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Measurement Mechanism and Experimental Research of the all Fiber Michelson Interferometer

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Abstract: With high sensitivity and precision, fiber optic interferometer has been applied widely. Simulation and experiments for micro-displacement measurement by optical fiber Michelson Interferometer are described. The simulation results show that the relation between the micro-displacement and the output optical signal is linearity, which indicates that the fiber Michelson Interferometer can be used to measure the laser-induced shock wave. The experimental has detected the propagation speed of laser shock wave in the Al samples impacted by pulsed laser.

Keywords: Fiber Michelson Interferometer; Micro-displacement; Laser shock wave; Aluminium

1 Introduction

Laser interaction with materials is a complex process involved micro-physics, chemistry, mechanics and so on, which presented with material temperature increases, combustion, generating shock waves and other macroscopic physical phenomena. Laser shock to improve surface properties of materials is a new surface modification technology and can be used broadly. As a means of metal machining, it can produce good economic and social benefits. At present, the transmission characteristics of laser induced shock wave mainly was measured by PVDF sensor. Due to the piezoelectric thin film of PVDF sensor[1,2], the parameter such as the area of sensor, the thickness of the adhesive and bonding the tightness has a great of influential factors.

The optical fiber Interferometer can measure the micro-displacement in nano-scale [3]. The diameter of the fiber core is relatively small, which is less than 10μm especially in single-mode fiber and equivalent to point measuring. Using light as a carrier, the thickness of the adhesive and tightness of bonding and other parameters influence on the measurement results can be avoided by non-contact measurement[4,5]. With the high signal-noise ratio, the optical fiber Michelson Interferometer is widely studied and applied. In this paper, the micro-displacement under pulsed laser shock waves was detected by using optical fiber Michelson Interferometer, and we can obtain the properties of laser shock wave across inversion.

2 Measurement Mechanism

As shown in figure 1, the all Fiber Michelson Interferometer can be used to measure nanometer level displacement. The test beam at fixed single wavelength is emitted by a semiconductor diode laser (LD), which is divided into two beams by an optical fiber coupler. Two mirrors (M1 and M2) reflect respectively the two beams. The returning light beams merge together at the optical fiber coupler and create the interference light, which is received by a photodiode (PD). When the piezoelectric transducer controller changes the displacement between the one of the fiber port (which is called the testing fiber), the output intensity of the interference light either cancel out or reinforce.

The output intensity of the interference light is

$$I_{out} = (I_1 + I_2 + I_{1r} + I_{2r}) + (I_{12} + I_{11r} + I_{12r} + I_{21r} + I_{22r} + I_{1r2r}) \quad (1)$$

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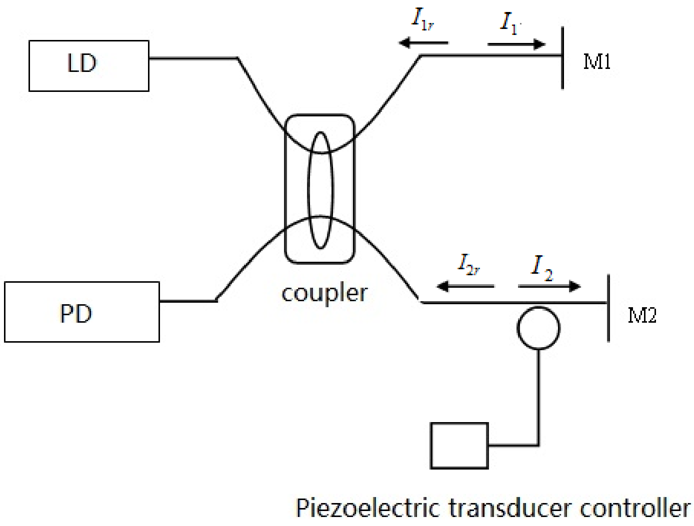

Figure 1: Work principles diagram of all Fiber Michelson Interferometer

where I_1,I_2 are respectively the output light intensities of the two fiber port, I_{1r},I_{2r} are respectively the light intensities reflected by the mirrors into the coupler, I_{12},I_{11r},I_{12r},I_{21r},I_{22r},I_{1r2r} are respectively the interference light intensities of the incidence light and the reflected light. And the Coherence can be expressed as

$$I_{ij} = 2\sqrt{I_i I_j}\cos(\varphi_{i-}\varphi_j), i \neq j \tag{2}$$

where φ_i is the phase of the light intensities, φ_{ir} is the phase of the reflected light.

When the coupler output ports are is fully symmetrical, it is supposed as$I_1 = I_2$. When the two arm length of the optical fiber coupler is adjusted to$\varphi_1 - \varphi_2 = \pi$, then $I_{12} = 2\sqrt{I_1 I_2}\cos(\pi) = -2\sqrt{I_1 I_2} = -2I_1$ and$(\varphi_1 - \varphi_{1r}) - (\varphi_2 - \varphi_{1r}) = \varphi_1 - \varphi_2 = \pi$, so $I_{11r} = -I_{21r}$ and$I_{12r} = -I_{22r}$, the output light intensity is expressed as

$$I_{out} = (I_1 + I_1 + I_{1r} + I_{2r}) - 2I_1 + I_{1r2r} = I_{1r} + I_{2r} + 2\sqrt{I_{1r}I_{2r}}\cos(\varphi_{1r} - \varphi_{2r}) \tag{3}$$

To analyze the relation between the displacement and the intensity, the schematic diagram of the fiber probe is shown as figure 2. The phase difference can be written as

$$\varphi_{1r} - \varphi_1 = 4\pi n_0 x_1/\lambda \quad n_0 = 1 \tag{4}$$

$$\varphi_{2r} - \varphi_2 = 4\pi n_0 x_2/\lambda \quad n_0 = 1 \tag{5}$$

Here x_2 is the displacement between the testing reference fiber end face and the mirror,x_1 is the displacement between the other fiber end face and the mirror, $n_0$is the refractive index of air and λ is the testing wavelength.

The phase difference$\varphi_{1r} - \varphi_{2r}$ can be written as

$$\varphi_{1r} - \varphi_{2r} = \varphi_1 - \varphi_2 + 4\pi x_1/\lambda - 4\pi x_2/\lambda = \pi + 4\pi(x_1 - x_2)/\lambda \tag{6}$$

Let us suppose the surface reflectivity R is 0.75, the reflected light intensity can be expressed in this ways

$$I_{1r} = 96\% \times 96\% \frac{S_{AEF}}{S_{AGH}} I_0 R \tag{7}$$

Here S_{AEF} and S_{AGH} are the Spherical cap area of AEF and AGH. Therefore (7) can be written as

$$I_{1r} = 96\% \times 96\% \frac{h_1}{h_2} I_0 R \tag{8}$$

$$I_{2r} = 96\% \times 96\% \frac{h_3}{h_4} I_0 R \tag{9}$$

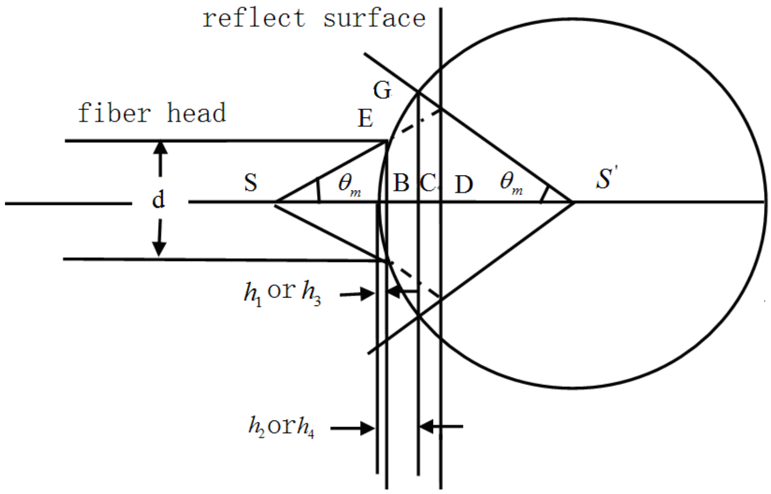

Figure 2: The schematic diagram of the fiber probe

The simultaneous equation(6),(8),(9)and (1)

$$\begin{aligned} I_{out} &= 96\% \times 96\% \frac{h_1}{h_2} I_0 R + 96\% \times 96\% \frac{h_3}{h_4} I_0 R \\ &+ 2\sqrt{(96\% \times 96\% \frac{h_1}{h_2} I_0 R) \times (96\% \times 96\% \frac{h_3}{h_4} I_0 R)} \cos(\pi + 4\pi(x_1 - x_2)/\lambda) \end{aligned} \tag{10}$$

According to the geometry relation

$$h_1 = AS' - BS' = \sqrt{(2x_1 + 0.5d/\tan\theta_m)^2 + (0.5d)^2} - (2x_1 + 0.5d/\tan\theta_m) \tag{11}$$

$$h_2 = AS' - CS' = AS''(1 - \cos\theta_m) = \sqrt{(2x_1 + 0.5d/\tan\theta_m)^2 + (0.5d)^2}(1 - \cos\theta_m) \tag{12}$$

$$h_3 = AS' - BS' = \sqrt{(2x_2 + 0.5d/\tan\theta_m)^2 + (0.5d)^2} - (2x_2 + 0.5d/\tan\theta_m) \tag{13}$$

$$h_4 = AS' - CS' = AS''(1 - \cos\theta_m) = \sqrt{(2x_1 + 0.5d/\tan\theta_m)^2 + (0.5d)^2}(1 - \cos\theta_m) \tag{14}$$

The normalized output intensity of the interference light is

$$\frac{I_{out}}{I_0} = 0.9216R(\frac{h_1}{h_2} + \frac{h_3}{h_4}) - 1.8432R\sqrt{(\frac{h_1}{h_2} \times \frac{h_3}{h_4})} \cos[4\pi(x_1 - x_2)/\lambda] \tag{15}$$

We input a damped signaldisplacement between the testing reference fiber end face and the mirror, m,b and k are the coefficient of the damped signal. We set the initial velocity is zero and the initial displacement is 0.000000002m (which is typically much less than a quarter of wavelength).the out signal is also the damped signal as shown in Figure3.

3 Experimental research

We used the all Fiber Michelson Interferometer measurement system to measure the deformation process of the laser induced shock waves. The schematic of this measurement apparatus is presented in Fig.4. The apparatus consists of two major components: the measurement system and the laser shock system.

A high power Q-switched neodymium glass laser (wavelength=1064nm, energy=1J, and pulse width=10 ns) is used for the laser shock system. The laser beam travels through the mirror and optical lens, then vertically radiate onto the sample surface with 2 mm spot radius.

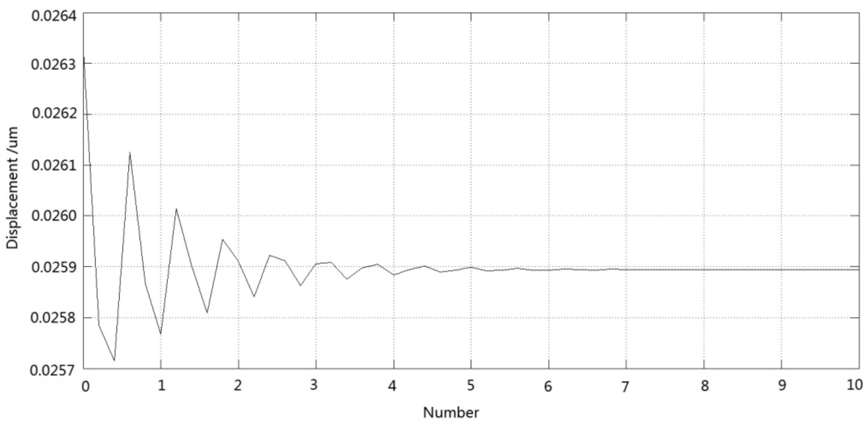

Figure 3: The damped output signal of simulation block

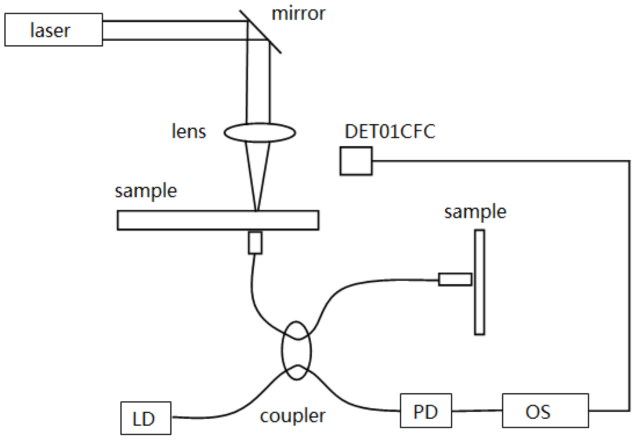

Figure 4: Experiment system

The measurement system is triggered by the photodiode (model is DET01CFC). The testing semiconductor laser operating at a wavelength of 1550nm and generating 20mW output power. the displacement between the fiber probe and the surface of aluminum is proportional to the deformation. Because the laser induced shock wave results in the deformation of the aluminum plates, the high-speed deformation process of aluminum sheet shocked by strong and short pulse laser can effectively express the laser induced shock wave.

The waveforms displayed in digital oscilloscope are shown in Figure 5. The energy is absorbed by structure and the oscillation is generated rapidly. Because of the boundary between the metal and the air, the shock waves are reflected when the arriving of the interface and act the surface. So the Gaussian laser pulses result in sustained oscillations and the duration of oscillation is bigger than the pulse width.

According to the velocity formula V=2d/t, where d is the thickness of the sample and t is the interval between the two waveform extremism, we acquire the wave velocity spreading in the aluminum material as shown in Table1.

Chose starting time of two adjacent pulse in three distinct groups: the average propagation velocity of shock wave in aluminum was calculated as 147731.50m/s.

4 Conclusion

This paper has designed a program of micro-displacement measurement based on the principle of optical fiber Michelson Interferometer, which used to detect surface deformation under laser shock. The simulation results show that the relation between the micro-displacement and the output optical signal is linearity, which indicates that the fiber Michelson Interferometer can be used to measure the laser-induced shock wave. The experimental results show that the average speed of

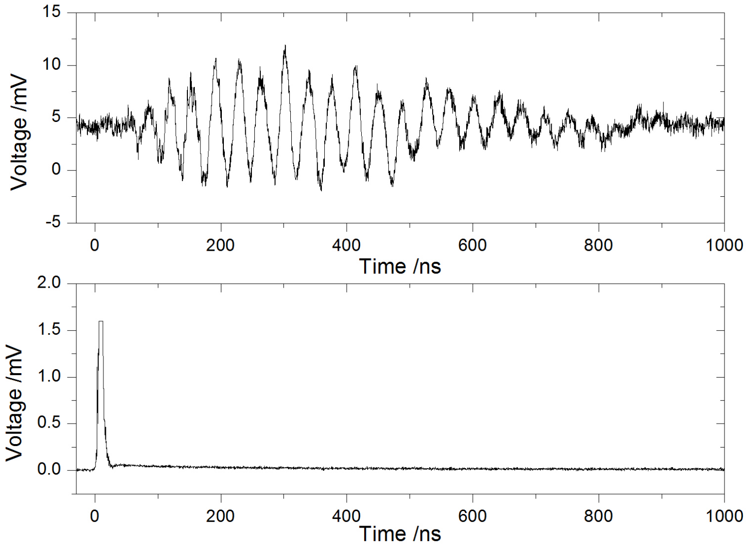

Figure 5: The deformation testing curve collected by digital

Table 1: the wave velocity spreading in the aluminium material

Number	thickness(d)	Time interval(t)	Wave velocity(v)
1	3mm	40.748ns	147246.49m/s
2	3mm	40.316ns	148824.29m/s
3	3mm	40.782ns	147123.73m/s

laser-induced shock wave in aluminum was 147731.50 m/s.

Acknowledgments

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