AN AC PHOTOMULTIPLIER FOR MEASURING THE INTENSITY IN THE FRESNEL AND FRAUNHOFER REGIONS OF LIGHT DIFFRACTED BY ULTRASONIC WAVES

Thesis for the Degree of M. S.

MICHIGAN STATE UNIVERSITY

Arthur Jared Crandall

1964

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ABSTRACT

AN AC PHOTOMULTIPLIER FOR MEASURING THE INTENSITY IN THE FRESNEL AND FRAUNHOFER REGIONS OF LIGHT DIFFRACTED BY ULTRASONIC WAVES

by Arthur Jared Crandall

An ac photomultiplier is described which is used to measure the time dependent light modulation caused by a continuous progressive ultrasonic wave of varying beam width. The width of the beam is varied to change the relative amount of amplitude modulation produced by the ultrasonic grating. The ac photomultiplier is also used to measure Fraunhofer diffraction patterns produced by a pulsed progressive ultrasonic wave in a glass block. The photomultiplier has good dc stability, good transient response, 15 Mc frequency response and high sensitivity.

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By

Arthur Jared Crandall

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A. J. C.

TABLE OF CONTENTS

LIST OF FIGURES

I. INTRODUCTION

Lucas and Biquard[1] and Debye and Sears[2] observed in 1932 that light transmitted through ultrasonic waves in a transparent medium produces interference phenomena very similar to those produced by an optical grating. Hiedemann[3] and his co-workers have shown that the "grating" produced by ultrasonic waves can be directly observed. Bachem[4] used a stroboscope to study the "grating" produced by progressive ultrasonic waves. Debye, Sack and Coulon[5] and Bar[6] demonstrated that the "image" of the grating is produced by the interference between the diffraction orders. Hiedemann and Schreuer[7] pointed out that "images of gratings" can always be observed in the Fresnel zone of the grating. Using optical gratings, they demonstrated that the aspect of the interference patterns depends on the plane in which the patterns are observed and that true grating images can only be observed in discrete planes as predicted by Rayleigh[8]. The interference or visibility pattern produced by stationary ultrasonic waves was extensively studied by Nomoto[9], who measured the light intensity distribution in the Fresnel zone. Pisharoty[10], Nath[11] and recently Cook[12] developed theories to describe the Fresnel interference of a sinusoidal phase grating, an arbitrary periodic phase grating and an arbitrary periodic grating, respectively. They used the method of superposition of waves which avoids the use of the complicated Fresnel-Kirchhoff integral.

For many years quantitative measurements of the Fresnel interference of light produced by ultrasonic waves were limited to the case of stationary waves. Colbert and Zankel[13] were the first to make such measurements in the case of progressive ultrasonic wave by using an ac photomultiplier. Later Aron[14] used an ultrasonic stroboscope and a dc photomultiplier. Aron's results agree very well with those obtained by Colbert and Zankel.

The ac photomultiplier described here was developed not only for the purpose of verifying the results of Colbert and Zankel, and Aron, but also for the study of light diffraction by progressive ultrasonic waves in transparent solids.

In solids most measurements of light diffraction by ultrasonic waves were made using standing waves because of the difficulty in obtaining progressive waves in a solid. Two notable exceptions are the measurements by Protzman[15] and by Mayer and Hiedemann[16] carried out in Plexiglas. A progressive wave was obtained by using a long sample of Plexiglas which has very high acoustic attenuation.

In the case of an ultrasonic pulse, when the length of the pulse is small in comparison with the length of the medium, the pulse acts as a progressive wave except near reflecting surfaces. Thus light diffraction by progressive ultrasonic waves in solids can be studied by examining the instantaneous diffraction pattern produced when the sound pulse crosses the light beam. An ac photomultiplier is placed on the particular Fraunhofer diffraction order to be measured and its output displayed on an oscilloscope. Sound intensity measurements may thus be made at any point in a transparent solid except near a reflecting boundary.

The purpose of this investigation is to determine the usefulness of ac photomultiplier techniques for some experimental problems. Two examples are described:

Measurement of the light intensity in the Fresnel zone of an ultrasonic "grating". (Part III)

Measurements of the Fraunhofer diffraction patterns produced by a pulsed ultrasonic wave in a glass block. (Part IV)

II. THEORY

A sound beam consists of periodic condensations and rarefactions of the medium which in turn produce a periodic variation in the refractive index. If a light beam is passed through this "sound grating" in general both phase and amplitude modulation of the light beam occur. If the resulting Fraunhofer diffraction spectrum is observed, the light is found to travel in directions described by

$$\sin \theta_n = \frac{-n\lambda}{\lambda^*}$$

where n is an integer and λ and λ^* the wavelengths of the light and ultrasound, respectively. This is the usual grating equation where the grating spacing is replaced by the ultrasonic wavelength.

The central problem in light diffraction theory is to determine the amplitudes of the light in the various orders. In the case of Fresnel interference, one is then concerned with the way in which the light traveling in these different directions interferes to produce the Fresnel pattern.

Consider the interaction of a monochromatic plane light wave and a sinusoidal, progressive, plane sound wave (Fig. 1). Let the light travel in the z direction and the sound in the x direction.

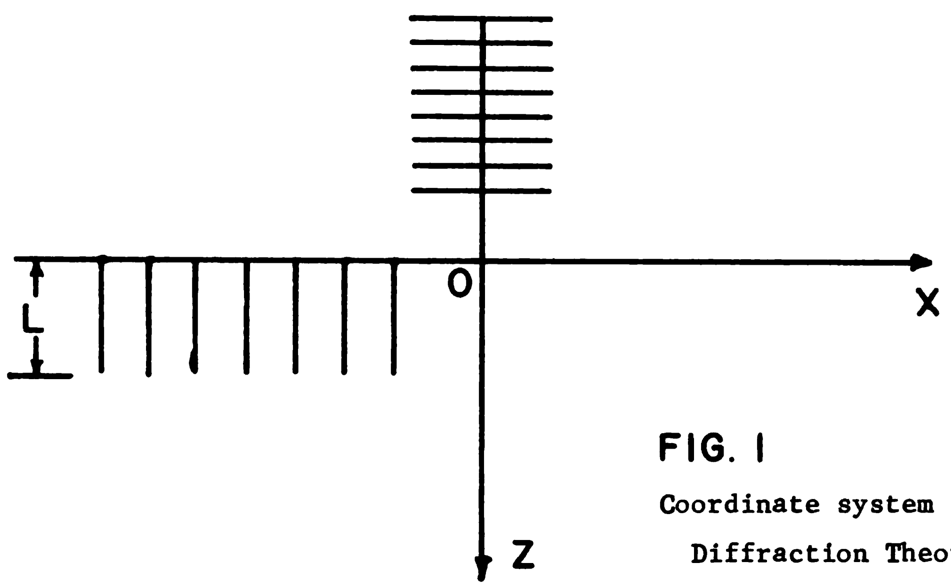


FIG. I

Coordinate system
Diffraction Theory

Let k and ω and k^* and ω^* be the wave numbers and the circular frequencies of the light and ultrasound, respectively. The index of refraction of the medium can be expressed as

$$\mu(x,t) = \mu_o + \mu\sin(k^* x - \omega^* t)$$

where μ_o is the index of refraction of the undisturbed medium and μ is the maximum variation of $\mu(x,t)$. The time dependence of this wave will be neglected because the sound beam appears stationary with respect to the time for light to travel the distance L through the sound beam. Then the wave equation can be written in the form

$$\nabla^2\psi - (\mu(x,t)/c)^2 \frac{\partial^2\psi}{\partial t^2} = 0 \qquad (1)$$

Since ψ is independent of y,

$$\frac{\partial^2\psi}{\partial x^2} + \frac{\partial^2\psi}{\partial z^2} - \frac{\mu_o^2 + 2\mu_o\mu\ \sin(k^* x - \omega^* t)}{c^2} \frac{\partial^2\psi}{\partial t^2} = 0 \qquad (2)$$

where the term in μ^2 is neglected because of the smallness of $\mu(\sim 10^{-5}\mu_o)$.

The light amplitude $\psi(x,z,t)$ can be expanded in a fourier series in x and t.

$$\psi(x,z,t) = e^{i\omega t} \sum_n \varphi_n(z) e^{ik\mu_o z} e^{in(k^* x - \omega^* t)} \qquad (3)$$

By substituting eq. (3) into eq. (2), comparing coefficients of $e^{in(k^* x - \omega^* t)}$ and neglecting second order terms in smallness one obtains the difference differential equation:

$$\frac{d\varphi_n}{dz} + \frac{v}{2L}(\varphi_{n-1} - \varphi_{n+1}) = \frac{-in^2 q}{2L}\varphi_n \qquad (4)$$

where $v = k\mu L$ and $q = \frac{k^{*2} L}{\mu_o k}$. The parameter v is sometimes referred to as the Raman-Nath parameter. From this difference-differential equation combined with the initial conditions

$$\varphi_o(0) = 1$$
$$\varphi_n(0) = 0 \qquad n \neq o$$

the $\varphi_n(v)$'s, which are the light amplitudes in the various diffraction orders, are obtained. The light intensity in the nth diffraction order is

$$I_n = \varphi_n^* \varphi_n$$

Raman and Nath[17] have shown that the solutions to eq. (4) reduce to Bessel functions $J_n(v)$ of order n and argument $v = \mu kL$ for the case where the right hand side is negligible. Experimentally this condition is adequately satisfied if $q < 0.2$ and $qv \leq 2$.

Cook and Klein* have programmed the Control Data 3600 computer to integrate eq. (4) numerically for various values of q and v. As can be seen this results in complex φ_n's.

For the pulse optical measurements in glass the experimental conditions are such that $q \sim 10^{-2}$, and thus the solutions of eq. (4) can be taken to be the Bessel functions, the $J_n(v)$. The intensity of the nth order is $I_n(v) = J_n^2(v)$.

For the visibility measurements, Bessel functions will also be used as the solutions, although $q \sim 0.1$. For the grating visibility pattern Cook and Klein's* solutions will be used for a comparison between the predicted amplitude modulation and that observed.

*Private communication.

Fresnel Interference Patterns

Hiedemann and Breazeale[18] have discussed Fresnel interference patterns for several types of gratings.

In the present investigation the ultrasonic wave served as a grating. The Fresnel interference pattern or visibility pattern is the intensity distribution of the light after passing through the sound beam (Fig. 2). The sound travels in the x direction and initially the light travels in the positive z direction. After passing through the sound beam the light may be considered as consisting of a number of plane waves AA' traveling in the directions θ_n. At a particular point in space the intensity of the light is the resultant of all of these partial waves. In this experiment a progressive ultrasonic wave is used so that the visibility pattern moves in space along with the sound wave, like a shadow.

One way of observing this pattern is to use stroboscopic light which "freezes" the motion of the visibility pattern. Aron[14] used an ultrasonic stroboscope and then observed the intensity distribution with a dc photomultiplier. He moved the photomultiplier in the z direction to obtain different visibility patterns for the same

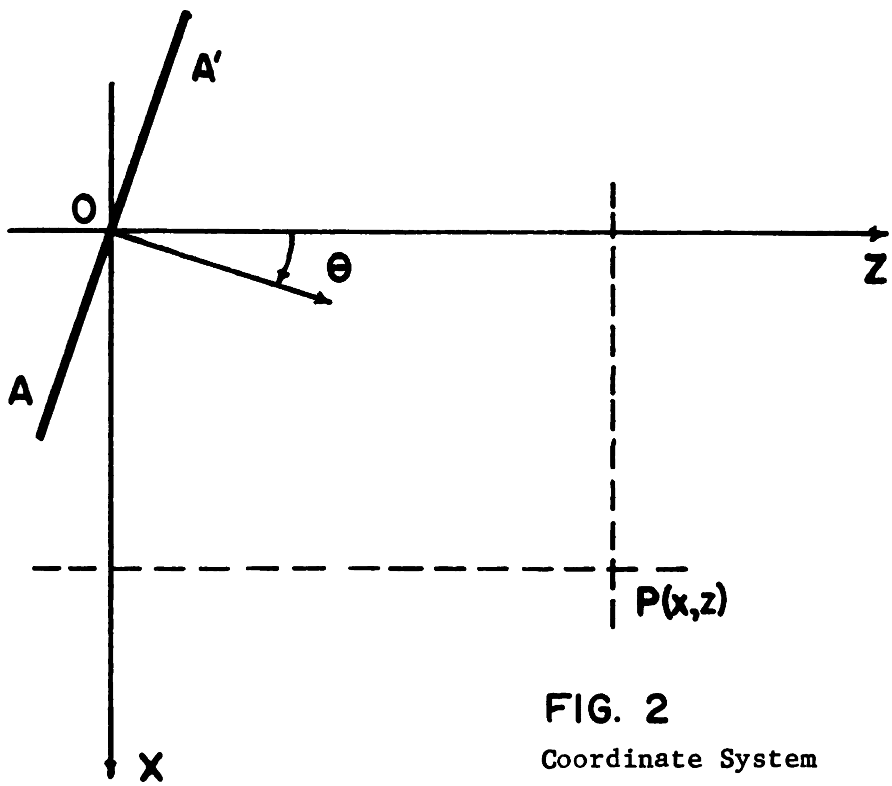


FIG. 2
Coordinate System
Interference Patterns

wave, and moved the photomultiplier in the x direction over several sound wavelengths to record a particular visibility pattern.

The ac photomultiplier used in this experiment was located at a given x and z position. Since the interference patterns moved with the sound wave, the photomultiplier received a time varying intensity distribution which could be displayed on an oscilloscope.

The Fresnel interference pattern (visibility pattern) at a point P(x,z) (see Fig. 2) was calculated[12] by summing the contributions from each partial wave of amplitude φ_n traveling in the direction $\Theta_n = -\sin^{-1}(n\lambda/\lambda^*)$.

The contribution of φ_n at P(x,z) is $\varphi_n \exp(-ik(x\sin\theta_n + z\cos\theta_n))$.

Using the approximation for small θ_n, $\sin\theta_n = -n\lambda/\lambda^* = \frac{-nk^*}{k}$,

$\cos\theta_n = 1 - \frac{1(nk^*)^2}{2(\;k\;)^2}$ and summing all the contributions

$$A(x,z) = e^{i\omega t} \sum_{n=-n_{max}}^{n\,max} \varphi_n \exp(ink^*x - ikz + \frac{in^2k^{*2}}{2k} z) \quad .$$

Then the intensity at P(x,t) is AA^*, that is,

$$I(x,z) = AA^* = \left| \sum_n \varphi_n \exp(ink^*x + \frac{in^2z}{D} \right|^2 , \tag{5}$$

where $D = 4\pi\, k/k^{*2} = \frac{2\lambda^{*2}}{\lambda}$ is the "true" repetition distance, that is

$$I(x,z) = I(x,z+D). \tag{6a}$$

An additional periodicity may be expressed as

$$I(x,z) = I(x+\lambda^*/2\;,z+D/2) \tag{6b}.$$

These two relationships may be verified by substitution into eq. (5) for the intensity.

Equation (6a) indicates that in the Fresnel field a pattern at distance z will repeat itself exactly at the same x coordinates at distances z+D. Equation (6b) predicts an identical pattern at

distances z+D/2, but at this distance the pattern will be shifted[14] by a distance $\lambda^*/2$.

The Control Data 3600 computer has been programmed to calculate the light intensity distribution of the interference pattern from eq. (5). The results predict that the visibility patterns at some positions in space become very complex for larger values of v. For example, for a v of 1.5 there are as many as three peaks and troughs per wavelength in the sound direction. For a v of three there are up to five peaks and troughs per wavelength.

III. MEASUREMENTS IN THE FRESNEL FIELD

The Fresnel interference pattern (visibility pattern) caused by an ultrasonic wave is of low intensity because the measurements are made in the collimated light beam. For a progressive ultrasonic wave these patterns move past the photomultiplier with the velocity of the ultrasonic wave. In order to resolve the detail of the visibility pattern, a photomultiplier must have high sensitivity and a frequency response broad enough to record the details of the pattern. For example, for a two Mc sound beam of intensity $V= 3$ a frequency response to 15 Mc is required. As the amount of detail in the interference pattern is increased, in order to resolve it, both the frequency response and the sensitivity of the photomultiplier must be increased. The latter follows from the requirement that the photomultiplier slit must be narrow in comparison with the width of the detail.

The photomultiplier circuit must maintain the wide-band high gain characteristics of the photomultiplier tube. The circuits used are shown in Figs. 3 and 4. The circuit will be described in more detail in the section on Pulse Optical Measurements.

Both 931A and 1P21 photomultiplier tubes were used. The 1P21 had greater sensitivity and was used for the majority of the measurements.

The value of R_L was adjusted to $200\,\Omega$ to match the impedance of the Hewlett Packard wide band amplifiers although the adjustment is not critical. The cascaded amplifiers were directly connected to the oscilloscope terminated by a $300\,\Omega$ resistance.

The sweep of the Tektronix oscilloscope was synchronized with the rf voltage applied to the transducer matching circuit. The signal for this purpose is obtained with a one turn pickup coil coupled to the impedance matching circuit.

Two light sources were used. One was a dc mercury arc. The other was an ac mercury arc whose light output varied as the ac voltage across the tube. A General Radio unit pulser was used to modulate the z axis of the oscilloscope when this ac source was used. The pulser would cause the oscilloscope trace to appear only when the light source was at maximum intensity.

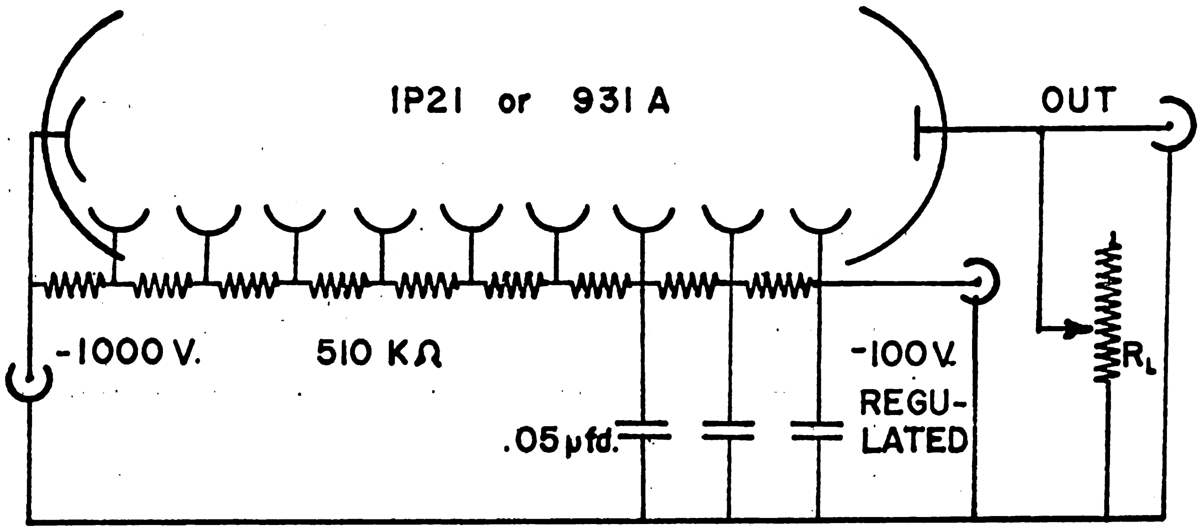


FIG. 3. PHOTOMULTIPLIER CIRCUIT

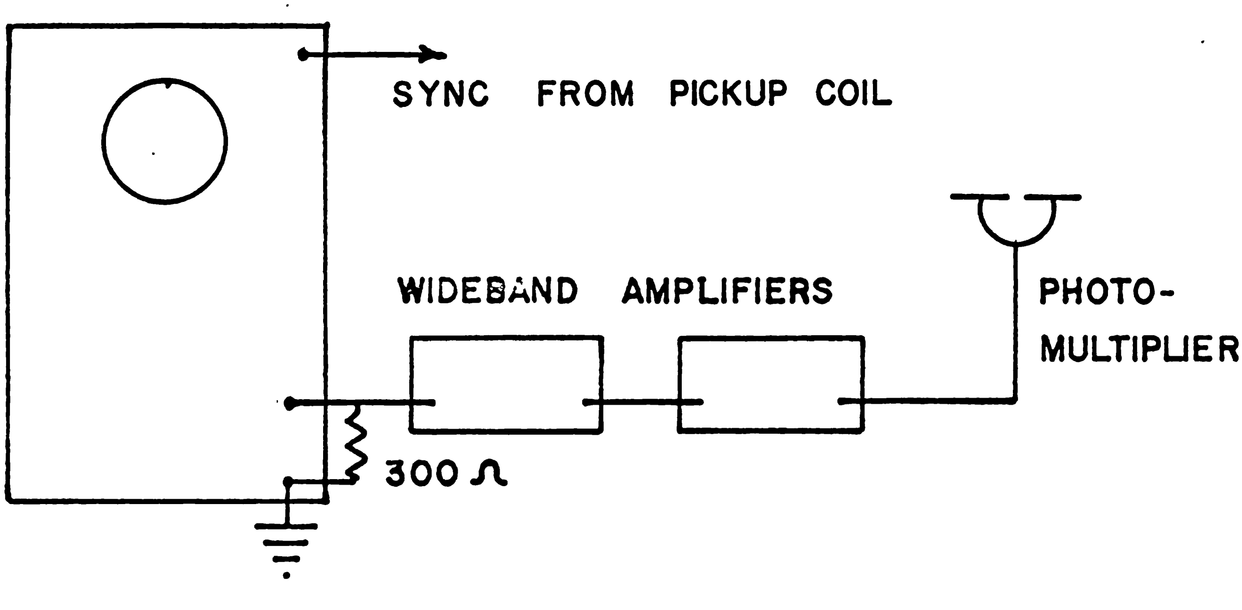


FIG. 4. VISIBILITY MEASUREMENT CIRCUIT

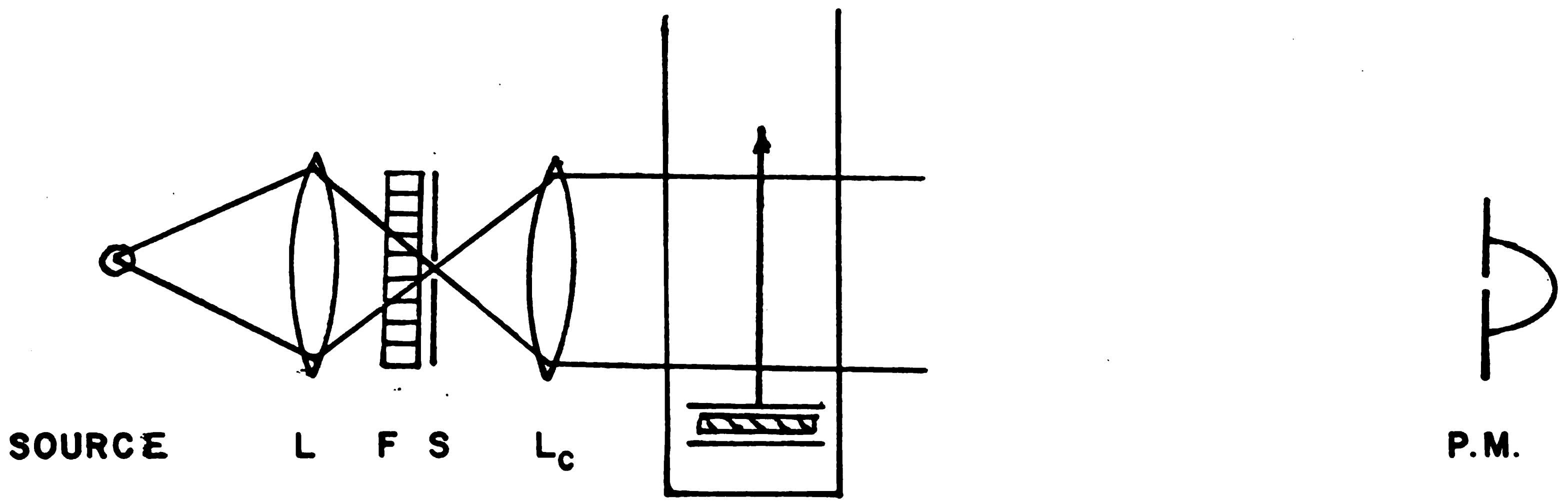


FIG. 5 OPTICAL ARRANGEMENT

A standard optical arrangement shown in Fig. 5 was used. An Osram HBO 100 W/2 high pressure percury arc (dc) and a GE H 100 A4 mercury arc (ac) were used as light sources S. The Osram HBO 100 W/2 lamp has a very high pressure, concentrated arc which tends to be unstable in most of the lamps tried. The arc rotates around the electrodes changing the amount of light passing through the source slit S_1. The GE H 100 A4 lamp has a moderately low pressure discharge contained in a large envelope. This discharge is very steady and is found to have less random fluctuation in intensity than the Osram lamp. A green filter F selects the mercury 5460 Å line.

The source slit and the collimating lens L_c control the angular spread in the light beam. With a short focal length lens and wide slit the angular spread will be large. This spread must be a small fraction of a sound wavelength at the photomultiplier location or the visibility pattern will be smeared out. This effect becomes more pronounced as the photomultiplier is moved away from the sound beam. The source slit should be narrowed and a collimating lens of sufficient focal length selected consistent with adequate illumination.

The tank contains water and has a castor oil termination to insure progressive waves.

The sound beam intensity may not be uniform in space. In order to obtain visibility patterns of constant "v" a schlieren system was used to observe the homogeneity of the sound beam. Then an aperture A about 2 cm in height selected the most homogeneous part of the sound beam.

Two air backed quartz transducers were used. The quartz plates were 5.08 cm in diameter with electrodes made of silver print. Variation of the width of the electrode allowed the width of the sound beam to be changed. The transducer used for the visibility patterns was driven on its fundamental frequency, 1.74 Mc. In order to increase the parameter q a second transducer was used. It had a nominal fundamental frequency of 1 Mc and was used on its third harmonic at 3.05 Mc.

A Variac was used to vary the rf voltage applied to the transducer. The Variac allowed voltage changes in small but discreet steps only. The accuracy in setting the voltage to a predetermined value was thus limited to at most $\pm$ 1.5% of the maximum possible value.

Values of v were obtained either from diffraction measurements or from comparison of the observed visibility patterns with theoretical predictions. A comparison showed the results of the two methods to be equivalent within experimental error.

Typical visibility patterns are shown on the following pages. One can see the increase in complexity of the patterns as v is increased from $\pi/2$ to π. These values were used for comparison with the results of Colbert and Zankel[13]. The theoretical calculation for v=3.15 is shown for comparison. The curves agree remarkably well. Some asymmetries were observed. In these cases it was often traced to the tendency for the electronic circuits to ring.

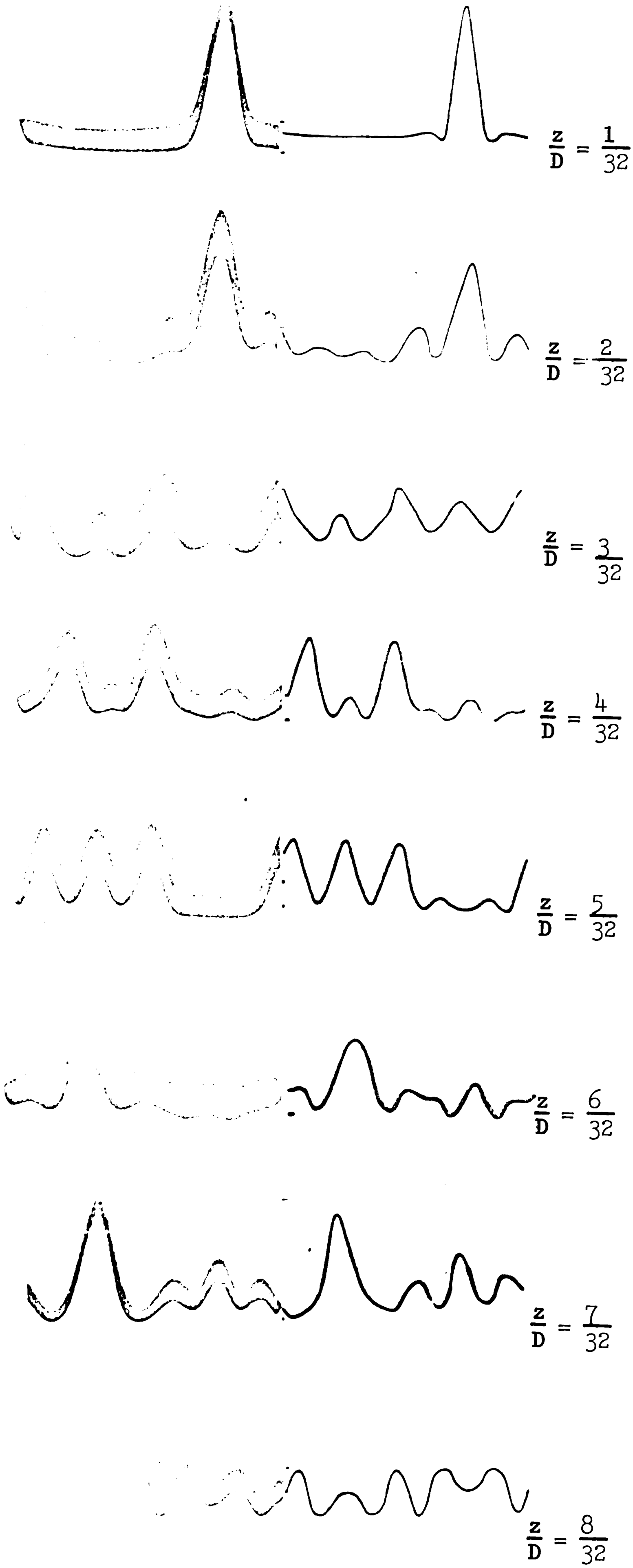
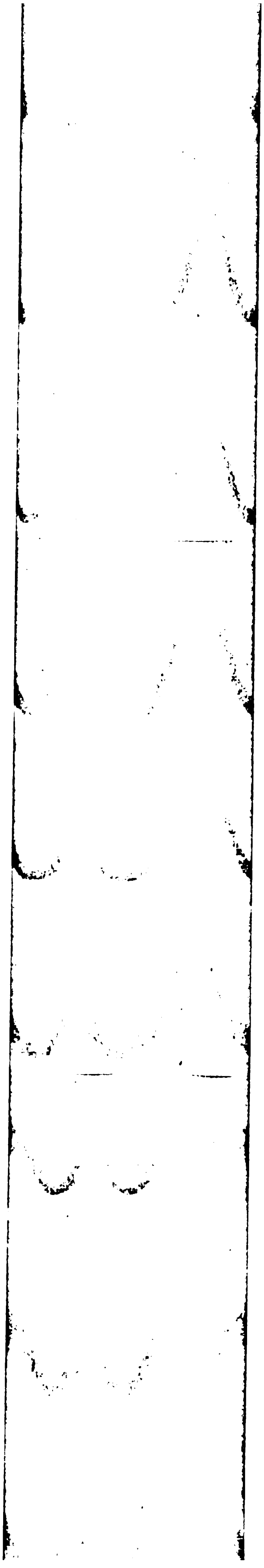


Fig. 6a

Visibility Patterns for a sound intensity $v = 3.15$. **Experimental oscilloscope traces and theoretical curves.**



$\frac{z}{D} = \frac{1}{32}$

$\frac{z}{D} = \frac{2}{32}$

$\frac{z}{D} = \frac{3}{32}$

$\frac{z}{D} = \frac{4}{32}$

$\frac{z}{D} = \frac{5}{32}$

$\frac{z}{D} = \frac{6}{32}$

$\frac{z}{D} = \frac{7}{32}$

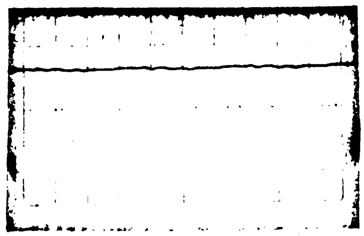
$\frac{z}{D} = \frac{8}{32}$

$\frac{z}{D} = \frac{9}{32}$

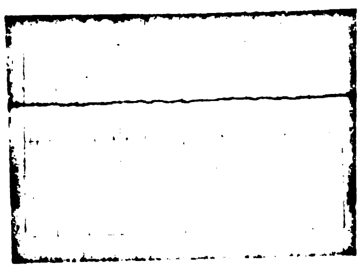
Fig. 6b

Visibility Patterns for a sound intensity $v=\pi/2$.

Fig. 7 Visibility patterns at the sound beam.



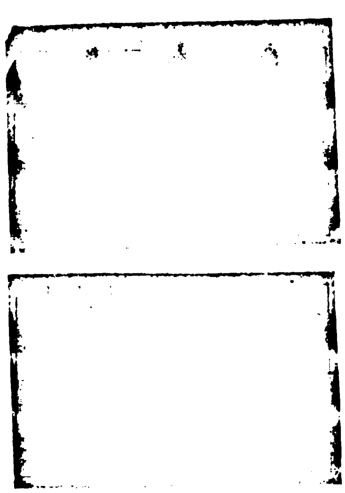
a) Pattern a repetition distance D from the exit plane for $v = 2.4$ and $Q = 0.45$.



b) Same conditions as in (a) but with the photomultiplier moved slightly to observe minimum amplitude modulation.

c) Theoretical pattern at exit plane for $v = 3$ and $Q = 0.57$.

d) Theoretical pattern for minimum amplitude modulation at $z = \frac{-3}{8} L$. The amplitude is three times its normalized value to show detail.



e) Patterns for $Q = 0.15$ at a distance D/2 from the center of the transducer ($v = 10$), and minimum amplitude positions for $v = 10, 8, 6, 4,$ and 2 in that order.

IV. PULSE MEASUREMENTS

A. Optical Arrangement

The optical system is the same as that used in the visibility measurements (Fig. 3) with the addition of lens L_f and a polarizer located just in front of the photomultiplier slit. Sound waves produce birefringence in the case of an isotropic transparent solid. However, the Raman-Nath theory can still be applied if one uses plane polarized light whose direction of polarization is either parallel to or normal to the direction of sound propagation. The ac light source was used because of its superior stability. The source slit is adjusted so that the width of its image at the photomultiplier slit is approximately 1/3 the spacing between adjacent diffraction orders. The photomultiplier slit is adjusted to be the same width as the source slit image. This arrangement allows maximum light transmission with a minimum of stray light.

B. The Ultrasonic Beam

For a continuous wave the homogeneity of the sound beam may be readily examined with a schlieren technique. Since the pulse duty cycle in this experiment is approximately 10^{-3}, one cannot observe a schlieren picture. One could try to use a time-exposure photograph but this would give an average of all the transits of the sound pulse before decaying.

By reducing the dimensions of the aperture and using different portions of the sound beam to produce a diffraction pattern one can obtain a good estimate of the homogeniety of the sound field. If the diffraction pattern remains constant in the region investigated for a fixed transducer voltage, this region is probably homogeneous.

After finding the most homogeneous part of the sound beam near the transducer the dimensions of the aperture were increased in order to allow adequate light to pass and still select a reasonably homogeneous portion of the sound field. The resultant aperture dimensions were about 2mm x 4mm.

In this experiment the medium was a 1"x1"x8" glass block of type EDF-1. The transducer was mounted so that the light traveled parallel to its 1" dimension.

C. The Photomultiplier Circuits

For pulse-optical measurements, that is measurements of the light diffraction pattern of a pulsed ultrasonic wave, the photomultiplier requirements of sensitivity and frequency response still hold. Dc stability was an additional requirement. When pulse optical measurements are made in solids, the sound pulse must be short compared to the pulse travel time in the solid. For a 3cm cube of glass the transit time is 6 μsec. So that the sound pulse should be on the order of 1 μsec long, a photomultiplier risetime of 0.3 μsec is necessary. The pulsed oscillator used here had a risetime of 0.5 μsec. Therefore a much longer sample had to be used. This also allowed longer pulses of 3 -10 μsec which was much longer than any photomultiplier risetime.

The basic photomultiplier circuit is shown in Fig. 3. In making measurements of zero order light intensity all of the light is in the central order except for that brief portion of the time, when the sound pulse crosses the light beam. Conversely in measurements of the higher diffraction orders the photomultiplier receives light only when the sound pulse crosses the light beam. The differences in the average current in the photomultiplier circuit associated with these different average light intensities produce unequal sensitivities of the system unless the dc voltage between the last dynode and the anode is well regulated. In addition the 0.05 μf capacitors C stabilize the voltages on the dynodes where the dynode current becomes appreciable.

The 931 photomultiplier tube was used in spite of its reduced sensitivity since its maximum anode current may be greater than the maximum anode current for the 1P21. This allowed a smaller value of the shunt resistor R_L for the same voltage to the oscilloscope. The value of R_L is practically dictated by the gain of the oscilloscope. The rise time and sensitivity of the photomultiplier circuit decrease with decreasing values of the load resistance. In order to obtain as fast a rise time as possible at a given sensitivity the gain of the oscilloscope was set at the maximum and the value of the load resistance was set to give full scale deflection of the oscilloscope for full light intensity.

The phase shifter (R.L.C. circuit) shown in Fig. 8 is used to trigger the General Radio 121-A unit pulser at the moment when the source light intensity is maximum. The unit pulser triggers the Tektronix 515A oscilloscope and the Arenberg PG 650 pulsed oscillator every 1/60 sec. This pulse repetition rate allows ample time for the sound pulse to decay. The unit pulser also produces a variable length 1-50 μsec square negative pulse which modulates the pulsed oscillator. An impedance matching circuit connects the output of the pulsed oscillator to the 1"x1/2" barium titanate 5 Mc transducer which is attached to the end of the glass block. Lens L_f focuses the various diffraction orders on the plane of the photomultiplier slit. The light pulses are detected by the photomultiplier and displayed on the oscilloscope. Inserting a small capacitor across the output terminals of the photomultiplier reduced the high frequency fluctuations caused by the source (Fig. 10abc). The capacitor and load resistor R_L were of such a size that the rise time increase was only slightly perceptible in the oscilloscope trace. The rf pulse to the transducer is displayed through the second input.

D. Results

Typical measurements of the zeroth and first diffraction orders appear on the following page (Fig. 9). Higher orders were also measured but are not included. All of the measurements indicate that the Raman-Nath theory is applicable under the experimental conditions used.

No significant asymmetries were observed in the diffraction spectrum.

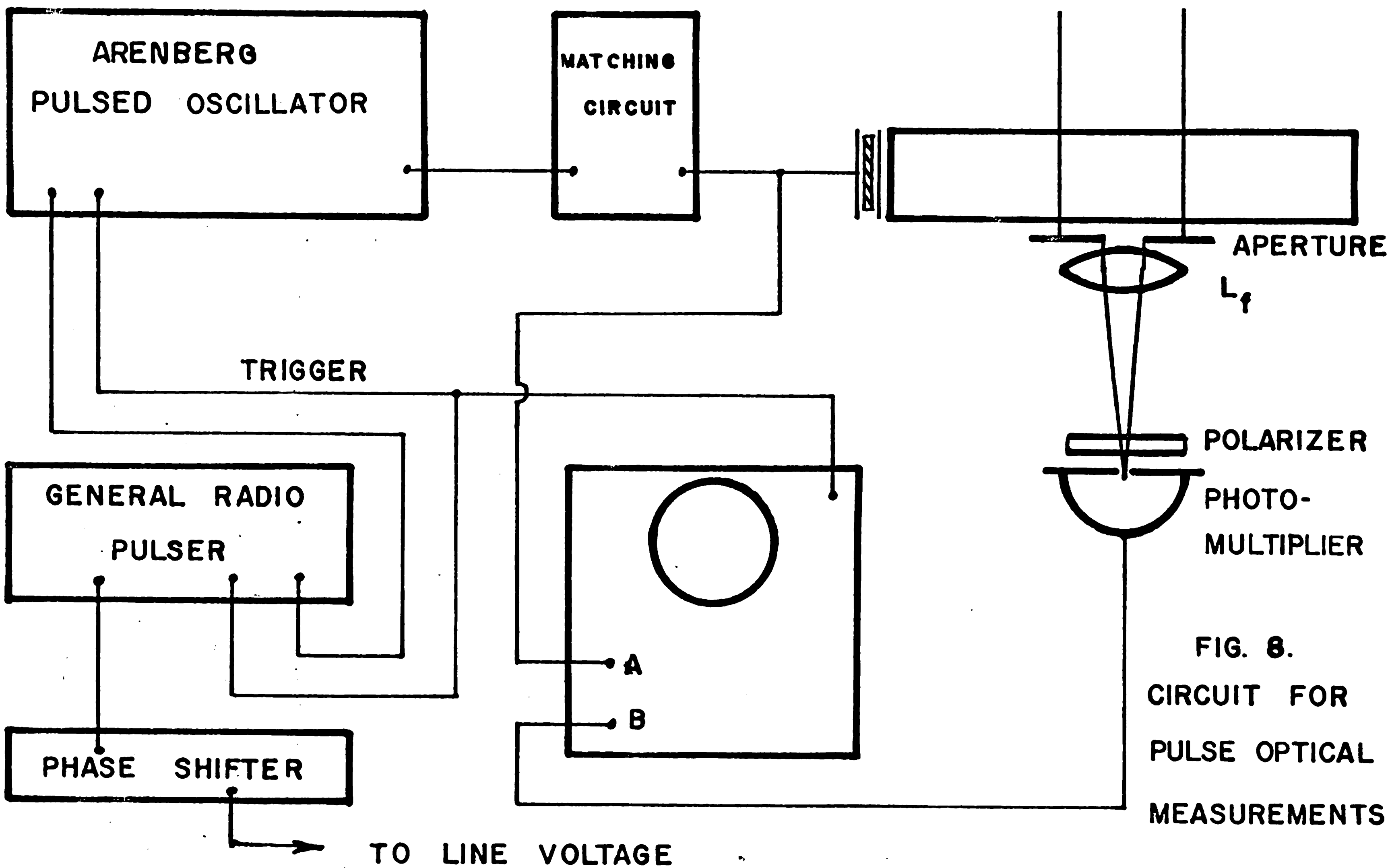


FIG. 8.
CIRCUIT FOR
PULSE OPTICAL
MEASUREMENTS

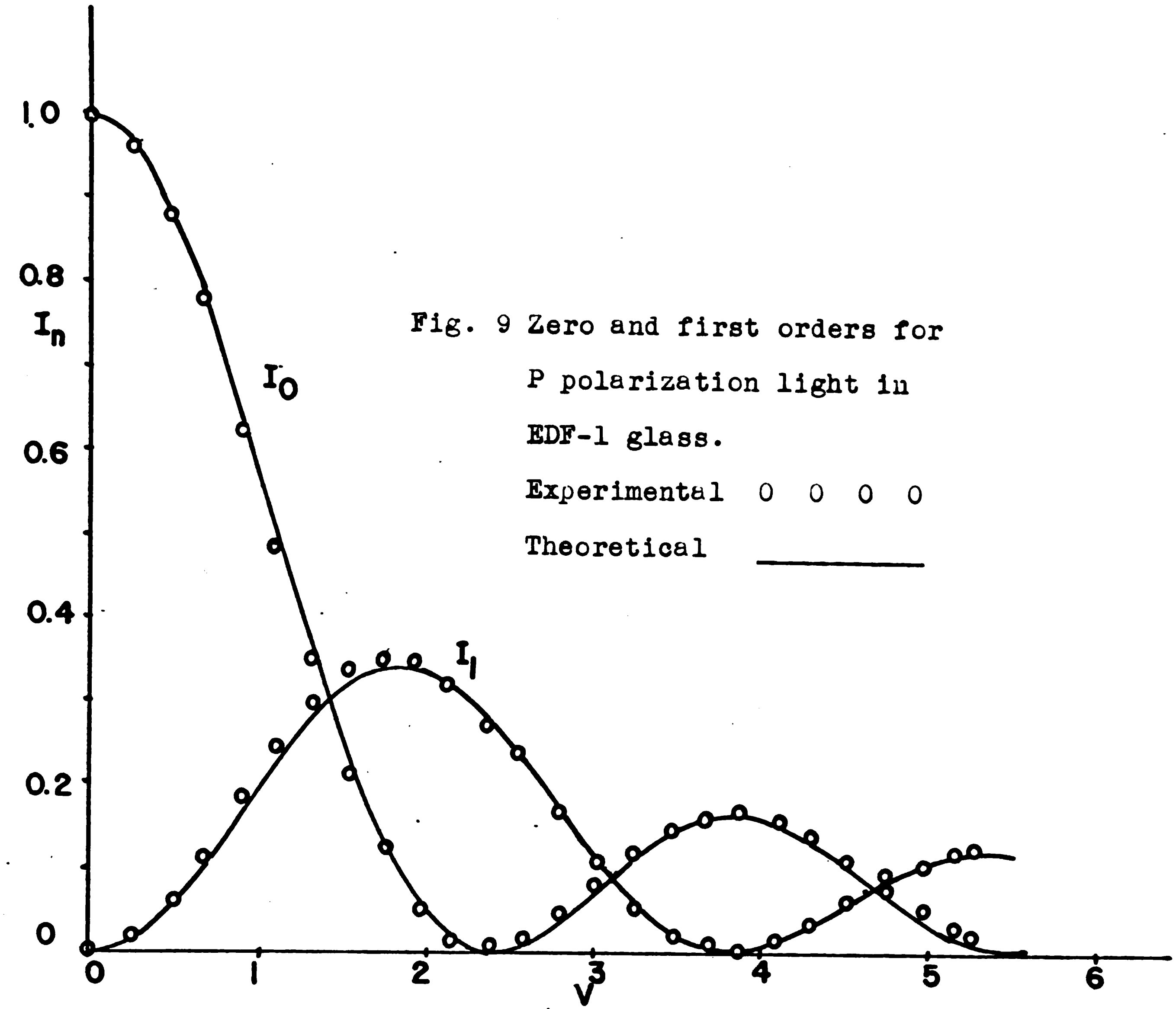
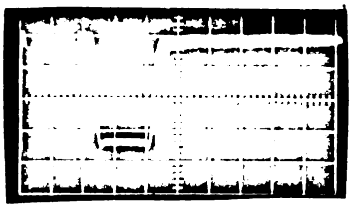


Fig. 9 Zero and first orders for P polarization light in EDF-1 glass.

Fig. 10 Oscilloscope traces from pulse optical measurements. Pulse length 10 μsec.



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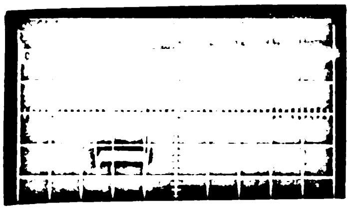

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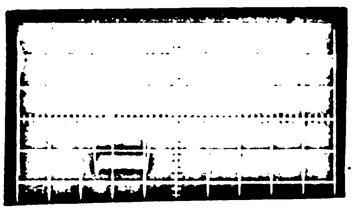


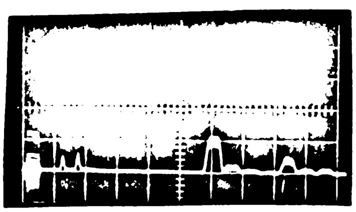
c

a,b,c Zero order measurement (first maximum) showing the effect of additional capacitance on noise and risetime.

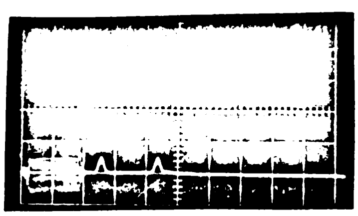
a) 500 $\mu\mu$fd.

b) 200 $\mu\mu$fd.

c) none.

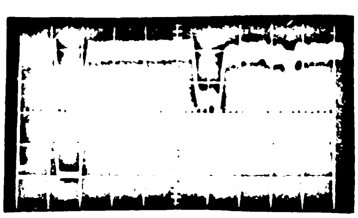


d

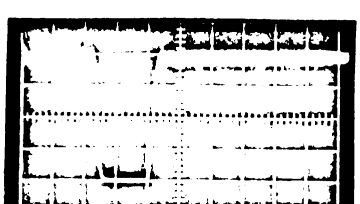


e

d,e First order (first minimum) showing two echoes (d) and scale expanded (e).



f



g

f,g Zero order (first minimum) showing two echoes (f) and scale expanded (g).

V. RESUME

The ac photomultiplier proves to be a useful research tool for measurements of the optical effects caused by ultrasonic waves in solids and liquids.

Visibility patterns may be used to determine sound intensities with a precision comparable to diffraction pattern measurenents. A set of calculated visibility patterns for various values of v and z must be on hand in order to compare these curves with those on the oscilloscope. This proceedure is more difficult than the deffraction pattern technique where one only measures one diffraction order with a dc photomultiplier.

Sound velocities may be determined with hegh precision for the case of progressive waves by using the visibility pattern to locate a point on the wave train. Since the visibility patterns have much detail, see Fig. 6a for instance, a wavelength may be located to the nearest tenth wavelength. Over a range of 200 wavelengths the precision would be 0.05%.

In diffraction pattern measurements the phase of the ϕ_n's is not determined because the intensity and not the amplitude is measured. The agreement between the visibility patterns at the sound beam and those calculated using the ϕ_n's calculated by the computer program of Cook and Klein show that the phase of the calculated ϕ_n's is correct.

The pulse-optical technique is the most signifigant development for future optical measurements. Measurements of progressive ultrasonic pulses in transparent solids is one field. Since sound intensity measurements may be made anywhere in the solid, reflection in the solid from a boundary may be very directly and precisely studied. Attenuation measurements also may be studied with greater attention towards the sources of the attenuation.

Since the comstruction of this photomultiplier, Klein* has constructed one which has been used for two other types of pulse-optical measurements, pulsed high frequency ultrasound in liquids

*private communication.

and pulsed standing waves in glasses. The use of pulsed ultrasound has reduced the heating effects of the ultrasound to negligible amounts in these two experiments. By appropriate ultrasonic pulse duty cycle, heating effects can be reduced by two or three orders of magnitude.

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