Acoustic Detection of laser-induced plasma emission by means of a fiber-Bragg grating sensor

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ABSTRACT:

Laser-induced breakdown spectroscopy (LIBS) is an analytical tool able to estimate the atomic composition of materials, without sample preparation and in a short time. One drawback of this technique is that the quantitative analysis is not as precise as other established methods, in part because of the pulse-to-pulse fluctuations of the energy delivered to the sample. These fluctuations can be compensated by monitoring the acoustic wave emitted by the plasma, which is related to the ablated mass. In this paper, we propose the use of a fiber-Bragg grating sensor to detect and measure the acoustic shockwave. A processing scheme is proposed to derive the acoustic energy from the sensor waveform. The experiments show that there is a correlation between the sensor's response and the laser pulse energy, so it can be used as a monitoring signal of the ablation process.

Key words: LIBS, FBG, laser induced plasma, acoustic wave.

1.- Introduction

Laser-induced breakdown spectroscopy (LIBS) is a powerful tool for the detection and characterization of materials in a quasi-non-destructive approach. It is based on the ablation of a tiny amount of material from the surface, using a focused beam from a pulsed laser [1]. The optical emission from the generated plasma is collected by a spectrometer, usually working in the visible range. The spectra are processed to identify and analyze the emission "peaks" of the different atomic species, from which the composition is estimated.

LIBS has been used for different applications, ranging from the identification of bacteria [2] to the remote analysis of the martian soil [3,4].

Some advantages of LIBS are that is a fast method, not requiring sample preparation, and it is able to detect small traces of elements within a material. However, for applications in which the quantitative measurement of the composition is needed, the attainable accuracy is not comparable to other methods, like X-ray fluorescence spectrometry (XRF). Among others, the matrix effects [5] and the pulse-to-pulse energy fluctuations [6] limit the capability of the LIBS method to perform precise quantitative analysis.

Several approaches have been suggested to improve the quantitative estimation of elements in samples. One of them is the measurement of the acoustic emission from the plasma, as an estimation of the overall energy delivered to the sample from each pulse.

It has been proved that the laser pulse produces a rapid vaporization of the material surface, and the expansion of the ablated vapor into the surrounding gas generates a compression wave that can be detected with an acoustic sensor. The intensity of the acoustic wave has proven to be linearly related to the amount of mass ablated in the sample by each laser pulse [7].

The acoustic emission is usually detected with standard microphones in the human acoustic detection range, allowing the measurement of the acoustic signal from distances up to several meters from the target [8].

In this paper, we propose the use of a fiber-Bragg grating (FBG) sensor, located in the proximity of the target material, to quantify the acoustic emission from the generated plasma. FBG acoustic sensors have been proposed as a sensitive and electromagnetic-immune alternative to standard electric transducers, as microphones [9] or hydrophones for SONAR applications [10]. In these sensors, the sound pressure is translated by the sensor structure to strain inside the optical fiber, which in turns modifies the Bragg wavelength of the grating. The shift in wavelength is tracked by an optoelectronic interrogation unit as a measurement of the induced strain, and thus of the acoustic wave.

In the following section, the experiments performed to capture the acoustic emission from the LIBS plasma using the FBG are described.

2.- Experimental setup and procedures

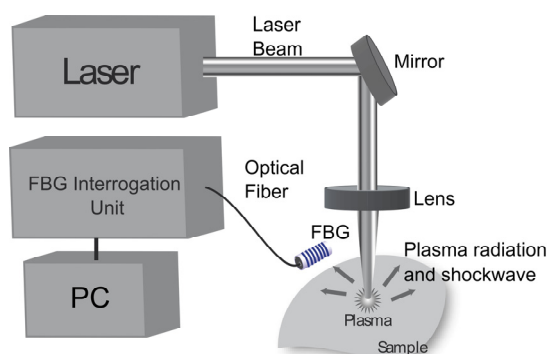A schematic view of the experimental setup is shown in Fig. 1.

Fig. 1: Experimental setup.

A Q-Switched Nd:YAG laser (LOTIS TII 1S-2147) emitting at 1064nm with pulse energy up to 0.9J and length of 16ns has been focused over a thick plate of brass (alloy of copper and zinc) that acts as the target material whose composition (zinc/copper ratio, or impurities concentration) is to be determined. The optical emission of the plasma is collected through a collimator by a silica multimode optical fiber connected to a CCD Spectrometer (model MS-260i with a Linespec linear CCD from ORIEL Instruments, adjusted for the 465-535nm range. Not shown in the figure).

At a distance of a few centimeters from the focus point is located the FBG acoustic sensor. The uniform Bragg grating has been created in the core of a standard singlemode fiber, with a Bragg wavelength of 1541.2nm. The bare fiber is embedded in a polymer foil with a surface of 25x15 mm^2, and clamped at two points. The mechanical structure created is expected to induce a strain on the FBG proportional to the received acoustic energy. An important parameter of the structure is its mechanical resonant frequency, which is 125Hz (experimentally measured).

The deviation of the Bragg wavelength of the FBG acoustic sensor in response to the shockwave has been dynamically recorded with a BraggMeter FS4200 FBG interrogation unit from FIBERSENSING, at a sample rate of 10KHz.

Due to the fact that the acoustic shockwave has high frequency components well above the resonant frequency of the FBG acoustic sensor, it is not easy to derive a measurement of the acoustic energy from the shape of the detected pulses [11]. This shape is closely dependent on the mechanical characteristics of the FBG sensor and its resonant frequency.

In order to derive a monitoring signal from the pulse waveform that can be linearly related to the acoustic energy, the following procedure has been devised: for each recorded pulse, that is, the strain-induced Bragg-wavelength shift, its mean value is first subtracted, and low-pass filtered to reduce the noise (Butterworth filter, order 15th, 0.1 normalized frequency); the difference between the upper and lower envelope of the pulse is then calculated, being the integral of this difference the estimation of the relative acoustic energy of the pulse (see Fig. 2).

Alternatively, the integration of the absolute value of the pulse waveform has been calculated as an alternative estimation.
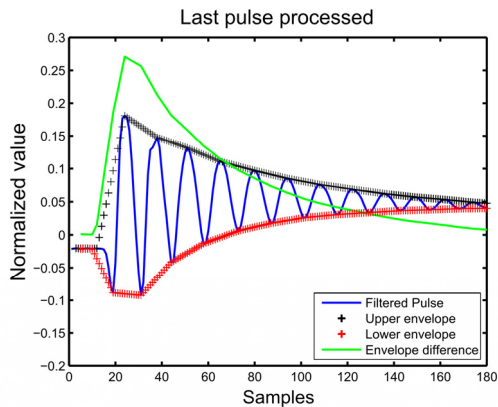

Fig. 2: *Signal processing of the detected acoustic wave.*

Fig. 3: *Response of the FBG acoustic sensor using two different processing schemes to estimate the relative acoustic energy (dots) and Laser pulse energy estimation (line).*

The experiments have been designed to acquire a sequence of laser pulses at a given pump energy. The energy of each pulse has been measured using a dichroic mirror and a Silicon photodiode (BPX65 from INFINEON Technologies). The time-resolved photocurrent of the photodiode has been integrated over the pulse length to obtain a relative estimation of the pulse optical energy. For a given laser pump flashlamp energy, a total of 24 pulses in sequence have been measured (both its energy through the photodiode and the acoustic energy through the FBG sensor) and averaged. It is expected that the plasma acoustic energy varies linearly with the laser energy, as the pulse-to-pulse fluctuations are averaged. If this is the case, the proposed FBG acoustic sensor could be used as an indicator of the laser energy effectively applied to the target material.

The next section shows the results obtained in the experiments.

3.- Results

A set of experiments has been performed by measuring with the above described procedure, both the laser pulse energy and the acoustic energy at different flashlamp energy settings, in the range from 32 to 48J. Fig. 3 shows the results. Each measurement point is from 24 consecutive averaged pulses.
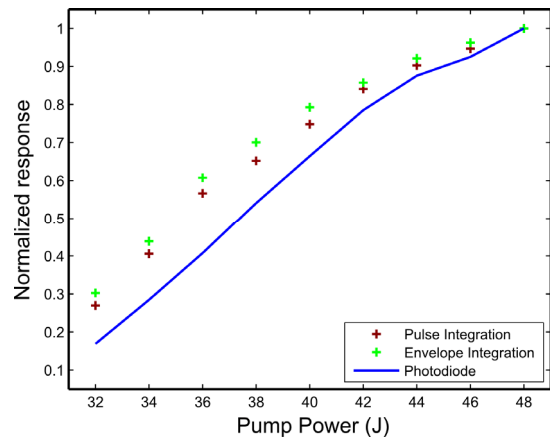
Firstly, it can be seen that the laser pulse energy estimation follows linearly to the laser flashlamp energy, as expected. The slight departure from linearity of the curve for pump energies above 44J can be attributed to the ionization of the air path, which increases the absorption of the laser radiation.

Secondly, it can be seen from Fig. 3 that both methods to estimate the plasma acoustic energy (using pulse and envelope integration of the Bragg-wavelength signal, respectively) give a similar value, with only a small offset between them. The saturation for large energies is more apparent in this case. This is an expected result because at such high energies, the air above the samples surface is heavily ionized, and the absorption of the laser beam is even increased by the ablated material [12].

In Fig. 4, the response of the FBG acoustic sensor is plotted against the photodiode response. In this case, the curve is fairly linear for both methods, thus allowing the use of those magnitudes as a monitoring signal of the laser-matter interaction.
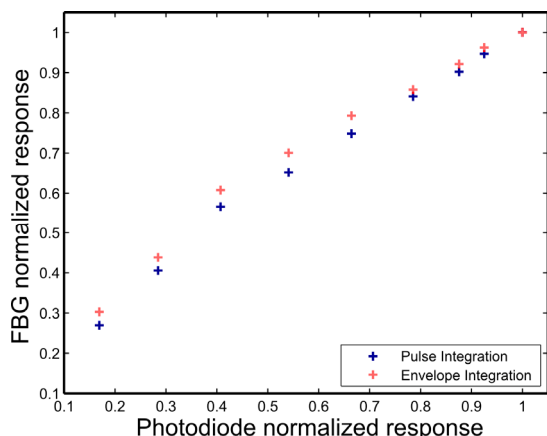
Fig. 4: Response of the FBG acoustic sensor against the measured laser pulse energy.

4.- Conclusions

In this paper, the use of an acoustic sensor based on a fiber-Bragg grating has been proposed to measure the acoustic shockwave produced by laser-induced plasmas. This can be very useful to correct the pulse-to-pulse variations of the laser energy delivered to the target material, thus increasing the accuracy of quantitative estimations of the material composition in LIBS applications. A processing scheme to derive, from the Bragg-wavelength shift of the sensor, the acoustic energy generated by the plasma, has been proposed. The experiments show that there is a linear relation between the detected acoustic signal and the laser pulse energy, thus confirming the feasibility of this kind of sensor. Future works are aimed at the improvement of the sensor's sensitivity to work at larger distances from the target, and the actual correction of each LIBS spectrum to improve the accuracy of quantitative estimations of the composition of the material.

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