Vol 18 No 3, March 2009
1674-1056/2009/18(03)/1141-06

Chinese Physics B

© 2009 Chin. Phys. Soc.
and IOP Publishing Ltd

Anisotropic optical feedback of single frequency intra-cavity He–Ne laser*

Zhou Lu-Fei(周鲁飞)[a], Zhang Bin(张 斌)[b], Zhang Shu-Lian(张书练)[a], Tan Yi-Dong(谈宜东)[a], and Liu Wei-Xin(刘维新)[a]

[a] *The State Key Laboratory of Precision Measurement Technology and Instruments, Department of Precision Instruments, Tsinghua University, Beijing* 100084, *China*

[b] *Department of Optics Science and Technology, National University of Defense Technology, Hunan* 410073, *China*

(Received 27 June 2008; revised manuscript received 16 August 2008)

This paper presents the anisotropic optical feedback of a single frequency intra-cavity He–Ne laser. A novel phenomenon was discovered that the laser output an elliptical polarized frequency instead of the initial linear polarized one. Two intensities with a phase difference were detected, both of which were modulated in the form of cosine wave and a fringe shift corresponds to a $\lambda/2$ movement of the feedback mirror. The phase difference can be continuously modulated by the wave plate in the external cavity. Frequency stabilization was used to stabilize the laser frequency so as to enlarge the measuring range and improve the measurement precision. This anisotropic optical feedback system offers a potential displacement measurement technology with the function of subdivision of $\lambda/2$ and in-time direction judgment. The three-mirror Fabry–Perot cavity model is used to present the experimental results. Given the lack of need of lasing adjustment, this full intra-cavity laser can significantly improve the simplicity and stability of the optical feedback system.

Keywords: optical feedback, single frequency, mode competition, displacement measurement
PACC: 5170, 4225, 4255L, 4225H

1. Introduction

King and Steward[1] first reported the feedback effect which showed periodic intensity tuning by feedback mirror movement. The laser intensity modulation caused by a movable external mirror was similar to that produced by a conventional optical interferometer, such as a fringe shift corresponding to an optical displacement of $\lambda/2$. The intensity modulation depth was also found to be comparable with that of an interferometer system.[2] Thus, for the advantages of simplicity, compactness, and economy, feedback lasers were widely used to measure Doppler velocity,[3−10] displacement,[11−16] distance, profile and vibration.[17−19]

Recently, considerable attention has been paid to the optical feedback of orthogonal dual frequency lasers. Li *et al*[20] first reported the intensity conversion between two orthogonal polarized modes. Fei *et al*[21,22] made some researches on the polarization hopping with a birefringence external feedback cavity. Liu *et al*[23,24] studied polarized optical feedback, and Mao *et al*[25−29] partitioned the optical feedback levels of He–Ne lasers and discussed the potential applications in displacement measurement. All these results enrich the experimental and theoretical research in optical feedback, particularly in the fields of orthogonal polarized lasers. However, the above-mentioned researches mainly focused on orthogonal polarized lasers by using birefringence element or magnets, which made the system complex and limited their application in industry for hard adjustment and instability. Also, half intra-cavity lasers were the main experimental target, little attention has been paid to full intra-cavity ones. In this paper, we investigate the anisotropic optical feedback effect of a single frequency full intra-cavity He–Ne laser with a wave plate in the external cavity. The laser initially output a linear polarized frequency. Then since the effect of anisotropic feedback, an elliptical polarized frequency was detected. Separated by a polarization beam splitter (PBS), two intensities with a phase difference were recorded, both of which were modulated in the form of cosine wave and a fringe shift corresponds to a $\lambda/2$ movement of the feedback mirror. Continuous adjusting of the phase difference was realized by rotating the wave plate. This anisotropic optical feedback approach offers a potential displace-

*Project supported by the National Natural Science Foundation of China (Grant No 60437010).

ment measurement technology with the function of subdivision of $\lambda/2$ and in-time direction judgment. Frequency stabilization was used to stabilize the laser frequency so as to enlarge the measurement range and improve the measurement precision. Theoretical analyses based on three-mirror Fabry–Perot cavity model were done and rightly justified the experimental results.

2. Experimental setup

The experimental setup is shown schematically in Fig.1.

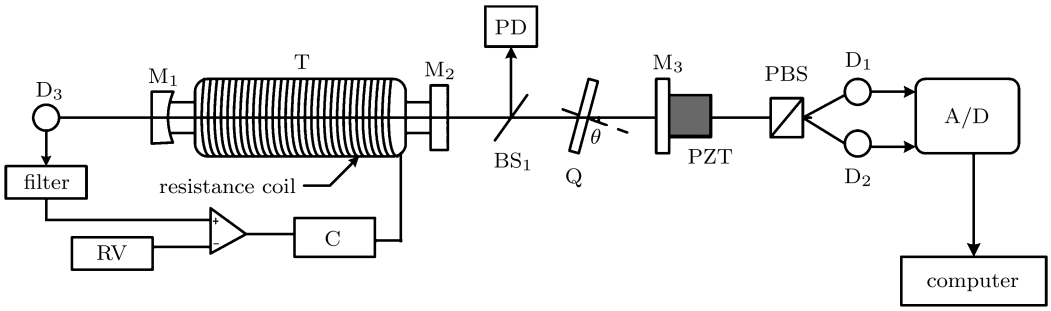


Fig.1. Experimental setup.

A full intra-cavity 632.8nm He–Ne laser is used, whose cavity length is 135mm. The inner diameter of the capillary is 0.98mm. M_1 is a concave cavity mirror, whose transmission rate is 0.5%. M_2 is the output cavity mirror with transmission rate of about 1.2%. Q is a three-level $\lambda/4$ wave plate in the feedback cavity. The angle θ is an adjustable angle between the normal direction of the wave plate and the laser axis. M_3 is the feedback mirror with reflectance rate of 55%, which is driven by a piezoelectric transducer (PZT). PBS splits the laser beam into two orthogonal polarizations. D_1 and D_2 are photo-electric detectors, whose measuring results are sent to a computer. BS_1 is a beam splitter and PD is a polarization detector which is made up of a polarizer and a $\lambda/4$ wave plate. Laser frequency stabilization is used for signal stabilization. The laser intensity detected by D_3 is compared with a reference voltage, and then the comparison signal is sent to the circuit board C, which controls the heating voltage of the resistance coil so as to control the laser cavity length as well as the laser frequency.

3. Experimental results

We first investigated the laser polarization. Without the feedback loop, we used a polarizer as the PD unit. When we rotate the polarizer, extinction was observed, which justified that the laser output a linear polarized frequency. After connecting the feedback loop, there was no extinction. We used a $\lambda/4$ wave plate in front of the polarizer and oriented the optical axis parallel to the initial polarization direction, extinction was then observed. This phenomenon justified that the laser output an elliptically polarized frequency instead of the initial linearly polarized one.

Laser intensity characteristics were also investigated. First, the wave plate was removed from the external cavity. We connected the feedback loop and drove the PZT with a triangular wave to modulate the feedback cavity. The laser intensity modulation curves are shown in Fig.2(a). The intensities are modulated in the form of cosine or quasi-cosine waveform. Due to isotropic feedback, these two waves are in-phase. Half wavelength movement of the feedback mirror will generate an undulation laser intensity fringe.

Then we put the wave plate into the feedback cavity and rotated it along the longitudinal axis to make a 45° angle between the laser polarization and the optical axes. Due to birefringence effect, the original laser mode $E_{\rm ex}$ in the external cavity would be split into two components, which were parallel to the optical axes of the wave plate. We defined it as $E_{\rm o}$ and $E_{\rm e}$. In Fig.2(b), the angle θ is 0, so the laser beam transmits rightly vertical to the wave plate, the two intensities ($I_{\rm o}$ and $I_{\rm e}$) still changes as quasi-cosine waveforms, but they are no longer in-phase but out-phase for the wave plate is a $\lambda/4$ one. Then we enlarged the angle θ step by step and got the results shown in Figs.2(c)–

(f). The phase difference is obviously modulated by the angle θ, and when θ equals to 16°, the phase difference is approximately $\pi/2$. Compared with the $\lambda/2$ resolution of a conventional optical feedback laser, this laser can achieve $\lambda/8$ resolution. And also, two quasi-cosine waveforms with phase difference of $\pi/2$ can use electronic subdivision to realize nanometre resolution.

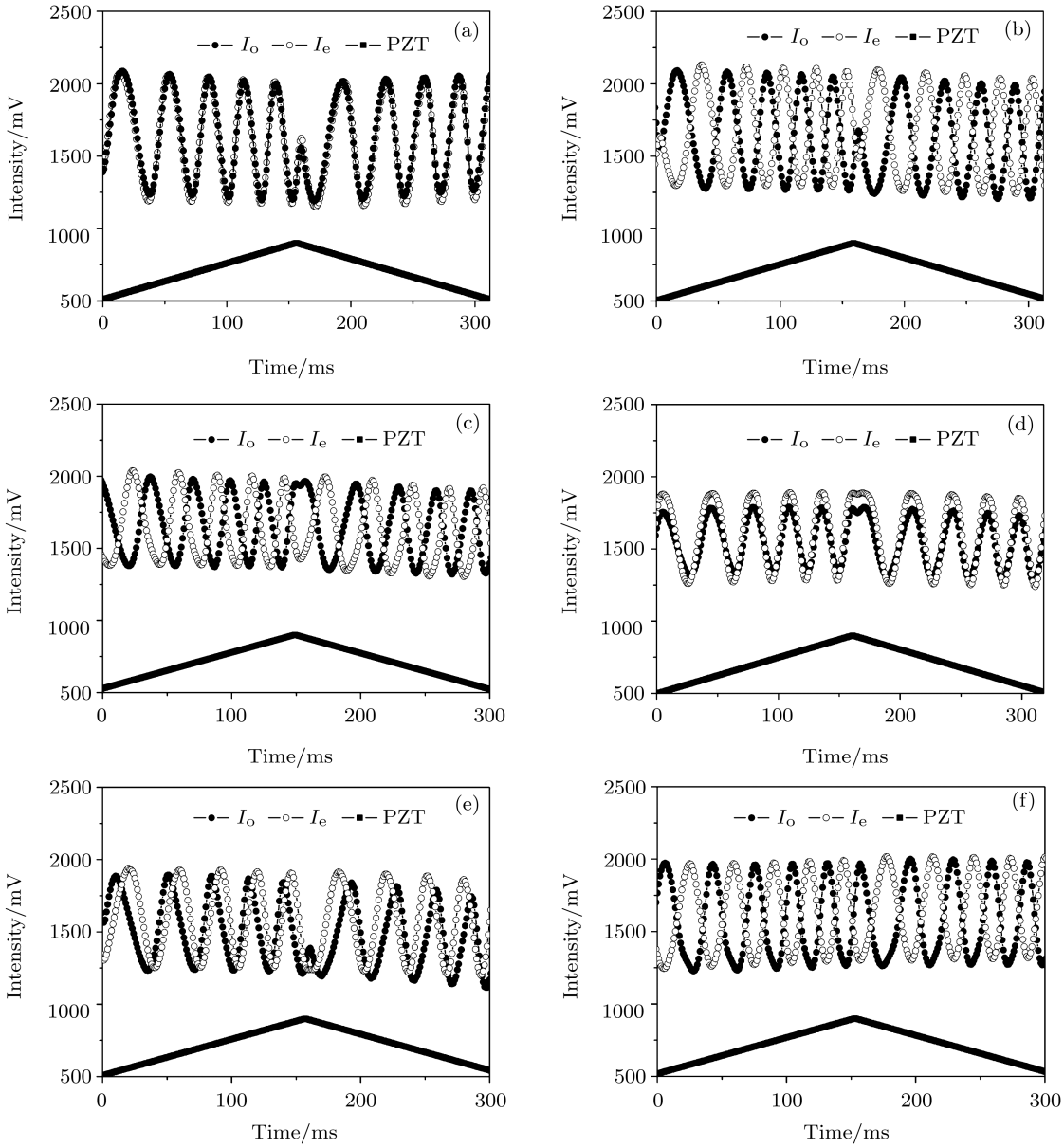


Fig.2. Intensity characteristics: (a) no wave plate; (b) $\theta = 0°$; (c) $\theta = 16°$; (d) $\theta = 22°$; (e) $\theta = 24°$; (f) $\theta = 30°$.

We choose Fig.2(c) for further analysis. When the voltage increases, the laser intensity I_o leads to I_e, while when the voltage decreases, I_o lags behind I_e. The absolute values of the phase difference on both sides of the PZT are the same. This phenomenon shows us a significant way for the judgment of direction. As a conclusion, this anisotropic laser feedback system can be used as a high-resolution and direction-interpretable displacement sensor.

4. Theoretical analysis

Considering the anisotropic optical feedback of the single-mode He–Ne laser, we use a three-mirror Fabry–Perot cavity model to present the experimental results given in the above section. Without consideration of wave plate in the external cavity, the initial electric vector $E_0(t)$ exiting from the output mirror travels a round trip in the laser internal and exter-

nal cavity. After a round trip, the final electric vector $E(t)$ can be written as

$$\begin{aligned} & E(t) \\ = & r_1 r_2 \exp\left(\mathrm{j}4\pi\nu\frac{nl}{c}+2gl\right)E_0(t) \\ & +r_1 T_2 r_3 \xi \exp\left(\mathrm{j}4\pi\nu\frac{nl+L}{c}+2gl\right)E_0(t), \end{aligned} \quad (1)$$

where r_1 and r_2 are the reflection rates of laser cavity mirror M_1 and M_2, $T_2 = 1 - r_2^2$ is the transmission rate of the laser coupled from the laser cavity to the external cavity, r_3 is the reflection rate of the feedback mirror, ν is the laser frequency, c is the light speed, n is the refractive index of the laser gas, l and L are the internal and external cavity length respectively, ξ is the feedback power ratio which is 0.55 in this anisotropic feedback system, and g is the linear gain per unit length due to the stimulated emission inside the laser cavity in the presence of feedback.

If the laser comes to equilibrium, there should be $E(t) = E_0(t)$. So we can obtain the following equation:

$$r_1 r_2 \exp\left(\mathrm{j}4\pi\nu\frac{nl}{c}+2gl\right)\left[1+\alpha\exp\left(\mathrm{j}4\pi\nu\frac{c}{L}\right)\right]=1, \quad (2)$$

where $\alpha = T_2 r_3 \xi / r_2$. So the excess gain g with optical feedback can be determined as

$$\Delta g = -\frac{\alpha}{2nl}\cos(4\pi\nu L/c). \quad (3)$$

For the birefringence effect of the wave plate in the external cavity, the original external cavity will form two different physical external cavities, which are denoted as L_o and L_e. The electric vector in the external cavity E_ex can be divided along two vertical directions as E_o and E_e, whose directions are parallel to the optical axes of the wave plate. The above-mentioned two electric fields with phase difference would separately affect the electric field in the laser cavity. Thus we also divided the initial electric vector $E_0(t)$ into two orthogonal parts, just parallel to E_o and E_e, defined as $E_{\mathrm{o}0}(t)$ and $E_{\mathrm{e}0}(t)$. With the same analysis method with Eqs.(1)–(3), we can get the excess gain with optical feedback along two orthogonal directions as

$$\begin{aligned} \Delta g_\mathrm{o} &= -\frac{\alpha}{2nl}\cos(4\pi\nu L_\mathrm{o}/c), \\ \Delta g_\mathrm{e} &= -\frac{\alpha}{2nl}\cos(4\pi\nu L_\mathrm{e}/c). \end{aligned} \quad (4)$$

Considering the birefringence effect of the wave plate, we can obtain the physical optical path difference of these orthogonal electric field as

$$\Delta L = L_\mathrm{e} - L_\mathrm{o} = (n_\mathrm{e} - n_\mathrm{o})d/\cos\theta, \quad (5)$$

where n_e and n_o are the refractive indices, d is the thickness of the wave plate, and θ is the rotation angle. Simply, the excess gain with the anisotropic external feedback can be written as:

$$\begin{aligned} \Delta g_\mathrm{o} &= -\kappa\cos\varphi, \\ \Delta g_\mathrm{e} &= -\kappa\cos(\varphi+\delta), \end{aligned} \quad (6)$$

where $\kappa = \alpha/(2nl), \varphi = 4\pi\nu L_\mathrm{o}/c$, and $\delta = 4\pi\nu\Delta L/c = 4\pi\nu(n_\mathrm{e}-n_\mathrm{o})d/(c\cos\theta)$.

The laser intensity can be expressed as[30]

$$I = I_0(1 - k\Delta g), \quad (7)$$

where k is a constant related to the laser operation parameters, and I_0 is the initial laser intensity without optical feedback. Synthetically considering Eqs.(6) and (7), we can conclude the two in-quadrature laser intensities with anisotropic external feedback as:

$$\begin{aligned} I_\mathrm{o} &= I_{\mathrm{o}0}[1+\beta\cos\varphi], \\ I_\mathrm{e} &= I_{\mathrm{e}0}[1+\beta\cos(\varphi+\delta)]. \end{aligned} \quad (8)$$

From the above equations we can see that the laser outputs two orthogonal electric fields with an adjustable phase difference. The laser will output an elliptically polarized frequency instead of the initial linearly polarized one, which is in good agreement with the experimental result. These orthogonal laser intensities are both cosine waveform and have a phase difference which can be modulated by rotation of the wave plate. For the wave plate is a three-level $\lambda/4$ one, when the angle θ is zero, the laser beam incidents on the wave plate vertically, $\delta = 4\pi\nu\Delta L/c = 13\pi$, it results in the two orthogonal intensities out-phase. Adjustable angle θ would cause an adjustable phase difference. Also, the phase relationship of these two intensities, which one leads or lags, depends on the movement direction of the feedback mirror, which can be used for the judgment of direction. The theoretical analyses are in good agreement with the experimental results.

5. Discussion

The experimental results are promising for application to precision displacement measurement with the function of subdivision of $\lambda/2$ and in-time direction judgment. When the phase difference of the intensities is $\pi/2$, processed by a trigger and counting circuit, a period of the signals can be subdivided into four parts and the resolution of $\lambda/8$ can be achieved. The direction judgment can be easily realized by the phase relationship. Compared with the direction judgment methods of the traditional optical feedback system, such as using the sign of the fast transition of the saw-tooth waveform, which is hard to realize by a circuit and will result in an acceptable measurement errors, this method can be easily realized and there is no error to be accumulated during the measurement. Furthermore, if we use resistance chain and logic subdivision, the resolution can be further improved, and nanometre measurement is prospective.

Frequency stabilization was used in this anisotropic feedback system, which can improve the measuring range and measurement precision. First, the measuring range is determined by the signal stability. The frequency stabilization can stabilize the laser frequency and make the signal be equivalent in the measurement process, resulting in an easier signal process for the circuit board so as to enlarge the measuring range. Also, frequency stabilization can decrease the wavelength fluctuation, which will decrease the measurement error and improve the measurement precision. Compared with heterodyne interferometers, thanks to the advantages of simplicity, robustness, low cost, self-aligning and single optical path, as well as needlessness of lasing adjustment, our anisotropic feedback system may take a significant character in displacement measurement.

6. Conclusion

In this paper, we explored a full intra-cavity He–Ne laser with anisotropic feedback effect, whose feedback power ratio is about 0.55. Since the effect of anisotropic feedback, the laser outputs an elliptically polarized frequency. Two orthogonal intensities with adjustable frequency difference were detected. When the phase difference is $\pi/2$, the signals can be processed and $\lambda/8$ resolution can be achieved. Also the displacement direction can be judged by the phase leads or lags. Frequency stabilization was used to stabilize the laser frequency so as to enlarge the measurement range and improve the measurement precision. Theoretical analyses based on three-mirror Fabry–Perot cavity model were done and the theoretical and experimental results were in good agreement. For the advantages of needlessness of oscillating alignment, simplicity, stability, low cost, this results show a novel foreground for displacement measurement. This anisotropic optical feedback approach can even achieve higher resolution by electric subdivision, which will further enhance the displacement measurement.

References

[1] King P G R and Steward G J 1963 *New Sci.* **17** 180
[2] Wang W M, Grattan K T V, Palmer A W and Boyle W J O 1994 *J. Lightwave Technol.* **12** 1577
[3] Rudd M J 1968 *J. Phys.* E **1** 723
[4] Churnside J H 1984 *Appl. Opt.* **23** 61
[5] Churnside J H 1984 *Appl. Opt.* **23** 2097
[6] Jentink H W, Mul F F M, Suichies H E, Aarnoudse J G and Greve J 1988 *Appl. Opt.* **27** 379
[7] Koelink M K, Slot M, Mul F F M, Greve J, Graaff R, Dassel A C M and Aarnoudse J G 1992 *Meas. Sci. Technol.* **3** 33
[8] Koelink M K, Mul F F M, Weijers A L, Greve J, Graff R, Dassel A C M and Aarnoudse J G 1995 *Appl. Opt.* **33** 1173
[9] Scalise L and Paone N 2002 *Otp. Lasers Eng.* **38** 1173
[10] Scalise L, Yu Y G, Giuliani G, Plantier G and Bosch T 2004 *IEEE Trans. Instrum. Meas.* **53** 223
[11] Tan Y D and Zhang S L 2007 *Acta Phys. Sin.* **56** 6408 (in Chinese)
[12] Yoshino Y, Nara M, Mnatzakanian S, Lee B S and Stran T C 1987 *Appl. Opt.* **26** 892
[13] Wang W M, Boyle W J O, Grattan K T V and Palmer A W 1993 *Appl. Opt.* **32** 1551
[14] Donati S, Giuliani G and Merlo S 1995 *IEEE J. Quantum Electron.* **31** 113
[15] Servagent N, Gouaux F and Bosch T 1998 *J. Opt.* **29** 168
[16] Giulian G, Norgia M, Donati S and Bosch T 2002 *J. Opt.* A: *Pure Appl. Opt.* **4** S283
[17] Bearden A, O'Neill M P, Osborne L C and Wong T L 1993 *Opt. Lett.* **18** 238

[18] Lacot E, Day R and Stoeckel F 1999 *Opt. Lett.* **24** 744

[19] Giuliani G, Bozzi-Pietra S and Donati S 2003 *Meas. Sci. Technol.* **14** 24

[20] Li L, Zhang S L, Li S Q and Xue P 2001 *Opt. Commun.* **200** 303

[21] Fei L G and Zhang S L 2004 *Opt. Exp.* **12** 6100

[22] Fei L G, Zhang S L, Li Y and Zhu J 2005 *Opt. Exp.* **13** 3117

[23] Liu G, Zhang S L, Li Y and Zhu J 2004 *Chin. Phys.* **13** 855

[24] Liu G, Zhang S L, Xu T, Zhu J and Li Y 2004 *Opt. Commun.* **241** 159

[25] Mao W, Zhang S L, Zhou L F, Liu X Y and Wang M M 2007 *Chin. Phys. Lett.* **24** 713

[26] Mao W, Zhang S L and Fei L G 2006 *Chin. Phys.* **15** 2036

[27] Mao W and Zhang S L 2006 *Chin. Phys.* **15** 340

[28] Mao W, Zhang S L, Xu T, Wan X J and Liu G 2007 *Chin. Phys.* **16** 3416

[29] Mao W and Zhang S L 2007 *Acta Phys. Sin.* **56** 1409 (in Chinese)

[30] Tan Y D and Zhang S L 2007 *Appl. Phys.* B **89** 339