Optics and Lasers in Engineering 111 (2018) 93–97

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

Estimation of the average velocity of a fluid by means of a single modulated beam

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A R T I C L E I N F O

Keywords:
Average fluid velocity
Flow velocity
Modulated photoconductivity
LDA

A B S T R A C T

We propose an optical method to estimate the average velocity of a liquid fluid circulating through a square pipe with transparent walls. The velocity is obtained from the photovoltage data measured in a semiconductor crystal when is illuminated with a single intensity modulated laser beam, transmitted through the pipe in a perpendicular direction of the moving fluid. Experimental results considering parameters as wavelength, modulation frequency, particles concentration and fluid speed were obtained, and a comparative statistical analysis considering additional measurements obtained by Laser Doppler Anemometry (LDA) as a reference, was performed too.

1. Introduction

In recent years, the applications of optical methods in physical or engineering topics of interest like flow velocity measurement [1,2] have been increasing, because of their non-intrusive and remote speed sensing features. Among these methods, Laser Doppler Anemometry (LDA) is perhaps the most mature of all because of its typically 2% accuracy as it is based on the Doppler frequency shift between two incoming and reflected test beams [3]. Other alternatives for flow measurement or related aspects include Doppler tomography [4], rotational Doppler effect [5], particle image velocimetry [6,7] or adaptive photodetectors [8]; a comprehensive review can be found in [9]. Most of these techniques provide "instant" measurement of velocity of particles moving with the fluid, which is required for in-deep research purposes. However, many applications in engineering need no more than average velocity or average flow rate over a period. The simplicity of this demand must be linked with a simplicity of the apparatus as well in order to get a suitable balance between cost and benefit.

For these reasons, we propose to consider other alternatives when a basic parameter, like average velocity of a liquid flow, is to be accomplished. The modulated photoconductivity is an experimental technique commonly used in photoconductors with one dominating type of carrier [10,11]. When a sample material is illuminated with a spatially uniform, frequency-modulated light intensity of a light beam:

$$I(t) = I_0(1 + m\, cos 2\pi f t) \tag{1}$$

the ac photo-excitation in the material generates an ac photocurrent with a phase shift between them. An analysis of this phase-shift, as a function of the modulation frequency f of the light, determines the energetic distribution of states in the bandgap of the photoconductor [12]. The modulated photocurrent flows through the sample and can be detected as an ac output photo-voltage; when the sample is not illuminated, photocurrent is proportional to its dark conductivity (σ_0), and under illumination, is proportional to $\sigma_0 + \Delta\sigma_{ph}$. Then, the detected photo-signal will be proportional to the photoconductivity of the material, given by:

$$\Delta\sigma_{ph} = \frac{\sigma_0}{1 + i2\pi f \tau} \tag{2}$$

where τ is the lifetime of the dominating carrier. Under certain cutoff frequency f_c the photocurrent remains approximately constant, but for frequency regimes higher than f_c, the photo-signal tends to decay inversely with respect to f.

Here we present a novel method to estimate the average velocity v on a fluid flow, based on the modulated photoconductivity response of a semiconductor. Required instrumentation for this method is simpler as compared with previous proposals since it requires only one laser beam and few components as it is explained below.

2. Materials and methods

In this section, we describe the experimental setup used for observation of modulated photoconductivity (Fig. 1). A laser beam is directed towards an n-doped Gallium Arsenide (GaAs) semiconductor sample to photo-excite it. A mechanical chopper, model SR540 by Stanford Research Systems, operation range 4 Hz–3.7 kHz and drift < 2%, was placed in between to introduce a modulation frequency f. The laser

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https://doi.org/10.1016/j.optlaseng.2018.07.001
Received 19 March 2018; Received in revised form 28 June 2018; Accepted 2 July 2018

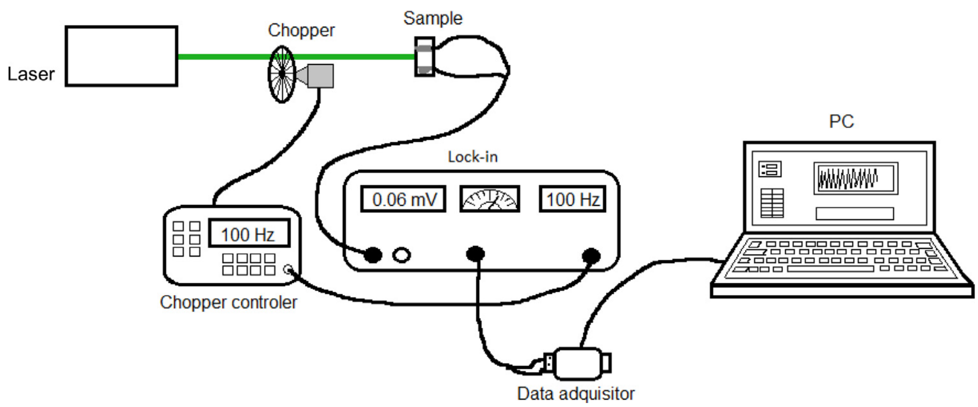

Fig. 1. Experimental setup for the observation of modulated photoconductivity.

beam illuminates the GaAs sample, which is coated with silver-paint electrodes; these are connected to a Lock-in amplifier, model SR830 DSP by Stanford Research Systems, gain accuracy ± 2% for a scale sensitivity 2 nV-1 V, where also converges an electrical reference generated by the chopper driver. Both frequencies, the reference and the one in the laser, are the same. For higher frequency range up to 10 kHz, an electro-optical modulator configured for intensity modulation and driven by an internal reference frequency from the Lock-in, was used instead of the chopper. The main electric signal of voltage drop through the electrodes, generated by photoconductivity of the sample, is amplified by means of a Fourier filtering procedure with assistance of the reference signal. As the Lock-in device performs as a bandpass filter with great factor of merit, it amplifies only a specific component modulated around f, from all incoming noise-embedded photo-signals [13]. The output signal is connect to a PC through a data acquisition board that has been set up at 1000/s sampling data rate. Therefore, photo-voltage data (V_{out} on subsequent graphics) are stored for further analysis.

A set of laser sources were tested to find out the adequate one, in terms of signal photo-voltage V_{out}, as observed in Table 1.

Afterwards, the method was applied for measuring the average velocity $\bar{v}$ of a fluid moving in a pipe of square cross section, with the hypothesis that photo-voltage varies according to the velocity of moving fluid. Thus, experimental setup was modified by introducing a close system of water circulation provided with a test section, represented by the pipe of square cross section and transparent walls, as shown in Fig. 2.

Table 1
Tested lasers used as illumination source.

Test	Laser source	Wavelength nm	Power mW	Chopper Frequency Hz
1	He-Ne	633	30	100
2	Ar^{+}Ion	532	50	100
3	Ar^{+}Ion	442	8	100

The laser beam illuminates at a certain point in the pipe centerline where tap water flows at different condition of average velocity. Immediately the beam light passes across the pipe, its frequency is modulated with the chopper at $f = 100$ Hz and afterwards it illuminates the GaAs crystal. The rest of the elements in Fig. 2 manage the output photo-voltage to be Lock-in amplified and finally the signal data are stored at the PC.

3. Results

3.1. Characterization with no fluid

Fig. 3 shows the results of system characterization, which allowed to choose the condition that best suits for this application. The plot in this figure indicates that GaAs photo-voltage V_{out} depends basically on the modulation frequency f and wavelength λ. As can be seen, when the system was tested at $\lambda = 532$ nm and in the 100–1000 Hz range, a

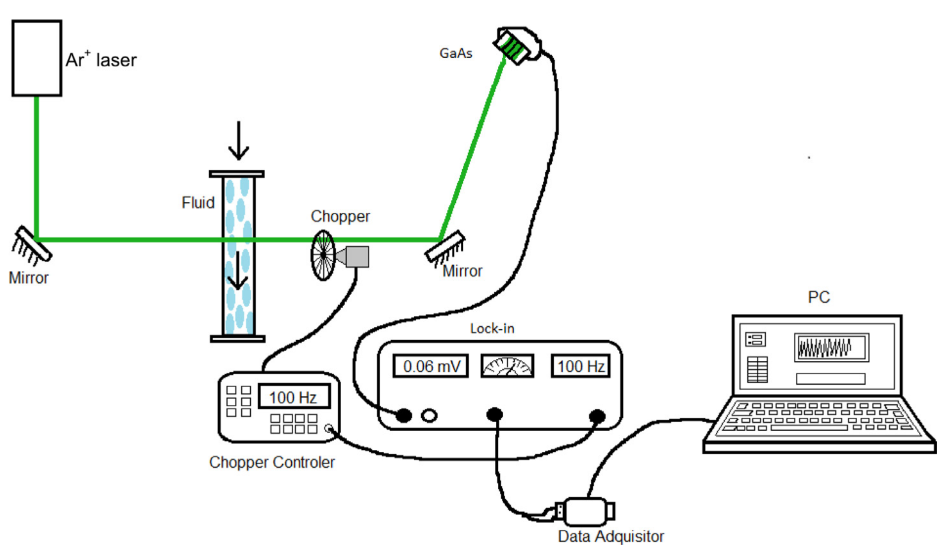

Fig. 2. Experimental setup for the study of average fluid velocity.