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Research on acoustical properties of the femtosecond laser ablation targets using fiber optic sensing probe

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ABSTRACT

The acoustic signals of the laser micro plasma expansion for the femtosecond laser ablating pure Al, Cu and Fe target materials have been detected by the fiber Fabry–Perot (*F–P*) acoustic emission sensing probe. The frequency and amplitude of the acoustic emission spectrum have been analyzed. The results show that the detected acoustic emission frequency spectrum pattern is fixed and different for the three kinds of target materials. The amplitude of the acoustic emission spectrum grows up along with the enhancement of laser ablation energy. The amplitude of the acoustic emission spectrum decreases when the detection distance is enlarged. The developed measuring system provides a potential method aiming at the detection of solid materials based on the acoustic signals excided by femtosecond laser ablating target materials using the fiber *F–P* acoustic emission sensing probe.

1. Introduction

At present, some studies about photoacoustic spectroscopic detection technique focus on a component of gas or liquid [1–5]. The mechanism of the photoacoustic spectroscopic is that the gas or liquid molecules absorb the radiation heat and both the temperature and pressure increase when the light beam penetrates the sample cells, which produces a sound that could be measured by a capacitive microphone [6–8]. For solid matter, however, the light source radiation absorption is much different. For a solid material, the light beam cannot penetrate the sample. There are some difficulties for the measurement of solid material component using the photoacoustic spectroscopic. However, as laser irradiates a solid material surface, laser energy is absorbed by the lattice and results in localized heated vaporization and photoionization. During this process plasmas is formed, which lead to acoustic signal due to the interaction of the expansion laser plasma with the air. The acoustic signal could be exclusively linked to the intrinsic property of the solid material. Therefore, it could provide some information about component for a solid material. Based on this, a new method for solid materials detection could be developed using the detection of the acoustic signal of the expansion laser plasma with the air.

Traditional light sources have a common shortcoming that their pulse widths reach nanosecond range (10^{-9} s), which usually induces thermal effect and light saturation phenomenon. As a result, the signal is greatly decayed and the detection precision is reduced to a large extent. Femtosecond laser has a pulse width as short as 10^{-14}–10^{-15} s. It is widely accepted that thermal effect of a laser irradiation becomes negligible when the pulse length is shorter than the time needed to couple the electronic energy to the lattice [9,10]. Therefore, thermal effect for the acoustic measure of the solid material could be overcome when a femtosecond laser was used as the light source. Moreover, the cross-sensitivity of the microphone to the temperature and pressure is also likely to be avoided.

On the other hand, common sensors used in photoacoustic spectroscopy are mainly piezoelectric transformer and capacitor, which suffer from electromagnetic interference in most cases. And charged particles in laser plasma also can produce electromagnetic interference to relegate measurement precision. Fiber optic sensors have the advantages of erosion resistance, small size, immunity from the disturbance of electric and magnetic fields, intrinsically safe [11–14]. The characteristic of immunity to electric and magnetic fields made fiber optic an appropriate substrate which could avoid the electro-magnetic disruptive influences from charged particles in laser plasma.

Based on the advantages of femtosecond laser and optical fiber sensor discussed above, a novel measurement method for solid materials could be developed. In this letter femtosecond laser was used to ablate pure Cu, Fe and Al target materials, and fiber *F–P* sensing probe was applied to the detection of the excited micro

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plasma acoustic signals during femtosecond laser ablation. The relationships between the expansion laser micro plasma frequency, amplitude and femtosecond laser energy as well as ablating distance have been studied. The experimental results are meaningful to the detection of solid material, and also helpful to the understanding of the interaction mechanism between femtosecond laser micro plasma shock waves and solid materials.

2. Experiments

2.1. The characteristics of the F–P sensor

(1) The light beam in the *F–P* sensor is actually located at the center of the quartz diaphragm, and the size of the light spot is far smaller than diaphragm's. The quartz diaphragm would de deformed under the air pressure *P*, and the maximum deflection is defined as $y_{\max}$. The deflection $y_{\max}$ at the center of a quartz membrane could be considered as the effective deflection i.e. the amount of actual cavity length change $\Delta d = y_{\max}$. When the signal is detected by the sensor, the diaphragm would oscillate at a very high speed, leading to the quickly change of the cavity length. So the interference signal strength IR varies with cavity length *d* very fast.

$$y_{\max} = \frac{3P(1-\mu^2)}{16E} \times \frac{a^4}{h^3} \quad (1)$$

Among this, *h* stands for the thickness of the diaphragm, *a* is the effective radius of the diaphragm, *E* is the Young modulus, μ is the Poisson ratio of the diaphragm. The pressure sensitivity of quartz diaphragm at the center can be defined as:

$$s_{\max} = \frac{y_{\max}}{P} = \frac{3(1-\mu^2)}{16E} \times \frac{a^4}{h^3} \quad (2)$$

(2) Modulation method of the optical fiber *F–P* sensor in the experiment is based on the double beam interference. When the wavelength of the tunable diode laser remains the same, the relation between reflection intensity IR and the cavity length is a cosine function as equation.

$$I_R \approx I_0 \times 2R(1-\cos\varphi) = 2RI_0\left(1-\cos\frac{4\pi d}{\lambda}\right) \quad (3)$$

In the equation, *R* stands for the surface reflectance, I_0 is the incident light intensity, and they are all constants. φ is the phase between two adjacent refracted beam.

(3) The Free Spectral Range (*FSR*) of the *F–P* sensor reflects dense degree of the interference fringes. It could be calculated as follow:

$$FSR = |\lambda_{m1} - \lambda_{m2}| \quad (4)$$

The relation between the length of cavity and FSR could be estimated as:

$$d = \frac{1}{2} \times \frac{\lambda_{m1}\lambda_{m2}}{|\lambda_{m2} - \lambda_{m1}|} \quad (5)$$

The length of cavity could be calculated when knowing λ_{m1}, λ_{m2}. From this, we know that longer the length, smaller the FSR, and the fringes would be more dense.

2.2. The principle of detecting method

The optic signal generated by tunable semiconductor laser would passes into the circulator through the fiber, and then into the sensors. The signal would be modulated when the sensor receives the acoustic signal of the plasma shock wave produced by femetosecond ablation targets. Then the modulated signal would be reflected back to the circulator. In this way, the signal owning sensing information is detected by the photodetector and analyzed through the data acquisition system. The modulated information wave could be real time observed in the computer finally. The schematic of experimental setup is shown in Fig. 1. A commercial Ti: sapphire femtosecond laser with 180 fs laser pulses and 780 nm central wavelength, 1 kHz repetition rate was used in the micromachining system (Japanese Cyber Laser Company; LS-IF-FW-C-401). For the *F–P* optical fiber sensing system, a tunable semiconductor laser with 1545 nm wavelength and 0.2 mw Power was used as the light source (Santec Company). The multi-channel data acquisition card of NI Company was used for data collection. The highly efficient signal processing circuit is developed independently by our laboratory.

The experiments were carried out as follows. Tunable semiconductor laser was used as light source in the measurement process. Femtosecond laser beam with a high power density and a short pulse was focused using a quartz lens. As the laser beam irradiate on pure Al, Cu and Fe target materials through a quartz glass sheet window of a sealed space, the laser micro plasmas could be formed, which led to an acoustic signal due to the expansion of the laser micro plasma. The acoustic signal is exclusively linked to the intrinsic property of the solid material

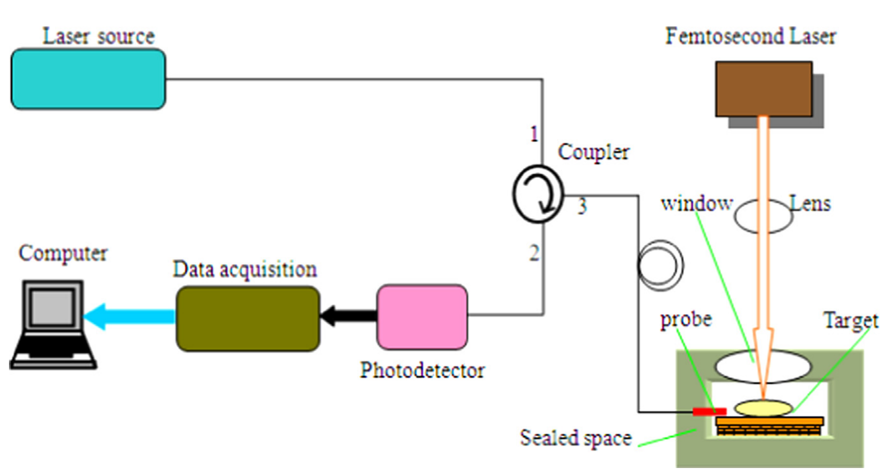

Fig. 1. Schematic layout of the experimental setup.