Modes competition in a birefringence cavity laser with optical feedback

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The modes competition characteristics in birefringence cavity laser are studied in different regions of the gain curve. The mode's intensity modulation depth with modes competition is much deeper than that without modes competition. When the average intensities of the two modes are comparable, the intensity modulation depth of either mode reaches its maximum. Modes competition can do more contribution to the mode's modulation depth than the percentage of light reflected back into the laser cavity does. These characteristics can be used to improve the sensitivity of an optical feedback system. A modes competition factor is introduced to either mode's intensity expression which describes the laser intensity more precisely.

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The optical feedback characteristics have been widely studied in gas lasers[1−4], microchip solid lasers[5], and semiconductor lasers[6,7]. Much attention is paid to the optical feedback characteristics in a single mode laser, which has been widely studied for velocimeter[1,4], ranging, displacement measuring[3,6], and imaging[8]. Some theoretical models have been created to explain the optical feedback phenomena[2,3,9−13].

The power tuning curve of a birefringence dual frequency laser has ever been studied[14]. In different regions of the gain curve, the modes competition strength is different. In some regions of the gain curve, the modes competition is too strong and only one mode can oscillate. So the laser is a single mode laser. But in some regions of the gain curve, two split modes can oscillate and the laser is a dual frequency laser. So the birefringence cavity laser can run as not only a single mode laser but also a dual frequency laser. We can make a research on the difference of the optical feedback characteristics between the single mode laser and the dual frequency laser by only using a birefringence cavity laser.

Recently, there is a great interest in the optical feedback in birefringence cavity laser using mode split technology[15]. When the birefringence cavity laser outputs two orthogonally polarized modes, the birefringence cavity laser runs as a dual frequency laser and the intensities of both modes are found to be inverted with respect to each other at the presence of optical feedback[16]. But under the condition where the laser outputs only one polarized light, the optical feedback characteristics of the birefringence cavity laser are not studied. And the sensitivity of the optical feedback system when the birefringence cavity laser runs as a dual frequency laser has never been compared with that when the birefringence cavity laser runs as a single mode laser. Furthermore, it is not studied in a large frequency difference dual frequency laser when only one polarized light is fed back into the laser cavity. These unknown characteristics should be studied which can suggest us how to improve the performance of optical feedback system using a birefringence cavity laser.

In this paper, we observe the intensity variation of the birefringence cavity laser and make a discussion on the optical feedback sensitivity at different regions of the gain curve. We have found a new way to improve the sensitivity of the optical feedback system.

Figure 1 shows the experimental setup. The 632.8-nm He-Ne birefringence cavity laser has a quartz crystal Q inside the laser cavity. The laser cavity is 150 mm long and composed of mirrors M_1 and M_2. T represents the laser tube. Mirror M_3 is the external feedback mirror with a reflectivity of 40%. P is a polarizer put in the external cavity. The external cavity length is 250 mm. W is a Wallaston prism which is used to separate the orthogonally polarized lights — o-light and e-light whose intensities are detected by the photoelectric detectors D_1 and D_2, respectively. The laser intensity changes every 0.08 mW, and the photoelectric detector changes 1000 mV. PZT_1 and PZT_2 are two piezoelectric transducers (abbr. PZTs) which are used to drive mirrors M_3 and M_2, respectively. PZT_1 and PZT_2 are driven by two output voltages of D/A indirectly. F-P is a Fabry-Perot scanning interferometer which is used to observe the oscillating modes.

Neglecting the light's multi-reflection in the external cavity, the laser output intensity with optical feedback can be expressed as[2]

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

where I_0 is the laser intensity without optical feedback; K is a constant; $\beta = t_2^2 r_3 / r_2$, t_2 is the transmission coefficient of M_2, r_3 is the reflection coefficient of M_3,

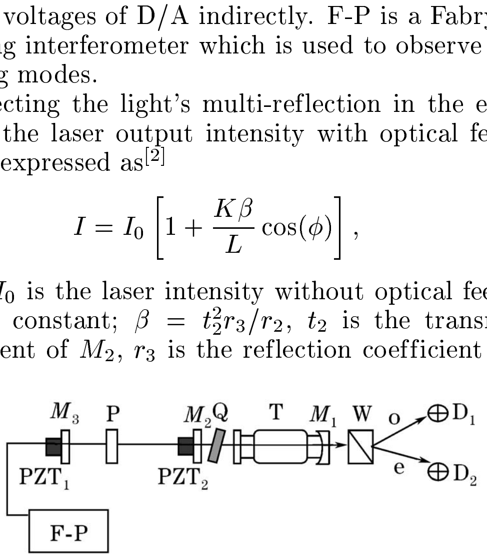

Fig. 1. Experimental setup of optical feedback using a birefringence cavity laser.

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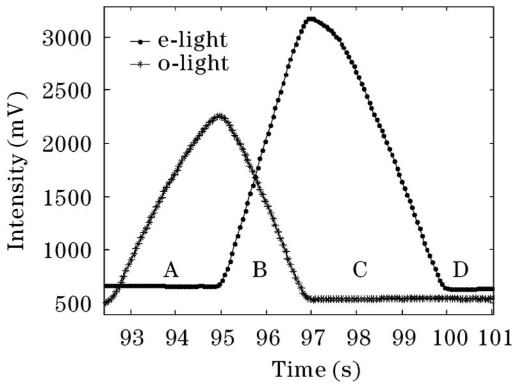

Fig. 2. Power tuning curve of the birefringence cavity laser.

r_2 is the reflection coefficient of M_2; $\phi = 4\pi\nu l/c$ is the external cavity phase delay, ν is the laser frequency, c is the speed of light in vacuum, l is the external cavity length. The fringe is produced when the external cavity length varies half of the laser wavelength.

Laser intensity varies while we tune the laser cavity length. The relationship between the laser frequency variation $\Delta\nu$ and the laser cavity length variation ΔL can be given by[14]

$$\frac{\Delta\nu}{\Delta} = \frac{\Delta L}{\lambda/2}, \tag{2}$$

where $\Delta = c/2L$ is the mode spacing of the laser. Laser cavity length varies $\lambda/2$ and the lasing mode will shift one mode spacing. In our experiments, the birefringence cavity laser is a short cavity laser and its mode spacing is larger than the lasing bandwidth. So when the laser cavity length is tuned by $\lambda/2$, the laser mode will pass through the whole lasing bandwidth once and the laser intensity varies one period. For a dual frequency laser, the intensities of its two lasing modes are inverted with respect to each other because of modes competition when the laser cavity is tuned as shown in region B of Fig. 2.

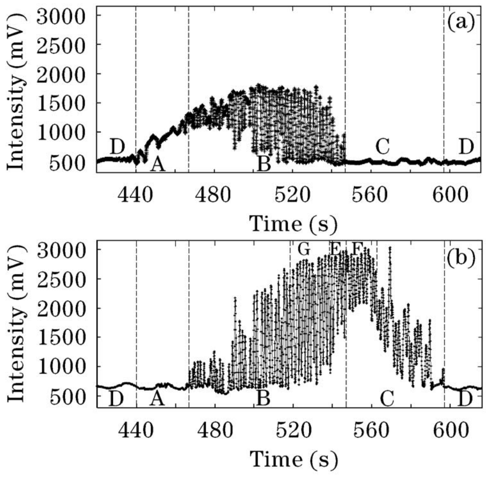

Fig. 3. O-light (a) and e-light (b) intensities when e-light is fed back into the laser cavity.

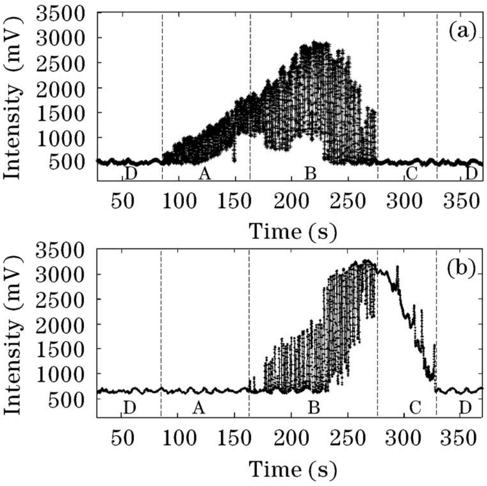

Fig. 4. O-light (a) and e-light (b) intensities when o-light is fed back into the laser cavity.

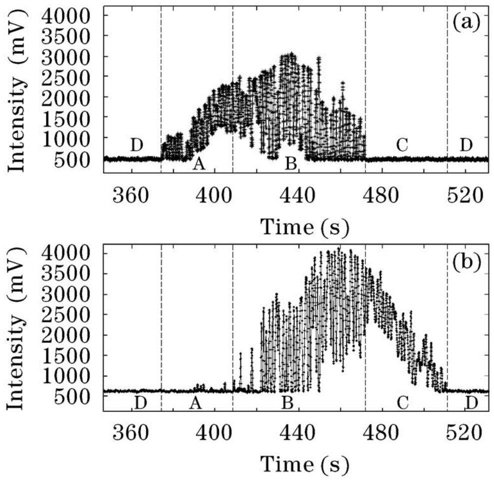

Fig. 5. O-light (a) and e-light (b) intensities when both lights are fed back into the laser cavity.

When the laser cavity is tuned at the presence of optical feedback, the laser intensity variation is due to not only the laser cavity tuning but also optical feedback. When the period of the laser cavity variation is much larger than that of the signal that drives the external mirror, the laser intensity curve is the laser power tuning curve modulated by the optical feedback signal as shown in Figs. 3, 4, and 5.

The modulation depth of the laser with optical feedback can be defined as

$$m = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}, \tag{3}$$

where $I_{\max}$ and $I_{\min}$ are the maximal and minimal laser intensities, respectively. At the presence of optical feedback in a birefringence cavity laser, the modulation depth is different at different range of the gain curve. In the region where there is no modes competition, the birefringence cavity laser works as a single mode laser. So the modulation depth can be calculated from Eqs. (1) and (3) as

$$m = \frac{K\beta}{L}. \tag{4}$$

But in the region where there is modes competition, the birefringence cavity laser works as the dual frequency laser. Neglecting the light's multi-reflection in the external cavity, the intensities of o-light I_{o} and those of e-light I_{e} can be expressed respectively as[16]

$$I_{\mathrm{o}} = I_{0\mathrm{o}} \left[1 + \frac{\kappa K \beta}{L} \cos(\phi) \right], \tag{5}$$

$$I_{\mathrm{e}} = I_{0\mathrm{e}} \left[1 - \frac{\kappa K \beta}{L} \cos(\phi) \right], \tag{6}$$

where $I_{0\mathrm{o}}$ and $I_{0\mathrm{e}}$ are the laser intensities of o-light and e-light without optical feedback. κ is defined as the modes competition factor which is not mentioned in Ref. [10]. $\kappa > 1$ for modes competition makes the light modulation depth deeper than that without modes competition. The light intensity equation with optical feedback is more precise in a dual frequency laser when κ is introduced. So the modulation depth in a dual frequency laser can be calculated as

$$m = \frac{\kappa K \beta}{L}, \tag{7}$$

which is always larger than that in Eq. (4).

The experimental results in Figs. 3, 4, and 5 show that κ reaches its maximum when both light average intensities are equal because of the strongest modes competition.

Firstly, we take off the feedback mirror and carry out an experiment to examine the power tuning curve of the birefringence cavity laser. When mirror M_2 moves a displacement of $\lambda/2$, a period of the power tuning curve can be acquired as shown in Fig. 2. The power tuning curve can be divided into four regions: region A where only o-light oscillates, region B where both lights can oscillate, region C where only e-light oscillates, and region D where no light oscillates. The laser is of a single mode in regions A and C. When the laser runs in region B, it is a dual frequency laser and its frequency difference is 122 MHz. In region B, o-light intensity is inverted with e-light intensity and this phenomenon is due to the modes competition between these two modes. The ranges of these four regions are not equal to each other compared with that in Ref. [8] where a 50—60 MHz dual frequency laser is used.

We fix mirror M_3 and tune the polarizer to make only e-light impinge on mirror M_3. We drive mirror M_3 with a triangle wave whose period is 11 s and at the same time we drive mirror M_2 with an increasing voltage. It costs 200 s when mirror M_2 moves a displacement of $\lambda/2$. The time that we drive mirror M_2 to move $\lambda/2$ is much longer than the period of the triangle wave. The experimental results are shown in Figs. 3(a) and (b) detected at the same time. The o-light intensity curve with optical feedback is shown in Fig. 3(a) while the e-light intensity curve is shown in Fig. 3(b). In region A, o-light oscillates and does not impinge on the feedback mirror M_3. So o-light intensity increases without obvious intensity modulation and e-light is zero intensity. But in region B, e-light starts oscillating and part of e-light is reflected back into the laser cavity by mirror M_3. Both light intensities are modulated and o-light intensity is inverted with e-light intensity although there is no o-light fed back into the laser cavity. With the average intensity of o-light decreasing and e-light increasing, the e-light modulation depth increases and then decreases. When the average intensities of both lights are equal, e-light intensity modulation depth reaches its maximum. O-light intensity modulation depth does not seem to vary very much. In region C, only e-light oscillates. Region E is the right part of region B and region F is the left part of region C. The e-light average intensity in region E is a little lower than that in region F. But e-light modulation depth in region E is deeper than that in region F. This is mainly because in region E e-light intensity is not only modulated by the optical fed back light but also affected by modes competition. At the presence of modes competition, the strong mode becomes stronger while the weak one becomes weaker. So modes competition can make one light modulation depth deeper. With e-light decreasing in region C, its modulation depth decreases too until no variation in region D. In region G, the average intensities of both lights are comparable and the modes competition between them is much stronger than that in region E where e-light average intensity is much higher than o-light. Although in region E there is much e-light fed back into the laser cavity, each light intensity modulation depth in region G is much deeper than that in region E. So at the presence of optical feedback in a dual frequency laser, modes competition can do more contribution to either modulation depth than the percentage of the light that is fed back into the laser cavity. We can improve the sensitivity of an optical feedback system using a dual frequency laser by tuning the two-mode average intensities equal. The region B in Fig. 3 is wider than that in Fig. 2. It means that optical feedback can make the region where both lights can oscillates wider in a birefringence cavity laser.

Then we tune the polarizer by 90 degrees and only o-light can pass through the polarizer and impinge on the external mirror M_3. We also drive mirror M_3 with the triangle wave and drive mirror M_2 with the increasing voltage. The experimental results are shown in Fig. 4. In region A, o-light oscillates and is fed back by mirror M_3. So o-light intensity increases with obvious intensity modulation. In region B, e-light starts oscillating. With e-light average intensity increasing, o-light average intensity starts increasing and then decreasing. When the average intensities of both lights are equal, both intensity modulation depths are maximum too. At the right side of region B, o-light average intensity is very low which is near zero and only very weak o-light is fed back into the laser cavity. But o-light modulation depth is nearly twice that in region A at the same average intensity level. This phenomenon also results from the modes competition between these two lights. So at the presence of very weak optical feedback, we can use modes competition to improve the sensitivity of optical feedback system. In region C, o-light is zero intensity and e-light decreases without obvious intensity modulation except several intensity peaks which come out occasionally. These peaks can also be seen in Fig. 2. These peaks results from optical feedback but why they come out irregularly is unknown. Comparing Fig. 2 with Fig. 3, we can see that o-light intensity modulation depth in Fig. 3 is deeper than that in Fig. 2 and e-light intensity modulation depth in Fig. 2 is deeper than that in Fig. 3. So it can improve one polarized light's modulation depth by only feeding it back into the laser cavity in a dual frequency laser.

Finally we take off the polarizer and fed back both o-light and e-light into the laser cavity. We still drive mirror M_3 with the triangle wave and drive mirror M_2 with the increasing voltage. The o-light and e-light intensity curves with optical feedback are shown in Fig. 5.

In region A o-light intensity increases with obvious intensity modulation but o-light modulation depth is lower than that in region B at the same average intensity level. In region B, both lights oscillate. With e-light average intensity increasing, o-light average intensity increases and then decreases. When the average intensities of both lights are equal, both intensity modulation depths reach their maximum too. In region C, e-light average intensity decreases with intensity modulation whose depth is lower than that in region B at the same average intensity level. So in the above three optical feedback experiments, modes competition can always improve the modulation depth of either light intensity.

In the final experiment, the polarizer is taken off and both lights can impinge on the external mirror. More light power is reflected back into the laser cavity compared with the first two optical feedback experiments. The polarizer can be regarded as an attenuator and nearly half of the laser output lights cannot pass through it in the first two optical feedback experiments. So the optical feedback level in the final experiment is much higher than that in the first two optical feedback experiments. But either intensity modulation depth in the final experiment is only comparable to that in the first two optical feedback experiments. It proves that again modes competition can do more contribution to either modulation depth than the percentage of the light that is fed back into the laser cavity.

The optical feedback characteristics of the oscillating mode have been studied at different regions of the gain curve in a birefringence cavity laser. In this paper, the optical feedback characteristics are firstly reported when only one kind of polarized light is fed back into the laser cavity in a large frequency difference dual frequency laser. It is found that modes competition can improve the intensity modulation depth at the presence of optical feedback. A mode competition factor κ is introduced into the laser intensity equation with optical feedback in a dual frequency laser and a more precise expression of the laser intensity is given. It can be used to improve the sensitivity of the optical feedback system by involving modes competition. Especially when the average intensities of both modes are equal to each other, either intensity modulation depth reaches its maximum for the modes competition is maximal. It also proves that modes competition can do more contribution to either modulation depth than the percentage of the light that is fed back into the laser cavity at the presence of optical feedback in a dual frequency laser.

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