waves parallel to the plate is very close to zero both in TGS and in the absorbing thin-metal surface layer. The sensitivity of the usual geometric configuration might decrease drastically.

IV. APPLICATION OF TV PYRICON TUBES TO VISUALIZE FAR-INFRARED RADIATION

The last but not the least advantage of pyroelectric detectors is to provide a large-area retina for the thermal TV vidicon tube. The infrared image is projected onto the crystal surface and transformed into an electric image which is inspected by the electron beam [8]. Such a tube is now very useful in the laboratory to see far-infrared radiation [9] either from thermal sources or from lasers. For instance, Fig. 4 and Fig. 5 show, respectively, the photograph of a TEM_{00} and of a TEM_{10} mode from a 337-μm laser.

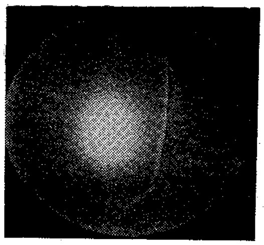

Fig. 4. Image of a TEM_{00} mode from an HCN laser (λ = 337 μm).

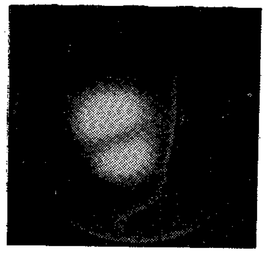

Fig. 5. Image of a TEM_{10} mode from an HCN laser (λ = 337 μm).

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Recent Advances in Commercial Fourier Spectrometers for the Submillimeter Wavelength Region

R. C. MILWARD

Abstract—**A slow-scan "real-time" Michelson interferometer and a new rapid-scan interferometer using signal averaging techniques and fast Fourier transform (FFT) spectrum computation are described and compared. Typical performances of both instruments are illustrated.**

I. INTRODUCTION

CURRENT commercial submillimeter wave interferometric Fourier spectrometers [1] may be generally divided into two categories according to the speeds at which they operate—the "aperiodic" type in which interferograms are scanned slowly (<1 Hz), and the "rapid-scan" type in which interferogram signals are modulated in the audio-frequency domain 10 Hz–10 kHz.

In the slow-scan interferometer, detector signals are suitably smoothed by analogue methods so that the results of a single interferogram scan suffice for the spectrum computations, whereas in the rapid-scan interferometer, a number of consecutively scanned interferograms are usually co-added and averaged to augment signal/noise ratios to a satisfactory level, before the infrared spectrum is computed.

In each case, greatly different requirements are demanded of the interferometer scanner, and the speed and

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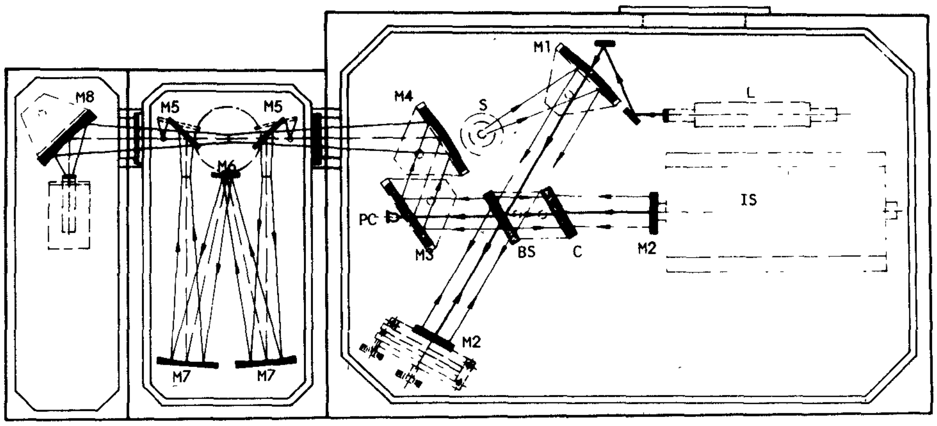
TABLE I
SPECIFICATIONS OF POLYTEC MIR 30 AND FIR 30 FOURIER SPECTROMETERS

SPECIFICATION	M I R - 30	F I R - 30
1) FREQUENCY RANGE	4000 - 400 cm^{-1} standard (8000 cm^{-1} optional)	1000 - 10 cm^{-1}
2) RESOLUTION CAPABILITY	0.7 cm^{-1} standard (for 32 K memory computer)	0.05 cm^{-1}
3) INTERFEROMETER TYPE	Michelson - 30° incidence configuration	Michelson - 30° incidence configuration
i) Source	Water cooled Globar	Water cooled high pressure Hg lamp
ii) Optics	All reflecting, ∅ - 50 mm	All reflecting, ∅ - 65 mm
iii) Beam Splitter	Germanium - coated KBr	2.5, 6, 15 and 50μm Mylar films mounted on automatic change facility
iv) Mirror Drive	Servo controlled linear saw-tooth scan, scan speeds 2.5 - 40 mm/s Maximum Mirror Displacement 10 mm	"slow" scan type scan speeds 1 - 50μm/s Maximum Mirror displacement 100 mm
v) Sampling Interval	0.6328μm and higher multiples from laser ref.	5μm and higher multiples from Moiré system
4) SAMPLE CHAMBER	Provides transmission and reflection (~ 11° incidence) configurations by means of remote selector. Image size variable 2 - 15 mm dia.	ditto
5) DETECTOR	PYROELECTRIC standard	GOLAY standard
6) DIGITISER	Unipolar 15 bits	Bipolar ± 13 bits
7) DIGITAL COMPUTER	32K-16 bit word core memory as standard	4K-16 bit word core memory as standard
8) FOURIER TRANSFORMATION	FAST FOURIER TRANSFORM ALGORITHM	"REAL-TIME" METHOD
i) Maxm. no. Spectrum Points	4K (double beam spectrum)	1.5K (double beam spectrum)
ii) Maxm. no. Interferogram "	8K	50K
9) SPECTRUM DISPLAY	5" STORAGE DISPLAY OSCILLOGRAPH	ditto
	250 mm X-t PEN RECORDER with separate wavenumber marker	ditto



M 1 Off-axis-paraboloid
M 2 Michelson mirror
M 3 Plane mirror
M 4 Off-axis-paraboloid
M 5 Plane mirror (hinged)
M 6 Plane mirror
M 7 Spherical mirror
M 8 Toroidal mirror
S Globar Rod
L He-Ne Laser
IS Interferometer Scanner
BS Beam Splitter Plate
C Compensator Plate
PC Photocell
D Pyroelectric Detector

Fig. 1. Optical ray diagram of MIR 30 interferometer.

storage capacity of the associated digital electronics. Furthermore, as a direct consequence of the different data acquisition rates, alternative methods can be used for achieving the desired interferogram-spectrum computation, the "real-time" transform method [2]-[4], or the more widely used "fast" Fourier transform (FFT) method [5].

The purpose of this paper, therefore, is to discuss the relative merits of the "slow-" and "rapid-scan" techniques, by specific reference to two recently developed commercial Fourier spectrometers, the Polytec FIR 30 and the Polytec MIR 30 (see Table I), which incorporate these alternative modes of operation and methods of spectrum computation.

II. SYSTEM DESCRIPTIONS

A. Optics Mechanics

Both instruments use the same modular construction for vacuum (~0.2-torr) operation, and the same all-reflecting optical system of maximum throughput 0.1–0.2-$cm^2 \cdot sr$, as shown in Fig. 1. Essential differences between the two interferometers are the light source, beam splitter, moving mirror drive and linear measurement system, and the infrared detector. Noteworthy features of the FIR 30 and MIR 30 interferometers are as follows.

1) A unique remotely actuated beam splitter change mechanism in the FIR 30 interferometer, which, in a

matter of seconds, permits any one of four beam splitter foils to be correctly positioned in the beam on external command, without the need to break vacuum and realign the Michelson mirrors.

2) The FIR 30 Michelson interferometer operates at a 30° incidence configuration to the beam splitter, in place of the normal 45° incidence, in order to reduce undesirable polarization effects caused by reflection from the beam splitter foil close to its Brewster angle (~57°).

3) The MIR 30 "saw-tooth" scanner operates under primary vacuum and is servocontrolled for constant scan velocity. The actual stroke length and number of sweeps made are computer controlled, so that the effective duty cycle is always optimized. The mirror motion is monitored by a separate He–Ne laser reference fringe system used in the axial ray configuration. A subsidiary marker pulse is used to initiate interferogram data storage.

4) A flexible sample chamber which provides transmission and reflection (~11° incidence) configurations as standard, and is readily adaptable to a wide range of cryostats and other spectroscopic accessories.

B. Detectors

Both instruments utilize room temperature infrared detectors as standard. The FIR 30 uses an updated pneumatic Golay [6] detector (Pye Unicam IR 50), which exhibits uniform spectral response over the whole submillimeter region, has a high responsitivity (6×10^5 V/W), and shows negligible long term drift in its output due to the utilization of all-solid-state optoelectronic components to minimize heat dissipation. Its high linearity of response and low (1.3×10^{-10}-W) noise equivalent power (NEP) make it the best room temperature detector available for Fourier spectroscopy in the 10–500-cm^{-1} range. The main disadvantage of this detector is its slow response time (~15 ms), which ultimately restricts the speed at which the Michelson interferometer may be scanned.

The MIR 30 utilizes a pyroelectric detector [7] as standard, which has the advantage of high speed (~1-ms response time), but has larger ($1 \sim 1.5 \times 10^{-9}$-W) NEP than the Golay detector. It thus becomes particularly advantageous with this kind of detector to scan interferograms rapidly, and improve signal/noise by accumulating several or more scans and averaging by digital means. The current-mode preamplifier circuitry used with these detectors however, has the undesirable property of greatly increased noise for modulation frequencies >1 kHz, and effectively limits the speeds at which interferograms may be scanned for useful signal/noise. The effective apertures of the Golay and pyroelectric detectors described here were 0.06- and 0.03-$\text{cm}^2 \cdot \text{sr}$, respectively.

C. Electronic Systems

The FIR 30 electronics control and data handling system embodies modern solid-state components and utilizes TTL logic. The optical signal is chopped at 12.5 Hz, and after detection is amplified, synchronously rectified, and smoothed to give a dc signal which is subsequently digitized by a bipolar 13-bit A/D converter (the unwanted constant term of the interferogram signal is electrically subtracted before digitization). The digitized interferogram values are then processed in "real time," as described in Section D.

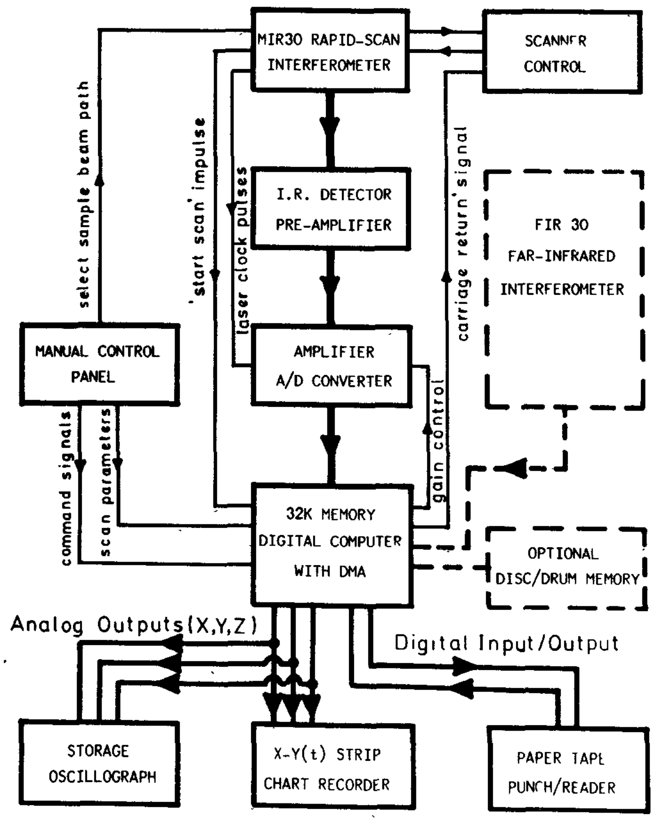


Fig. 2. MIR 30 interferometer electronic block diagram.

The MIR 30 electronics is depicted in Fig. 2. The optical interferometer produces audio-frequency interferogram signals, which are amplified and subsequently digitized by a monopolar 15-bit A/D converter at a rate controlled by the laser reference clock pulses (typically 4 kHz). Both instruments incorporate a digital data system based on a universal minicomputer with direct memory access. A 4K 16-bit word core memory suffices for the FIR 30 instrument whereas the MIR 30 system requires 32K 16-bit core memory and hardware multiply/divide arithmetic. In the MIR 30 system, the computer has direct control on the interferogram signal amplification, the length of mirror travel, and the total number of scans to be made.

D. Fourier Transformation

All practical spectrum computations for infrared Fourier spectroscopy [1] involve a double summation of Fourier terms, taken over an array of wavenumber points and over an array of interferogram points. This offers the possibility of *two equivalent but nonidentical methods* of spectrum processing, according to the order in which this double summation is carried out.

1) The summation is first carried out over spectrum points, from each individual interferogram data point in turn, while the interferometer is in motion. This is the basis of the so called "real-time" method of computation used in the FIR 30, which was first conceived by Yoshinaga [2]. The great advantages of this method are that the entire spectrum of interest is being continually updated and can be observed on an oscilloscope screen at any stage of the interferogram scan, to give the operator instant "feedback." Furthermore, as only computed spectrum points are stored in the computer memory and not interferogram points, it is possible with a relatively small memory computer to process a large number of spectrum points; also, the overall optical resolution is not limited by the size of computer memory. Thus in the FIR 30, the 4K 16-bit core memorycom puter may process double beam transmission or reflection spectra of up to 1500 points. The time of calculation for 1500 spectrum points is 0.4 s, which ensures that the computer is always ahead of the typical interferogram data rate of ≤ 1 Hz. Use of the real-time computation method is thus normally restricted to slow-scanning interferometers, although a special purpose real-time computer has been recently constructed [4], which can, for example, compute 1000 spectrum points at a data acquisition rate of 1 kHz.

2) The summation is first carried out over interferogram points. In such cases, as with the MIR 30, the "fast Fourier algorithm" [5] is normally adopted, to greatly reduce computing time for large arrays. The advantages of this method, as employed in the MIR 30 system, are that it allows a fast interferogram data acquisition rate limited only by the speed of the A/D converter and data storage time ($\sim 20\ \mu$s). Furthermore, it allows a full phase error correction of the recorded interferogram following the method of Forman *et al.* [8], which is important for high spectral intensity accuracy (the "real-time" method only allows a first order three point parabola correction to be made). The great disadvantage of the method is that as both interferogram and spectrum points must be stored, a large computer memory capacity is required, particularly when high resolution is required. For example, the 32K 16-bit core memory used in the MIR 30 allows interferograms of 8K length to be stored, which for the case of a 1.26-μm sampling interval would permit an optical resolution of 0.7 cm^{-1}. Higher (5–10 times) resolution capability can be achieved through the use of a 128K/256K fixed head disk memory, which is provided as an option.

E. Data Input–Output

In the FIR 30 instrument, all information regarding the spectrum computation and commands for the flow of input and output data are given through a teletype terminal.

In the MIR 30 instrument however, the experimental parameters are directly dialed by digital switches on the control panel, and all system commands are given by means of push button switches. The MIR 30 instrument, on initiation of a "start" command, makes three preliminary interferogram sweeps, from which the computer sets the interferogram signal amplification to the optimum value, i.e., when the dynamic range of the A/D converter is ~ 80 percent filled. The interferometer then carries out the predetermined number of interferogram scans. The interferogram data are accurately indexed, co-added, and averaged (with double word precision) in the computer memory. When interferogram measurements are complete, the "compute spectrum" command may be given. After an interval of 5-s computation time, the transformed spectrum of 4K wavenumber points is written in the computer memory and simultaneously displayed on the oscillograph screen.

Inteferogram and spectrum data may be plotted on a strip chart recorder in analogue form, or punched out on paper tape for further processing (interferogram bands may always be read in again for further spectrum computations).

III. PERFORMANCE

The basic rules of conventional infrared grating spectrometers also apply to Fourier spectrometers, i.e., that the spectral resolution and low wavenumber scan limit are ultimately limited by detector signal/noise considerations. Consequently, the best performances are obtained for transparent samples such as gases. Fig. 3 illustrates the high resolution capability of the standard FIR 30 spectrometer—the H_2O doublet at 59.9 cm^{-1} has been clearly resolved. Only a few specially constructed research interferometers [9], [10] (all of which use liquid helium cooled bolometers as opposed to the room temperature detector used here) have hitherto achieved this resolution quality in the far infrared.

Fig. 4 demonstrates the FIR 30 performance over a wider wavenumber range, for solid samples. The trace shows a superposition of two double-beam transmission spectra scanned consecutively, using different beam splitters for overlapping ranges, and illustrates the convenience afforded by a remote vacuum beam splitter

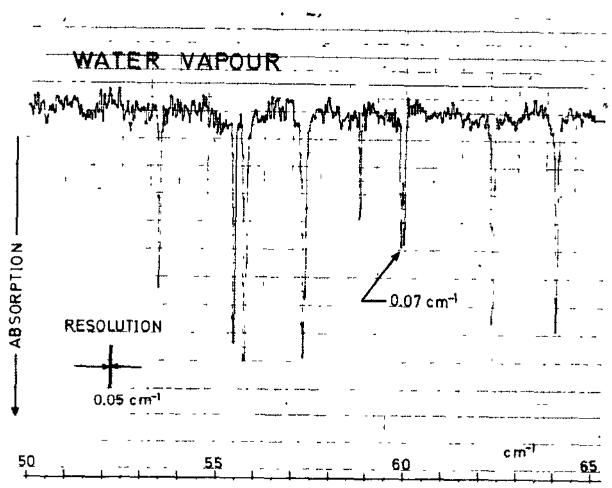


Fig. 3. High resolution portion of H_2O pure rotational spectrum recorded in $\sim$3-h scan time with the FIR 30 interferometer.

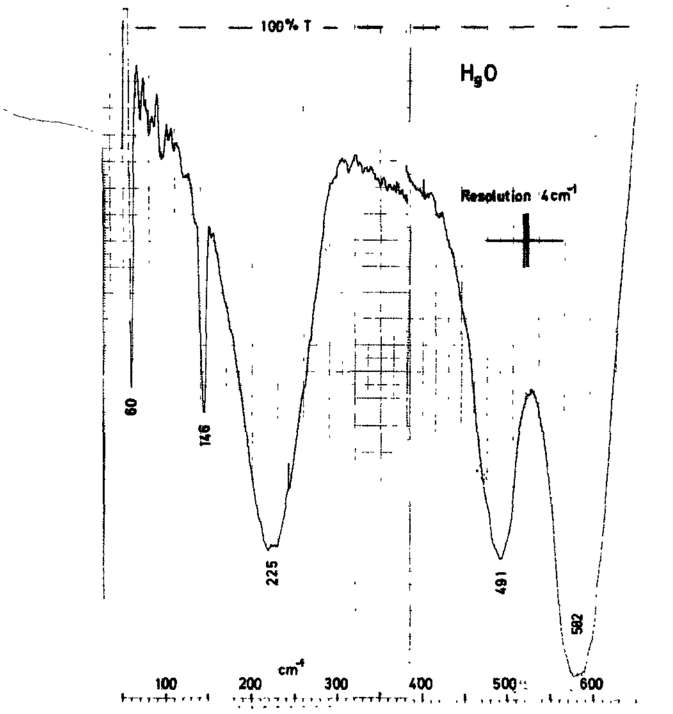


Fig. 4. Transmission spectrum of powdered HgO sample measured using 2.5- and 6-μm beam splitters with the FIR 30 interferometer. Total recording time ~30 min.

change mechanism, with regard to time saving and reproducibility of results.

Fig. 5 illustrates the resolution capabilities of the MIR 30 interferometer (in this case limited to 0.7 cm^{-1} by the computer 32K core memory) for midinfrared gaseous spectroscopy. The $H^{35}Cl$–$H^{37}Cl$ rotational fine splittings of ~2-cm^{-1} magnitude have been clearly resolved.

Fig. 6 illustrates the rapid-scan ability of the MIR 30 interferometer to record a 1.4-cm^{-1} resolution midinfrared spectrum in only 2-s data acquisition (the total time elapsed from starting the interferogram scan to seeing the transformed spectrum on the oscilloscope screen was less than 10 s!). When somewhat inferior resolution suffices, data acquisition times become proportionately shorter—for example, an 11-cm^{-1} resolution inteferogram may be measured in 0.25 s. Fig. 6 also illustrates the power of digital signal averaging to improve signal/noise—the improvement between the average of ten scans and a single scan is approximately in agreement with the "square root law" for random noise.

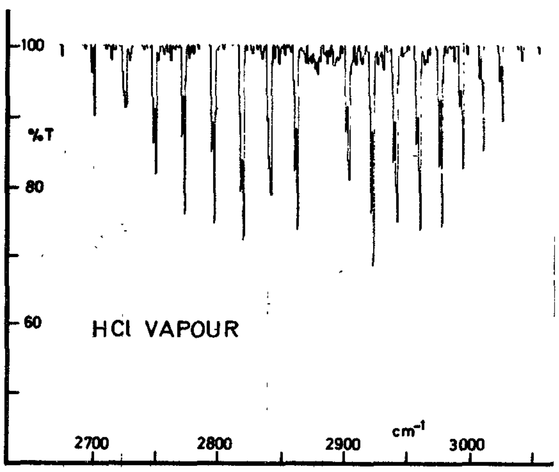


Fig. 5. Hydrogen chloride fundamental vibration—rotation spectrum recorded at 0.7 cm^{-1} with the MIR 30 interferometer. The transmission spectrum was computed from the averages of 200 "reference" and "sample" interferogram scans. Total recording time was ~35 min.

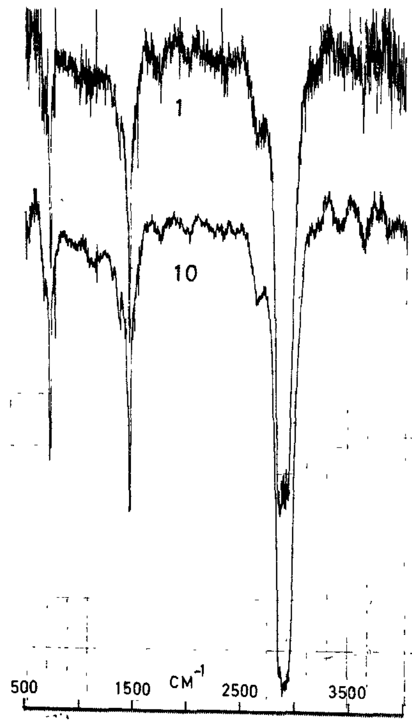


Fig. 6. Midinfrared transmission spectrum of a 50-μm polyethylene foil recorded at 1.4-cm^{-1} resolution using the MIR 30 interferometer. The two traces indicate the spectra obtained from the Fourier transforms of 1, and 10 averaged interferogram scans. Data acquisition times were 2 and 20 s.

IV. CONCLUSIONS

The *advantages* of rapid-scan interferogram modulation relative to slow-scan modulation for infrared interferometric Fourier spectroscopy may be summarized as follows.

1) Faster data acquisition times, which allow the possibility of time-resolved spectroscopy, such as "on-the-fly" IR measurements of gas chromatograph effluents.

2) Minimized "flicker" noise in detector and signal handling electronics is achieved through use of audio-frequency modulation.

3) Theoretically doubled optical signal through the absence of a chopper blade, which in practice is somewhat offset by the less than 100-percent-effective duty cycle of the "saw-tooth" scanner.

4) Long term stability problems in the interferometer and electronics are rendered less critical, as short scan times are involved.

The *disadvantages* would appear to be the following.

1) Rapid-scan mechanisms are usually much more restricted in stroke length (hence resolution) and weight of moving components than a slow-scan system.

2) Satisfactory signal/noise ratios must normally be

achieved through digital signal averaging, which is more complicated and expensive to arrange than the simple analogue smoothing used in the slow-scan method.

Ultimately in practice however, the success of each method hinges on the best detector available. Thus in the energy limited far infrared, where the Golay detector is still the most sensitive room temperature device available, the slow-scan method appears to have the edge over the rapid-scan method, as evidenced by the quality of spectra which have to date been recorded by commercial instruments. In the midinfrared, where characteristically higher energy sources are available, the lower sensitivity of the pyroelectric detector is less critical, and is more than compensated for by the advantages afforded by the rapid-scan method.

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High-Resolution Submillimeter-Wave Fourier-Transform Spectrometry of Gases

J. W. FLEMING

***Abstract*—Modern interferometric techniques now permit the measurement of broad-band absorption spectra of gases at submillimetric wavelengths to high resolution with comparative ease. This paper describes briefly some new spectra of H_2O, N_2O, and SO_2 in the 10–40 cm^{-1} (0.33 to 1.4 THz) region, at a resolution of 0.05 cm^{-1}.**

INTRODUCTION

HIGH-RESOLUTION broad-band spectrometry in the submillimetric region can be achieved most readily using the technique of Fourier-transform spectrometry [1], [2]. Providing particular attention is paid to certain key points, then fairly simple and cheap instrumentation is capable of resolutions better than 0.1 cm^{-1} below 100 cm^{-1}. We show in this paper how a simple Michelson two-beam interferometer is used to record spectra at a nominal resolution of 0.05 cm^{-1} in the 10–40 cm^{-1} (0.33–1.4 THz) region. The data obtained are of particular importance in studies of the submillimetric-wave properties of the earth's stratosphere.

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EXPERIMENTAL

The instrumentation used was the NPL–Grubb Parsons[1] cube interferometer; phase modulation [3] of the radiation was employed. The detector was a liquid-helium-cooled Rollin-type of photoconductor. This, together with the transmission characteristics of the interferometer, restricted the spectral bandpass to the region 10–40 cm^{-1}. The gases were contained in a single-pass absorption cell fitted with TPX windows; path lengths of 933 mm and 203 mm were used. Single-sided interferograms were observed up to a maximum optical path difference of 100 mm, which corresponds after transformation to a nominal unapodized resolution of 0.05 cm^{-1}. A step-recording technique with a sampling interval of 40 μm was used, and, with an amplifier time constant of 300 ms, the total recording time for a single interferogram was about 50 min. The signal-to-noise ratio in the analog-output signal was 2000:1, and this was then sampled by a

[1] Sir Howard Grubb Parsons & Co. Ltd., Walkergate, Newcastle-upon-Tyne, England.