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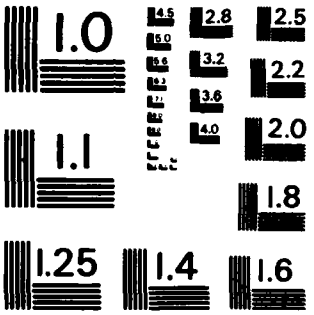

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Noncontact techniques of optical probing of photoacoustic pulses provide new opportunities for ultrasonic and/or spectroscopic measurement in hostile environments (e.g., flames, corrosive fluids, dangerous aerosols, etc.) and also basic understanding of photoacoustic generation processes. This paper provides examples of such applications in the new field of "optical ultrasonics" (whereby ultrasonic determinations of flows, temperatures, etc., are measured optically), including "optical ultrasonic spectroscopy" (whereby ultrasonic dispersion and relaxarions are measured optically).

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TECHNICAL REPORT NO. 3

Optical Probing of Photoacoustic Propagation for Noncontact Measurement of Flows, Temperatures and Chemical Compositions

By

A. C. Tam, H. Coufal, W. Zapka and B. Sullivan

IBM Research Laboratory
San Jose, California 95193

October 21, 1983

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Research Report

OPTICAL PROBING OF PHOTOACOUSTIC PROPAGATION FOR NONCONTACT MEASUREMENT OF FLOWS, TEMPERATURES AND CHEMICAL COMPOSITIONS

A. C. Tam
W. Zapka
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B. Sullivan

IBM Research Laboratory
San Jose, California 95193

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OPTICAL PROBING OF PHOTOACOUSTIC PROPAGATION FOR NONCONTACT MEASUREMENT OF FLOWS, TEMPERATURES AND CHEMICAL COMPOSITIONS†

A. C. Tam
W. Zapka*
H. Coufal
B. Sullivan

IBM Research Laboratory
San Jose, California 95193

ABSTRACT: Noncontact techniques of optical probing of photoacoustic pulses provide new opportunities for ultrasonic and/or spectroscopic measurements in hostile environments (*e.g.*, flames, corrosive fluids, dangerous aerosols, *etc.*), and also basic understanding of photoacoustic generation processes. This paper provides examples of such applications in the new field of "optical ultrasonics" (whereby ultrasonic determinations of flows, temperatures, *etc.*, are measured optically), including "optical ultrasonic spectroscopy" (whereby ultrasonic dispersion and relaxations are measured optically).

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*Present Address: IBM Deutschland GmbH, D-7032 Sindelfingen 1, Federal Republic of Germany

INTRODUCTION

Most photoacoustic (PA) experiments have been performed by using some types of transducers in contact with, or in close proximity to, the sample to detect the acoustic signal. These are contact PA monitoring techniques. There are situations where noncontact PA monitoring techniques are necessary or preferable. For example, the sample may be remote or inaccessible (*e.g.*, in a vacuum chamber). Also, for high temperature or highly reactive samples, the use of contact transducers or other material probes may result in chemical modifications, aging, irreproducibilities or other difficulties. Several ways for noncontact photothermal (PT) detections have been demonstrated in the literature. For example, Nordal and Kanstad[1] have developed the technique of "photothermal radiometry" which relies on the detection of the increased black-body radiation from the sample after optical absorption.[2] A thermal refractive index gradient is also produced which causes "thermal lensing"[3] and "probe-beam refraction"[4] effects. These PT techniques have been shown to be useful for spectroscopy[5] and subsurface imaging[6] applications, but not for determining the ultrasonic properties of the sample. The PT techniques do not provide such information, because no ultrasonic propagations are involved.

OPTICAL ULTRASONICS

We have recently developed the noncontact technique of "optical ultrasonics," whereby only optical beams are used to excite and to probe the sample to perform ultrasonic measurements.[7] This represents one area of application of photoacoustic (PA) techniques, and is to be distinguished from the conventional PA spectroscopy technique, as summarized in Table I. The optical ultrasonic technique has the following advantages compared to conventional contact ultrasonic methods: (a) measurements can be reliably and easily made in hostile environments, and (b) nonperturbing measurements can be made with high spatial

and temporal resolution. This provides an all-optical method for performing ultrasonic velocity, dispersion or attenuation measurements in the sample. Parameters that can be derived from such noncontact acoustic measurement technique include temperature and composition (which affect the stationary acoustic velocity) and flow velocity (which affects the directional variation of the observed acoustic velocity). This new experimental technique has been successfully applied to corrosive gases[7] and liquids,[8] to a flowing pure air stream[9] and to a propane-air flame for temperature-profiling.[10]

Our first experiment[7] is concerned with ultrasonic velocity measurements in hot, corrosive metal vapors, namely, a saturated Cs vapor in the temperature range of 300°C to 520°C. A flashlamp-pumped dye laser (Candella LFDL-1) is used to cause the transient plasma formation in a saturated Cs vapor. The excitation pulse energy, E, is adjustable from 1 mJ to 1 μJ. The transient plasma formation causes sudden heating, and an acoustic pulse is produced. We observed that the propagation of this cylindrical acoustic pulse can be monitored by a weak cw probe laser (HeNe or Kr) which is parallel to, but displaced from, the pulsed excitation beam with a variable displacement R. The acoustic pulse arriving at the probe beam causes transient deflections of the probe, observed by using a knife edge to block half of the probe beam before detection with a fast photodiode. The observed relation of the range R of the acoustic pulse versus the propagation time t (as measured by the probe beam deflections) shows an initial supersonic propagation (which is faster for larger E) and an ultimate linear sound propagation (at large t). We found that our data provide verifications of the blast wave trajectory predicted by Vlases and Jones,[11] which was previously verified only for acoustic pulses of much larger Mach numbers.

We have recently demonstrated[9] a new application of the laser-induced acoustic source for measurements in a flowing gas. We show that we can monitor the flow velocity of a pure

particulate-free gas (as well as liquid) to an accuracy of 5 cm/sec and simultaneously measure the fluid temperature to an accuracy of 0.1°C. Such noncontact measurements were not possible previously by other known laser-scattering methods (like laser Doppler velocimetry, coherent anti-Stokes Raman scattering or stimulated Raman-gain spectroscopy). The experimental arrangement for the simultaneous measurement is shown in Figure 1. An acoustic pulse in a flowing air stream is produced at position 0 by the dielectric breakdown produced by a pulsed excitation laser (Nd:YAG laser, ~10 mJ energy and 10 nsec duration). Three probe HeNe laser beams, 1, 2 and 3 at distances ℓ_1, ℓ_2 and ℓ_3 from 0, are used to monitor the acoustic pulse arrival time t_1, t_2 and t_3, respectively. The acoustic pulse arrival at each beam is signified by the transient deflections of the beam. We have shown that the three probe beams provide enough data to give both the flow velocity and the fluid temperature simultaneously; furthermore, possible errors due to a blast wave being produced at the origin can be minimized[9] by suitably positioning the probe beams and by suitable data reduction. This new "noncontact" flowmeter and thermometer is demonstrated[10] to be ideally suitable for flame diagnostics.

QUANTITATIVE PA PROFILE MEASUREMENT; – OPTICAL ULTRASONIC SPECTROSCOPY

Although PA pulse generation was known for a long time and theories[12,13] have been developed, a quantitative experimental verification of the dependence of PA pulse profile on the excitation laser profile (spatial and temporal) has been lacking so far. This is quite difficult in previous measurements using transducers or microphones due to the limitations of instrumental ringing and slow risetimes.

In our present experiment, an excitation laser pulse of various durations (10 nsec to 1 μsec) and various beam diameter (10 μm to 1 mm) is used to generate the PA pulse in a

liquid (*e.g.*, ethanol). The PA pulse profile is detected by a focused cw probe laser beam (HeNe) that is parallel to but displaced from the excitation beam. The arrival of the PA pulse at the probe beam causes a transient probe deflection which is proportional to the spatial derivative of the PA pulse profile. This provides a true measurement of the PA pulse shape, since the previous instrumental limitations, due to the use of transducers, are eliminated.

Some results are indicated in Fig. 2. The theoretical PA pulse profile generated by a Gaussian laser pulse[13] is indicated as curve (a). The theoretical probe beam deflection signal is obtained by differentiating the above curve, as given in (b). An observed probe deflection signal is shown in curve (c). There is reasonably good agreement between curves (b) and (c); the difference between them is believed to be due to the excitation laser pulse being not exactly Gaussian, as assumed in the calculation.

The above totally optical method of PA pulse profile monitoring opens up a new application, namely, noncontact optical probing of ultrasonic relaxation and dispersion measurements, *i.e.*, "optical ultrasonic spectroscopy" which is not to be confused with opto-acoustic or photoacoustic spectroscopy. Chemical reactions, nucleation, precipitation and other physical changes in a system frequently result in changes in the ultrasonic absorption or dispersion spectra. This causes a well-defined distortion and attenuation of the PA pulse as it propagates through the sample; the position dependent PA profiles are reliably detected by our probe deflection technique.

Table I

Summary of Various Applications of Photoacoustic (PA) Techniques

Photoacoustic Techniques	Principle of Operation	Examples
1. PA spectroscopy	Absorption spectrum is obtained by varying the excitation wavelength to produce a corresponding variation in acoustic response. Constant quantum efficiency for thermal de-excitation is usually assumed.	Contact acoustic detection includes the use of gas coupled microphones and piezoelectric transducers. Noncontact acoustic detection includes a variety of probe-beam deflection techniques.
2. PA monitoring of de-excitation	The quantum efficiency for thermal de-excitation is varied (*e.g.*, by changing concentrations, temperature, electric fields, *etc.*) to make inference on the quantum efficiency of a complimentary channel.	Contact acoustic detection has been generally used; complimentary channels include luminescence, photochemistry, photoelectricity and energy transfer.
3. PA sensing of physical properties	The thermal or acoustic waves generated in the sample are used to sense subsurface features, material composition or crystallinity, sound velocities, flow rates, temperatures, *etc.*	Contact acoustic detection has been generally used to sense subsurface features. Noncontact acoustic detection for various velocities and temperature sensing measurements involve the use of probe beams, and are called the techniques of "optical ultrasonics."
4. PA generation of mechanical motions	PA pulses or shock waves (*e.g.*, due to boiling or breakdown) may generate mechanical motions efficiently.	Liquid droplet formation and ejection from a nozzle have been demonstrated (see Ref. 14).

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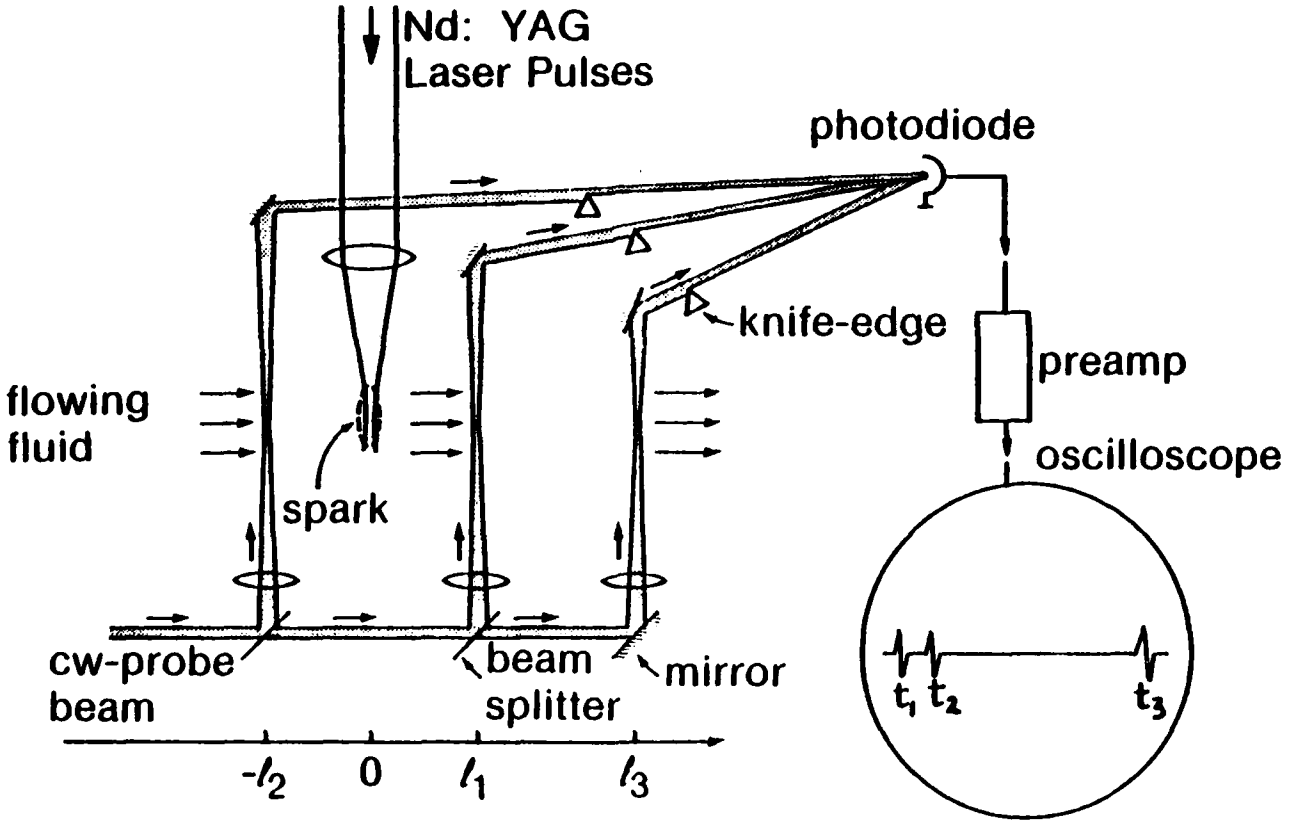

Figure 1. Experimental arrangement to perform noncontact "optical ultrasonic" sensing of flow velocity and temperature simultaneously in a gas or liquid.

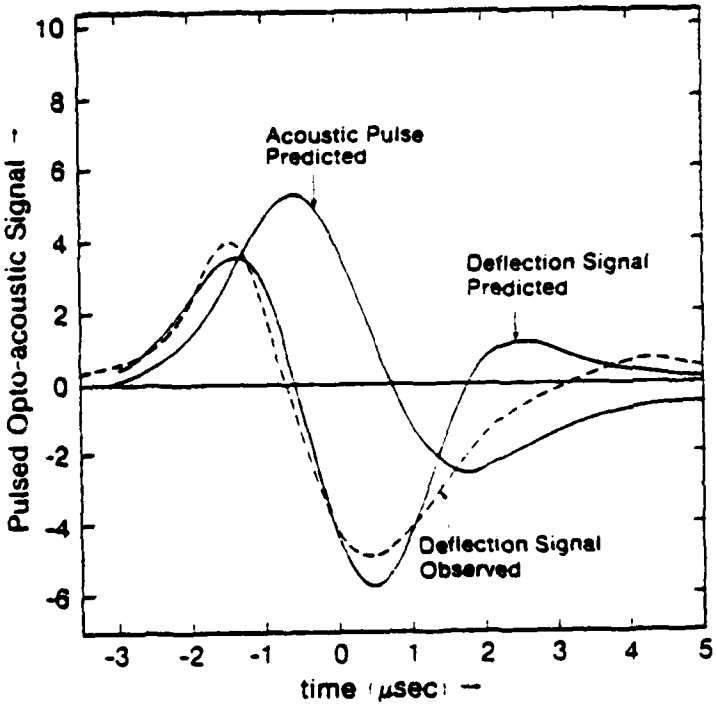

Figure 2. Pulsed photoacoustic profile excited by a laser pulse of full-width at half maximum about 2 μsec.


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