

## Photoacoustic Laser Doppler Velocimetry Using the Self-mixing Effect of RF-excited CO<sub>2</sub> Laser

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A new laser Doppler velocimeter employing a CO<sub>2</sub> laser has been developed by using its photoacoustic effect. A change in the pressure of a discharge, induced by mixing of a returned wave with an originally existing wave inside the cavity, is employed to detect the Doppler frequency shift. We found that a Doppler frequency shift as small as 50 kHz was detected, and also a good linear relationship between the velocity and the Doppler frequency shift was obtained.

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### I. INTRODUCTION

With the invention of the laser in 1960 it was natural that people should start considering measuring the velocity of a material by measure of the 'Doppler effect'. This Doppler effect can be used to measure the velocity of a body which scatters the light.

A laser velocimeter using the Doppler effect domain has been investigated and developed for application in many areas. The LDV utilizes the coherent properties of laser, providing high spatial resolution and fast response measurement. LDVs have been modified to have various configurations for many usages. Among these configurations, the self-mix or optical feedback technique was first introduced by Rudd [1] to measure the Doppler velocity of scattering particles with a He-Ne laser. This technique is attractive for Doppler velocity measurements because the careful optical alignment required by conventional optical heterodyne detection to match the local oscillator and signal modes is not required. The similar technique was studied for LDV using a CO<sub>2</sub> laser by Churnside [2] and a semiconductor laser diode by Shinohara et al. [3] The extension of optogalvanic methods to radio-frequency and DC excited lasers has been made [4], but is poor in signal to noise ratio because of the high level of

plasma discharge noise which then occurs.

In case of an LDV using a CO<sub>2</sub> laser, a liquid nitrogen cooled Mercury Cadmium Telluride (MCT) detector is used to detect a Doppler shifted signal. Since the liquid nitrogen should be replenished in the MCT detector at a predetermined time interval, it has been a disadvantage for field use. The purpose of this paper is to describe the photoacoustic detection method of a Doppler-shifted signal in the self-mixing type CO<sub>2</sub> laser Doppler velocimeter without using an MCT detector.

It is well known that the mixing occurs when light, scattered back from the moving object into the laser cavity, interferes with light inside the laser. This mixing causes a large fluctuation in the laser intensity with Doppler frequency [5], in turn, it makes a similar fluctuation in the pressure of the plasma tube because the pressure increases as the laser intensity increases. Fluctuations in the pressure are called the photoacoustic effect (PA) [6], which is commonly described in terms of a change in gas pressure in response to emission or absorption of radiation. The M. Villagran-Muniz group showed a photoacoustic effect in a CO<sub>2</sub> laser [7].

The photoacoustic effect is based on the generation of acoustic waves in a medium due to interaction of the medium, with modulated or pulsed electromagnetic

radiation. Most of the techniques related to this effect are based on the production of a net macroscopic amount of heat in the medium upon absorption of light, which generates pressure waves that can be detected by means of microphones or ultrasonic transducers [8]. We show here how photoacoustic signals generated in laser discharge can be used for real-time measurement of different frequency in a CO<sub>2</sub> laser Doppler velocimeter (LDV).

## II. PRINCIPLE OF MEASUREMENT

It is a well-established fact that electromagnetic radiation scattered by a moving object suffers a change in frequency in proportion to the velocity of the scattering object [9]. When a plane monochromatic wave is incident on a particle moving with velocity  $\vec{v}$  such that  $v$  is much less than  $c$ , the velocity of light. For a stationary particle the number of wave-fronts striking the particle per unit time  $\nu_i$  would be  $\nu_i = c/\lambda$ . The number of wave-fronts incident upon a moving particle per unit time, i.e. the frequency  $\nu_p$  apparent to the particle is

$$\nu_p = \frac{c - \vec{v} \cdot \vec{i}}{\lambda_i} \quad (1)$$

Where  $\nu_i$  is the frequency of the incident light,  $\lambda_i$  is the wavelength of the incident light,  $c - \vec{v} \cdot \vec{i}$  is the velocity difference between the particle and the illuminating wave and  $\vec{i}$  is the unit vector parallel to  $\vec{k}_i$ , the wave vector of the incident light.

The wavelength  $\lambda_p$  apparent to the particle is  $\lambda_p = c/\nu_p$ . Substituting from equation (1) gives

$$\lambda_p = \frac{\lambda_i c}{c - \vec{v} \cdot \vec{i}} \quad (2)$$

For a stationary observer viewing along the direction  $-\vec{k}_s$  the apparent scattered wavelength is

$$\lambda_s = \frac{c - \vec{v} \cdot \vec{i}}{\nu_p} \quad (3)$$

Where  $\vec{s}$  is the unit vector parallel to  $\vec{k}_s$ , the wave vector

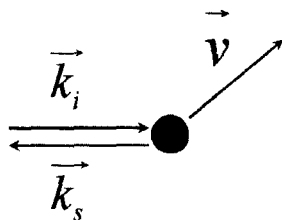


FIG. 1. Diagrammatic representation of incident and scattered waves in relation to the velocity vector of a moving object.

of the scattered light. In a similar way,  $\vec{v} \cdot \vec{s}$  represents the component of the particle velocity along the direction  $\vec{s}$ , and therefore  $c - \vec{v} \cdot \vec{s}$  is the velocity difference between the moving particle and the scattered light.

Hence the frequency  $\nu_s$  of the scattered radiation is  $\nu_s = c/\lambda_s$ . Substituting from equations (2) and (3) we obtain

$$\nu_s = \frac{c(c - \vec{v} \cdot \vec{i})}{\lambda_i(c - \vec{v} \cdot \vec{s})} \quad (4)$$

The change in frequency of Doppler shift is given by  $\nu_D = \nu_s - \nu_i$

$$\nu_D = \frac{c}{\lambda_i} \left( \frac{c - \vec{v} \cdot \vec{i}}{c - \vec{v} \cdot \vec{s}} - 1 \right) \quad (5)$$

For  $|\vec{v}| \ll c$

$$\nu_D = \frac{\nu \cdot (\vec{s} - \vec{i})}{\lambda_i} = \frac{n}{\lambda_0} \vec{v} \cdot (\vec{s} - \vec{i}) \quad (6)$$

Where  $n$  is refractive index of the medium surrounding the scattering particle,  $\lambda_0$  is the vacuum wavelength of the incident radiation. The light scattered by a moving object is Doppler shifted:

$$\nu_D = 2\nu \cos(\theta)/\lambda \quad (7)$$

where  $\nu_D$  is the resulting Doppler shift,  $\nu$  is the velocity of the moving target,  $\theta$  is the angle between the optical axis and the direction of the velocity of the moving object, and  $\lambda$  is the wavelength of the laser. The fluctuations  $\Delta P$  of the radiation pressure inside the cavity under self mixing conditions can be written as [13]:

$$\Delta P \propto \cos(2\pi\nu_D t)$$

and the photoacoustic signal  $S$  can be given by [12]:

$$S = C \alpha \Delta P$$

where  $C$  is the cavity constant,  $\alpha$  is the absorption coefficient.

In order to examine our experimental configuration along with its possibilities, the photoacoustic signal  $S$  as a function of the angle  $\theta$  and the target velocity  $\nu$  was measured.

## III. EXPERIMENT

The block diagram of the experimental arrangement is mainly based on the design described in Refs. 4. Figure 1 shows the outline of the present experiment. The laser used in this work was an air-cooled gas circulation type RF excited CO<sub>2</sub> laser. The laser cavity total length was 690 mm, composed of a 10-m radius of curvature gold coated total reflector and a flat ZnSe

partial reflector. Reflectivity of the output mirror was 70%. It was supplied with a 1:1:3 mixture of  $\text{CO}_2:\text{N}_2:\text{He}$  gas and typically operated at 30 torr of gas pressure. The electrodes of the RF discharge tube were made of aluminum and had a width of 5 mm and a length of 300 mm. The RF discharge tube is sealed at both ends with ZnSe Brewster windows. The output power and frequency of the RF generator were respectively, 90 W and 83 MHz. The  $\pi$ -matching circuit produced an impedance match between the RF generator and laser cavity, thereby minimizing a reflection of RF power. This laser oscillates in the fundamental transverse mode and in a single longitudinal mode at 10.59  $\mu\text{m}$  P(20) line. The maximum output power of 2 W corresponds to efficiency near 15 percent. The relative high efficiency of  $\text{CO}_2$  lasers enhances the photoacoustic effect.

A 25 mm focal length ZnSe lens is used to focus the laser beam onto a diffuse rotating wheel which was made of aluminum with 40 mm diameter and 10 mm thickness. We attached the wheel to a blade of an optical chopper (SR540). Altering the voltage of the dc motor changes the rotating velocity of the wheel. A photo interrupter is installed on the optical chopper side and a thin blade interrupter is attached to one side of the wheel to calibrate its rotating velocity. A photo interrupter generates one pulse per revolution of the wheel.

A commercial condenser microphone combined with a field-effect-transistor preamplifier is inserted in the laser resonator, which is located at the far end of the RF discharge electrode to protect the microphone from a high intensity RF discharge. The microphone signal is directly processed by a dynamic signal analyzer (SR785). A capacitor was used to couple the microphone signal with a dynamic signal analyzer while blocking the dc bias component of the microphone. Figure 3 is a typical example of Doppler signal obtained by the photoacoustic detection method; 15.1 kHz is the Doppler. The Doppler signal bandwidth is wider than that of the switching noise produced by the power supply. Such a

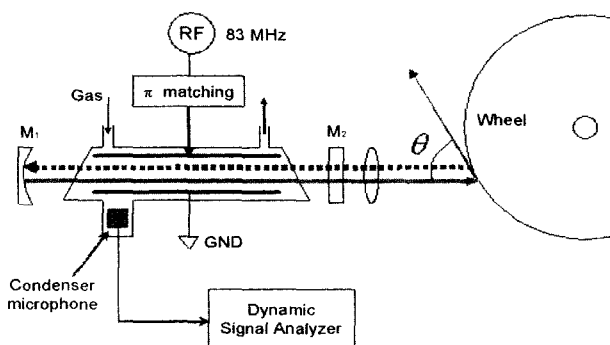


FIG. 2. Experimental setup for the self-mixing type laser Doppler velocimeter using photoacoustic effect. (Solid line: output beam of laser, Dashed line: a part of scattered light from the surface of the wheel,  $M_1$ : Si total mirror,  $M_2$ : ZnSe partial mirror)

phenomenon can be caused by many reasons including vibrations of the rotation wheel surface and laser speckle. It can be considered to be a Doppler signal bandwidth spread caused by subtle effects on the surface of the target and inside the laser resonator [13]. The spread of the Doppler signal bandwidth negatively affects the precision and uncertainty of the measurement.

The Doppler-shifted frequency  $f_D$  was observed by changing the rotating velocity  $v$  of the wheel and/or the angle  $\theta$  between the direction of the laser beam and that of the rotating velocity. The scattered light on the surface of the wheel is Doppler frequency shifted. The light then reenters the laser resonator and mixed with original light, which is called a self-mixed effect. A laser light strength within the resonator is modulated to difference frequencies of the original light and the scattered light by self mixing. Modulation of light in the resonator caused a change of pressure inside the resonator, whereby a photoacoustic signal varying in response to the laser light strength is generated. When the frequency of photoacoustic signal is measured, the Doppler shifted frequency can be measured.

A relationship between the Doppler frequency and the rotating velocity is plotted in Fig. 4 for the detection of the photoacoustic signal. Due to the mechanical limits of the wheel, the rotating velocity was not constant for low velocity. In order to reduce the measurement error caused by the unstable rotating velocity of the wheel, we employed an averaging function in SR785 to obtain the average value of ten samples. It can be seen that there is a good linear relationship between two variables. A low signal to noise ratio at higher velocity is caused by the attenuation of signal for higher frequencies ( $\sim 50$  kHz). It was found that a photoacoustic signal from 0 kHz to 50 kHz is proportional to the velocity of the wheel.

The maximum measurable frequency is expected to be several MHz, because the photo acoustic signal from

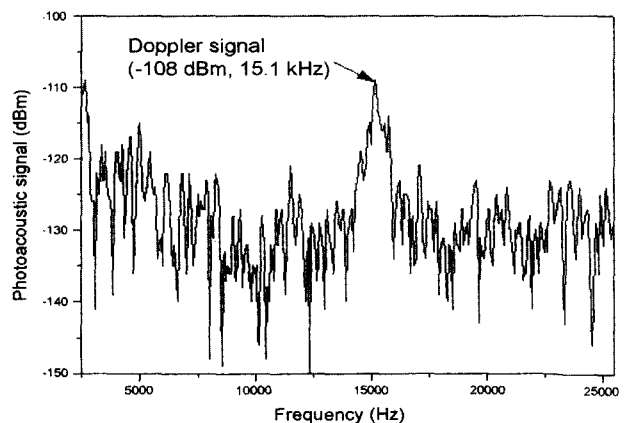


FIG. 3. Typical example of a photoacoustic signal obtained from the condenser microphone in the laser resonator. A fluctuating amplitude and phase of the scattered light made a broadening of the peak at the Doppler frequency.

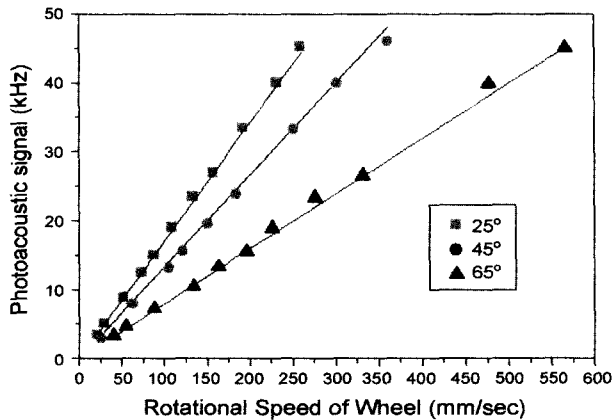


FIG. 4. Measured Doppler frequency as a function of the object velocity component. The solid line was calculated from Eq. (7).

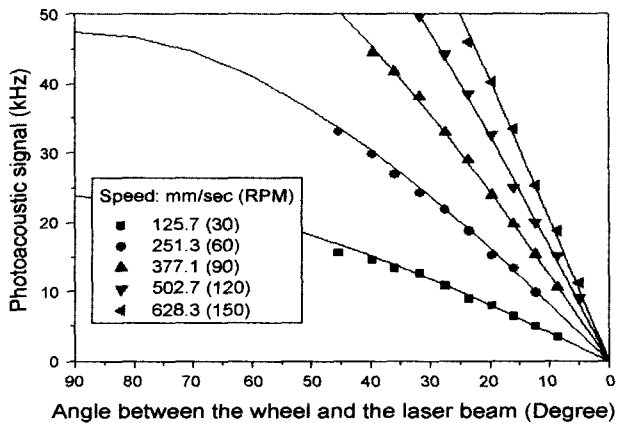


FIG. 5. Measured Doppler frequency as a function of the angle between the light beam direction and the velocity of the object. The line was calculated from Eq. (7).

laser gas is in the range of  $\tau_{th} \gg 1/f \gg \tau_{nr}$ . Here,  $\tau_{th}$  is the thermal relaxation time and  $\tau_{nr}$  is the nonradiative lifetime of the excited energy state of the molecule. While  $\tau_{th}$  is on the order of seconds,  $\tau_{nr}$  is typically  $10^{-6} \sim 10^{-9}$  s [13,14]. But we measured a maximum photoacoustic signal of 50 kHz, because we used a commercial condenser microphone which has a maximum 20 kHz bandwidth.

We also verified that the frequency depends linearly on the cosine of the angle  $\theta$  between the velocity and the light beam. For a definite value of  $v$ , the change of frequency with respect to  $\cos \theta$  is examined. The relationship observed between frequency range and  $\cos \theta$  is in good agreement with Eq. (7) for experimental values of  $v = 251$  mm/s and  $\lambda = 10.59$   $\mu$ m.

#### IV. CONCLUSION

We have demonstrated a CO<sub>2</sub> laser Doppler velocimeter, which is based on the photoacoustic effect. In comparison with other optical methods, such as using

liquid nitrogen cooled MCT detectors to detect the Doppler-shifted frequency, the arrangement of the system is compact enough for many applications. A Doppler-shifted frequency as high as 50 kHz was detected using this method, and a good linear relationship between the Doppler velocity and the Doppler-shifted frequency was obtained. This can be used to determine the velocity of a moving object, and it can be applied to measure frequency variation without using liquid a nitrogen cooled MCT detector.

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[3] A. A. Rhee and B. B. Kim, "Fiber lasers", *Opt. Lett.* Vol. 33, no. 2, pp. 11-22, 2000.  
[4] W. H. Louisell, *Quantum Optics*, R. J. Gluber ed., (Academic, New York, 1969) pp. 680-742.
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