

A Two-Wavelength Infrared Interferometer/Polarimeter System for CIT**C. H. Ma, D. P. Hutchinson, and K. L. Vander Sluis****Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831**

The results of a feasibility study of a two-wavelength infrared interferometer/polarimeter system for measurements of electron density and plasma current profiles in the Compact Ignition Tokamak (CIT) are presented. The system utilizes CO₂ lasers at a wavelength of 10.6 μm , and water-vapor lasers at 28 μm . Both magneto-optic and electro-optic polarization-modulation techniques have been used to determine the sensitivity and time response of the polarimetry at 10.6 μm . Measurement of a simulated plasma Faraday rotation demonstrated a sensitivity of approximately 0.01° for a CO₂ laser polarimeter with an electro-optic CdTe crystal modulator.

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The results of a feasibility study of a two-dimensional infrared interferometer/polarimeter system for simultaneous measurements of electron density and plasma current profiles in the CIT are reported. A two-wavelength system at wavelengths of 10.6 and 28 μm is proposed to correct the measuring errors caused by mechanical vibrations of the optic components. The choice of these wavelengths results mainly from a trade-off, being sufficiently short to limit both the angle of beam refraction by plasma density gradients and the ellipticity of the polarized wave to an acceptable value, yet sufficiently long to obtain adequate sensitivity for the measurements.¹ A schematic diagram of the CO₂ laser system is shown in Fig. 1. A Bragg cell diffracts approximately 50% of the laser power into a reference beam. The acousto-optic cell also introduces a frequency shift, Δf , of 40 MHz in the diffracted beam. The probing beam is passed through a polarization modulator, a plasma simulator, and is mixed with the reference beam. Both magneto-optic and electro-optic polarization-modulation techniques have been utilized to determine the sensitivity and time response of the polarimetry. Cadmium telluride (CdTe) crystal polarization rotators are used as the modulators and the plasma simulator. The magneto-optic modulator consists of a 210:1 rf current transformer, a 4:1 bifilar-wound matching transformer, and a CdTe crystal. The primary of the current transformer is connected in series with a

0.01- μ f capacitor to achieve a resonant frequency of approximately 80 kHz. The secondary is a three-turn copper coil which acts as the load of the transformer. The CdTe crystal of 12.5 \times 12.5 \times 50.8 mm is mounted in the center of the secondary coil. The electro-optic modulator consists of a ZnSe fresnel $\lambda/4$ rhomb, and a CdTe crystal of 4 \times 4 \times 50 mm with a half-wave voltage of 4.24 kV. An indium doped CdTe crystal of 12.5 \times 12.5 \times 50.8 mm is used in the plasma simulator. A solenoid of 7.6-mm ID, 94-mm OD, and 65 mm long produces a magnetic flux density approximately 2.7 KG at a dc current of 3.5 A. The detector is a liquid-nitrogen cooled HgCdTe photovoltaic diode. The output of the detector, V_s can be expressed by the following relation:

$$\begin{aligned}
 V_s &= \left\{ \sqrt{RP_p} \cos[\theta_p + \theta_m \sin(\omega_m t)] \sin(\omega t + \phi) \right. \\
 &\quad \left. + \sqrt{RP_r} \sin[(\omega + \Delta\omega)t] \right\}^2 \\
 &= \frac{1}{2} RP_p J_1(2\theta_m) \sin(2\theta_p) \sin(\omega_m t) \\
 &\quad + R \sqrt{P_p P_r} \cos[\theta_p + \theta_m \sin(\omega_m t)] \cos(\Delta\omega t + \phi) \\
 &\quad + \text{terms of dc and other frequencies} \quad (1)
 \end{aligned}$$

Where R is the responsivity of the detector, θ_m is the amplitude of the modulation angle, ω_m is the modulation frequency, ϕ is the phase shift due to plasma density, θ_p is the poloidal field-induced Faraday rotation in plasma, $J_1(2\theta_m)$ is the Bessel function of the first kind with order one, and P_p and P_r are the power of probing and reference beam at the detector, respectively.

In the first of two experiments to determine the performance characteristics of the electro-optic modulation system, a mechanical polarization rotator was inserted in the path of the probing beam, and was set at 45° with respect to the polarization of the incident beam. Under this condition, a Faraday rotation of 90° was simulated. Figure 2(b) shows the output signal of the detector and the modulation signal of the RF modulator. The frequency spectrum of the heterodyne beat signal at 40 MHz and the side-band frequencies of ± 70 KHz is illustrated in Fig. 2(a). It can be seen in the figures that for a modulation of about 33%, the signal-noise ratio of the side-bands is approximately 20 dB. The high signal-noise ratio was achieved with only one watt of CO_2 laser power and without any beam focusing. The output signal can be synchronously detected by two lock-in amplifiers at 40 MHz and 70 KHz. However, due to limited resources, the signal was analyzed by only one lock-in amplifier synchronized to the modulation frequency (October, 1987). Since the signal at the modulation frequency is only proportional to the power of the probing beam, this measurement was performed with reference beam blocked. The output signal of the detector with probing beam only is shown in Fig. 3(b). The modulation signal is also illustrated in this figure. Figure 3(a) shows the frequency spectrum of the modulated signal. The output voltage of the lock-in amplifier, V , is given by:

$$V = V_0 \sin(2\theta_p) \quad (2)$$

Where $V_0 = 1/2 ARP_p J_1(2\theta_m)$, and A is the voltage gain of the amplifier. For CIT plasma parameters, the maximum value of θ_p is approximately 1.5° . Therefore, V can be considered as a direct measure of θ_p and Eq. (2) becomes

$$\theta_p = V/2V_0 \quad (3)$$

The calibration constant V_0 can be obtained by setting the mechanical polarization rotator at few degrees ($\leq 4^\circ$) and measuring the value of V.

Our second experiment studied the transient performance of the polarimeter. The plasma simulator coil was driven by a pulsed current. The rotation caused by this simulator coil was directly proportional to the current which was monitored by a current probe. The simulated Faraday rotation and the amplifier output were simultaneously displayed on an oscilloscope. Typical oscillograph traces are shown in Fig. 4. As shown in the figure, for a simulated rotation of approximately 1.8° , the output voltage of the amplifier is about 330 mV. The base line of the output voltage is in the range of 1-2 mV. Therefore, a sensitivity of approximately 0.01° was achieved. The time delay between the simulated and measured rotations was due to the large RC constant (3 mS) of the lock-in amplifier. Evidently, the time resolution of the polarimeter can be easily improved by

increasing the modulation frequency and using lock-in amplifiers with faster time constants. A magneto-optic polarization modulator has been successfully designed, constructed, and tested. The performance characteristics of the polarimeter with this modulator are being investigated.

An interferometer/polarimeter system employing a 28 μm water-vapor laser has been proposed by T. Fukuda et al. and has been tested on a field-reversed theta pinch plasma.³ To our knowledge, the feasibility of using polarization-modulation techniques in polarimeters has not yet been examined at this wavelength. We are currently designing a 28 μm laser system and intend to investigate the performance of 28 μm polarization modulators.

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1. C. H. Ma and D. P. Hutchinson, *Bull. Am. Phys. Soc.* 32, 1870 (1987).
2. C. H. Ma, D. P. Hutchinson, P. A. Staats, K. L. Vander Sluis, D. K. Mansfield, H. Park, and L. C. Johnson, *Space Power* 6, 221 (1986).
3. T. Fukuda, S. Goto, T. Ishimura, and H. Ito, *Int. J. IR & MM Waves* 5, 1039 (1984).

Fig. 1. Experimental configuration for the polarization-modulation CO₂ laser polarimeter.

Fig. 2. (a) Frequency spectrum of the heterodyne beat signal at 40 MHz and the side-band frequencies of ± 70 kHz. (b) Output signal of the detector (upper trace) and the modulation signal at 70 kHz (lower trace) with both probing and reference beams.

Fig. 3. (a) Frequency spectrum of the modulated signal at 70 kHz. (b) Output signal of the detector (upper trace) and the modulation signal (lower trace) with probing beam only.

Fig. 4. Simulated Faraday rotation angle (lower trace) and the measured lock-in amplifier output (upper trace) vs. time for a simulated CIT plasma. Traces indicate that the Faraday rotation measurement has a sensitivity of about 0.01°.

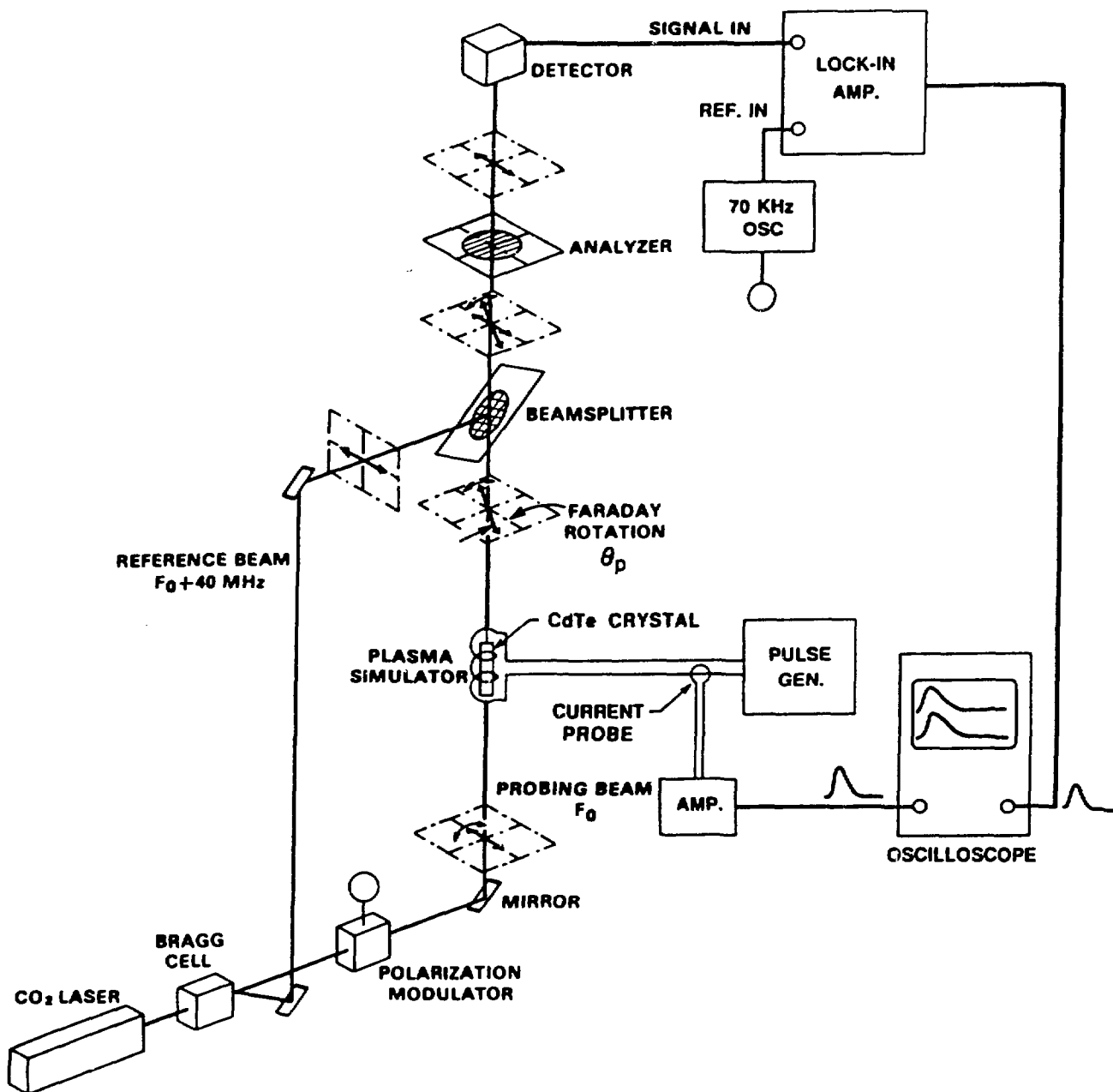
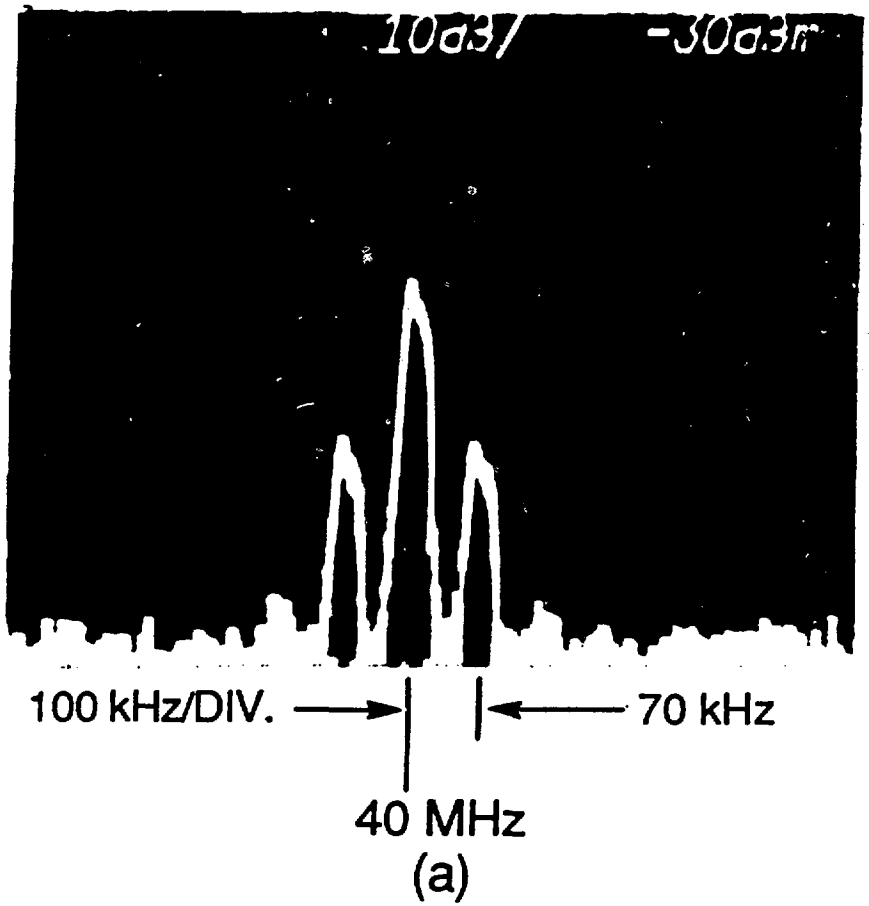


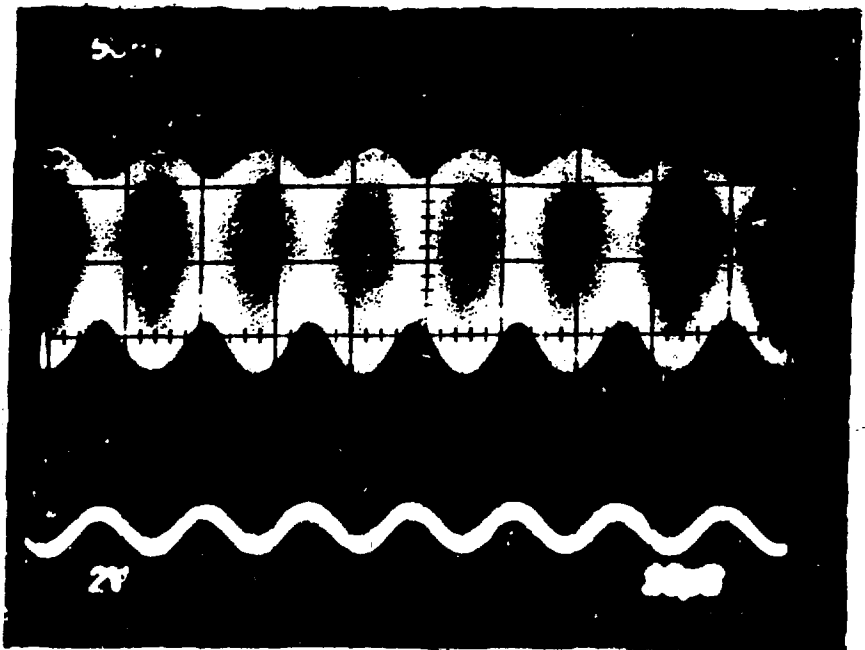
Fig. 1

(10dB/DIV.)



SIGNAL

REF.

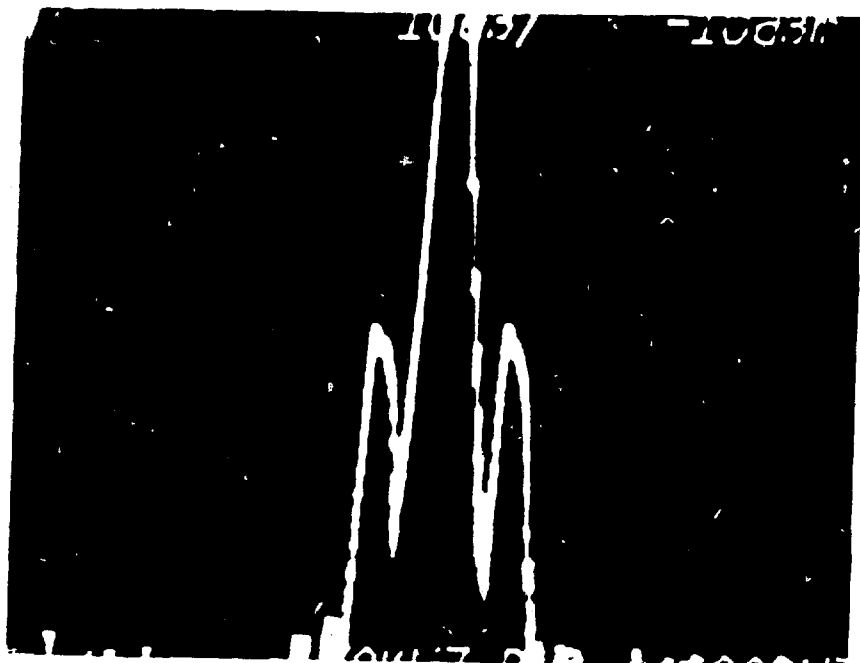


TIME (10 μs/DIV.)

(b)

Fig. 2

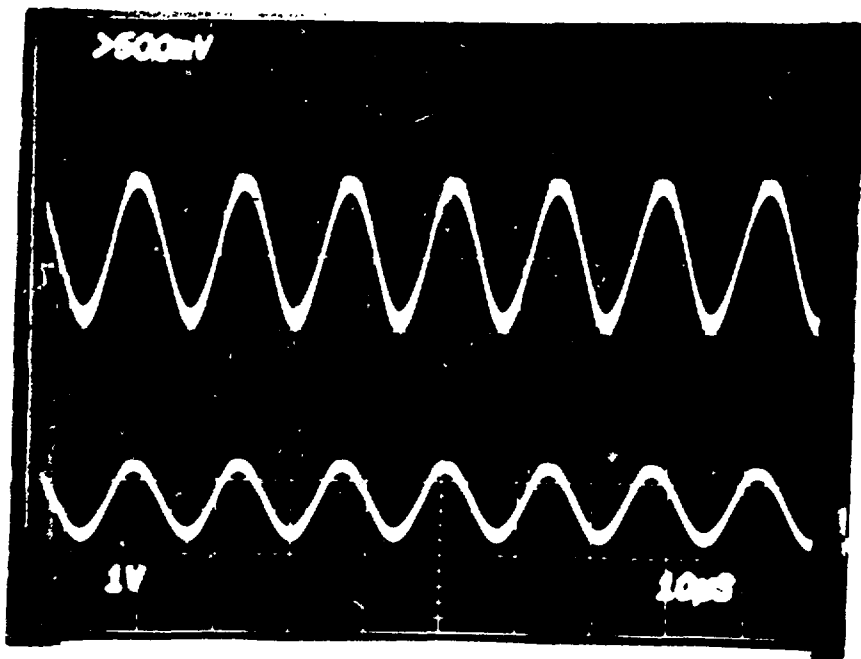
(10dB/DIV.)



100 kHz/DIV. → | ← 70 kHz
DC
(a)

SIGNAL

REF.

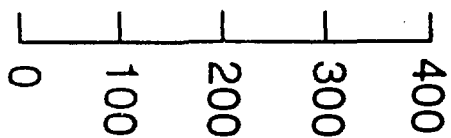
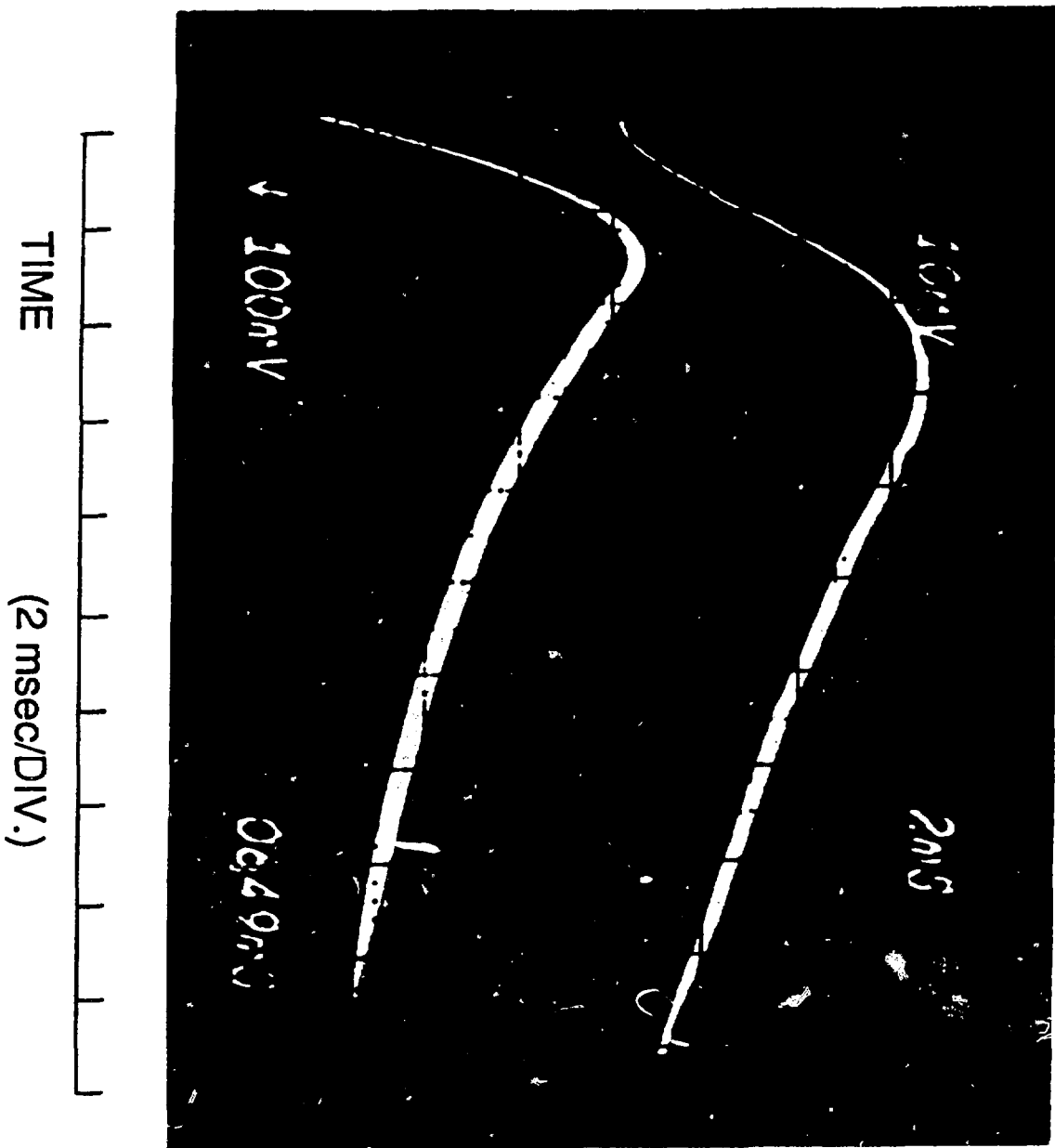
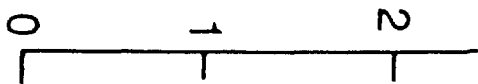


TIME (10 μs/DIV.)

Fig. 3

(b)

SIMULATED FARADAY
ROTATION ANGLE (deg)



OUTPUT VOLTAGE OF
LOCK-IN AMP. (mV)

Fig. 4