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Optical feedback characteristics in a dual-frequency laser during laser cavity tuning*

Liu Gang(刘 刚)†, Zhang Shu-Lian(张书练),
Li Yan(李 岩), and Zhu Jun(朱 钧)

State Key Laboratory of Precision Measurement Technology and Instruments, Department of Precision Instruments, Tsinghua University, Beijing 100084, China

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The optical feedback characteristics in a Zeeman-birefringence dual-frequency laser are studied during the laser cavity tuning in three different kinds of optical feedback conditions: (i) only //-light is fed back; (ii) only ⊥-light is fed back; (iii) both lights are fed back. A compact displacement sensor is designed using the experimental result that there is a nearly 90 degrees phase delay between the two lights' cosine optical feedback signals when both lights are fed back into the laser cavity. The priority order that the two lights' intensity curves appear can be used for direction discrimination. The resolution of the displacement sensor is at least 79 nm, and the sensor can discriminate the target's moving direction easily.

Keywords: dual-frequency laser, optical feedback, self-mixing, displacement sensor
PACC: 4210J, 4225J, 8170G

1. Introduction

Optical feedback is the phenomenon that the laser intensity can be modulated when the laser output lights reenter into the laser cavity. It is found that the laser intensity modulation caused by a movable external mirror is similar to that produced by a conventional optical interferometer. A fringe is produced when the feedback mirror moves a displacement of half the laser wavelength.[1] Optical feedback is also called self-mixing interference. The optical feedback characteristics have been widely studied for velocity measuring,[2−4] ranging, displacement sensing,[5−11] and imaging.[12,13] Compared with the traditional interferometer, the optical feedback system is much simpler and compacter for it has only one interference channel. Theoretical models have also been created to explain the optical feedback phenomena.[14−19]

Considerable attention has been paid to the optical feedback in semiconductor lasers when designing a displacement sensor using optical feedback.[5−8] At a certain optical feedback level the optical feedback signals are sawtooth-like waves which can be used to discriminate the moving direction of the target.[6,7] But it is not very convenient to control the optical feedback level. It has been pointed out that the optical feedback in a short cavity HeNe laser belongs to the weak optical feedback level.[9] There is no need to control the optical feedback level in an optical feedback system using a short cavity HeNe laser. It is easy to obtain cosine waves at a low optical feedback level.

In this work, the optical feedback characteristics of the Zeeman-birefringence[20] dual-frequency laser[21,22] are studied under three different optical feedback conditions during the laser cavity tuning. When one kind of the two orthogonally polarized lights is fed back into the laser cavity, the intensity modulation magnitude of this kind of light is larger than that of the other. When both lights are fed back into the laser cavity, their intensity modulation magnitudes are comparable to each other and nearly the same. When both lights are fed back into the laser cavity, there is a phase delay which is $\pi/2$ between the intensity curves. This phenomenon can be used to design a displacement sensor whose resolution can reach at least 79 nm and the moving direction of the feedback mirror can be discriminated easily.

*Project supported by the National Natural Science Foundation of China (Grant No 60437030).
†E-mail: liugang98@mails.tsinghua.edu.cn

2. Experimental setup

In Fig.1 the 632.8 nm HeNe Zeeman-birefringence dual-frequency laser used has a half-intracavity. The laser cavity is 155 mm long and composed of mirrors M_1 and M_2. U is the laser tube and F is the force exerted on the transmission window plate T which is used to produce the birefringence effect. B is the magnetic field applied to the laser tube, which is parallel to the force F. The dual-frequency laser outputs two orthogonally polarized lights—//-light and $\perp$-light which are parallel and perpendicular to the magnetic field respectively. The frequency difference of the Zeeman-birefringence dual-frequency laser is 6.7MHz. The PZT P_1 is used to drive the mirror M_1 to realize the laser cavity tuning. P is the polarizer put in the external cavity which is used to feed one of the two orthogonally polarized lights back into the laser cavity. Mirror M_3 is the external feedback mirror with a reflectivity 40%. P_2 is the PZT driving mirror M_3. The external cavity consists of mirrors M_3 and M_2, whose length l is 310 mm. A Walloston prism W is used to separate the two orthogonally polarized lights whose intensities are detected by the photo detectors D_1 and D_2 respectively. F-P is a Fabry–Perot scanning interferometer which is used to observe the oscillating modes.

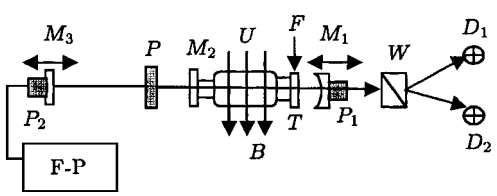


Fig.1. Optical feedback system using a Zeeman-birefringence dual-frequency laser.

3. Experimental results

We have made a research on the optical feedback characteristics of the Zeeman-birefringence dual-frequency laser during the laser cavity tuning. We tune the polarizer P to make only $\perp$-light impinge on mirror M_3. We drive mirror M_3 with a triangle signal and at the same time we drive mirror M_1 with an increasing voltage which varies very slowly. It takes 200 seconds when mirror M_1 moves half the laser wavelength, and the laser mode shifts one mode separation. The experimental results are shown in Fig.2(a) when mirror M_1 moves half the laser wavelength during the optical feedback. The vertical axis represents the laser intensity while the horizontal axis represents the time.

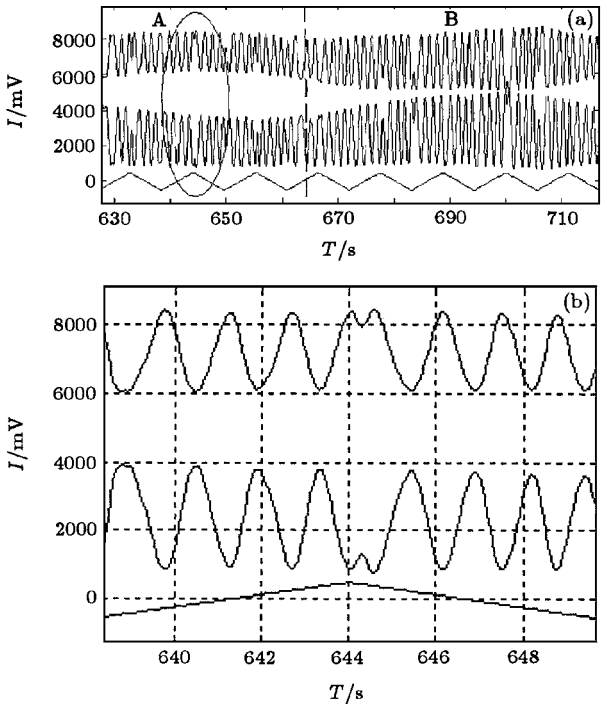


Fig.2. An observation of two orthogonally polarized lights' intensities when the $\perp$-light is fed back into the laser cavity. (a) The lights' intensity curves during the laser cavity tuning; (b) a local zoom view of the elliptical part in (a).

The //-light's intensity curve is shifted up by 4500 mV to discriminate it from the $\perp$-light's intensity curve. So the upper curve is the //-light's intensity curve, the middle curve is the $\perp$-light's intensity curve, and the lower triangle curve is the signal with which the feedback mirror is driven. In region A the laser is a single-mode laser and in region B the laser is a dual-longitudinal-mode laser. When the laser works as a dual-mode laser, either light's average intensity modulation magnitude is larger than that when it works as a single-mode laser. The minimal modulation magnitude of optical feedback signals is 1200 mV which is much larger than the laser intensity drift of about 350 mV caused by the laser cavity tuning. When we use the fringe counting method to count the fringes in Fig.2(a), the laser intensity drift caused by the laser cavity tuning makes no miscount if we set the voltage difference between the upper cut-off and the lower cut-off voltages of the hysteresis comparator higher than the maximal laser intensity drift. The laser intensity drift of the two intensity curves varies adversely. And the optical feedback fringes of both lights are also inverted to each other as shown in Fig.2(b) which is a local zoom of Fig.2(a) where a fringe is produced when the feedback mirror moves half the laser wavelength.

The intensity modulation magnitude of the ⊥-light is a little larger than that of the //-light in Fig.2. But when we tune the polarizer P to let only the //-light impinge on the feedback mirror and detect the optical feedback signals during the laser cavity tuning, the intensity modulation magnitude of the //-light is obviously larger than that of the ⊥-light as shown in Fig.3(a). The intensities of both lights are also inverted to each other as shown in Fig.3(b), which is a local zoom view of Fig.3(a).

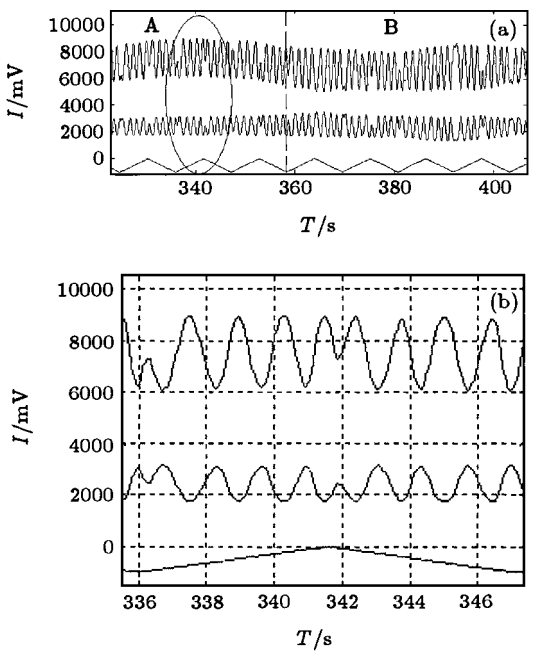


Fig.3. An observation of two orthogonally polarized light intensities when the light is fed back into the laser cavity. (a) The light intensity curves during the laser cavity tuning; (b) a local zoom view of the elliptical part in (a).

When we take off the polarizer P and feedback both lights into the laser cavity, the intensity modulation magnitude of the //-light is nearly equal to that of the ⊥-light, as shown in Fig.4(a). But both light's optical feedback fringes are not inverted to each other as shown in Fig.4(b), which is a local zoom view of Fig.4(a). There is a $\pi/2$ phase delay between the //-light's and the ⊥-light's intensity curves when the driving voltage of the feedback mirror is increased. But the phase delay is $3\pi/2$ when the driving voltage decreases. So when the driving signal increases, the //-light appears prior to the ⊥-light. When the driving signal decreases, the ⊥-light appears prior to the //-light. The information of the moving direction of the feedback mirror is related to which one of the two lights appears first. Based on this phenomenon, we can design a displacement sensor which can discriminate the moving direction of the feedback mirror easily.

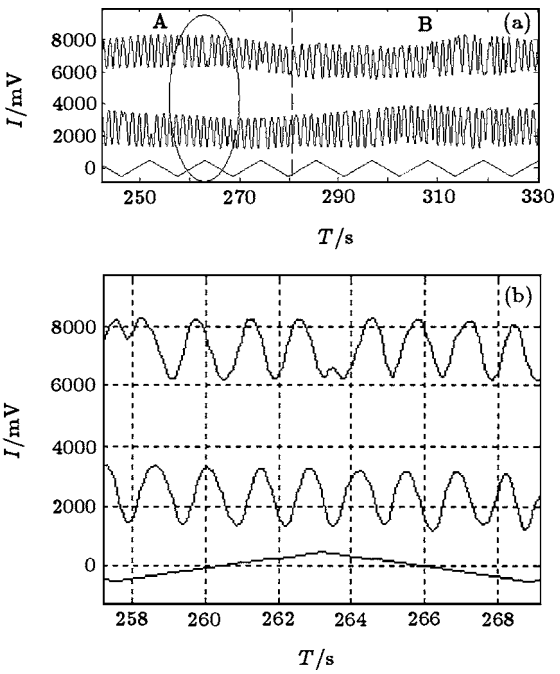


Fig.4. An observation of two orthogonally polarized lights' intensities when both lights are fed back into the laser cavity. (a) The lights' intensity curves during the laser cavity tuning; (b) a local zoom view of the elliptical part in (a).

In Fig.4(b), we can observe two cosine waves directly from the optical path, between which there is a 90 degrees phase delay. Then we can inverse the above two cosine waves and obtain another two cosine waves. We input these four cosine waves, among which there is a 90 degrees phase delay in turn, to a four-bold circuit to realize electronic division. After the electronic division we can obtain the displacement information of the feedback mirror, as shown in Fig.5.

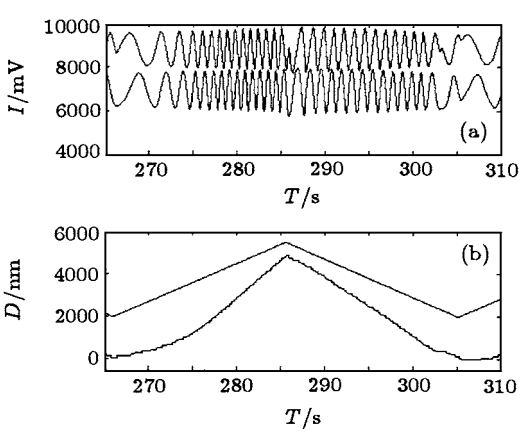


Fig.5. Displacement results after electronic division. (a) Original two input signals for the four-bold circuit; (b) displacement curve of the PZT versus time.

Both subfigures in Fig.5 are obtained at the same time. The upper curve is the //-light's intensity curve while the lower curve is the $\perp$-light's intensity curve in Fig.5(a). It is known that in an optical feedback system a fringe is produced when the feedback mirror moves a displacement of $\lambda/2$, 316.4 nm. We can count out that there are 15 fringes produced when the driving voltage of the PZT on mirror M_3 increases and the PZT's total displacement is $(\lambda/2)\times 15 = 4746$ nm. As the driving voltage is increased, the fringes turns from sparse to dense. This is caused by the nonlinearity of the PZT that drives the feedback mirror. When the curves in Fig.5(a) are processed by the four-bold circuit, the results are shown in Fig.5(b) where the displacement curve of the feedback mirror is shown as the lower curve, and the upper curve is the triangle wave that drives the PZT. With the driving voltage increasing linearly, the displacement curve does not increase linearly because of the nonlinearity of the PZT. The displacement curve during the increase of the driving voltage is different from that during the decrease of the driving voltage because of the hysteresis effect of the PZT. Both the nonlinearity and the hysteresis characteristics of the PZT can be measured by the displacement sensor designed in this work. In the displacement curve of Fig.5(b), there are two minimal points showing that the displacements are zero. It means that there is no miscount when the PZT's length varies a period. There are 62 counts detected within the period of the PZT shortening or extending. Every count measures $\lambda/8 = 79$ nm, and the PZT's total displacement measured is $(\lambda/8)\times 62 = 4904$ nm obtained by using our optical feedback system.

By using a conventional optical feedback system, the PZT's total displacement will be $(\lambda/2)\times 15 = 4746$ just by counting the 15 fringes in Fig.5(a), this is 158 nm less than the much exact value 4904 nm, because the resolution of the system used in this work is higher than the conventional optical feedback system.

4. Theoretical analysis

When a transverse magnetic field is applied to the laser which just works under two longitudinal modes, each mode is split into two orthogonally polarized frequencies with the frequency difference being 6.7MHz. When the intensity of one polarized frequency in a mode decreases, the same polarization direction frequency in the adjacent mode will increase during the laser cavity tuning. So the two frequencies in the same polarization direction for the adjacent modes make up with each other. And this is why the laser intensity drift caused by the laser cavity tuning is not obvious, compared with the optical feedback signals in the above experimental results.

The laser intensity with optical feedback can be expressed as[17]

$$I = I_0[1 + m\cos(\varphi)], \tag{1}$$

where I_0 is the laser intensity without optical feedback; m is the modulation coefficient of the optical feedback system; $\varphi = 4\pi l/\lambda$ denotes the external cavity phase delay when the light undergoes a round trip in the external cavity, and l is the external cavity length. For a dual-frequency laser, it can output two orthogonally polarized lights and the intensity of these two lights can be expressed as:

$$I_{//} = I_{0//}[1 + m\cos(\varphi)], \tag{2}$$

$$I_{\perp} = I_{0\perp}[1 + m\cos(\varphi + \Delta\varphi)], \tag{3}$$

where $I_{0//}$ and $I_{0\perp}$ are the intensities of the //-light and the $\perp$-light without optical feedback respectively. $\Delta\varphi$ is the phase delay between the two lights' intensity curves caused by the modes competition. When only one kind of the orthogonally polarized lights is fed back into the laser cavity, this kind of the polarized light's intensity varies actively with the movement of the feedback mirror. But the other kind of the polarized light's intensity will vary passively due to the modes competition between these two orthogonally polarized lights in the laser cavity. Modes competition makes the two lights' intensities inverted to each other with $\Delta\varphi = \pi$. But in the condition that both lights are fed back into the laser cavity, the intensity of either light varies actively with the movement of the feedback mirror because either of the polarized lights in the laser cavity can interfere with the light of the same polarization from the external cavity. Under this condition, the modes competition is quite complex, the two lights' intensity curves are not inverted to each other with $\Delta\varphi = \pi/2$ obtained experimentally.

5. Discussion

In the above three different optical feedback conditions, the following conclusions can be drawn:

a) When one kind of the polarized lights is fed back into the laser cavity, this kind of light's intensity modulation magnitude is larger than the other polarized light's.

b) When both lights are fed back into the laser cavity, the lights' intensity modulation magnitudes are comparable and nearly the same.

c) When one kind of the polarized lights is fed back into the laser cavity, the two lights' intensity curves are inverted to each other.

d) When both lights are fed back into the laser cavity, there is a phase delay, which is not π, between the intensity curves of the two orthogonally polarized lights. The phase delay varies π when the moving direction of the feedback mirror changes, and this can be used for direction discrimination.

It is very important that the laser intensity drift of either of the polarized lights varies not obviously as compared with the modulation magnitude of the optical feedback signals in the Zeeman-birefringence dual-frequency laser used. This characteristic can be used to eliminate the miscount caused by the laser intensity drift.

When we use the fringe counting method to measure the target's displacement in an optical feedback system, we set the voltage difference between the upper and the lower cut-off voltages of the hysteresis comparator higher than the maximal laser intensity drift but lower than the minimal modulation magnitude of the optical feedback signals. And the miscount caused by the laser intensity drift can be eliminated.

If we used the traditional HeNe laser instead of the Zeeman-birefringence dual-frequency laser by taking off the magnetic field applied to the laser tube, the intensity tuning curves of the different polarized lights without optical feedback are shown in Fig.6(a). In Fig.6, the circle point curve is the //-light's intensity curve and the dot point curve is the $\perp$-light's intensity curve. The magnitude of each polarized light's intensity drift is larger than the minimal modulation magnitude of the optical feedback signals. So if this kind of laser is used, the temperature variation always makes the laser cavity tuned and leads to miscount.

For the Zeeman-birefringence dual-frequency laser used, its intensity tuning curves of the different polarized lights without optical feedback are shown in Fig.6(b). The magnitude of each polarized light's intensity drift is not very obvious and is smaller than the minimal modulation magnitude of the optical feedback signals. So there will be no miscount although the temperature variation makes the laser cavity tuned in the application.

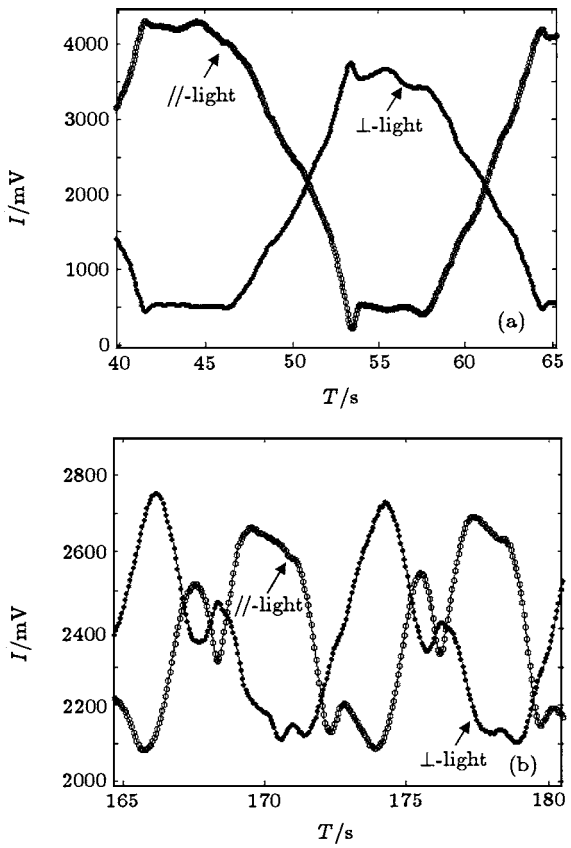


Fig.6. The intensity tuning curve of the laser (a) without the magnetic field; (b) with the magnetic field.

The compact displacement sensor designed in this work can reach a resolution of 79 nm and the direction of the feedback mirror can be discriminated easily. The optical feedback system also has a potential improvement on the measurable range. Limited by the maximal varying length of the PZT, we can only measure a maximal length about 4904 nm using the PZT that drives the feedback mirror. We have also carried out experiments when we set the external cavity at different length such as 285, 335, 360, 385, 410 mm and so on until the external cavity length reaches 535 mm. The displacement sensor designed in this work can also work well. So we can predict that this displacement sensor has a large measurement range for the good coherent characteristics of the HeNe laser.

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