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DETECTION OF FOURIER TRANSFORM INFRARED (FTIR) LIGHT BY A PHOTOACOUSTIC DETECTOR

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The responsivity and NEP ratings of three types of photoacoustic cells has been studied. A 0.5 cc nonresonant photoacoustic cell has an Nep of 15 $nW/Hz^{\frac{1}{2}}$ at 320 Hz with a responsivity that decreases with increasing modulation frequency of the incident light. A resonant cell with ar active volume of 3 cm length by 1 cm diameter shows an NEP of 24 $nW/Hz^{\frac{1}{2}}$ at the Q=7 resonance of 5.2 kHz and exhibits an NEP of 120 $nW/Hz^{\frac{1}{2}}$ over a broad frequency range from 2 to 13 kHz. This cell exhibits an NEP of 25 $nW/Hz^{\frac{1}{2}}$ at 320 Hz with responsivity decreasing with increasing modulation frequency up to 1 kHz. An optical deflection system showed poorer NEP but indicated a 200 fold increase in membrane deflection per Watt of incident power compared with a conventional microphone. Another order of magnitude improvement in deflection/Watt is possible, but current optical and capacitive techniques for sensing this motion are not useful.

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PREFACE

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DETECTION OF FOURIER TRANSFORM INFRARED (FTIR) LIGHT BY A PHOTOACOUSTIC DETECTOR

1. INTRODUCTION

It is imperative that sensor technology in the mid infrared spectral range advance beyond the performance boundaries of the current generation of devices. Most high sensitivity mid-IR band detectors at high modulation frequencies are based on the cooled Mercury Cadmium Telluride (MCT) device operating in photoconductive or photovoltaic mode. While much engineering effort has been expended in the development of this and related detector technologies, for battlefield use the system suffers from the requirement of a cryogenic cooling mechanism. This adds weight and maintenance complexity. There are several pyroelectric devices available (e.g. deuterated triglycine sulfate, DTGS) which have better responsivity than an MCT detector at room temperature and at low modulation frequencies, but none which compares favorably with its performance when the detector is operating at 77 K and at high modulation frequencies.

A conceptual alternative to this detection scheme is to use a photoacoustic detector. While the photoacoustic detector is an energy integrating device and thus suffers from 1/f responsivity loss, it can be made to function at room temperature with very inexpensive, light-weight components. It is the objective of this article to describe a series of measurements on an actual photoacoustic detector which were aimed at determining the noise equivalent power of a practical device and to assess the range of the performance of this device. In this way a realistic assessment of the potential for such a detector to serve as a replacement for the MCT detector may be made.

The photoacoustic detector typically incorporates a sensing medium (an absorbing gas, liquid or solid) in a sealed container. Modulated incident light is absorbed by the sensing medium and converted indirectly to a pressure wave which is then sensed by microphones or piezoelectric transducers. The technology itself is well documented in many recent monographs. Most work with photoacoustic techniques has been involved with a spectroscopic examination of the sensing medium. There has been little work with the concept of using the sensing medium to determine the radiant intensity of the incident light. The Golay detector is one of the few commercial examples of such a device. However, because of the mechanical design of this detector, the frequency response of the Golay cell was limited to modulation frequencies below a few hundred Hertz. What is needed is a photoacoustic detector of bandwidth sufficient to examine light

across the 8-12 micron mid-IR range with responsivity vs. noise equivalent power (NEP) comparable to that of the best commercial MCT detectors and which does not require cooling.

It is the objective of this work to examine the plausibility of fabricating a photoacoustic (PAS) cell to detect 8-12 micron radiation with sensitivity comparable to that of a cooled MCT but with that PAS cell operating at room temperature. There are several literature reports indicating the potential for generating very high detectivity levels from gas phase PAS cells[1]. This study has focussed on defining the broad band acoustic response of both non-resonant and resonant PAS cells using commercial microphones and optical deflection systems. A calibration procedure has been defined using an Argon ion laser and NO2 gas so that reasonably accurate responsivity and noise figures of merit may be obtained. Furthermore, a comparison figure between the responsivity of a hexane soot and a gas as a sample has been defined.

2. EXPERIMENTAL

The nonresonant PAS cell has been described earlier[2]. A Bruel and Kjaer 4165 0.5 inch foil electret microphone was used throughout as the microphone. This was impedance matched with 2642 preamp and subjected to a gain of 40 dB (x100) by using a Bruel and Kjaer 2810 preamp. A Rofin MKII chopper was used to square wave chop the incident light from a Hughes 3225H 2 mW Helium Neon laser or a Cyonics 2202-10MLL air cooled 10 mW Argon ion laser. When high modulation frequencies were required, either the higher harmonics from the chopper modulated light were used or the laser light was passed through an Intra-Action SWM-50 50 MHz acousto-optic modulator (AOM) which was in turn modulated through the video input mode by the output from Hewlett Packard 3325A signal generator. The AOM therefore modulated the incident laser at 100 MHz underneath a 100% modulation depth envelope and acoustic frequencies twice that specified by the frequency synthesizer. This in turn introduces higher harmonics into the output modulation resulting in a fundamental frequency modulated power only 67% of that read by the power meter, an Ando AQ2704 power meter. All power readings were corrected for

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[1] Optoacoustic Spectroscopy and Detection, Ed. Y.H. Pao, Academic Press, N.Y., N.Y., p.25 (1977).

[2] M.G. Rockley, Applied Spectroscopy, 34, 405 (1980).

fraction of light absorbed by the sample, reflections at window interfaces and any losses due to harmonics subtracting from the average power at the fundamental.

The resonant photoacoustic cell was a simple aluminum cylinder with bore of length 3 cm and diameter 1 cm.. The 4165 microphone was placed end on with the incident light entering the sample chamber through a window at the opposite end of the chamber. Provision was made for a gas to enter the chamber through a side vent. No attempt was made to polish the interior of the sample chamber or assure parallelism of the end components since obtaining the highest resonance quality factor (Q) was not the particular aim of the work. A measured Q of 7 indicated that the Q was indeed spoiled.

The output from the PAS cells was analyzed by a Hewlett Packard 3582A spectrum analyzer giving signal amplitude readings and system noise floor readings, the latter being compensated for bandwidth and being displayed in units of $dBV/Hz^{1/2}$. For experiments on the resonant cell it was necessary to measure the phase of the signal as well. For such measurements the signal was also analyzed by a Stanford Research Systems SR530 lock-in amplifier set to amplitude and phase tracking mode. For experiments in which the modulating source was the AOM, the lock-in amplifier was set for operation at the first harmonic of the frequency synthesizer reference.

To calibrate the nonresonant cell, NO2 gas was generated from nitric acid and copper and subjected to drying prior to being placed in the cell. The incident laser beam (488 nm from Ar^+ laser) was modulated by the chopper and the incident power prior to the sample chamber and after exit from the sample chamber was measured and corrected for attenuation by windows. In this way the exact light power absorbed by the sample could be inferred. Because the percent transmittance was never less than 75%, small fluctuations in the laser power could introduce some error. Therefore, the transmitted power as a function of time was measured, together with the PAS signal strength. The resulting plot showed a fairly linear decrease with time, the slope of the plot giving the response of the cell in mV/Watt absorbed. The signal decreased with time because the NO2 leaked gradually into the region occupied by the microphone preamp (contained hermetically inside the PAS cell) and because the NO2 was absorbed by O-rings and reacted with the aluminum of the PAS cell.This cell was then used to calibrate the response of a hexane soot prepared by combustion of hexane in an open flame[3].

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[3] M.S. Akhter, A.R. Chugtai, and D.M. Smith, Applied Spectroscopy, 39, 143 (1985).

It was estimated that 80% of the light which impinged on the soot was absorbed, since transmitted light was negligible but some reflection did occur from the hexane soot.

A photodeflection cell was also built. It was identical to the resonant cell described above except that the bore was filled with a precision glass capillary of inner diameter 3 mm. Instead of the microphone at the rear of the chamber a Melles Griot nitrocellulose pellicle (7 microns thickness) was sealed with a 20 micron by 3 mm air gap to allow static pressure equalization. About 100 microns away from this pellicle was placed an uncoated quartz plate. An incident 1 mm diameter HeNe laser was focussed through a 1 inch diameter f/1 lens onto the interface between the quartz plate and the pellicle, so configuring a low finesse etalon arrangement. The reflected fringes were observed at a distance of 18 inches from the etalon. At this distance the fringes were about 1.0 mm apart and were observed through a 0.3 mm aperture by a United Detector Technology UDT451 photodiode operating in photovoltaic mode with a high frequency cutoff about 25 kHz. The output from this photodiode was then analyzed as described above. This output was amplitude modulated by deflection of the membrane and was therefore susceptible to laser drift, macroscopic motion of the optics, etc. A better measure of the membrane motion may be obtained by using phase modulation in which a Zeeman Split two frequency laser (such as the Optra Optralite) responds to the pellicle motion independently of laser drift or macroscopic optics motion. The theoretically obtainable performance from such a system is included in Table I under the title "Phase Detection".

3. RESULTS AND DISCUSSION

The results are summarized in Table I. NEP is the noise equivalent power, NED is the noise equivalent membrane displacement, Disp/W is the membrane displacement per watt of absorbed light power, and the gain refers to a correction for the 40 dB gain of the 2810 preamplifier for the commercial microphone. The pellicle noise figure was generated by both AM laser power fluctuations and by the noise of the UDT detector and integrated operational amplifier.

The hexane soot was found to generate a signal 20% the amplitude of the NO2 gas used in the PAS cells. While on might expect the ratio to be 5% based on the square root of the solid/gas density ratios for an infinitely thin solid, this high response is somewhat anomalous. Because of its efficiency, as observed in the nonresonant PAS cell, it was used as the signal generator for the experiments with the resonant and deflector PAS cells, being more convenient to handle.

TABLE I

Relative Performance of Various PAS Detectors

Microphone:
(@ 322 Hz)

Noise	=	15 microvolts/$Hz^{1/2}$
R	=	1000 V/W
NEP	=	1.5 x 10^{-8} Watts/$Hz^{1/2}$
NED	=	0.003 nanometers/$Hz^{1/2}$
Disp/W	=	10 micrometers/40 Volts * R*0.01 (Gain)
	=	2 micrometers/Watt

Pellicle:
(@ 322 Hz)

Noise	=	38 microvolts/$Hz^{1/2}$
R	=	100 V/W
NEP(am)	=	3.8 x 10^{-7} Watts/$Hz^{1/2}$
Disp/W	=	8 nanometers/39 microWatts
	=	200 micrometers/Watt

Phase Detection

Noise	=	0.002 waves
in 10 kHz	=	1.2 micrometers/$Hz^{1/2}$
NEP(pm)	=	6 x 10^{-8} Watts/$Hz^{1/2}$ *

* Theoretical value only.

By analysis of the results in Table I, it can be seen that the PAS nonresonant cell is 2000 times less sensitive than an MCT detector at 320 Hz. The resonant cell was observed to be 3000 times less sensitive than an MCT detector at 5.2 kHz. An optically sensed pellicle arrangement is a factor of 10 less sensitive than a conventional acoustic cell because of the limitations of optical sensing methods.

By using an AOM system as described above, the response of the resonant cell was studied as a function of frequency. The results are shown in Figures 1 and 2. Two resonances are observed, one at 5.2 kHz and a second smaller resonance at 10 kHz. The response shows the characteristic 1/f dependence only at low frequencies. Above 1.5 kHz, the response of the cell is reasonably flat with frequency except for the resonances.

However, the resonant cell shows a characteristic phase shift across the spectrum with particularly sharp changes in signal phase at the acoustic resonances, an expected behavior. For systems in which phase variation with analysis frequency introduces unmanageable errors, it is clear that an acoustically resonant PAS cell would not be of use for infrared light detection. If, however, this phase shift constitutes a wavelength discrimination advantage, then acoustically resonant PAS cells may offer unique comparisons and advantages over DTGS and perhaps MCT detectors.

4. CONCLUSIONS

The conventional nonresonant photoacoustic cell cannot replace a cooled MCT detector for use in sensing ambient temperature emission from remote sources which has been processed by an FTIR for several reasons. It is insensitive by a factor of 2000:1. It exhibits a 1/f response making it unusable above 2-3 kHz modulation frequency.

A resonant photoacoustic cell may under certain conditions be used to replace a cooled MCT detector. A resonant cell with a broad frequency response out to 15 kHz, as described in this work, is insensitive by a factor of 3000:1 compared with a cooled MCT detector. However, this gap in response could be decreased by a factor of 10 by using (a) a 1" electret microphone (instead of a 0.5 " electret as used here); (b) by using a fill gas of Argon which increases both signal to noise ratio and resonance Q and which decreases the resonance frequencies. Any remaining improvement would have to be achieved by increasing the resonance Q. It can only be presumed (in lieu of measurement) that this will increase responsivity. A factor of 300 improvement in Q would be needed for such a system giving a resultant useable detector with a Q of 2000. While there are reported examples of such high Q photoacoustic detectors[4], such a high Q sensor would not be useful as a detection element in a spectrometer unless it could be fabricated with resonances at certain appropriate wavelengths (i.e. acoustic modulation frequencies resulting from FTIR processing of incident light). In that case, these resonances would correspond in the 8-12 micron spectral range to bandpasses of 0.5 cm^{-1} FWHM at 1000 cm^{-1} ! A multiple resonance cell is not unthinkable, however. The simple Q-spoiled resonant cell described in this work exhibited at least two resonances.

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[4] L.J. Thomas III, M.J. Kelly, N.M. Amer, Applied Physics Letters, 32, 736 (1978).

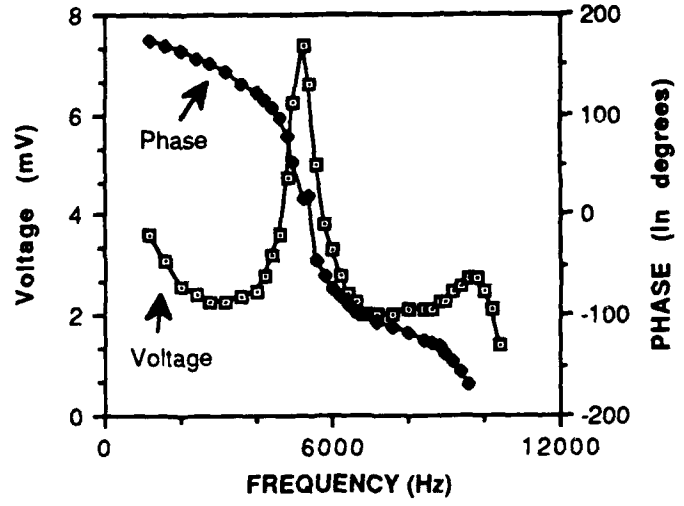

Figure 1. Response of a Resonant Photoacoustic Cell with the Associated Phase Variation

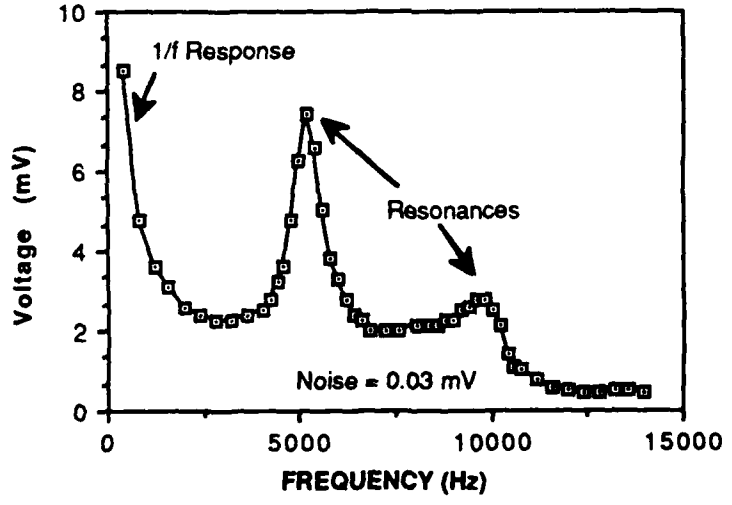

Figure 2. Frequency Response of a Resonant Cell

An optical deflection system using a nitrocellulose membrane in place of a microphone membrane can be used as a photoacoustic sensor. However, even when the membrane is only 0.5 microns thick and phase modulation laser methods are used to sense the motion of the membrane, under optimum circumstances the performance of such a detector is not better than can be obtained from a conventional electret microphone in a conventional PAS cell. The limitation arises from the mechanism for detecting the motion of the diaphragm. Capacitive techniques require a close working distance between the two plates of the capacitor for best sensitivity. However, that proximity introduces viscous damping into the membrane oscillation with attendant Brownian motion limited noise performance. This is observed for a nickel film on an electret microphone. If the motion of the diaphragm is sensed by phase modulation techniques, accurate electronic clocks must be used to measure the motion. This restricts the resolution of the motion as observed by interference between two frequency shifted components of a probe laser to 0.002 laser wavelengths with an update rate (bandpass) of 10 kHz. Since the motion of the pellicle diaphragm (7 microns thick) observed in this work is about 200 microns per absorbed Watt, the noise equivalent power for such a system is higher than that observed using a microphone in a regular PAS cell. The displacement per Watt of a nitrocellulose pellicle is 200 times greater than that observed for a nickel film on a microphone in part because of the absence of viscous damping which sets the noise floor for high quality commercial microphones. However, this gain in responsivity for the pellicle system cannot be measured by current phase modulation optical techniques.

This work shows that the replacement of cooled MCT detectors by PAS detectors is not unthinkable. However, microphones with much greater responsive surface area (without attendant and defeating increases in PAS cell volume) must be designed and membrane deflection measurement must be made by more sophisticated or novel optical and/or electronic techniques.