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Dual-Beam, Second-Derivative Tunable Diode-Laser Infrared Spectroscopy Applied to Trace-Gas Measurement

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Prepared by Sandia National Laboratories, Albuquerque, New Mexico 87185
and Livermore, California 94550 for the United States Department
of Energy under Contract DE-AC04-76DPO0789

Printed March 1981

Sandia National Laboratories

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Printed April 1981

DUAL-BEAM, SECOND-DERIVATIVE TUNABLE DIODE-
LASER INFRARED SPECTROSCOPY APPLIED TO TRACE-GAS MEASUREMENT

D. R. Tallant and R. G. Jungst

ABSTRACT

A dual beam diode laser spectrometer has been constructed using off-axis reflective optics. The spectrometer can be amplitude modulated for direct absorption measurements or frequency modulated to obtain derivative spectra. The spectrometer has high throughput, is easy to operate and align, provides good dual beam compensation, and has no evidence of the interference effects that have been observed in diode laser spectrometers using refractive optics. Unpurged, using second derivative techniques, the instrument has measured 108 parts-per-million CO (10 cm absorption cell, atmospheric pressure-broadened) with good signal/noise. With the replacement of marginal instrumental components, the signal/noise should be substantially increased. This instrument was developed to monitor the evolution of decomposition gases in sealed containers of small volume at atmospheric pressure.

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INTRODUCTION

The narrow line width ($\sim 10^{-5} \text{ cm}^{-1}$) of lead salt semiconductor diode lasers has led to their employment as sources for the Doppler-limited spectroscopy of gases at low pressure (e.g., see Ref. 1) and for observing species in molecular beams.^{2,3} Despite their limited single-mode continuous tuning range of approximately one wave number, diode lasers are useful for Doppler-limited spectroscopy since the intensity profile of a single lasing mode is approximately linear over absorption line widths of 0.01 cm^{-1} or less. However, the mode profile often has structure which is comparable to the approximately 0.1 cm^{-1} wide line profiles of gases broadened by atmospheric pressure. Thus, the diode laser mode structure limits the ability to observe the absorption line profiles of atmospheric pressure-broadened gases. The sensitivity of laser diode spectroscopy for atmospheric pressure-broadened gases may be improved by sampling the gas and expanding it to low pressure in long path multipass cells.⁴ For certain applications, for example in flames,⁵ expansion of the gas to low pressure is not practical.

Derivative techniques tend to suppress spectral structure different in width from an absorption line, discriminate against noise frequencies different from the modulation frequency, and help reduce the effects of variations in source output intensity. Applying second derivative techniques⁶⁻⁹ to low pressure gases in White cells provides greater sensitivity than direct transmission measurements.¹⁰ However, the wavelength modulation required to provide a second derivative signal for the absorption line of a gas broadened by atmospheric pressure is comparable to the width of the structure exhibited within a diode laser mode. In this case, the second derivative signal from the diode laser mode structure can obscure the derivative signal from an absorption line.

Dubs and Günthard¹¹ addressed the problem of compensating laser diode spectra for the variations in mode intensity that occur as the mode is

scanned by constructing a double beam spectrometer. This spectrometer utilized a dual beam chopping system in which a relatively high frequency chopper modulated the laser beam for lock-in detection, and a rotating mirror operating at a lower frequency directed the laser beam alternately to sample and reference channels. The sample and reference channels were recombined on a single detector whose output was monitored by a lock-in amplifier tuned to the high frequency modulation. The output from the lock-in amplifier was electronically separated into sample and reference channel signals by a sample and hold switch. The sample and reference channel signals were ratioed to provide transmission versus frequency spectra with relatively flat, constant background signals over one wave-number scan ranges.

In the work to be described here, a double beam laser diode spectrometer based on the dual chopping principle of Dubs and Günthard but utilizing both frequency modulation (derivative spectroscopy) and amplitude modulation was evaluated for the measurement of atmospheric pressure-broadened gas absorption lines. The application to which this work is potentially directed involves the determination of the rate of decomposition of organic species, in specific environments, as evidenced by their evolution of simple gases (CO , CO_2 , N_2O , NO). Certain constraints, e.g., the requirement that the gases be measured in a sealed system of small volume at atmospheric pressure, precluded the sampling of the gases and their expansion to low pressure in a long path White cell.

The double beam spectrometer developed for these measurements differs from that of Dubs and Günthard in the relative simplicity of its optics, the use of all-reflective optics, the application of derivative techniques, and the subtraction rather than ratioing of sample and reference beam signals. This work, however, confirms the assertions of Dubs and Günthard as to the basic workability of the dual chopping principle, the advisability of placing absorption cells past the monochromator used to isolate lasing

modes, and the utility of scanning the monochromator simultaneously with the diode laser in order to maximize the scanning range of the lasing modes. In addition, the spectrometer described here displays high throughput compared to a commercial instrument, surprising ease of alignment, and good compensation of sample and reference beams.

EXPERIMENTAL

Laser Source

The diode laser source and control electronics (for diode temperature and current) were manufactured by Laser Analytics. The diode employed in this work (also manufactured by Laser Analytics) was designed to provide output from 2080 to 2330 cm^{-1} by temperature and current control. This lasing range includes the fundamental absorption bands of CO, N_2O and CO_2 . The diode was mounted in a refrigerator head manufactured by CTI (Model 20).

Spectrometer

A Laser Analytics laser optical assembly (Model LOA) was used in some preliminary single beam measurements until it was determined that dual beam compensation was required. The final design of the double beam spectrometer constructed in the course of this work is depicted in Figure 1. The output of the laser diode is collected by an f/1 input off-axis aspheric mirror (A) (Perkin-Elmer 186-0110, 90° ellipse, with foci of 33.8 and 203 mm from the mirror center) and focused onto the entrance slit of a Spex 1402, 0.85 meter double monochromator. The monochromator was operated at 0.8 cm^{-1} bandwidth using 300 groove/mm (4 μm blaze) gratings and 1 mm wide entrance and exit slits. The entrance and exit slits are vertically apertured to 2 mm and 1 mm, respectively. On exiting the monochromator, the laser beam is approximately collimated by an 18 cm focal length, 5 cm diameter off-axis parabola (B) and directed to a beam steering instrument (C) (Newport Research Corporation, BSD-1) which drops the beam to a working height of 21 cm above the optical table and directs it to a rotating mirror (D). The rotating mirror consists of a 3 mm thick polished aluminum disk

Figure 1. Dual Beam Spectrometer.

A, off-axis elliptical mirror; B, F, G, off-axis parabolic mirror; C, beam steering instrument; D, rotating mirror; E, flat mirror; H, InSb detector; I, absorption cell; J, tuning fork chopper.

machined into two 90° sectors. The rotating mirror is mounted on a PAR Model 125 chopper drive and is rotated at 7 Hz. The reference beam is that which passes through the rotating mirror. The sample beam reflects off the rotating mirror, folds back off a flat mirror (E), and passes through the absorption cell (I). Two off-axis parabolic mirrors (F, G, with the same specifications as B) focus the sample and reference beams onto the detector. The detector is a 1 mm (vertical) by 2mm (horizontal) chip of InSb cooled to liquid nitrogen temperature. With its matched preamplifier, the detector achieves a peak response of 1.1×10^6 volts/watt in the 4 to 5 μm region.

Initially the dual beam spectrometer (Figure 1) was assembled with flat mirrors at F and G instead of parabolic reflectors. The slight divergence of the diode laser beam reflected from parabolic mirror B, coupled with the spatial complexity of the lasing modes, resulted in overfilling of the detector element, making it necessary to closely match the sample and reference beam path lengths in order to obtain similar mode profiles from the two beams. In the final instrumental design the laser diode beams are focused onto the detector with parabolic mirrors. This relaxes the requirement for equal length in the sample and reference beams and increases the spectrometer throughput.

Also in the initial spectrometer design, a pellicle beam splitter (8 μm thick) and two detectors were used instead of a rotating mirror and one detector. The thinness of the pellicle beam splitter minimized both displacement of the transmitted beam and interference effects. However, it was not possible to obtain a pellicle beam splitter which had both high transmission and reflection efficiencies in the infrared and also the ability to transmit and reflect visible radiation (for optical alignment). The spatial complexity of the lasing modes is such that two detectors not possessing identical dimensions in their sensitive areas will not provide the same intensity profile for the sample and reference

beams. Because of this spatial complexity, adequate dual beam compensation is not possible without two such detectors, which were not available. For these reasons, the pellicle beam splitter/dual detector arrangement was abandoned in favor of the rotating mirror/dual modulation approach.

Modes of Operation

The spectrometer can provide either transmission spectra or derivative spectra. In either mode of operation the rotating mirror separates the source beam into sample and reference beams, imposing a 14 Hz amplitude modulation on each beam. Transmission spectra are obtained by amplitude modulating the diode laser source beam with a 400 Hz tuning fork chopper, (J) in Fig. 1, placed at the entrance slits of the monochromator. With a lock-in amplifier tuned to the 400 Hz amplitude modulation frequency, dual beam compensated transmission spectra are obtained. In addition, the sample and reference beams can be observed individually, e.g., to determine the shape of the lasing mode profile (reference beam). In obtaining transmission spectra the diode laser source beam is amplitude modulated by both the rotating mirror (14 Hz) and the tuning fork chopper (400 Hz). This mode of operation is therefore referred to as dual amplitude modulation. To obtain derivative spectra the diode laser source beam is frequency modulated at 1000 Hz instead of amplitude modulated at 400 Hz. To accomplish frequency modulation a sine wave is superimposed on the current ramp used to scan the diode laser output frequency. With a lock-in amplifier tuned to the first harmonic of the frequency with which the laser is frequency modulated, the diode scan yields the second derivative of the mode profile and of any absorption features. By frequency modulating the laser while chopping the beam with the rotating mirror, dual beam compensated derivative spectra are obtained. The amplitude of the frequency modulation is that which produces the maximum second derivative absorption signal without significantly broadening its profile. The derivative mode of

operation is referred to as frequency/amplitude modulation, since the laser beam is electronically frequency modulated (1000 Hz) in addition to being amplitude modulated by the rotating mirror (14 Hz).

Signal Acquisition

The signal acquisition electronics and timing diagrams are analogous to those published by Dubs and Günthard¹¹ and readers are referred to their publication for amplification of the description that follows. The output from the detector pre-amplifier (containing alternately information from the reference and sample beams) is fed into a lock-in amplifier (PAR 124A) set at a smoothing time constant of 1 msec. With this time constant the output of the lock-in amplifier follows the intensity variations concomitant with the alteration of the reference and sample beam intensities without introducing significant crosstalk. A sample and hold switch based on the design of Dubs and Günthard separates the temporally discriminated signals representing the reference and sample beam intensities and directs them to individual holding integrators. Then, in contrast to the referenced work, the two outputs of the sample and hold switch, which represent the sample and reference beam intensities, are subtracted (rather than ratioed). The circuit employed for subtraction¹² of the two signals includes a stage of variable amplification for both the sample and reference signals in order to compensate the two signal levels for optical and/or electronic attenuation not related to absorption by the gas in the sample beam. Since only one of the 90° sectors on the rotating mirror is flat enough to provide a stable sample beam signal, only half of each revolution of the rotation mirror is usable for integration. Each channel is therefore integrated only once (with a 20 msec gate) for each 140 msec (7 Hz) revolution. This duty cycle of seven, combined with an RC time constant of 0.1 to 0.2 sec for the holding integrators, yields an effective time constant of 0.7 to 1.4 sec for the signal acquisition electronics. Either the reference beam signal,

the sample beam signal, or the subtracted signal can be recorded, using an X-Y recorder whose X axis is driven by a voltage ramp derived from the current ramp used to scan the laser diode in frequency.

Spectrometer Alignment

For ease of assembly, modification, and alignment, the spectrometer shown in Fig. 1 is mounted on an optical table (Newport Research Corp.) covered with a grid of tapped mounting holes. Alignment of the system is accomplished by passing a low power visible laser beam through the instrument from the detector to the source. The entire spectrometer can be assembled from parts and aligned in a few hours.

Gas Samples

The absorption cells have a 10 cm pathlength and 5 cm diameter salt windows. They were filled to atmospheric pressure (~ 630 Torr or 8.4×10^4 Pa) with a commercial gas mixture (Airco) consisting of a known concentration of CO diluted in air.

THEORY

In a single beam measurement of the transmission of a gaseous absorber, the intensity (I) of the transmitted beam is the observed quantity,

$$I = I_0 e^{-abc} \quad (1)$$

where the variables have their standard definitions.¹³

In second derivative spectroscopy the second derivative of the intensity is the observed quantity, which is given by⁶

$$\begin{aligned} d^2 I / d\lambda^2 = & (I/I_0) (d^2 I_0 / d\lambda^2) + I (bc)^2 (da/d\lambda)^2 \\ & - (2I/I_0) (dI_0/d\lambda) (da/d\lambda) bc - I bc (d^2 a / d\lambda^2) \end{aligned} \quad (2)$$

where I_0 and a are both functions of wavelength. At the peak of the

absorption profile, where $da/d\lambda = 0$, Eq.(2) simplifies to

$$d^2 I/d\lambda^2 = (I/I_0) d^2 I_0/d\lambda^2 - Ibc(d^2 a/d\lambda^2) \quad (3)$$

and subtraction of the second derivative of the reference beam intensity $d^2 I_0/d\lambda^2$ leaves for the observed second derivative signal, S,

$$S = - \left[1 - \left(\frac{I}{I_0} \right) \right] \left(\frac{d^2 I_0}{d\lambda^2} \right) - Ibc \left(\frac{d^2 a}{d\lambda^2} \right) \quad (4)$$

Eq.(4) relates the observed second derivative signal at the peak of the absorption profile to the concentration of the absorber. From Eq.(1) one obtains

$$[1 - (I/I_0)] = 1 - e^{-abc} \quad (5)$$

The right hand side of Eq.(5) is approximately equal to abc or $(I/I_0) abc$ as the following table shows.

TABLE I

I/I_0	$\frac{1 - e^{-abc}}{[1 - (I/I_0)]}$	$\ln(I/I_0) = -abc$	$(I/I_0) abc$
0.700	0.300	0.357	0.250
0.950	0.050	0.051	0.049
0.99500	0.00500	0.00501	0.00499
0.999500	0.000500	0.000500	0.000500

The table shows that $(I/I_0)abc$ approximates $[1 - I/I_0]$ as well as abc does for values of $[1 - (I/I_0)] \leq 0.3$. Substituting $(I/I_0)abc$ (instead of abc) for $[1 - (I/I_0)]$ in Eq.(4) results in Eq.(6) which may be subsequently simplified because of this substitution

$$S = - (I/I_0)abc (d^2 I_0/d\lambda^2) - Ibc (d^2 a/d\lambda^2) \quad (6)$$

From Table I, it is noted that the substitution of $(I/I_0)abc$ for $[1 - (I/I_0)]$ introduces about 20% maximum error into the first term of Eq.(6) for $[1 - (I/I_0)] \leq 0.3$. With CO as the absorber and under the

experimental conditions of this study, the magnitude of the first term in Eq. (4) is an approximately constant 15% to 20% of the total second derivative signal, S , for $[1 - (I/I_0)] \leq 0.3$. Therefore the substitution of $(I/I_0)abc$ for $[1 - (I/I_0)]$ could result in no more than 5% inaccuracy in the right hand side of Eq. (6) for values of $[1 - (I/I_0)] \leq 0.3$.

Collection of terms in Eq. (6), leads to Eq. (7)

$$S = -Ibc [(a/I_0)(d^2 I_0/d\lambda^2) + (d^2 a/d\lambda^2)] \quad (7)$$

Concentration is expressed explicitly in Eq. (7), but the transmitted intensity at the peak of the absorption profile is also included in the equation. All other factors are assumed to be constant. Comparison of second derivative signal intensities to absorber concentrations must therefore allow for any significant attenuation of the sample beam by the absorber.

RESULTS AND DISCUSSION

The initial experiments with single beam second derivative spectroscopy utilized a Laser Analytics Model LOA spectrometer in the single beam mode and only the lock-in amplifier for signal acquisition. The results are presented in Fig. 2 for (a) 934 parts-per-million CO (78.1 Pa partial pressure), (b) 108 parts-per-million CO (9.0 Pa partial pressure), and (c) background ($d^2 I_0/d\lambda^2$). The second derivative of the mode profile ($d^2 I_0/d\lambda^2$) is the background signal which limits sensitivity in these single beam experiments.

Several difficulties inherent in the acquisition of these data are not apparent in Fig. 2. The absorption of atmospheric CO over the path-length of the spectrometer is significant and yields a signal that is 1/3 to 1/2 the intensity of the second derivative profile obtained for 108 parts-per-million CO (Fig. 2). Therefore the spectrometer must be purged with a high purity gas. This entails considerable inconvenience

Figure 2. Single-beam second derivative spectra of CO (2161.97 cm^{-1}) in air at atmospheric pressure (630 Torr or 84 kPa) for 10 cm absorption path; Model LOA spectrometer purged to eliminate atmospheric CO.

since the spectrometer case must be opened in order to change absorption cells. Interference fringes appear in many spectra and degrade sensitivity.¹⁰ These can be suppressed in some cases (as in Fig. 2) by slightly defocusing the collimating lens at the spectrometer input. These fringes are not related to reflections from the windows of the absorption cells. The fringes are suspected to represent the beat frequency between two sets of more closely spaced interference fringes. Typically, it is necessary to realign the collimating lens in the LOA when an absorption cell is added to or removed from the LOA spectrometer. This is considered the direct result of a design which locates the absorption cell before the monochromator in the optical path. Consequently, mode profiles are observed to change as absorption cells are changed. With the variation in the mode profile, one can expect changes in the second derivative background signal ($d^2 I_0 / d\lambda^2$ in Fig. 2) and questionable reproducibility of the data.

The throughput of the dual beam spectrometer (Fig. 1) is relatively high. A factor of ten increase in laser power throughput over that of the LOA was observed with the dual beam instrument, using flat mirrors for F and G (Fig. 1). Replacement of these flat mirrors with parabolic mirrors produced another factor of ten increase in throughput. While this implies two orders of magnitude improvement in throughput for the dual beam spectrometer of Fig. 1 over the LOA, some caution is appropriate in interpreting these results since the LOA may not have been in optimum alignment.

The performance of the dual beam spectrometer on a relatively narrow absorption line is depicted in Fig. 3. In Fig. 3(a) and 3(b) the spectrometer is dual amplitude modulated (i.e., chopped by the tuning fork and beam split by the rotating mirror) to yield transmission spectra. Fig. 3(a) depicts the laser mode profile (reference beam). Fig. 3(b) shows the dual beam compensated transmission spectrum obtained when the

Figure 3. Spectra of CO line (~ 1 Torr, ~ 133 Pa) at 2103.27 cm^{-1} under ~ 10 Torr total pressure (1330 Pa) in 10 cm path length absorption cell using dual beam spectrometer (Fig. 1)

- (a) Reference beam only; dual amplitude modulation.
- (b) Dual beam mode with absorption cell in sample beam; dual amplitude modulation.
- (c) Second derivative dual beam mode; frequency/amplitude modulation.

sample beam, containing a 10 cm pathlength of 1 Torr (~ 133 Pa) of CO at 10 Torr (~ 1330 Pa) total pressure, has been subtracted from the reference beam, leaving only the absorption line profile. In Fig. 3(c) the spectrometer has been frequency/amplitude modulated (i.e., the derivative mode of operation), and the sample and reference beam derivative signals subtracted to leave only the second derivative of the absorption line profile. Note that for both dual amplitude modulation and the frequency/amplitude modulation the dual beam compensation/subtraction technique yields a flat baseline that is perturbed mainly by random noise.

The performance of the dual beam spectrometer on gases broadened by atmospheric pressure is depicted in Fig. 4. In Figs. 4(a) and 4(b) dual amplitude modulation is used to obtain transmission spectra of the mode profile (reference beam) and the mode profile with the 934 parts-per-million (78.1 Pa) CO absorption peak superimposed (sample beam). Frequency/amplitude modulation with subtraction (dual beam compensation) of the sample and reference signals yields second derivative spectra of 934 parts-per-million (78.1 Pa) CO (Fig. 4(c)), 108 parts-per-million (9.0 Pa) CO (Fig. 4(d)), and the background signal due to an absorption cell filled with argon (Fig. 4(e)). These spectra were obtained without purging any portion of the optical path of the spectrometer. Absorption cells can be interchanged in the beam and, without any adjustment of the spectrometer alignment, the spectra will reproduce roughly within the random noise levels shown.

In the course of this work the output of the laser diode deteriorated to such an extent that, even with the relatively high throughput of the dual beam spectrometer, signal levels were approaching detector noise levels. At the same time the upper limit of the laser diode tuning range was reduced to near 2100 cm^{-1} . Subsequent to the acquisition of the data in Fig. 4, the laser diode output deteriorated below the threshold of usefulness. A replacement for this diode was not obtained because of

Figure 4. Spectra of CO line at 2103.27 cm^{-1} broadened by atmospheric pressure in a 10 cm pathlength absorption cell using the dual beam spectrometer.

- (a) Reference beam; dual amplitude modulation.
- (b) Sample beam with 934 parts-per-million CO; dual amplitude modulation.
- (c) Second derivative dual beam mode; sample beam with 934 parts-per-million CO; frequency/amplitude modulation.
- (d) Second derivative dual beam mode; sample beam with 108 parts-per-million CO; frequency/amplitude modulation.
- (e) Second derivative dual beam mode; sample beam with absorption cell containing argon; frequency/amplitude modulation.

programmatic restrictions. Detection of CO concentrations less than 108 ppm and the incorporation of improvements to the spectrometer were therefore not attempted.

A comparison of Figs. 2 and 4 shows that dual beam operation greatly decreased the contribution of the mode profile to the background of the second derivative scans. This is evidenced by the relatively flat baseline in Fig. 4(e). The second derivative signals from the sample and reference beams before subtraction (dual beam compensation) are four to five times the second derivative signal shown in Fig. 4(d) for 108 parts-per-million (9.0 Pa) CO. The remaining uncompensated background variation is mainly random noise associated with the detector. The relative contribution of this noise could be greatly decreased by using a laser diode whose output has not severely deteriorated. The rotating mirror also contributes to the random noise because it is not mounted firmly to the table but rather on springs. This imparts a small rocking motion to the mirror which causes the sample beam to wander partially off the detector. The spectra in Fig. 4 were obtained without any input filtering to the lock-in amplifier. Such filtering would also decrease the random noise. Since the scans in Fig. 4 required only 200 seconds to complete, the time constant on the integrators in the sample and hold switch could be increased, with a concomitant increase in scan time.

The second derivative signals in Fig. 4 can be compared to the CO concentrations through Eq. (7). Second derivative signals for the 934 parts-per-million CO (Fig. 4(c)) and the 108 parts-per-million CO (Fig. 4(d)) were measured at the peak of the absorption profile from the baseline shown in Fig. 4(e). The ratio of these signals is 5.9. The transmittance of the 934 parts-per-million CO sample was measured to be 69% (see Fig. 4(a) and Fig. 4(b)), while the transmittance of the 108 parts-per-million CO sample was calculated to be 96%. Correcting the second derivative signal ratio for transmittance (multiply by 96/69) yields a calculated CO concentration ratio of 8.2, in reasonable agreement with

the actual ratio of 8.65.

CONCLUSION

The alignment and operation of the dual beam spectrometer were found to be surprisingly easy. Most problems encountered were related to the deteriorated state of the laser diode and instabilities in its temperature control electronics. The high throughput of the dual beam spectrometer partially compensated for the low diode output. This instrument should also facilitate the study of gases at low pressure. The smaller frequency modulation required to produce second derivative profiles of narrow ($\leq .01 \text{ cm}^{-1}$) absorption lines (as compared to atmospheric pressure broadened lines) reduces the contribution of the mode profile ($d^2 I_0 / d\lambda^2$) to the second derivative spectrum. This leads to better dual beam compensation. In addition, the interference fringes that limit the sensitivity of single-beam derivative measurements¹⁰ have not been observed in this instrument. The lack of interference effects is attributed to the use of off-axis reflective optics, which reflect no rays back along the optic axis. Simultaneous scanning of the diode laser frequency and the monochromator wavelength¹¹ has been accomplished, but this technique does not appear to improve the compensation achieved by subtraction of the sample and reference beams. The data presented in this paper were obtained by scanning the diode laser with the monochromator at a constant wavelength. Purging the dual beam spectrometer should be necessary only in spectral regions with high atmospheric absorption (e.g., by CO_2).

The dual beam spectrometer can be improved. To obtain spectra of gases broadened by atmospheric pressure, a monochromator with a bandwidth of about 2 cm^{-1} would be sufficient. A smaller bandwidth actually increases the curvature of the mode profile and, therefore, its second derivative signal ($d^2 I_0 / d\lambda^2$). A rotating mirror that has flatter reflective surfaces and which is mounted on a more stable base and rotated at

a higher frequency would improve signal/noise. A detector with a larger sensitive area would help alleviate problems associated with any laser beam directional instabilities remaining in the spectrometer. These modifications would increase the capabilities of the dual beam spectrometer without compromising its throughput and relative ease of operation.

ACKNOWLEDGMENT

We would like to thank J. C. Cummings for the loan of the aspheric optics used in this work and his advice on optical design.

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