Vol 15 No 9, September 2006
1009-1963/2006/15(09)/2036-06
Chinese Physics
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Intensity tuning characteristics of double-mode He–Ne laser with optical feedback*

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(Received 17 October 2005; revised manuscript received 14 February 2006)

This paper investigates the intensity tuning characteristics of a double longitudinal modes He–Ne laser subjected to optical feedback. The intensity undulations of the total light and the two modes are observed for different external cavity length. Two modulations of the internal cavity length are performed. One is only for the internal cavity length being modulated and the other is for both the internal and the external cavity length being modulated. The undulation frequency of the total light is found to be determined by the ratio of external cavity length to internal cavity length in both modulations. When the external cavity length is integral times of the internal cavity length, the fringe frequency of the total light could be seven or even more times of that in conventional optical feedback. A simple theoretical analysis is presented, which is in good agreement with the experimental results. The potential use of the experimental results is also discussed.

Keywords: tuning characteristics, optical feedback, double longitudinal modes
PACC: 5170, 4225, 4255F

1. Introduction

It is well known that laser behaviours, especially the static and dynamic properties, can be significantly affected by external optical feedback: that is, feedback of a portion of the laser output into the laser cavity from a reflecting surface external to it. Studies have been focused mainly on the He–Ne lasers[1−10] and the semiconductor lasers,[11−15] in connection with polarization-resolved experiments and dynamic instabilities. One of the unstable features of semiconductor laser output is that the power drops with the frequency within the range of several tens of megahertz. This phenomenon is known as low-frequency fluctuation and has attracted much attention.[16,17] However, little research has been done concerning the instability of the output power corresponding to the frequency fluctuation in He–Ne lasers with optical feedback.

In this paper we systemically study the effects of optical feedback on the intensity tuning characteristics with frequency tuning in a double longitudinal modes He–Ne laser. It is unlike previous intensity modulation researches,[6−10] which are mainly caused by the changes in the optical path length of the external cavity. Here we present the laser intensity properties corresponding to the variation of laser frequencies in two different modulations. In the first modulation, the laser frequencies are modulated over the laser gain curve by changing the internal cavity length. In the other one, both the internal cavity length and the external cavity length are modulated. Special physical phenomena have been observed. When the external cavity length is larger than the internal cavity length, several undulatory curves whose profile is similar to a half-wave rectification of sine are overlapped on the intensity tuning curves of the two modes. And the intensity of the total light is irregular. While the external cavity length is integral times of the internal cavity length, the laser output power is steady and periodic. $\lambda/2$ change of the internal cavity length makes the laser frequency change one longitudinal mode interval and makes the intensity of the total light undulate several periods. The modulation frequency, as well as the amount of sub-peaks in the intensity modulation curves of the two longitudinal modes, is determined by the ratio of external cavity length to internal cavity length. When the external cavity length is N times of the internal cavity length, in comparison with conventional optical feedback, the fringe frequency of

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the laser output power would be N times in the first modulation and (N+1) times in the second modulation. The experimental results observed is important not only for laser physics study but may also for applications in the future, such as high accuracy and self-calibration displacement sensors.

2. Experimental setup

Experiments have been performed with a half-intracavity, double longitudinal modes, linearly polarized, operating at 632.8nm He–Ne laser. The ratio of gaseous pressure in the laser is He:Ne=7:1 and Ne^{20} : Ne^{22}=1:1. The experimental setup is shown schematically in Fig.1.

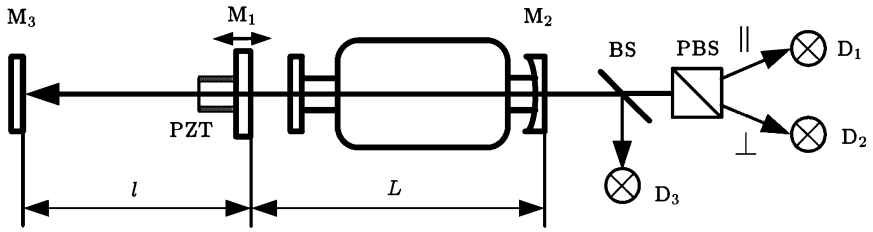


Fig.1. Schematic diagram of the experimental setup. M_1, M_2, M_3: mirrors; BS: beam splitter; PBS: Wollaston prism; PZT: piezoelectric transducer; D_1, D_2, D_3: photo detectors.

The laser internal cavity is composed of a plane mirror M_1 and a concave mirror M_2 with reflectivity of R_1=0.994 and R_2=0.995 respectively. The laser internal cavity length L is 170mm. M_3 is the external feedback mirror with a reflectivity of 30%, which is used to reflect beams back into the laser cavity. And the external feedback cavity length is l. BS is a beam splitter which is used to separate the tail lights into two parts. One part is separated by a Wollaston prism PBS into two orthogonally polarized lights—∥-light and ⊥-light whose intensities are detected by photo detectors D_1 and D_2 respectively. The other part is detected by D_3. By using a scanning interferometer, we can observe that the laser is always operating with two longitudinal modes.

3. Experimental results

At first, we do not introduce optical feedback, so the external feedback mirror M_3 is removed from Fig.1. When the length of internal cavity is tuned by PZT, the laser frequency is modulated, as well as the output intensities of the laser. The intensity modulation curves are shown in Fig.2.

In Fig.2 and also in the following other figures, the relationship between PZT voltage and the variation of the laser internal cavity length is linear. I_1 and I_2 represent the intensities of the two longitudinal modes respectively. And I_3 represents the intensity of the total light. The solid-circle curve is for I_1. The open-circle curve is for I_2, and the starred curve is for I_3.

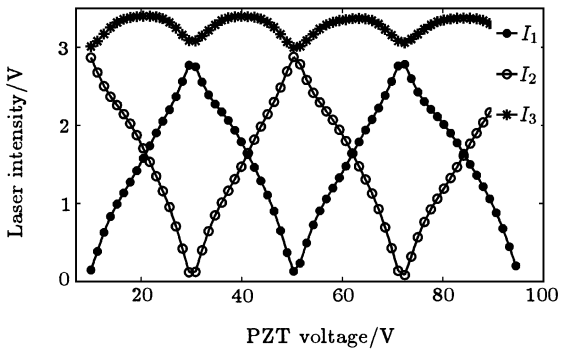


Fig.2. Intensity tuning properties corresponding to the variation of laser internal cavity length without optical feedback.

From Fig.2, we can observe the changes of intensities with tuning of successive resonance of the laser cavity over the Doppler line. When one of the laser frequencies is tuned to the centre of the gain curve, the output intensity falls to the minimum. When both frequencies are tuned symmetrically to the centre of the gain curve, the output intensity reaches the maximum. Due to an equal mixture of Ne^{20} and Ne^{22}, the Lamb dip is suppressed. From the intensity modulation curves of the two longitudinal modes, we also can find that the two modes oscillate simultaneously during the tuning. And the lasing bandwidth almost equals two times of the longitudinal mode interval. When the length of the laser internal cavity changes by $\lambda/2$, the laser frequency varies by one longitudi-

nal mode interval and the intensity of the total light undulates one period, while each mode's intensity fluctuates a half-period.

Then optical feedback is considered in the following experiments. Feedback mirror M_3 is placed at the end of the laser. Mirrors M_2 and M_3 form the external feedback cavity and the external cavity length is l. When we tune the laser internal cavity length, the laser frequencies are modulated over the laser gain curve. For different external cavity length l, the intensity modulation curves are changed greatly. The intensity tuning characteristics for different external cavity length are shown in Fig.3. In order to discriminate these three light intensity curves easily, the starred curve is shifted up along the vertical axis by about 2.0 V in Fig.3 and the following figures.

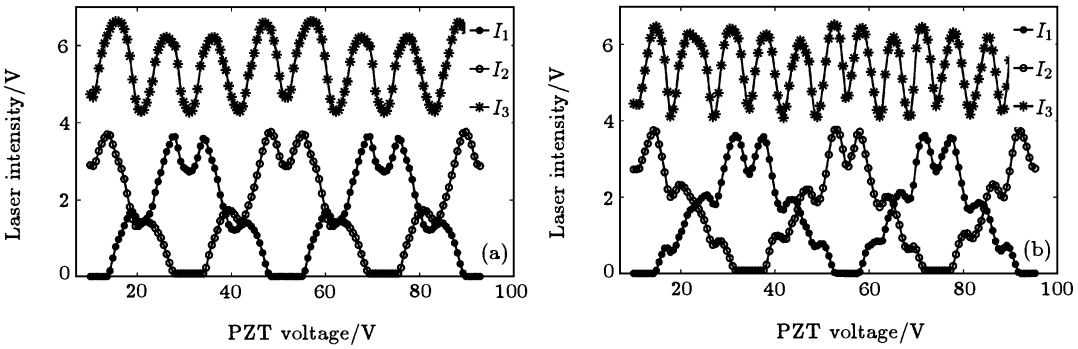


Fig.3. Intensity tuning properties corresponding to the variation of the laser internal cavity length with optical feedback. The external cavity lengths are (a) l=2L=340 mm, (b) l=3L=510 mm.

From Fig.3, we can find that the intensity modulation curves with optical feedback are different from the curves without optical feedback. When the length of the laser internal cavity changes $\lambda/2$, the laser frequency varies by one longitudinal mode interval, but the intensity undulation curve of the total light no longer corresponds to one period. Also, the intensity modulation curves of the two longitudinal modes changed and several sub-peaks in a period can be found. The curves are overlapped by an undulatory curve whose profile is similar to a half-wave rectification of sine.

What is more important is that the intensity tuning curves are sensitive to the external cavity length. For different ratio of external cavity length to internal cavity length, the intensity modulation frequency of the total light and the amount of sub-peaks in the intensity modulation curves of the two longitudinal modes are different. When l=2L, the intensity tuning curves are shown in Fig.3(a). The intensity of the total light undulates two periods when laser frequency varies by one longitudinal mode interval and four sub-peaks superposed on the longitudinal modes' tuning curves can be found. When l=3L, the intensity of the total light undulates three periods and six sub-peaks superpose on the longitudinal modes' tuning curves, as shown in Fig.3(b).

This indicates that the intensity modulation frequency, as well as the amount of sub-peaks in the intensity modulation curves of the two longitudinal modes, is determined by the ratio of external cavity length to internal cavity length. When the external cavity length is N times of the internal cavity length, the intensity modulation frequency of laser with optical feedback is N times of that without optical feedback. And the amount of sub-peaks on the longitudinal modes' tuning curves is $2N$ in a period.

In the second modulation, M_1 and M_3 form the external cavity and the feedback cavity length is also defined as l, as shown in Fig.1. When the internal cavity mirror M_1 is scanned by PZT, both the internal cavity length and the external cavity length are modulated. The intensity tuning curves for different external cavity length are shown in Fig.4.

From Fig.4, we can see that the intensities of the total light and the two longitudinal modes are both modulated by the length of internal cavity with optical feedback. When the laser frequency varies by one longitudinal mode interval, the laser output power undulates several periods, and several sub-peaks whose profiles are similar to a half-wave rectification of sine, overlap on the intensity modulation curves of the two longitudinal modes.

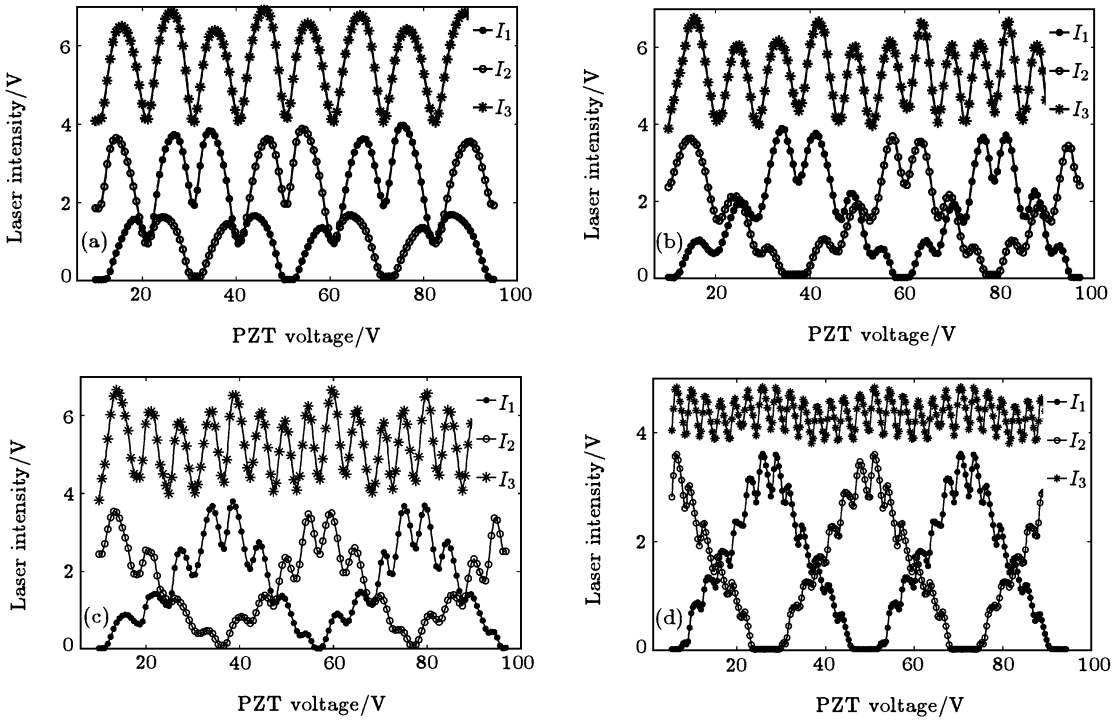


Fig.4. Intensity tuning properties when the internal cavity length and the feedback cavity length are both modulated. The external cavity lengths are (a) l=L=170mm, (b) l=2L=340mm, (c) l=3L=540mm, (d) l=6L=1020mm.

When l=1L, the intensity tuning curves are shown in Fig.4(a). The intensity of the total light undulates two periods when the laser frequency varies by one longitudinal mode interval and four sub-peaks superposed on the tuning curves of the two longitudinal modes can be found. When l=2L, l=3L or l=6L, the laser intensity modulation curve I_3 undulates three periods, four periods, or seven periods, as shown in Fig.4(b), Fig.4(c) and Fig.4(d) respectively.

This indicates that the intensity modulation frequency of the total light, as well as the amount of sub-peaks in the intensity modulation curves of the two modes, is determined by an integer N. N is defined as the ratio of external cavity length to internal cavity length. Different from the results in Fig.3, the intensity modulation frequency is proportional to N+1.

4. Theoretical analysis

Various theories based on Lamb's theory have been developed and used, primarily for explaining the internal cavity tuning characteristics without optical feedback. Some other theories[4−6] are also demonstrated when we consider the optical feedback, but primarily for explaining the polarization properties of a single mode. In our study here a simple theory is presented to relate to the experimental results given in Section 3.

It is well known that when the length of the laser internal cavity changes $\lambda/2$, the laser frequency varies by one longitudinal mode interval and the laser output power undulates one period. This is easy to be understood because $\Delta v = v_0 \times \Delta L/L$, where v_0 is the central frequency of laser medium, Δv is the variation of laser frequency, ΔL is the variation of laser internal cavity length.

First, let us consider the modulation that only the laser internal cavity length is modulated. Under the weak optical feedback regime, due to $R_3 \ll R_2$, according to the model given in Ref.[18] of equivalent cavity of Fabry–Perot interferometer, the equivalent mirror reflectivity of M_2 can be given by

$$R_{\text{eff}} = R_2 + 2(R_2R_3)^{1/2}(1 - R_2)\cos\varphi_f, \qquad (1)$$

where $\varphi_f = 4\pi vl/c$ represents the external cavity phase.

Accordingly, the two longitudinal modes' intensities can be written as

$$I_{1\text{ or }2} = I_{1\text{ or }2v} + \kappa\cos\varphi_{1\text{ or }2f}, \qquad (2)$$

where I_{1v} and I_{2v} are the intensities of the two longitudinal modes without optical feedback, κ is the feed-

back factor of intensity. From Eq.(2), the intensity tuning curves of the two modes are superposition of the intensity tuning curves of the two modes without optical feedback and sine wave.

Considering that the frequency difference between the two longitudinal modes always equals one longitudinal interval $\Delta = c/2L$, we can express the external cavity phase as

$$\begin{aligned}\varphi_{2f} =& 4\pi v_2 l/c = 4\pi(v_1+\Delta)l/c \\ =& 4\pi v_1 l/c + 2\pi = \varphi_{1f} + 2\pi l/L. \end{aligned} \quad (3)$$

When the external cavity length l is N times of the internal cavity length L, we can obtain

$$\cos\varphi_{2f} = \cos(\varphi_{1f} + 2N\pi) = \cos\varphi_{1f} = \cos\varphi_f, \quad (4)$$

where N is a positive integer.

Thus, the laser intensity I_3 can be expressed as the sum of the two mode intensities as

$$I_3 = I_1 + I_2 = I_{1v} + I_{2v} + 2\kappa\cos\varphi_f. \quad (5)$$

The modulation frequency of the laser output power is determined by the phase variation of the external cavity, which can be expressed as

$$\Delta\varphi_f = 4\pi l \cdot \Delta v/c. \quad (6)$$

Considering the spectral range $\Delta v = c/2L$, $\Delta\phi_f = 2\pi l/L = 2\pi N$, we know that ϕ_f shows N periods. Therefore, when l=$2L$ or $l = 3L$, the intensity modulation curve I_3 undulates 2 periods or 3 periods respectively, as shown in Fig.3. For the intensity modulation of the two longitudinal modes, one period corresponds to two longitudinal mode intervals. So the amount of sub-peaks on their tuning curves is two times of N.

When the external cavity length l is not integral times of the internal cavity length L, Eq.(4) is not tenable any more. The external cavity phases of the two modes are not matching. The modulation of laser output power will be irregular.

Then, let us consider another situation: that both the internal cavity length and the external cavity length are modulated. In this experiment, the optical feedback cavity length is also modulated, besides laser frequency, a longitudinal mode interval corresponded to $\lambda/2$ variation of internal cavity length will cause $\lambda/2$ variation of the feedback cavity length at the same time. Thus, one more period can be seen in Fig.4. And the amount of sub-peaks on two modes' tuning curves is two times of N+1. Therefore, when $l = 1L$, $l = 2L$ or $l = 3L$, the intensity modulation curve I_3 undulates 2 periods, 3 periods or 4 periods, and 4 sub-peaks, 6 sub-peaks or 8 sub-peaks appeared on their intensity modulation curves I_1 and I_2 can be seen respectively. When $l = 6L$, the intensity modulation curve I_3 undulates 7 periods, but one or two sub-peaks have been suppressed because of mode competition. Thus, a period of I_1 and I_2 has 12 or 13 sub-peaks, just as those in Fig.4(d).

The above analyses show that the intensities of the laser and the two longitudinal modes are both modulated by the length of internal cavity with optical feedback. The modulation frequency of the laser output intensity is determined by the ratio of external cavity length to internal cavity length. The theoretical analyses are in good agreement with the experimental results.

5. Conclusions and discussion

The intensity tuning properties of a double longitudinal mode He–Ne laser subjected to optical feedback have been investigated. The intensities of the laser and the two longitudinal modes are both modulated by the length of internal cavity with optical feedback. We mainly focus on a particular situation: the external cavity length is integral times of internal cavity length. It has been shown that when only the internal cavity length is modulated, the intensity modulation frequency of the total light is proportional to the ratio N of external cavity length to internal cavity length, when both the internal and the external cavity length are modulated, the intensity modulation frequency of the total light is proportional to N+1. When $l = 6L$, the curve I_3 undulates 7 periods in Fig.4(d), and thus one-fourteenth of the central wavelength of laser can be obtained. If the ratio N is large enough, a more precision displacement corresponding to one fringe of optical feedback can be got. The central frequency of the lasing bandwidth or the laser transition line is almost invariable (its repeatability is typically of the order of 10^{-8}). Every N fringes or N+1 fringes correspond to $\lambda/2$ where the frequency varies by one longitudinal mode spacing. That is to say, a sensor based on these phenomena can calibrate itself once every N fringes or N+1 fringes and there is no error to be accumulated during the measurement. So our results are promising for application in a displacement sensor not only with high accuracy but also with self-calibration capability. The research can also be applied to other kinds of lasers.

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