned to the top of its gain curve. The klystron frequency  $\nu_{kly}$  was measured on a calibrated wave meter and  $\nu_{beat}$  was read on a spectrum analyzer. Improvements of over 2 orders of magnitude in accuracy of the measurement will be realized mainly with the use of stabilized lasers. The harmonic generation and mixing take place on a single diode irradiated simultaneously with  $\nu_x$ ,  $\nu_1$ ,  $\nu_2$ , and  $\nu_{kly}$ . The beat frequency is amplified and detected with a spectrum analyzer. The diodes used in the experiments will be conventional tungsten on silicon for the 1-THz range, and most likely tungsten on nickel at the higher frequencies. There is also the possibility that the Josephson junction may be used at 10 THz. The measurement scheme is summarized in Table I.

The He-Ne laser is locked to the methane absorption using the technique devised by Barger and Hall.<sup>2</sup> Two CO<sub>2</sub> lasers stabilized with the Freed and Javan<sup>3</sup> technique will be used in this scheme. The water vapor laser may be locked to the stabilized R10 line of the CO<sub>2</sub> laser. The HCN laser is phase locked to a quartz controlled reference chain. The wavelength comparison was done directly with a krypton standard in a specially constructed Fabry-Perot interferometer.<sup>4</sup>

Progress in this series of measurements will be described and, hopefully a definitive value of the speed of light will be announced.

#### M.7 Anisotropy in the Dicke Narrowing of Rotational Raman Lines, A. D. May, B. K. Gupta, and S. Hess, Department of Physics, University of Toronto, Toronto, Ont., Canada.

Dicke narrowing and collisional broadening of spectral lines has been studied by a number of authors (cf. Cooper *et al.* 1968). For Raman scattering from gases at densities  $\rho$  such that the product of the mean free path  $l$  and the momentum transfer  $q$  is much less than one, the lines have a Lorentzian profile with a half-width  $\Delta\nu_{1/2}$  given by

$$\Delta\nu_{1/2} = \Delta\nu_{di} + \Delta\nu_{coll} = \left( \frac{q^2 D_0}{2\rho\pi} \right) + B\rho \quad (1)$$

where  $D_0$  and  $B$  are the diffusion constant at 1 amagat and the broadening coefficient, respectively. The decrease of  $\Delta\nu_{di}$  with increasing density reflects the effect of collisions in damping the translational motion of the molecules. The increase in  $\Delta\nu_{coll}$  with density reflects the increasingly rapid perturbation of the internal molecular motion with increasing collision frequency. Due to their different dependence on density these two effects of molecular collisions may be separated.

The experimental apparatus consisted

of a 250-mW He-Ne laser, a high-pressure scattering cell, a Fabry-Perot interferometer which could be scanned by small pressure steps and photon counting electronics. The polarization of the laser beam was in the vertical direction, and all observations were made horizontally at a scattering angle of 90°. The line shape of the  $S_0(1)$  line was measured over a range of densities from 2.5 to 58 amagat with a polaroid set to select the vertically polarized light. This was followed by a similar set of measurements with the polaroid rotated 90° to observe only the horizontally polarized component of the scattered light.

Fig. 1 shows the observed profile of the  $S_0(1)$  Raman line of H<sub>2</sub>, for the two polarizations at about 2.5 and 46 amagat units of density. At the highest density the two curves have the same width. Thus we conclude from (1) that the broadening coefficient is the same for both polarizations. The low density profiles are below the minimum in the width versus density curve (cf. Cooper *et al.* 1968) where  $\Delta\nu_{di}$  makes the largest contribution to the total width. As the instrumental width was about 1.6 GHz we see that the small difference in the widths, apparent in the figure actually corresponds to a significant difference in  $\Delta\nu_{di}$ . The experimental curves were compared with theoretical curves computed by convoluting the instrumental function  $I(\omega)$ , the translational function  $G_s(q, \omega)$  given by Nelkin and Ghatak (1964), and a pressure broadened Lorentzian line  $L(\omega)$ . A least square fit of all the profiles yields for each polarization only two constants,  $D_0$  and  $B$ . For the  $I_{vv}$  spectrum we find  $D_0$  and  $B$  equal  $1.60 \pm 0.05 \text{ cm}^2 \text{ s}^{-1}$  and  $0.0537 \text{ GHz/amagat}$ , while for the  $I_{vh}$  spectrum  $D_0$  and  $B$  equal  $1.80 \pm 0.05 \text{ cm}^2 \text{ s}^{-1}$  and  $0.0536 \text{ GHz/amagat}$ . As anticipated the broadening coefficient is independent of polarization. The two diffusion coefficients are different.

Consider the case of vertically polarized incident light being scattered (in a horizontal plane) through an angle  $\theta$ . If  $\mathbf{k}_i$  and  $\mathbf{k}_s$  are the wave vectors of the incident and scattered light, respectively, then it is the motion of the molecules along  $\mathbf{q}$ , where  $\mathbf{q}$  equals  $\mathbf{k}_s - \mathbf{k}_i$ , that determines  $\Delta\nu_{di}$ .

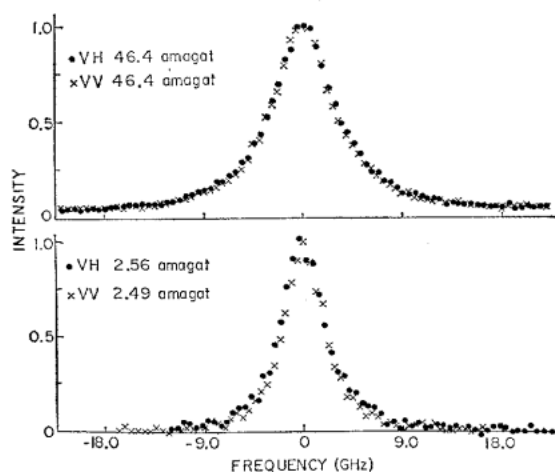


Fig. 1.

<sup>2</sup> R. L. Barger, and J. L. Hall, *Phys. Rev. Lett.*, vol. 22, no. 4, 1969.

<sup>3</sup> C. Freed and A. Javan, *Appl. Phys. Lett.*, vol. 17, p. 53, 1970.

<sup>4</sup> R. L. Barger and J. L. Hall, in preparation.