Vol 15 No 2, February 2006
1009-1963/2006/15(02)/0340-07

Chinese Physics

© 2006 Chin. Phys. Soc.
and IOP Publishing Ltd

Strong optical feedback in birefringent dual frequency laser*

Mao Wei(毛 威)† and Zhang Shu-Lian(张书练)

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

(Received 31 May 2005; revised manuscript received 29 September 2005)

Strong optical feedback in a birefringent dual frequency He–Ne laser with a high reflectivity feedback mirror has been investigated for the first time. The output characteristics of two orthogonally polarized modes are demonstrated in two different optical feedback cases: one is for both modes being fed back and the other is for only one of the modes being fed back. Strong mode competition can be observed between the two modes with strong optical feedback. And when one mode's intensity is near its maximum, the other mode is nearly extinguished. When both modes are fed back into the laser cavity, the mode competition is stronger than when only one mode is fed back. The difference in initial intensity between the two orthogonally polarized modes plays an important role in the mode competition, which has been experimentally and theoretically demonstrated.

Keywords: strong optical feedback, intensity modulation, dual frequency laser, mode competition
PACC: 4210J, 4255F, 4255A

1. Introduction

The optical feedback phenomenon in lasers, also called self-mixing interference, which can dramatically affect the output intensity of lasers, was first reported by King and Steward.[1] It was found that 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 $\lambda/2$, λ being the oscillation wavelength of the laser, and the intensity modulation depth was also found to be comparable with that of a conventional interferometric system.[2] Compared with conventional interference, the self-mixing interference system has not only similar phase sensitivity and modulation depth ratio, but also inherent simplicity, compactness and robustness as well as self-aligning capability. Thus, much research based on self-mixing interference has been carried out. And it has been widely used in the fields of Doppler velocity measurement,[3−10] displacement,[11−15] imaging and vibration.[16−18] To explain the self-mixing interference phenomena, some theoretical models have been proposed.[12,19−22]

In recent years, much attention has been paid to the optical feedback of orthogonally polarized dual frequency lasers. Li *et al* [23] first reported the total light's intensity characters using a birefringent dual frequency laser with the reflectivity of an external feedback mirror being 50%. Liu *et al* have made some research on the variations of different polarized modes' intensities in a birefringence dual frequency laser[24,25] and birefringence-Zeeman dual frequency laser[26] with the reflectivity of a feedback mirror being 40%. Fei and Zhang[27] researched the phase relationship between the two modes' intensity curves in the optical feedback with the reflectivity of a feedback mirror being 20%. However, all the researches focus on characteristics of weak optical feedback only. Little attention has been paid to the cases of different optical feedbacks.

In scientific research and in the manufacturing industry, the reflectivity of the processing surface of some materials, such as nanometre material, reaches about 90%. So, studying strong optical feedback is of significance. In this paper, the optical feedback with the reflectivity of an external feedback mirror being

*Project supported by the Major Program of National Natural Science Foundation of China (Grant No 60438010).
†E-mail: maow03@mails.tsinghua.edu.cn

as high as 88% in a birefringent dual frequency He–Ne laser is studied for the first time. We carry out the experiments in two different optical feedback cases: one is for both modes being fed back and the other is for only one of the modes being fed back. In each case, we use different initial intensities of the two modes to research the optical feedback of orthogonally polarized modes in detail. Both modes' intensities and the laser power output are also discussed and analysed. Strong mode competition between these two modes can be obviously observed and the experimental results show that the optical feedback level and the initial intensity of mode play important roles in the mode competition. When both modes are fed back and their initial intensities are equal, the intensity curve of laser power output in a period has two peaks with the same size, which is greatly different from that of the weak optical feedback. The fringe frequency of the optical feedback signal can be doubled. So it can double the resolution of a self-mixing system. Based on these new phenomena, the potential applications of the experimental results are also discussed.

2. Experimental setup

The experimental setup is shown schematically in Fig.1. A 632.8 nm He–Ne laser with a half-intracavity is used. The cavity consists of a plane mirror M_1 and a concave mirror M_2 that has a radius of 1m. Their reflectivities are R_1=0.990 and R_2=0.995, separately. The discharge tube T is filled with He:Ne=7:1 and ^{20}Ne:^{22}Ne=1:1 gas mixture to suppress the lamb-dip in the power output curve. QC is a uniaxial quartz crystal inside the laser cavity, with which the half-intracavity forms an orthogonally polarized dual frequency laser. Due to the birefringent effect of QC, a single mode of the laser can be split into two orthogonally polarized modes (we call the two modes o-light and e-light). θ is the angle between the crystalline axis of QC and the laser axis, which determines the difference in frequency between the two modes. In this experiment, we obtain a frequency difference of 300 MHz. M_3 is an external feedback mirror with a reflectivity of as high as 88%. The laser cavity length L is 155 mm and the external cavity length l is 195 mm. PZT_1 and PZT_2 are two cannular piezoelectric transducers that drive the mirrors to modify the laser cavity length and the external cavity length, respectively. W_1 and W_2 are Wollaston prisms used to separate the two orthogonally polarized modes. BS_1 and BS_2 are beam splitters with a reflectivity of 45%. F-P is a Fabry–Perot scanning interferometer and used to observe the mode distribution. D_1, D_2 and D_3 are photoelectric detectors for measuring intensities of the o-light, e-light and the total light, respectively. The laser power output is 0.45mW in the absence of M_3.

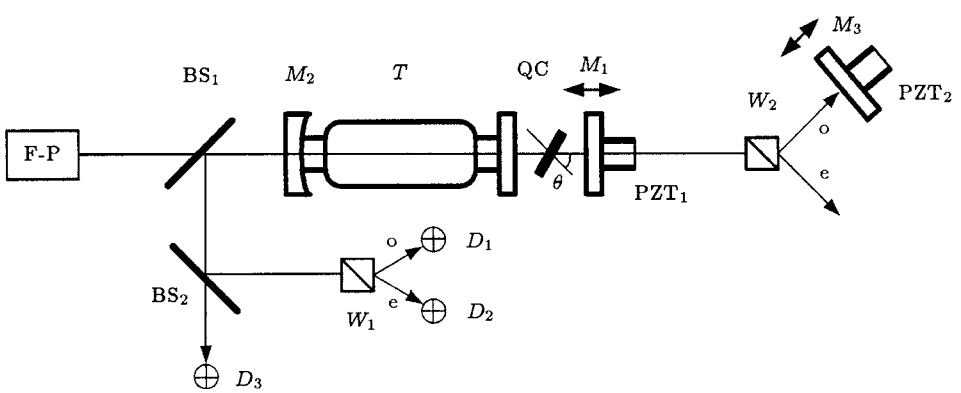


Fig.1. Experimental setup.

3. Experimental results

Two kinds of experiments are carried. One is for only one of the modes being fed back, and M_3 feeding only the o-light back into the laser cavity by using the Wollaston prism W_2. The other is for both the o-light and e-light being fed back into the laser cavity without separating.

At first, we modify the laser cavity length by driving PZT_1. When the initial intensity of o-light is equal to that of e-light in the absence of M_3, we stop changing the laser cavity length. Then we connect the feedback loop and drive PZT_2 with a saw-tooth wave to make mirror M_3 feed the o-light back into the laser cavity. In this situation, we detect the output intensities of the two orthogonally polarized lights and the total light. The experimental results are shown in Fig.2(a).

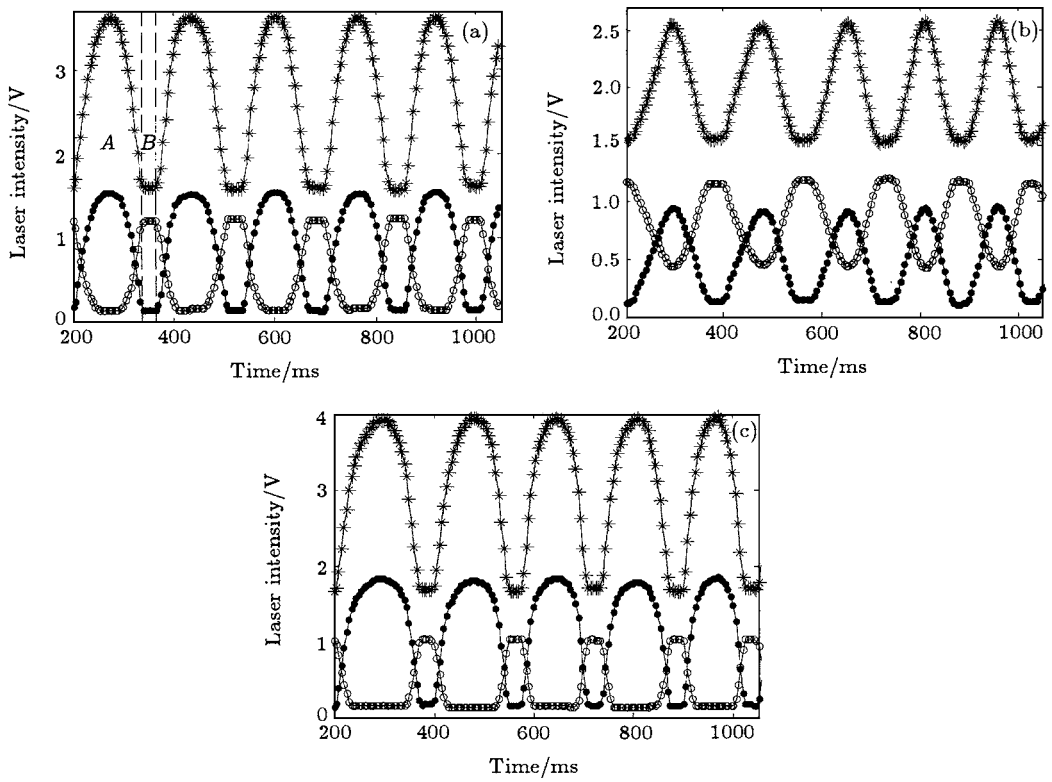


Fig.2. Intensities of the o-light, e-light and total light with only the o-light fed back (a) when the initial intensity of the o-light is equal to that of the e-light; (b) when the initial intensity of the o-light is lower than that of the e-light; (c) when the initial intensity of the o-light is bigger than that of the e-light.

In Fig.2(a) and also in the following other figures, the vertical axis represents the laser intensity and the horizontal axis represents the time. The solid-circle curve is for the o-light intensity. The open-circle curve is for the e-light intensity. In order to discern these three light intensity curves easily, the starred curve is shifted up along the vertical axis by 0.3V in Fig.2. And we take the starred curve as the total light intensity variation curve. Figure 2(a) shows that in a period corresponding to the feedback mirror moving a displacement of half the laser wavelength, the intensity modulation curves can be divided into two regions: Region A where the intensities of two modes are both modulated by the length of the external cavity, and Region B where none of the mode intensities is modulated. In Region A, the intensities of o-light and e-light are changing alternatively. When the o-light intensity is close to its maximum, the e-light intensity is zero. While the e-light intensity reaches its maximum, the o-light intensity is zero, which is because of the strong mode competition. We can observe from the Fabry–Perot scanning interferometer easily that when one mode is near its maximal intensity, the other will be extinguished. The total light intensity variation curve is like a cosine waveform. In Region B, the e-light intensity reaches its maximum and keeps invariable, while the o-light is extinguished. The total light intensity keeps invariable too but in its minimal value.

Then we drive PZT_1 to modify the laser cavity length to make the initial intensity of the o-light is lower than that of the e-light in the absence of M_3. We connect the feedback loop, and the experimental results are shown in Fig.2(b). The curve is still possessed of a region exhibiting that the e-light and the total light intensities keep invariable in a period. In the other regions, the intensities of o-light and e-light change alternatively too. When the e-light intensity reaches its maximum, the o-light intensity is zero. But when the o-light intensity reaches its maximum, the e-light intensity drops down to its minimum. Compared with Fig.2(a), the mode competition is not strong enough to make the e-light extinguished. The e-light is in a more favourable situation to oscillate than the o-light. The total light intensity variation curve is also like a cosine waveform but its modulation depth is much shallower than that in Fig.2(a).

Finally, we drive PZT_1 to make the initial intensity of the o-light bigger than that of the e-light. We connect the feedback loop, and the experimental re-

sults are shown in Fig.2(c). Comparing Fig.2(c) with Fig.2(a), we can find that they are almost the same except that the o-light is in a more favourable situation to oscillate than that in Fig.2(a).

In the second type of experiment, we take off W_2 and re-dispose the mirror M_3 to feed back both the o-light and e-light into the laser cavity without separating. We also drive PZT_1 to modify the laser cavity length to change the ratio between initial intensities of the o-light and e-light. Then we connect the feedback loop. The experimental results are shown in Fig.3. In order to discern the three light intensity curves easily, the starred curve is shifted up along the vertical axis by 2.0V.

In Fig.3(a), the two mode intensity curves reveal that only one mode can oscillate mostly in a period. When the o-light begins to oscillate, the e-light will be extinguished. And when the o-light begins to be extinguished, the e-light will oscillate. They oscillate alternatively. It also can be observed from the Fabry–Perot scanning interferometer that when one mode jumps out, the other disappears. It is hard for them to oscillate at the same time because of the strong mode competition. When one of them can oscillate, the o-light (or the e-light) intensity curve is of cosine waveform. The total light intensity curve is also detected, which has two peaks with the same size in a period of the optical feedback curve. The intensity modulation depth of either mode is comparable to that of the total light.

In Fig.3(b), the initial intensity of the o-light is lower than that of the e-light. Strong mode competition can also be observed in which only one mode can oscillate mostly in a period. The o-light and the e-light are oscillating alternatively too. But the modulation depth of the o-light intensity is not much deeper than that of the e-light intensity. The e-light is in a more favourable situation to oscillate. The total light intensity curve also has two peaks but not with the same size. Compared with Fig.3(a), the modulation depth of the total light intensity is much deep.

In Fig.3(c), the initial intensity of the o-light is bigger than that of the e-light. Comparing Fig.3(c) with Fig.3(b) shows that the curves of the o-light and e-light are symmetrical to each other but the effect of o-light and e-light are changed accordingly.

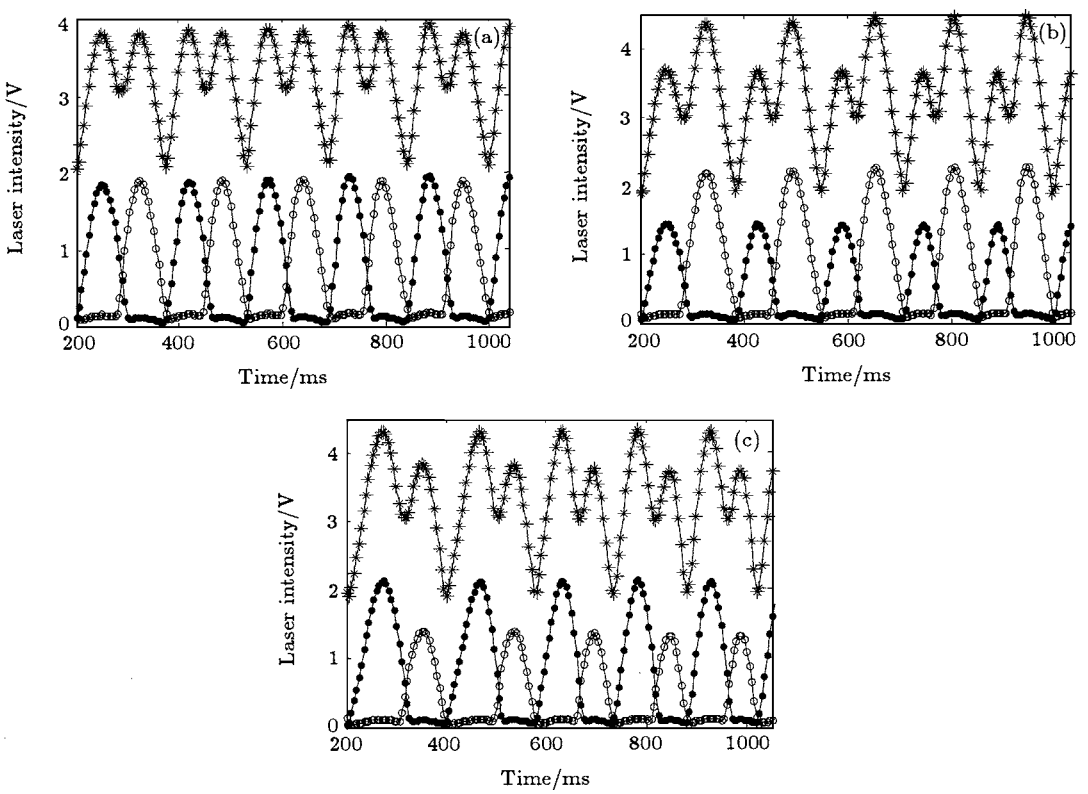


Fig.3. Intensities of the o-light, e-light and total light with both modes fed back (a) when the initial intensity of the o-light is equal to that of the e-light; (b) when the initial intensity of the o-light is lower than that of the e-light; (c) when the initial intensity of the o-light is bigger than that of the e-light.

4. Theoretical analysis

In the presence of optical feedback, according to the self-consistency of standing wave cavity, the re-injected light will cause a change in the threshold gain of the laser as follows:[19,20]

$$\Delta g = g - g_0 = -\frac{\xi}{L}\cos\phi, \tag{1}$$

where g and g_0 are the laser threshold gain with and without optical feedback respectively, ξ is proportional to the reflectivity of external feedback mirror, L is the laser cavity length, and $\phi = 4\pi\nu l/c$ denotes the external cavity phase delay when the light undergoes a round trip in the external cavity.

Because the two orthogonally polarized lights share the same laser gain available in the laser cavity, we can obtain[23]

$$\Delta g_{\rm o} = -\Delta g_{\rm e} = -\frac{\xi}{L}\cos\phi, \tag{2}$$

where $\Delta g_{\rm o}$ and $\Delta g_{\rm e}$ are o-light and e-light gain variations, respectively. This is due to the mode competition between the two orthogonally polarized lights.

The laser intensity with optical feedback can be expressed as[19]

$$I = I_0(1 - k\Delta g), \tag{3}$$

where k is a constant, I_0 is the laser intensity without optical feedback. In Eq.(3), there must exist $1 - k\Delta g \geq 0$, for there is no negative intensity.

Substituting Eq.(2) into Eq.(3), we can express the laser intensity of o-light $I_{\rm o}$ and that of e-light $I_{\rm e}$, respectively as

$$I_{\rm o} = I_{0o}(1 + m\cos\phi), \tag{4}$$

$$I_{\rm e} = I_{0e}(1 - m\cos\phi), \tag{5}$$

where $m = k\xi/L$ is the modulation coefficient of the optical feedback system, $I_{0\rm o}$ and $I_{0\rm e}$ are the laser intensities of o-light and e-light without optical feedback. So the difference in intensity between o-light and e-light is determined by their initial intensities and the reflectivity of external feedback mirror. It is the difference in initial intensity between the two orthogonally polarized lights that strongly affects their mode competition. When the intensity difference is big enough, it must be considered that the mode competition will make the weak light have no gain to oscillate.

In the first optical feedback case, in which only the o-light is fed back into the laser cavity, as $\Delta g_{\rm o}$ and $\Delta g_{\rm e}$ change alternatively, the laser intensities of the two lights will change alternatively, too. From Eq.(4) and Eq.(5), we can obtain that when one light intensity reaches its maximum, the other reaches its minimum, and when one light intensity reaches its minimum, the other reaches its maximum, features of which are just the same as those of the curves in Fig.2(b). Compared with Fig.2(b), the initial intensities of the o-light are much bigger than those in Fig.2(a) and Fig.2(c). So the intensity differences are larger. Strong mode competition should be considered in which when the o-light intensity is near its maximal intensity, the e-light intensity is zero, the features of which are just the same as those of the curves in Region A in Fig.2(a) and Fig.2(c). When o-light intensity is zero, there is no light feedback into the laser cavity. The laser intensity will not be modulated. So the e-light intensity will remain invariable when the o-light is extinguished. Based on these considerations the simulated intensity curves of the two orthogonally polarized modes are presented in Fig.4, which shows two examples. One is for the initial intensity of the o-light being equal to that of the e-light and the other is for the initial intensity of the o-light being lower than that of the e-light, while in both cases fed back is only the o-light. The simulation results in Fig.4 are in agreement with the experimental results in Fig.2(a) and Fig.2(b).

In the second optical feedback case, both modes are fed back into the laser cavity, and their intensities are modulated. From Eq.(4) and Eq.(5), we can see that when two modes are both fed back the difference in intensity between the two modes is much larger. The mode competition is so strong that only one mode can oscillate mostly in a period. When one mode is extinguished, the intensity of the other mode is of cosine wave just the same as the curves in Fig.3. Because of the difference in initial intensity between the two modes in Fig.3, the two peaks of the total light intensity curve are not the same in size all the time. The simulated intensity curves of the two orthogonally polarized modes are shown in Fig.5 in two cases. One is for the initial intensity of the o-light being equal to that of the e-light and the other is for the initial intensity of the o-light being lower than that of the e-light, while both modes are fed back in both cases. The starred curve denoting the variation of the total light intensity is shifted up along the vertical axis by 2.0V. The simulation results in Fig.5 are in good agreement with the experimental results in Fig.3(a) and Fig.3(b).

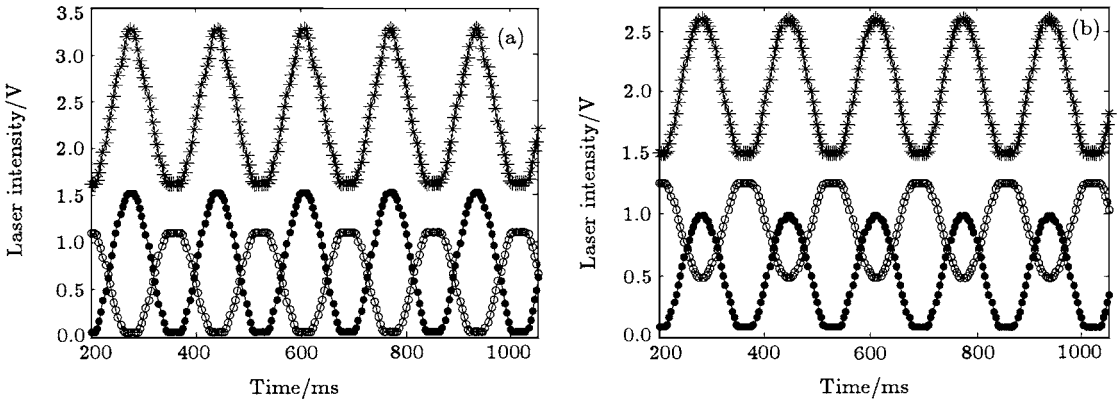


Fig.4. Simulation results of the o-light, e-light and the total light intensities with only the o-light fed back (a) when the initial intensity of the o-light is equal to that of the e-light; (b) when the initial intensity of the o-light is lower than that of the e-light.

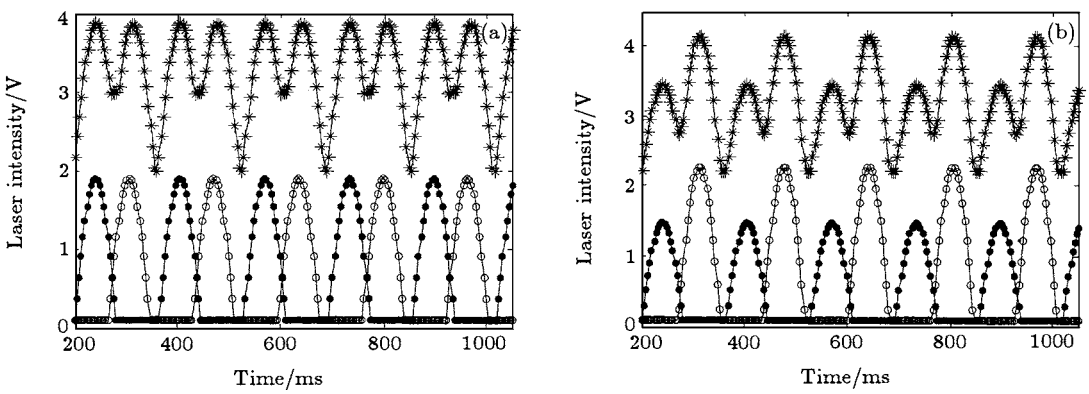


Fig.5. Simulation results of the o-light, e-light and the total light intensities with both modes fed back (a) when the initial intensity of the o-light is equal to that of the e-light; (b) when the initial intensity of the o-light is lower than that of the e-light.

5. Discussion

In this paper, the optical feedback characteristics of two orthogonally polarized modes have been studied in a strong optical feedback regime, with the reflectivity of an external feedback mirror reaching as high as 88%. Strong mode competition can be obviously observed, especially when both modes are fed back. The difference in intensity between the two orthogonally polarized modes affects their mode competition strongly, which is determined by their initial intensity and the optical feedback strength. In Fig.2, because of the difference in initial intensity between o-light and e-light, their mode competition is absolutely different. In the second optical feedback case, both lights are all fed back, no matter what their initial intensities are, there still exists the strong mode competition. Compared with the work in Refs.[22–24], which was done with the reflectivity of feedback mirror being as low as 20%, 40% and 50%, the mode competition is so strong that when one light begins to oscillate, the other will be extinguished. It is hard for them to oscillate together. And the sizes of the sub-peaks are determined by the initial intensities of o-light and e-light.

Mode competition for the available laser gain must be considered during the optical feedback. The two modes share the same available laser gain, and the stronger one will suppress the weaker one. It makes the mode competition for the available laser gain possible. If we do not consider mode competition, the external cavity phase difference $\Delta\phi$ between o-light and e-light can be expressed as

$$\Delta\phi = |\phi_{\mathrm{o}} - \phi_{\mathrm{e}}| = 2\pi \frac{l}{L} \frac{\Delta\nu}{\Lambda}, \tag{6}$$

where $\Delta\nu$ is frequency difference between the two orthogonally polarized modes, and Λ=1000MHz is longitudinal mode spacing of laser. In our experiment, the calculated result is $3\pi 4$. But based on the experimental results, the frequency difference is about $\pi/2$. It is the mode competition that affects the phase relationship between the two intensity modulation curves.

In Fig.2(a), the modulation depth of the total output light intensity is larger than that of either light's intensity. This feature can be used to improve the self-mixing system sensitivity for displacement. If we want to obtain one light intensity curve which keeps invariable in its maximum intensity, we can just fed one light back into the laser cavity as shown in Fig.2. When both modes are fed back, the total output light intensity in a period has two peaks with the same size as shown in Fig.3(a). So the fringe frequency of the optical feedback signal can be doubled. It also can double the resolution of a self-mixing system. For a 632.8-nm He–Ne laser, the system has a resolution of 160-nm. For the o-light or the e-light intensity in Fig.3, they can be used to generate the pulse signals. A pulse signal is produced when the feedback mirror moves a displacement of $\lambda/4$, which gives another way to generate pulse signals.

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, Graaff R, Dassel A C M and Aarnoudse 1995 *Appl. Opt.* **33** 5628
[9] Scalise L and Paone N 2002 *Opt. 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] Yoshino Y, Nara M, Mnatzkanian S, Lee B S and Stran T C 1987 *Appl. Opt.* **26** 892
[12] Wang W M, Boyle W J O, Grattan K T V and Palmer A W 1993 *Appl. Opt.* **32** 1551
[13] Donati S, Giuliani G and Merlo S 1995 *IEEE J. Quantum Electron.* **31** 113
[14] Servagent N, Gouaux F and Bosch T 1998 *J. Opt.* **29** 168
[15] Giulian G, Norgia M, Donati S and Bosch T 2002 *J. Opt. A: Pure Appl. Opt.* **4** S283
[16] Bearden A, O'Neill M P, Osborne L C and Wong T L 1993 *Opt. Lett.* **18** 238
[17] Lacot E, Day R and Stoeckel F 1999 *Opt. Lett.* **24** 744
[18] Giuliani G, Bozzi-Pietra S and Donati S 2003 *Meas. Sci. Technol.* **14** 24
[19] Wang W M, Grattan K T V, Palmer A W and Boyle W J O 1994 *J. Lightwave Technol.* **12** 1577
[20] Wang C L, Wu J and Lin J T 2002 *Chin. Phys.* **11** 1033
[21] Wang C L, Wu J and Lin J T 2003 *Chin. Phys.* **12** 1120
[22] Liu G, Zhang S L, Zhu J and Li Y 2003 *Opt. Commun.* **221** 387
[23] Li L, Zhang S L, Li S and Xue P 2001 *Opt. Commun.* **200** 303
[24] Liu G, Zhang S L, Li Y and Zhu J 2004 *Chin. Phys.* **13** 855
[25] Liu G, Zhang S L, Li L, Li Y and Zhu J 2003 *Opt. Commun.* **231** 349
[26] Liu G, Zhang S L, Xu T, Zhu J and Li Y 2004 *Opt. Commun.* **241** 159
[27] Fei L G and Zhang S L 2004 *Opt. Exp.* **12** 6100