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Frequency domain and wavelet analysis of the laser-induced plasma shock waves☆

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ABSTRACT

In addition to optical emission, another trace of interest that laser-induced plasma provides is a form of acoustic feedback. The acoustic emission (AE) signals were obtained using both microphone and piezo transducers. This kind of optoacoustic signals have some distinct features resembling the short, burst-like sounds, that may differ significantly depending mainly on the sample exposed and irradiance applied. Experiments were performed on atmospheric pressure by irradiating various metallic samples. The recorded waveforms were examined and numerically processed. Single-shot acoustical spectra have shown significant potential of providing valuable supplementary information regarding plasma propagation dynamics. Moreover, the general approach suggests the possibility of making the whole measurement system cost-effective and portable.

1. Introduction

Laser-induced plasma (LIP) formation mechanisms have been extensively studied ever since the invention of a pulsed laser source. The wealth of information stored in a tiny plasma can be extracted using different, though sometimes complementary techniques [1]. Atomic emission spectroscopy (AES) is certainly the most common tool for investigating LIP dynamics, electron number density, excitation temperature, ionic and neutral distributions *etc.* The whole area of research, shortly called LIBS (Laser Induced Breakdown Spectroscopy) is recognized as a promising method of determining elemental presence (and concentration) in the analytic sample (ie. alloys, powders, soils, aerosols). Bearing in mind the extreme application in an extraterrestrial environment [2,3], it becomes immediately clear that this technology is strongly *in situ* oriented. Possible drawbacks in terms of relatively large limits of detection, signal intensity fluctuations and matrix effects compared to the other sample-analysis techniques are in majority of cases, compensated with a haste data acquisition and analysis. Yet, more fundamental research should be done in these fields in order to make the technique mature enough.

The plasma acoustic emission has already been well recognized to be feasible for diagnosis [4]. The works of Laserna group [5,6] have demonstrated the usefulness of acquiring the acoustical spectra in providing supplementary data regarding LIP propagation dynamics. Moreover, the correlation between acoustic and optical emission signals provides alternative way of LIBS emission spectra normalization (internal standard) due to ablation fluctuations [7–9] and also for accounting matrix effects corrections [10]. The acoustical measurements were also well impaired with the laser-assisted, inductively coupled plasma atomic emission spectroscopy (LA-ICP-AES) [11,12]. The results of these and other similar investigations are summarized in an extensive review by Zorov et al. [13]. Besides, various techniques have been developed for the ablation process monitoring purpose [14,15]. All former applications were based on the fact that the amount of ablated material is proportional to the AE signal intensity. As the acoustic signal does not present a strong function of the sample geometry, this approach should not be limited strictly to laboratory conditions. Therefore, special attention should be attributed to plasma-transducer distance, laser irradiance levels and interference with other audible sources.

The laser-material interaction presents the first step in the formation of AE signal as it appears even at lower irradiance below and around the ablation threshold. When the sample is exposed to the short, low energy laser pulse, the transferred momentum induces the recoil momentum that causes the material to oscillate (photo-elastic effect). These oscillations result mainly with transverse waves. On the other hand, when higher irradiance is applied (above breakdown threshold) the ablated material is evaporated and ionized, resulting with the fast expanding plasma. The expansion velocity and plasma properties are dominantly influenced by laser energy [16] and the surrounding environment [17,18]. Essentially, that rapid expansion is responsible for creation of the shock wave which eventually turns into an ordinary acoustic wave. There are also studies dealing with shock wave formation [19] and propagation [20] in the ablative regime.

This work however, aims at providing insights on the alternative ways of observing phenomena in laser generated plasma and points

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out to the possibility of making the measurement system inexpensive, portable and suitable for accompanying LIBS, or in general, laser ablation diagnostics.

2. Experimental

Multiple samples were made from the high purity aluminum (Al), copper (Cu) and gold (Au) plates of the same dimensions. Each of them was polished, cleaned with ethanol and placed in compact chamber. The chamber itself is mounted on a *xy*–*z* translation stage. All measurements presented in this work were conducted in air at atmospheric pressure. Beside metallic samples, the air breakdown (without the sample, but at the same plasma location) stood as a reference. The mechanical vacuum pump was continuously employed to ensure a flowing regime. The schematic of the experimental setup is given in Fig. 1.

The Nd:YAG laser, EKSPLA NL 311 (wavelength 532 nm, pulse width 6 ns, repetition rate 1 Hz) was used together with a plano-convex lens of 100 mm focal length for sample ablation. The focal spot sizes were determined by means of a digital microscope. Measurements of the laser pulse energies were performed using a Coherent FieldMaxII TOP, coupled with pyroelectric sensor. Reflected laser light from the frontal chamber window was taken into consideration by measuring the pulse energy values behind the (removable) chamber front window. Therefore, the energies delivered to the samples were varied from 23 to 126 mJ, keeping the irradiance levels in the intermediate interval from $5 \cdot 10^8$ to $2 \cdot 10^{10}$ W/cm^2. Since the chamber was originally designed for the classical LIBS experiments, it contains two quartz side windows (3 mm thickness). The window cavities served as a holders for the pair of condenser microphones (Audio-Technica ATR3350), positioned approximately 30 mm away from the plasma source. These microphones were inserted into a stiff sponge side damper that tightly fits into cavities. The lavalierd type of microphone was chosen due to its small diaphragm, which is found to be much more suitable for capturing short length signals, especially from small sources. By varying the position of the microphones along the *z* axis (see Fig. 2), one may obtain a lot of information about anisotropy and gradients in acoustical response inside of the chamber. The captured AE signals were processed with ZOOM H6, 24-bit multichannel portable recorder capable of providing 96 kHz sampling rate. On the other hand, the direct coupling with the target material was achieved by placing the piezo diaphragm (Murata, 7BB-20-6 L0, resonant frequency 6 kHz) directly to the backside of the sample. Acquisition of piezo signals is performed with HAMEG HMO2024 oscilloscope without the need of a pre-amplifier. The influences of the possible undesirable mechanical vibrations were kept to minimum by placing an elastic insulator between sample holder and the diaphragm.

2.1. Calibration of the measurement system

Frequency response measurements of the experimental chamber were carried out in order to make a clear distinction of its eigenfrequency components contribution to the overall spectra. The pair of the small speakers (AKG K315) used as a sound source, was placed inside of the chamber to an approximate location of the plasma, while the position of the microphones remained the same as formerly mentioned. These speakers reproduced high quality waveform audio file (WAV) stereo signal (96 kHz, 24-bit) emitted from a ZOOM H1 portable recorder (player mode). Any other lossy data compression format such as MP3 (MPEG-2 Audio Layer III) would not be appropriate because of the high distortion effects, especially above 12 kHz. The artificial signal is generated as stereo PCM (Pulse-Code Modulation) WAV file, containing subsequent single-frequency components (tone generator with uniform frequency distribution in time interval τ). Dominant frequency $\nu(t)$ of the artificial signal was generated as:

$$\nu(t) = \nu_0 + d_\nu t; \tag{1}$$

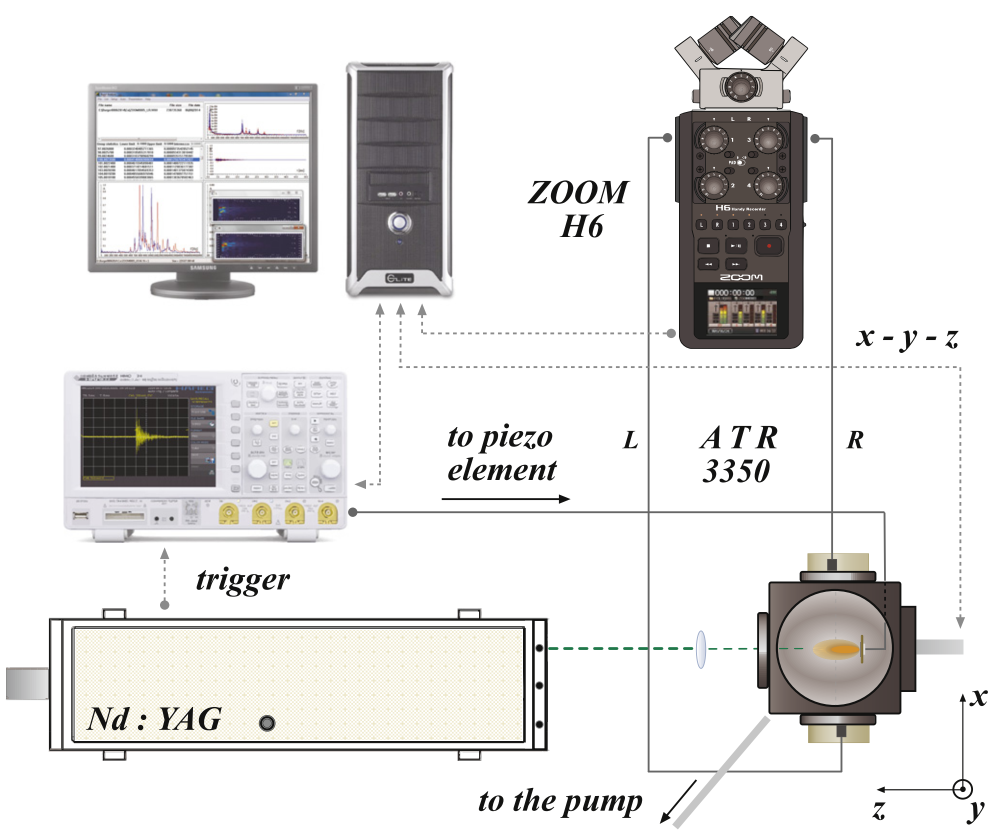

Fig. 1. The schematic of the experimental setup.