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DEVELOPMENT OF A FAST RESPONSE ROTATING POLARIMETER FOR A FARADAY ROTATION MEASUREMENT

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Japan Atomic Energy Research Institute

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Development of a Fast Response Rotating Polarimeter for a Faraday Rotation Measurement

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(Received February 2, 1994)

This paper describes a method for using a spindle sustained with active magnetic bearing to make a rotating half waveplate frequency more fast. The time interval of the zero-cross phase measurement is 189 μsec in this experiment. The magnetic bearing is applicable to increase the rotating waveplate frequency by a factor of 2 – 3 compared with the conventional one. The waveplate speed as well as the deviation with respect to the stationary laser beam has no influence on the amplitude and phase shift of the rotating polarized beam signal. There is also no influence of the mirror reflections on the phase shift. The overall phase resolution is estimated to be about 0.1 degrees.

Keywords: Half Waveplate, Active Magnetic Bearing, Rotating Polarized Beam, Faraday Rotation, Poloidal Magnetic Field, Current Density Profile, Tokamak Plasma, Nuclear Fusion

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[+] Department of Fusion Facility

ファラデー回転角測定のための高速偏光計の開発

日本原子力研究所那珂研究所炉心プラズマ研究部
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松田　俊明

（1994年2月2日受理）

本書はプラズマ中を通った回転偏光面の位相変化測定から電流分布を求める装置を製作するにあたって、その応答性を良くするために偏光面の回転周波数を高めるための方法について述べたものである。この方法の特長は半波長板を磁気浮上型スピンドルに取り付けることによって、偏光面の回転数を従来のものより2－3倍高めることを可能にしたことにある。本実験では零交叉による位相測定時間間隔は189μsecである。信号の振幅と位相は回転半波長板の速度と静止ビームに対する相対的なずれに対して一定である。光学ミラー群を用いた任意の位置への伝送による信号の位相変化は無視できる程度に十分小さい。信号のS/N比から求めた全体の位相分解能の計算値は約0.1度である。

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1. Introduction

Knowledge of the current density profile in the tokamak plasma gives important information of the safety factor profiles, the plasma instabilities and the plasma confinement characteristics. Diagnostics of the poloidal magnetic field in the tokamak are usually based on the effect of motional Stark,[1,2] or Faraday rotation.[3-7] One of the principal advantages of the polarization technique of spectral lines is that a measurement of the magnetic pitch angle is localized to the intersection of the geometric viewing cone and the neutral beam.[1,2] However, the disadvantage of this technique is slow time response (~10 msec) due to the use of lock-in amplifiers. Recently, plasma current density measurements have been made with a rotating polarized laser beam.[5,6] One of the advantages of the polarization technique of the rotating polarized beam is its accuracy. Because the rotation angle is directly measured. This technique is essentially different from the one which uses the signal amplitude.[3,4] However, the overall response time of the phase measurement of the rotating polarized beam technique is limited to be ~1 msec due to the signal averaging to increase the signal-to-noise ratio *S/N*.[5]

The period of the internal disruption in the medium size tokamak plasmas is from 1 to 20 msec.[8] However, the decreasing phase period of the instability is of the factor of 100 μsec. Therefore, we need a faster response time of the polarimeter to measure directly the current profile in the decreasing phase of the instability of the tokamak plasmas. We have realized a faster rotating polarized beam by using the half waveplate mounted on the spindle sustained with the active magnetic bearing. For simplicity, a linear polarized He-Ne laser of wavelength 632.8 nm was used in this experiment, however a far-infrared laser of wavelength 100-200 μm is desirable for measuring the Faraday rotation angle in the tokamak plasmas.

In the following section, the experimental apparatus is described. The waveplate sustained with the active magnetic bearing is described. Next we show the results on the experiment of the rotating polarized beam. Then the experimental results are discussed. Finally we summarize the experiment.

2. Experimental Setup and Procedure

A crystal quartz half waveplate of diameter 29 mm and thickness 1 mm is mounted on a spindle of length 260 mm.[1*] In order to increase the rotating waveplate frequency, the waveplate and its attachment to the spindle are carefully processed within 4 μm. The spindle is sustained by the active magnetic bearing and is driven by a power supply of frequency about 50 kHz. The waveplate is run at about 10,000 to 80,000 r.p.m. The waveplate rotation produces a rotating linear polarized laser beam of transmitted light. The nonuniformity of the waveplate reflectivity is over all controlled to be as small (<0.25 %) as possible so as to reduce harmonics of a

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[1*] Manufactured by SEIKO SEIKI Co., Ltd., Narashino, Japan.

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rotating polarized beam signal. Because the harmonics of the signal increased with the transmission nonuniformity.

A Helium-Neon laser oscillator, the rotating waveplate, optical components, and detector diodes are arranged as shown in Fig. 1. A laser beam of wavelength 632.8 nm is linearly polarized and its polarization ratio is larger than 500. A beam diameter and its divergence are 0.72 mm and 1.1 mrad, respectively.

A rotating polarized beam is split into two channels, reference and Faraday channels as shown in Fig. 1. The each measured reflectivity of p and s waves of the splitter is 51.8 and 52.5 %, respectively. In order to examine the polarimetry characteristics between the two channels, a Faraday rotator of angle θ=44.0 degrees is used to shift the rotating polarized angle of the Faraday channel. The each rotating polarized beam is detected through the linear polarizer by the diode which frequency characteristic is flat up to 300 MHz.

The waveplate deviates toward the radial and axial directions from the relative position with respect to the stationary laser beam. In order to examine the influence of the waveplate deviations on the rotating polarized beam signal, the spindle deviations are used to be measured by calibrated magnetic pickup coils. The response time of the pickup coils is about 500 μsec. The influence of the waveplate deviations on the phase of the rotating polarized signal is examined by measuring the phase difference between a signal from a marker on the waveplate and the rotating polarized beam signal.

Many mirrors, which the reflectivity of p and s waves is different each other, will be introduced in the transmission system of a laser beam of polarimeter/interferometer. The beam is transmitted in this experiment to a set of mirrors to examine the influence of the mirror number N_m on the transmission characteristics of the rotating polarized beam. The phase difference between points P and P0~P7 shown in Fig. 1 is measured in turn on the zero crossing of the oscillograms. A typical difference of the measured mirror reflectivity between p and s waves is bellow 1 %.

The frequency ratio of the rotating polarized signal to the rotating waveplate is monitored with a frequency counter. The signals are also analyzed with a F.F.T. analyzer.

3. Experimental Results

Polarimetry characteristics between the reference and Faraday channels have been examined at about 10,000 - 80,000 r.p.m. by using the known Faraday rotator of angle θ=44.0 degrees. Two typical rotating polarized signals without the Faraday rotator in the Faraday channel are shown in Fig. 2(a). The upper and lower traces in the figure show the reference and Faraday signals, respectively. The sweep time of the oscillogram is 50 µsec/div. Here, the waveplate is run at v_r=80,000 r.p.m., which the speed corresponds to the rotating waveplate frequency f_r=1.33 kHz. No phase difference between the two channels is observed as shown in Fig. 2(a). On the other hand, when the Faraday rotator is set in the Faraday channel, the phase difference is observed as shown in Fig. 2 (b). These figures show that the central frequency is 5.3 kHz and different each other, will be introduced in the transmission system of a laser beam of polarimeter/interferometer. The beam is transmitted in this experiment to a set of mirrors to examine the influence of the mirror number N_m on the transmission characteristics of the rotating polarized beam. The phase difference between points P and P0~P7 shown in Fig. 1 is measured in turn on the zero crossing of the oscillograms. A typical difference of the measured mirror reflectivity between p and s waves is bellow 1 %.

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The influence of the waveplate deviation on the rotating polarized beam signal has been examined. First the relation of the frequency spectrum between the rotating polarized beam and radial waveplate deviation signals was examined. There was no relation between the two spectra at v_r=10.000-80,000 r.p.m. A typical frequency spectrum of the rotating polarized signal at v_r=80,000 r.p.m. is shown in Fig. 3(a). The figure shows that the central peak is 5.3 kHz and that the ratio of the each side peak to the central peak is below 1 %. On the other hand, a typical frequency spectrum of the radial waveplate deviation at v_r=80,000 r.p.m. is also shown in Fig. 3(b). In the figure, a central peak of frequency 1.3 kHz and many side peaks are observed. Two peaks at frequency 3.7 and 7.4 kHz in Fig. 3(b) correspond to the distortions due to the mechanical resonance of the spindle. Because, each frequency of the two peaks was constant at v_r=10,000 -80,000 r.p.m. The ratio of the each resonant peak to the central peak is below 1 %. The figures 3 (a) and (b) show that the radial waveplate deviation has no influence on the rotating polarized signal.

The relation between the radial waveplate deviation d_r and the rotating polarized signal has been directly examined. The radial and axial deviations were measured as a function of the speed v_r. The dependence of the radial deviation d_r on the rotation speed v_r is shown in Fig. 4. The deviation d_r decreases at first with the rotation speed v_r and then increases with v_r. The minimum radial deviation is 4 μm at v_r=50,000 r.p.m. The rate of the radial deviation to the beam diameter is below 1×10^{-3}. On the other hand, the axial deviation was from 0.5 to 0.4 μm (not shown in Fig. 4).

The amplitude change and phase shift of the rotating polarized signal have been studied at v_r=10,000-80,000 r.p.m. The amplitude of the rotating polarized signal was constant at the same speeds. The phase difference between a marker on the waveplate and the zero-cross of the signal was also constant at the same speeds. For example, the dependence of the signal amplitude on the speed v_r is shown in Fig. 5. Here the amplitude is normalized at v_r=10,000 r.p.m. The dependence of the phase shift subtracted by the one at v_r=10,000 r.p.m. on the speed v_r is also shown in the same figure. The amplitude and the phase shift are almost constant at v_r=10,000 - 80,000 r.p.m. The figure shows that the rotating polarized beam signal is also independent of both the radial deviation and the waveplate speed v_r, even if the radial deviation varies as shown in Fig. 4.

The influence of reflections on the phase shift of the rotating polarized beam signal has been examined by using many mirrors. No phase shift of the rotating polarized signal with varying the mirror number N_m was observed, except the signal-to-noise ratio S/N decreases with the mirror reflection. As example, the phase shift between points P and P0~P7 as shown in Fig. 1 is plotted as a function of the mirror number N_m (see Fig. 6). Here the waveplate is run at 80,000 r.p.m. This fact shows that a set of mirrors transmits the rotating polarized beam without a phase shift of its signal.

Frequency spectra of the reference and Faraday signals have been also studied, because the determination of the phase resolution between the two channels is affected by the signal-to-noise ratio S/N. Frequency spectra at v_r=80,000 r.p.m. of the reference (upper) and Faraday (lower) signals are shown in Fig. 7(a) and (b), respectively. The figure shows that the signal-to-noise ratio S/N is at least 550.

4. Discussion

The polarization transformation for the half waveplate is

$$\begin{pmatrix} E_x' \\ E_y' \end{pmatrix} = \begin{pmatrix} \cos 2\omega t & \sin 2\omega t \\ \sin 2\omega t & \cos 2\omega t \end{pmatrix} \begin{pmatrix} E_x \\ E_y \end{pmatrix}, \tag{1}$$

where, ω is a rotating angular frequency of the waveplate. The overall transformations E_{xr}, E_{xF} to the one direction x of the reference and Faraday channels are given as

$$|E_{xr}|^2 = \left(\frac{E_0^2}{2}\right)(1+\cos 4\omega t) \tag{2}$$

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$$|E_{\mathrm{XF}}|^2=(\frac{E_0^2}{2})(1+\cos(4\omega t+2\theta)), \qquad (3)$$

respectively. Thus, the frequency of the rotating polarized signal is four times as large as the rotating waveplate frequency f_r, and the measured phase shift is twice the Faraday rotator angle θ as shown in Fig 2.

The radial waveplate deviation is 5 - 10 µm at 10,000-80,000 r.p.m. as shown in Fig 4. No influence of the waveplate deviation on the rotating polarized signal is observed as shown in Fig. 3 and 5. This is because that the radial waveplate deviation with respect to the stationary laser beam is less than 10^{-3} of the beam diameter. This means that some radial waveplate deviations within the beam diameter are permissible. These characteristics from the point of optical view are very convenient for increasing the rotating waveplate frequency.

Side peaks of the rotating polarized signal appear as shown in Fig 3(a). This is considered to depend mainly on the deviation from the square current-voltage characteristics of the detector diodes.

No effect of the mirror reflections on the phase shift of the rotating polarized beam signal has been observed as shown in Fig 6. This is because that the overall transformations to the one direction of the rotating polarized beam are still given as eq. (2) or (3). This is very suitable for the positioning in the tokamak machine hall of the laser oscillator and the spindle, which locations are limited by both the intensity of the magnetic field and the complex geometry of the tokamak machine. Because the laser beam has to be introduced to the diagnostic port of the tokamak and the spindle should be run in no magnetic field. On the basis of the fact that there is no influence of the mirror reflections on the phase shift of the signal, the oscillator and spindle are able to be placed in position apart from the tokamak machine.

The noise of the reference and Faraday signals results in an accuracy decrease in determining the phase difference between the two channels. The phase resolution $\Delta\phi$ of the usual zero-crossing type technique is proportional to the inverse signal-to-noise ratio,

$$\Delta\phi=N/S \tag{4}$$

Frequency spectra as shown in figures 7(a) and (b) show that the ratio S/N is about 550. Then, the phase resolution is estimated to be about 0.1 degrees in this experiment.

The small side peaks appear in the frequency spectra as shown in figures 7(a) and (b). They have no affects on the determination of the phase shift between the two channels because the frequency of the side peak is always constant.

Finally, we will discuss the response time of this polarimeter. The response time τ_r is expressed as τ_r~$2.2\,\tau$. Where the time constant τ is the inverse of the angular frequency of the rotating polarized signal. Then the response time τ_r is ~$2.2\,\tau$ =66 μsec, since τ is 30 μsec at v_r=80,000 r.p.m. If we adopt a method for using the unusual zero-crossing technique to measure the phase difference between the two channels, the measuring period is 189 μsec.

In order to make the zero crossing period small, a more fast speed of the waveplate is needed. The rotation speed is limited by both the tensile strength of the crystal quartz and the mechanical resonance distortion of the spindle. The allowable periphery speed of the waveplate is estimated to be 560 m/sec from the tensile strength of the crystal quartz. This shows that the waveplate will withstand a faster rotation speed. On the other hand, the most harmful resonance distortion frequency is equal to the rotation one. The distortion frequency is greater than the rotation one by a factor of about three as shown in Fig. 3 (b). On the basis of these facts, we are going to increase the waveplate speed.

We are now building a rotating polarimeter/interferometer for measuring the current profile in the JFT-2M tokamak plasma. Where two barrel gas (CH_2F_2) lasers, which are induced with a grating tuned high power CO_2 laser, will be run at a wavelength of 184.6 μm (at a intermediate frequency of 2 MHz) and at each power of 250 mW. The signal-to-noise ratio *S/N* was estimated to be at least 1,000 from the NEP value of a Schottky detector, and then the estimated phase resolution is about 0.05 degrees. While, the Faraday rotation angle in the typical JFT-2M plasma was estimated to be 3-5 degrees.

5. Conclusions

We have studied a fast response polarimeter of a rotating difference between the two channels, the measuring period is 189 μsec.

In order to make the zero crossing period small, a more fast speed of the waveplate is needed. The rotation speed is limited by both the tensile strength of the crystal quartz and the mechanical resonance distortion of the spindle. The allowable periphery speed of the waveplate is estimated to be 560 m/sec from the tensile strength of the crystal quartz. This shows that the waveplate will withstand a faster rotation speed. On the other hand, the most harmful resonance distortion frequency is equal to the rotation one. The distortion frequency is greater than the rotation one by a factor of about three as shown in Fig. 3 (b). On the basis of these facts, we are going to increase the waveplate speed.

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5. Conclusions

We have studied a fast response polarimeter of a rotating polarized laser beam by using a spindle sustained with the active magnetic bearing. Its performance is summarized as follows:

(1) The maximum rotation and peripheral speeds of the waveplate are in this experiment 80,000 r.p.m. and 121 m/sec, respectively. The rotating linear polarized beam signal of frequency 5.3 kHz is obtained and the time interval of the zero-cross phase measurement is 189 µsec. The active magnetic bearing is applicable to increase the rotating plate frequency by a factor of 2-3 compared with the conventional one. The upper rotation speed is limited by both the tensile strength of the crystal quartz and the mechanical resonance distortion of the spindle.

(2) The rotating polarized signal is independent of both the rotation speed and the radial deviation of the waveplate. Its amplitude and phase are constant at both the rotating speeds of 10,000-80,000 r.p.m. and the radial deviations of 5-10 µm. Where, the waveplate deviations are less than 10^{-3} of the beam diameter. There is no restriction on the rotation speed from the point of the optical view. Some radial waveplate deviations less than the laser beam diameter are permissible.

(3) The phase shift of the rotating polarized signal is independent of mirror number, however the signal-to-noise ratio decreases with the mirror reflectivity. This permits the free location of the laser system including the spindle which should be run in no magnetic field.

(4) The resolution of the zero crossing technique is proportional to the inverse signal-to-noise ratio. The large signal-to-noise ratio is important to increase the phase resolution. The overall resolution of

this polarimeter is estimated to be about 0.1 degrees.

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We would like to acknowledge B. Rice of LLNL for his useful information about polarization techniques. Many thanks are also due to Dr T. Yamauchi and the other members of Experimental Plasma Physics Laboratory for helpful discussions. We also acknowledge Drs. H. Maeda, M. Shimizu, I. Kondo, A. Funahashi, M. Ohta, H. Kishimoto, Y. Tanaka and S. Tamura for their continuous encouragement.

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8) for example, H. Soltwisch: Rev. Sci. Instrum. **59** (1988) 1599.

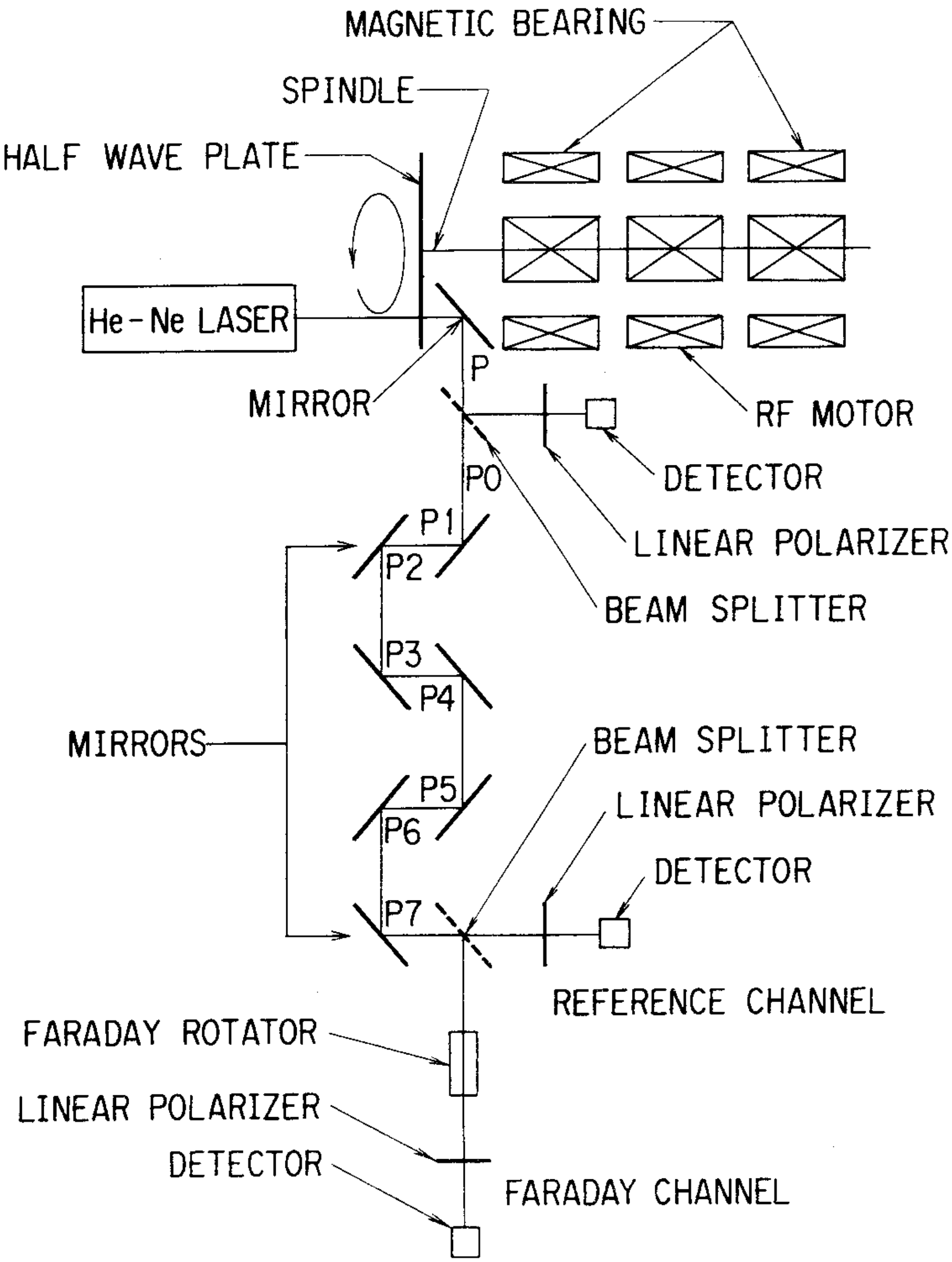

Fig. 1 Schematic layout of the rotating polarimeter.

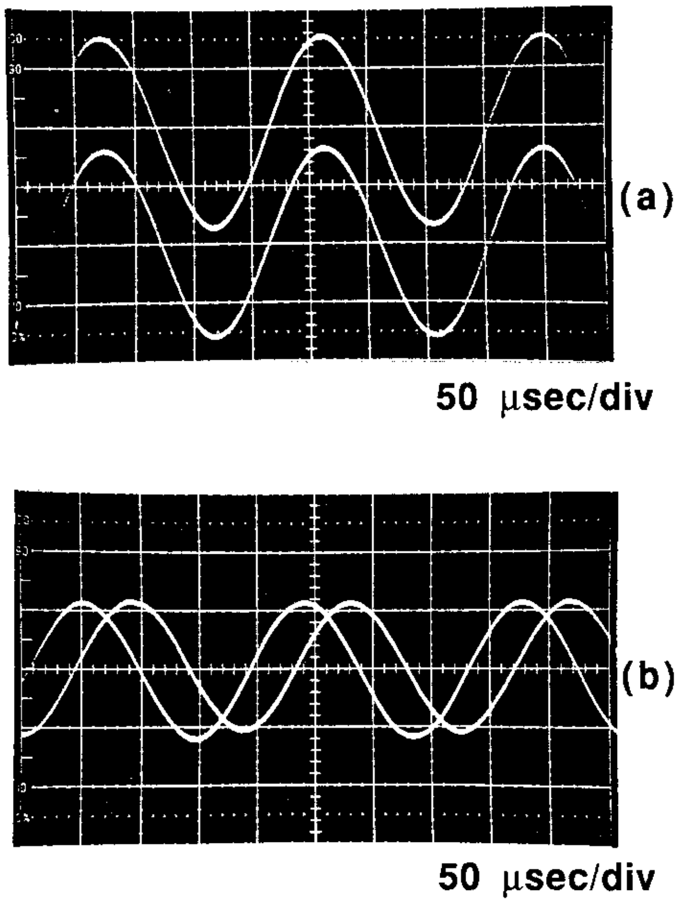

Fig.2 Sine waveforms of the reference and Faraday signals in the case without(a) and with(b) the Faraday rotator (rotator angle θ=44.0 degrees). Upper and lower signals show the reference and Faraday signals, respectively. Where the sweep time is 50μsec/div.

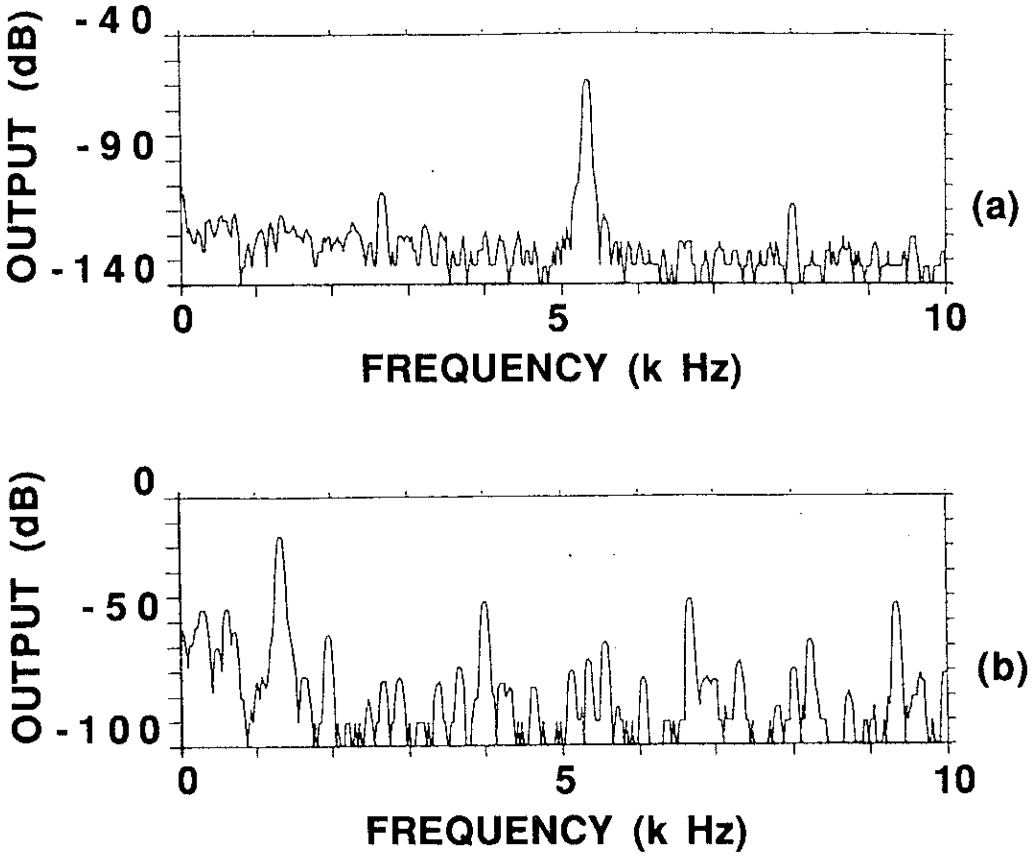

Fig.3 Typical frequency spectra of the rotating polarized beam signal(a) and the radial waveplate deviation(b) at a rotation speed of v_r=80,000 r.p.m. Where the waveplate deviation d_r with respect to the stationery laser beam is monitored by calibreted magnetic pickup coils.

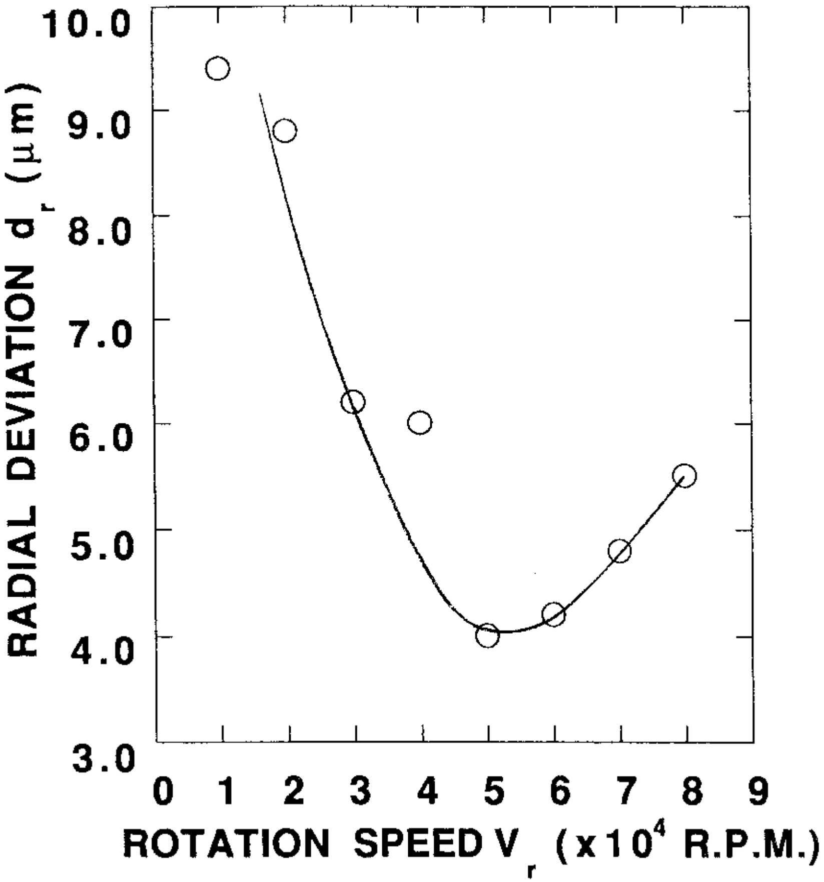

Fig.4 Variation of the radial waveplate deviation d_r as a function of the rotation speed v_r. Where the waveplate deviation d_r with respect to the stationary laser beam is monitored by calibrated magnetic pickup coils.

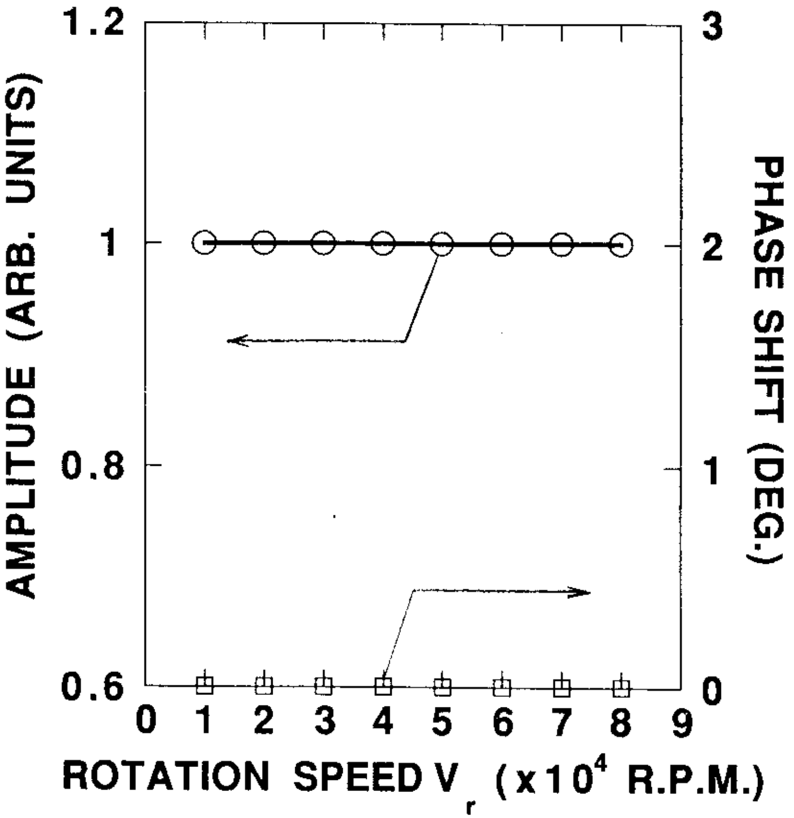

Fig.5 The amplitude and phase shift dependence of the rotating polarized signal on the rotation speed v_r. Here, the phase shift is examined by measuring the phase difference between the maker on the rotating half waveplate and the polarized beam signal. In the figure, the phase shift subtracted by the one at v_r=10,000 r.p.m. is plotted as a function of the rotation speed v_r. The amplitude is also normalized at v_r=10,000 r.p.m.

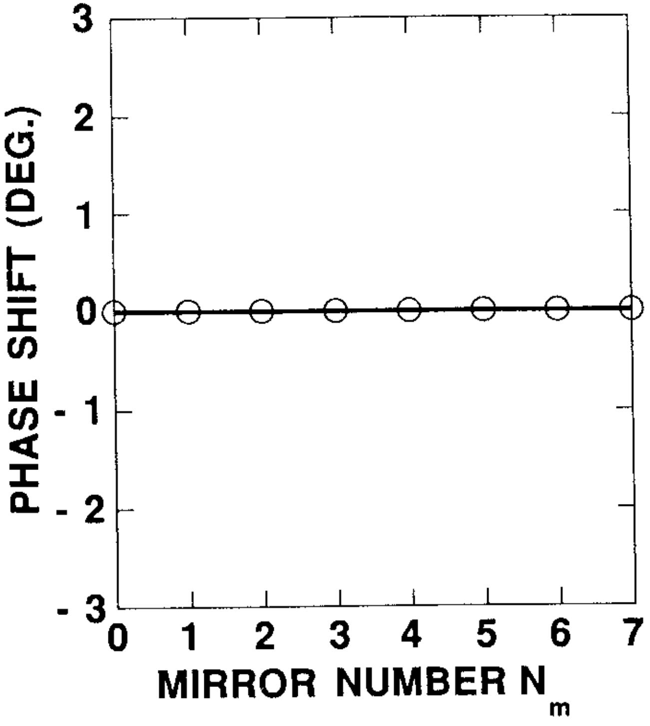

Fig. 6 Typical phase shift dependence of the rotating polarized signal between points P and P0～P7 on the mirror number N_m in the light transmission system. The phase difference is measured from the zero crossing on the oscillogram. Where the waveplate runs at v_r=80,000 r.p.m.

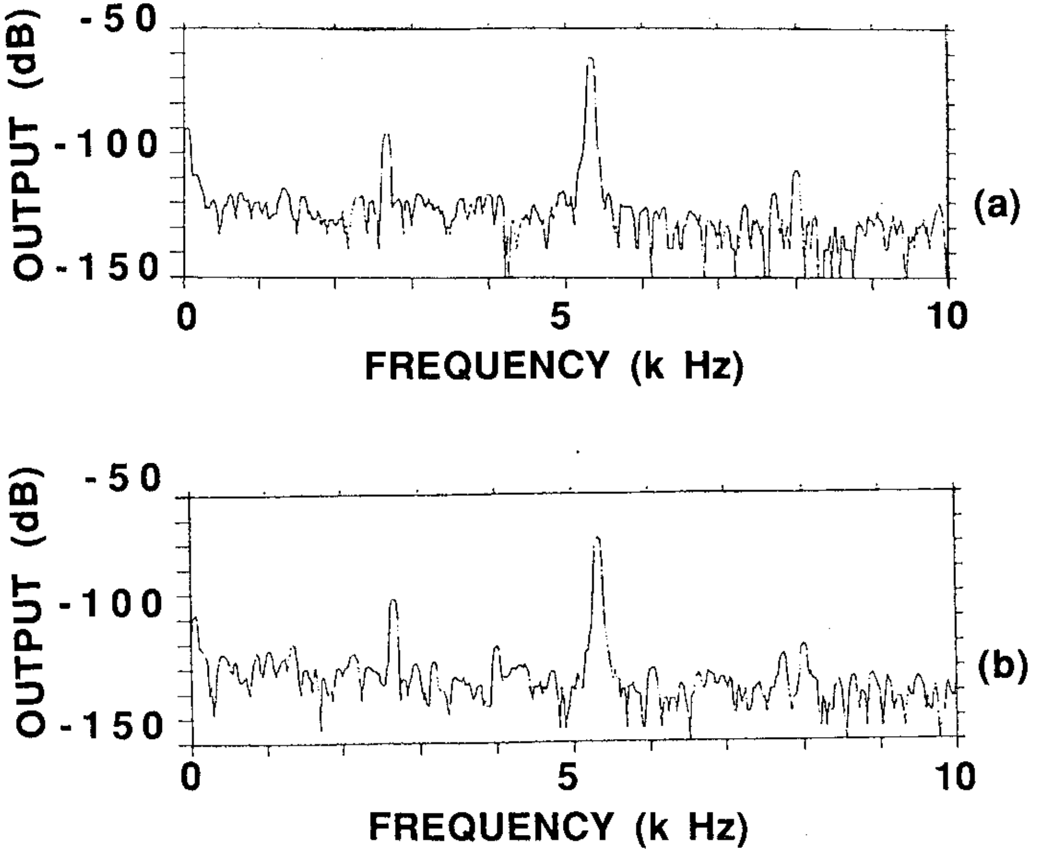

Fig. 7 Typical frequency spectra of the reference(a) and Faraday (b)signals at a rotation speed v_r=80,000 r.p.m.