Vol 16 No 11, November 2007
1009-1963/2007/16(11)/3416-07

Chinese Physics

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Optical feedback characteristics in a helium neon laser with a birefringent internal cavity*

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(Received 4 November 2006; revised manuscript received 9 May 2007)

The output characteristics of optical feedback in a helium–neon laser with a birefringent internal cavity are studied systematically in five different regions of the gain curve for the two orthogonally polarized modes. When the laser operates in the two end regions of the laser gain curve, one of the two orthogonally polarized modes will be a leading one in optical feedback. Strong mode competition can be observed. However, when the laser operates in the middle region of the laser gain curve, the two modes can oscillate equally with optical feedback. Besides the intensity of the two polarized lights, the total light intensity is also studied at the same time. M-shaped optical feedback curves are found. Particularly, when the average intensities of the two lights are comparable, the intensity modulation curve of the total light is doubled, which can be used to improve the resolution of an optical feedback system.

Keywords: optical feedback, birefringent internal cavity, self-mixing interference, mode competition
PACC: 4255F, 8170G, 4210J

1. Introduction

Optical feedback, also called self-mixing interference, has been widely studied in gas lasers,[1−8] microchip solid lasers[9−12] and semiconductor lasers.[13−16] Many new optical feedback characteristics are found and widely used in the fields of displacement sensor,[7,13,15,17−20] Doppler velocity measurement,[2,21−23] imaging and vibration.[10,24] To explain these phenomena, some theoretical modes[25−28] also have been proposed.

Recently, considerable attention has been paid to the optical feedback of orthogonally polarized dual-frequency lasers. Li *et al*[29] first reported the intensity conversion between the two modes in a dual-frequency laser. Fei *et al*[5,30] have made some research on the polarization hopping with a birefringent external feedback cavity. Liu *et al*[31] studied polarized optical feedback. All these results enrich the experimental and theoretical researches in optical feedback, particularly in the field of orthogonally polarized optical feedback. However, little attention has been paid to the oscillating positions of the two orthogonally polarized modes on the gain curve. Furthermore, optical feedback in a laser with a birefringent internal cavity, which can be used as a single-mode laser or a dual-frequency laser, has not been studied.

In this paper, we systematically study the intensity characteristics of optical feedback in a helium–neon laser with a birefringent internal cavity. Novelty intensity output characteristics of the two orthogonally polarized modes and the total light are presented. Strong mode competition can be observed. M-shaped intensity modulation curves of the total light have been found, which are unique and only observed in our experiment. Especially, when the two polarized modes run symmetrically around the centre of the laser gain curve, average intensities of the two modes are comparable and the modulation depth of each peak of the M-shaped curves is also comparable to that of the total light. Thus, the optical feedback fringe of the total light can be doubled. The doubled fringe is independent of the external cavity length, which can be used to improve the resolution of the optical feedback system greatly in a considerable measurement range. Theoretical analysis is presented, which can well explain the experimental results. The potential use of the experimental results is also discussed.

*Project supported by the Major Program of the National Natural Science Foundation of China (Grant No 60438010).
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2. Experimental setup

The experimental setup is shown schematically in Fig.1. A 632.8 nm helium-neon laser with a birefringent internal cavity is used. The cavity consists of a concave mirror M_1, a plane mirror M_2, a discharge tube T and a uniaxial quartz crystal QC inside the laser cavity. θ is the angle between the crystalline axis of QC and the laser axis, which determines the frequency difference between the two modes. T is filled with gas mixtures of He:Ne = 7:1 and ^{20}Ne:^{22}Ne = 1:1 to suppress the lamb-dip in the power output curve. The internal cavity length l is 160 mm. M_3 is an external feedback mirror with a reflectivity of 25.8%. M_2 and M_3 compose the external feedback cavity with a length L 200 mm.

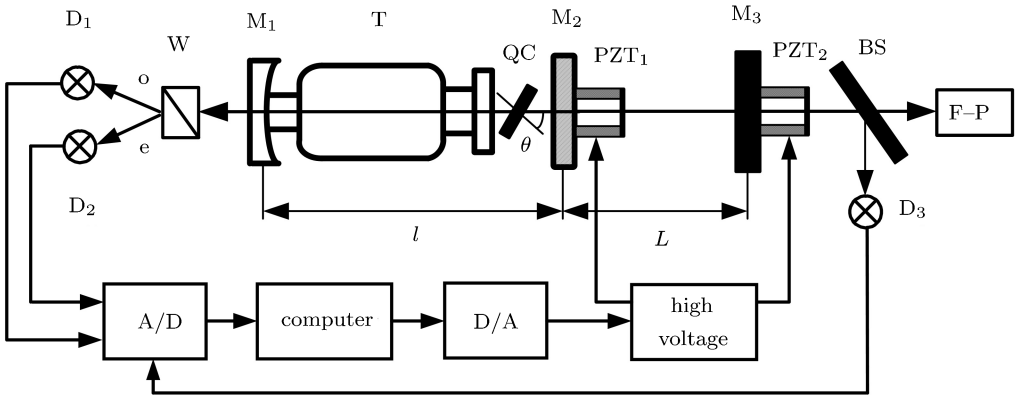


Fig.1. Experimental setup. M_1, M_2, M_3: mirrors; T: discharge tube; QC: quartz crystal; BS: beam splitter; W: Wollaston prism; PZT_1, PZT_2: piezoelectric transducers; D_1, D_2, D_3: photoelectric detectors; F–P: Fabry–Perot scanning interferometer.

PZT_1 and PZT_2 are two piezoelectric transducers that drive the mirrors M_2 and M_3 to modulate the laser internal and external cavity lengths, respectively. The tail light of the laser is divided by a Wollaston prism W. The two polarized lights are then detected by photoelectric detectors D_1 and D_2. BS is a beam splitter that is used to separate the light from M_3 into two parts. One part is detected by a detector D_3. The other part is detected by a Fabry–Perot scanning interferometer F–P, which is used to observe the modes distribution. The three intensity signals are gathered by the A/D card and then sent to a computer.

3. Experimental results

Firstly, we do not introduce optical feedback, so the external feedback mirror M_3 is removed from Fig.1. By tuning the length of the internal cavity, the laser frequencies sweep across the laser gain curve sequentially. When the length of the laser internal cavity changes half a wavelength of the laser, the laser frequency varies by one longitudinal mode interval. The detected power tuning curve of the helium–neon laser with a birefringent internal cavity is shown in Fig.2.

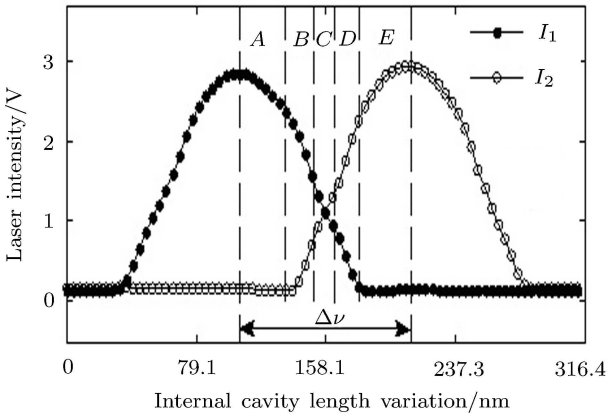


Fig.2. Power tuning curve of the helium-neon laser with a birefringent internal cavity.

In Fig.2 and also the following figures, the solid-circle curve is for I_1 and the empty-circle curve is for I_2. I_1 and I_2 represent the intensities of the o-light and the e-light, respectively. According to different oscillating positions of the two modes on the laser gain curve, the power tuning curve between the two peaks, which corresponds to the frequency spacing $\Delta\nu$ of the two orthogonally polarized modes, can be divided into five regions: region A where only the o-light oscillates;

region B where both the o-light and the e-light can oscillate, the average intensity of the o-light is larger than that of the e-light; region C where both lights can oscillate and the average intensities of the two lights are nearly equal; region D where both the two lights can oscillate, and the average intensity of the o-light is lower than that of the e-light; region E where only the e-light oscillates.

In regions A and E, the mode competition is so strong that only one mode can oscillate, so the laser is a single-mode laser.[32] In the other three regions, both modes can oscillate and the laser is a dual-frequency laser. In these regions, the frequency difference of the laser is about 100 MHz. Thus, the laser with a birefringent internal cavity can run as not only a single-mode laser but also a dual-frequency laser.

Secondly, optical feedback is considered in the following experiments. Before carrying out each experiment, we modify the laser internal cavity length to set the laser oscillating in the desired region. Then we connect the feedback loop and drive PZT_2 with a saw-tooth wave to modulate the length of the external feedback cavity. When the laser operates in regions A, B, C, D and E, the intensity modulation characteristics of the two orthogonally polarized lights and the total light are shown in Figs.3(a), 3(b), 3(c), 3(d) and 3(e), respectively.

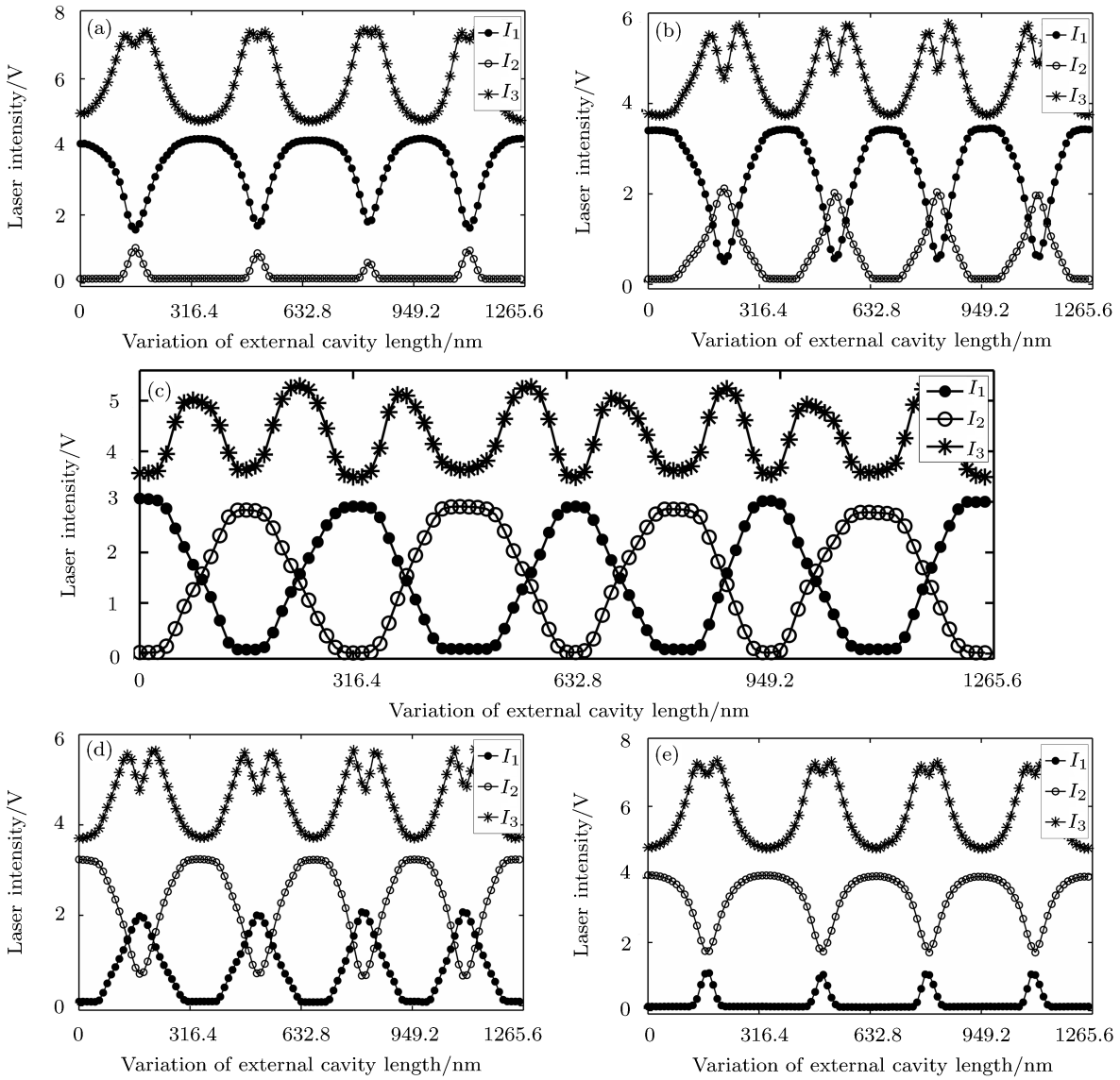


Fig.3. Intensity modulation characteristics of the two orthogonally polarized lights and the total light, in regions (a) A; (b) B; (c) C; (d) D; (e) E.

In Fig.3 and the following figures, the vertical axis represents the laser intensity and the horizontal axis represents the length variation of the external cavity. The curve with stars denotes I_3, that is, the intensity of the total light. In order to see these curves easily, the I_3 curve has been shifted up vertically by about 4V.

When the laser operates in region A, from Fig.3(a) we can find that the o-light is the absolutely leading part in optical feedback. Although in region A only o-light can oscillate without optical feedback, the intensities of the two lights are both modulated by the variation of the external cavity length with optical feedback. The laser threshold, as well as the mode distribution of the laser, is changed. Thus, when the o-light intensity is close to its minimum, the e-light can have a little gain to oscillate. The mode competition is still so strong that the oscillating time of the e-light is very short in a period. We can easily observe from the Fabry–Perot scanning interferometer that the e-light is extinguished all the time except that the o-light intensity reaches its minimum in optical feedback. From the curve with stars, we can see that a small trough appears on the peak of the intensity modulation curve of the total light in each period.

Comparing I_1 and I_3, we can find that these two curves are inverted with respect to each other. This phenomenon is the well-known sign inversion[15,27] phenomenon in optical feedback. The intensities of I_1 and I_2 are detected from the front emission direction, and the total light intensity I_3 is detected from the tail emission direction of the laser. It is because there is a phase difference of π between the two emission directions of the laser.

In region B, both lights can oscillate and the average intensity of the o-light is larger than that of the e-light. The experimental results are shown in Fig.3(b). In the region, the intensities of o-light and e-light change alternately. The o-light is in a relatively leading position in optical feedback. When the o-light intensity is close to its maximum, the e-light intensity is zero. However, when the e-light intensity reaches its maximum, the o-light intensity drops down to its minimum. Compared with Fig.3(a), the mode competition is not strong enough to make the e-light extinguish in nearly all the period. The intensity modulation curve of the total light is M-shaped. Two peaks appear on the M-shaped curve in a period. The modulation depths of each peak are much larger than that in Fig.3(a). But the modulation depth of the total light is lower than that in Fig.3(a).

In region C, we can find that the intensity conversion between the two lights is equal and fair. Neither of the two modes is in a leading position in optical feedback. The two curves are inverted with respect to each other. The modulation depths of the peaks of the M-shaped curves are much larger than those in Fig.3(b). They are comparable to the modulation depth of the total light. Thus, the optical feedback fringe has been doubled.

In region D, the e-light is in a relatively leading position in optical feedback. Comparing Fig.3(d) with Fig.3(b), they are nearly the same except that the roles of the o-light and the e-light are exchanged.

In region E, the e-light is in an absolutely leading position in optical feedback. The o-light can oscillate only when the intensity of the e-light is close to its minimum. Compared with Figs.3(b), 3(c) and 3(d), the intensity modulation depth of the total light in Figs.3(a) and 3(e) is much larger, because of the strong mode competition between the two orthogonally polarized modes.

4. Theoretical analysis

The power tuning curve of a helium-neon laser with a birefringent internal cavity has been reported in Ref.[33] The tuning characters of gas lasers with a Brewster window can be successfully analysed with Lamb's scalar semi-classical theory, and a study[32] based on the vectorial extension[34] of Lamb's theory has been achieved for frequency-split lasers with orthogonal polarizations. In this section, we are concerned about the optical feedback characteristics of the two orthogonally polarized lights and the total light in different regions.

Based on a three-mirror Fabry–Perot cavity model for a single-mode gas laser, when the laser comes to balance with optical feedback, the following equation can be obtained:

$$r_1 r_2 \exp[\mathrm{i}(4\pi v n l/c) + 2gl][1 + \zeta \exp(\mathrm{i}4\pi v L/c)] = 1, \quad (1)$$

where r_1 and r_2 are respectively the reflection coefficients of M_1 and M_2, v is the laser frequency, l is the length of the laser internal cavity, L is the length of the external feedback cavity, ζ is the optical feedback factor, g is the linear gain per unit length.

Considering that the external feedback cavity may not be aligned well and the mode competition, either light's second round trip in the external cavity

should be taken into account. Thus, ζ can be expressed as

$$\zeta = \frac{(1-r_2^2)r_3}{r_2}[1 + r_2 f \exp(\mathrm{i}4\pi vL/c)], \qquad (2)$$

where r_3 is the reflective coefficient of the feedback mirror M_3, f is the coupling efficiency of the light's second re-entering the laser cavity.

Substituting Eq.(2) into Eq.(1), and considering that the laser intensity is in proportion to the variation of the laser gain, the following expression can be obtained:

$$I = I_0 + \frac{K\alpha}{2l}\Big[\cos\Big(\frac{4\pi}{c}vL\Big) + \xi\cos\Big(\frac{8\pi}{c}vL\Big)\Big], \qquad (3)$$

where I_0 is the laser initial intensity without optical feedback, K is a constant, $\alpha = (1-r_2^2)r_3/r_2$, ξ is proportional to $r_3 f$, which is very small.

The above expression describes the intensity of a single-mode laser. For a helium–neon laser with a birefringent internal cavity, two main factors should be considered. One is that the initial intensities of the two modes are different in the five regions. So we introduce two initial intensity coefficients η_o and η_e for the o-light and the e-light, respectively. The other is that, no matter whether the laser runs as a single-mode laser or a dual-frequency one, mode competition between the two orthogonally polarized modes exists. We assume that φ represents the phase delay caused by the mode competition. In our experiments, the frequency difference of the laser is about 100 MHz. It is smaller than the line-width of the homogeneous broadening gain curve of a helium–neon laser, which is about 200 MHz. So the phase between the two modes mainly depends on mode competition.[5] From the experimental results, we can find that the intensities of the two lights are inverted with respect to each other in the five regions. So φ should be chosen to be π radians.

Based on the above analysis and Eq.(3), the intensities of the two modes can be expressed as

$$\begin{aligned} I_1 &= \eta_\mathrm{o} I_0 + \frac{K\alpha}{2l}[\cos(\phi_\mathrm{o}) + \xi\cos(2\phi_\mathrm{o})], \\ I_2 &= \eta_\mathrm{e} I_0 - \frac{K\alpha}{2l}[\cos(\phi_\mathrm{e}) + \xi\cos(2\phi_\mathrm{e})], \end{aligned} \qquad (4)$$

where $\phi_\mathrm{o} = 4\pi v_\mathrm{o} L/c$, $\phi_\mathrm{e} = 4\pi v_\mathrm{e} L/c$, I_1 and I_2 represent the intensities of the o-light and the e-light with optical feedback, respectively.

The total light intensity is detected from the tail emission direction, while the intensities of the two modes are detected from the front emission direction of the laser. Considering the sign inversion phenomenon,[15,27] the intensity of the total light I_3 can be obtained:

$$I_3 = I - (I_1 + I_2), \qquad (5)$$

where I represents the DC part of the intensity.

In region A, only the o-light oscillates. So $\eta_\mathrm{o} \gg \eta_\mathrm{e}$. In region B, both the o-light and the e-light can oscillate, the average intensity of the o-light is larger than that of the e-light. Then we can obtain $\eta_\mathrm{o} > \eta_\mathrm{e}$. In region C, the average intensities of the two lights are comparable to each other and $\eta_\mathrm{o} = \eta_\mathrm{e}$. Similarly, in region D, $\eta_\mathrm{o} < \eta_\mathrm{e}$, and in region E we can have $\eta_\mathrm{o} \ll \eta_\mathrm{e}$. In each region, the higher the one light's initial intensity is, the easier the light scrabbles for gain. Thus, the light will be in a leading position in optical feedback.

When one of the two orthogonally polarized modes is in a leading position in optical feedback, it must be considered that the strong mode competition will make the weak mode have no gain to oscillate. At the same time, there must exist I_1, $I_2 \geq 0$ in Eq.(4), for there is no negative intensity.

As the modes move to the centre of the gain curve, the modulation depths of the two peaks of the M-shaped curves increase because more gain can be obtained. Especially, when the two modes oscillate symmetrically around the centre of the laser gain curve in region C, the average intensities of the two modes as well as the modulation depth of each peak of the M-shaped curves, are comparable to each other. Thus, the optical feedback fringe is doubled.

The above theoretical analysis can well explain the experimental results.

5. Discussion

Optical feedback level is a very important parameter because it determines the optical feedback characteristics of a laser. For a semiconductor laser, we all know that the optical feedback regimes can be classified into four regimes by the optical feedback factor C.[13,19] However, for a helium–neon laser, we cannot judge the optical feedback level by C, because the reflectivity of the laser cavity mirror M_2 is nearly 1 and this results in $C \ll 1$, no matter how high the reflectivity of the external feedback mirror is. Reference [7] has defined the optical feedback regimes in birefringent dual-frequency lasers with large frequency

difference. Comparing the experimental results in this paper with those results in Ref.[7], we see that we are working on a strong feedback regime, although the reflectivity of the external feedback mirror is only 25.8%. It is because we have much small frequency difference, which will bring about strong mode competition and increase the optical feedback level.

The theoretical analysis proposed in this paper can well explain the experimental results. However, there are still a few mismatches with the results in Section 3. Firstly, the widths of the intensity modulations are different in every period for obtaining the experimental results, especially at the beginning and at the end of the PZT voltage sweep. It is due to the nonlinearity of PZT voltage with the variation of the external feedback cavity length. Secondly, in the theoretical analysis, we have considered both alignment and misalignment of the external feedback mirror. But the misalignment degree of the external feedback mirror is hard to measure precisely. This affects the value of the coupling efficiency and results in a little mismatch in modulation depth and waveform, compared with the experimental results.

The motivation for optical feedback studies has been twofold. From the fundamental physics point of view, our result may enrich the experimental and theoretical researches in optical feedback, particularly in the field of orthogonally polarized optical feedback. From the results, some conclusions can be drawn. Firstly, a doubled fringe can be obtained in the optical feedback system, which contains a helium–neon laser with a birefringent internal cavity. Secondly, different oscillating positions of the laser modes on the laser gain curve will affect the optical feedback. Thirdly, modes distribution of the laser can be affected by optical feedback. Fourthly, low reflectivity of the external feedback mirror will also cause strong optical feedback, because there exists strong mode competition between the two orthogonally polarized modes.

From the engineering point of view, the experimental results will reveal some potential applications. When the laser operates in region A (or E), the total intensity of the laser is inverted with the intensity of the o-light (or the e-light). If we want to obtain two signals with the phase difference of π, we can modify the laser internal cavity to make the laser operate in region A or region E. In the two regions, one mode is in an absolutely leading position in optical feedback. Strong mode competition can increase the intensity modulation depth at the same optical feedback levels. Thus, it can be used to improve the sensitivity of the optical feedback system by introducing mode competition. In regions B and D, M-shaped optical feedback curves are found. Each peak of the total light's intensity modulation curve has two sub-peaks. For the intensity of the e-light in Fig.3(b) or the o-light in Fig.3(e), it can be used to generate the pulse signals. In region C, the frequency of the intensity modulation curve of the total light is doubled. And the doubled fringe obtained in our system is independent of the external cavity length. The result can be used to greatly improve the resolution of the optical feedback system with a birefringent internal cavity. For a 632.8 nm helium–neon laser, the resolution of the self-mixing sensing system can reach 158.2 nm only based on the fringe counting method.

6. Conclusion

In summary, an optical feedback in a helium-neon laser with a birefringent internal cavity is proposed and demonstrated. The output characteristics of the two orthogonally polarized modes and the total light in five different oscillating regions for the two modes on the laser gain curve are presented. The doubled intensity modulation curve of optical feedback is acquired and mode competition is observed. The oscillating positions of the two orthogonally polarized modes on the gain curve without optical feedback can affect the output characteristics of optical feedback and mode competition greatly. Theoretical analysis, as well as the discussion, is presented.

References

[1] King P G R and Steward G J 1963 *New Sci.* **17** 180
[2] Rudd M J 1968 *J. Phys.* E **1** 723
[3] Ovryn B and Andrews J H 1998 *Opt. Lett.* **23** 1078
[4] Scalise L and Paone N 2002 *Opt. Laser Eng.* **38** 173
[5] Fei L and Zhang S 2004 *Opt. Express* **12** 6100
[6] Mao W and Zhang S 2006 *Chin. Phys.* **15** 2036
[7] Mao W, Zhang S, Zhang L, Zhu J and Li Y 2006 *Chin. Phys. Lett.* **23** 1188
[8] Mao W and Zhang S 2006 *Chin. Phys.* **15** 340
[9] Lacot E, Day R and Stoeckel F 1999 *Opt. Lett.* **24** 744
[10] Kenju O, Kazutaka A and Jing-Yuan K 2002 *Opt. Lett.* **27** 1339
[11] Wan X, Zhang S, Liu G and Fei L 2005 *Opt. Eng.* **44** 104204

[12] Wan X, Zhang S, Liu G and Fei L 2004 *Chin. Phys. Lett.* **21** 2175
[13] Giuliani G, Norgia M, Donati S and Bosch T 2002 *J. Opt. A Pure Appl. Opt.* **4** S283
[14] Yasaka H, Yoshikuni Y and Kawaguchi H 1991 *IEEE J. Quantum Electron.* **27** 193
[15] Addy R C, Palmer A W and Grattan K T V 1996 *J. Lightwave Technol.* **14** 2672
[16] Yu Y, Giuliani G and Donati S 2004 *IEEE Photonics Technol. Lett.* **16** 990
[17] Donati S, Giuliani G and Merlo S 1995 *IEEE J. Quantum Electron.* **31** 113
[18] Yoshino Y, Nara M, Mnatzkanian S, Lee B S and Stran T C 1987 *Appl. Opt.* **26** 892
[19] Mao W and Zhang S 2006 *Appl. Opt.* **45** 8500
[20] Mao W, Zhang S, Cui L and Tan Y 2006 *Opt. Express* **14** 182
[21] Koelink M K, de Mul F F M, Weijers A L, Greve J, Graaff R, Dassel A C M and Aarnoudse J G 1995 *Appl. Opt.* **33** 5628
[22] Shinohara S, Mochizuki A, Yoshida H and Sumi M 1986 *Appl. Opt.* **25** 1417
[23] Kawai R, Asakawa Y and Otsuka K 1999 *IEEE Photon. Technol. Lett.* **11** 706
[24] Bearden A, O'Neill M P, Osborne L C and Wong T L 1993 *Opt. Lett.* **18** 238
[25] Mao W and Zhang S 2006 *Appl. Opt.* **45** 7723
[26] Lang R and Kobayashi K 1980 *IEEE J. Quantum Electron.* **QE-16** 347
[27] Groot P J D, Gallatin G M and Macomber S H 1988 *Appl. Opt.* **27** 4475
[28] Wang W M, Boyle W J O, Grattan K T V and Palmer A W 1993 *Appl. Opt.* **32** 1551
[29] Li L, Zhang S, Li S and Xue P 2001 *Opt. Commun.* **200** 303
[30] Fei L, Zhang S, Li Y and Zhu J 2005 *Opt. Express* **13** 3117
[31] Liu G, Zhang S, Xu T, Zhu J and Li Y 2004 *Opt. Commun.* **241** 159
[32] Zong X, Liu W and Zhang S 2005 *Chin. Phys. Lett.* **22** 1906
[33] Li Y, Zhang S, Han Y, Fu J, Gao J and Ou J 2000 *Opt. Eng.* **39** 3039
[34] Fork R L and Pollack M A 1965 *Phys. Rev.* A **139** 1408