Jpn. J. Appl. Phys. Vol. 39 (2000) pp. 1136–1139
Part 1, No. 3A, March 2000

Polarization Properties and Frequency Stabilization of an Internal-Mirror 1523 nm He–Ne Laser under Axial Magnetic Field

Tong-Long HUANG[1,2], Jow-Tsong SHY[1], Tyson LIN[3] and Hai-Pei LIU[2]
[1]*Department of Physics, National Tsing Hua University, Hsinchu, Taiwan 300, R.O.C.*
[2]*Institute of Optical Sciences, National Central University, Chung-Li, Taiwan 320, R.O.C.*
[3]*PhysicsTeaching and Research Center, Feng Chia University, Taichung, Taiwan 407, R.O.C.*

(Received October 29, 1999; accepted for publication December 20, 1999)

The polarization properties of an internal-mirror 1523 nm He–Ne laser under an axial magnetic field were investigated. When the axial magnetic field was around 12 mT, the laser operated in single mode with two opposite circularly polarized components near the center of gain profile. In addition, due to the competition between these two opposite circularly polarized components, each mode had only one circularly polarized component survived when the laser operated in the two-mode region. We could stabilize the laser frequency at either the center of gain profile or the symmetric two-mode taking advantage of the power difference between the two circularly polarized components of the laser output, and the stability achieved was better than 1 MHz.

KEYWORDS: polarization properties, axial magnetic field, 1523 nm He–Ne laser, frequency stabilization, symmetric two-mode, polarization flip

1. Introduction

A survey of the industrial and regulatory requirements for frequency standards for optical communications concluded that frequency standards for 1500 and 1300 nm bands is needed for wavelength division multiplexing (WDM) fiber-optical communication systems, and an accuracy of order 1 part in 10^9 is desired for national laboratory use, with one order of magnitude less for a transfer standard, and one more order less for the field applications.[1)] In 1500 nm band the 1523 nm He–Ne laser, diode laser, and Er-doped fiber laser are suitable for this purpose. The internal-mirror 1523 nm He–Ne laser has some advantages over diode and Er-doped fiber lasers in high spectral purity and narrow linewidth.[2)] The study of frequency stabilization of internal-mirror 1523 nm He–Ne laser is valuable for the fiber optical communication applications.[3)]

For 1523 nm He–Ne laser transition ($2s_2 \rightarrow 2p_1$, $J = 1 \rightarrow J = 0$), the theory of Polder and Van Haeringen[4)] predicts that the laser output has no preference of polarization for single mode operation. However, the experiment of De Lang and Bouwhuis[5)] showed that the laser output has a small but definite tendency of circular polarization, which can be attributed to the difference between the relaxation rates of the quadrupole moment and the angular momentum in the degenerated $J = 1$ level.[6)] For two-mode operation, due to mode interaction, theory predicts either elliptical or circular oppositely polarized modes.[7,8)]

Tomlison and Fork have studied the polarization properties of single mode internal-mirror 1523 nm He–Ne lasers in a weak axial magnetic field ($\leqq$1.6 mT).[9,10)] The laser output showed strong coupling between the two opposite circularly polarized components of the single cavity mode. Using the power difference between the two components, they were able to stabilize the laser to a stability of 400 kHz.[11)] One should note that their lasers were very different from the commercial internal-mirror lasers in structure and had very small cavity anisotropy.

The mode properties and frequency stabilization of a commercial internal-mirror 1523 nm He–Ne laser have been studied by Junttila and Stahlberg.[12)] The output modes showed oppositely elliptical or circular polarization, which agreed with the theoretical predications of Lenstra and Herman.[7,8)] Using the ratio of the intensities of the two modes as the error signal, they were able to stabilize the laser frequency within 10 MHz on one hand, and the total output power within 1% on the other. However, due to strong mode competition, the mode configuration for stabilization is quite restricted.

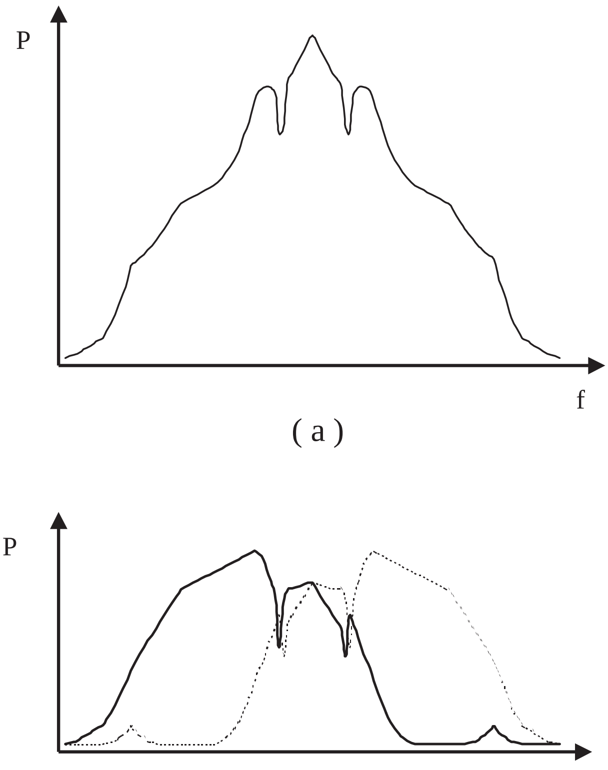
We have studied the mode properties of a commercial internal-mirror 1523 nm He–Ne laser. This laser showed different polarization properties as Junttila and Stahlberg's observations. In free running, the laser operates at two or three modes, and each mode contains two orthogonal linearly polarized components. The reason is that the cavity anisotropy of our laser is stronger than theirs. However as we applied a small transverse magnetic field (2.5 mT), the output had two orthogonal linearly polarized modes over a wide range, and it could be easily stabilized within 1 MHz using the modified two-mode method. The detail results can be found in our previous publication.[13)]

In this paper, we will present our studies on the polarization properties of the same commercial internal-mirror 1523 nm He–Ne laser in axial magnetic field from 2 mT to 30 mT. Under a proper axial magnetic field, we could stabilize the laser frequency at either the center of gain profile or the symmetric two-mode using the power difference between the two circularly polarized components of the laser output, and the stability was better than 1 MHz.

2. Polarization Properties

The laser tube studied was a Melles Griot 05-LIR-150 1523 nm internal-mirror He–Ne laser tube that has been used in our previous investigations.[13)] The laser operates at two or three modes and has an output of 0.85 mW and a mode spacing of 441 MHz (corresponding to cavity length of 34 cm). An axial electromagnet about 17 cm long (half the cavity length) which could produce an axial magnetic field of up to 30 mT was used in this study. The longitudinal modes were monitored by sending the rear laser beam into a 7.5 GHz FSR scanning confocal Fabry-Perot interferometer. A linear polarizer and a quarter-wave plate were used to identify the polarization of each longitudinal mode.

For an internal-mirror He–Ne laser the polarization properties usually depend on the cavity anisotropy as the applied magnetic field is weak.[14)] Under an axial magnetic field, if the magnetic field is small, the polarization properties of our laser are the same as the free running operation. When the magnetic field was higher than 2 mT due to the magnetic-field-induced anisotropy in the active medium, each mode will be split into left-hand and right-hand circularly polarized components (denoted as σ^- and σ^+) by the Zeeman effect. The polarization and power of the modes were investigated as a function of their frequencies. The emission profile of the laser output was recorded by using an oscilloscope camera. Figure 1(a) shows a sketch that recorded output power versus frequency of the laser under an axial magnetic field of 6 mT. The width of total emission profile is approximately twice the mode spacing of the laser. In Fig. 1(a), there were two dips on the both sides of the center of gain profile. To recognize the phenomenon, we can refer to Fig. 1(b), which shows the sketch of σ^- and σ^+ emission profile. When σ^- of the mode operated at the power maximum, its power could suddenly drop as the mode move to higher frequency. At this moment, the two opposite circularly polarized components of the mode changed their power, appeared as polarization flip. The same result happened as the mode move to lower frequency. The major cause of cross saturation was the other polarized component comes into lasing. However, the phenomenon would disappear as axial magnetic field increased up to 10 mT. In additions, the σ^- and σ^+ emission profile all have a region of about 200 MHz where the power of σ^- or σ^+ component equals to zero. Each mode has only one circularly polarized component in this region. By Fig. 1(a), we can find this region around the symmetric two-mode operation, and the higher frequency mode should have σ^+ polarization. The reason is that the upper level of the 1523 nm laser transition is $2s_2$, while the lower level is $2p_1$. Since the transition is $J = 1 \rightarrow J = 0$ type, under axial magnetic field, the Zeeman splitting is shown in Fig. 2. The g value of the upper $2s_2$ is not measured and a reasonable assumption is that it is approximately 1.3. The gain profile of a 1523 nm He–Ne laser in an axial magnetic field splits into a gain doublet for the two allowed transitions σ^- and σ^+ with a separation of 36.4 MHz/mT approximately.[15)] Furthermore the σ^- and σ^+ transitions share the same lower level, there exits coupling between the two opposite circularly polarized components of the mode.



(a)

(b)

Fig. 1. (a) A sketch of the oscilloscope camera recorded emission profile of the laser in an axial magnetic field of 6 mT. (b) The sketch of the observed σ^- and σ^+ emission profile, solid and dotted line corresponds to the σ^- and σ^+ emission profile respectively. (P: relative mode power; f: emission frequency)

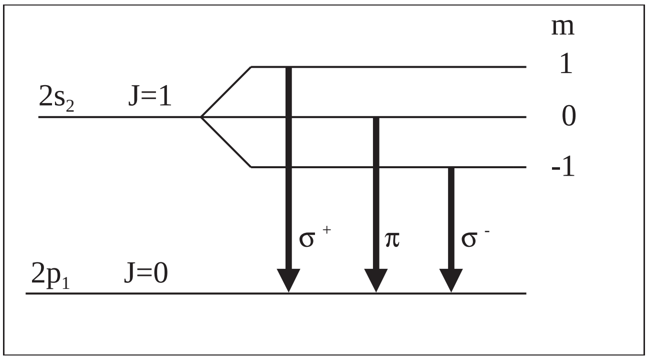


Fig. 2. The Zeeman splitting of the $2s_2$ and $2p_1$ levels in Ne for the $J = 1$ to $J = 0$ 1523 nm lasing transition.

For the field strength above 6 mT, our laser was possible to achieve single mode operation as one mode was near the center of gain profile. When we applied an axial magnetic field from 16 mT to 30 mT, the Zeeman splitting was larger than mode spacing. In such a case the width of gain profile allowed two or three modes operation. The center mode contained two opposite circularly polarized components, and two side modes had only one circular polarization. When the magnetic field was up to 30 mT, the σ^- and σ^+ emission profile could be completely separated, each mode would has only one circular polarization, and the σ^- and σ^+ polarized modes behaved more or less independently.

For observing the above situation, the power difference between these two opposite circularly polarized components of the modes were detected by two Ge photodiodes using the output from the rear mirror of the laser through a quarter wave plate and a polarizing beam splitter. The difference in the output voltages of the photodiodes is thus proportional to the power difference two opposite circularly polarized components. The power difference recorded under the influence from 2 mT to 26 mT axial field strength is shown in Fig. 3. Every section corresponds to the power difference as the laser frequency scanned over the whole gain profile. The positive slope and smooth part was known as the two-mode region of the section when the field was from 2 mT to 14 mT, while crossing zero point corresponded to symmetric two-mode operation. The negative slope part was three-mode region of the section as the field was less than 6 mT and the single mode region as the field was from 6 mT to 14 mT. In this region there

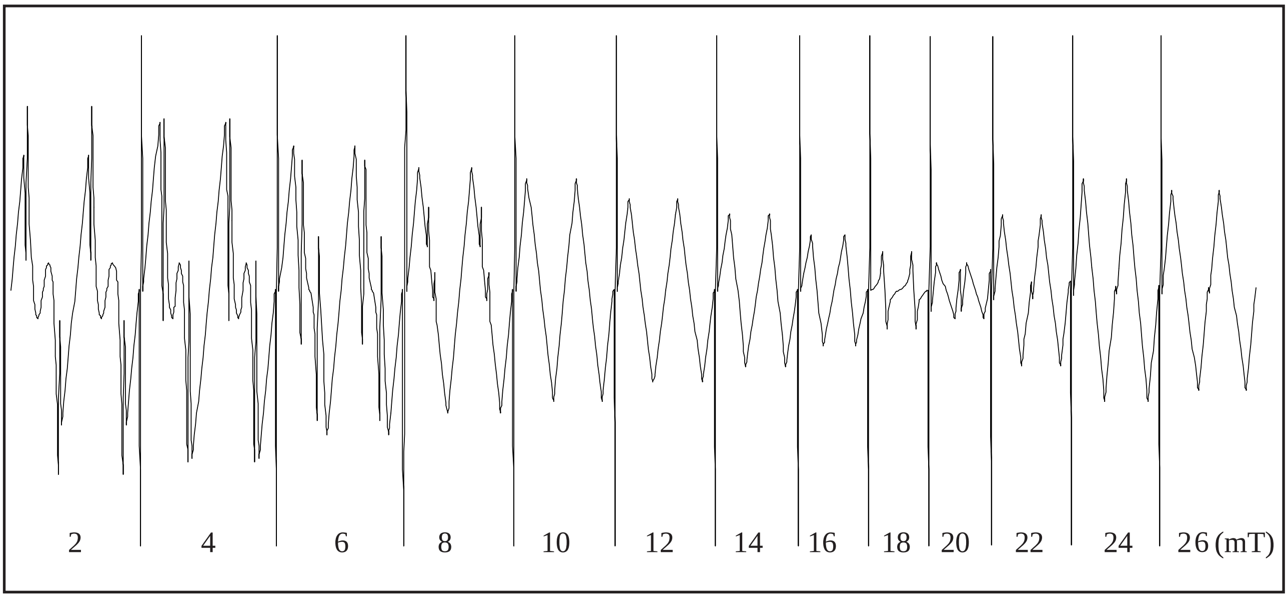


Fig. 3. The power difference recorded under the influence of several axial magnetic field strengths. Every section corresponds to the power difference as the laser frequency scanned over the whole gain profile.

exists more than two transitions except in the field larger than 10 mT due to the polarization flip of opposite circularly polarized components. When the magnetic field was greater than 16 mT, the laser operated at two to three modes, the positive slope and the negative slope part corresponded to three-mode region and the two-mode region respectively.

Because of the fact that the polarization flip of opposite circularly polarized components exist as the field strength is less than 10 mT, the laser is not suitably stabilized at the single mode region. However, if we select the axial magnetic field around 12 mT, the laser can be stabilized at either the center of gain profile or symmetric two-mode position. In addition, when the gain profile splitting is larger than the width of the mode spacing under strong axial magnetic field, the laser would lead to poor frequency stability.

3. Frequency Stabilization

For frequency stabilization of our longitudinal Zeeman laser, the laser tube was placed in the center of a cylindrical permanent magnet of 2.4 cm in thickness that produced longitudinal magnetic field strength of 40 mT at its center. The polarization properties were similar to the field strength of 14 mT with axial electromagnet.

When the laser was turned on, the rear beam passed through a quarter wave plate, and the two linearly and orthogonally polarized components were separated by a polarizing beam splitter and detected by two Ge photodiodes. The difference in the output voltages of the photodiodes was obtained by using a differential amplifier and adopted as error signal. The output of differential amplifier was connected to a feedback loop that controlled the current through a self-adhesive noninductive foil heater wound on the center of laser tube. The feedback circuit was similar to that designed by Mio and Tsubono.[16)]

A typical recorder trace of the error signal before and after starting the feedback loop is shown in Fig. 4. Before starting the feedback loop, the major cause of frequency and amplitude fluctuations is the change in the cavity length of the laser tube due to thermal expansion. In Fig. 4 the zero crossing point with positive slope corresponds to symmetric two-mode operation and the zero with negative slope corresponds to single mode at the center of gain profile. The peak to bottom value of the error signal corresponds to the frequency range that the laser tube scans through half a mode spacing (i.e. 220 MHz). In this case the laser was locked at the center of gain profile, where the frequency difference between the two circular polarized components was about 400 kHz. The frequency stability can be estimated from the fluctuation in the power difference as the feedback loop is on. Figure 4 shows the frequency stability achieved is better than 1 MHz ($\Delta f/f = \pm 3 \times 10^{-9}$). If we change the signal of +- and −-terminal of differential amplifier, our laser can lock at symmetric two-mode position. The frequency stability is the same as the laser lock at single mode operation.

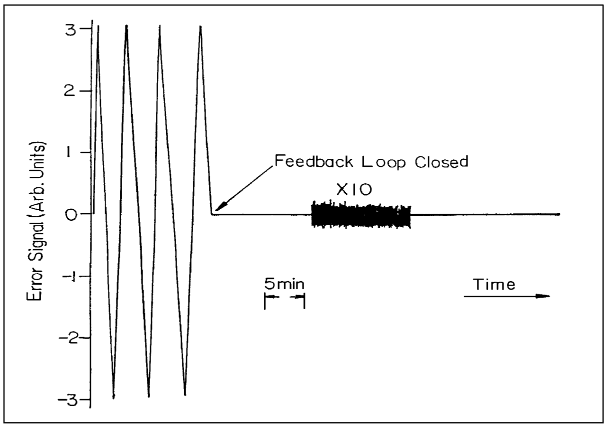


Fig. 4. Typical result for frequency stabilization of longitudinal Zeeman laser. The laser tube scans through half a mode spacing as the error signal changes from maximum to minimum.

4. Conclusions

For most of the applications, a frequency stabilized internal-mirror two-mode He–Ne laser is oscillating in two orthogonally polarized modes, and the modes are symmetrical with respect to the center of the gain profile. In previous reports, under free running operation or a small transverse magnetic field, the commercial internal-mirror 1523 nm He–Ne laser was stabilized by the modified two-mode method. One of the modes was tuned closer to the center of the gain profile and the other mode on the wing.[12,13] However, under an axial magnetic field from 2 mT to 26 mT, the laser frequency can be locked at symmetric two-mode location by simple two-mode method. In fact, this stability is better than the method using transverse magnetic field which we reported previously.[13] Since the laser can be locked to symmetric two-mode, the lock point will not shift due to laser power variation.

When we applied an axial magnetic field around 12 mT, the laser frequency can stabilize at not only symmetric two-mode but also the center of gain profile. The output of the stabilized longitudinal Zeeman laser can obtain that single mode contains two opposite circularly polarized components at the center of gain profile or two orthogonally and circularly polarized modes locate at the symmetric two-mode position.

Acknowledgements

The authors wish to thank the supports by the National Science Council of the Republic of China, Lee-Ming Institute of Technology, and National Tsing Hua University.

1) D. J. E. Knight, P. S. Hausell, H. C. Leeson, G. Duxbury and J. Meldan and M. Lawrence: Proc. SPIE **1837** (1993) 106.
2) J. W. Eerkens and W. W. Lee: Proc. SPIE **500** (1984) 131.
3) C. W. Wu and H.-C. Chang: IEEE Photon. Technol. Lett. **9** (1997) 206.
4) D. Polder and W. V. Haeringen: Phys. Lett. **19** (1965) 380.
5) H. De Lang and G. Bouwhuis: Phys. Lett. **20** (1966) 383.
6) D. Polder and W. V. Haeringen: Phys. Lett. A **25** (1967) 337.
7) D. Lenstra and G. C. Herman: Physica C **95** (1978) 405.
8) D. Lenstra: Phys. Rep. **59** (1980) 299.
9) W. J. Tomlinson, R. L. Fork: Phys. Rev. **164** (1967) 466.
10) M. Sargent III, W. E. Lamb, Jr. and R. L. Fork: Phys. Rev. **164** (1967) 436.
11) W. J. Tomlinson, R. L. Fork: Appl. Opt. **8** (1969) 121.
12) M.-L. Junttila and B. Stahlberg: Phys. Scr. **41** (1990) 667.
13) T.-L. Huang, T. Lin and J.-T. Shy: Jpn. J. Appl. Phys. **32** (1993) 849.
14) T. Lin and J.-T. Shy: Jpn. J. Appl. Phys. **29** (1990) 878, and references there in.
15) W. Culshaw and J. Kannelaud: Phys. Rev. **133** (1964) 691.
16) N. Mio and K. Tsubono: Jpn. J. Appl. Phys. **29** (1990) 883.