

# Two-Mode Frequency Stabilization of an Internal-Mirror 612 nm He-Ne Laser

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(Received July 21, 1999; Accepted November 29, 1999)

## ABSTRACT

We studied the polarization properties of a short internal-mirror 612 nm He-Ne laser. We found that polarization flip did not occur at the symmetric two-mode location but near the center of the power profile. Therefore, the laser could be frequency-stabilized using the two-mode method, and the stability achieved was better than  $5 \times 10^{-10}$ . This laser can be used as a light source in length measurements using multi-color interferometers.

**Key Words:** 612 nm He-Ne laser, polarization flip, frequency stabilization, two-mode method

## I. Introduction

Gauge blocks are widely used in industry for precision length measurements. Usually, the gauge blocks are calibrated by a gauge block interferometer using a frequency-stabilized 633 nm He-Ne laser as the light source. However, the single-color interferometer has limited performance in accuracy and calibration range. To improve the performance, the two-color or multi-color interferometer using the method of exact fractions has been adopted (Pugh and Jackson, 1986). Therefore, the frequency-stabilized 612 nm He-Ne laser is a valuable light source for length measurements made using interferometers.

The transition of the 612 nm He-Ne laser shares the same upper level ( $3s_2$ ,  $J = 1$ ,  $g = 1.295$ ) with the 633 nm laser transition, and its lower level is  $2p_6$  ( $J = 2$ ,  $g = 1.229$ ). The emitting cross section of the  $3s_2 \rightarrow 2p_4$  transition at 633 nm is five times larger than that of the  $3s_2 \rightarrow 2p_6$  transition at 612 nm. For high-precision frequency stabilization, 612 nm He-Ne lasers can be stabilized to hyperfine transitions of the iodine molecule (Ma and Hall, 1990; Jaatinen and Brown, 1995; Bisi and Bertinetto, 1997), but this requires a complex and delicate optical system. The two-mode method for frequency stabilization of an internal-mirror He-Ne laser is economical and convenient. It can be used to stabilize the frequencies of two orthogonal linearly polarized modes at the symmetric two-mode location of a He-Ne laser by means of their intensity

difference. In the case of a 612 nm He-Ne laser, to our knowledge, there have not been any reports on frequency stabilization using the two-mode method in the literature. The main reason is its complicated polarization behavior within the power profile (Rowley and Gill, 1990). Usually, an internal-mirror 612 nm He-Ne laser exhibits polarization flip at the center of the power profile and the symmetric two-mode location. Under such operation conditions, frequency stabilization using the two-mode method is difficult to achieve.

Bondarchuk *et al.* (1989) studied a homemade 612 nm He-Ne laser tube and stabilized the laser by stabilizing the power ratio of the two orthogonal linearly polarized modes. To avoid polarization flip, the laser was stabilized on imbalance of the output power of the two orthogonal polarized modes with stability about  $1 \times 10^{-7}$ . In addition, Eom *et al.* (1990) stabilized an internal-mirror 612 nm He-Ne laser under a transverse magnetic field using the beat frequency stabilization method. They stabilized the laser frequency at the center of the power profile with a stability of  $5 \times 10^{-9}$  over a time period of one hour.

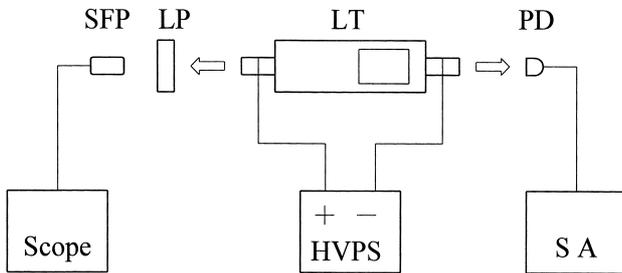
In this paper, we report on our investigations on the polarization behavior of a short internal-mirror 612 nm He-Ne laser. Although the laser showed a preference for polarization, there still existed two orthogonal linearly polarized modes at the symmetric two-mode location. The laser was then locked using the two-mode method for the first time, and stability better than  $5 \times 10^{-10}$  was achieved.

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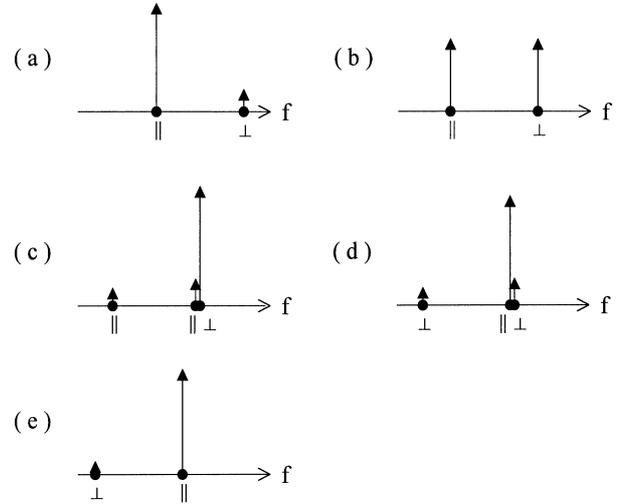
## II. Polarization Properties

The laser tube we used was a Melles Griot (Irvine, CA, U.S.A.) 05-LOR-024S 612 nm internal-mirror He-Ne laser tube with an output power of 1.2 mW and a mode spacing of 733 MHz. The experimental setup for our study on polarization properties is shown in Fig. 1. We directed the laser rear beam into a Technical Optics (Onchan, Isle of Man, U.K.) SA-1-RG scanning confocal Fabry-Perot interferometer to monitor the longitudinal modes. A linear polarizer was inserted in front of the Fabry-Perot interferometer to identify the polarization plane of each longitudinal mode. The front output beam was coupled to a fast PIN photodiode, and the beat frequencies between different modes were observed using a radio frequency (RF) spectrum analyzer.

After the laser was turned on, two oscillating modes drifted to lower frequency and swept across the power profile due to thermal expansion of the laser tube. The mode configuration and polarization properties are shown in Fig. 2. Outside of the polarization flip region, the modes were linearly polarized and orthogonal to each other, and the polarization planes, denoted as  $\perp$ - and  $\parallel$ -polarization, were fixed with respect to the laser tube as shown. This is similar to the case of the internal-mirror 633 nm He-Ne laser and is the same as the theoretical prediction made by Lenstra and Herman (1978). Polarization flip occurred when the higher frequency mode oscillated close to the center of the power profile and the other mode near the edge of the power profile as shown in Fig. 2(c) and (d). At this point, the higher frequency mode contained two orthogonal linearly polarized components, and the frequency difference between these two components was about 20 kHz as observed using the spectrum analyzer at the beat note of 730 MHz. These two components exchanged power, and the edge mode was then forced to change the direction of polarization through mode competition. After the polarization flip, each mode recovered to one polarization component. The center



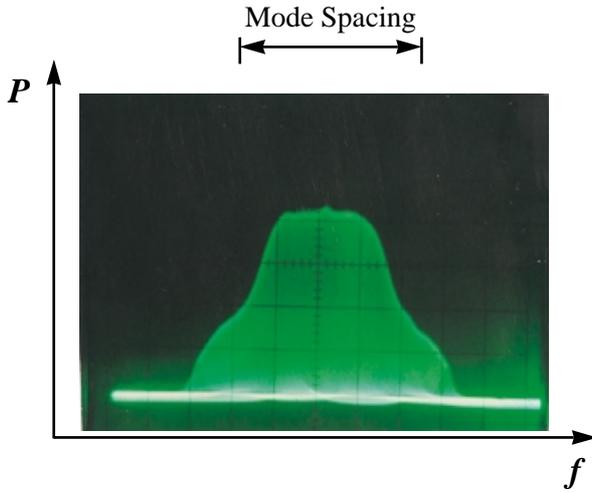
**Fig. 1.** Experimental setup for our study on polarization properties. SFP: scanning Fabry-Perot interferometer; LP: linear polarizer; LT: laser tube; PD: photodiode; HVPS: high voltage power supply; SA: spectrum analyzer.



**Fig. 2.** The polarization configuration of our laser tube. The height of the arrow shows the relative mode intensity, and  $f$  is the emission frequency. The laser showed a preference for polarization. The higher frequency mode had  $\perp$ -polarization while the other had  $\parallel$ -polarization. At (c)  $\rightarrow$  (d), the polarization flip occurred in order to maintain this preference.

mode always had  $\parallel$ -polarization and the side mode  $\perp$ -polarization. To identify the mode location of the polarization flip, the total power of the laser was recorded using an oscilloscope and photographed with an exposure time long enough to record the whole power profile. The power profile is shown in Fig. 3. We found that a characteristic peak at the center occurred because the mode contained two orthogonal linearly polarized components. The peak was near the center of the power profile and corresponds to the location of polarization flip.

Based on the above observations, we found that the laser showed a preference for polarization near the center of the power profile. The higher frequency mode always had  $\perp$ -polarization and the other  $\parallel$ -polarization. Thus, the polarization flip occurred in order to maintain this preference near the center region. According to theory, the preference for polarization is dependent on the angular-momentum quantum numbers of the lasing levels because of saturation-induced anisotropy in the medium (Lenstra, and Herman, 1978). In general, the saturation-induced polarization preference for two-mode and multi-mode operation is more complicated than that for a single mode laser due to the mode coupling. For a 633 nm He-Ne laser with three-mode operation, polarization flip often occurs at the center of the profile and at the symmetric two-mode location (Halse, 1979). Although the angular-momentum of the transition levels of a 612 nm He-Ne laser are the same as that of a 633 nm one ( $j = 1 \rightarrow j = 2$ ), polarization flip in our laser did not occur in the symmetric two-mode region. This is probably due to anisotropy



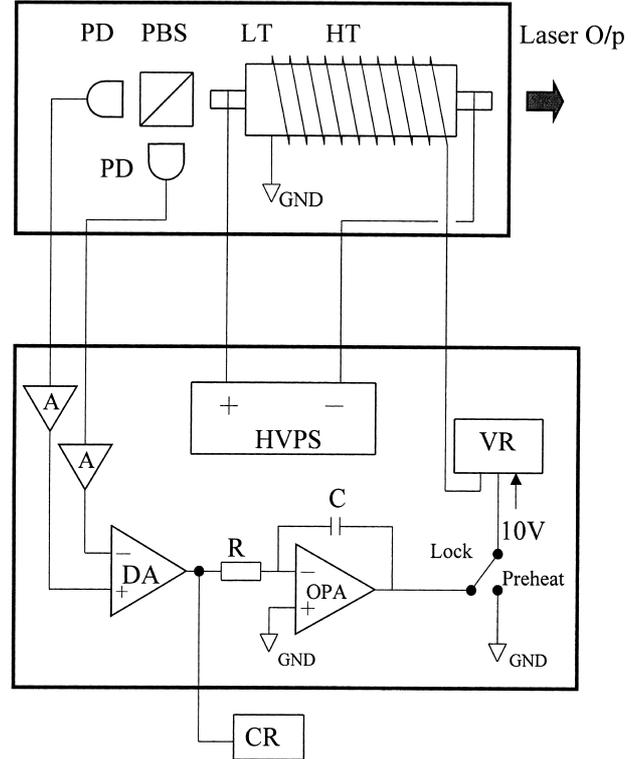
**Fig. 3.** Typical power profile of the laser modes recorded using an oscilloscope and photography;  $P$ : power;  $f$ : emission frequency. The characteristic peak occurred because the mode contained two orthogonal linear polarized components, and it corresponded to the location of polarization flip.

caused by the reflecting mirrors (Puntambekar *et al.*, 1982). As mentioned above, the emitting cross section of the 612 nm He-Ne laser transition is five times less than that of the 633 nm He-Ne laser transition, and the anisotropy of the mirrors more easily dominates the laser cavity anisotropy. However, unlike the green He-Ne laser (Lin and Shy, 1990; Lazar and Schellekens, 1995), polarization flip in our laser can not be eliminated by applying a transverse magnetic field to the tube.

### III. Two-Mode Frequency Stabilization

The two-mode frequency stabilization method uses the power difference between two orthogonal polarization modes of the laser as the error signal. Although polarization flip occurred near the center region for our laser, we found that the power difference of the two modes outside of the polarization flip region still could be used as the error signal for frequency stabilization.

Figure 4 shows the experimental arrangement for frequency stabilization of our laser tube. We wrapped a thin heating foil around the laser tube to control the length of the cavity. A copper coil wrapped in the opposite direction was used to cancel the axial magnetic field produced by the heating foil. The two orthogonal linearly polarized modes from the rear laser output beam were separated by a polarizing beam splitter and then detected by two photodiodes. The difference of the output power  $I_{\parallel} - I_{\perp}$ , used as the error signal, and we used a simple integral feedback circuit (Mio and Tsubono, 1990; Huang *et al.*, 1993) to control the current flowing through the thin heating foil wound around the laser tube. A typical recorded



**Fig. 4.** Experimental setup for frequency stabilization of a 612 nm He-Ne laser; PD: photodiode; PBS: polarizing beam splitter; LT: laser tube; HT: heater; A: amplifier; DA: differential amplifier AMP-01; R: resistor; C: capacitor; OPA: operational amplifier LF-356; VR: voltage regulator LM7805; HVPS: high voltage power supply; CR: chart recorder.

trace of the error signal before and after the feedback loop was turned on is shown in Fig. 5. Before the feedback loop was turned on, the major cause of frequency drift and amplitude variation was the cavity length change due to thermal expansion. When the higher frequency mode was near the center of the power profile and swept across the region of polarization flip, the error signal changed rapidly from minimum to maximum. In this region, the laser was not suitable for frequency stabilization due to polarization flips. On the other hand, outside the polarization flip region, the error signal slowly changed from maximum to minimum. The range between the peak and bottom values of the error signal corresponded to the frequency range in one cavity mode spacing (733 MHz). The zero crossing point was not located at the center of the error signal since the total power of  $\parallel$ -polarization was larger than that of  $\perp$ -polarization. After the feedback loop was turned on, the laser tube was locked in symmetric two-mode operation ( $I_{\parallel} - I_{\perp} = 0$ ). The frequency instability estimated from the fluctuation of the error signal (Sasaki, 1983) was about 200 kHz, so we achieved a relative frequency stability of better than  $5 \times 10^{-10}$ .

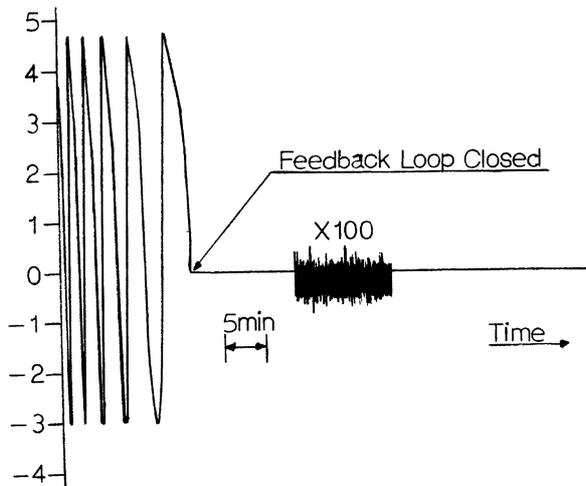


Fig. 5. Typical recorded trace of the error signal before and after the feedback loop was turned on.

#### IV. Conclusions

According to the theoretical description, the preference for polarization arises from the anisotropy of the medium and the cavity (Puntambekar *et al.*, 1982). However, the polarization preference under two-mode operation is more complicated due to mode-mode interaction. To stabilize a 612 nm He-Ne laser at the symmetric two-mode location, we have investigated the polarization properties of a short internal-mirror 612 nm He-Ne laser. The laser showed a preference for polarization whenever the higher frequency mode was close to the center of the power profile and polarization flip occurred. But polarization flip did not occur at the symmetric two-mode location, and the power difference between the two orthogonal modes could be used as the error signal for the conventional two-mode method. Thus, we could lock the laser at the symmetric two-mode location by using the two-mode method with a stability of better than  $5 \times 10^{-10}$ .

We have been engaged in developing two-mode stabilized He-Ne lasers at 543 and 612 nm. The frequency stabilized 612 nm He-Ne laser reported here will be used

as a light source for a gauge interferometer at the Center for Measurement Standards, Taiwan, R.O.C.

#### Acknowledgment

The authors wish to thank the National Science Council of the Republic of China and the Lee-Ming Institute of Technology for financial support.

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## 波長 612 nm 內鏡式氦氖雷射之雙縱模頻率穩定

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### 摘 要

在本篇文章中，我們研究一支波長 612 nm 的內鏡式短共振腔氦氖雷射之偏振特性。我們發現這支雷射的偏振轉變並未出現在兩縱模位於對稱位置上，而是出現在較高頻率的縱模接近功率增益曲線中心位置時。因此，這支波長 612 nm 的內鏡式氦氖雷射可以應用雙模穩頻法將其頻率穩定，其穩定度可達  $5 \times 10^{-10}$ 。這支雷射可以應用在塊規干涉儀中，作為多波長干涉長度測量儀的光源。