ERIM
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MEMORANDUM TO: VLA Optical Processor File

FROM: C. Dwyer JCD

SUBJECT: Film Coherent Optical Quality Considerations

Introduction

Photographic films consist of an emulsion which is coated on a clear plastic support material (or base). Total film thickness varies from product to product over a range of about 45 μ (for ultra-thin estar base films) to 200 μ. Any film, however, has a variation in thickness amounting to several percent of its nominal value. This thickness variation represents several wavelengths of light so that for most applications, film cannot be considered an optical flat. Common practice in coherent optical systems is to use a liquid gate to alleviate the phase errors generated by these thickness variations. Figure 1 illustrates a typical liquid gate configuration. The relative phase of a ray of light transmitted through the gate is

$$\phi = \frac{2\pi}{\lambda} D$$

where D is the optical path length which, in this case, is the sum of the optical path lengths in the fluid and the film (ignoring the optical flats). The optical path is the product of the path length and the index of refraction. The phase of a ray of light transmitted through the thickest portion of the film is thus (see figure)

$$\phi_1 = \frac{2\pi}{\lambda} \left\{ (S-t)\, n' + tn \right\}$$

and the corresponding phase of a ray transmitted through the thinnest portion of the film is

$$\phi_2 = \frac{2\pi}{\lambda} \left\{ (S-t')\, n' + t'n \right\}$$

The difference in relative phase, $\Delta\phi$, represents a phase error in the optical system and is given by

$$\Delta\phi = \phi_2 - \phi_1 = \frac{2\pi}{\lambda} \Delta n \, \Delta t \qquad (1)$$

where

$\Delta n = n'-n$ (index mismatch)

$\Delta t = t-t'$ (film thickness variation)

Effect of Residual Phase Errors

Table 1 gives the index of refraction of a few film bases and gate fluids which are commonly used in combination.

Using triacitate films without a liquid gate (i.e., with air as the gate fluid) Δn from Eq. (1) is 0.48. With a freon liquid gate Δn is 0.13. Therefore, phase errors will be reduced by a factor of 4 when using a freon liquid gate. In a xylene liquid gate Δn is 0.02, and, consequently, phase errors are reduced by a factor of 24. Other comparisons and computations can be made in a similar fashion.

In order to see how these phase errors and the use of a liquid gate affects the impulse response of a coherent optical system, a basic Fourier transforming set up was made as illustrated in Figure 2. Figures 3, 4, 5, and 6 show enlargements of the impulse response obtained under various conditions. Kodak 5460 film is the acetate base with a total film thickness of 150 μ and 3414 is the estar base film of total thickness 75 μ.

Measurement of Residual Phase Errors

It is difficult, if not impossible, to convert measurements of the impulse response into phase error for the case of acetate film bases in a xylene liquid gate. The residual phase errors are obviously very small, so that their effects on the impulse response are very subtle. Moreover, it is likely that there are other phase errors in the optical system (even as simple as this one is) which are as large, or larger than the residual phase errors, due to film thickness variations. One possibility would be to measure the impulse

TABLE I

MATERIAL	INDEX	REFERENCE
Cellulose Triacetate film base	1.48	Kodak Publication M-63, "Physical and Chemical Behavior of Kodak Aerial Films"
Estar film base	1.50 ± 0.01	(Same as above)
Air	1.00	Handbook of Chemistry and Physics
Xylene gate fluid	1.50*	(Same as above)
DuPont Freon 113	1.35	DuPont Publication B2, "Freon Technical Bulletin"

* Average value of m, o, and p-xylenes of which most xylene is a combination.

response (amplitude and phase) obtained with the film outside the liquid gate. Then a Fourier transform computation would generate the wavefront emerging from the film. This method is possible, but would not be trivial.

A much simpler way of measuring the phase errors is to measure the film thickness variations, Δt, using an interferometric technique. The experimental arrangement is shown in Figure 7. The piece of film to be measured is simply supported in air so that its surface is approximately flat. It is illuminated with a collimated coherent light source. A portion of the wavefront striking the front surface of the film is reflected, while most is transmitted. Of that transmitted and striking the rear surface, a similar portion is again reflected and the major portion is again transmitted. The two beams reflected from the front and rear faces of the film will be of approximately equal amplitude and will interfere forming high contrast fringes localized on the front surface of the film. Pictures of these fringes, taken with a camera for four pieces of film selected at random, are shown in Figures 8, 9, 10, and 11. The collimated beam illuminating the film sample in this case had a wavelength of 633 nm and was apertured to a circle of diameter 3¼ cm.

The formation of the interference fringes is due to optical path variations of the light which is transmitted into the film and reflected off the back face. The relative phase of the wavefront reflected from the back face with respect to the wavefront reflected at the front face is (approximately):

$$\phi_r = \frac{2\pi}{\lambda} 2nt$$

This phase will change by 2π and cause one complete fringe whenever the film thickness, t, changes by

$$\hat{\Delta t} = \frac{\lambda}{2n} \qquad \text{for one fringe}$$

Thus, each fringe is due to a thickness change of $\lambda/3$ (approximately true for both acetate and estar base films).

It cannot be determined from looking at the fringes whether the film thickness is increasing or decreasing. This does not really represent a serious problem since we don't really care whether a single fringe represents an increase or decrease in the film thickness. But, the cumulative effect is a serious problem, because if we now count three fringes over, we cannot determine with certainty, whether this represents a net thickness change of λ or $\lambda/3$ (i.e., $\lambda/3 + \lambda/3 + \lambda/3$ or $\lambda/3 + \lambda/3 - \lambda/3$ or other combinations producing the same net results).

If we make some auxiliary assumptions, we can obtain unambiguously a thickness profile for the film. The first assumption is that a change from increasing to decreasing film thickness and vice-versa is manifested in the fringe pattern by an increase in fringe spacing. This assumption is justified if both the thickness profile and its first derivative are smooth "slowly" varying functions. Therefore, in order for the thickness to change from increasing to decreasing, the derivative must go through zero. The fringe spacing, which is proportional to the derivative, will then increase as the derivative becomes zero.

The second assumption we make is that every time there is an increase in fringe spacing, i.e., every time the derivative becomes zero, the derivative does, in fact, change sign. It would seem that this second condition may be true only half of the time. If the derivative is positive and becomes zero, it is just as likely to become positive again as to become negative. However, it is not always necessary to use this second assumption; often times the fringe patterns contain added information which allow us to determine positively whether the derivative changed sign. When a fringe or set of fringes forms a closed loop, then we can be sure that the derivative has gone through zero and changed sign near the center of such a pattern. When this type of information is lacking, we simply invoke our second assumption and use it as a convention. In this way we obtain an interpretation which is a "reasonable" one, but which may be wrong in certain specific cases. This kind of interpretation is adequate for some purposes, namely, establishing the magnitude of phase errors which can be expected in an optical system from a given combination of film and liquid gate fluid.

The fringe patterns shown in Figures 8 through 11 have been interpreted in this way. First, an arbitrary fringe is selected as a zeroeth fringe or a nominal film thickness. This has been marked in red in the figures. Fringes corresponding to an increasing thickness are marked in green and counted. Fringes corresponding to a decreasing thickness are marked in blue and counted. Everytime a return to a nominal thickness is made, the fringe is again marked in red. Only every third fringe corresponding to changes in film thickness of λ are colored.

From this interpretation, the maximum and minimum film thickness can be found. Using Eq. (1) the peak-to-peak phase error can be computed. In the examples, a xylene liquid gate is assumed for the acetate films, and a freon gate for the estar film.

The smaller thickness variations of the thin estar base film is evident in Figure 11. The crushing of the estar base as it is rolled out in the manufacturing process, is also made visable by the very closely spaced and more regular fringe structure which is superimposed on the more gross fringe structure.

Estar base films exhibit a birefringence amounting to as much as 0.02 change in the index of refraction. This phenomon limits the minimum phase errors which can be obtained with estar base films since phase error due to birefringence cannot be cancelled by a liquid gate. The phase error could be as much as:

$$\Delta \phi_b \leq \frac{2\pi}{\lambda} \Delta n_b t \qquad \text{(birefringence)}$$

$$\leq \frac{2\pi}{\lambda} [0.02] \, 63\mu$$

$$\leq 4\pi$$

It may be possible to use a mixture of xylene and another fluid to obtain an arbitrarily good index match to the acetate base films. In this case the birefringence of the acetate film ($\Delta n = 0.00001$) and the index mismatch of the gelatin emulsion would limit the expected phase errors. Phase errors due to birefringence will be

$$\Delta \phi_b \leq \frac{2\pi}{\lambda} [0.00001]\ 150\,\mu \qquad \text{(acetate birefringence)}$$

$$\leq 0.85^{\circ}$$

In order to estimate the residual phase errors due to thickness variation and index mismatch of the gelatin coating we assume the same percentage thickness variation as was found for the base, i.e.,

$$\Delta t \simeq 7\lambda \; \frac{\text{emulsion thickness}}{\text{total thickness}}$$

$$= 7\lambda \; \frac{6\,\mu}{150\,\mu} = 0.28\,\lambda$$

The index of refraction of gelatin varies somewhat with relative humidity and processing conditions. As a nominal value, at 70% relative humidity, the index of gelatin is 1.50.

Thus, using a gate fluid which is the best possible match to the base, will leave a difference of 0.02 with the gelatin.

$$\Delta\phi \le \frac{2\pi}{\lambda} \Delta t \, \Delta n$$

$$\simeq 2^{o}$$

The phase errors due to the film could thus be reduced to just a few degrees by using a mixture gate fluid. Considerable care would be required in mixing the fluid. It is likely that the phase errors due to the glass gate windows will be larger than the residual errors due to the film.

CD:sd

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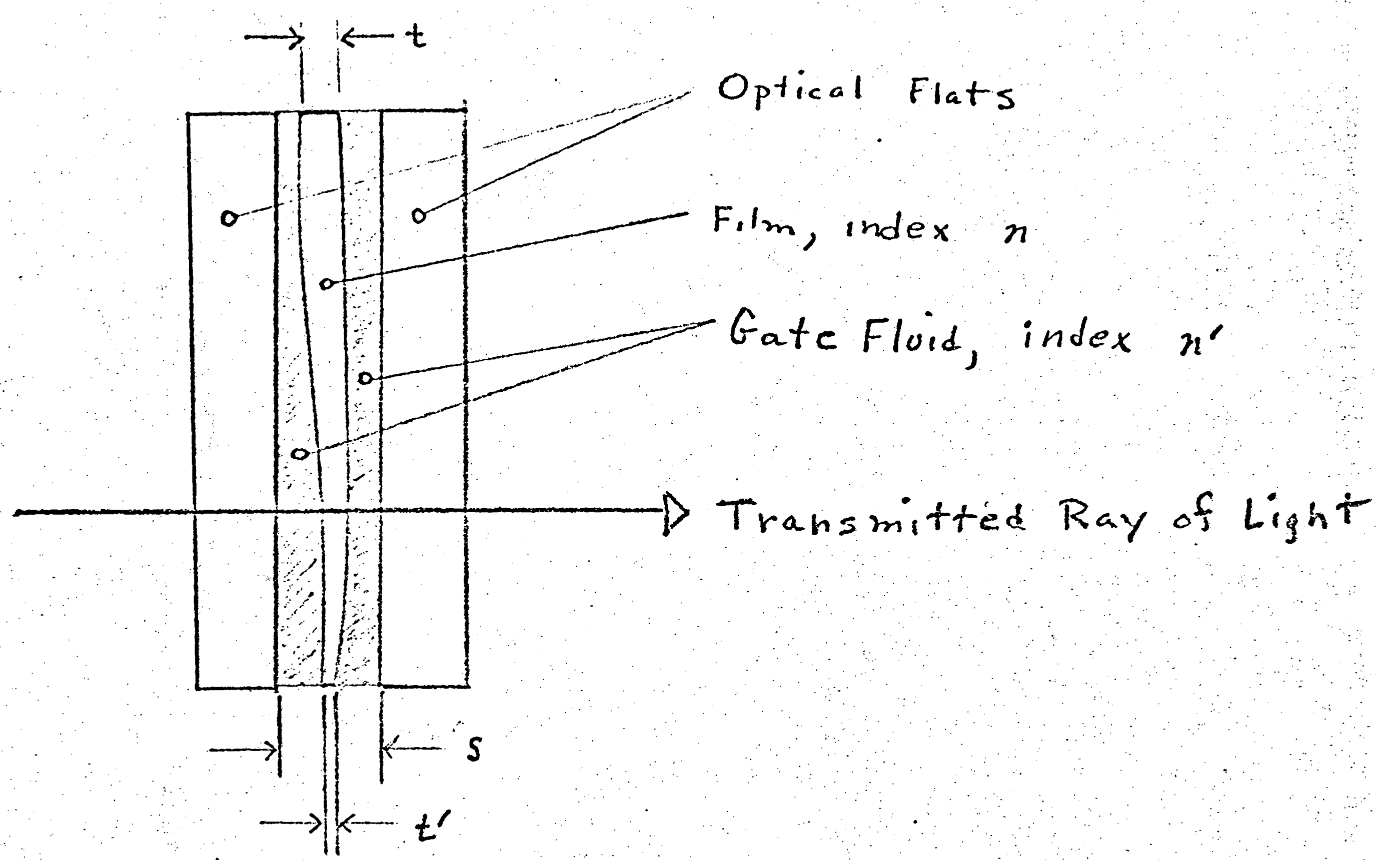

t
Optical Flats
Film, index n
Gate Fluid, index n'
Transmitted Ray of Light
s
t'

FIG 1

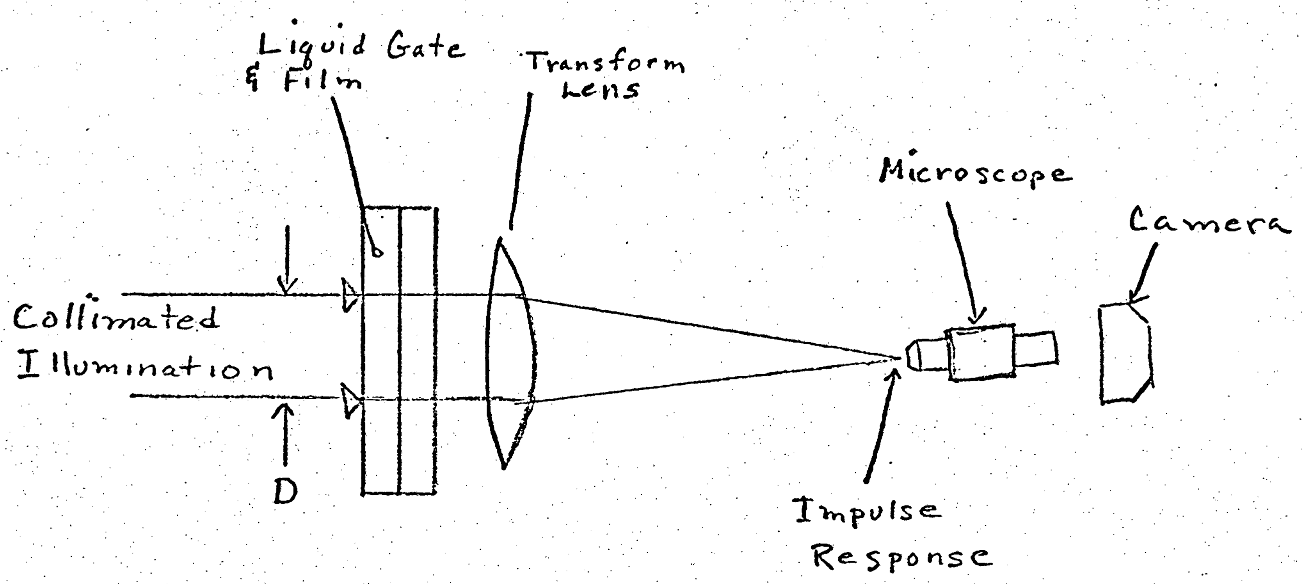

Liquid Gate
& Film
Transform
Lens
Microscope
Camera
Collimated
Illumination
D
Impulse
Response

FIG 2

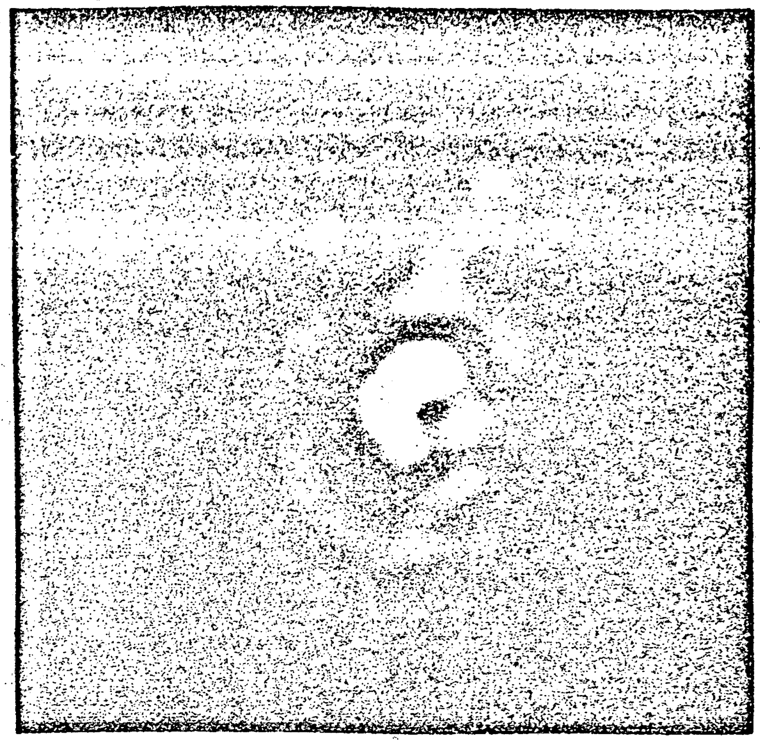


FIG 3

150μ Acetate Film Base
3¼ cm Aperture, $\lambda = 633nm$
No Liquid Gate

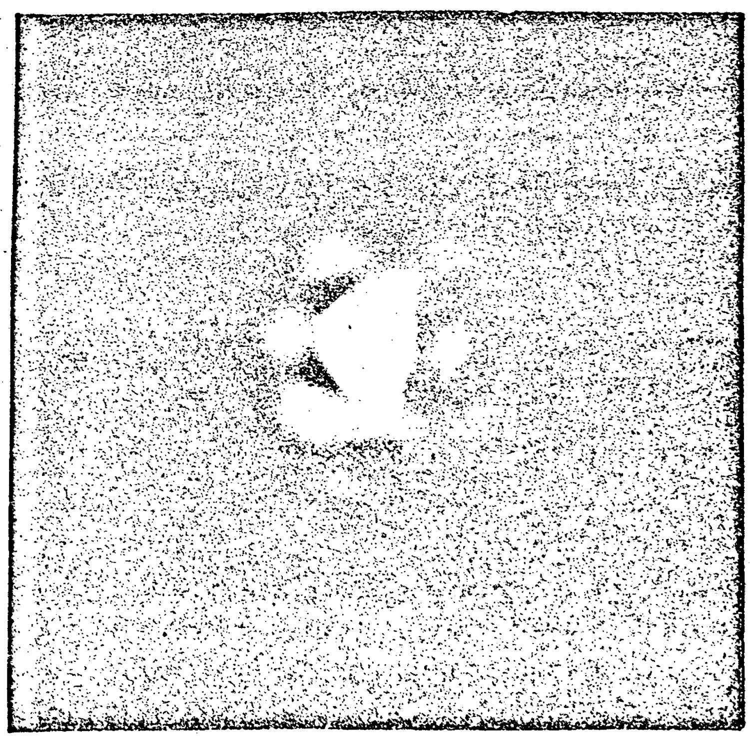


FIG 4

75μ Estar Film Base
3¼ cm Aperture, $\lambda = 633 nm$
No Liquid Gate

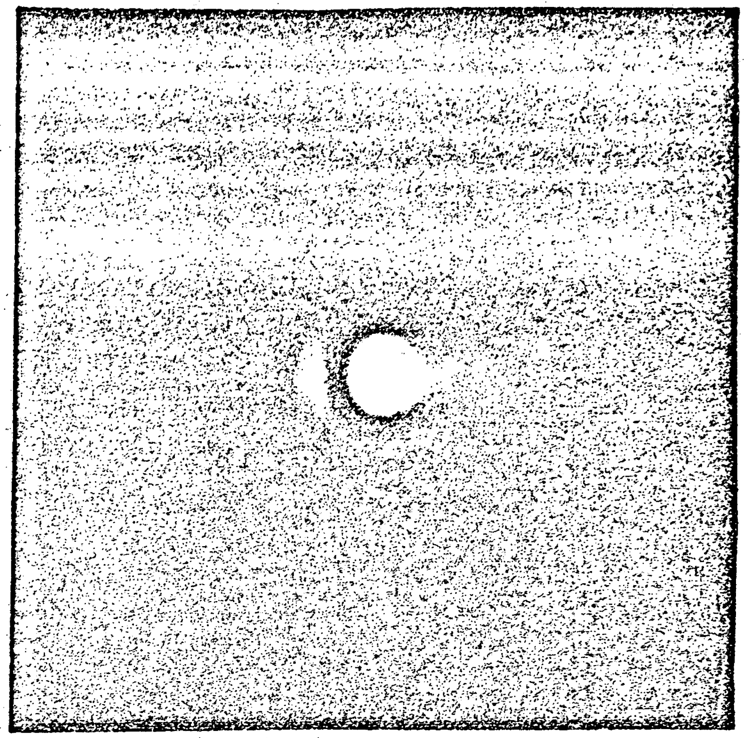


FIG 5

150 μ Acetate Film Base

3¼ cm Aperture, λ = 633 nm

Freon Liquid Gate

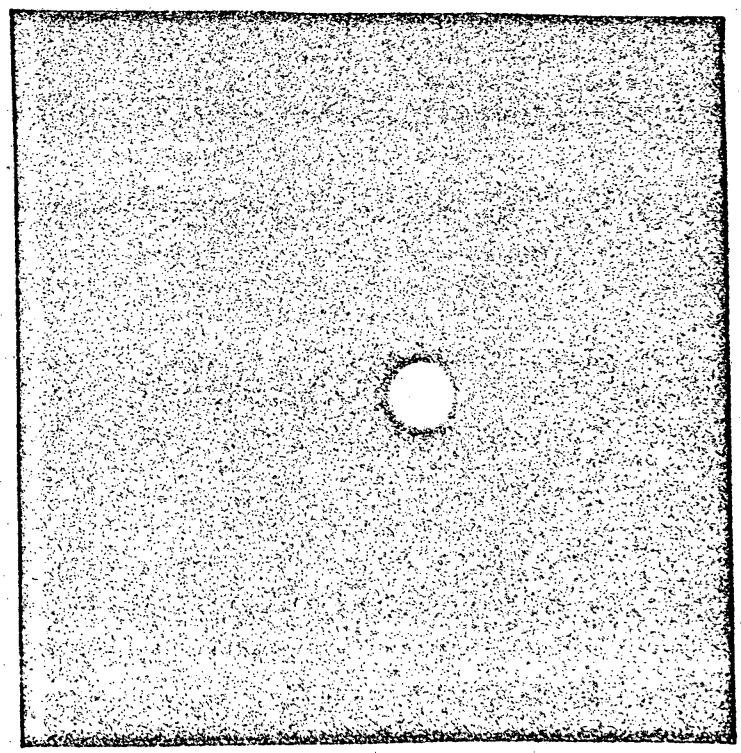
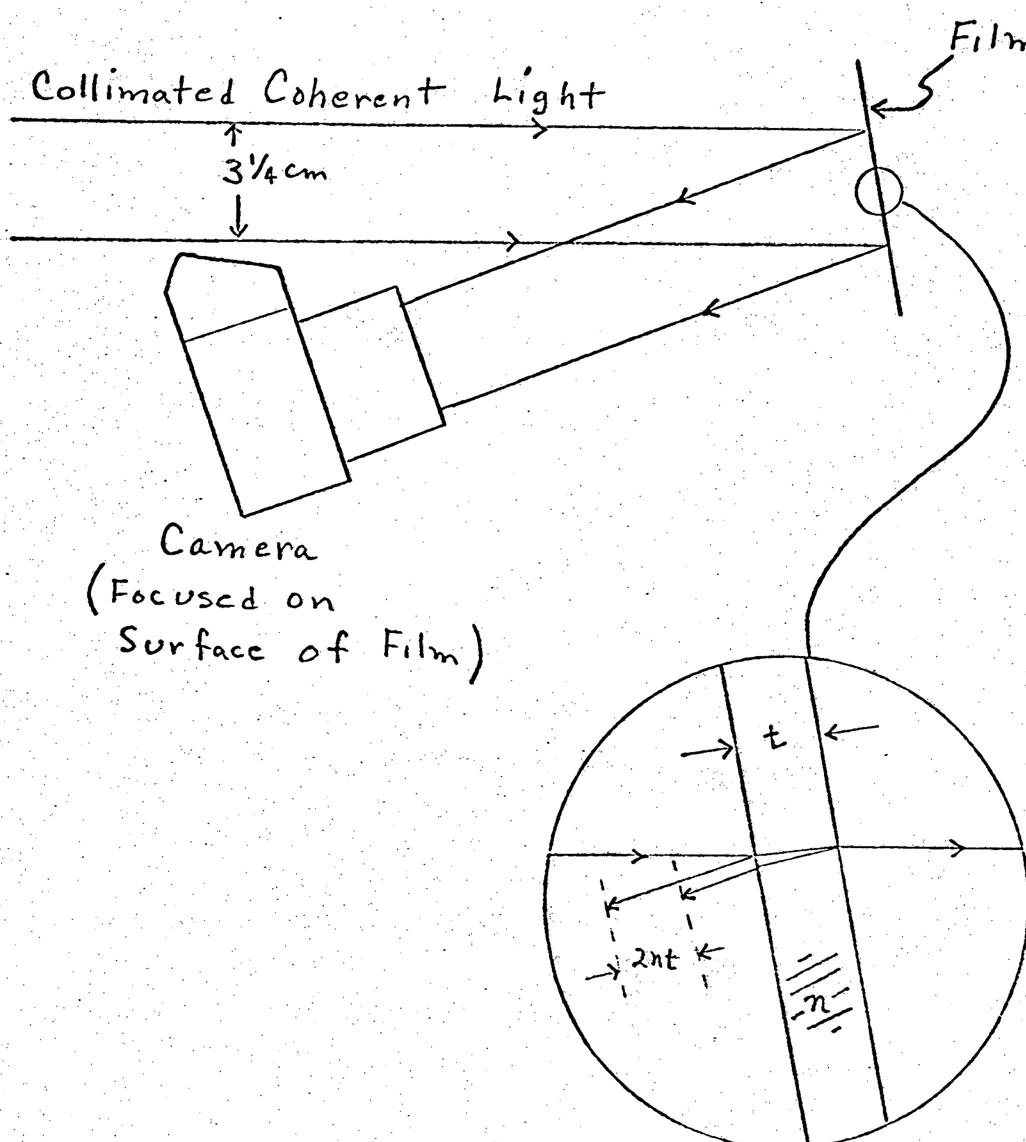


FIG 6

150 μ Acetate Film Base

3¼ cm Aperture, λ = 633 nm

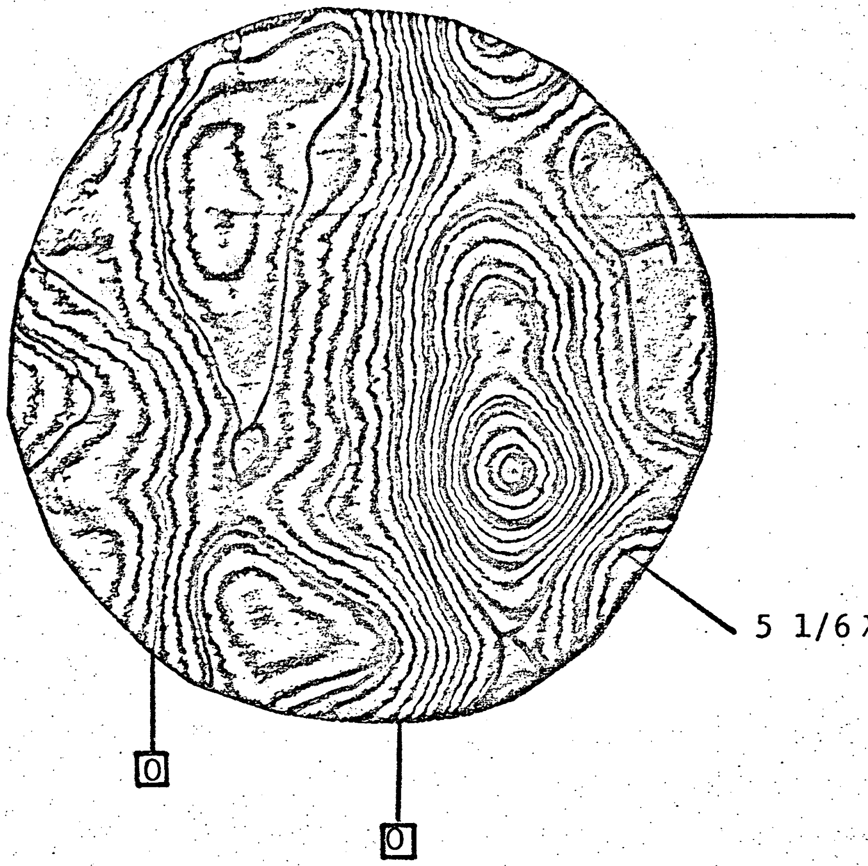
Xylene Liquid Gate



Film
Collimated Coherent Light
3¼ cm
Camera
(Focused on
Surface of Film)
t
2nt
n

FIG 7

EK 5460 Film



$|\Delta t| \leq 7\lambda$

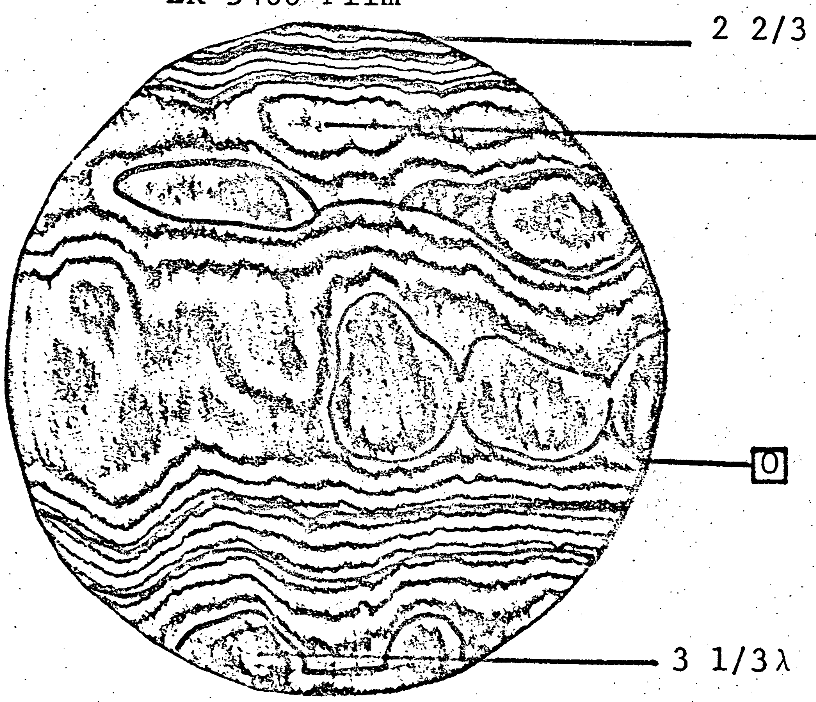
$\Delta\phi = \frac{2\pi}{\lambda}[0.02]7\lambda$

$= 50^{o}$

$= \pm 25^{o}$

Figure 8

EK 5460 Film



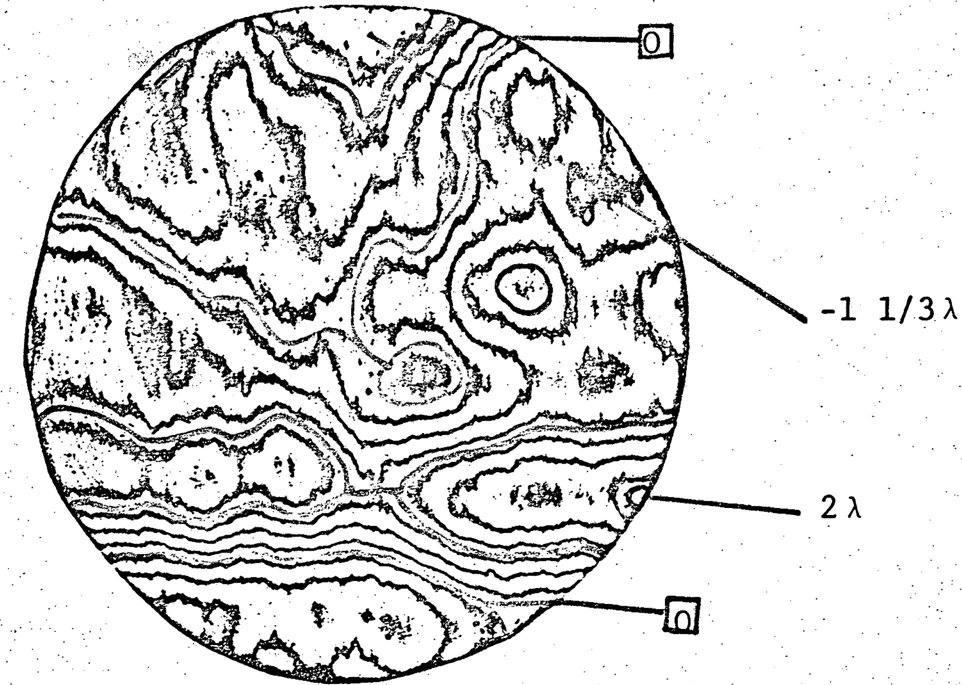
$|\Delta t| \leq 3\ 1/3\lambda$

$\Delta\phi = 24^{o}$

$= \pm 12^{o}$

Figure 9

EK 5460 Film



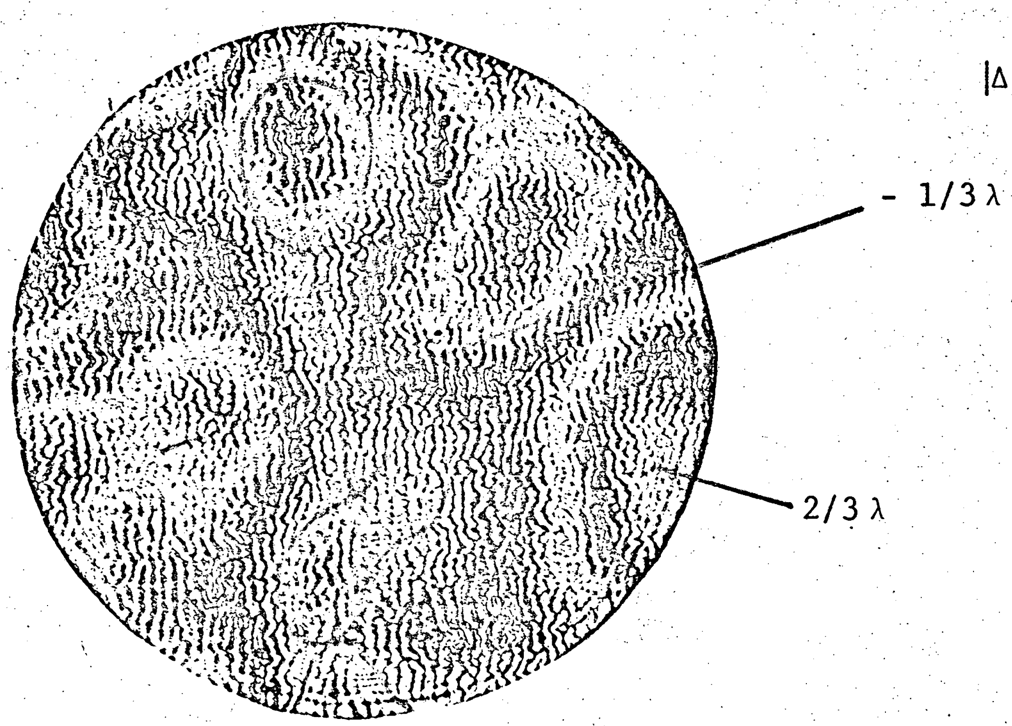
$|\Delta t| \leq 3\ 1/3\lambda$

$\Delta\phi = 24^{o}$ (xylene)

$= \pm\ 12^{o}$

Figure 10

EK 3414 Film



$|\Delta t| \leq \lambda$

$\Delta\phi = \frac{2\pi}{\lambda}\ [0.15]\lambda$ (freon)

$= 54^{o}$

$= \pm\ 27^{o}$

Figure 11