INTERIM REPORT ON INVESTIGATIONS OF ELECTRO-MAGNETO-OPTICAL TECHNIQUES FOR DISPLAY PURPOSES

by

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INTRODUCTION AND SUMMARY

This report describes the progress made by the Willow Run Research Center between 1 April and 1 October 1954 on U. S. Navy Special Devices Center Project 9-U-74. During this first six-month period, effort was directed principally toward investigating various electro- and magneto-optical techniques applicable to the intensity modulation and scanning of light beams for display purposes. One of the ultimate aims of the work in this field is to find techniques of optical control which will provide displays having characteristics comparable to or better than television-type displays.

A survey of the display field (Sec. 2) showed that, for most rapid results, effort could most profitably be expended on display techniques based on electro- or magnetostrictive methods which provide micromotions suitable for optical control. Of the three optical methods -- interference, diffraction, and reflection control--interference appears to be most promising, considering the present state of the art.

The theory of interference methods of optical control is discussed in Section 3. It is shown that it should be possible to obtain:

1. Sufficient intensity from a beam-scanning device to be useful for display purposes,
2. Direct sweep angles up to 30°,

3. Definition of 500 lines, and
4. Intensity modulation percentages of close to 100.

It is also shown that materials having the response frequencies needed are available.

Both a controllable transmission and a controllable reflection interferometer have been constructed and tested (Sec. 4). On the basis of these tests, it has been decided to use the former for sweeping and the latter for intensity modulation. A side product of this experimental work was the development of a controllable spectrometer and a micromeasurement device for measuring changes in length of the order of 2 Å.

II

APPROACH TO THE PROBLEM

When Project 9-U-74 was initiated, a search was made (Ref. 2) of the literature on television-type displays. From this review, several conclusions were reached concerning the most useful methods of approach to the problem of scanning of light beams, namely:

1. Within the scope of the contract, it would not be feasible to attempt to compete with the excellent and large-scale efforts being expended on cathode-ray tube type television systems, especially since no basically new methods to increase intensity and definition were found.
2. Electro- or magnetostrictive means of changing the inclination of a reflecting surface give changes of a degree or less at frequencies of the order of tens of kilocycles. This indicated that these methods should not be pursued further.
3. Traveling ultrasonic wave methods have been used by several organizations for optical intensity modulation, but have not been used for beam scanning. These methods, as presently set up, apparently give a rather low intensity output. Hence, they were not pursued further.
4. The "Eidophor" system of color television projection involves complexity and expense far beyond the scope of this project. Therefore it was not considered feasible to work on this system.
5. The Kenyon rapid film development method does not produce an

instantaneous display. This method, therefore, could not be used.

From the foregoing considerations, it appeared that the effort could best be spent on developing methods for controlling a beam of light after it had left the source. It seemed at first that it might be possible to control light by interference, by diffraction, and by reflection methods. Micromotion methods for such control (Ref. 4) have apparently not been investigated heretofore.

Of these three methods, interference has thus far proven to be the most practical. By combining the work of Hadley and Dennison on interference (Ref. 2) with electro- and magnetostrictive methods, it was possible to develop a controllable interference filter (Ref. 4). A subsequent experiment with such a filter showed that, for a given plate separation and for polychromatic incident light, the color transmitted depended on the angle of incidence (Fig. 1). Conversely, for monochromatic incident light, the angle of transmission depended on the plate separation. This angle dependence was also found by applying the formulas of Hadley and Dennison. The foregoing led to the idea that if a strongly converging beam of monochromatic light were placed incident on a narrow-band controllable filter (Ref. 4), the convergent beam would be transmitted only at that angle for which the plate separation and angle of incidence satisfied Hadley and Dennison's equations. The theoretical development of this idea and the resultant experimental work are described in more detail in the following two sections.

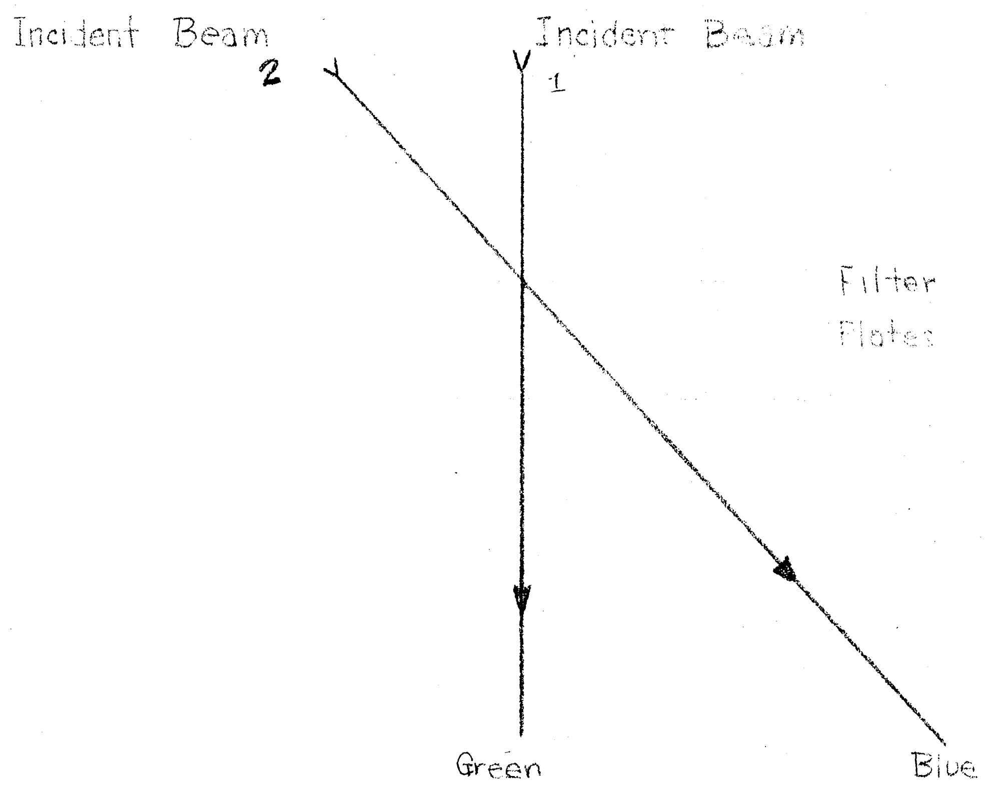

FIG. 1 COLOR TRANSMITTED BY INTERFERENCE FILTER AS A FUNCTION OF ANGLE OF INCIDENCE

III

THEORY OF INTERFERENCE METHODS OF OPTICAL CONTROL

3.1 Intensity

Hadley and Dennison arrived at the formula

$$T_F = \frac{T^2}{(1-R^L)^2 - 4R^L \sin^2 \left[\frac{2\pi \Delta (n_3^2 - \sin^2 \theta)^{\frac{1}{2}}}{\lambda} + y^L \right]} \qquad (1)$$

for the transmission of light through a parallel-plate interference filter in which the transmission elements are partially conducting metallic films. Neglecting the effect of the phase constant y^L, and making the filter symmetric with respect to the direction of the incident light (so that the direction superscript L drops out) leads to the formula:

$$T_F = \frac{T^2}{(1-R)^2 + 4R \sin^2 \left[\frac{2\pi \Delta (1-\sin^2 \theta)^{\frac{1}{2}}}{\lambda} \right]} \qquad (2)$$

where

T_F = transmission ceofficient of the filter

T = transmission coefficient for a single dielectric-backed metallic layer

R = reflection coefficient for a single dielectric-backed metallic layer

n_3 = index of refraction of the material between the metallic layers (here $n = 1$ for air spacing)

$\triangle$ = spacing between the metallic layers

θ = angle between incident light ray and the normal to the filter plates

The intensity can be calculated from Equation 2. That is, the percentage of the light transmitted at a particular wavelength can be found as a function of the filter parameters T and R defined above. Using the fact that the transmission maximum occurs when the argument of the $\sin^2$ term is $m\pi$ and assuming $T = 0.1$ and $R = 0.8$ (typical values for aluminum coating (Ref. 5):

$$T_{F_{max}} = \frac{T^2}{(1-R)^2} = \frac{(0.1)^2}{(1-0.8)^2} = 25\%$$

It is possible, however, to obtain thin metallic coatings, especially silver, for which the absorption in the visible region is less than that of aluminum. For commercially available fixed (i.e., non-controllable) filters, transmission maxima up to 37% for band width of 240 Å, have been obtained (Ref. 7).

In addition, under certain conditions, dielectric types of fixed interference filters have been made (Ref. 8) with much higher transmission coefficients for narrower bandwidths. It is reasonable to assume that some of these techniques can be used for controllable interference filters and sweep mechanisms. Thus, theory indicates that sufficient intensity can be obtained from a beam-scanning device to be useful for display purposes.

3.2 Sweep Angle

To investigate the manner in which the beam can be made to sweep, we find the maximum of the transmission coefficient (and hence the intensity) with respect to the angle θ, i.e. we set

$$\frac{\partial T_F}{\partial \theta} = 0$$

Carrying out this calculation:

$$T_F = T^2 \left\{ (1-R)^2 + 4R \sin^2 \left[\frac{2\pi\Delta}{\lambda} \cos\theta \right] \right\}^{-1}$$

$$\frac{\partial T_F}{\partial \theta} = -T^2 \left\{ \quad \right\}^{-2} \cdot \left\{ 8R \sin\left[\frac{2\pi\Delta}{\lambda} \cos\theta \right] \cos\left[\frac{2\pi\Delta}{\lambda} \cos\theta \right] \frac{2\pi\Delta}{\lambda} (-\sin\theta) \right\} = 0 \qquad (3)$$

This expression equals zero if its numerator equals zero. If we do not choose the case where Δ or sin θ are identically zero, then

$$8R \sin\left[\frac{2\pi\Delta}{\lambda} \cos\theta \right] \cos\left[\frac{2\pi\Delta}{\lambda} \cos\theta \right] = 0$$

$$4R \sin 2\left[\frac{2\pi\Delta}{\lambda} \cos\theta \right] = 0$$

whence

$$\frac{4\pi\Delta}{\lambda} \cos\theta = m\pi$$

so that

$$\cos\theta = \frac{m\lambda}{4\Delta}$$

Considering only the first order separation of the plates,

$$\cos \theta = \frac{\lambda}{4\Delta} \tag{4}$$

Figure 2 is a plot of the variation of the angle of maximum transmission with a change in separation of the plates. It can be seen that for a change in plate spacing of about 1/8 wavelength, over the first order, the sweep angle variations of the order of 30°. Thus, the magnitude of the sweep is theoretically sufficient for the needs of a display device.

3.3 Beamwidth

For an interference sweep mechanism to be useful in a high-speed display device such as TV, it should have sufficiently small angular dispersion to permit definition of the order of 500 lines. A brief calculation shows that it should be possible to achieve such definition. Consider Figure 3. We wish to find the angular beamwidth $\delta\alpha$ at any angle of incidence α as a function of the bandwidth. The fractional bandwidth is $\frac{\delta\nu}{\nu}$. Since $r + \Delta_1$ is the path of the longest wave which can be transmitted, and r is that of the shortest, $\frac{\delta\nu}{\nu}$ can be expressed as:

$$\frac{\delta\nu}{\nu} = \frac{\nu_2 - \nu_1}{\nu} = \frac{c/\lambda_1 - c/\lambda_2}{c/\lambda} \approx \frac{\delta\lambda}{\lambda} \tag{5}$$

providing the bandwidth is sufficiently small. Then

$$\frac{\delta\nu}{\nu} \approx \frac{\delta\lambda}{\lambda} \approx \frac{\Delta_1}{r} \tag{6}$$

We see also from the figure that

$$\frac{\Delta_1}{S} \approx \tan\alpha \ ; \qquad S = r\,\delta\alpha \tag{7}$$

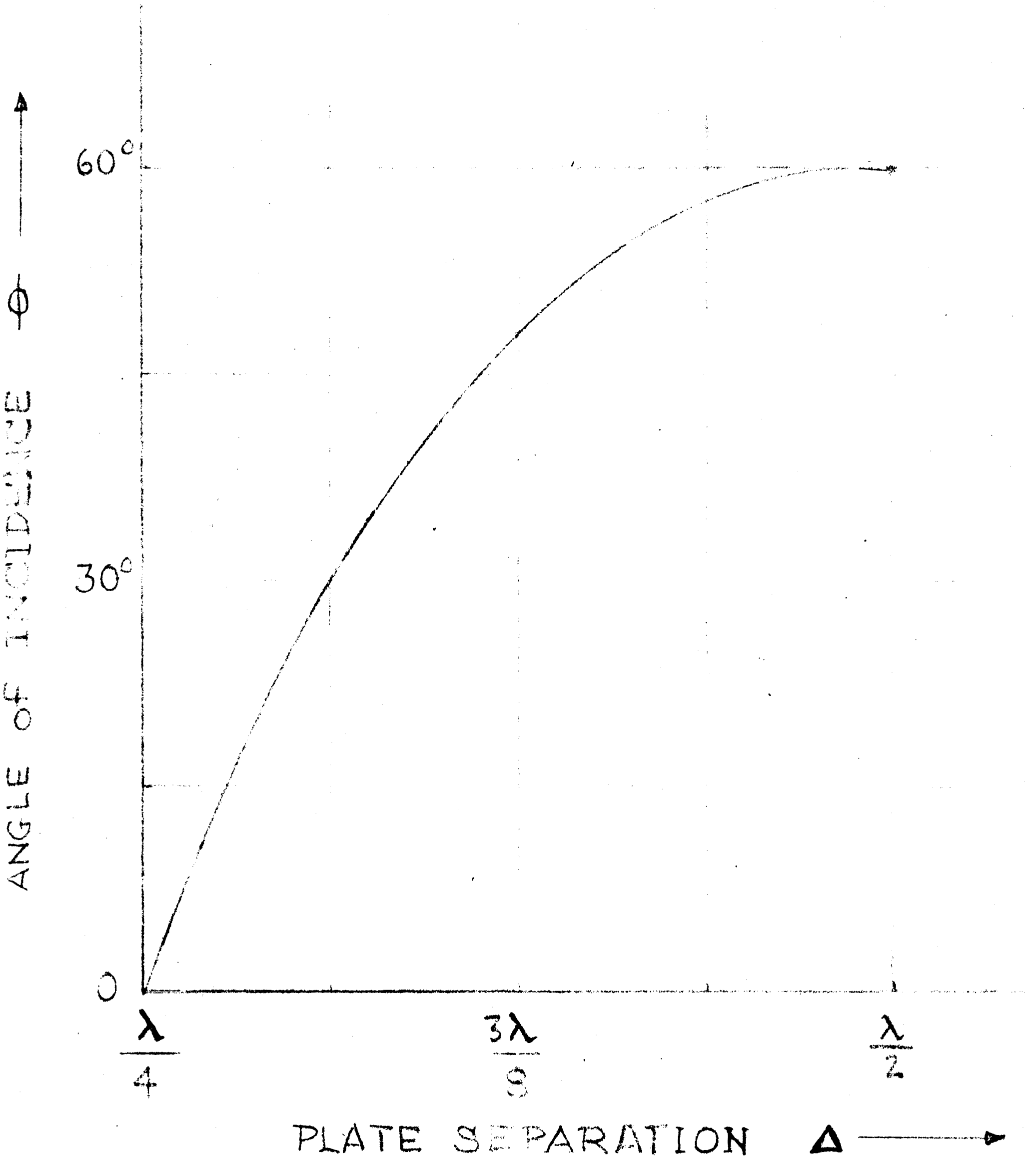

FIG. 2 ANGLE OF MAXIMUM TRANSMISSION OF A FIXED WAVELENGTH AS A FUNCTION OF PLATE SEPARATION

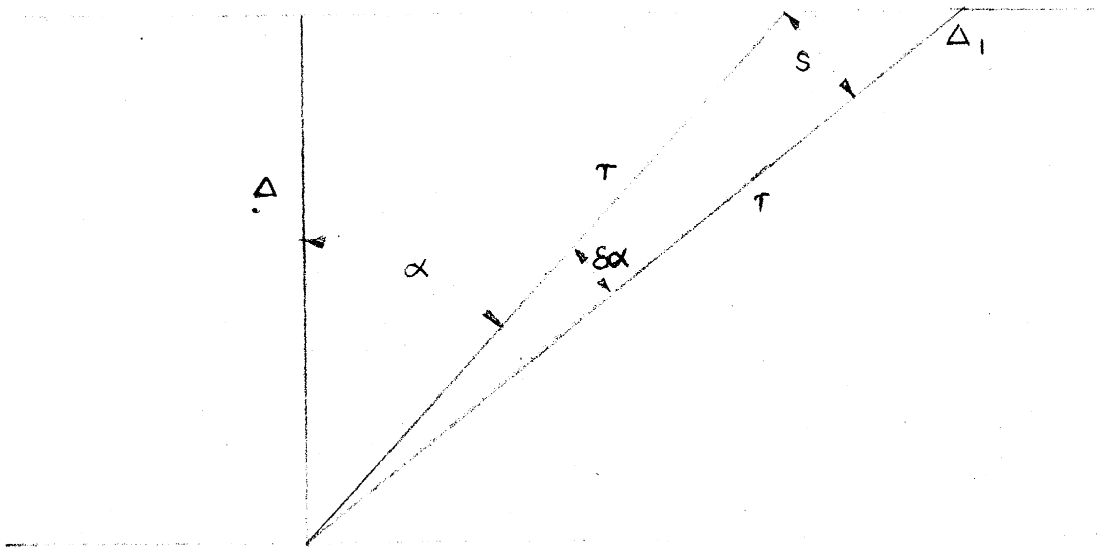

FIG. 3. GEOMETRY of ANGULAR BEAMWIDTH CALCULATION

$$\frac{\Delta_1}{r} = \delta\alpha \tan\alpha \qquad (8)$$

Then

$$\delta\lambda = \lambda\, \delta\alpha \tan\alpha \qquad (9)$$

For a 500-line scan and for a 30° sweep,

$$\delta\alpha = \frac{1}{500} \times 30^\circ = .06^\circ = 1.05 \times 10^{-3} \text{ radians}$$

Considering a sweep from 30° to 60°, for example:

For $\alpha = 30^\circ$, $\tan\alpha = .577$. Taking $\lambda = 5460$ Å (mercury green),

$$\delta\lambda = \lambda\, \delta\alpha \tan\alpha = 5460 \text{ Å} \times 1.05 \times 10^{-3} \times .577$$

$$= 3.3 \text{ Å}$$

For $\alpha = 60^\circ$, $\tan\alpha = 1.73$

$$\delta\lambda = 5460 \text{ Å} \times 1.05 \times 10^{3} \times 1.73$$

$$10.0 \text{ Å}$$

Since $\delta\lambda$ is a monotonic function of $\tan\alpha$, these end points define the range of bandwidths necessary to achieve the desired definition.

3.4 Intensity Modulation

A display device must be capable both of sweeping and of intensity modulating a beam. A reflection interferometer is preferable to a transmission interferometer for intensity modulation since the work of Hadley and Dennison has shown that a reflection-type interference filter will pass 100% of the radiation frequency for which it is tuned and will reject all of the radiation having a wavelength $\frac{2n+1}{2}$ times that of the radiation passed. This theoretical modulation can be closely approached in practice.

3.5 Frequency

The modulation frequency is determined by both the mechanical and electrical constants of the system. It was pointed out in Reference 4, for example, that for a 1 cm nickel bar vibrating in the fundamental mode when supported at one end:

$$f = \frac{v}{4L} = \frac{4.85 \times 10^5 \text{ cm/sec}}{4 \times 1 \text{ cm}} \cong 120\text{KC}$$

where

f = frequency

v = speed of sound in nickel

L = length of bar

Where high frequencies are required, certain magnetostrictive ceramic ("Ferramic") materials are available which have response frequencies of tens of megacycles.

The frequencies quoted are for bars without mass loading. These can be closely approximated in a reflection interference device. In a transmission interference device, the mass of the quartz optical flat loads the strictive driving element and thus decreases the frequency. The experimental results indicate that this lower response is still within a usable range.

IV

EXPERIMENTAL RESULTS

4.1 Transmission Interferometer

The transmission beam sweeping device is shown schematically in Figure 4. The theory underlying its operation was presented in Sections 3.1, 3.1, and 3.3. Considered geometrically, we see that the direction of the incident light for which constructive interference occurs varies with the distance between the two plates. As the plate separation Δ changes, the angle at which a line of fixed length just spans the inter-plate gap varies. Since we are placing a converging wedge of light incident upon the plates, there will be an angle over the angular wedge α for each separation distance at which the rays will interfere constructively.

This experimental arrangement has been tried (Fig. 5). As predicted, a beam of sodium light could be projected on a screen a short distance away. The angular displacement of the beam was limited by the aperture of the instrument in this case, but was of the order of several degrees. The angular width of the beam could not be measured accurately but was of the order of a fraction of a degree.

4.2 Reflection Interferometer

An interferometer was constructed using reflection optics, as shown in Figures 6 and 7. A convergent beam of monochromatic radiation was directed at the interferometer plates. Upon changing the separation of the plates by a little less than half a wavelength, the angular position of the output beam was changed about 15°. This result indicates that

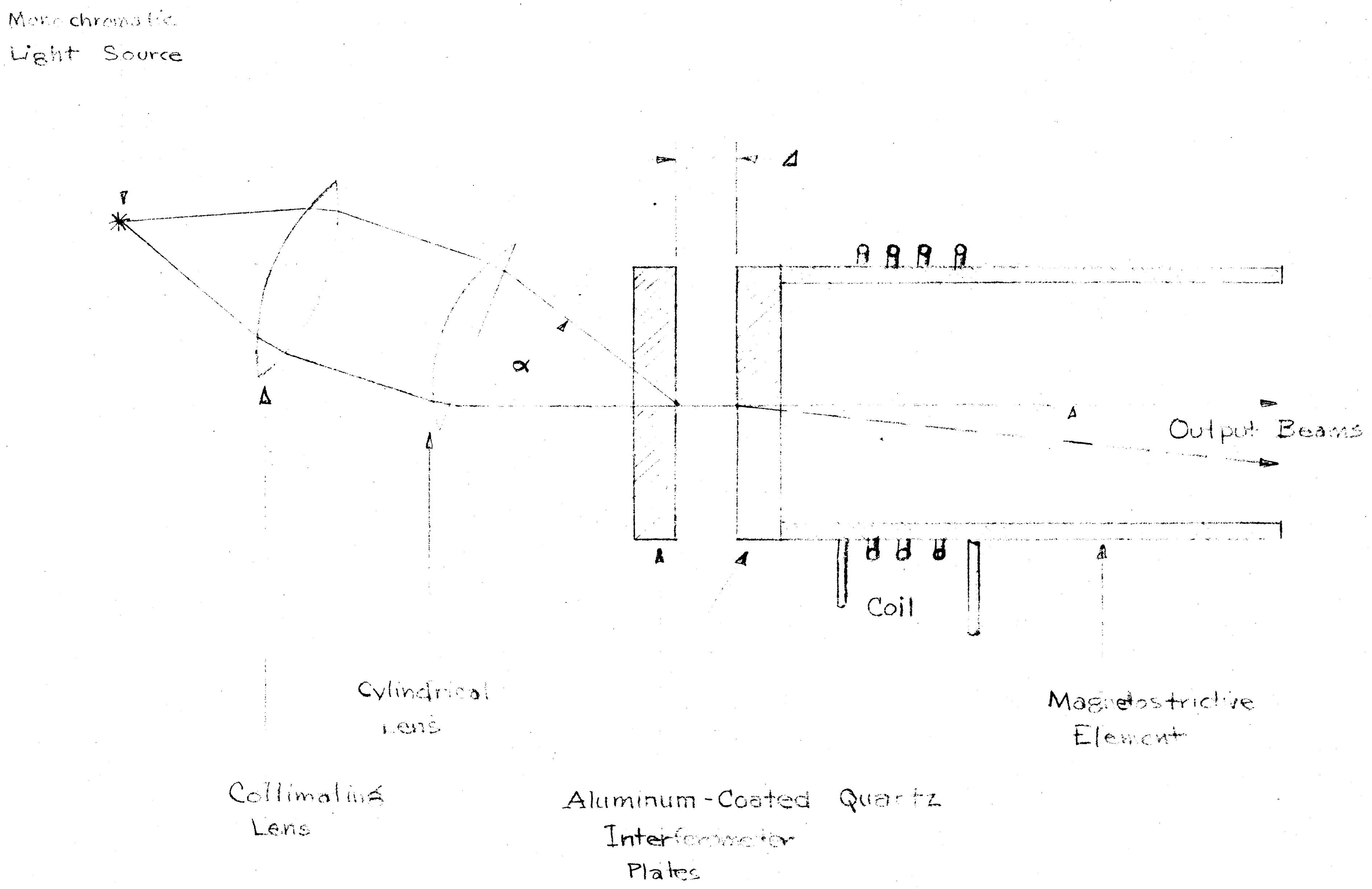

FIG. 4 TRANSMISSION BEAM SWEEP APPARATUS

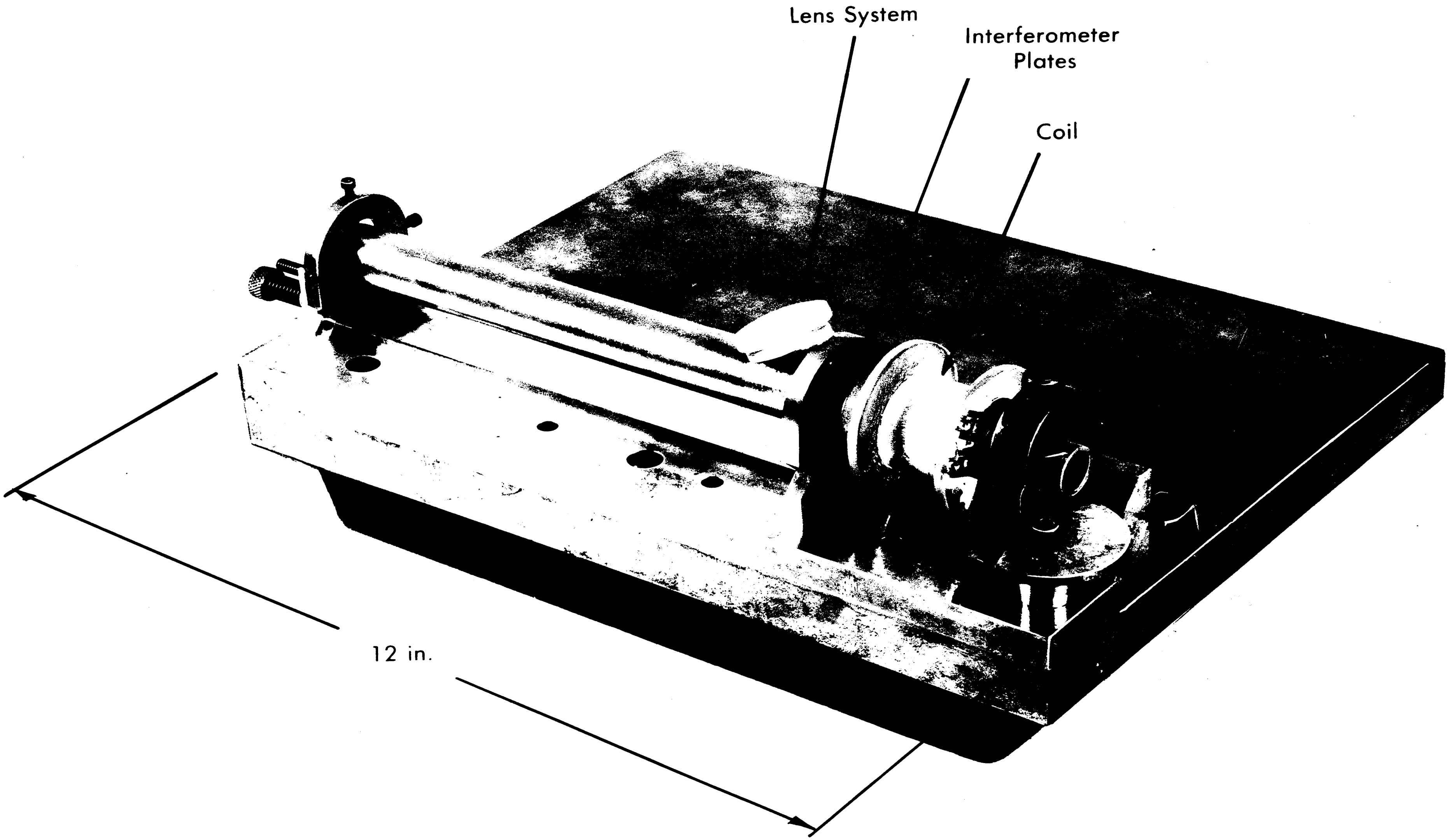

FIG. 5 EQUIPMENT USED IN TRANSMISSION EXPERIMENTS

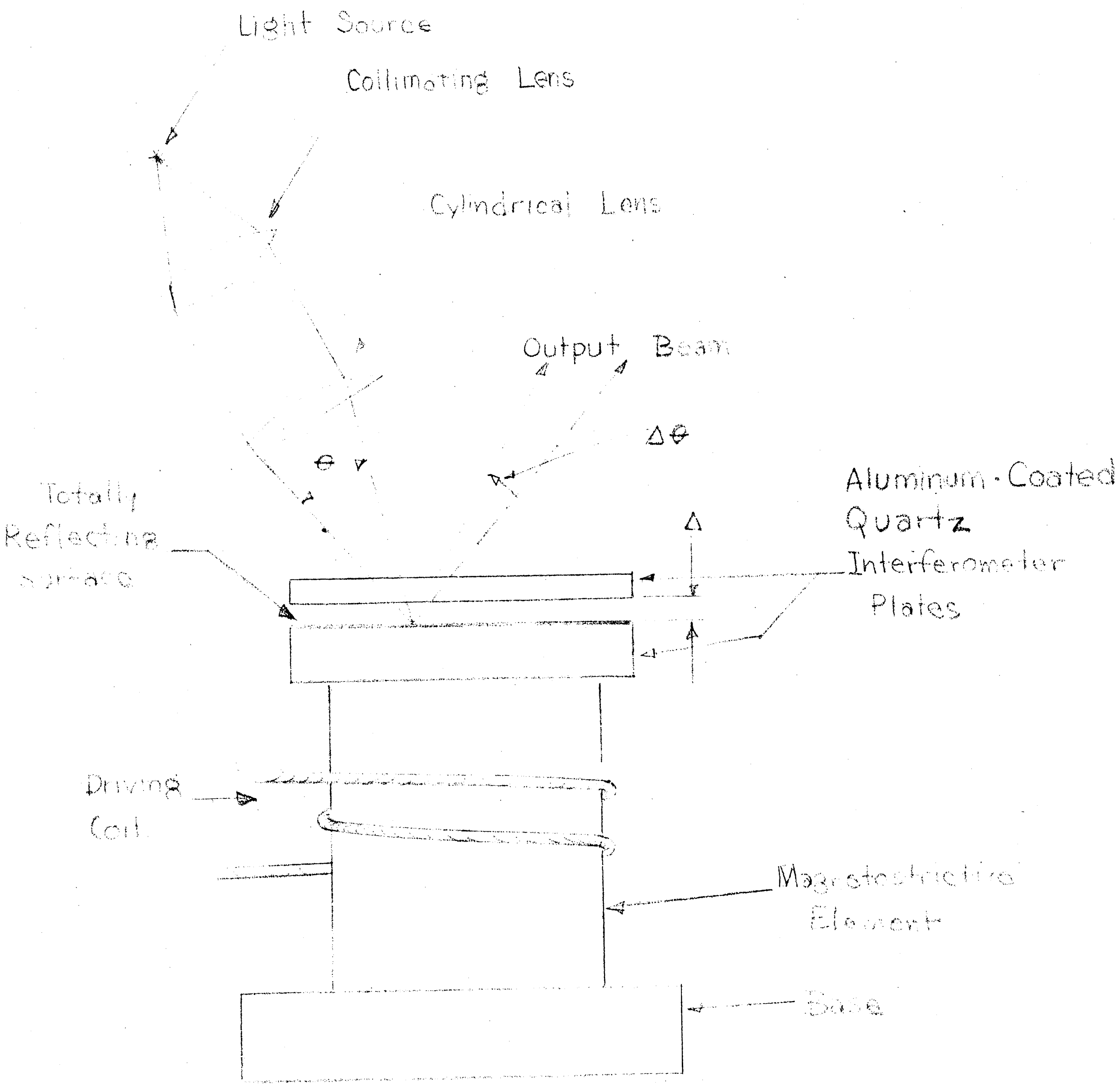

FIG. 6 REFLECTION BEAM SWEEP APPARATUS SCHEMATIC

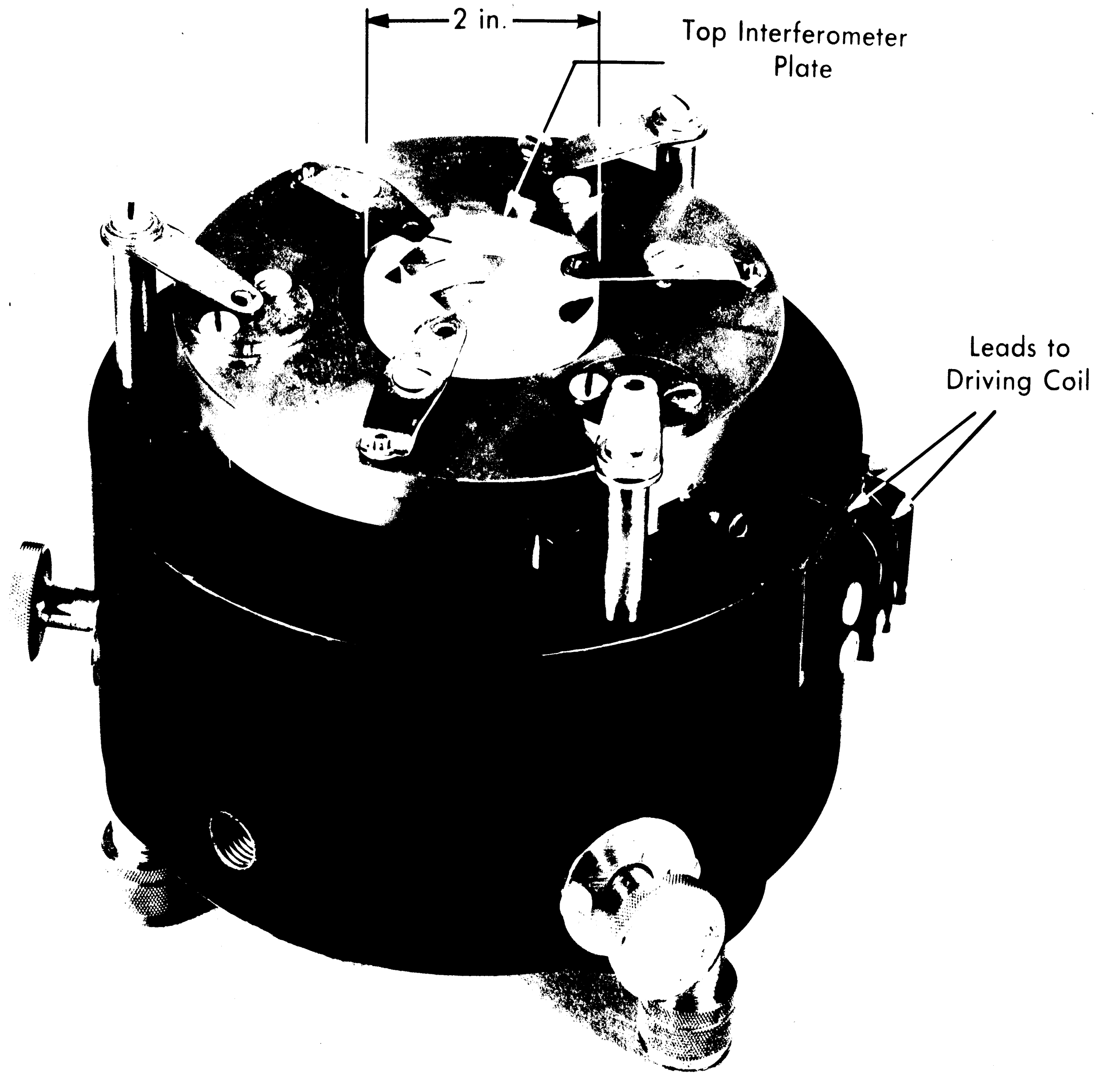

FIG. 7 EQUIPMENT USED IN REFLECTION EXPERIMENTS

the plates were set to about second-order separation in sodium light (Sec. 3.2).

In reflection interferometers the bandwidth of the energy passed is too great (Ref. 2 and 6) for use in a beam-sweeping apparatus. That is, in terms of angle, a large bandwidth permits the light to pass through the plates for a wide range of angles of incidence. However, this difficulty can be turned to advantage by using this phenomenon for intensity modulation. Here, the modulation can extend over a 100% intensity range with small losses, as pointed out by Hadley and Dennison, and the curve of Figure 2 is not so sharp as to make it difficult to attain any desired position of separation. In addition, with reflection optics, there is no need to attach a quartz mass to the magnetostrictive element as in transmission optics. This is particularly advantageous in the intensity modulation case, since the intensity modulation frequency is the highest in the system.

The end of a magnetostrictive ceramic rod has been polished optically flat. Since this rod will oscillate at frequencies up to the order of tens of magacycles, modulation of intensities can be accomplished at and above television video frequencies with very little light loss.

From the foregoing considerations, it has been decided to use the controllable reflection interferometer for intensity modulation, and the controllable transmission interferometer to sweep a bright beam for the horizontal raster. The much slower frame rate motion can be produced by using a bimetallic magnetostrictive strip or other variable angle reflection apparatus. Such a raster and modulation setup is shown in Figure 8.

4.3 Other Magnetostrictive Experiments

In the process of experimenting with beam deflection, several interesting side effects were noted. These effects are described below.

4.3.1 Controllable Spectrometer

The transmission interferometer was set up with its plates slightly tilted. Parallel rays of sodium light were then passed through it. Upon changing the separation of the plates magnetostrictively, straight parallel interference lines were caused to move sidewise across the field of view. The number of these lines was dependent upon the order of interference, and it was possible to arrange the plates so that only one order of spectrum appeared. The red and green lines in the sodium tube appeared as well as the yellow sodium line.

In addition, as is predicted by theory (Ref. 6),it was found that the resolution, which is a function of both the reflectivity and the spacing, could be increased greatly by increasing the plate separation. Hence an elementary model of a variable resolution, voltage-controllable spectrometer has been produced. This spectrometer is shown in Figure 9.

4.3.2 Micromeasurement Device

The transmission interferometer was also set up in conjunction with a spectrometer, as shown in Figure 10. As the separation of the interferometer plates was changed, the lines of the mercury source,

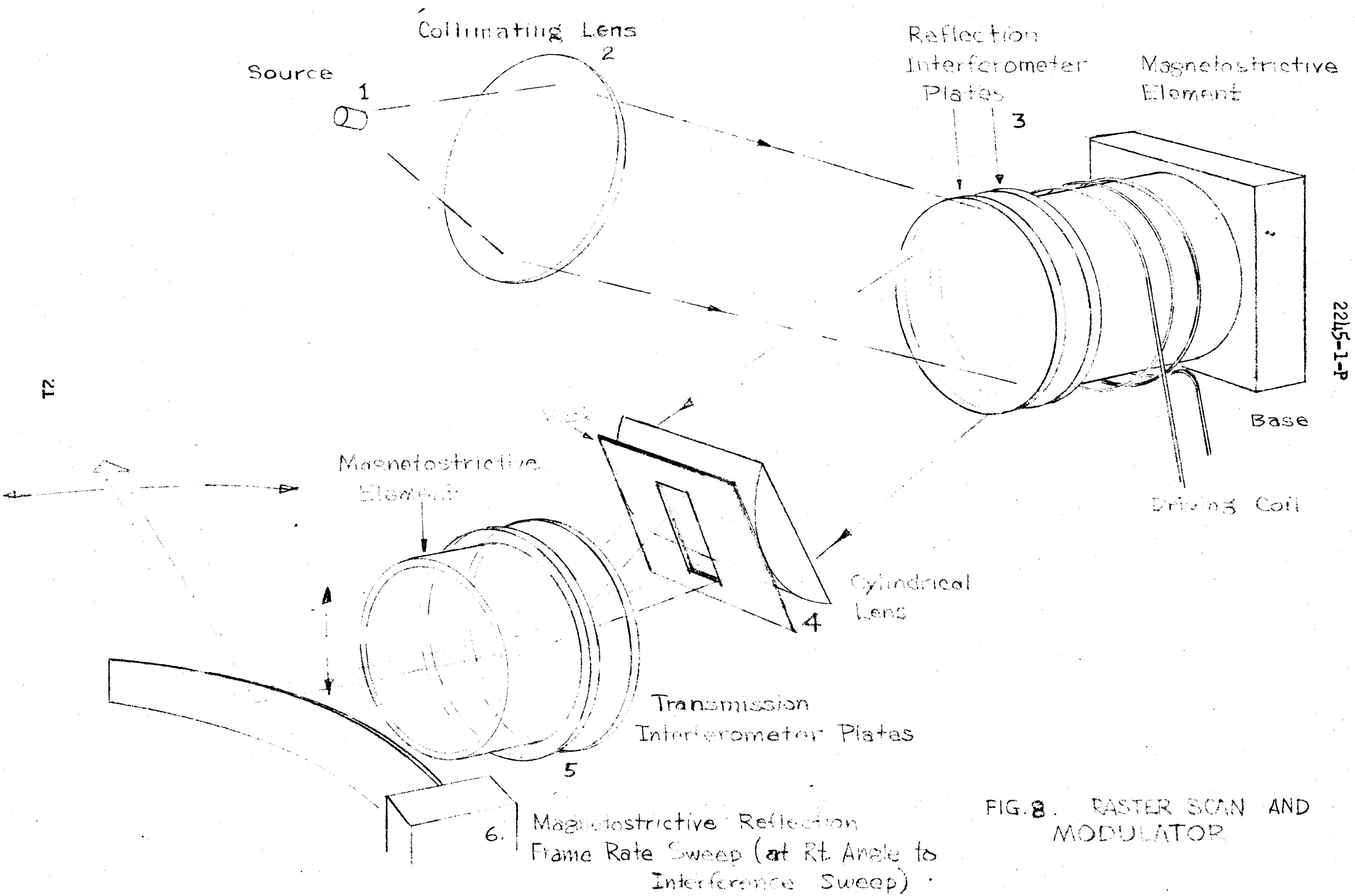

FIG. 8. RASTER SCAN AND MODULATOR

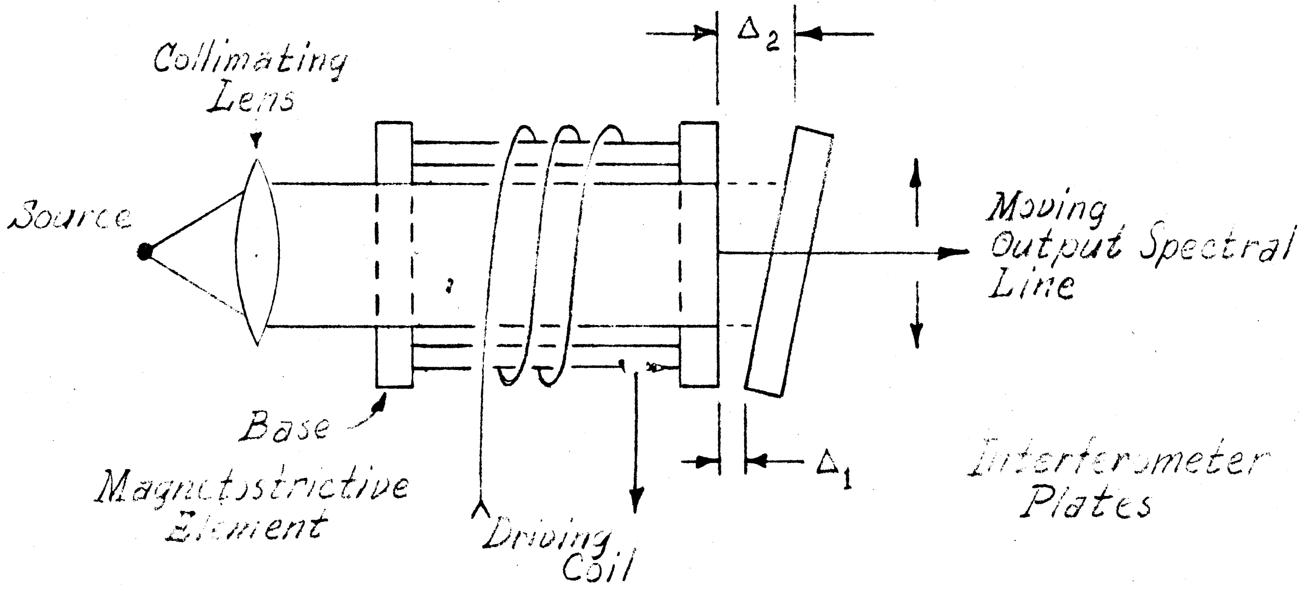

FIG. 9 VARIABLE RESOLUTION, VOLTAGE-CONTROLLABLE SPECTROMETER

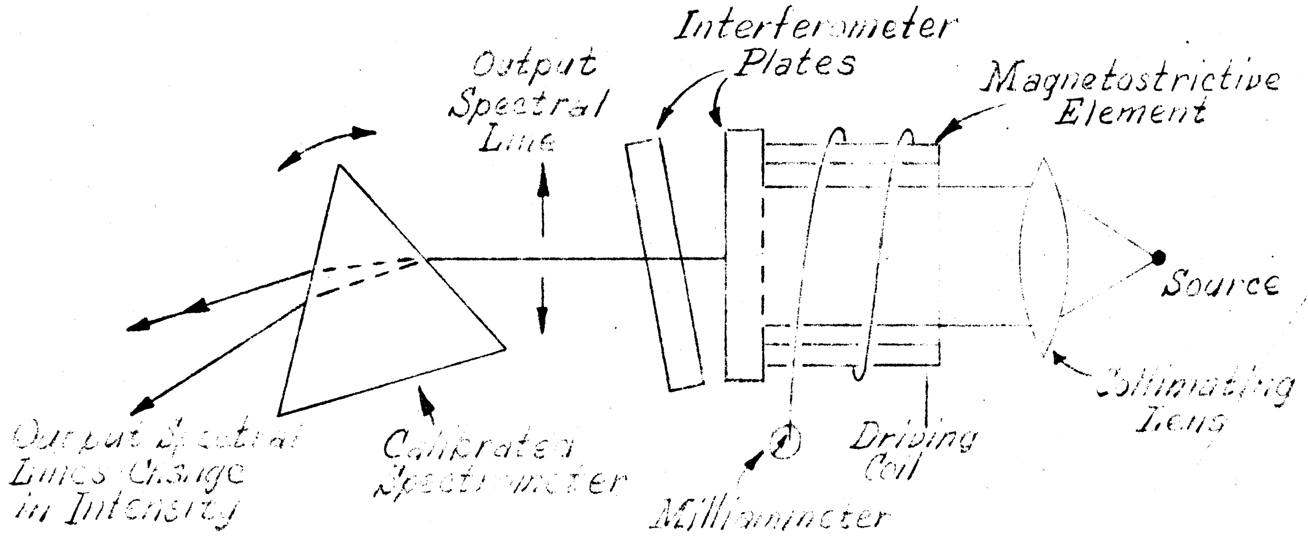

FIG. 10 MICRO MEASUREMENT APPARATUS

as viewed in the spectroscope, became brighter and darker depending upon whether the filter was transmitting or rejecting the frequency being observed. An important feature of this method is that, by using spectrum lines of known wavelengths, it provides a yardstick by which small changes in length can be measured accurately. By calibrating the milliammeter in series with the magnetostrictive driving coil against these known wavelengths, it is possible to measure length changes of 2Å for a current change of 1 milliampere.

4.4 Inhomogeneous Field Experiments

During the literature search, several phenomena, including the Kerr, Faraday, and Voigt effects (Ref. 3), were reconsidered as possible methods of providing control of optical radiation. These effects cause birefringence of a medium under electric or magnetic fields. Birefringence refers to the change in index of refraction of an optical medium with change in polarization. These effects indicate that the index of a medium may depend, in some way, upon the nature (e.g. magnitude, geometry, and type) of the applied field.

An experiment was set up as shown in Figure 11. A hollow prism was filled with various liquids such as mono-bromonaphthalene, nitrobenzene, and other materials of high refractive index or high Kerr effect. Up to 10,000 volts were applied to electrodes 1 and 2 to produce an inhomogeneous electric field within the liquid medium. Although high-speed deflections have not yet been obtained, certain of the liquids produced, in addition to the standard birefringence effect, a very slow shift of

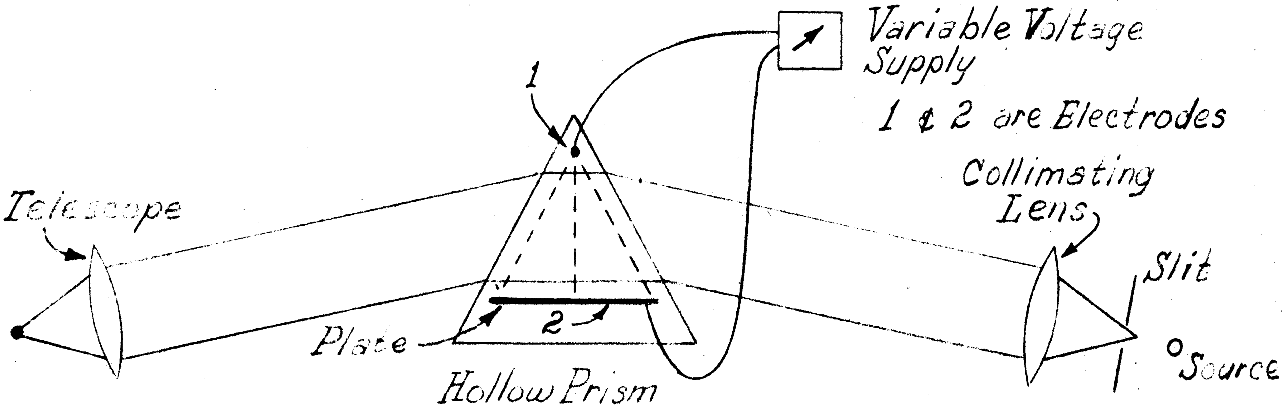

FIG. 11 INHOMOGENOUS FIELD EXPERIMENT

the line positions. In one case, splitting of the spectral lines occurred. A discussion of these phenomena has not been found in the literature. They are apparently not well known, and it seems that further investigation would be a very profitable line of endeavor.

V

PLANS FOR FUTURE WORK

In accordance with the terms of the contract, the next six months will be devoted to building what is, according to present knowledge, the best possible mechanism to produce a single line sweep, and to making an experimental investigation of intensity modulation and scanning control. A report containing this information and basic component design data will then be written. It is intended that this equipment will be of the type shown schematically in Figure 4.

REFERENCES

1. "Monthly Report for June 1954; Project 9-U-74" University of Michigan, Willow Run Research Center (1 July 1954)

2. "Reflection and Transmission Interference Filters" L.N. Hadley and D.M. Dennison, J. Opt. Soc. Am. 37, 451-465 (1948) and 38, 483-496 (1948)

3. "Physical Optics" R. W. Wood, MacMillan Co. (1934)

4. "Controllable Interference - Type Optical Filter" R. Blythe, J. Opt. Soc. Am. 44, 336-339 (1954)

5. "Monthly Report for July 1954; Project 9-U-74" University of Michigan, Willow Run Research Center (1 August 1954)

6. "Fundamentals of Optics" F.A. Jenkins and H.E. White, McGraw-Hill Book Co. (1950)

7. Informal communication from the Farrand Optical Company, New York City

8. "Quarterly Technical Report No. 5" The Bausch and Lomb Optical Company Contract DA-44-009-eng-18 (23 April through 22 July 1951)

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