Vol 17 No 2, February 2008
1674-1056/2008/17(02)/0644-05
Chinese Physics B
© 2008 Chin. Phys. Soc.
and IOP Publishing Ltd

Intensity modulation characters of orthogonally polarized HeNe lasers with different optical feedback level*

Cui Liu(崔 柳)†, Zhang Shu-Lian(张书练), and Wan Xin-Jun(万新军)

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

(Received 1 February 2007; revised manuscript received 4 May 2007)

This paper demonstrates the intensity modulation characters of orthogonally polarized HeNe lasers with different optical feedback level generated by the variable reflectivity of external reflector. The modulation depths of the orthogonally polarized frequencies are increased when the optical feedback level becomes strong. It also observes that the modulation amplitudes are different for different external cavity length. Based on the vectorial extension of Lamb's semi-classical theory, it finds that the calculations are consistent with the experimental results.

Keywords: intensity modulation, optical feedback, frequency split
PACC: 5170, 4255B, 4260H

1. Introduction

When a birefringent element, e.g. quartz crystal or stressed glass, is inserted into the resonance cavity of a laser, the output frequency will split into two orthogonally polarized ones.[1,2] This frequency split effect of laser has attracted the interest of many researchers and been applied in studies of dual frequency lasers' design,[2] displacements measurement[3] and angles measurement,[4] etc. On the other hands, when partial beams of the laser output is coupled by an external reflector back into the resonator, the interference between the reinjected field and the stationary field causes laser intensity modulation.[5−7] This phenomenon, called optical feedback effect or self-mixing interference, is widely studied for its sensing potential,[8] which has now covered displacement,[9,10] velocity,[11] vibration, and surface profile measurement.[12] However, the intensity modulation characters of frequency splitting lasers with different optical feedback level have not been successfully studied quantitatively and systematically.

In this paper, the influence of both frequency split effect and optical feedback effect on the intensity modulation of HeNe lasers are considered synthetically. By inserting a quartz crystal into a HeNe laser's resonance cavity, the original single mode laser changes to the orthogonally polarized one with two frequencies, o-ray and e-ray. The modulation depths of the two orthogonally polarized frequencies are both increased as the optical feedback level becomes strong. The modulation amplitudes change with different external cavity length value. Based on the vectorial extension of Lamb's semi-classical theory,[13] we calculate the intensity modulation depth curves when the external reflector's reflectivity changes from 0 to 1, and the results agree well with the experiments. These researches may offer guidance to the development of laser feedback interferometers.

2. Experimental setup

The experiments are carried out on a single-mode, operating at 632.8nm, linearly polarized HeNe laser shown in Fig.1. T is the discharge tube filled with Ne^{20}:Ne^{22}=1:1 gas mixture to suppress the Lamb dip in the output intensity curve. The ratio of gaseous pressure in laser is He:Ne=7:1.

*Project supported by the State Key Program of National Natural Science of China (Grant No 60438010).
†E-mail: l-cui04@mails.tsinghua.edu.cn

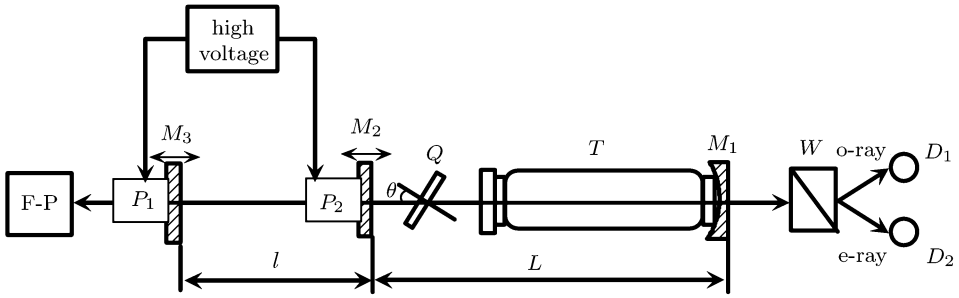


Fig.1. The optical feedback experimental setup using a HeNe laser with frequency split.

A plane mirror M_2 and a concave mirror M_1 which has a radius of 1m form the half-intracavity laser. Their reflectivities are $R_2 = 0.995$, $R_1 = 0.999$, respectively, and the distance between them is L=150mm. M_3 is the external feedback mirror with the reflectivity changing in the range of (0, 1) used to reflect laser beams back into the laser. M_2 and M_3 together form the feedback external cavity, whose length is l. A birefringent component made of quartz crystal Q is inserted into the cavity to split one frequency of the laser into two orthogonally polarized frequencies (o-ray and e-ray). The frequency difference of the two frequencies can be changed from 40MHz to one longitudinal mode spacing by changing the angle θ between the crystalline axis of Q and the laser axis. D_1, D_2 are photoelectric detectors which are used to detect the output intensities of two orthogonally polarized lights, respectively. W is a Wollaston prism which separates the different polarized lights. P_1 and P_2 are two piezoelectric transducers (PZT) driven by the high voltages. P_1 is used to drive the feedback mirror M_3 to move along the laser axis and P_2 drives the cavity mirror M_2 to realize the laser cavity tuning and choose the resonant mode oscillating in the cavity which can be observed by the Fabry-Perot scanning interferometer F-P.

3. Experimental results

We first modify the laser cavity by driving PZT P_2 and make the single mode of the laser oscillate around the central transition frequency of Ne atoms, and then adjust the angle θ to make the two split frequencies' difference be around 200MHz. The spectrum graph observed by the F-P of the laser is shown in Fig.2.

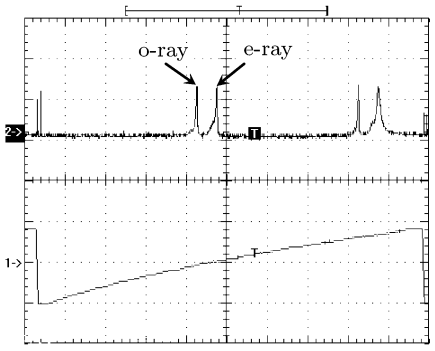


Fig.2. The spectrum graph of the frequency split HeNe laser observed from the oscillograph.

Curve 1 of Fig.2 is the driven voltage of the scanning interferometer and curve 2 is the spectrum graph of the laser. From curve 2, we can see that one frequency is split into two ones (o-ray and e-ray) and they are orthogonally polarized and tested by a polarizer.

Then we connect the feedback loop and drive the PZT P_1 with a periodical triangular wave to make the feedback mirror M_3 moving axially along the laser and reflect the output beam back into the cavity. The modulated intensities of o-ray and e-ray detected by D_1 and D_2 are shown in Fig.3 when the values of R_3 are 0.47, 0.057, 0.006, respectively.

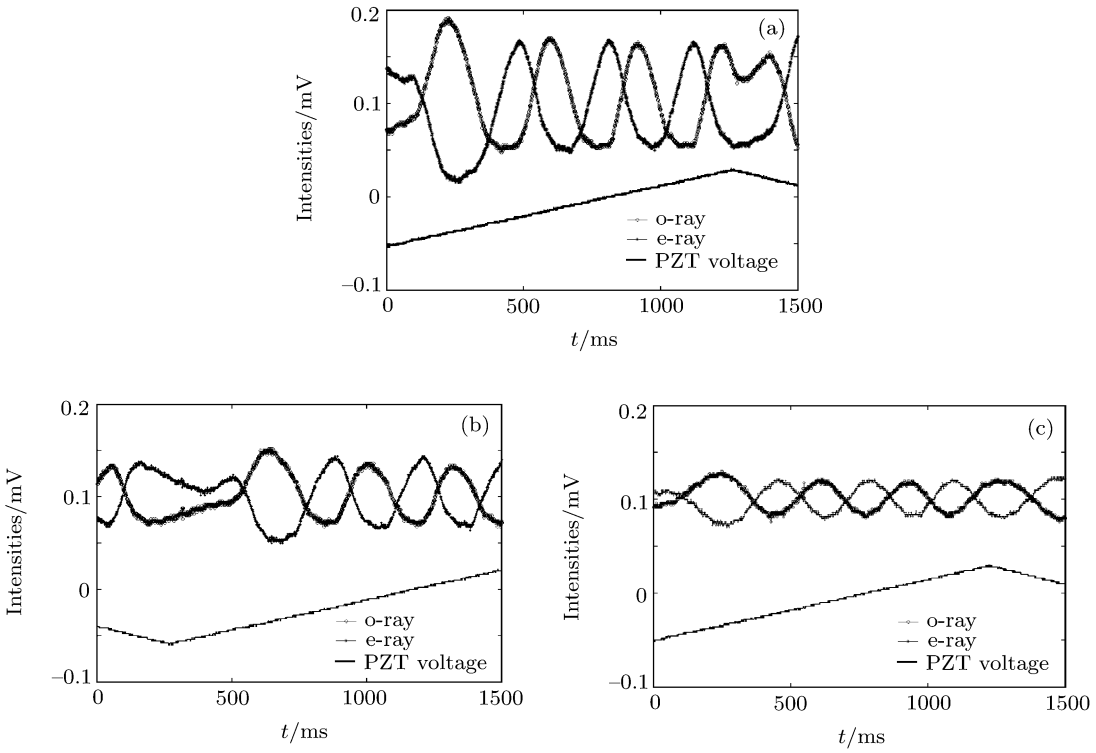


Fig.3. The experimental intensities modulated curves of o-ray and e-ray with different values of R_3. (a) R_3=0.47; (b) R_3=0.057; (c) R_3=0.006.

In Fig.3, the upper two curves represent the intensities of o-ray and e-ray, respectively, and the triangle wave is the voltage driving the PZT P_2. Fig.3 shows that the modulation depths of the two orthogonally polarized frequencies are both increased with the optical feedback level when it becomes strong. A series of experiments are present to research into the intensity modulation characters of orthogonally polarized HeNe lasers with the value of R_3 when it changes from 0 to 1, and the experimental results are shown in Fig.4(a).

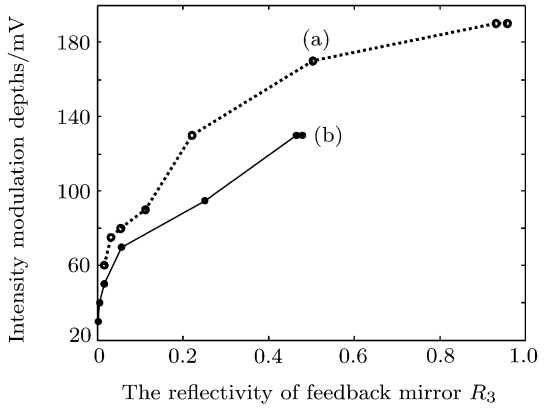


Fig.4. The experimental results of intensity modulation depths changing as the feedback mirror's reflectivity with different external cavity length l, (a) l_a=100mm, (b) l_b=75mm.

The external cavity length is l_a=100mm and l_b=75mm for Fig.4(a) and Fig.4(b), respectively. In Fig.4(b), the value of R_3 changed from 0 to 0.5. The experimental results represent that the modulation depths of the two orthogonally polarized frequencies are both increased with the optical feedback level becoming strong and the modulation amplitudes are different for different external cavity length.

4. Theoretical analysis

In order to explain these novel phenomena, we analyse our optical feedback system using the theoretic model based on the vectorial extension of Lamb's semi-classical theory, the laser intensities modulation ΔI by the feedback effect can be expressed as[14]

$$\begin{aligned}\Delta I_1 &= I_1 - I_{o1} = c(\beta_2 - \theta)(R_{f1} - R_2)/4DL,\\ \Delta I_2 &= I_2 - I_{o2} = c(\beta_1 - \theta)(R_{f2} - R_2)/4DL,\\ D &= \beta_1\beta_2 - \theta_{12}\theta_{21}. \end{aligned} \quad (1)$$

Where I_1 and I_2 are the steady state intensities of o-ray and e-ray with optical feedback, I_{o1} and I_{o2} are those without optical feedback. β_1 and β_2 are the saturation parameters, θ_{12} and θ_{21} are cross-saturation coefficients, using third-order perturbation theory, we

have $\theta_{12} = \theta_{21} = \theta$, c is speed of light in vacuum. $R_{\rm f1}$ and $R_{\rm f2}$ are the reflectivities of o-ray and e-ray in the equivalent feedback system in which the laser mirror M_2 and the external mirror M_3 form an external Fabry–Perot interferometer which now replaces the end mirror M_2 of the simple two-mirror laser cavity shown in Fig.5.

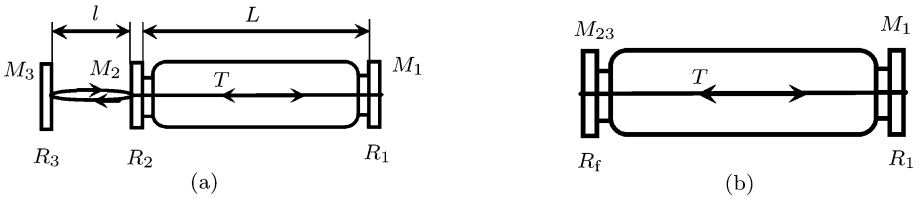


Fig.5. Schematic of (a) feedback effect in a He–Ne laser, (b) an equivalent system.

For a certain laser, β_1, β_2 and θ are constant. The equivalent mirror reflectivity $R_{\rm f}$ can be given by

$$R_{\rm f1} = R_2 + T_2^2 R_3 + 2T_2 r_2 r_3 \cos\delta_1,$$
$$R_{\rm f2} = R_2 + T_2^2 R_3 + 2T_2 r_2 r_3 \cos\delta_2. \qquad (2)$$

Here

$$\delta_1 = \delta_2 + \frac{4\pi l}{c}\Delta\nu$$

is the external phase difference between successive reflected beams with the frequency difference $\Delta\nu = \nu_1 - \nu_2$. The reflectivity R_2 and transmissivity T_2 of mirror M_2 are related by $R_2 + T_2 = 1$. r_2 and r_3 are the reflection coefficient of M_2 and M_3, respectively. t_2 is the transmission coefficient of M_2.

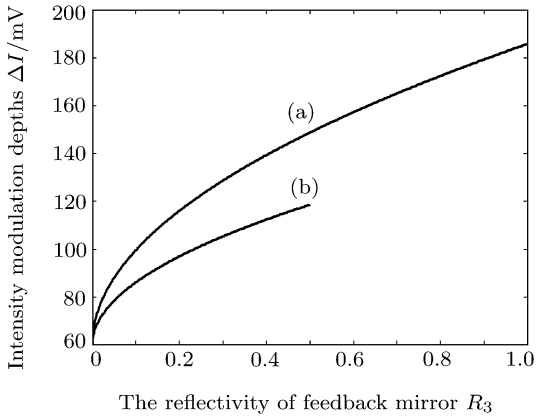


Fig.6. The calculated results of intensity modulation depths changing as the feedback mirror's reflectivity with different external cavity length l, (a) $l_{\rm a}$=100mm, (b) $l_{\rm b}$=75mm.

Because the two frequencies (o-ray and e-ray) are orthogonally polarized, we use Doyle's expressions[15] for β_1, β_2 and θ in our model which extend the semi-classical gas-laser theory of Lamb to describe the behaviour of a gas laser having generalized polarization characteristics. And the calculated results are shown in Fig.6.

Comparing Fig.6 with Fig.4, we can see that the calculated results are in good agreement with the experimental results. The stronger the optical feedback level is, the deeper the intensity modulation is. For different external cavity length, the modulation amplitudes are changed, too.

5. Conclusions

The intensity modulation characters of HeNe lasers with optical feedback effect and frequency split effect was studied quantitatively and systematically in this paper. When the optical feedback level changed from weak to strong as the external reflector's reflectivity is adjusted from 0 to 1, the modulation depths of the orthogonally polarized frequencies, o-ray and e-ray, are increased. Another novel phenomenon is that the modulation amplitudes change with different external cavity length value. Based on the vectorial extension of Lamb's semi-classical theory, we calculate the intensity modulation depth curves when the external reflector's reflectivity changes from 0 to 1, and the results agree well with the experiments. These researches may offer guidance to choose the target reflectivity in the development of laser feedback interferometers.

References

[1] Yang S and Zhang S 1988 *Opt. Commun.* **68** 55
[2] Zhang S, Jin Y, Fu J, Han Y and Li Y 2001 *Opt. Eng.* **40** 594
[3] Li Y, Zhang S and Han Y 2000 *Opt. Eng.* **39** 3039
[4] Zhang S, Li K, Ren M and Deng Z 1995 *Appl. Opt.* **34** 1967
[5] Peek T, Bolwijn P and Alkemade C 1967 *Am. J. Phys.* **35** 820
[6] Liu Y, Zhang S and Qian X 2007 *Chin. Phys.* **16** 463
[7] Huang L, Luo X, Fang J, Zhao Y and Tang G 2005 *Acta Phys. Sin.* **54** 543 (in Chinese)
[8] Liu G, Zhang S, Li Y and Zhu J 2005 *Chin. phys.* **14** 1984
[9] Kao J, Kikuchi M, Yamaguchi I and Ozono S 1995 *Meas. Sci. Technol.* **6** 45
[10] Jukka H, Leszek K and Myllylä R 2005 *Opt. Eng.* **44** 080504
[11] Lorenzo S, Yu Y, Guido G, Guy P and and Bosch T 2004 *IEEE Trans. Instrum. Meas.* **53** 223
[12] Day R, Lancot E, Stoeckel F and Bruno B 2001 *Appl. Opt.* **40** 1921
[13] Lamb W 1964 *Phys. Rev.* **134** A1429
[14] Cui L and Zhang S 2005 *Opt. Express* **13** 6558
[15] Doyle W M and Mattew B 1966 *Phys. Rev.* **147** 359