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Doppler tomography of mass-transfer processes in condensed media induced by femtosecond laser pulses

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Abstract. **A femtosecond laser scheme for studying laser-induced mass transfer is proposed. A Doppler velocity meter using a femtosecond Ti: sapphire laser is created. A thermal capillary convection initiated by this laser in paraffin is investigated (with a spatial resolution of 15 μm).**

Keywords: *femtosecond laser, doppler velocity meter, laser-induced mass transfer*.

The progress achieved recently in the development of femtosecond lasers with a high average power (in excess of 10 W) opened up new ways for studying the physics of interaction of high-power laser radiation with matter and numerous applications related to high-precision material processing. Mass transfer arising under these conditions can be monitored by means of laser Doppler anemometry using a back-scattered signal.

In the case when a mode-locked laser is employed in a monostatic Doppler velocity meter, the localisation of the volume of measurements is determined, as shown in [1], by the spatial width of a light pulse. When a femtosecond laser is used, the longitudinal size of the volume of measurements may reach several micrometers, which makes it possible to extract the information concerning the distribution of flow velocities within sufficiently small spatial scales (fractions of a millimetre).

The purpose of this work is the creation of a velocity meter based on a femtosecond laser and the application of this device for the investigation of mass transfer in a melted bath using a scheme with a single laser source, similar to the approach implemented in our paper [2] with the use of a continuous-wave CO_2 laser [2]. A specific feature of this scheme is that it combines excitation and probing functions and ensures a high spatial resolution ($\sim$ 10 μm). Paraffin was chosen as an object of our studies because, first, it has a sufficiently low threshold of melting and, second, the results for these material can be compared with the data obtained using other experimental schemes [3].

Our experimental setup was based on a Michelson interferometer. One of the mirrors of this interferometer was placed on a micrometric translation stage, which allowed us to vary the delay of the scattered component of probing laser radiation with respect to reference radiation. A 'power-producing' beam passed through a lens and was focused onto an object, which played the role of the second mirror in the Michelson interferometer. The reference and signal beams were brought in a spatial coincidence behind a beam splitter, and a heterodyne signal at the Doppler frequency ω_D was selected with a photodetector. The amplitude of this signal depends on the delay time τ of the reference radiation pulse with respect to the signal pulse: $i(t,\tau) \sim |B(\tau)|\cos(\omega_D t + \varphi)$, where $B(\tau)$ is the correlation function of the field [1].

We used in our experiments a 0.8-μm Ti: sapphire laser with an average output power up to 150 mW, a pulse duration of 100 fs, and a pulse repetition rate of 100 MHz. The intensity of radiation focused on a target by a lens with $f = 4$ cm was $\sim$ 10 kW cm^{-2}. Liquid paraffin was preliminarily mixed with soot, which ensured efficient absorption of laser radiation. Thermal capillary convective flows were induced in a bath with a paraffin melt under these conditions. The output signal of the photodetector was fed to an S4-74 analogue spectrum analyser, which was attached to a computer for a standard data-processing procedure [2].

First, we determined the longitudinal size of the measurement volume, which was equal to 15 μm. For these measurements, we employed a technique similar to low-coherence tomography, when one of the interferometer arms is modulated with a low frequency and an amplitude $\sim \lambda$. A metal foil was placed in the focus of the lens as an object. The longitudinal size of the volume of measurements was determined from the change in the amplitude of the output signal of the photodetector in response to a change in the length of the other interferometer arm. We observed no increase in the measurement volume in the case of scattering from the bulk of paraffin (a 0.5-mm-thick paraffin layer was applied to the foil in these measurements). Such an increase could occur, for example, due to a strong dispersion or multiple scattering.

Fig. 1 compares the averaged spectra of scattered radiation corresponding to the melting of paraffin with a laser operating in the continuous-wave and mode-locked regimes. In the former case, the spectrum is diffuse, displaying no well-pronounced Doppler-shifted component. This is due to large sizes of the volume of measurements and a predominant contribution of surface to scattering. In the latter case, we observe a well-pronounced Doppler-shifted component, which arises due to the scattering of radiation

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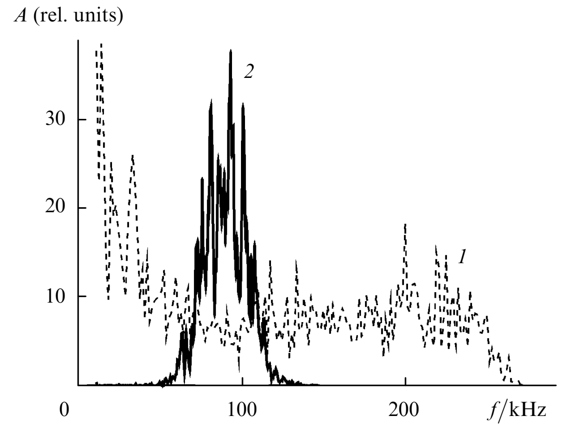

Figure 1. Spectra of the Doppler signal of backward scattering in a convective flow paraffin melted bath induced Ti:sapphire laser in a the continuous-wave regime (*1*) and the mode-locked regime (scattering from the distance $z \sim 100$ μm in the bulk of the melted bath) (*2*).

by a convective flow in the bath with melt ensuring the mass transfer. As the volume of measurements is displaced along the vertical coordinate, the Doppler component is shifted and its amplitude changes due to the change in the delay of the reference arm of the interferometer.

Fig. 2 displays the average power of scattered radiation (the area of the spectrum) and the convection rate ($V = \lambda f_D/2n_0$, where f_D is the gravity centre of the spectrum and $n_0 \approx 1.5$ is the refractive index of paraffin) as functions of the depth z ($z = \Delta l/n_0$, where Δl is the difference of optical path lengths of the reference and probing beams). No signal is observed when the reference and signal pulses are mismatched in time. When the volume of measurements coin-cides with the surface of melted paraffin, the power of the signal first steeply increases and then smoothly decreases as the measurement volume is displaced toward the inside of the melted bath. The minimum rate is observed when the volume of measurements lies on the surface of the melted bath. The spectrum is localised around zero, displaying no well-pronounced shifted component.

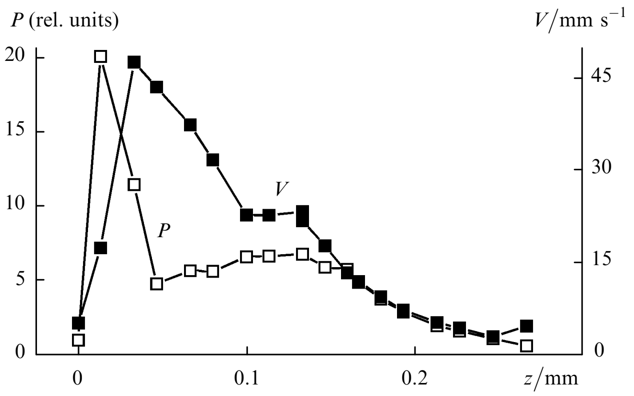

Figure 2. Power P of scattered radiation and the convective flow velocity V as functions of the position of the measurement volume in a melted bath.

The spectrum becomes qualitatively different at the depth of 15 – 20 μm, where it features a well-pronounced Doppler component. The rate under these conditions increases up to 5 cm s^{-1}. As the depth of the volume of measurements increases further, the rate monotonically decreases. Apparently, the last point in the plot corresponds to the boundary of the melted bath. These results agree well with model predictions concerning the formation of convective flows in a melted bath [3, 4].

Note that, when a material melts under the action of laser radiation, the laser-irradiated area is characterised either by surface deformation (regime of near-surface melting) or by the formation of a deep narrow channel (regime of dagger melting). The approach proposed in this paper not only allows the distribution of convective flow rates to be measured with a high resolution, but also permits the ablation rate and the depth of the hole produced in the target to be determined.

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