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SURFACE ACOUSTIC WAVE PROBING WITH SPACED INTERDIGITAL TRANSDUC--ETC(U)
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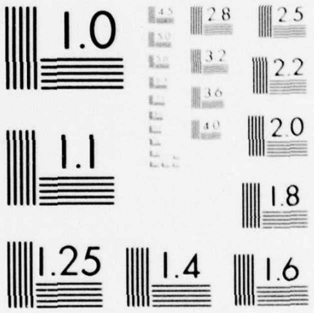
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SURFACE ACOUSTIC WAVE PROBING WITH SPACED INTERDIGITAL TRANSDUCERS

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Preprint

G. L. Report No. 2536

(12) 25p.

(11) February 1976

(14) GL-2536

(15)

Contract: N00014-75-C-0632

to be submitted to

Rev. Scientific Instruments

Edward L. Ginzton Laboratory
W. W. Hansen Laboratories of Physics
Stanford University
Stanford, California

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ABSTRACT

We have found that interdigital surface acoustic wave (SAW) transducers deposited on glass substrates and positioned very close to a piezoelectric crystal delay line surface ("spaced transducers") may be used to simulate identical transducers fabricated directly on the surface, for pretesting and prealignment of SAW devices.

A novel spaced transducer mounting technique has been developed that utilizes a free floating gimbal, which permits positioning the spaced transducer substrate next to the delicately polished SAW substrate without any mutual wiping. This feature greatly extends the reliability of the spaced transducer and overcomes the problem of damaging the surface polish. The gimbal mechanism is mounted on a mobile support which assures good positioning and orientation accuracy. A number of important uses for the new spaced transducer configuration in connection with surface acoustic wave delay line simulation are described, and a brief treatment of the electrical and coupling properties of spaced transducers is also presented.

1. INTRODUCTION

Recent experiments[1,2] performed with large recirculating surface acoustic wave delay lines have led to the development of spaced interdigital transducers (IDT's). The spaced transducers have not been developed as alternatives to IDT's deposited directly on piezoelectric substrates, but as a new and powerful means for comprehensive non-destructive evaluation of SAW substrates of arbitrary geometries. Although the original motivation for this development was to avoid damaging very fragile crystal substrates such as bismuth germanium oxide, other important uses have been found.

While permanent transducers fabricated directly on the piezoelectric substrate follow the particle motions of the surface acoustic waves, the spaced transducers are never brought into direct mechanical contact with the piezoelectric substrate. Instead, the electromechanical coupling occurs entirely across a submicron airgap which separates the glass transducer substrate (usually a thin microscope cover slide) from the optically polished piezoelectric substrate used to propagate the surface waves. The presence of this airgap prevents mechanical loading of the piezoelectric substrate by the comparatively massive glass transducer substrates and consequent damping of the SAW, and minimizes the damage which can be caused to either surface as a result of mechanical contact. Although the presence of the airgap tends to decrease the electrical efficiency, it does not significantly alter the acoustic radiation pattern of the spaced transducer as compared to an identical transducer fabricated directly on the substrate. In other words, the spaced transducer exhibits an effective acoustic aperture which is approximately the same as that of an identical interdigital transducer <u>in intimate contact</u> with the substrate.

We have demonstrated the usefulness of the spaced transducer probe configuration in numerous experiments designed to evaluate the delay line potential of polished delay line blanks and of new crystal orientations. Spaced transducers can also be used to launch and to receive phase shifted SAW signals propagating on a rotating crystal cylinder (rotation sensing). They have also been used extensively in diagnostic tests of large wraparound delay lines in conjunction with a highly stable rf phase bridge. In this application it is possible to scan the entire surface of a prospective delay line for possible defects such as (1) polishing scratches,

(2) local material inhomogeneities, and (3) substrate geometrical alignment errors incurred during fabrication.

Spaced transducers have also found important uses for experimentally determining the optimum location and orientation of permanent SAW transducers in SAW devices. They have also been used extensively in nondestructive evaluation of experimental waveguiding structures fabricated on crystal substrates.[3]

The concept of using a separated medium (or spaced) transducer is not new.[4] However, previous mounting designs have not allowed for frequent repositioning of spaced transducers to new locations without causing damage to crystal substrates and sacrificing measurement accuracy. By placing the spaced transducer in a free floating gimbal and simultaneously developing an optical monitoring technique we have developed an accurate diagnostic tool which is straightforward to operate and can be used to obtain repeatable data with minimum operator effort. We must add that the spaced transducer configuration described in this paper has not been developed to replace the highly successful point probe designs of other workers.[5] They have basically different purposes. The point probe is used when one desires to make a point-by-point mapping of an acoustic beam profile. The spaced IDT, on the other hand, can excite and analyze acoustic beams which are replicas of those produced by directly deposited IDT's, on arbitrary substrate geometries, and can be used for nondestructive testing of an arbitrary substrate before permanent transducer depositions.

2. DESCRIPTION OF THE SPACED TRANSDUCER GIMBAL MOUNT

In order to obtain good electromechanical coupling, the spaced transducer operating in the VHF frequency range must be separated from the piezoelectric

SAW substrate by an airgap of typically a few thousand angstroms. Furthermore, the width of the airgap separating the two substrates must be reasonably uniform. If this were not the case, the SAW beam launched by the spaced transducer would not exhibit the same diffraction properties as the beam launched by an identical transducer deposited directly on the substrate.

In early attempts to position the transducer parallel to the crystal surface, only vertical movement of the transducer substrate was allowed. This arrangement proved unsatisfactory since it resulted in nonuniform deformation of the spaced transducer and, often, in mechanical loading of the piezoelectric substrate in the direct path of the acoustic beam. Furthermore, repeatable diagnostic tests of SAW delay lines could not be undertaken because the operator could not monitor and adjust the width of the airgap separating the transducer electrode structure from the substrate. Serious difficulties were also experienced with scratching of the spaced transducer electrode metallization and of the delay line crystal polish in repeated application of the spaced transducer to the crystal. Based on the experience with earlier models it has been possible to design a new system which provides good positioning accuracy, and avoids damaging of the delicate surface polish.

In our new design we insure automatic parallelism by suspending the spaced transducer in a free-floating gimbal with crossed axes of rotation. The key feature of this design is that the axes of rotation are coplanar with the surface of the spaced transducer glass substrate and intersect one another at the center of the spaced transducer electroded region. This property has made the present design successful while earlier designs were not, because it insures that the spaced transducer substrate does not move laterally relative to the piezoelectric crystal substrate. By eliminating the wiping motion between the spaced transducer and the crystal substrates, we have eliminated the major cause of spaced transducer failure and substrate scratching. Furthermore, by placing the gimbal mount atop a precision micropositioner we have greatly increased the mobility of our spaced transducers, opening the way to new applications.

The basic design of the flexible spaced transducer support is illustrated in Fig. 1. This design utilizes free-floating gimbals providing free rotation through small angles about orthogonal horizontal axes for a single spaced transducer substrate mounted atop and centered on the intersection of the vertical rotational axis. The spacer pads are seen mounted on each of these gimbals and are located symmetrically with respect to the vertical rotation axes.

The placement of the fulcrums of the gimbal support in the plane of the spaced transducer is essential. If the gimbal axis were located either below or above the transducer substrate mutual wiping of the crystal surface and the transducer substrate would result. In the knife edge design of Fig. 1 the posts are placed far enough apart to avoid interference with the edges of delay line plates.

The gimbal mounts are the principal elements of our experimental apparatus as shown in Fig. 2. In the particular configuration shown in Fig. 2, a delay line is rigidly mounted in an aluminum fixture above the spaced transducer and directly beneath the microscope viewing part. A traveling reticle microscope, used to monitor the positioning of the spaced transducer, is seen mounted directly above the delay line with its line of sight normally centered on the spaced transducer center of symmetry.

The spaced transducer is viewed through the transparent delay line substrate as it is being raised toward the lower surface of the crystal delay line. It may also be viewed, however, from below using a specially designed mirror incorporated permanently in the gimbal design shown in Fig. 2. This feature extends the usefulness of the mount to the probing of piezoelectric substrates which are not transparent to light. The mirror also has other uses. For instance, it may be used to illuminate the spaced transducer from below and also to expose a layer of photoresist on the crystal substrate.

The spaced transducer gimbals are mounted on precision micromanipulators which have been designed to provide three translational degrees of freedom as well as a rotational degree of freedom in the plane of the spaced transducer. The spaced transducers themselves are not visible in Fig. 2.

3. POSITIONING OF SPACED TRANSDUCERS AGAINST FLAT PIEZOELECTRIC CRYSTAL SURFACES USING FREE-FLOATING GIMBAL MOUNTS

The spaced transducers were fabricated using 1000 Å thick depositions of Cr-Al on substrates consisting of standard glass microscope cover slides approximately 2.5 cm square and of thickness in the range of 100 to 150 microns. The metallization of the microscope slides is performed without any previous processing other than the standard solvent cleaning operations and rf sputter etching.

The thin glass transducer substrates are normally affixed to the gimbal mounts in such a way that the transducer interdigitated electrode pattern is centered with the two horizontal rotation axes of the gimbal. The transducer substrate is then raised with respect to the piezoelectric substrate as indicated in Fig. 3. Thin strips of flexible plastic tape positioned on the corners of the glass substrate are intended to prevent the two surfaces from coming into direct contact. The tapes are typically 50 microns thick and 0.25 cm wide. Another small pad is placed on the bottom side of the spaced transducer substrate and directly below the transducer interdigital pattern. Pressure applied from below through this support pad produces a slight bulge in the glass plate, causing the spaced transducer electrodes to approach, but not to touch, the flat crystal surface. Wiping motion of the glass plate or the tape, against the delicate polish of the piezoelectric substrate, is thus avoided because of the centrally symmetric and coplanar placement of the spaced transducer with the mutual intersection of the gimbal rotation axes.

As the center portion of the glass substrate approaches the surface of the piezoelectric substrate, a characteristic pattern of optical fringes is produced by the conical space formed between the optically polished crystal surface and the top surface of the glass cover slide. A typical pattern of the optical fringes is shown in Fig. 4. The symmetrical positioning of the optical fringes around the interdigitated portion of the spaced transducer may be used to estimate the relative parallelism of the two surfaces. Viewing with the microscope allows the operator to monitor the positioning of the spaced transducer glass substrate in relation to the crystal surface, and to readjust the pressure on the glass plate until the desired oval fringe pattern becomes visible.

It is straightforward, in practice, to readjust the pressure on the glass substrate such that (1) the optical fringes are symmetrical closed loops centered on the center of symmetry of the electroded transducer area,

(2) the entire active area of the transducer electrode lies within one optical fringe, thus assuring that the space transducer is sufficiently close to the crystal surface for efficient coupling, and (3) the transducer electrodes are sufficiently parallel to the surface. The appearance of a symmetric oval fringe pattern indicates mutual parallelism of the two surfaces. When the central zone of the fringe pattern is centered on and is longer than the transducer aperture, the proper acoustic beam width is obtained, and the spaced transducer is near enough to the crystal surface for efficient coupling.

4. ELECTRICAL CHARACTERISTICS OF SPACED INTERDIGITAL TRANSDUCERS

The electrical input impedance parameters of spaced transducers can be calculated using a linear series equivalent circuit. The formalism is similar to that used to calculate electrical parameters of directly deposited transducers, except that the presence of the airgap separation is explicitly induced. The presence of the airgap changes the electrical behavior of spaced transducers in two important ways: (1) it reduces the magnitude of the SAW velocity perturbation $\Delta v/v$, and (2) it makes the transducer capacitance C_T strongly dependent on the spatial separation.

The quantity $\Delta v/v$ is the fractional velocity change of the surface wave propagating on the surface of a piezoelectric substrate whose surface has been coated with an infinitesimally thin perfectly conducting film. The velocity perturbation $\Delta v/v$ is physically related to the shorting out of the electric fields in the piezoelectric substrate by the build-up of image charges in the metallic film. The effect of the metallic overlay is reduced if the shorting plane is placed some distance above the surface of the piezoelectric substrate. For small perturbation $\Delta v/v \approx 1/2\ k^2$, where k^2 is the electromechanical coupling constant for surface acoustic waves. Because $\Delta v/v$

exhibits a dependence on the spatial separation, it is also strongly frequency dependent. This effect is not present in directly deposited SAW transducers.

In order to characterize the input-output electrical behavior of our spaced transducers we have used the series model of Auld and Kino.[6] In this model the effect of the airgap separation can be explicitly included by using the expression originally developed by Kino and Reeder[7] for separated medium SAW amplifiers. In this way it is possible to obtain a useful electrical characterization of the spaced transducer which can be readily applied to practical problems.

The real and the imaginary parts electrical input impedance of spaced transducers (including the "lift-off" factor) are given by:

$$\hat{R}_a(\omega) = \frac{8N}{\pi\omega_0 C_T}\left(\frac{\Delta v}{v}\right)_d = \frac{8N}{\pi\omega_0 C_T}\,\frac{1 + \tanh\left(\frac{\omega d}{v_{SAW}}\right)}{1 + \frac{\epsilon_p}{\epsilon_0}\tanh\left(\frac{\omega d}{v_{SAW}}\right) e^{-2\frac{\omega d}{v_{SAW}}}} \qquad (1)$$

and

$$C_T = \left[\left(1 + \frac{\epsilon'}{\epsilon_0}\right) + \frac{\left(1 + \frac{\epsilon_p}{\epsilon_0}\right)\frac{\ell}{2e}}{\left(1 + \frac{\epsilon_p}{\epsilon_0}\right) + \frac{\ell}{2d}}\right] N\,\epsilon_0\, h \qquad (2)$$

$$\hat{X}_a(\omega) = R_a(\omega_0)\left(\frac{\sin 2\pi N\left(\frac{\omega - \omega_0}{\omega_0}\right) - 2\pi N\left(\frac{\omega - \omega_0}{\omega_0}\right)}{2\pi^2 N^2\left(\frac{\omega - \omega_0}{\omega_0}\right)}\right), \qquad (3)$$

where

$$\epsilon_p = (\epsilon_{yy}\epsilon_{zz} - \epsilon_{yz}^2)^{1/2} \qquad (4)$$

N = the number of interdigital electrode pairs,

$(\Delta v/v)_d$ = SAW velocity perturbation as a function of airgap width,

ω_0 = transducer synchronous frequency,

d = width of the airgap,

ℓ = interelectrode spacing

h = aperture of the spaced transducer,

ϵ' = effective dielectric constant of the glass substrate,

ϵ_p = effective dielectric constant of the piezoelectric substrate,

V_{SAW} = SAW propagation velocity.

The geometry is shown in Fig. 5.

Equation (1) can be used to estimate spaced transducer design parameters for optimum coupling efficiency. However, in most nondestructive testing applications optimization of transducer electrical parameters is not necessary because spaced transducer insertion losses are only a few dB greater than those of permanent transducers. A comparison of design parameters for $Bi_{12}GeO_{20}$ is given below.

The quantity $N/\omega_0\ C_T R_a(\omega_0)$ can be interpreted as the effective coupling constant for operation at midband. The electrical coupling can be optimized when this quantity is set equal to N^2, where N is the number of active electrode pairs. Thus, on $Bi_{12}GeO_{20}$, maximum conversion efficiency can be achieved with $N = 23$, assuming 1 micron airgap and dielectric constant $\epsilon_T \approx 30$. For comparison, only eight electrode pairs would be required for a directly deposited transducer. It is seen from Eq. (1) that gap spacing d must be much smaller than λ (~ 32 microns at 54.5 MHz) because of the strong influence of the large $Bi_{12}GeO_{20}$ dielectric constant on the "lift-off" factor.

We have measured the electrical input impedance for an eight electrode pair transducer spaced above $Bi_{12}GeO_{20}$ in the frequency range around 54.5 MHz. The experimental results are compared with calculated data in Fig. 6. We note a very close agreement except for frequencies above 57 MHz. This discrepancy is caused by bulk mode generation at frequencies slightly above the synchronous frequency for generation of surface waves, and is not included in our spaced transducer model.

5. APPLICATIONS

In the various applications of the gimbal mounted spaced transducer, one characteristic of the device is repeatedly demonstrated: the spaced transducer allows simulation of the behavior of a normal transducer deposited on a a piezoelectric surface, without the necessity of actually placing that transducer on the surface.

One of the most important uses of the spaced transducer has been in connection with large wrap-around delay lines of long time delay. For example, it was used to align the permanent transducers on a 495 μsec SAW delay line on BGO.[2] In this application the spaced transducer was used as a probe, whose purpose was to determine the optimum locations for depositing permanent transducers. In this case, an input transducer was permanently deposited on the delay line blank, producing a SAW beam which traveled around the periphery of the delay line in a helical path. The spaced transducer was used as a receiving transducer, and was experimentally moved to determine the location and orientation which gave optimum beam capture as evidenced by maximum output response. Referring to Fig. 3, a thin layer of photoresist was placed on the piezoelectric substrate beforehand, not in the path of the surface wave beam, but in areas that fell directly under inactive registration mark images on the spaced transducer substrate. These registration mark images were then transferred optically to the photoresist layer by illumination, using the mirror shown in Fig. 1. Later, using a new layer of photoresist in the transducer area, plus the photolithographic mask that was used originally to construct the spaced transducer images, a permanent transducer was deposited having the precise position and orientation of the spaced transducer.

The utilization of spaced transducers to establish optimum orientations of the input or output transducers on practical delay lines has been justified by the assumption that the radiation pattern of a spaced transducer closely approximates that of a transducer of the same aperture, but placed in intimate contact with the piezoelectric substrate. To test this assumption, we compared an experimental profile of a SAW beam launched by a spaced transducer, with calculated profile using a diffraction theory[8] for transducers deposited directly on the surface of a delay line. The measurement was performed at 54 MHz on a 001-110 bismuth germanium oxide delay line in which the SAW beam was launched by one spaced transducer and received by another. In this configuration, one spaced transducer was used as a mobile probe while the other, which launched the SAW beam, remained stationary. The experimental arrangement of the two transducers is shown in Fig. 7. Both transducers had active aperture $h = 0.125$ cm , and 8 electrode pairs. The axes of the two transducers are mutually parallel but offset transversely by a distance d . The insertion loss of the delay line is then measured as a function of the transverse displacement d for a fixed longitudinal displacement of $Z \cong 10$ cm .

The results are shown in Fig. 8. Note that the perpendicular distance Z between the two transducers is contained in the factor K , which is defined by the relation $K^2 = \frac{2\pi}{2(1-2\alpha)\lambda Z}$, where α is the anisotropy parameter for the crystalline substrate ($\alpha = 0.136$ for Z/110 cut BGO).

The calculations involved differ from some earlier cases in that the objective was to evaluate the insertion loss due to diffraction as observed in the terminal behavior of delay lines, including the integrating effects of the transducers, rather than to calculate point-by-point amplitudes within the acoustic beam. The theory gives the theoretical insertion loss between the input power supplied to one transducer and the output power extracted from the other transducer, due to diffraction effects alone (that is, omitting electrical insertion loss at the transducers, and crystal scattering losses and air loading losses in the crystal). The correspondence between experiment and theory is seen to be quite close, from which we can conclude that the spaced transducer does indeed launch a SAW beam with the proper diffraction spreading.

A related application of the present spaced transducers has been the evaluation of new SAW waveguiding structures.[3] In this application the noncontacting nature of the spaced transducer made it expedient to remove one experimental waveguiding configuration and to replace it with another on the same substrate without the need to redeposit new permanent transducers, which is difficult to do on some materials, such as $Bi_{12}GeO_{20}$, without damaging the substrate. Consequently, valuable single crystal substrates could be conserved and significantly shorter turn-around times realized. These transducers are very useful in evaluating SAW device performance on new materials before their properties and anisotropy are fully known, with comparative simplicity and good reproducibility of results. A later development, that of using the spaced transducer to measure the "acoustic" circumference of large crystal plates, is described elsewhere.[9]

CONCLUSIONS

A system has been devised which can accurately position mobile interdigital transducers within submicron distances from polished piezoelectric substrates, without substrate damage, such as to excite SAW beams on the substrates which are substantially identical to those excited by directly deposited transducers. These spaced transducers have been found to be important in experimental optimization of SAW devices. This includes: nondestructive testing of SAW delay line blanks for both material inhomogeneities and geometrical and polishing tolerances; determining the optimum locations and orientations of interdigital transducers before accurately depositing the transducers, including direct optical transfer of the optimum transducer coordinates; and simplifying the testing of new SAW device designs for which transducer deposition is complicated and non-essential to the evaluation of the device mechanism.

ACKNOWLEDGEMENTS

The authors would like to express their appreciation for the contributions of L. Goddard and D. Walsh in all aspects of transducer fabrication, and G. Bicker for the fabrication of experimental apparatus.

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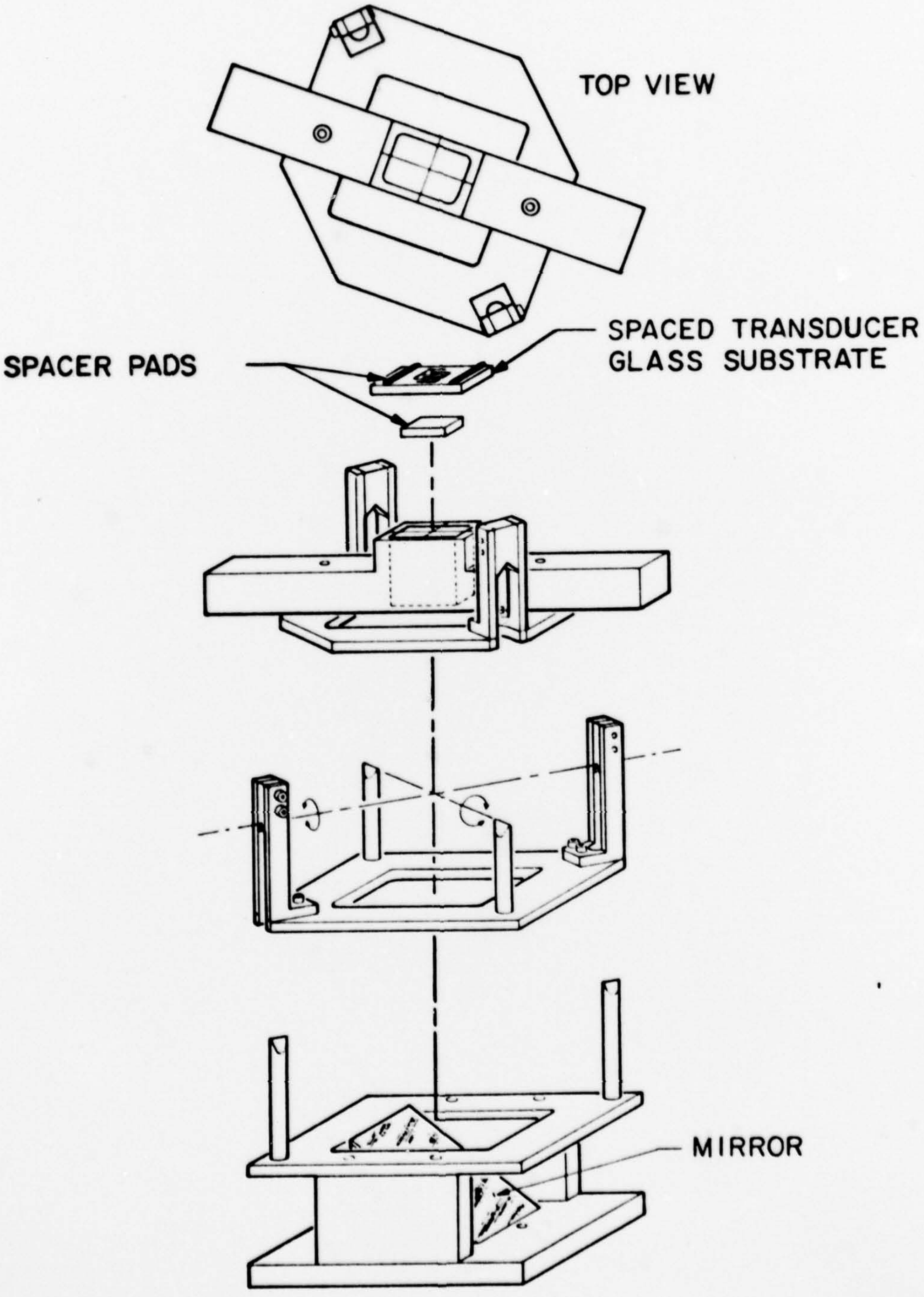
FIGURE CAPTIONS

1. The knife-edge supported gimbal spaced SAW transducer mount. The tilted mirror is used to illuminate the spaced transducer glass substrate from below.
2. Complete apparatus used in precision probing of SAWs on $Bi_{12}GeO_{20}$ and $LiNbO_3$ delay lines.
3. (a) Configuration for surface wave probing.
   (b) Configuration for transfer of reference marks.
4. Typical optical fringe pattern observed when a spaced transducer is placed close to the SAW delay line surface.
5. Spaced transducer geometry.
6. Electrical input impedance of a spaced-ID transducer as a function of frequency. The synhcronous frequency of this transducer is 54.5 MHz.
7. Offset transducer notation.
8. Comparison of measured SAW beam profiles with theory. The SAW beam is launched and received using identical spaced-ID transducers of 0.125 cm aperture width, and separated by 10 cm.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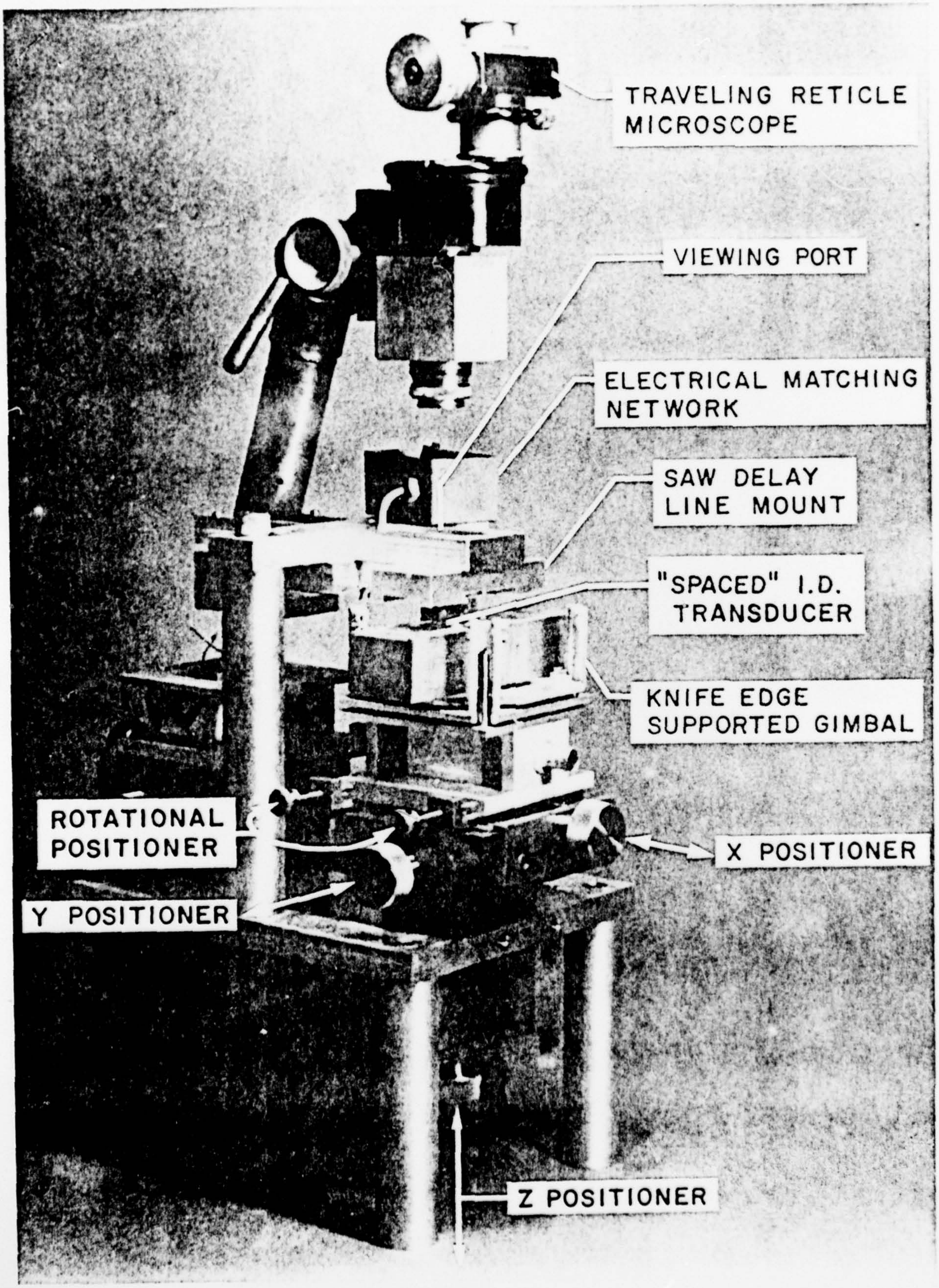
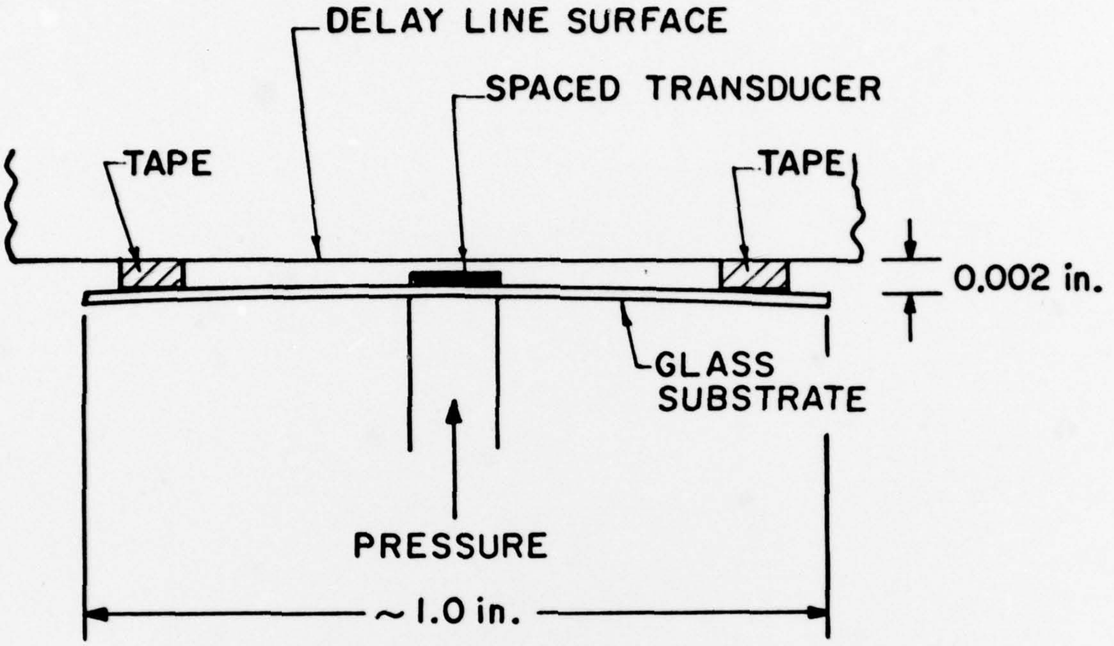
SPACER PADS
MIRROR


TRAVELING RETICLE MICROSCOPE
VIEWING PORT
ELECTRICAL MATCHING NETWORK
SAW DELAY LINE MOUNT
"SPACED" I.D. TRANSDUCER
KNIFE EDGE SUPPORTED GIMBAL
ROTATIONAL POSITIONER
X POSITIONER
Y POSITIONER
Z POSITIONER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TAPE
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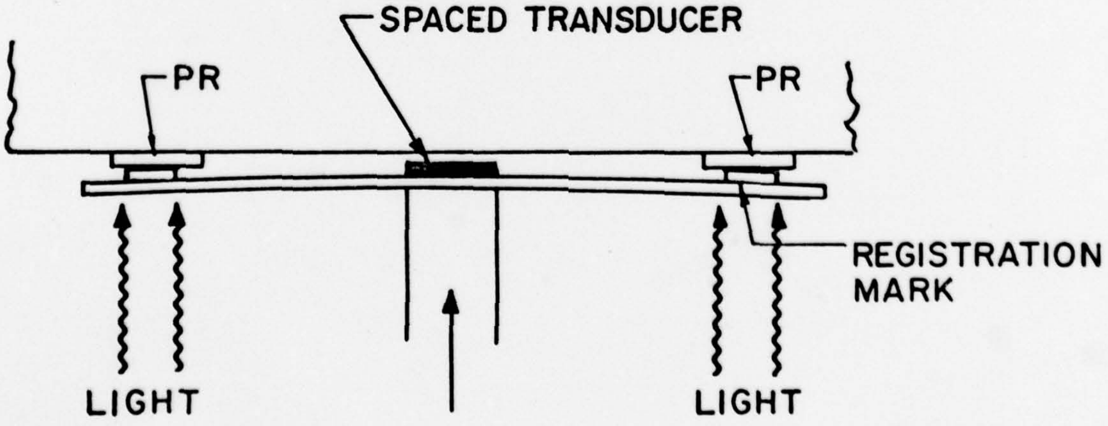
GLASS SUBSTRATE
PRESSURE
~ 1.0 in.

(a)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(b)

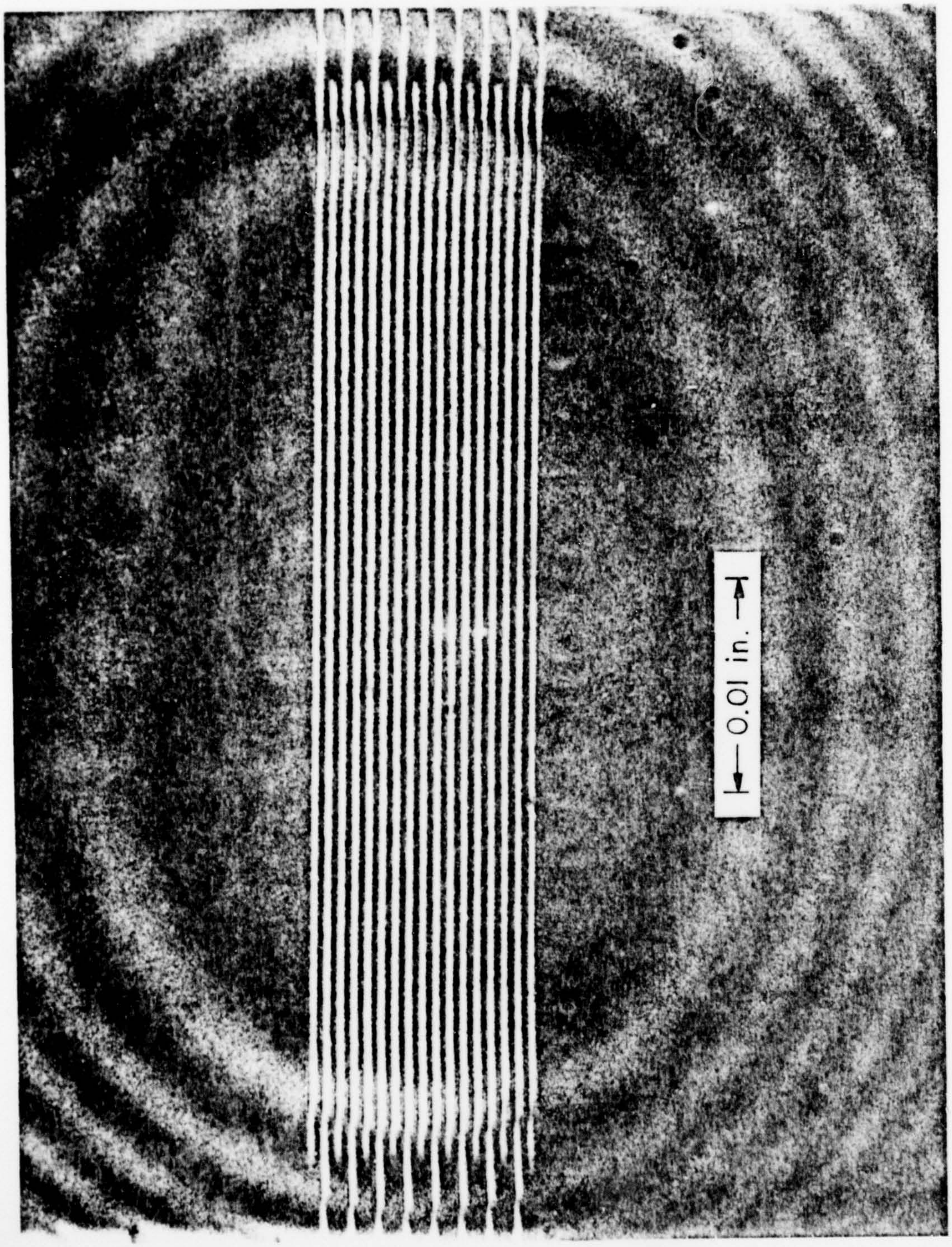
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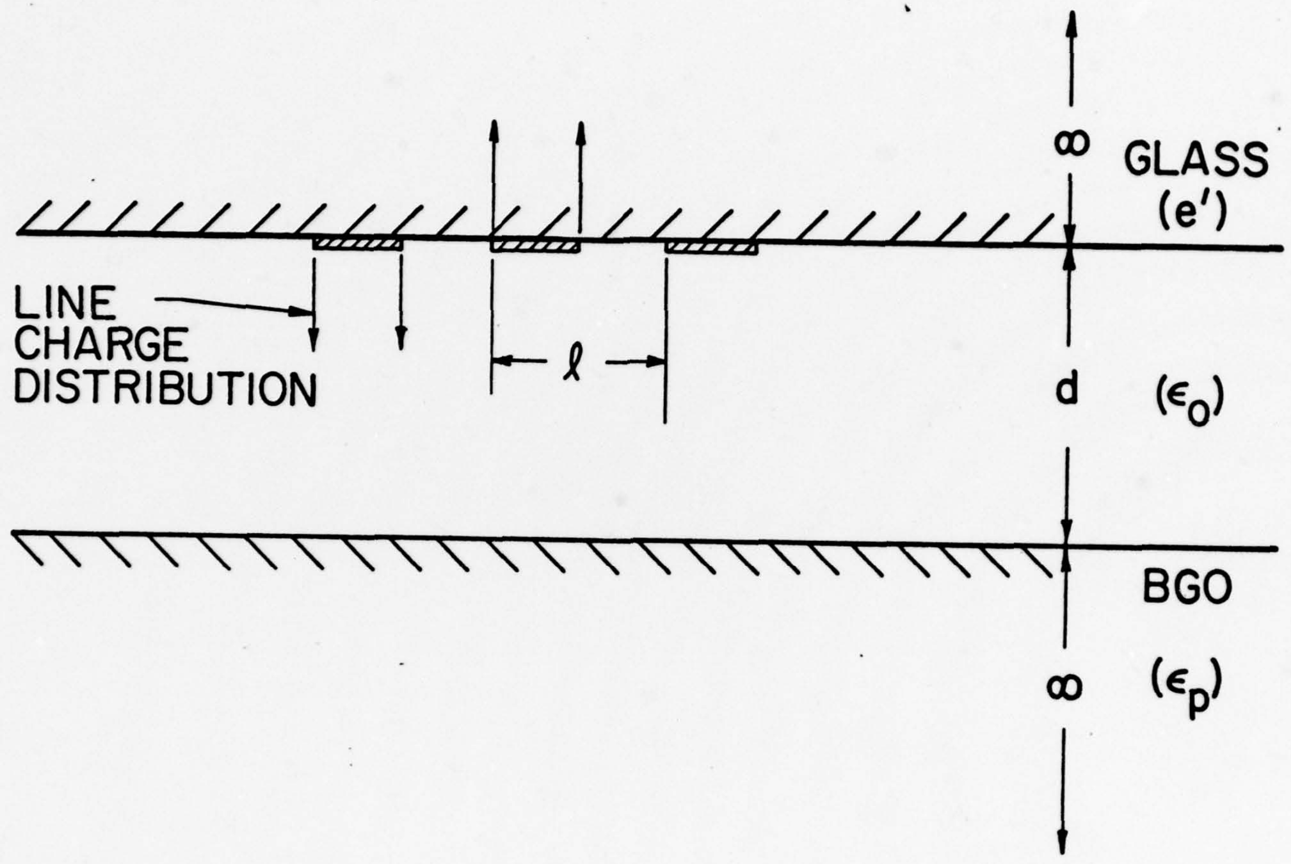
Fig. 2



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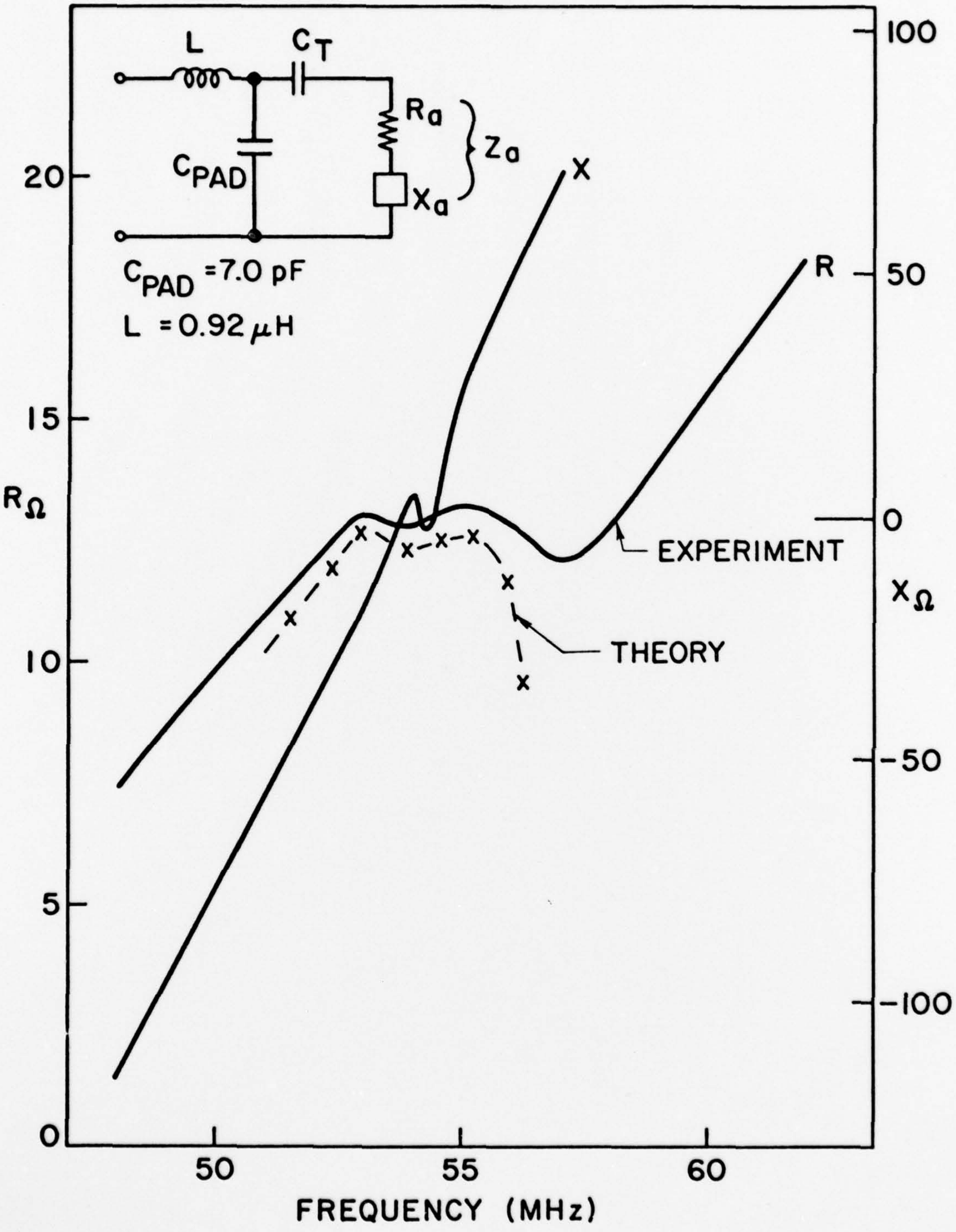
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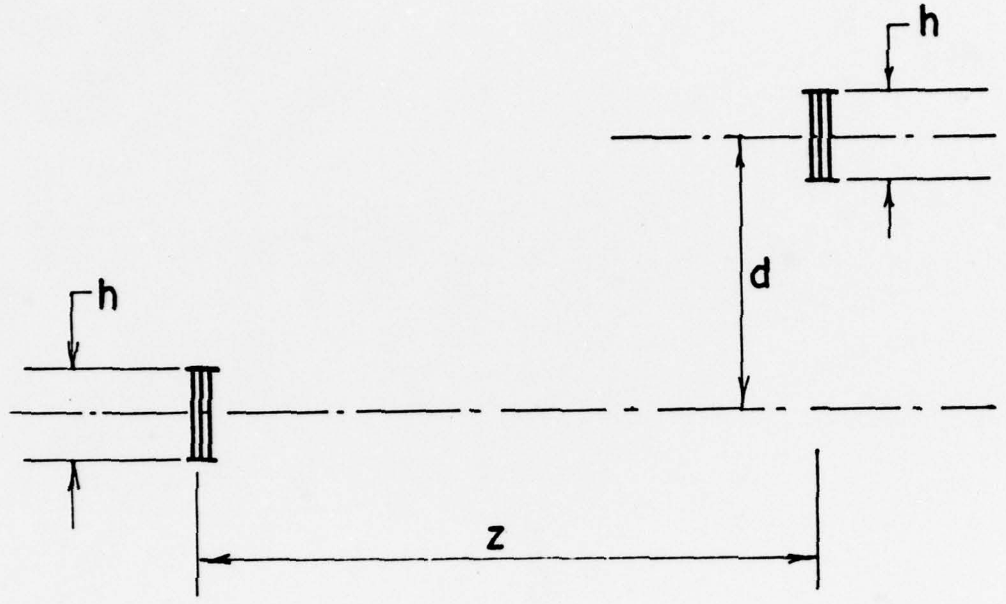
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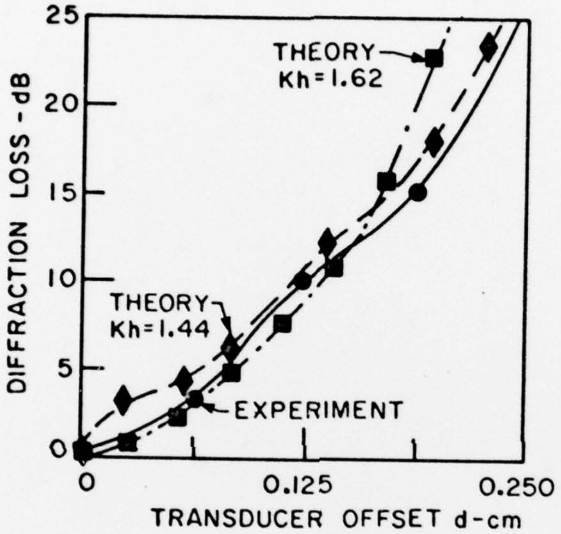

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THEORY Kh=1.44
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TRANSDUCER OFFSET d-cm