Temperature Measurement and Mechanical Mapping using Brillouin Scattering

Temperaturmessung und mechanische Kartierung mittels Brillouin-Streuung

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Transient Grating Spectroscopy (TGS), Measurement of Sound Velocity
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Abstract

In experimental fluid mechanics, the measurement of the Doppler frequency for the investigation of flow velocities is mature. In this contribution, we demonstrate that Doppler-based measurements are also beneficial for the study of temperature of fluids. The Brillouin scattering technique used, is based on an interaction of optical waves (photons) with acoustic waves (acoustic phonons). The Brillouin measurement instruments enable an unique investigation of combustion processes and also the mechanical properties of cells and tissues in biomedicine.

Zusammenfassung

In der experimentellen Strömungsmechanik ist die Messung der Doppler-Frequenz für die Erfassung von Strömungsgeschwindigkeiten eine Standardmethode. In diesem Beitrag zeigen wir, dass Doppler-Messungen der Schallgeschwindigkeit sich für die Erfassung der Temperatur von Fluiden eignen. Genutzt wird Brillouin-Streuung, die auf einer Wechselwirkung optischer Wellen (Photonen) mit akustischen Wellen (akustische Phononen) beruht. Die Brillouin-Messtechnik eignet sich die Untersuchung von Verbrennungsströmungen als auch der mechanischen Eigenschaften von Zellen und Geweben in der Biomedizin.

Introduction

Random variations in local density lead to inelastic scattering of light. This Brillouin scattering effect is based on the destruction and generation of a phase-matched sound wave (acoustic phonons) and results in an optical Doppler frequency shift compared to the incident light wave. Quantum mechanics describes this relationship with the law of conservation of energy for a photon-phonon interaction. An incident photon of the frequency f_L is scattered by destruction or generation of a phonon with the frequency f_S into a photon with the frequency $f_B = f_L \pm f_S$ (anti-Stokes and Stokes scattering). For an isotropic material and a monochromatic laser wave, the Brillouin frequency shift is $f = f_B - f_L = \pm 2\, n\, V_A \cos(\theta/2) / \lambda$, with the refractive index

n, the sound velocity V_A, the scattering angle θ between the laser wave and the Brillouin light wave and the laser wavelength λ [1]. For a backscatter arrangement in a confocal microscope, the mean value is the scattering angle of $\theta \approx 0°$. For this, the following resonance condition of light waves (photons) and ultrasonic waves (acoustic phonons) is present: an integer multiple of the light wavelength equal to twice the wavelength of the ultrasound (Bragg diffraction). Using a monochromatic lightwave, this resonance condition allows the acquisition of mechanical information. With the assumption of a longitudinal sound wave with the velocity $V_A = \sqrt{(E/\rho)}$, the modulus of elasticity E and the density ρ it yields [1]:

$$f = \pm\, 2\, n \sqrt{E} \,/\, (\lambda \sqrt{\rho}). \qquad (1)$$

A correlation between the refractive index n and the density ρ of the sample can be derived with Lorentz-Lorenz equation. The equation expresses the refractive index as a function of the polarizability α and the number N of molecules per unit volume: $n^2 \approx 1 + 4\, \pi\, N\, \alpha$. Here N is a proportional variable to the density, whereby the dependencies $n / \sqrt{\rho}$, see Eq. (1), partially compensate. The Brillouin frequency shift is only dependent on the mechanical properties of the sample, the density and elasticity. In addition to these measurement variables, the temperature of a fluid can be determined using calibration methods [2, 3].

Spontaneous Brillouin Scattering

The Brillouin microscopy has many advantageous properties, such as non-contact and label-free measurements. Especially, it provides three-dimensional measurements of the elasticity, meaning studies can be accomplished in the volume of the sample. In addition, in vivo measurements are possible. Consequently, there is a great interest in this measurement technique. However, there are several challenges. First, the frequency shift of inelastic Brillouin scattering is very small compared to the frequency of the laser. Second, biological turbid samples have a large background signal from elastic Rayleigh and Mie scattering. Third, the scattering cross section of the spontaneous scattering is very small, so that even at high laser powers relatively long averaging times are necessary. The first challenge can be mastered with a beat experiment, in which the laser wave interferes with the Brillouin wave on a photodetector. However, the inclusion of the second challenge, namely the separation of the inelastic Brillouin scattering from the elastic Rayleigh scattering, leads to a different measurement method. Multi-beam interference of a Fabry–Pérot interferometer (FPI) enables a high spectral selection. A Virtually Imaged Phase Arrays (VIPA) is a modified FPI with three different coatings, to enhance the light efficiency. Furthermore, a VIPA has an adjustable dispersion so that high-resolution single-shot camera-based measurements can be accomplished. Together with a confocal microscope Brillouin measurements of tissues and cells with subcellular resolution and with only one optical access are possible. With these measuring properties, there is a great potential for the Brillouin microscopy for biomedicine. However, one problem is the low cross section of spontaneous Brillouin scattering. For a laser power in the measurement volume of about 15 mW, the measurement time per pixel is about 0.5 seconds for a sufficient signal-to-noise ratio (SNR) [4, 5]. Therefore, long measurement times are required for imaging. In the following section, we present a promising approach to increasing the speed of measurements.

Stimulated Brillouin Scattering

Compared to spontaneous scattering, a significantly higher cross section can be achieved by stimulation. Stimulated Brillouin scattering can be treated with a general theoretical model of light scattering as inhomogeneous thermodynamic variation, which is mainly caused by pressure fluctuations. Stimulated Brillouin scattering [6-9] has already been used with a pump-probe arrangement for the Brillouin measurement of mechanical properties [10-16].

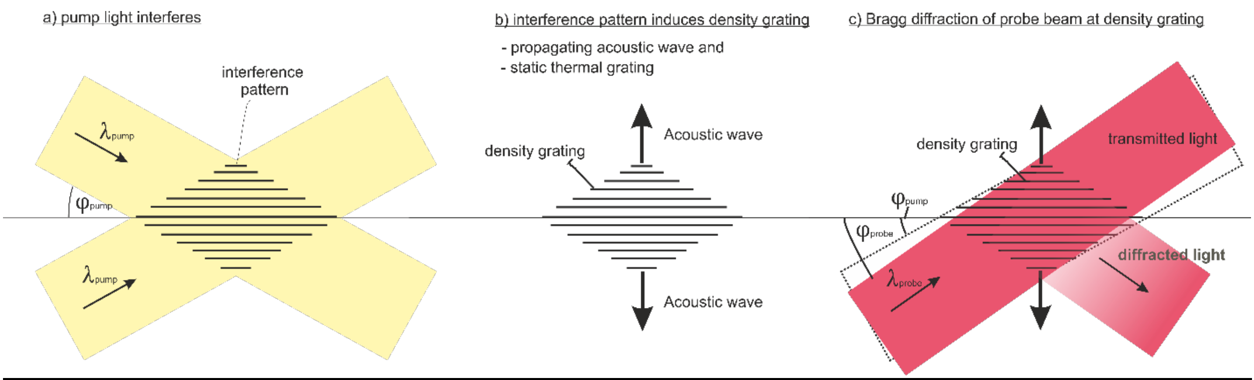

Figure 1: Principle of impulsive stimulated Brillouin scattering. Left (a): generation of an interference fringe system with two coherent pulses of a pump laser, center (b): generation of a density grating by means of electrostriction or thermic effects. Right (c): Bragg diffraction of the probe laser beam at the three-dimensional refractive index grating (dynamic holography).

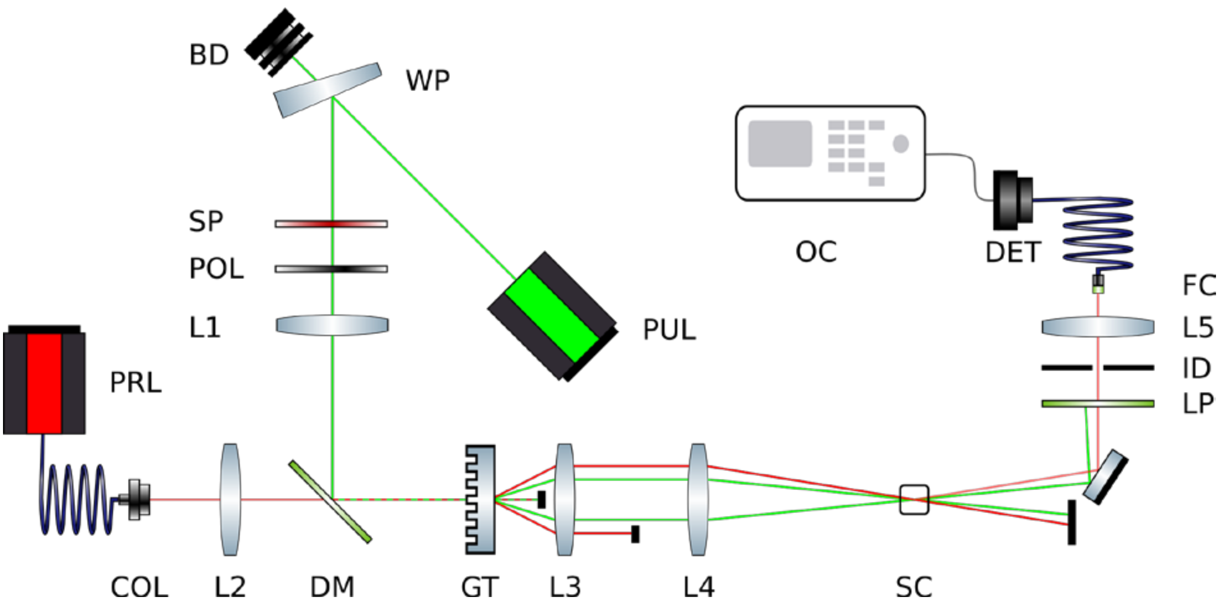

Figure 2. Measurement system using impulsive stimulated Brillouin scattering. PUL - pulsed laser; PRL - probe laser (cw); BD - beam dump; WP - wedge prism; SP - shortpass; POL - polarizer; L1 to L5 - lenses (achromatic doublets); COL - collimator with fiber coupling; DM - dichroic mirror (longpass); GT - grating, LP - longpass; ID - Iris Diaphragms; FC - fiber coupling with longpass; DET - detector; OC – oscilloscope; SC - specimen

The impulsive stimulated Brillouin scattering benefits from the use of high-power laser pulses. The pulsed laser beam is split into two coherent beams, using a Mach-Zehnder interferometer setup. The superposition of the coherent laser beams leads to the formation of an interference fringe system, which generates a density grating with the fringe spacing *d*. Counterpropagating acoustic waves (acoustic phonons) are generated in the measurement volume which lead to refractive index waves, see Fig. 1. A cw-laser probes the running refractive index gratings by Bragg diffraction, resulting in Doppler-frequency shifts. An amplitude modulated beam of twice the Doppler frequency results: $f_M = 2\ V_A / d$. This optical signal is converted into an electrical signal by a photo detector, see Fig. 2.

Measurement Results

Different fluids were measured using the impulsive stimulative Brillouin scattering. A Q-switch laser with a pulse duration of about 10 ns generates the transient density pattern, which propagates at the sound velocity, resulting in a Doppler signal. The Fig. 3 shows the time signal and Fourier spectra of acetone. The mean Doppler frequency is 178 MHz, corresponding to a sound velocity of 1187 m/s. Fig. 4 shows the analog results for methanol. The mean Doppler frequency is 168 MHz, which results in a sound velocity of 1116 m/s.

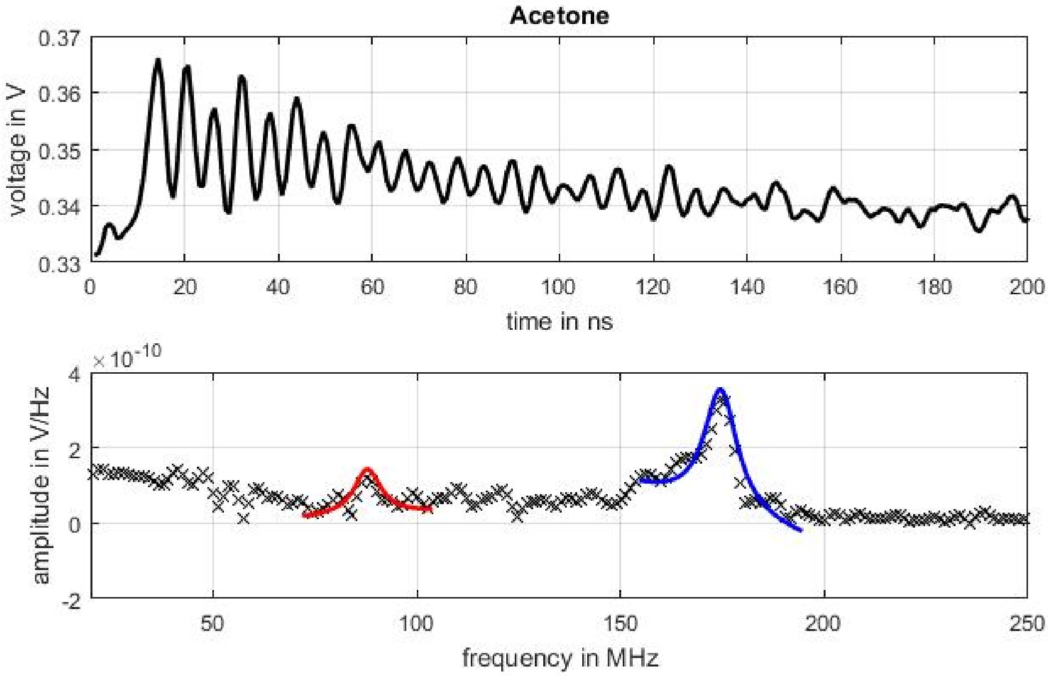

Fig. 3. Brillouin measurement of acetone, C_3H_6O. Top: Time signal. Bottom: Fourier spectrum (red regression line: single Doppler frequency, blue regression line: double Doppler frequency)

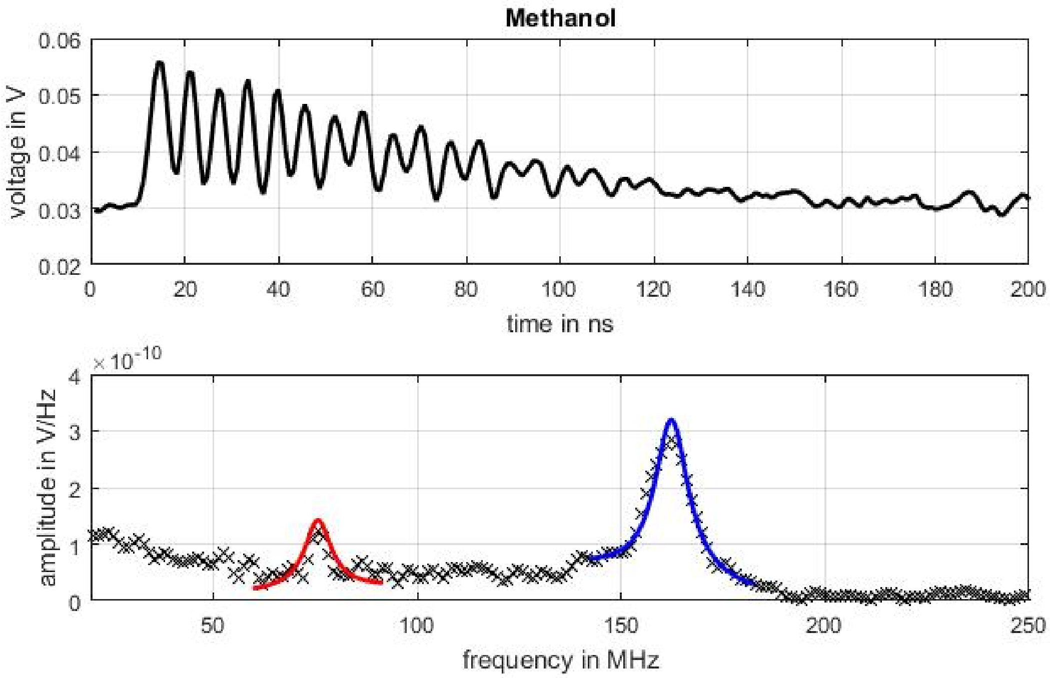

Fig. 4. Brillouin measurement of methanol (methyl alcohol, CH_3OH). Top: Time signal. Bottom: Fourier spectrum (red regression line: single Doppler frequency, blue regression line: double Doppler frequency)

Conclusion

The stimulated Brillouin scattering benefits from the use of high-energy laser pulses. The superposition of two coherent laser beams leads to the formation of an interference fringe system, which generates a density grating. Counterpropagating acoustic waves are propagating in the measurement volume, where a cw-laser beam is probing the information on the sound velocity. The technique enables to measure the temperature of fluids as well as to map the elasticity of tissues and cells. Promising fields of application are fluid mechanics and microfluidics [17-24] as well as flow cytometry [25, 26].

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