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Experimental research on dual polarized laser optical feedback microscope

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Abstract: The principle of laser optical feedback microscope was presented and demonstrated. Three methods to advance the vertical resolution of laser optical feedback microscope were experimentally studied. The first one is to detect the two polarized lights' intensities separately with a Wollaston prism instead of to detect the whole light's intensity. The second is that both of the two orthogonally polarized lights of a birefringent dual frequency laser are fed back. The third one is that only one of the orthogonally polarized lights is fed back. The experimental results show that the modes competition between orthogonally polarized lights can be used to improve the vertical resolution of laser optical feedback microscope effectively.

Key words: laser optical feedback; vertical resolution; modes competition; microscope

1 Introduction

Optical feedback phenomenon in laser, which can dramatically affect the output intensity of laser, was first reported by King in 1963^[1]. When the light of laser output is reflected or scattered by the surface of an external object, a portion of the light is fed back into the laser resonance cavity. After the feedback light, which contained the information of external object, mixing with the light in the internal cavity, the laser output power is changed with the variation of the feedback light's phase and amplitude. Because the laser intensity modulation caused by a movable external object is similar to that produced by a conventional optical interferometer, such as a fringe shift corresponding to an optical displacement of half wavelength of the laser, the phenomenon of optical feedback is also called

self-mixing interference^[2-4].

Compared with conventional interference, self-mixing interference system not only has similar phase sensitivity and modulation depth ratio, but also has inherent simplicity, compactness and robustness as well as self-aligning capability. Thus, much theoretical and experimental research based on self-mixing interference has been done in the fields of Doppler velocity measurement^[5-6], distance and displacement. In addition, it also has been applied to the imaging^[7-9]. The new three-dimensional scanning confocal microscope based on laser optical feedback not only can detect the sample's shape, but also can detect the sample's reflectivity, compared with conventional optical microscope. The instrument has some another important characteristics, such as simple, providing three dimension image, having very high vertical resolution and horizontal resolution, no harm to the cell in the meas-

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urement, and so on.

In this paper, three new experiments of dual polarized laser optical feedback have been presented and demonstrated. Experimental results show that the modes competition between orthogonally polarized lights can be used to improve the vertical resolution of Laser Optical Feedback Microscope effectively.

2 Principle of laser optical feedback microscope

The experimental setup of Laser Optical Feedback Microscope system is shown schematically in Fig. 1. The output light of He-Ne laser

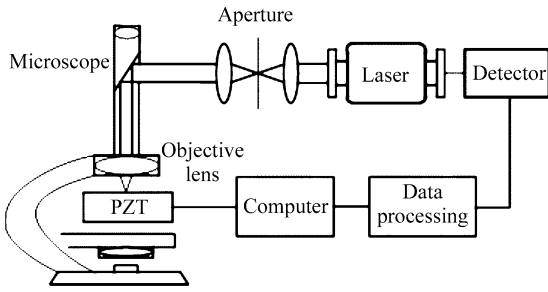


Fig. 1 Principle scheme of laser optical feedback microscope

is collimated by a space filter first, and then changes its incidence direction through a half-reflecting mirror. After being focused by a microscope objective, the light vertical incidences into the PZT scanning table. The tiny samples to be measured are placed on the table. When the focused light scans the sample, the laser output power is modulated by the variation of optical feedback cavity length L , which determined by the sample's thickness. So after the detected signal being processed by a computer, the sample's three dimension image can be got.

The laser output power is affected strongly by the variation of the feedback light's phase and amplitude, which are determined by the total optical distance and the sample's reflectivity, re-

spectively. So the relative intensity $\eta(t)$ of Laser Optical Feedback Microscope and the optical feedback length $L(t)$ meet the cosine-function relation. It can be expressed as

$$\eta(t) = \frac{I_0 - I_f}{I_0} = K \cos \left[\frac{4\pi}{\lambda} L(t) \right], \quad (1)$$

where I_0 is the laser output power without optical feedback; I_f is the laser output power with optical feedback; K presents the feedback factor of intensity; $L(t)$ is the feedback cavity length and λ is the wavelength of laser.

The feedback factor of intensity K is determined by

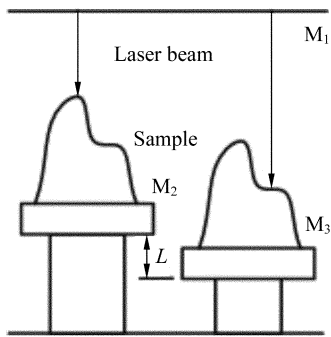
$$K = 2\tau t_p \left(\frac{N}{N_{th}} - 1 \right)^{-1}, \quad (2)$$

$$\tau = \frac{c}{2n_c L_c} \frac{1 - R_2^2}{R_2} (fR_3). \quad (3)$$

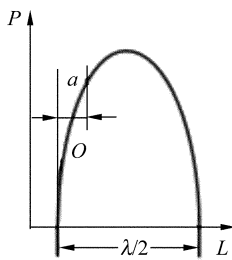
where t_p is the photon's average life in the laser cavity; N is the amount of reverse particles; N_{th} is the threshold when the particles reverse; c is the velocity of light in vacuum; n_c is the effective refractive index in the laser cavity; L_c is the length of laser gain medium; R_2 is the reflectivity of M_2 ; R_3 is the reflectivity of M_3 ; f presents the coupling intensity between the feedback light and the oscillating modes.

The principle of the Laser Optical Feedback Microscope to measure samples' shape is shown in Fig. 2. The focused laser beam scans from the edge of a sample to be measured. By using electronic feedback and piezoelectric transducer control system, the laser outputs an invariable intensity. We name it fiducial intensity, as shown in Fig. 2(a). The optical distance between M_1 and M_3 is controlled constantly in measuring. So the variation of the PZT's length indicates the sample's shape. We called this measurement technique is invariable laser output power method. When the sample's shape chan-

ges in $\lambda/4$, the laser output power varies with the sample's shape monotonously. So this method can solve the problem of direction discrimination in the tradition interferential measurement system. And it can also offer a very high vertical resolution.



(a)



(b)

Fig. 2 Measuring method of invariable laser output power

Fig. 2 shows the relationship between the laser output power P and the variation of PZT's length. When L changes a half wavelength, the laser output power undulates a period. O is the fiducial intensity point. When the laser output power is not equal the fiducial intensity, we adjust the voltage of PZT to make the power reach it. So the variation of PZT's length corresponds to the sample's shape in the scanning. And the region α corresponding to the minimum variation of the laser output power can be detected for determining the vertical resolution, which is affected strongly by the modulation depth of laser output power.

3 Experimental system of common single-mode laser optical feedback microscope^[9]

The experimental setup of common optical feedback is shown in Fig. 3. A half-intracavity, single-mode, operating at 632.8 nm He-Ne laser is composed by a plane mirror M_2 and a concave mirror M_1 which has a radius of 1 m. Their reflectivities are $R_1 = 0.999$ and $R_2 = 0.986$, respectively. The discharge tube T is filled with He:Ne=7:1 and $^{20}\text{Ne} : ^{22}\text{Ne}=1 : 1$ gas mixture to suppress the Lamb dip in the output power curve. M_3 is the external feedback mirror with a reflectivity of 50% to feed the output light back into the laser internal cavity. P is piezoelectric transducer which drives the external cavity feedback mirror. D_1 is photoelectric detector for measuring the laser output power. C is processing circuit.

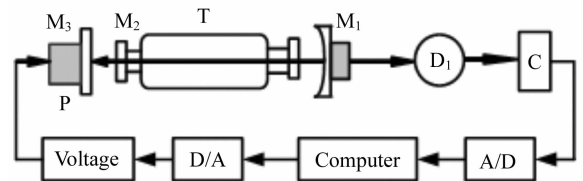


Fig. 3 Experimental setup of common optical feedback

The measuring is controlled by a computer. So the modulation of M_3 and the detecting of laser output power can be done simultaneously. The voltage driven the piezoelectric transducer changes every 40 V, the laser feedback mirror moves a half wavelength. The range of the voltage is set from 0 V to 180 V. And the laser intensity will modulate four and a half periods. The non-linearity of the piezoelectric transducer is about 10%.

The detected intensity is expressed by voltage quantity mV. The whole light's intensity

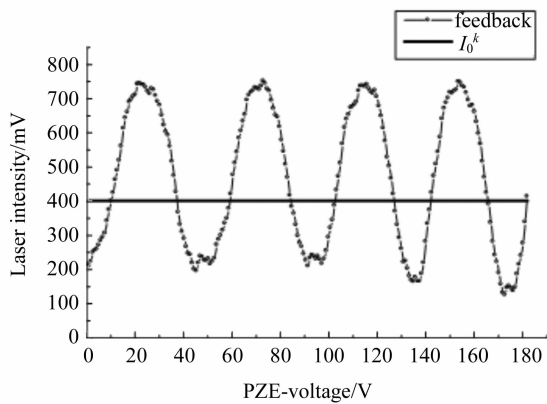


Fig. 4 Whole light's intensity curve of common experimental system

curve is shown in Fig. 4.

From the above figure we can see that, when the PZT's voltage changes from 72.8 V to 91.6 V, the voltage quantity of the laser intensity changes from 753.1 mV to 214.7 mV. The ratio is 28.6 mV/V.

4 New experimental systems of dual polarized laser optical feedback microscope

4.1 Detecting the two polarized lights' intensities separately

In this experimental system of laser optical feedback, we will separate the light to be detected into two parts according to their polarization, which are called \parallel -light and \perp -light. They will be detected separately. After the signals being processed, they will be sent into a computer to control the scanning and measuring. The experimental setup is shown in Fig. 5. W is Wollaston prism used to separate the two polarized lights. D_1 and D_2 are photoelectric detectors for measuring the \parallel -light's and \perp -light's intensities, respectively.

Before the feedback loop is connected, we adjust the laser internal cavity length to make

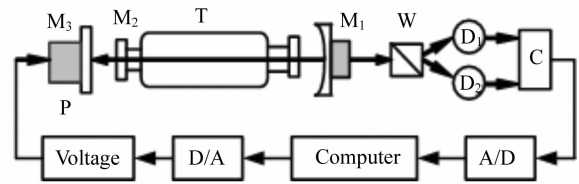


Fig. 5 Experimental setup for \parallel -light's and \perp -light's intensities being detected separately

the laser operate in two modes by PZT. The detected intensity curves from D_1 and D_2 are shown in Fig. 6.

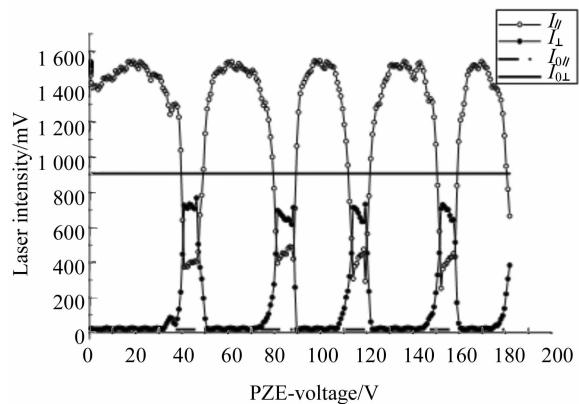


Fig. 6 \parallel -light's and \perp -light's intensity curves for the two lights being detected separately

The optical feedback curves in Fig. 4 are different from that in Fig. 6, where the two polarized lights are detected separately. Because of the modes competition between the two oscillating modes, a kind of polarized light gains advantage. At the same time, another polarized light has a certain output. From Fig. 6 we can see that, when the PZT's voltage changes from 88.6 V to 97.4 V, the intensity difference of the two polarized lights changes from 0 mV to 1524.8 mV. So the ratio is 173.3 mV/V.

4.2 Optical feedback experimental system of both o-light and e-light are fed back

In this experiment, a birefringent dual frequency He-Ne laser is used. Both of the two orthogonally polarized modes (we call the two modes o-light and e-light) are fed back. Compared with the experimental setup in Fig. 5, the

difference is that between the discharge tube T and M_1 , a uniaxial quartz crystal Q is added. Q is an element to make the laser frequency split. And the frequency difference is 117 MHz. The Wollaston Prism used here is to separate the two polarized lights.

Firstly, we modify the laser internal cavity length. When the o-light's initial intensity is equal to the e-light's initial intensity in the absence of M_3 , we stop changing the laser cavity length. Then we connect the feedback loop and drive PZT with a saw-tooth wave to make mirror M_3 feed both o-light and e-light back into the laser cavity. The detected intensity curves from D_1 and D_2 are shown in Fig. 7.

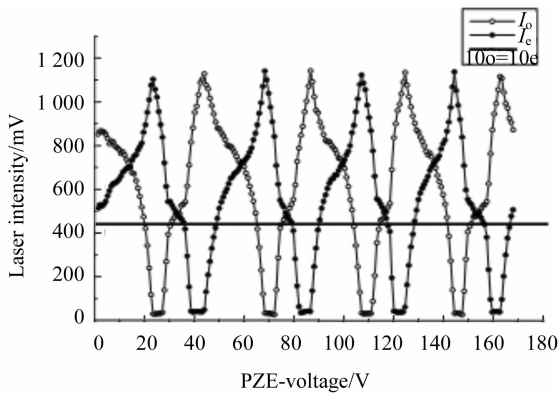


Fig. 7 o-light's and e-light's intensity curves for both of the two orthogonally polarized lights being fed back

In Fig. 7, there is also strong modes competition between o-light and e-light. However, the modes competition is fair because the two modes' initial intensities are equal. The intensities of o-light and e-light change crossly. When one light's intensity reaches its maximum, the other one's is its minimum. When one light's intensity is its minimum, the other one's intensity is its maximum. The average of the two mode's intensity is comparable. From Fig. 7 we can see that, when the voltage of PZT changes from 78.1 V to 87.3 V, the intensity difference of the two polarized lights changes from 0 mV to 1100.5 mV. The ratio is 119.6 mV/V.

4.3 Optical feedback experimental system of only o-light is fed back

The experimental setup is shown in Fig. 8. The laser is also a birefringent dual frequency He-Ne laser. The frequency difference is 117 MHz. The difference is that only one of the two orthogonal polarized lights is fed back (o-light is fed back in this experiment). The feedback mirror M_3 is replaced by a Wollaston prism and a reflector. The Wollaston Prism is used to separate the o-light and e-light. The reflector is used to feed o-light back into the laser.

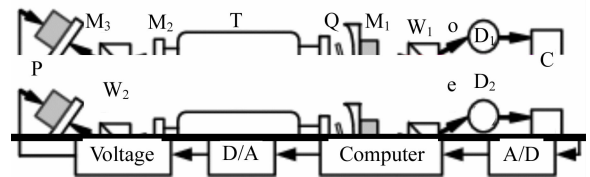


Fig. 8 Experimental setup for only o-light being fed back

We modify the laser internal cavity length first to make the o-light's initial intensity is equal to the e-light's initial intensity in the absence of M_3 . Then the feedback loop is connected. The detected intensity curves from D_1 and D_2 are shown in Fig. 9.

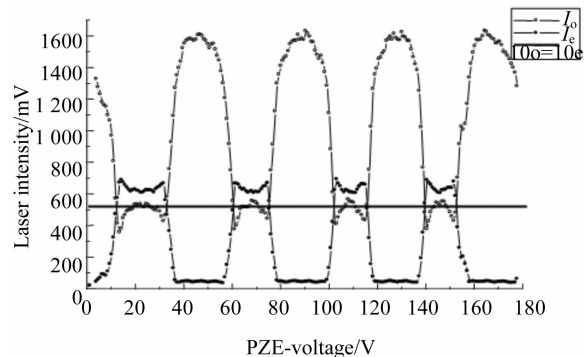


Fig. 9 o-light's and e-light's intensity curves for only o-light being fed back

Although the two modes' initial intensities are set equal with each other, modes competition between o-light and e-light is unfair in Fig. 9. From the figure we can see the o-light gains ad-

vantage in oscillation, because only o-light is fed back. The modulation depth of o-light is very large, while the modulation depth of e-light is very small. From Fig. 7 we can calculate that, when the voltage of PZT changes from 76.3 V to 87.7 V, the intensity difference of the two polarized lights changes from 0 mV to 1 643.9 mV. The ratio is 144.2 mV/V.

5 Experimental results analysis and discussion

When dual polarized laser optical feedback is brought into the normal experimental system of Laser Optical Feedback Microscope, the intensity modulation depth of the two polarized lights increases greatly because of modes competition, as shown in Fig. 6, Fig. 7 and Fig. 9. In common optical feedback system, the voltage of PZT changes every 1 V, the voltage quantity of the laser intensity changes 28.6 mV. However, when the modes competition between // -light and \perp -light is used in the dual polarized laser optical feedback experimental system, the voltage of PZT changes every 1 V, the intensity difference of the two polarized lights changes 173.3 mV; when the modes competition between o-light and e-light of birefringent dual frequency He-Ne laser is used in the dual polarized laser optical feedback experimental system, the voltage of PZT changes every 1 V, the intensity difference of the two polarized lights changes 119.6 mV; and when only o-light is fed back in the dual polarized laser optical feedback experimental system, the voltage of PZT changes every 1 V, the intensity difference of the two polarized lights changes 144.2 mV.

Because of modes competition effect, the variation of one polarized light's intensity or the intensity difference between the two polarized modes can reach as much as 1 500 units in experimental system of dual polarized laser optical

feedback microscope. After considered the modes competition effect, the modulation depth of laser intensity and the signal-to-noise are increased greatly, which makes the minimum vertical distance can be distinguished decrease greatly. So the vertical resolution of laser optical feedback microscope can be improved greatly. Compared with the vertical resolution of common optical feedback system, the vertical resolution of new dual polarized optical feedback systems have been improved 6.1 times, 4.2 times and 5.0 times, respectively.

In the three new optical feedback methods, the vertical resolution is improved differently. It relates to the structure of laser optical feedback system and the strength of modes competition. Compared with the first method, the laser has larger loss in the third method, although one polarized light gains advantage in both of the methods. So the resolution in the third method is smaller than that in the first method. Comparing the second method and the third method, the laser has larger loss in both of the two methods, but o-light gains advantage in the third method. So the resolution in the third method is larger than that in the first method. The improved resolution mainly uses the modes competition effect between the two polarized lights. And in the modes competition, if one polarized light gains advantage, the resolution will be improved greater than the situation that both of the two polarized lights gain advantage. The experimental results show that the modes competition between orthogonally polarized lights can be used to improve the vertical resolution of laser optical feedback microscope effectively.

6 Conclusion

Based on the principle of laser optical feedback microscope, three experimental system of dual polarized laser optical feedback have been presented and experimental studied. Experimen-

tal results show that using dual polarized laser optical feedback can improve the vertical resolution of Laser Optical Feedback Microscope. Compared with the vertical resolution of common optical feedback microscope system, the vertical resolution can be improved 6.1 times in the experimental system of detecting the two polarized lights' intensities separately; the verti-

cal resolution can be improved 4.2 times in the experimental system of both o-light and e-light are fed back; and the vertical resolution can be improved 5.0 times in the experimental system of only o-light is fed back. The modes competition between orthogonally polarized lights can be used to improve the vertical resolution of laser optical feedback microscope effectively.

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