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SELF-COMPENSATING AUTOMATIC ELLIPSOMETER

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SELF-COMPENSATING AUTOMATIC ELLIPSOMETER MANUAL

Contents

SELF-COMPENSATING AUTOMATIC ELLIPSOMETER MANUAL

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ABSTRACT

A self-compensating automatic ellipsometer has been built for the measurement of transient thin films. The performance characteristics of this instrument are superior to any similar equipment now in use. The slewing rate of the system was found to be 1.6°/msec over a range of 50° of the rotation of the Faraday cells. A resolution of 0.08° in a fast mode and 0.0007° in a slow mode has been achieved.

I. INTRODUCTION

Ellipsometry is an optical method for the examination of surfaces based on laws of reflection of polarized light by Drude.[1] The term ellipsometry is generally defined in a more restricted sense as an optical technique for the determination of thickness and optical constants of bare surfaces and thin surface films. When polarized light is incident on film covered surfaces, the state of polarization of the reflected light is different from that of a film-free surface. This technique is particularly noted for its sensitivity in detecting and measuring extremely thin surface films. Another advantage of this technique is the possibility of in situ measurements.

An ellipsometer determines the change of the state of polarization due to reflection by measuring the azimuth of polarizer and analyzer before and after reflection. Two parameters Δ and ψ [2] can be calculated from this measurement. This automatic ellipsometer was designed primarily to study film formation and film growth on metal electrodes. Fast dynamic changes of the status of thin surface layers should be followed. The slewing rate of the ellipsometer was found to be 1.6°/msec over a range of 55° of the azimuth readings of the polarizer and of 50° of the azimuth readings of the analyzer.[4] Under conditions which result in an azimuth change of a full turn for a film thickness increment of one wavelength, the slewing rate corresponds to film growth rates up to 2.5 μ/s. The other purpose of the construction was to maintain an optimum resolution of the electronic azimuth readings in the fast mode of operation and to increase it over the best manually obtainable resolution of 0.01° in a slower mode. With a uniform, highly reflecting surface, resolution of 0.08° in a fast mode and 0.0007° in a slow mode, has been demonstrated.[4] This resolution in azimuth corresponds to a resolution of film thickness of approximately 0.01 monolayers and of changes in optical constants of 0.1% or better for materials such as Ag, Au, Ni.

The instrument employs an electronic rotation of the plane of polarization of incident and reflected light by means of two Faraday cells,[5,6] to take the place of the mechanical rotation of polarizer and analyzer prisms over the dynamic range.* A control signal is derived from a 10 kHz modulation of the Faraday rotation to drive a null-seeking control loop. Figure 1 illustrates that by applying a sinusoidal modulation, the amplitude of the resulting signal is proportional to the displacement from the minimum and undergoes phase reversal when passing the minimum This signal, whose sign indicates direction of the error and whose magnitude increases with the displacement, drives the power supplies of the Faraday magnets to turn the plane of polarization of analyzer and polarizer to minimize the signal. Current measurements of the Faraday coils are used as azimuth readings and displayed in two digital voltmeters, calibrated in degrees of azimuth rotation with readings to 0.001°. The signals are also recorded by a multiple-channel light beam oscillograph. This report describes construction and operation of the different parts of the automatic ellipsometer.

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*A summary of the difference between this present ellipsometer and the one designed by Layer,[6] which did not perform satisfactorily, is given in the Appendix. A complete discussion of the reasons for the failure of Layer's approach is found elsewhere.[7]

II. AUTOMATIC ELLIPSOMETER

In addition to the usual manual arrangement of an ellipsometer, two Faraday cells are introduced to rotate the plane of polarization of both analyzer and polarizer as shown in Fig. 2. They serve two purposes: to turn and to modulate the electric light vector. The light beam from a mercury lamp (L) is filtered (F) and collimated (C) before passing the polarizer (P), polarizer Faraday cell (PF) and compensator (Q). After reflection by a sample (S), the light passes the analyzer Faraday cell (AF) and the analyzer (A) and is detected by a photo-multiplier (PM). Then this signal is amplified, filtered, phase sensitive detected and integrated in the controller (CT). The integrated signal drives the bipolar DC-current power supplies (PS1, PS2) to the Faraday cells (AF, PF) so as to turn the plane of polarization. Thus the light signal reading the photomultiplier current is minimized. The system operates as a null-seeking control loop. Modulation current is supplied to the Faraday cells from two power amplifiers (PA1, PA2). One oscillator (O) supplies the input to the two power amplifiers as well as the reference for the two phase sensitive detectors in the controller (CT). Both modulating currents carry the same frequency, but are shifted by 90° relative to one another. The DC-current of both power supplies (PS1 and PS2) is recorded with a multiple-channel light beam oscillograph (G) and two digital bipolar voltmeters (DVM). It is a measure of the state of polarization and is calibrated in degrees of rotation of the plane of polarization of analyzer and polarizer. During operation the manual analyzer (A) and polarizer (P) stay in a fixed position and their reading must be added to the electronic angle reading of the analyzer and polarizer Faraday cells.

A. Light Source

The light source for this system is a high pressure mercury arc lamp (Osram HBO, 100W-2) with an arc size of $0.25\times0.25\ mm^2$ (Fig. 3, Table I). It is used with an Oriel C-12-20 universal lamp power supply (75-200W). An interference filter (Oriel No. 2201) is used to provide a monochromatic source of $\lambda = 546.1\pm5$ nm (Fig. 4).

The light source is characterized by a low ripple and steady light output which was measured to be less than 1% rms. The current regulation is within 1% with 10% change of the line voltage. This fast acting control circuit compensates for changes within the lamp and produces maximum arc stability. The ignitor is supplied in a separate small package to allow for short RF carrying leads without the necessity of locating the lamp power supply close to the lamp. (Spark gap voltage is adjustable to compensate for corrosion and to permit changing the ignition.) The operating voltage of the lamp will start at 10-12 V and slowly rise as the lamp warms up to 18-28 V. During the ignition (0.5s) the current should be set manually to 5-6 A (fine adjust at position 6), but at no time should the total product $V\times A$ exceed 100W. As the lamp ages, the voltage slowly increases and therefore the current should be monitored perodically to be sure that 100W are not exceeded.

B. Faraday Cells

The Faraday cells rotate the plane of polarization of linearly polarized light based on the Faraday effect. The Faraday rotation is described by the following equation

$$\theta = VH\ell$$

where θ = Faraday rotation, minutes of arc

V = the Verdet constant min/Oe-cm*

H = magnetic field applied, Oe

ℓ = length of light path through the material, cm

For a solenoid, the magnetic field is proportional to the applied current. Therefore, the current is a measure of the Faraday rotation once the Verdt constant and the length of the glass (= length of the light path) are known. A cylindrical Schott SF6 glass of V = 0.09 min/Oe-cm of ℓ = 15.25 cm of length is used.[3] After grinding, polishing (end surfaces are parallel within 1 min) and annealing the surfaces** of the cores were covered with an antireflecting coating of MgF_2 (see Table II). The solenoids are made up of three concentric windings (Fig. 5). The center winding of 51 turns (diam 3.05 cm = 1.2 in.) and the middle winding of about 7 turns (diam 7.62 cm = 3 in.) carry the modulation current. The latter is wound counter to the inner winding and is used to minimize inductive coupling between the inner and the outer windings. The outer winding is 7 layers of square, hollow copper tubing wound about 4 turns per 2.54 cm and rated to carry 200 A. This winding provides the principal field for the Faraday rotation. Temperature rise of the cooling water, under flow conditions presently limited by elbow turns, is listed in Table III, which also gives measured field strengths at the center of

**The glass was annealed by heating it from room temperature to 400°C in one hour. The furnace with the glass was kept for one day at 400°C. The cooling rate was 1.5° C/h for the first 50°C, then 2.5° C/h down to room temperature.

*

$$1 \text{ Oe} = 79.577472 \frac{A}{m} = \frac{10^3}{4\pi} \frac{A}{M} \text{ (SI-unit)}.$$

the coil. Faraday rotation is about 1°/5 A. Table IV shows the variation of the magnetic field inside the DC solenoid.

C. Faraday Cell DC-Power Supplies

The Faraday cell DC-power supplies (PS) are bipolar, operational, current regulated power supplies with a current rating of ±125 A (corresponding to ±25° rotation of the plane of polarization of the Faraday cells) with a compliance voltage of ±10 V. The maximum slewing rate of the supplies with the Faraday cell solenoids is approximately 9 A/msec corresponding to 1.8° rotation/msec. Operationally (small signal) the power supply and magnet have an approximate bandwidth of 400 Hz.

The power supply uses a complimentary output stage consisting of banks of parallel high power transistors adjusted to zero quiescent current. Current sampling is done with four 20 A-50 mV meter shunts connected in series. Indium foil is used on the shunt interfaces to minimize contact resistance between shunts. Extreme care in layout is necessary in this unit to minimize ripple output due to stray fields.

D. Controller

1. Signal Channel

The signal is detected by a photomultiplier tube (RCA IP21) used with a high voltage regulated DC power supply (Power Designs Pacific, Inc., Model 3K-20). Because most of the statistical noise in the photomultiplier is caused by random fluctuations in the electron current (shot noise) the tube housing is not cooled.

Figure 6 is a block diagram of the controller system. Each block is an individual circuit model whose characteristics (bandpass, gain, time-delay) are determined by external components (resistors, capacitors).

The signal channel follower (F) is a 10× preamplifier connecting an operational amplifier in the "follower-with-gain" position.

The tuned amplifier (TA) is an operational amplifier with a band reject feedback network. The circuit is a bandpass amplifier with a bandwidth of about 400 Hz and center frequency is 10 kHz. The gain of this stage is approximately 75.

The tuned amplifier feeds the two quadrature detection channels. The first circuit in each channel is a variable gain stage (A1, A2) (adjusted externally with "AC gain" (see Fig. 7)). The gain stage is followed by a simple inverting operational amplifier (I1, I2) to provide full wave phase synchronous detection by the full-wave demodulator (L1, L2).

This detector is an integrated circuit FET switch with a normally open contact, a normally closed contact and a switch driver circuit within the same package. One side of each contact is connected to become the output of the detector. The detected signal is available on the controller front panel "Det. Out" (Fig. 7) for adjusting phase relations in the system. Also, the switch drive signal is available on the controller front panel "Ref. Out" (Fig. 7).

The detector output signal (displayed in the "Output Voltage" panel meter (Fig. 7)) is fed into an analog integrator (Int 1, Int 2) with a variable time constant (range 0.001 sec to 5 sec). The amplifier used in this integrator is a high gain, low drift, low input current offset, low voltage offset unit. All these factors contribute to the quality of the minimum-reading that this system will provide. Any offset from compensation produces a DC component at the input of the integrator which generates an error signal that, in turn, results in a change in magnet current. Any noise in the error signal has a similar effect. The integrator output signal is used as the control for the Faraday cell DC-current power supplies (PS1, PS2). This output is open-circuited (by means of manual switches) during setup or preparation periods (loop open-closed switch on the controller front panel, Fig. 7). Under open-loop conditions, the magnet current can be adjusted manually.

2. Reference Channel

The reference channel starts with a 10 kHz oscillator (O) (Fig. 6) (Burr-Brown 4023/24). The frequency of this oscillator is fixed, but may be modified by external components.

The oscillator output signal is used as the modulation source to one of the Faraday cells after amplification in an (address) modulation amplifier (M1) (Bogen, C100). The amplitude of the modulating current can be adjusted manually ("AC Amplitude", Fig. 7).* The oscillator also feeds a quadrature generating circuit (QC) (an operational amplifier connected as a differentiator) to provide 90° of phase shift. The quadrature signal is the source for the second modulation amplifier (M2).

The quadrature signal also feeds an integrated circuit level detector (N.S.C. LM 311) (LD) whose output is a square wave at the reference frequency with levels corresponding to TTL logic levels (OV and +4V). The square wave from the level detector is now used to generate the reference signals for the phase synchronous detectors in the signal channels.

*Position 6.00 corresponds to 10 A peak-to-peak corresponding to ±2° modulation rotation.

A pair of series connected integrated circuit monostable multivibrators (TD1, TD2) are used to generate the reference signal in each channel, the first of which is adjustable and is used for phase adjustment ("Phase", Fig. 7). The adjustment range is almost 360° for a 10 kHz signal. The second monostable circuit in each channel is adjusted to form a symmetrical square wave at the reference frequency (SWG 1, SWG 2). The monostable multivibrator outputs are then buffered through a TTL inverter circuit (SN7400) and then fed to the phase synchronous detector inputs (L1, L2).

E. Readout System

A block diagram of the readout system is shown in Fig. 8. The DC-current signals can be monitored on a Honeywell 1108 Visicorder Galvanometer using fluid damped galvanometers (M 1650) (see Table V).

The Faraday cell current signals are amplified (in data amplifiers (DA1, DA2) gain range from 10 to 10,000)) and filtered in a variable time constant averaging circuit (F1, F2). Both amplification and filtering can be varied externally. Filter time constants are 0 sec, 0.001 sec, 0.01 sec, 0.1 sec, 1 sec and 10 sec. In addition to the regular outputs from the filter, there is an attenuated output designed to match the characteristics of a Honeywell sensitive galvanometer (M24-350) (see Table V).

Two more signals can be monitored simultaneously. They are first passed through a differential amplifier (D3, D4) for isolation and then through data amplifiers (DA3, DA4) (gain range 1 through 1000, externally variable).

All signals are then processed through a Honeywell T6GA-500, 6 channel galvanometer amplifier (G) and simultaneously recorded with the Visicorder galvanometer.(V).

In the case of the sensitive galvanometer (M24-350) the output signal of the galvanometer-amplifier-filter is used to drive the galvanometer without using the 6 channel galvanometer amplifier (G).

Two digital voltmeters (Electro Numerics, Model 3412) are mounted in a separate panel and are used for slow readings of the Faraday cell DC-currents. The front panel is shown in Fig. 9. The full scale reading of the instruments is ±39.999 mV with a resolution of 1 μV. The accuracy in the temperature range $+5°C \leqslant T \leqslant 45°C$ is ±0.005% reading, ±0.005% full scale. The full scale step response is 3s. Their input resistance is 100 KΩ and typical bias current is 10 pA. Each meter can be connected to one of four inputs, which can be chosen by input selector switch P1/A1. Input Nos. 1 (in back) and 4 (on front panel) are direct inputs to the voltmeter. Input No. 2 is connected to a attenuator (P2/A2) on the front with approximate ranges (X1, X10, X100 and X200). They should be used only in the case of a signal which is larger than 40 mV to give a rough idea of the order of magnitude of the signal. Input No. 3 is connected to a separate potentiometer on the front with fine (P3/A3, "Range fine") and coarse adjustment (P4/A4, "Range coarse"). The potentiometer for the coarse adjustment is placed at the right and left side behind the panel. The potentiometers (P3/A3) are used to calibrate the reading to read directly in degrees rotation of the plane of polarization. P5/A5 are calibration potentiometers for the two voltmeters whereas P6/A6 are their zero adjustments. P7 is used to switch the input of the two voltmeters (inputs of meter No. 1 become inputs of meter No. 2).

III. MANUAL OPERATION

This instrument can also be used manually. By opening the loops of the controller of analyzer and polarizer ("Loop open", Fig. 7) the system operates as a manual ellipsometer. The AC-modulation coils of analyzer and polarizer Faraday magnets replace the chopper. Signal and reference channel operate as a phase sensitive detector (Fig. 6). The current of both DC-Power supplies should be set to zero (DVM-reading of polarizer and analyzer 0.000) or completely shut off. The minimum photomultiplier current can be achieved by rotating manually the polarizer and analyzer-circle until the two panel voltmeter ("Output Voltage", Fig. 7) indicate zero. One will notice that the manual operation is less accurate, because the resolution of the circle-reading is ±0.01°.

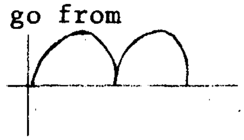
IV. CONTROLLER ADJUSTMENT

A. Phase

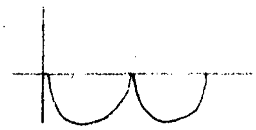
The sequence of adjustment to set up proper phase relationships between analyzer and polarizer (90° difference) signals is as follows:

1. Compensate the system manually with loops open and no DC current in the Faraday cells, for minimum transmitted light, observed visually.

2. Rotate the analyzer manually and observe the signal at the analyzer detector output (analyzer signal "Detector Out", Fig. 7). This signal should go from

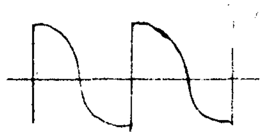


to

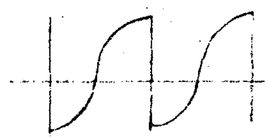


as you rotate through the null. If it does not, adjust the "phase" control of the analyzer until is does.

3. Rotate manually the analyzer. As you rotate through null, the signal should be the S-curve of a phase detector detecting a quadrature signal, i.e.,



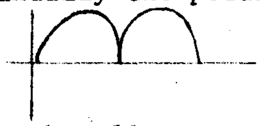
or



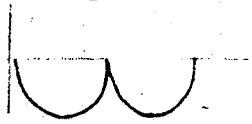
observed with the polarizer signal "Detector Out". Adjust polarizer phase control.

4. If this phase relationship (90° difference) cannot be achieved, adjust the "Treble" and "Level" controls of the polarizer modulation amplifier until the phase relations are as indicated above. Be careful to try and maintain the AC peak-to-peak current output (10 A) at an approximateiy fixed value through this adjustment, corresponding to about ±2° modulation rotation (measured by inserting a 25 A-50 mV shunt into the AC power amplifier output.

5. Observe the polarizer phase detector output ("Detector Out") while rotating manually the polarizer. Now this signal should go from



to



as one rates through null.

6. If necessary, the phase control "Phase" of the polarizer should be adjusted while observing the polarizer detector output "Detector Out".

7. The phases should now be separated by approximately 90°. If not, steps 2-6 have to be repeated.

The above procedure could as well have been done by reversing the roles of the analyzer and polarizer.

One will note at this time that the Faraday cell AC modulation currents are not exactly in quadrature (Lissajou figures generated with the signals from the two AC power amplifier shunts) although the phase detectors are. To minimize cross-talk between analyzer and polarizer channels, the following fine-adjustment procedure is followed.

8. Ascertain calibration of digital voltmeter output in degrees circle reading (input selectors P and A, input connectors No. 3).

9. Close both loops and note DVM-readings (Digital Voltmeter) of analyzer and polarizer. The manual circles of analyzer and polarizer should be set, so that the DVM-reading is 0 ± 0.003°.

10. Change manually the analyzer circle up to ±20° in steps of 5° and note the polarizer DVM-reading.

11. Repeat step 10 for the polarizer.

12. Changes of the polarizer DVM-reading while the analyzer is changed should be less than 0.02° (cross-modulation) and vise versa. If not, the phase has to be adjusted.

13. Change the phase of the polarizer by turning the polarizer "Phase"-helipot to reduce cross-modulation. Repeat steps 8-11 until no further adjustments are necessary.

B. Gain

A feature of this system which bears careful watching by the user is the fact that loop gain in the nulling loops is a function of photomultiplier voltage, light intensity and modulation.

Increasing the photomultiplier tube voltage increases the tube gain. Using diaphragms or slits to decrease the size of the reflecting area or using a "poor" reflecting surface decreases the amount of light transmitted as well as the loop gain. The "AC gain" controls (Fig. 7) adjust the modulation current gain of each channel. Normally, it should not be necessary to use these adjustements (low position).

"AC amplitude" adjusts the level of modulation in both Faraday cells. It is set to 6.6 A peak-to-peak at 400 on the potentiometer corresponding to about ±1.66° rotation of the plane of polarization of analyzer and polarizer.

"Time constants" adjusts the integrator time constant. As this is the dominant time constant of the system, the response time is determined by this adjustment. This may be used, for instance, to lower noise levels in the case when the surface under test exhibits a poor null (noisy). Photomultiplier noise (shot noise) will be decreased also by a longer time constant. Long time constants should also permit a higher degree of resolution than shorter time constants.[4] The numbers (0.001 sec through 5 sec) are only relative figures since any system variation which changes loop gain will also change the system's response time.

The most significant feature of changing the loop gain is, however, not actually changes of gain but changes in bandwidth (response time), which accompany the change in gain. Figure 10 illustrates this point. It shows an open-loop gain-bandwidth diagram. From this figure, one sees that the bandwidth is a function of the gain: increasing the gain (phototube high voltage, light intensity, AC-gain, AC-amplitude) corresponds to an increase of the bandwidth. The vertical line indicates the position of the "time constant" (selected externally). Variation of the "time constant" changes the bandwidth. An increase of the "time constant" (toward increasing bandwidth) means a loss of high frequency gain. Conversely, the decrease of the "time constant" can be used to increase response time due to a loss of gain. If the gain becomes so high as to allow oscillations of the system (they will appear as a low level ripple of about 400 Hz on the magnet current signal), increasing the "time constant" will generally eliminate the oscillations.

V. ALIGNMENT OF THE MECHANICAL PART OF THE AUTOMATIC ELLIPSOMETER

A. Alignment of the Optical Axis

The angle of incidence used is fixed at 75°. A polygon mirror or an alignment prism with two reflecting faces at 150° 0 min 32 sec to each other is used to align the optical axes. The following procedure is to be followed:[3]

1. With the Quarter wave plate removed, the polygon mirror or alignment prism resting on the tripoid is positioned between the telescopes so that its surface(s) is facing one telescope.
2. Using an Abbe Lamont Autocollimating eyepice, one face of the prism is brought to be perpendicular to the optical axis of one telescope by adjusting the tripoid legs to bring the crosshairs of the eyepiece and their reflecting image into coincidence.
3. The same autocollimation procedure is then carried out with the second telescope. Half of the error is compensated by adjusting the position screws on the telescope for vertical and horizontal movement. The remaining error is compensated by adjusting the legs of the tripoid.
4. To check the alignment, the pinhole is placed in the polarizer and the eyepiece in the analyzer. A mercury light is used to illuminate the pinhole. By rotating the polygon mirror by 75°, the mirror is used as the reflecting surface. Using the alignment prism, one face of it can be used as a reflecting surface. The image of the pinhole is observed through the eyepiece. Without adjusting the legs of the tripoid, one should be able to place the image of the pinhole at the center of the crosshairs. If not, the alignment procedure should be repeated (step 2-3).

B. Alignment of the Manual Polarizer and the Analyzer Circles

The way to the alignment of the circles of polarizer and analyzer will depend on finding the minimum light intensity at extinction settings of the polarizer and the analyzer. The extinction setting of the analyzer will depend on the setting of the polarizer. However, extinction intensity is at a minimum when the transmission axis of the polarizer is either parallel to the plane of incidence (p-position) or perpendicular to the plane of incidence (s-position). A stainless steel alignment mirror is used as the reflecting surface. The following procedure has to be followed:

1. Calibrate the reading of the digital voltmeters (DVM) in degrees by using the coarse and fine adjustements P3/P4, A3/A4 in Fig. 9.
2. Set high voltage of photomultiplier to -800 V.
3. Remove quarter-wave plate.
4. Close both loops of analyzer and polarizer.
5. Turn the polarizer to s-position (90° azimuth = 0° circle reading).*
6. Turn the analyzer to p-position (0° azimuth = 90° circle reading).*
7. Note DVM-reading of analyzer and polarizer.
8. Loosen collar screws of polarizer carrier and rotate it until a zero reading of the DVM is obtained.
9. Repeat step 8 for the analyzer.

*With the arrangement of optical components that is used (light source, polarizer, compensator, sample, analyzer and detector), the circle reading of this particular ellipsometer is based on an angle measured counter-clockwise from the plane perpendicular to the plane of incidence when looking into the beam. Thus, polarizer and analyzer circles read, 0° and 90° respectively, for s and p transmission.

10. Open both loops of analyzer and polarizer and set, if necessary, manually the manual DC-power supplies to zero current.
11. Minimize, if necessary, photomultiplier current manually by rotating the carrier of the polarizer. At minimum, the front-panel voltmeter "Voltage Output" (Fig. 7) of the polarizer will be at zero. Note that the sensitivity of the panel meter is better than ±0.01°. Tighten the screws.
12. Repeat step 11 for the analyzer.
13. Note the circle-reading of analyzer and polarizer.
14. Close both loops of analyzer and polarizer.
15. Note DVM-reading of analyzer and polarizer.
16. Check if the sum of the circle reading and the reading of the DVM-reading is

    A = 90.000 ± 0.003°

    P = 0.000 ± 0.003°

    If this is not the case, repeat step 4-15.

C. Alignment of the Compensator Circle Setting

1. Insert quarter-wave plate and rotate compensator circle to s-position (90° azimuth = 0° circle reading).
2. Set high voltage of photomultiplier to -800 V.

3a. Turn polarizer to s-position (90° azimuth = 0° circle reading).

b. Turn analyzer to p-position (0° azimuth = 90° circle reading).

4 Close loops of both analyzer and polarizer. One will note that the reading of the digital voltmeters (DVM) is much more noisy than in Section B.

5. Rotate manually the quarter-wave plate until both DVM of analyzer and polarizer show approximately zero reading.

6. Note both readings of DVM's of polarizer and analyzer.
7. Open both loops of analyzer and polarizer.
8. Minimize photomultiplier current manually by rotating the quarter wave plate in its holder. At minimum photomultiplier current both front panel voltmeters "voltage output" (Fig. 7) will go through zero. Note that the sensitivity of the panel voltmeter "output voltage" Fig. 7) is better than ±0.01°.
9. Close both loops of analyzer and polarizer.
10. Check, if both DVM-readings of analyzer and polarizer are

    A = 90.000 ± 0.01°

    P = 0.000 ± 0.01°

    If this is not the case, repeat step 5-9.

ACKNOWLEDGEMENTS

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*H. J. Mathieu

APPENDIX

This present design of an automatic ellipsometer is based on ideas of Winterbottom,[5] who suggested an all-electronic approach. Layer[6] designed a self-nulling ellipsometer based also on Winterbottom's ideas, but his approach fails to give a response time in the order of 1 msec and to follow dynamic changes of polarizer and analyzer over a range of more than 1°. His design used a Faraday cell, different from the one suggested by Winterbottom who proposed two different magnets for compensation and modulation. Layer proposed instead, one single solenoid as Faraday cell carrying both compensating and modulation current. There are several reasons for the failure of Layer's approach:

1. The self inductance of his solenoid is too high (by a factor of over 1000), which decreases the amplitude of the modulation rotation to 0.2°, which is too low by about a factor of 10.
2. The modulation frequency of 500 Hz is much too low to give a reasonable signal within a response time of 1 msec. Fifty readings/s seem to be the limit.
3. The heat dissipation of the solenoids of 300 W with 10 A is too high not to affect the optical properties of the diamagnetic glass inside the solenoid and limits the dynamic range of polarizer and analyzer to 1°.

Therefore, this present design of the solenoid, of the electronic controller and of the power supplies had to be different. A complete discussion is found elsehwere.[7]

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LIST OF TABLES

Table I. 100 W mercury lamp-data.*

Operating Voltage	20-30 V
Operating Current	2.5-3.3 A
Horizontal Intensity	260 cd
Flux	2200 lm
Average Brightness	1100 cd/mm^2
Effective Arc Size (W×Ht)	0.25×0.25 mm^2
Average Life	200 hrs
Bulb Diameter	10 mm

*Osram, HBO, 100 W/2.

Table II. Optical properties of SF-6 glass.*

Symbol	Value	Description
α	$8.1 \cdot 10^{-6}$	$\frac{\Delta\ell}{\ell}$ thermal expansion
ℓ	15	length (cm)
n_C		refractive index (λ = 656.25 nm)
$n_{C'}$		refractive index (λ = 643.85 nm)
n_d	1.80609	refractive index (λ = 587.56 nm)
n_e	1.81357	refractive index (λ = 546.07 nm)
n_F		refractive index (λ = 486.13 nm)
$n_{F'}$		refractive index (λ = 479.99 nm)
n_g		refractive index (λ = 435.84 nm)
n_F-n_C	0.03172	
n_d-n_C	0.00911	
n_F-n_d	0.02261	
n_F-n_e	0.01513	
n_g-n_F	0.01934	
ν_d	25.41	$\frac{n_d - 1}{n_F - n_C}$

Table II. Continued

Symbol	Value	Description
ν_e	25.22	$\frac{n_e - 1}{n_{F'} - n'_{C'}}$ Abbe number
ρ	5.18	density $\frac{g}{cm^3}$
T_g	423	transformation temperature (°C)
τ_i	0.996	transmission for a thickness of 25 mm (λ = 546.07 nm)
V	0.09	Verdet constant $\frac{min}{Oe \cdot cm}$

*Schott & Gen., Mainz, West Germany.

**

$$1 \text{ Oe} = 79.577472 \frac{A}{m} = \frac{10^3}{4\pi} \frac{A}{m} \text{ (SI-unit)}$$

Table III. Solenoid data.

			Water		
Current	Terminal Voltage	Field (at center)	Inlet Temp.	Outlet Temp.	Rise
30 A	0.8 V	300 Oe*	15°C	15°C	0
60 A	1.7 V	600 Oe	15°C	18°C	3°C
90 A	2.4 V	900 Oe	15°C	24°C	9°C
120 A	3.6 V	1200 Oe	15°C	34°C	19°C
150 A	4.1 V	1500 Oe	15°C	44°C	29°C

* $1\ \mathrm{Oe} = 79.577472\ \frac{A}{m}\ \frac{10^3}{4}\ \frac{A}{m}$ (SI-unit)

Water inlet pressure	30 lb gage
Water flow	1 ℓ/5 min
Coil resistance	0.030 Ω
Coil inductance (DC)	1.05 mH (at 200 Hz)
Coil inductance (AC)	37.2 μH (calc.)

Table IV. Calculated variation of the magnetic field inside the DC coil (relative units).

R	Z	B_{AX}	B_{RA}
0.00	0.00	253.707	0.000
0.00	0.25	253.090	0.000
0.00	0.50	251.224	0.000
0.00	0.75	248.061	0.000
0.00	1.00	243.530	0.000
0.00	1.25	237.537	0.000
0.00	1.50	229.980	0.000
0.00	1.75	220.769	0.000
0.00	2.00	209.856	0.000
0.00	2.25	197.279	0.000
0.00	2.50	183.205	0.000
0.00	2.75	167.963	0.000
0.00	3.00	152.039	0.000
0.25	0.00	254.149	0.000
0.25	0.25	253.402	0.616
0.25	0.50	251.547	1.248
0.25	0.75	248.403	1.911
0.25	1.00	243.896	2.616
0.25	1.25	237.928	3.372
0.25	1.50	230.395	4.181
0.25	1.75	221.197	5.029
0.25	2.00	210.277	5.886
0.25	2.25	197.660	6.698
0.25	2.50	183.503	7.389
0.25	2.75	168.138	7.873
0.25	3.00	152.063	8.076

Table IV. Continued

R	Z	B_{AX}	B_{RA}
0.50	0.00	254.931	0.000
0.50	0.25	254.330	0.221
0.50	0.50	252.510	2.474
0.50	0.75	249.423	3.789
0.50	1.00	244.989	5.193
0.50	1.25	239.105	6.705
0.50	1.50	231.648	8.330
0.50	1.75	222.498	10.048
0.50	2.00	211.564	11.802
0.50	2.25	198.833	13.485
0.50	2.50	184.431	14.937
0.50	2.75	168.683	15.961
0.50	3.00	152.137	16.390

R Radial distance from solenoid axis (inches) (1 inch = 2.54 cm)

Z Axial distance from coil center (inches)

B_{AX} Axial magnetic field (relative units)

B_{RA} Radial magnetic field (relative units)

Table V. Galvanometer characteristics.

Type	Nominal Undamped Natural Frequency (Hz)	Flat (±5%) Frequency Response (Hz)	Nominal Coil Resistance (Ω)	Sensitivity	Maximum Peak-to-Peak Deflection (in.)
M24-350	24	0-15	135.0	4.92 in/mV	8
M1650	1650	0-1000	26.8	4.0 in./V	8

Table VI. Status of ellipsometer variables, externally adjustable.

Channel No. 1, Polarizer (yellow)	
Phase	1.78
AC Gain	0.00
AC Amplitude	3.00
DC-Power Supply Helipot	5.16
DVM-Calibration ("Range Fine")	6.20
Channel No. 2, Analyzer (blue)	
Phase	5.50
AC Gain	0.00
AC Amplitude	4.00
DC Power Supply Helipot	4.97
DVM-Calibration ("Range Fine")	4.94
Correction Factors[3]	
dP	0.00°
dA	0.00°
dQ	0.00°
Mercury Lap Power	
Coarse Adjustment	Hg
Fine Adjustment, Position for Ignition	6
(After 0.5 Min.)	4
Voltage (After Ignition)	10 V
(After 0.5 Min.)	25-30 V
Current (For Ignition)	6 A
(After 0.5 Min.)	2.6-3.0 A

Table VII. Print list.

8S9883	Magnet coil
8S3133	IMRD Interfacial phenomena Galvanometer amplifier-filter
8S3161	IMRD Faraday cell controller Slot 13 PCB
8S9834	Logic diagram
8S9842	Slot 15 reference channel
8S9892	Slot 5 signal
8S9862	Slots 9 and 11 signal channels
8S9871	Slot 17 BCB oscillator card
8S9933	Controller chassis wiring
8S3063	Digital voltmeter panel

FIGURE CAPTIONS

Fig. 1. Effect of parabolic transfer curve (schematic).

1. Off minimum to the left, resulting in a negative output signal.
2. Minimimum, resulting in a zero output signal.
3. Off minimum to the right, resulting in a positive output signal.

Fig. 2 . Block diagram of self-nulling ellipsometer.

A	Analyzer
AF	Analyzer Faraday cell
C	Collimator
CT	Controller
DVM	Digital voltmeter (2)
F	Filter (λ = 546.1 nm)
G	Galvanometer-oscillograph (Channel 1-6)
L	High pressure mercury arc lamp
O	Oscillator
P	Polarizer
PA	Power amplifier
PF	Polarizer Faraday cell
PM	Photodetector
PS	DC current power supply
Q	Compensator
S	Sample
T	Telescope

Fig. 3. Output spectrum of 100 W mecury lamp (Osram HBO 100 W/2).

Fig. 4. Spectral transmission of interference filter (Oriel, Model No. 2203).

Fig. 5. Faraday cell magnet (print No. 859883).

Fig. 6. Controller system block diagram.

A1, A2	Amplifier (gain 1-100×)
AF	Analyzer Faraday magnet
F	Follower (gain 10×)
Int 1, Int 2	Integrator (0.001-0.5s)
I1, I2	Inverting operational amplifier
L1, L2	Phase sensitive detector
LD	Level detector
M1, M2	Modulation amplifier
O	Oscillator
PF	Polarizer Faraday cell
PM	Photomultiplier
PS1, PS2	DC-current power supply with manual current control
QC	Quadrature circuit
SWG1, SWG2	Square wave generator
TA	Tuned amplifier
TD1, TD2	Multivibrator with phase adjustment

Fig. 7. Controller front panel.

Fig. 8. Block diagram of self-nulling ellipsometer recording system.

AF Analyzer Faraday magnet

D3, D4 } Differential amplifier

DA1, DA2 } Data amplifier (10-1000×)

DA3, DA4 } Data amplifier (1-300×)

F1, F2 } Filter (time integrator 0.001-10s)

G Galvanometer amplifier (0-1×)

PF Polerizer Faraday magnet

V Visicorder: Light beam oscillograph

X Additional signal input

Fig. 9. Digital voltmeter front panel

Analyzer adjustments (A) and polarizer adjustments (P)

1 input selector

2 attenuator (1, 10, 100, 200)

3 potentiometer (fine adjustment) for angle calibration

4 potentiometer (coarse adjustment) for angle calibration

5 range adjustment for digital voltmeter

6 zero adjustment for digital voltmeter

7 switch to exchange the inputs (A ↔ P)

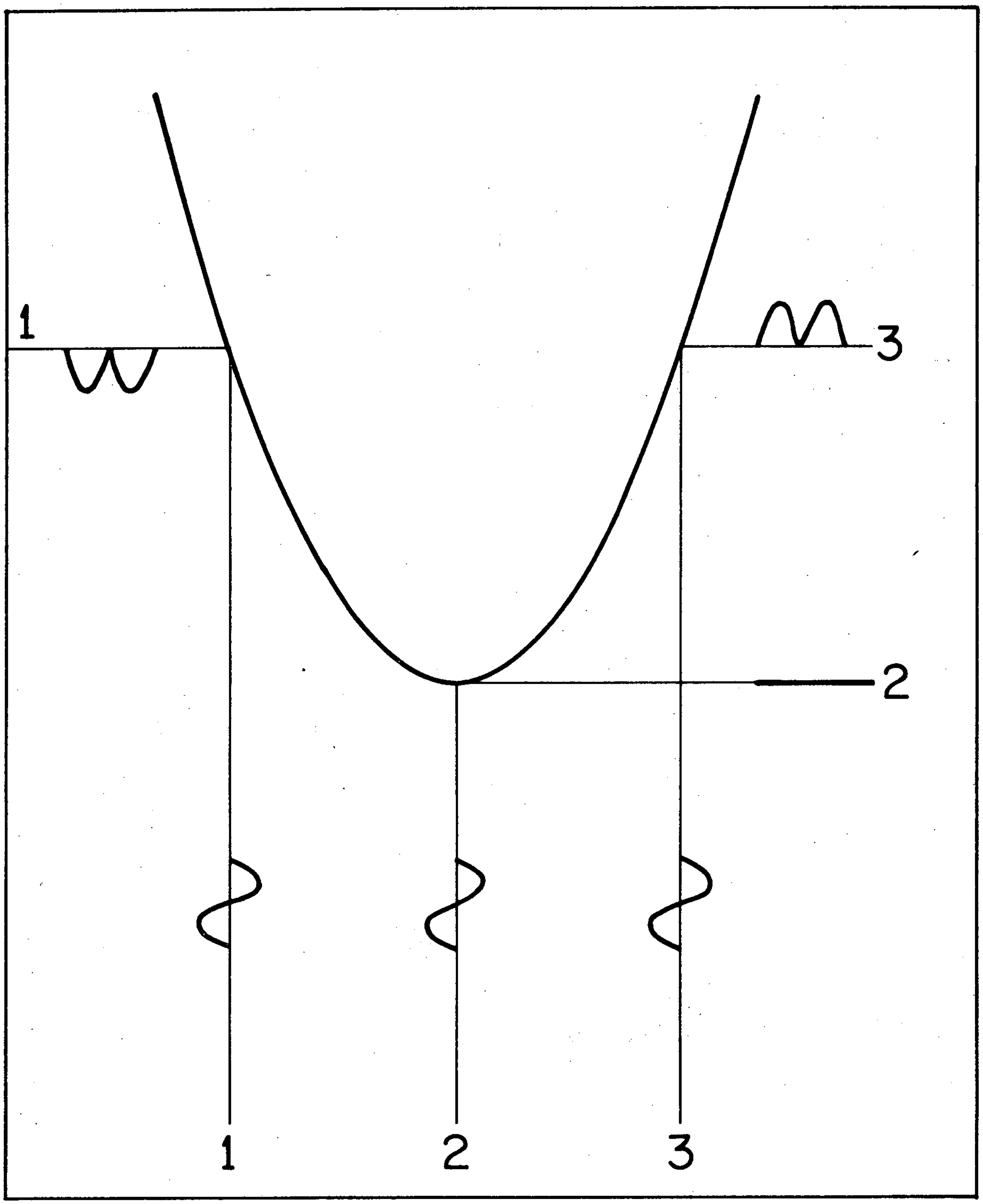
4P, 4A } front panel BNC-input

Fig. 10. Gain-bandwidth diagram.

a basic curve

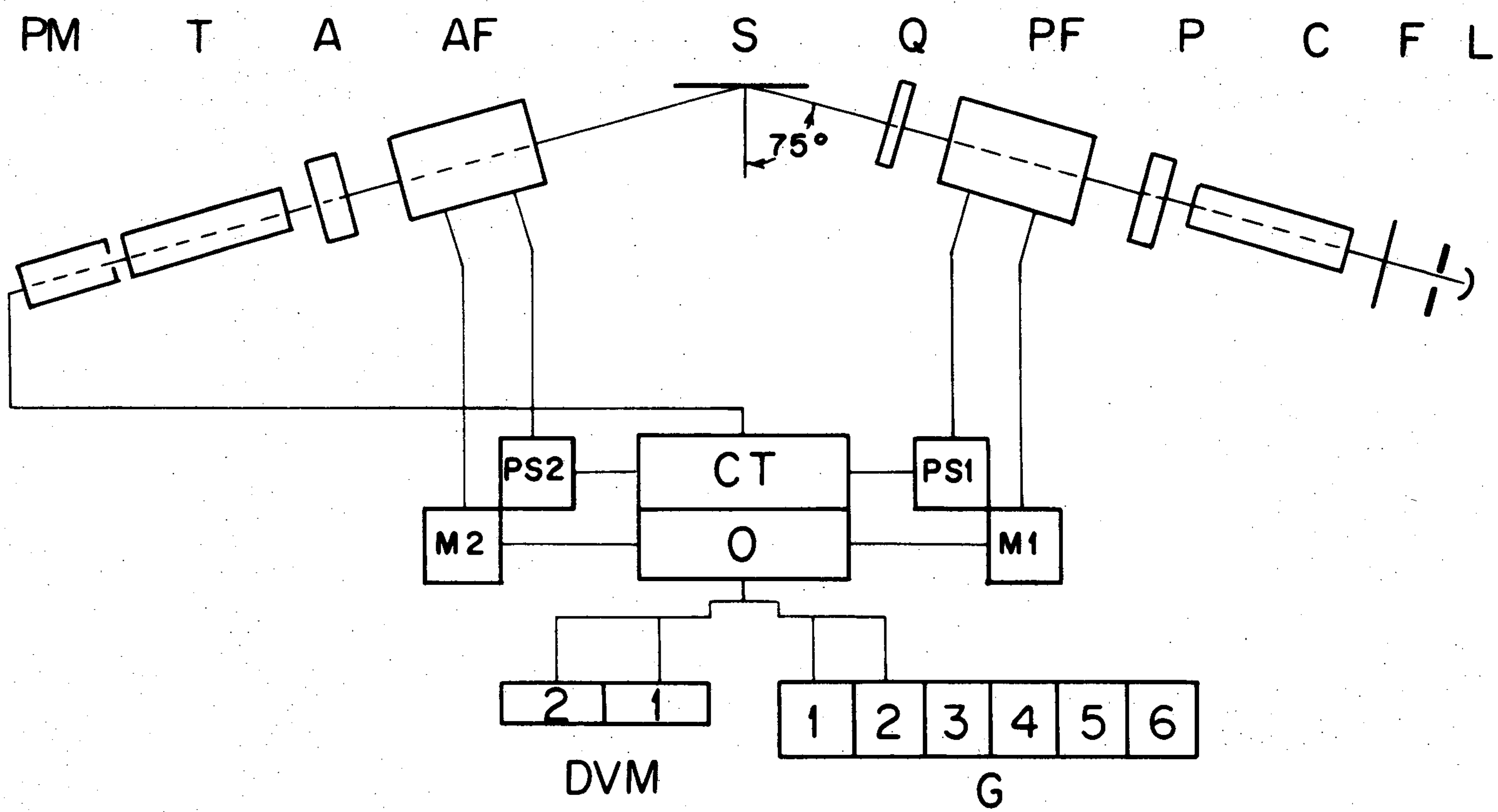
b effect of increased gain (light level, AC-amplitude, photomultiplier voltage)

c effect of decreased gain



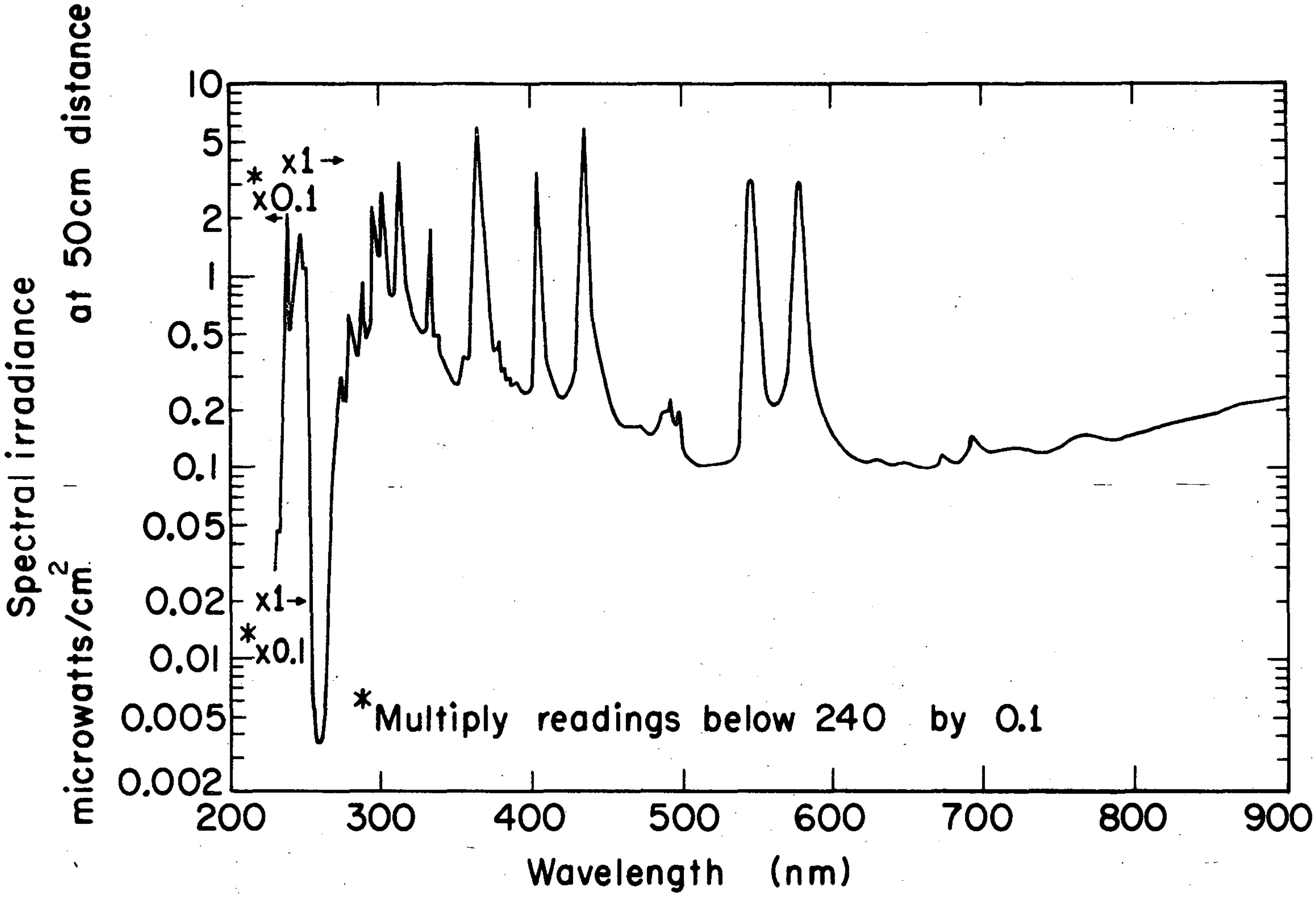
XBL 735-2948

Fig. 1



XBL7212 - 4927

Fig. 2



XBL735-2945

Fig. 3

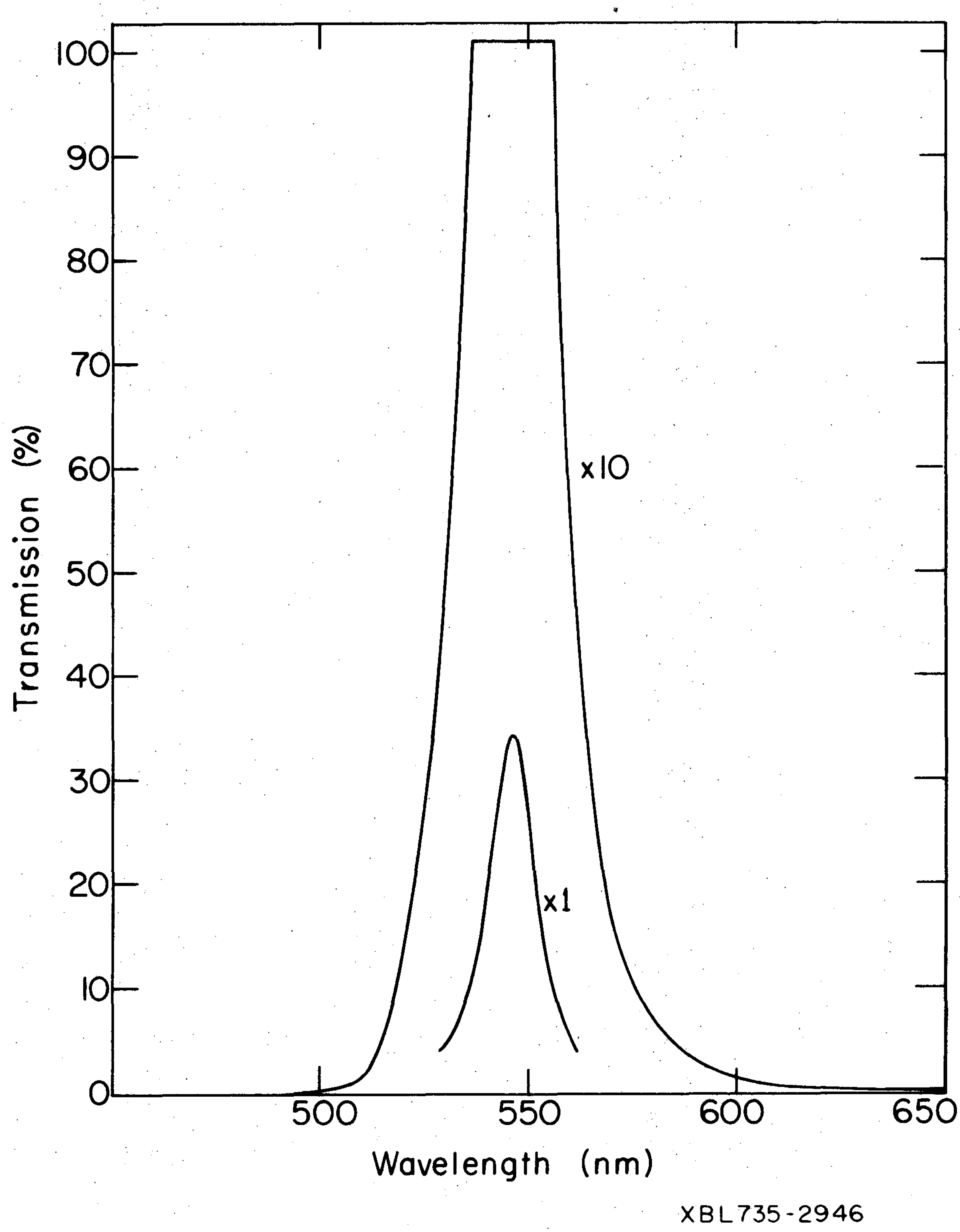
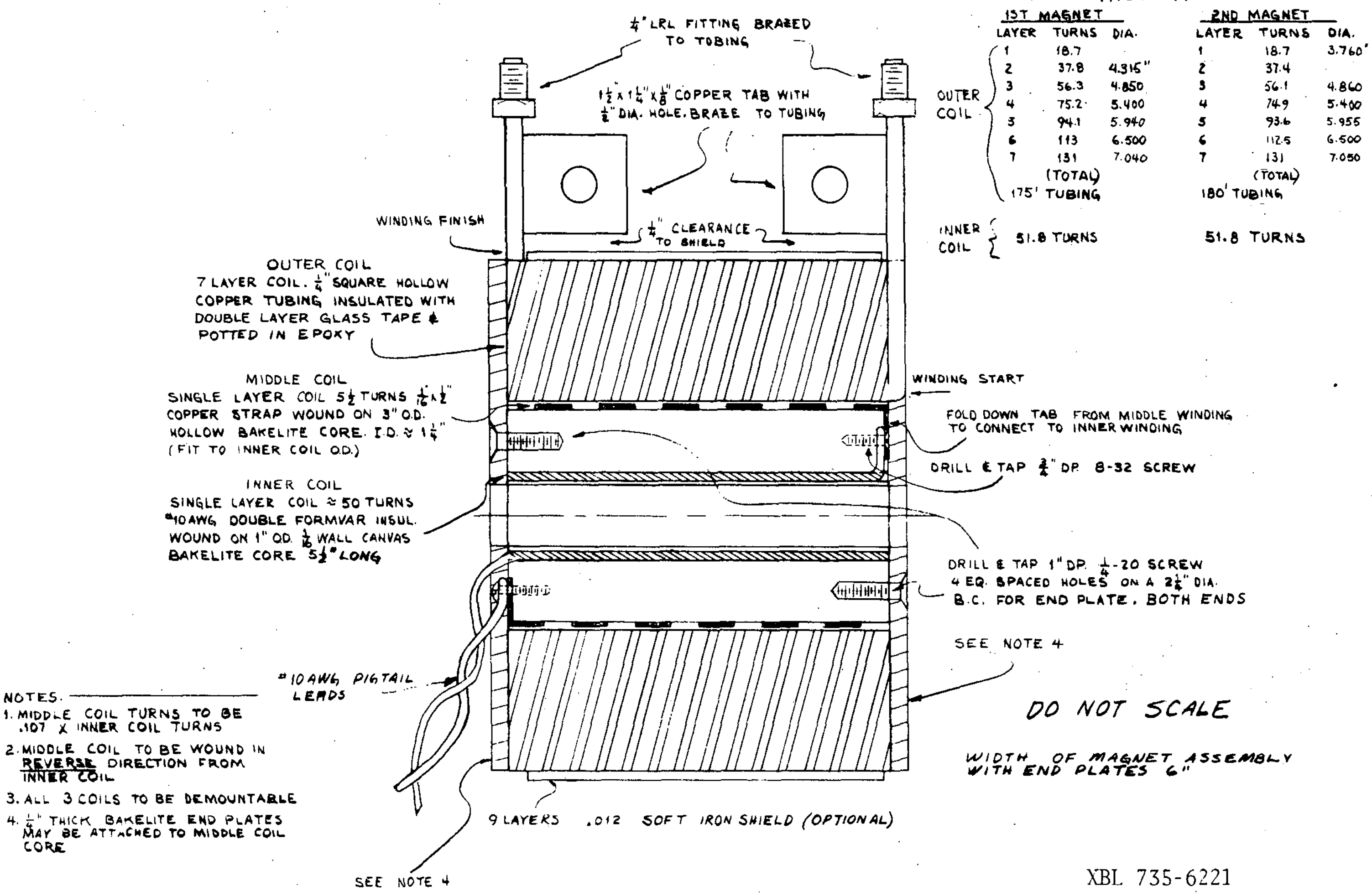

100
90
80
70
60
50
40
30
20
10
0
Transmission (%)
x10
x1
500
550
600
650
Wavelength (nm)
XBL735-2946

Fig. 4



HISTORY

	1ST MAGNET			2ND MAGNET		
	LAYER	TURNS	DIA.	LAYER	TURNS	DIA.
OUTER COIL	1	18.7		1	18.7	3.760"
	2	37.8	4.315"	2	37.4	
	3	56.3	4.850	3	56.1	4.860
	4	75.2	5.400	4	74.9	5.400
	5	94.1	5.940	5	93.6	5.955
	6	113	6.500	6	112.5	6.500
	7	131	7.040	7	131	7.050
		(TOTAL) 175' TUBING			(TOTAL) 180' TUBING	
INNER COIL		51.8 TURNS			51.8 TURNS	

XBL 735-6221

Fig. 5

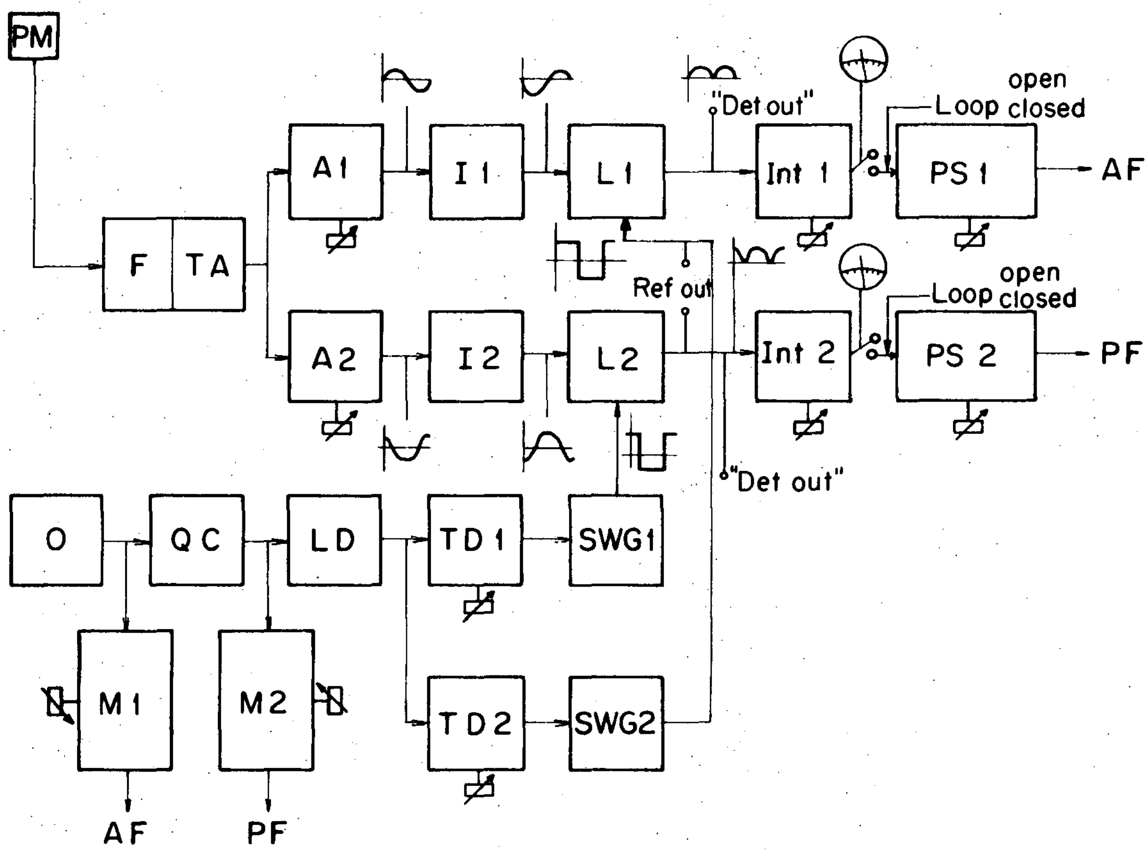


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Fig. 6

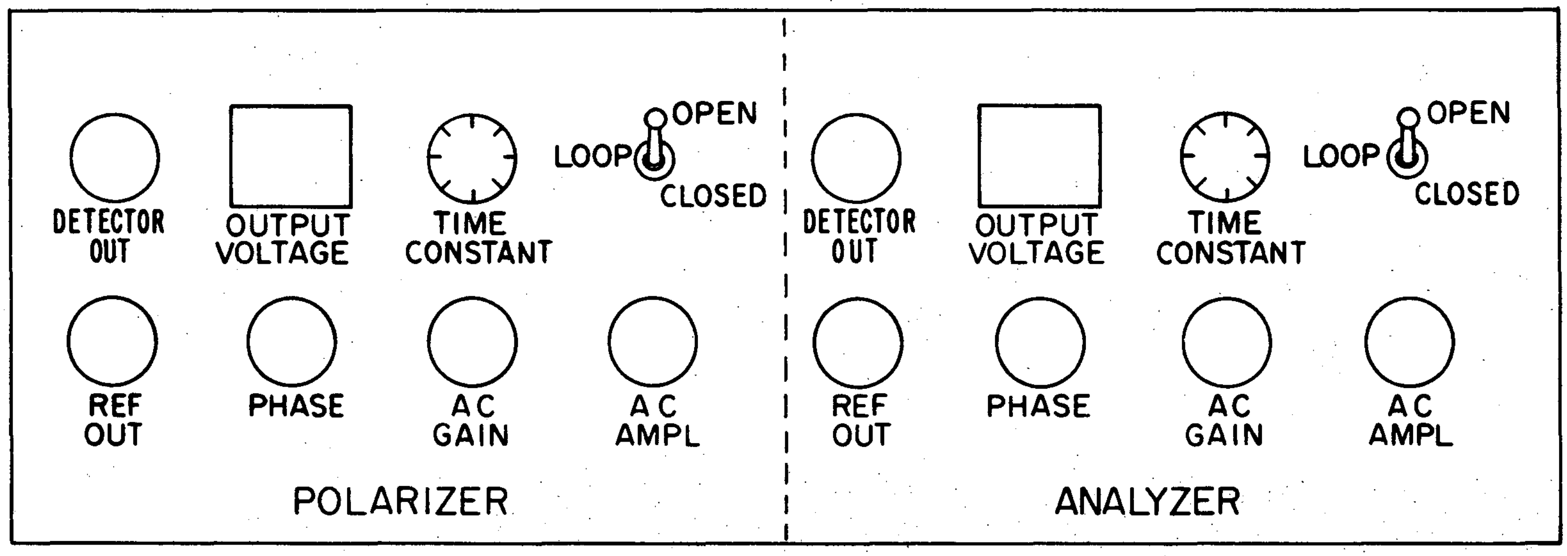

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Fig. 7

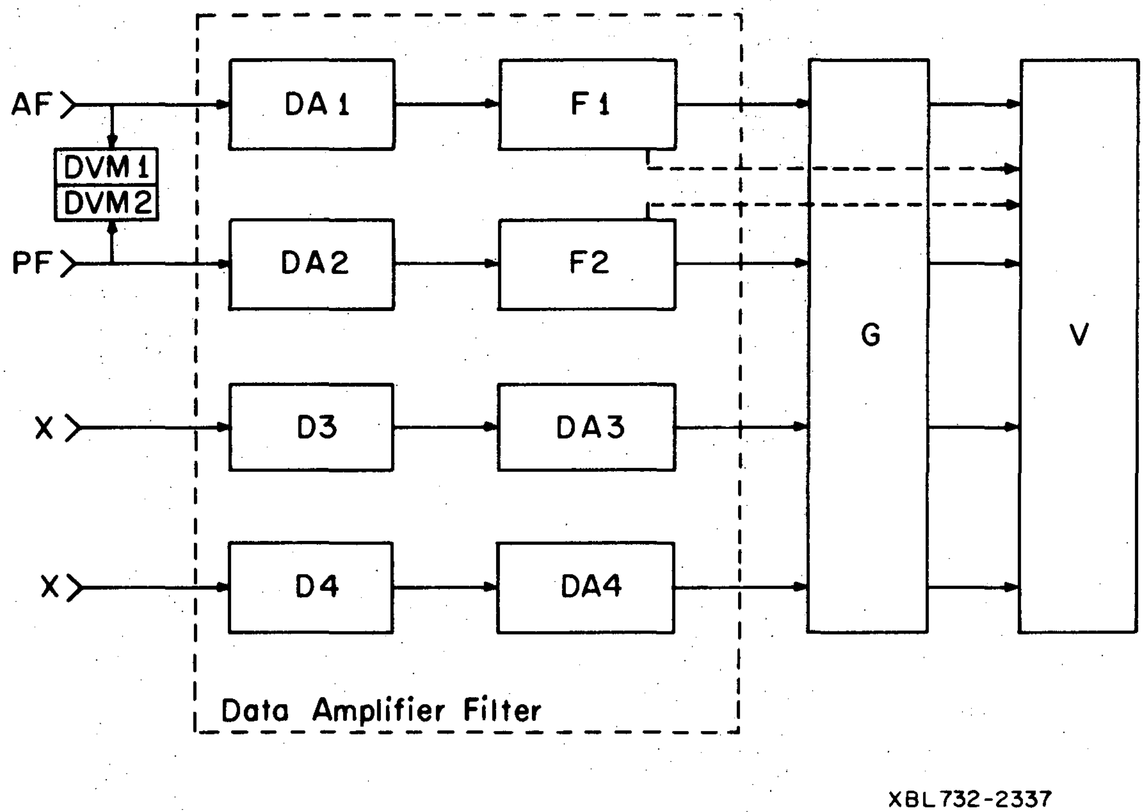
AF
PF
X
X
DVM 1
DVM 2
DA 1
DA 2
D3
D4
F 1
F 2
DA3
DA4
Data Amplifier Filter
G
V
XBL732-2337

Fig. 8

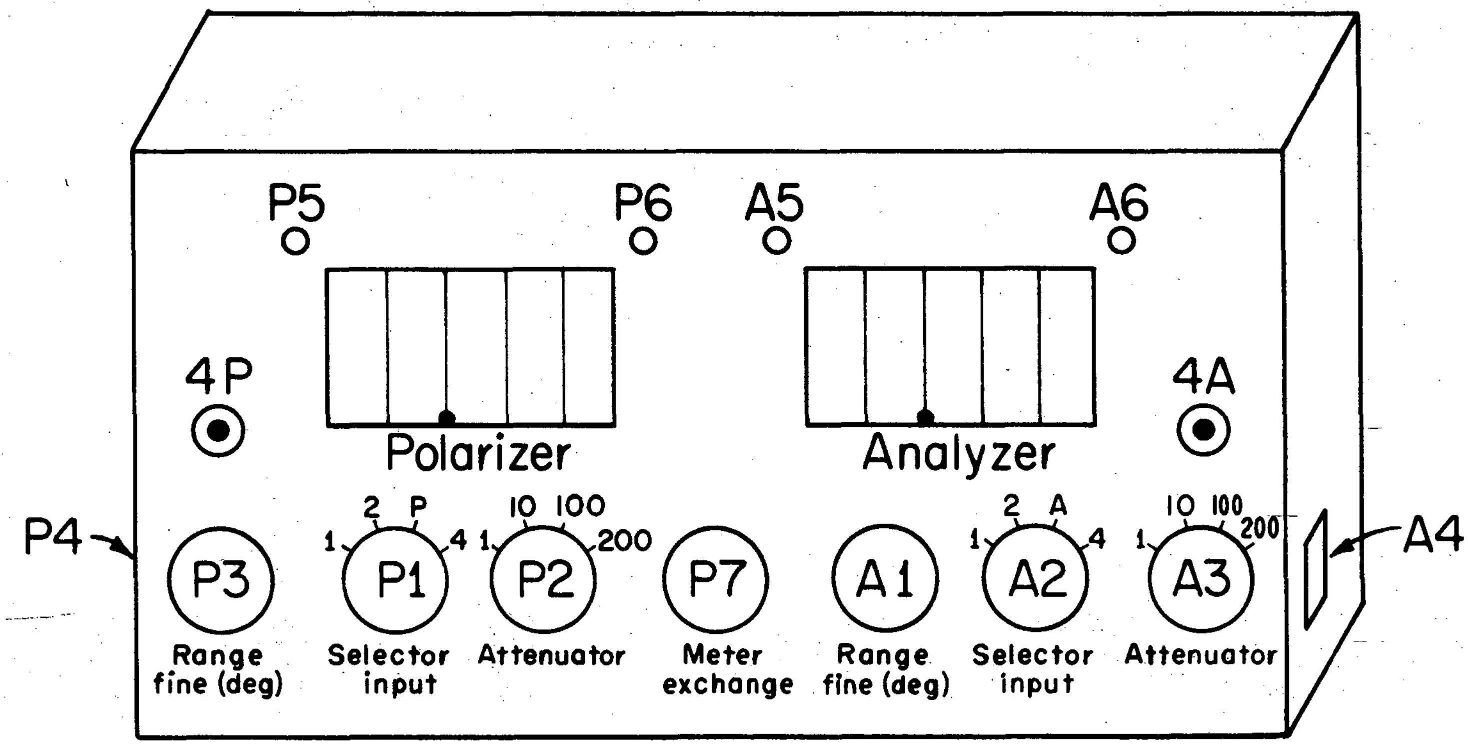

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Fig. 9

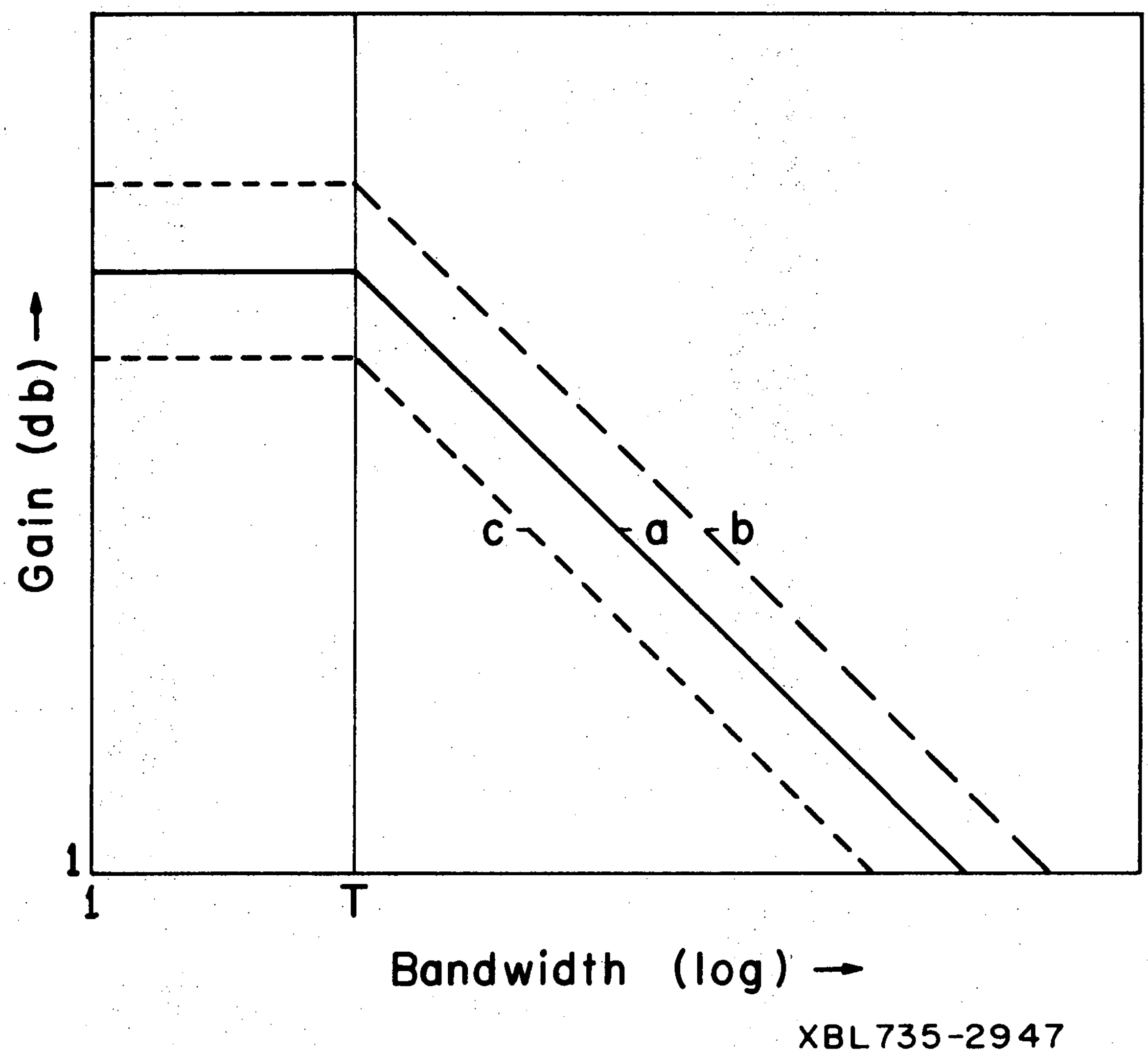

Fig. 10

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