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A birefringent cavity He–Ne laser and optical feedback*

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Strong modes competition makes only one of o-light and e-light oscillate in a birefringent dual-frequency laser when the angle between the crystalline axis and the laser beam is nearly zero. When the oscillated mode is in a different part of the gain curve, the detected intensity curves of o-light and e-light are quite different in the existence of optical feedback. The curves are divided into five cases. Three cases of the experimental results can be used for direction discrimination. The polarization characteristics of the birefringent cavity He–Ne laser are also discussed without optical feedback.

Keywords: dual-frequency laser, optical feedback, direction discrimination, birefringent
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1. Introduction

The optical feedback characteristics of a gas laser induced by an external optical feedback were first reported by King and Steward.[1] It was found that the laser intensity modulation in an optical feedback system was similar to that produced by a conventional optical interferometer. Much work on optical feedback has been done based on the above phenomena. The optical feedback phenomena have been widely studied for imaging,[2−7] displacement,[8−10] velocity measurement, or for vibrometry.[11−19] In order to explain the self-mixing interference phenomena, some theoretical models are presented.[8,20−26] The optical feedback characteristics of the orthogonally polarized lights have been studied by Li *et al*[27] using a single mode He–Ne laser. It is reported that the polarization direction of the laser beam is not stable with the optical feedback on. Occasionally, the laser output beam changes its polarization direction in a feedback cycle. The polarization characteristics of the laser beam cannot be controlled in a He–Ne laser with optical feedback (see Ref.[27]).

In this paper, we set up an optical feedback system using a birefringent cavity He–Ne laser. With this system, the polarization characteristics of the laser beam can be controlled easily and can be used for direction discrimination of the feedback mirror.

2. Experimental setup

Figure 1 shows the experiment setup. The 632.8 nm He–Ne birefringence cavity laser containing Ne of ^{20}Ne:^{22}Ne=1:1 has a quartz crystal Q inside the laser cavity. θ is the angle between the crystalline axis and the beam in the crystal plate, which is nearly zero degree. The laser cavity with a cavity length 145 mm is composed of mirrors M_1 and M_2. Mirror M_3 is the external feedback mirror with a reflectivity 40%. The external cavity length is 170 mm. W is a Wallaston prism which separates the different polarized lights. P_1 and P_2 are two piezoelectric transducers (PZTs) which are used to drive mirrors M_3 and M_2 respectively. The PZTs are driven by two output voltages of a D/A card indirectly. One of the output voltages (called U_1) changes 125 mV and P_1 changes a displacement of $\lambda/2$; the other output voltage (called U_2) is used to drive P_2. λ is the wavelength of the laser. D_1 and D_2 are two photoelectric detectors for measuring the intensity of polarized light. The laser intensity changes every 0.08 mW, and the photoelectric detector changes 1000 mV.

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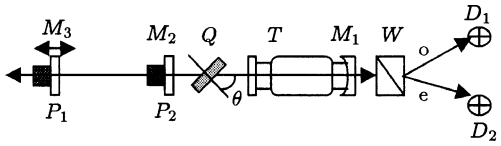


Fig.1. The experiment setup.

It is noted that there is no mode splitting when θ is between 0° and 2.8°.[28] When θ is nearly zero, the laser frequency difference is lower than 40 MHz and strong mode competition makes one of the two modes (o-light and e-light) dies out. So only one single mode can oscillate in the birefringent cavity laser used in this paper and there is no frequency difference. This kind of laser is called a frequency-locked dual-frequency laser. This phenomenon can be observed from a scanning interferometer. So the laser used is not a real birefringent dual-frequency laser but a laser with a birefringent cavity.

3. Theoretical analysis

The laser output intensity with optical feedback can be expressed as [21]

$$I = I_0\left[1 + \frac{K\beta}{L}(\cos(\phi) + \rho\cos(2\phi + \delta))\right], \quad (1)$$

where $\beta = \dfrac{t_2^2 r_3}{r_2}$, t_2 is the transmission coefficient of M_2, r_3 is the reflection coefficient of M_3, r_2 is the reflection coefficient of M_2; $\rho = r_3^2$ is the reflectivity of M_3; $\phi = 4\pi\nu\dfrac{l}{c}$ is the external cavity phase delay which is equal to the optical path along which light undergoes a round trip in the external cavity, ν is the laser frequency, c is the speed of light in vacuum, l is the external cavity length; δ is the phase difference caused by non-collimation of the external cavity. The laser intensity I consists of three parts. One is the constant part I_0 and the others are the mono-frequency part $I_0\dfrac{K\beta}{L}\cos(\phi)$ and the double-frequency part $I_0\dfrac{K\beta\rho}{L}\cos(2\phi + \delta)$. The laser intensity modulation is caused by the last two parts. The fringe frequency of optical feedback curves is determined by the mono-frequency part. The fringe is produced one when the external cavity length varies half of the laser wavelength.

Mode competition has been studied in a small frequency split dual-frequency laser.[29] It is found that in some regions of the lasing bandwidth, one mode-split frequency will extinguish due to modes competition and in the other regions two mode-split frequencies will work together. But when optical feedback is induced, what will happen has never been discussed. The laser used in Ref.[29] is a birefringent cavity dual-frequency laser and has a small frequency difference 37 MHz. In this paper we use a birefringent cavity laser and induce optical feedback. The mode competition is not similar to that in Ref.[29], as will be discussed in Section 4.

4. Experimental results

We connect the feedback loop and modify the laser cavity by driving PZT P_2 until the laser intensity is zero. The laser is of zero intensity as the single mode moves out of the gain curve. At this moment, the D/A output voltage U_2 is 1025 mV. Increasing U_2 and when U_2 is over 2335 mV, the laser intensity is zero again. So the P_2 extends a displacement of $\lambda/2$ when U_2 varies from 1025 to 2335 mV. While doing the experiments, we observe the intensity variations of o-light and e-light with U_2 increasing step by step from 1025 to 2335 mV with optical feedback. The experimental results are divided into five cases according to different U_2 variation range.

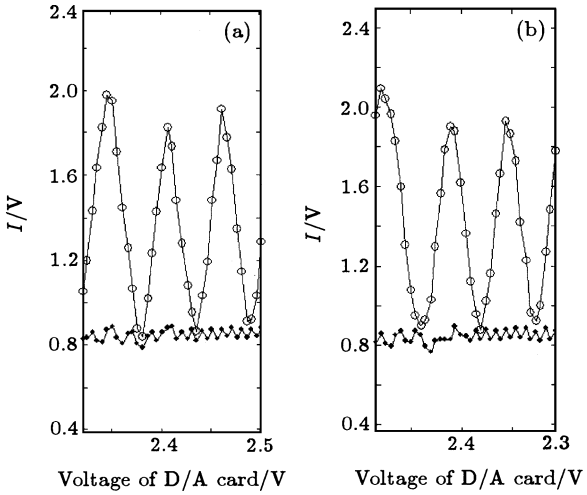


Fig.2. The laser intensity versus U_1 when U_2 is stable at one voltage between 1075 to 1295 mV. (a) U_1 is increasing; (b) U_1 is decreasing.

First, when U_2 varies from 1025 to 1075 mV, the laser intensity is zero. When U_2 varies from 1075 to 1295 mV, one polarized light (we take it as o-light) oscillates and the detected curves are shown in Fig.2. The phenomenon in Fig.2 is named as case 1 and the phenomenon in Fig.3 is named as case 2 and so on. In Fig.2 and the following figures except Fig.7, the vertical axis represents the laser intensity. The horizontal axis represents the voltage U_1. We take the

circle point curve as o-light's intensity variation curve and the dot point curve as e-light's one. In Fig.2 it is shown that o-light's fringe is produced when P_1 moves a displacement of $\lambda/2$ but e-light is of zero intensity all the time no matter whether U_1 is increasing or decreasing. So only o-light oscillates inside the laser cavity with optical feedback in case 1.

Second, in case 2, U_2 varies from 1295 to 1565 mV with the feedback loop on and the detected curves are shown in Fig.3. Whether U_1 is increasing or decreasing, o-light exists all the time and one fringe is produced when P_1 moves a displacement of $\lambda/2$. But when U_1 is increasing, e-light exists stably and varies inversely to o-light. The average intensity of e-light becomes stronger while the average intensity of o-light becomes weaker when U_2 is increasing. Figure 3(a) gives an example when the average intensity of e-light equals that of o-light. However, when U_1 is decreasing, e-light exists not very stably and the average intensity of e-light is quite low.

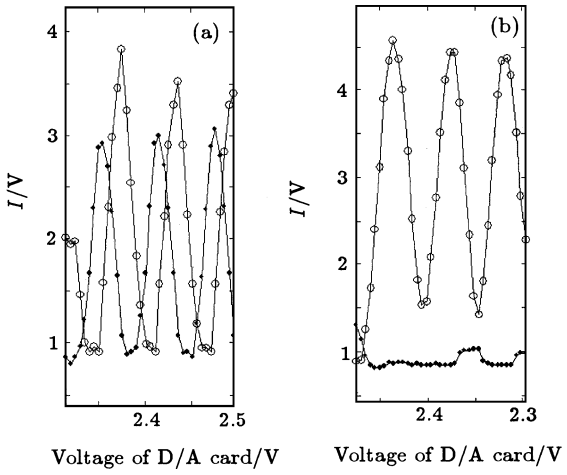


Fig.3. The laser intensity versus U_1 when U_2 is stable at one voltage between 1295 to 1565 mV. (a) U_1 is increasing; (b) U_1 is decreasing.

Then in case 3, U_2 varies from 1565 to 1895 mV with the feedback loop on and the detected curves are shown in Fig.4. No matter whether U_1 is increasing or decreasing, there exist both o-light and e-light. But when U_1 is increasing, the average intensity of e-light is much higher than that of o-light. The intensities of o-light and e-light vary inversely to each other. However, when U_1 is decreasing, the average intensity of o-light is much higher than that of e-light. Comparing Fig.4(a) with Fig.4(b), we can see they are nearly the same except that the roles played by the intensities of o-light and e-light are different.

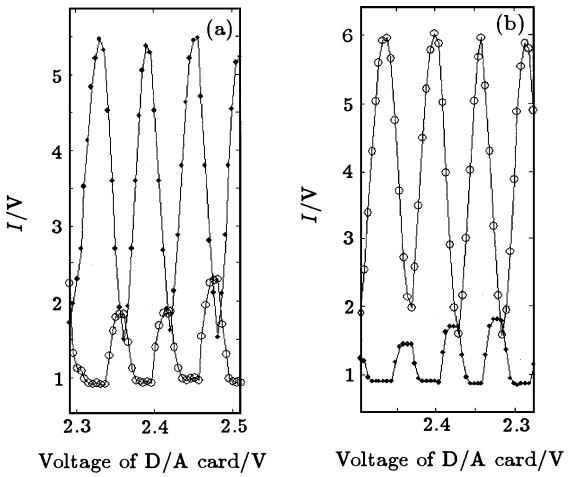


Fig.4. The laser intensity versus U_1 when U_2 is stable at one voltage between 1565 to 1895 mV. (a) U_1 is increasing; (b) U_1 is decreasing.

In case 4, U_2 varies from 1895 to 2185 mV with the feedback loop on; the detected curves are shown in Fig.5. Whether U_1 is increasing or decreasing, e-light always exists. But when U_1 is decreasing, o-light exists stably and varies inversely to e-light. The average intensity of o-light becomes weaker while the average intensity of e-light becomes stronger when U_2 is increasing. Figure 5(b) gives an example when the average intensity of e-light is equal to that of o-light. However, when U_1 is increasing, the average intensity of o-light is much lower than that of e-light, as shown in Fig.5(a).

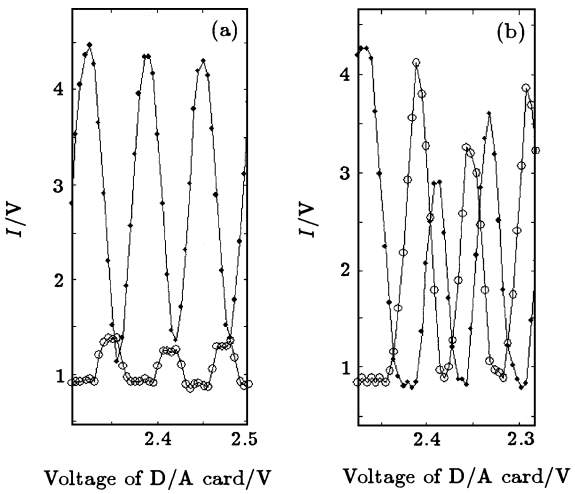


Fig.5. The laser intensity versus U_1 when U_2 is stable at one voltage between 1895 to 2185 mV. (a) U_1 is increasing; (b) U_1 is decreasing.

Finally, in case 5, U_2 varies from 2185 to 2335 mV with the feedback loop on and the detected curves are shown in Fig.6. Whether U_1 is increasing or decreasing, e-light exists and o-light has a zero intensity.

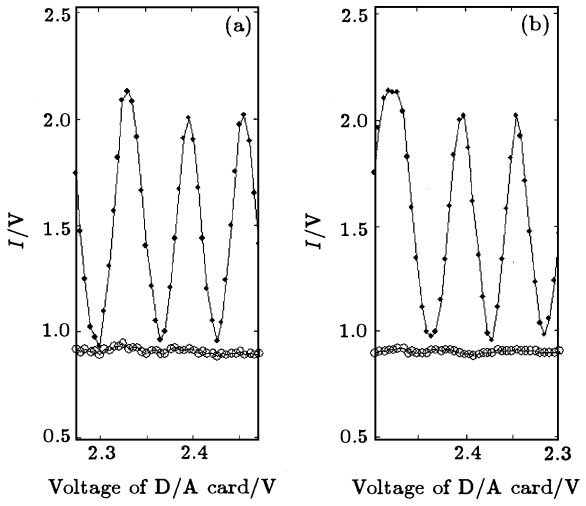


Fig.6. The laser intensity versus U_1 when U_2 is stable at one voltage between 2185 to 2335 mV. (a) U_1 is increasing; (b) U_1 is decreasing.

From the above experimental results, we can see that only one kind of polarized light exists in cases 1 and 5. With optical feedback, o-light prefers to exist alone at the left part of the gain curve, while e-light prefers to exist alone at the right part of the gain curve. In the middle part of the gain curve, both e-light and o-light exist together. We can draw a conclusion that the mode competition in the middle part of the gain curve is weaker than that in the other part of the gain curve. Compared with the experimental result in Fig.4 of Ref.[29], the mode competition characteristics in a birefringent cavity laser with optical feedback are different from those in a small frequency difference dual-frequency laser. We have carried out another experiment in order to explain the lights' characteristics in the birefringent cavity laser with optical feedback.

Removing M_3 in Fig.1, we drive P_2 and detect the laser output intensity. The curves detected are shown in Fig.7. The solid line curve is o-light's intensity variation curve and the dot point curve is e-light's. When U_2 is increasing, o-light firstly oscillates. Suddenly, o-light disappears and e-light oscillates at the right part of a period of the laser output power curve, as shown in Fig.7(a). It is shown that the polarization direction of the laser beam changes and e-light prefers to exist at the right part of the gain curve. However, when U_2 is decreasing, e-light first oscillates and suddenly disappears and simultaneously o-light oscillates, as shown in Fig.7(b). The polarization direction of the laser beam changes again, and it is shown that o-light prefers to exist at the left part of the gain curve. So the characteristics of o-light and e-light without optical feedback are the same to that with optical feedback. From Fig.7, we can also see that in the middle part of the gain curve both o-light and e-light can exist. But which light can exist in the middle part of the gain curve depends on which one oscillates first. Comparing Fig.7 with the experimental result in Fig.4 of Ref.[29], we see that the mode competition characteristics are quite different in a frequency-locked dual-frequency laser and a small frequency difference dual-frequency laser.

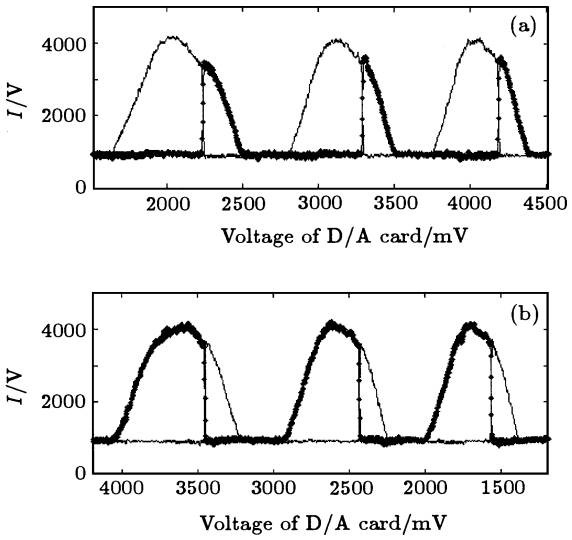


Fig.7. The laser intensity versus U_2 without optical feedback. (a) U_1 is increasing; (b) U_1 is decreasing.

5. Discussion

In cases 2, 3 and 4, the oscillating mode is in the middle part of the gain curve. We can see that o-light and e-light can exist together in the presence of optical feedback. The moving direction of the feedback mirror can be discriminated in the above three cases. In case 2, the average intensity of e-light is much stronger when U_1 is increasing than that when decreasing. In case 3, the average intensity of e-light is stronger than that of o-light when U_1 is increasing, but weaker when decreasing. In case 4, the average intensity of o-light is much weaker when U_1 is increasing than that when decreasing. So each of the above three cases can be used for direction discrimination. The above experimental results can also be observed when the external cavity changes in a scale of 6 μm which is limited by P_1.

For a traditional self-mixing interference sensing system, the optical feedback fringe is a sinusoidal wave when the feedback level is low, and a sinusoidal fringe cannot be used for direction discrimination. In this

paper, we have carried out a research on the low optical feedback characteristics of a birefringent cavity He–Ne laser. With the self-mixing interference system in this paper, we can discriminate the moving direction of the feedback mirror in three different ways. The polarization characteristics of the birefringent cavity laser are also discussed in the absence of optical feedback. It is found that o-light exists in most part of the gain curve when the laser cavity shortens, while e-light exists in most part of the gain curve when the laser cavity extends. This feature can also be used for direction discrimination.

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