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# Low-frequency modulation of 0.6328 μm He–Ne laser by transverse magnetic field intensity[☆]

Yi Hanwei[a,*], Sun Ruiyan[b], Zheng Yiqun[b], Ding Peizhu[c]

[a] *Department of Optical Physics, Changchun Institute of Optics and Fine Mechanics, 7 Weixing Road, Changchun 130022, People's Republic of China*

[b] *Traditional Chinese Pharmacy Department, Changchun College of Traditional Chinese Medicine, Changchun 130021, People's Republic of China*

[c] *Institute of Atom and Molecules Physics, Jilin University, Changchun 130023, People's Republic of China*

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## Abstract

Effect of transverse magnetic field on 0.6328 μm He–Ne laser light polarized parallel and perpendicular to transverse magnetic field has been studied in this paper. Low-frequency modulation of two kinds of polarized laser light is completed and low-frequency modulation of polarization degree is put forward. © 2000 Elsevier Science Ltd. All rights reserved.

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## 1. Introduction

Longitudinal magnetic field has been used to restrict plasma to increase its density in an $Ar^+$ laser. Polarized laser light was obtained by transverse magnetic field according to the Zeeman effect [2]. A detailed study of the effects of transverse magnetic field which is applied to a fraction of discharge capillary of He–Ne laser operating at 0.6328 μm was reported by Crisp [1,3]. 500–1000 G transverse magnetic field applied to a portion of plasma tube can result in complete linear polarization of laser output. If magnetic field is changed in certain scope of transverse magnetic field intensity, polarization degree will be changed. Therefore, two kinds of polarized laser light and polarization degree can be modulated at low frequency by electrical current through coil on magnetic iron. The low-frequency modulation of the two kinds of

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[*] Corresponding author.

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polarized laser light and polarization degree by transverse magnetic field is studied in our laboratory. This modulation method can be used in remote indication, remote controlling technique and remote sensing technique. In the process signals can avoid electric interference.

## 2. Theoretical analysis

Stimulated radiation transition of a 0.6328 μm He–Ne laser line takes place between levels $2P_4$ and $3S_2$ [4]. Without a magnetic field and radial asymmetry, the output laser beam is non-polarized. Because of the effect of the transverse magnetic field, splitting of the $2P_4$ and $3S_2$ levels takes place. After splitting these two levels, three laser lines are formed. One of them is the $\pi$ component, which is polarized parallel to the magnetic field, its magnetic quantum number difference $\Delta M = 0$. The other two laser lines are the $+\sigma$ component, magnetic quantum difference $\Delta M = 1$, and the $-\sigma$ component, magnetic quantum number difference $\Delta M = -1$. They are polarized perpendicular to the magnetic field.

According to the Zeeman effect, the space between laser line frequencies by transverse magnetic field intensity is

$$|v - v_0| = \Delta v_z = |\Delta M| g \mu_B B/h, \tag{1}$$

where $v$ is the frequency of the $+\sigma$ component, or $-\sigma$ component; $B$ is the transverse magnetic field intensity; $g$ is Lande's splitting factor; $\mu_B$ is the Bohr magneton and $h$ is Planck's constant. The frequencies of the $\pi$ component, $+\sigma$ component and $-\sigma$ component are $v_0$, $v_1 = v_0 + \Delta v_z$ and $v_2 = v_0 - \Delta v_z$, respectively. Every component is a longitudinal mode. Therefore the longitudinal mode becomes three longitudinal modes by transverse magnetic field. Then a single-mode He–Ne laser becomes a three-mode He–Ne laser by transverse magnetic field. The frequency difference between the $+\sigma$ component and the $\pi$ component, or between the $\pi$ component and the $-\sigma$ component depends on the magnetic field intensity $B$. The frequency shift of $v_1$ and $v_2$ relative to $v_0$ is increased, as $B$ is increased, while the two laser lines of the $+\sigma$ component and the $-\sigma$ component are moved gradually towards the two sides of the gain profile. In this process the $\pi$ component does not move. The gain of the $+\sigma$ and $-\sigma$ components decreases gradually, until the gain of the two components is lower than threshold and they cannot exist. At the same time the predominance of the $\pi$ component increases gradually, until there is only the $\pi$ component oscillation.

According to laser theory, small signal gain in inhomogeneous broadening is

$$G_{i0} g_i(v) = (n/c) B_{21} h v \Delta N_0 g_i(v), \tag{2}$$

where $n$ is the refractive index of the active medium, $c$ is the speed of light, $B_{21}$ is the constant characteristic of atom system, and $\Delta N_0$ is the population inversion without input light. Doppler-broadening line shape is described by a Gaussian distribution,

$$g_i(v) = g_0 \exp[-(v - v_0)^2/\Delta v^2], \tag{3}$$

where $\Delta v$ is the half-width of the Doppler-broadening line, and $g_0$ is a coefficient. Multi-mode He–Ne laser output power is

$$p = K_0 d^2 T I_{s0}[G_m/(\alpha + T) - 1], \tag{4}$$

where $d$ is the diameter of the capillary, $T$ is the transmissivity, $\alpha$ is the attenuation in one single route, $I_{s0}$ is the saturation parameter, $K_0$ is a coefficient, and $G_m$ is the maximum value of $g_i$. $G_{i0}.g_i(\mathrm{v})$ is used instead of $G_m$ to obtain the output power of the $+\sigma$ laser line and the $-\sigma$ laser line. Then we obtain

$$p = K_0 d^2 T I_{s0}[G_{i0} g_{(i}(v)/(\alpha + T) - 1]. \tag{5}$$

Substituting formulae (1)–(4) into (5) gives

$$p(v) = E[F \exp(-k^2 B^2) - 1], \tag{6}$$

where

$$E = K_0 d^2 T I_{s0}$$

$$F = (n/c) B_{21} h v \Delta N_0 g_0,$$

$$k = g \mu_B / h.$$

Formula (6) shows that the output power of laser light polarized perpendicular to the magnetic field is

$$I_s = p/s = (E/s)[F \exp(-k^2 B^2) - 1], \tag{7}$$

where $s$ is the section area of the laser beam. If $B = 0$ then

$$I_s = I_p = (E/s)[F - 1], \tag{8}$$

where $I_p$ is the intensity of the laser light polarized parallel to the magnetic field. If we do not consider the effect of the magnetic field on total output laser power, $I_p$ and $I_s$ should be complementary,

$$I_s + I_p = 2(E/s)(F - 1). \tag{9}$$

From (7)–(9) we obtain that

$$I_p = (E/s)\{F[2 - \exp(-k^2 B^2)] - 1\} \tag{10}$$

Formula (7) shows that $I_s$ is a monotonic decreasing as the magnetic field intensity increases, while formula (10) shows that $I_p$is a monotonic increasing, as the magnetic field increases. Therefore, in a region of $B$, between $B_1$ and $B_2$, the curve can be approximately considered as a straight line. Bias of $B$ is set up in the place between $B_1$ and $B_2$. $I_p$ and $I_s$ vary linearly as the magnetic field intensity varies. If the magnetic field is modulated by a low-frequency harmonic signal at the same time, $I_p$ and $I_s$ are modulated by a low-frequency signal.

In fact, the magnetic field near the two sides of the magnetic iron is non-uniform. In particular, the thick coil on the magnetic iron makes the magnetic field more non-uniform. Because of the non-uniform magnetic field intensity, spectral lines are broadened. But broadening of the 0.6328 μm laser line is small, while broadening of the 3.39 μm laser line is large under the same conditions. The gain of the laser line is inversely proportional to the line width, so that the decrease in gain of the 3.39 μm laser line is greater than the decrease in gain of the 0.6328 μm laser line. The 3.39 μm laser line and the 0.6328 μm laser line have the same higher energy level $3S_2$, therefore more excited atoms at the higher level are used to produce 0.6328 μm laser light. At the same time the 3.39 μm laser light is suppressed, and the 0.6328 μm laser light is intensified by increasing the transverse magnetic field intensity.

## 3. Experimental set-up

Fig. 1 shows the experiment set-up. The soft iron core with coil has a gap and a He–Ne laser is inserted into the gap. When magnetic field intensity $B$ is less than 1400 G, magnetic field intensity $B$ of magnetic iron is directly proportional to the electric current $J$ in the coil, magnetic field intensity $B$ and electric current $J$ have the following relation

$$J = bB,$$

where $b = 0.00125$ A/G. The transverse magnetic field is formed in the capillary of the He–Ne laser. A low-frequency harmonic signal is sent to amplifier A from the low frequency generator. At the same time, a DC bias is supplied to produce a magnetic field intensity bias in the He–Ne laser. The output laser is split into two beams by a double refraction crystal Cy. The laser beam is received by detectors $D_1$ and $D_2$, and these signals are monitored on the oscilloscope Os.

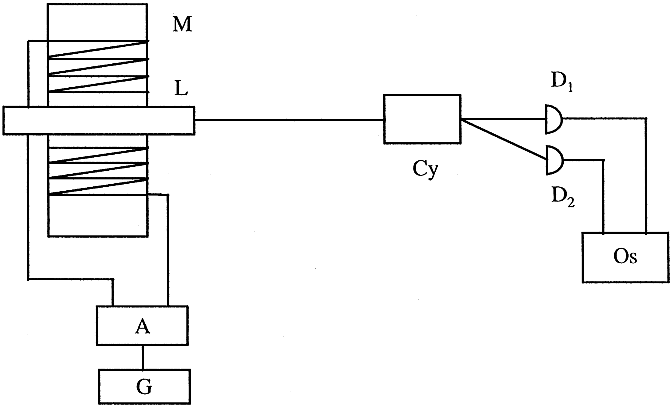

Fig. 1. Experimental set-up. (L) He–Ne laser; (M) magnetic iron with coil; (A) amplifier; (G) signal generator; (Cy) double refraction crystal; ($D_1$, $D_2$) photodetectors; (Os) oscilloscope.

## 4. Experimental result

Fig. 2(a) shows the relation of the intensity of the laser beam polarized perpendicular to magnetic field intensity $B$. $I_s$ continuously decreases, when 180 G $< B <$ 750 G, as the magnetic field intensity $B$ increases. $I_s$ decreases linearly as $B$ decreases, when 240 G $< B <$ 750 G. The bias is set up in this region. $I_s$ is modulated by a low-frequency magnetic field intensity. Meanwhile, the harmonic wave is detected, which is of opposite phase compared to the input signal. Fig. 2(b) shows the relation of the intensity of the laser beam polarized parallel to magnetic field $B$. $I_p$ linearly increases as $B$ increases when 240 G $< B <$ 750 G. When $B$ is greater than 750 G, $I_p$ begins to be saturated. Bias is set up in this region. $I_p$ is modulated by a low-frequency magnetic field intensity, and meanwhile the wave in the same phase as the input signal is observed on the oscilloscope.

When $B <$ 203 G the magnetic field intensity is weak, $\Delta v_z$ is small, there is strong mutual effect among the modes and the continuity is broken in this region [1,3].

The polarization degree of the output laser light is $P = |(I_s - I_p)/(I_s + I_p)|$. The relation between $P$ and $B$ is shown in Fig. 3. $P$ is linearly increasing approximately as $B$ is increasing, when 230 G $< B <$ 700 G. When $B =$ 750 G, $P =$ 99.6% [1]. Bias is

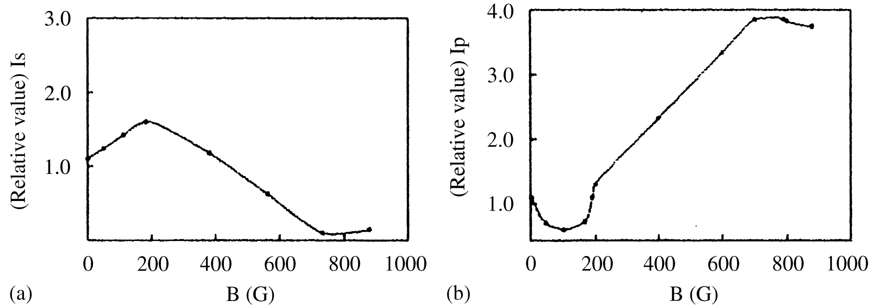

Fig. 2. (a) Intensity $I_s$ of laser beam polarized perpendicular to magnetic field versus intensity $B$ of magnetic field; (b) intensity $I_p$ of laser beam polarized parallel to magnetic field versus intensity $B$ of transverse magnetic field.

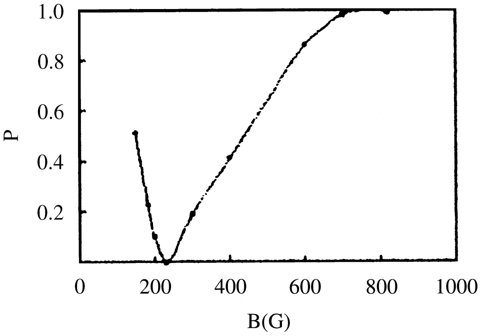

Fig. 3. Polarization degree $P$ versus intensity $B$ of transverse magnetic field.

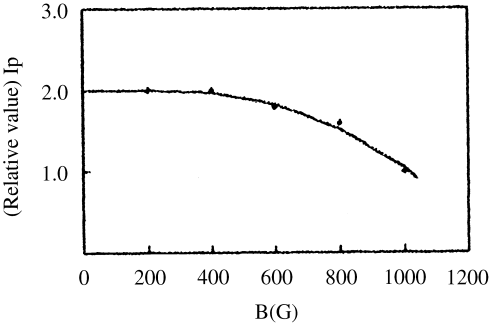

Fig. 4. Intensity $I'_p$ of received signal of laser beam polarized parallel to transverse magnetic field versus intensity $B$ of transverse magnetic field. Upper cut-off frequency is 830 Hz.

set up in this region, then the polarization degree can be modulated by the transverse magnetic field intensity. The advantage in doing this is that $I_p$ and $I_s$ are used at the same time. If the intensity of the He–Ne laser beam in the air is disturbed then $I_p - I_s$ and $I_p + I_s$ vary to the same scale, and $P$ is not disturbed.

The relation between intensity $I'_p$ of the received signal and modulation frequency $f$ is shown in Fig. 4. It shows that the upper cut-off frequency is 830 Hz. The input sinusoidal signal intensity keeps a constant magnetic field intensity bias at 450 G. When the modulation frequency $f$ increases, inductive reactance of the coil increases so that the modulated current through the coil, the modulated magnetic field intensity and the intensity of received signal decreases.

## 5. Conclusion

When the He–Ne laser is in the transverse magnetic field, the laser beams have two linearly polarized components. Both the He–Ne laser beam polarized parallel to the transverse magnetic field and He–Ne laser beam polarized perpendicular to the transverse magnetic field can be modulated at low frequency. The waves of these two modulated beams are opposite in phase. Modulation frequency is restricted by inductive reactance of the coil.

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