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Real Time Velocity Measurement with All-fiber Self-mixing Speckle System

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Abstract

A novel method for real time velocity measurement is proposed. All-fiber laser measurement system is built by an erbium-doped fiber amplifier (EDFA). The measuring principle is based on laser self-mixing speckle, modulations of laser output caused by the optical feedback from an outer moving object. The generation of speckle signal is theoretically analyzed and experimentally obtained. A Labview programme is developed for waveform acquisition, noise reduction and numeric calculation. The signal processing shows a linear relationship between the energy density of speckle signal and the velocity of the moving object. In the experiments of real time velocity measurement by a rotating aluminum plate, we obtained measurement error less than 4.1% in the range of velocity from 234 to 508 mm/s. The study indicates that the all-fiber self-mixing speckle system can be applied in remote velocity sensing and measurement.

Keywords: real time velocity measurement; erbium-doped fiber laser; energy density; self-mixing speckle

1. Introduction

Self-mixing speckle measurement is a technique of optical feedback application. Self-mixing speckle occurs when light output from a laser, part of the light is backscattered from a moving rough surface, mixing with the original light in the laser cavity, causing modulation of the laser output. The light backscattered carries information of the object under test, which is detected by a photodiode (PD) as self-mixing speckle signals. We can obtain the information of the object by signal processing. In recent years, self-mixing speckle has been applied in measurement of physics, mechanics, chemical materials, etc. In

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2005, Zakian [1] developed the self-mixing interferometry method to determine the sizes of sub-micron particles and measure flows in a narrow diameter. He investigated the particle sizes using polystyrene particles and flow measurement of milk. In 2006, domestic researchers [2] studied the linear dependence between the spectrum mean frequency and velocity of solution, and discussed the effects of background and concentration of solution in the experiments. For utility to velocity sensing of solid, Shibata [3] researched that the mean frequency of the speckle signal is directly proportional to the target velocity in 1996, but in his paper, the laser beam spot diameter must be greater than 0.36 mm and kept constant. Until now, most applications of self-mixing speckle are based on semiconductor laser diodes [4-7]. In recent years, fiber lasers have been applied widely in optical fiber communications and sensor, because they provide stable milliwatt output power and own a narrow line width. In our paper, we introduce the traditional speckle to a 1550nm EDFR laser. Before, we have studied the self-mixing speckle in EDFR and its application to velocity sensing [8], advanced the fractal analysis of self-mixing speckle signal [9]. Moreover, we adopted the spectrum energy density of the dynamic speckle signals to detect dynamic target distance [10]. The previous works make some success, but there are still some works to do to achieve real-time measurement and to improve the measured precision and signal noise ratio (SNR).

In this paper, our experiment of real-time velocity measurement is based on self-mixing speckle in an erbium-doped fiber-optic ring laser. In order to apply the self-mixing speckle to real-time velocity measurement, a new analytical approach, energy density of self-mixing speckle is introduced. A labview programme is operated to carry out the data acquisition and signal processing, so as to realize the velocity measurement instantaneously.

2. Principle

The experiment setup is shown in Fig.1. Pump light is coupled into the laser ring cavity using a wavelength-division multiplexer (WDM). Spontaneous radiation is produced in length of erbium-doped fiber (EDF). The radiation output from the 2nd port of a 3-port optical circulator, part of them is reflected by a fiber Bragg grating (FBG), and 1550nm wavelength is selected and travelling in the ring cavity until it is stable. In a same time, part of the light transmits through the FBG and illuminates on the moving object. A portion of light is reflected or scattered by the moving surface, coupled into the fiber system, and then mixing with the original light in the ring cavity, that causes modulations of the laser output. The output of modulated laser is detected by a PD as self-mixing speckle signal, which is shown in oscillograph and save to a personal computer (PC). On the PC, the speckle signal is processed by a programme.

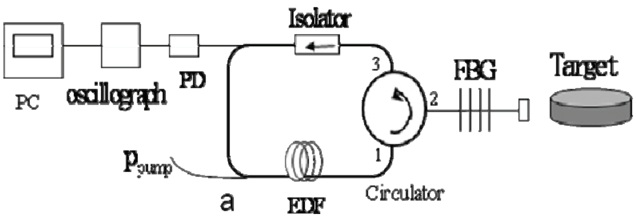


Fig. 1 System for velocity measurement of self-mixing speckle

On the assumption that the pump light coupled into the cavity at Point A, it can be expressed as

$$E = E_0 \exp[-i(\omega t + \varphi)] \quad (1)$$

So the reflected light from FBG to Point A can be written as

$$E_1 = E_0 \exp[-i(\omega t + \varphi + n_c L_D k + n_f L_f k)] \cdot r_2 \cdot r \quad (2)$$

where $r = \varepsilon_{12}\varepsilon_{23}$, ε_{12} and ε_{23} is the 3-port optical circulator transmitted ratio respectively from port 1st to 2nd and from port 2nd to 3rd . r_2 is the reflectivity of FBG. n_c and n_f is the refractive index of EDF and fiber respectively. L_D and L_f is the length of EDF and fiber respectively.

The reflected or scattered light from the target surface to Point A is

$$E_2 = E_0 \exp[-i(\omega t + \varphi + n_c L_D k + n_f L_f k + 2kL_E)] \cdot \xi^2 \cdot U_0(x,y) e^{-i\phi(x,y)} \cdot f \quad (3)$$

Where L_E is the distance between the laser fan-out and the plate profile. $U(x_0, y_0)$ is the complex amplitude of the speckle field that fed back the laser.

References to Peter D. Dragic theory [11] about injection-seeded EDF ring laser, the transcendental equation for the power is deduced

$$\begin{aligned} &P_S^s(\alpha_S L - \frac{(\varepsilon_1\varepsilon_2 k - 1)P_S^{out} + \varepsilon_2(1-k)P_{seed}}{P_S^s} - \ln(\varepsilon_1\varepsilon_2 k + \frac{\varepsilon_2(1-k)P_{seed}}{P_S^{out}})) \\ &= P_P^{in}(1 - \exp(-\alpha_P L + \frac{P_S^s}{P_P^s}\alpha_S L - \frac{P_S^s}{P_P^s}\ln(\varepsilon_1\varepsilon_2 k + \frac{\varepsilon_2(1-k)P_{seed}}{P_S^{out}}))) \end{aligned} . \quad (4)$$

here, the subscripts P and S refers to the pump and laser wave-lengths, respectively. The emission P_S^s and P_p^s are the saturation power of the laser and the pump. α_s (α_p) is the small signal absorb coefficient, L is the length of the EDF. ε_1, ε_2 are the ratios of power in and out of the EDF, respectively. k is the ratios of power splitting of the coupler. P_S^{out} is the output power of the second port of 3-port optical circulator. P_{seed} is the power of the injection-seeded light, and P_P^{in} is the pump power at the input.

As depicted in Fig.1, P_{seed} includes the reflected light both from the FBG and the target. It can be wrote as following

$$P_{seed} = ((1-k)^2 \mu + k^2 \eta) \cdot P_s^{out} . \quad (5)$$

here, η is the reflection ratio of the FBG, and μ is the coefficient defined as the ratio of the power fed back into the laser to that outside of the fiber, which is effected by the attribute of target. It has the relationship as following

$$\mu \propto \left|U(x_0, y_0)\right|^2 / \left|E_{out}\right|^2 . \quad (6)$$

where E_{out} is the optical field that illuminates the surface of the diffused object. (x_0, y_0) is the coordinate where the speckle field injects the laser. $U(x_0, y_0)$ is the complex amplitude of the speckle field that fed back the laser. It is calculated by the theory of wave scattering from the rough surface [12].

$$\begin{aligned} U(x,y) = E_{out} \cdot \int &A(X,Y)\exp(-i4\pi h(X,Y)/\lambda) \cdot \\ &\exp(-i2\pi(X \cdot x + Y \cdot y)/\lambda L_E) dXdY \end{aligned} \quad (7)$$

where λ is the laser wavelength, (x, y), (X, Y) are the coordinates along the speckles field and the scattering area, $A(X, Y)$ is the aperture function of scattering area, $h(X, Y)$ is the altitude function of the random surface.

The output power $P_{\det}$ detected by the PD is described

$$P_{\det} = k(1-k)(\mu+\eta)\cdot P_S^{out} \tag{8}$$

The Eq.(1) is solved numerically for P_s^{out} . Then P_s^{out} is plugged into Eq.(8), the power of the laser output can be counted finally.

In the analysis, both of the amplified spontaneous emission (ASE) and excited state absorption (ESA) are neglected. Because ESA is weak when the laser is pumped into the 980-nm band and ASE diminishes when the laser is well above threshold.

3. Experiment

The experiment is carried out by the setup shown in Fig.1. The work wavelength is 1550nm by the FBG operating on broad band light emission from the EDF laser. An aluminium plate connected with a stepper motor is qua surveyed object, whose velocity is controlled by computer exactly. In respect that the distance between the surface of the object and the laser fan-out has influence on speckle signal, its value is fixed during the experimentation.

At the beginning, the distance between the laser fan-out and the plate profile is fixed at 1.5 mm. The aluminium plate is moving uniformly at different velocity, separately. From the oscillograph we can observe the amplitude variety as portrayed in Fig.2. As we can see, when the velocity changed, the speckle amplitude also changed. Furthermore, the faster the velocity is, the bigger the amplitude is. In order to depict their relationship, defined a parameter ρ_E for energy density

$$\rho_E = \frac{\sum_{i=1}^{N} |E_i|}{N}. \tag{9}$$

Where N is samples, it is set to 10K in our study. E_i is the value of amplitude when N is equal to i.

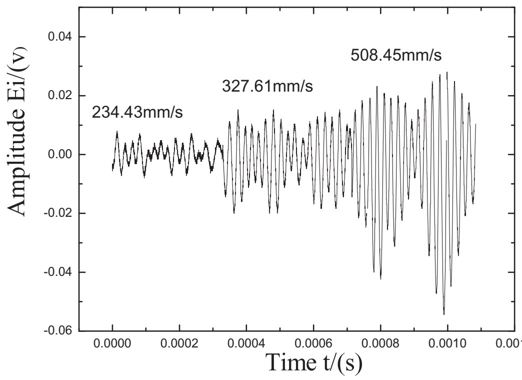


Fig. 2 Signals of self-mixing speckle at different velocity

To compute the self-mixing speckle energy density, the signal processing is achieved on a PC. The processing program (Data Acquisition VI) is written by the graph language labview. In Fig.3, the block diagram and the front panel of the data acquisition VI is portrayed. In the block diagram, the self-mixing speckle signal is transmitted to the computer via Ethernet network. Then the signal is filtered by a butterworth lowpass. Moreover, the energy density is calculated by a matlab function. In the front panel, the value of the speckle energy density is output real time in the diagram. The average of energy density can also be obtained by setting the measured times. The two graph windows show the speckle signal before and after filtering.

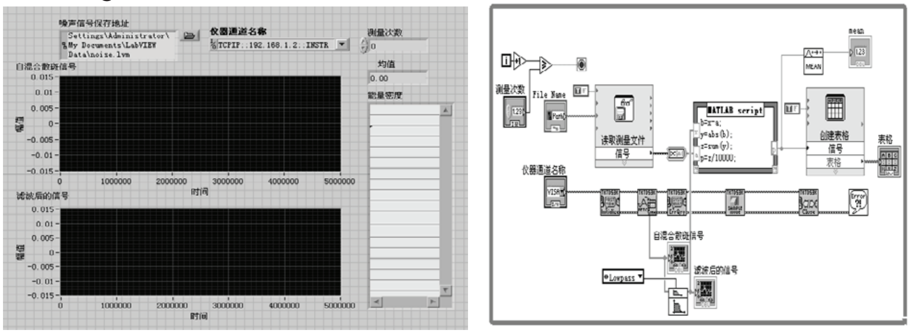


Fig. 3 Block diagram and front panel of data acquisition VI

On the computer, the angular speed of the aluminium plate is controlled and displayed. The plate's diameter is known as 20 mm. According to the transformation relationship between angular speed and line speed $v = \omega \cdot (d/2)$, the line velocity of the side of the plate can be wrote out quickly. So, when the plate is moving at a certain speed, both of the self-mixing speckle energy density and its line speed can be calculated by computer. Change the velocity and repeat the experiment 12 times. We obtain two serial of data, then fit them. A linear relation between the speckle energy density and the plate line velocity is acquired, as depicted in Fig.4. The function of the curve is given by

$$V = 31395\rho_E + 130.66 \ . \quad (10)$$

The related linearity coefficient is 98.9%. This result indicates that the self-mixing speckle in an EDF laser can be applied to velocity sensing. Once the speckle energy density is figured out, the target velocity will be obtained by the equation above.

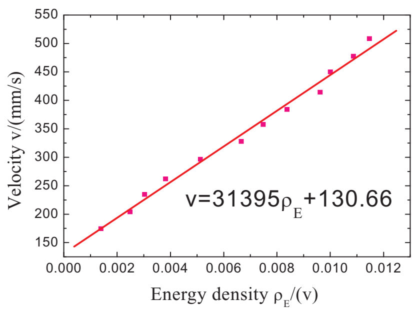


Fig. 4 Linear relation between energy density and velocity

To achieve velocity measurement, we write another VI (Velocity Measurement VI), which is shown in Fig.5. Compared to the data acquisition VI, there is a formula function added behind the matlab function in the block diagram. As the speckle energy density is calculated by the matlab function, plug it into the Eq. (10) written in the formula function, and then the target velocity is obtained. In the front panel of velocity measurement VI, the self-mixing speckle signal, velocity-time curve and the velocity is displayed.

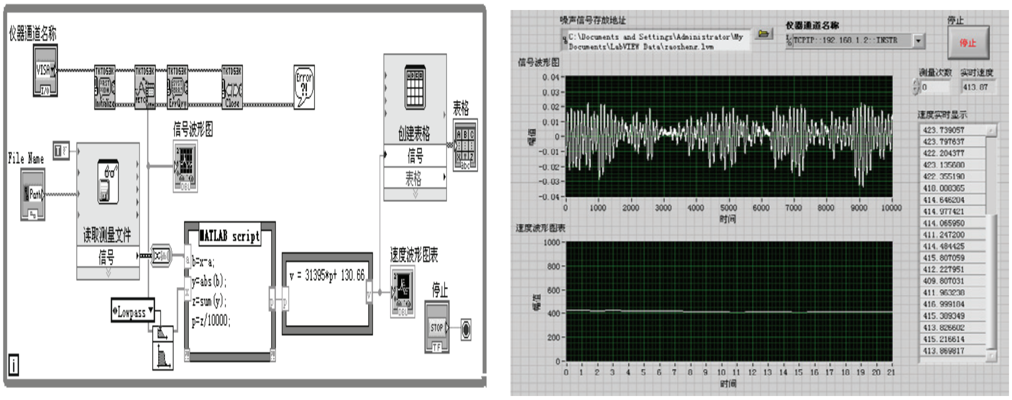
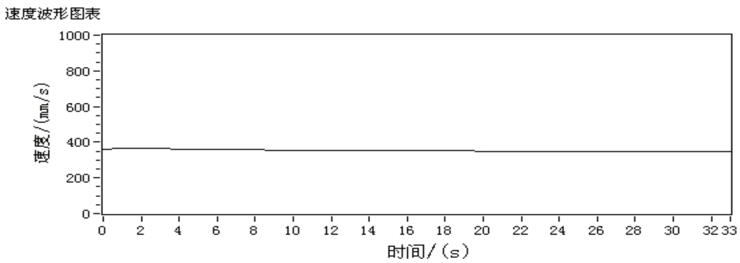


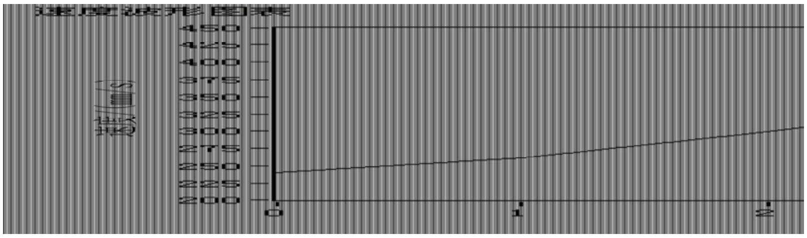
Fig. 5 Block diagram and front panel of velocity measurement VI

4. Experimental result and validate

The aluminium plate velocity is fixed at 357.54 mm/s on the PC. When it is rotating equably, the velocity is surveyed by our system. Fig.7 (a) shows the measured result. Here the velocity-time curve is portrayed like a horizontal line as the plate is moving at a constant speed. It proves the high stability of our measured result and less affection by environment.



(a)



(b)

Fig. 7 Velocity-time diagram. (a) 357.54 mm/s, (b) velocity increased from 241.67 mm/s to 414.29 mm/s

When the aluminium plate is moving at shifting velocity, which is increased from 241.67 to 414.29 mm/s, the measured velocity-time curve, as depicted in Fig.7 (b), is close to a beeline with a certain slope. It testifies that the measured result by this system also is steady when the target moving at variable velocity.

For a further investigation, we repeat experiments 10 times at different velocity. Then compared the measured velocity with the real velocity, the contrasted diagram is depicted in Fig.8. We can see in this diagram, at a range of velocity from 234 and 508 mm/s, the error between measured and real velocity is less than 4.1%, which proves the measurement error of the all fiber self-mixing system is low.

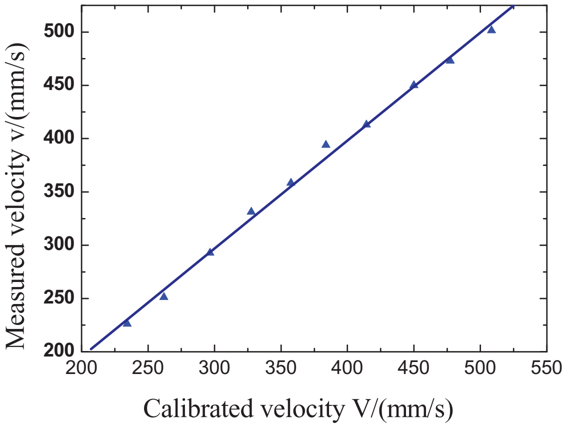


Fig. 8 Comparison of the values between measured velocity and calibrated velocity

5. Discussion of error sources

First, when there is nothing before the laser fan-out, we detected some weak signals by the PD. The weak signal is portrayed in Fig.6, and it is found to be insensitive to the environmental change. So we collected a set of the noise data at random and saved it. In the experiment, before the speckle signal is processed by labview, it subtracted the noise data saved early. Second, in the velocity measurement VI, we adopted a butterworth lowpass to filter the incidental noise. Third, the distance between the laser fan-out and the plate profile is fixed at a certain value. In experiment, the distance is fixed at 1.0mm, 1.5mm, 2.0mm, and 2.5mm, respectively. The line velocity of the plate is measured repeat at each distance. The result is shown in Fig.7. In this graph, the linear relation between energy density and velocity is changed when the distance is different. It proves that the self-mixing speckle signal is affected by the distance between laser fan-out and the target.

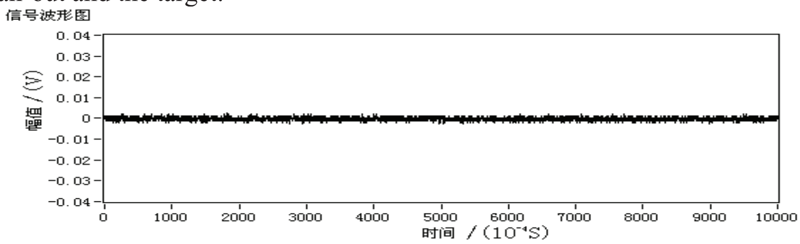


Fig. 6 Noisy signal

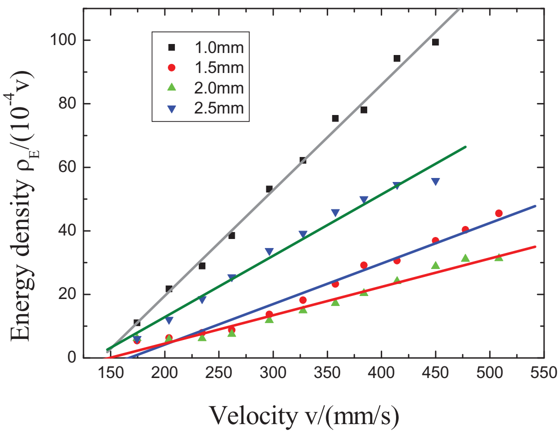


Fig.7 Linear relation between energy density and velocity at different distance from the laser fan-out and to plate profile

Conclusion

In this paper, we have demonstrated the real time velocity measurement with an all-fiber laser self-mixing system. Theoretical analysis of the self-mixing speckle and signal processing of the energy density is discussed. A labview programme is developed and used to waveform acquisition, noise reduction and numeric calculation. The experimental result shows that real time velocity measurement is carried out at low measurement errors. This study indicates that the all-fiber self-mixing speckle system can be applied in real time velocity tracing and sensing.

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