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ABSORPTION OF ULTRASONIC AND HYPERSONIC WAVES IN LiF SINGLE CRYSTALS

by

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ABSTRACT

Attenuation of ultrasonic-hypersonic stress waves in LiF single crystals is analyzed. As a mechanism for attenuation the vibrating pinned-dislocation model of Koehler is treated; a resonant peak in attenuation vs frequency was sought. Some other mechanisms, including temperature dependence, are considered. Various causes of modulation of the exponential decay of the acoustic wave are discussed.

CONTENTS

I. INTRODUCTION

The purpose of this project was to analyze the attenuation of a stress wave as a function of frequency in the ultrasonic-hypersonic transition region (600 - 1800 Mc) in lithium fluoride single crystals. The stress wave was induced by a pulse of electromagnetic energy transmitted to a reentrant cavity and transformed to acoustic energy in a quartz piezoelectric transducer bonded to the LiF specimens. The axes of the specimens were, respectively, the [100], [110] and [111] crystallographic directions. These axes were the ones of pure propagation of the longitudinal acoustic stress waves employed in the present study. Attenuation of these waves was determined from the nature of the decay of a pattern of echos corresponding to reflections from the ends of the specimens. The model, or mechanism of attenuation considered, was that of the damped motion of a pinned dislocation loop vibrating as a stretched string. This model was proposed by Koehler and has been treated by Koehler and by Granato and Lücke. A resonance peak in the attenuation-frequency curve, predicted by Granato and Lücke to exist in the high megacycle region was sought.

The relationship of crystallographic orientation factor to this model is considered, various difficulties and limitations of experimental technique are discussed and

discrepancies between theory and experiment are presented. General mechanisms of the attenuation and of the interaction of the stress wave with the solid lattice are discussed, with special attention given to the importance of parallelism of the end faces of the specimens. Attenuation as a function of temperature, after a theory of Woodruff and Ehrenreich, is briefly considered.

II. EXPERIMENTAL

1. The Cavity

One kilomegacycle (10^9 cps) is defined in this investigation as that frequency separating the sonic (to $2x10^4$ cps) and the ultrasonic regions from the hypersonic (to $2x10^{10}$ cps) region with respect to acoustic waves.[1] Likewise one kilomegacycle is defined as the lower limit of a microwave region which lies just below the infrared region in the electromagnetic spectrum[2] (Fig. 1). In this experiment microwaves are generated, and converted into hypersonic waves in a specimen of LiF by means of a cavity resonator and a quartz piezoelectric transducer (Figs. 2 & 3).

Much below the microwave region electromagnetic oscillations can be sustained by means of a simple resonant circuit consisting of a coil and a capacitor. Increasing the resonant frequency of such a circuit, however, requires a proportionate reduction in physical size of these components. The latter involves an increasing resistance to sustained oscillations and causes a drastic reduction in the figure of merit or Q of the circuit, where

$$Q = \frac{2\,\pi\ (\text{energy stored})}{\text{energy dissipated per cycle}} .$$

To solve these problems the circuit can be replaced by a single coil which would combine a certain inductance with the capacitance of the gap at one end of the coil. In such a case the dimensions of the circuit become comparable to the wavelength of the oscillations (30 cm at 1 kMc) and energy is lost by radiation. This problem is met by using an enclosed metal cylinder for which the absolute values of the circuit constants are not known. All electric and magnetic fields are confined, and if the dimensions of the cylinder are properly chosen[3] (Fig. 2), electromagnetic oscillations will be sustained at the desired frequency. In this experiment, therefore, all signals were transmitted by shielded coaxial cables, while a resonant cavity instead of a wired thin metallic film[4, 5, 6, 7] was used to apply an oscillating field to the piezoelectric transducer.

The resonant cavity used in this experiment is of the reentrant, or hybrid type which was chosen because of the intense electric field developed between the reentrant post and one wall (Fig. 3). Excellent analyses of the field configuration and of the frequency-dimension relations of reentrant cavities have been made.[8, 9] Any closed cavity of this type has associated with it a triple infinity of resonant modes (field configurations) each with an associated unique value of resonant frequency, and each corresponding to a possible solution of Maxwell's equations. For a given mode and given cavity shape, this resonant frequency depends, according to the principle of similitude,[9] inversely upon the size of the cavity. It is reasonable to assume[3, 8, 9] that in this experiment the existing mode of electromagnetic vibration was the lowest, or fundamental, as shown in Fig. 3. Since the free-space wavelength, $\lambda = c/f$ ($c = 3\times10^{10}$ cm/sec), of the signal sent to the cavity is in good agreement with Moreno's definition of cavity wavelength,

$$\lambda_o = 2\pi\sqrt{\frac{Z_o \rho_1^2}{2\delta} \ln \frac{\rho_2}{\rho_1}}$$

(where the terms are defined in Fig. 2),[3] it is further assumed that the wavelength is approximately the free-space value within the cavity. For energy considerations $Q = 2\pi$ (energy stored/energy lost per cycle) = (resonant frequency/ bandwidth)[10] should be high, but for good resolution of echos the Q should be low (implying a wideband system). A reentrant cavity with its high surface-to-volume ratio, therefore, combines a Q which is relatively low for cavities (17% of a perfect cylinder), with a mode which can be assumed to be low when $Z_o < 1/4\ \lambda_o$.[3, 9, 10]

There is a transition from the TM_{010} mode (axial electric field)[9, 10] of a perfect-cylindrical cavity, through a TM_{oop} mode ($p \ll 1$) of the hybrid cavity,[9] to the TM_{001} mode (radial electric field)[9, 10] of the perfect-coaxial cavity as the reentrant post is inserted. (The designation TM indicates a mode having a magnetic field transverse to the axis of the cavity, while the subscripts indicate, respectively, the number of full-period, half-period and half-period variations along the angular, radial and axial coordinates). Favorable to the field configuration shown in Fig. 3 is the method of coupling whereby a loop is oriented to insert a magnetic field in the region where this field is theoretically most intense.[9, 11] The position of the post (Figs. 2 & 3), however, provides a small gap, δ , for an intense electric field. The resonant frequency of the cavity is increased by increasing δ , but limiting cases exist such that the resonant frequency goes neither to zero nor to infinity as δ goes to zero or to Z_o, respectively.[9]

It is this writer's opinion that the progressive reduction in size of the echo patterns obtained (Figs. 7, 8, & 9) as the resonant frequency was either decreased or increased about a value of 1200 Mc is due to a deterioration in the quality of this electric field at very small and at large values of δ . Although the position of one wall was also variable, no discernible change in echo pattern was realized by so altering the dimension Z_o.

The intense oscillating electric field vibrated a quartz piezoelectric crystal, which, acting as a transducer, converted electromagnetic to acoustic vibrations. The latter were transmitted to the LiF specimen to which the quartz crystal was bonded. Insertion of the transducer-LiF assembly into the cavity most assuredly disturbed the field, but no account for such disturbance was made other than a compensating "tuning" of the cavity. This was accomplished by adjusting the position of the reentrant post, or of a tuning rod, as shown in Fig. 2. (The early runs made in this study employed a "fixed" cavity, tunable only over a narrow range of frequencies by the adjustment of a brass probe, Fig. 10.)

2. The Transducer

The transducer was an efficient, high-Q motor-generator which allowed mutual conversion of electrical and mechanical vibrations. The piezoelectric effect owes its existence to a lack of center of symmetry in the crystal such that a uniform stress will produce a separation of the centers of gravity of the positive and negative charges. This produces an induced dipole moment which is necessary for the production of polarization.[12] Quartz, or SiO_2, crystallizes in the trigonal trapezohedral class of the hexagonal system, with a unique six-fold axis of symmetry. The Z-axis, along a crystal of hexagonal cross section, three equally spaced X-axes passing through the corners of the cross section and three equally spaced Y-axes passing perpendicularly through the mid-points of the sides describe the properties of the crystal.[12] The Z-axis is the optical axis and, due to its symmetry, produces no piezoelectric effect when electrical stresses are applied. The X-axes and the Y-axes are, respectively, the electrical and the mechanical axes. If a flat section is cut from a quartz crystal such that its flat sides are perpendicular to an X-axis, the section is an X-cut crystal and will vibrate longitudinally in an oscillating electric field. Y-cut, AC-cut and BC-cut (modified Y-cuts)[1] crystals, on the other hand, produce shear waves when excited by such a field. Equivalent electronic circuits for piezoelectric crystals have been calculated.[10, 12] They will not be discussed here.

The resonant frequency of the transducer depends on its dimensions, on the mode of vibration and on the dielectric and elastic constants for this mode. Variations in the dielectric and elastic constants which may have been caused by the method of holding and bonding the transducer to the specimen (Fig. 3), and by changes in temperature were neglected. A simple longitudinal mode of vibration was assumed, so that the thickness of the transducer became the determining factor with respect to its resonant frequency. A quartz transducer with a resonant frequency of 10 Mc is 0.03 cm thick, so would have to be extremely thin in the region of kilomegacycle frequencies.[1] Therefore, a transducer with a fundamental frequency of 10 Mc was used, with the assumption that higher order harmonics of 10 Mc in the kilomegacycle range would be excited by the electric field. Another theory, however, discounts the importance of the thickness of the transducer and states that hypersonic waves are generated only at the surface of the transducer (i.e. at spatial discontinuities of the alternating piezoelectric stress), with the remainder of the quartz acting only as a transmission medium.[1, 13] The experimental results found in this study, however, bear out the existence of "high order harmonics". The transducer was merely considered to be a half wavelength "organ pipe" with $f_n = nf_{fund.}$ where n = 1, 2, 3, 4, 5 .... . But the electric field drove both faces of the transducer in phase, while the odd harmonics of a half wavelength organ pipe are 180° out of phase from one end to the other. Therefore only the even harmonics of 10 Mc existed in the transducer so that n = 2, 4, 6, 8, ... and for this project, in fact, echo patterns were obtained only at intervals of 20 Mc. It might be mentioned, however, that while the Q of these harmonics is about that of the fundamental, the magnitude of the piezoelectric effect is progressively less for higher harmonics.[10] Further discussion of acoustic waves is reserved for Sec. III-5.

3. The Bond

Especially critical at the high frequencies employed in this project were both the method of bonding the transducer to the specimen, and the nature of the bonding material. The bond had to be thick enough to provide a homogenous and continuous medium for transmission of acoustic waves, but not so thick as to cause excessive attenuation of these waves. Many similar experiments have been made in the low megacycle region, and of the various bonding materials mentioned in the literature,[1, 4, 5, 6, 14, 15, 16, 17, 18, 19] all tend to fail at hypersonic frequencies or at low temperatures or both. In all but one run of this project Dow Corning 200 Silicone Fluid with a viscosity of 2.5 million or 1.0 million centistokes was used as the bonding agent. This fluid was easy to apply and to remove, did not react with the quartz or the LiF, and exhibited good transmission qualities at all temperatures investigated. Bonds were made, however, which provided relatively good results at room temperature, but relatively poor results at liquid helium temperature, and vice versa. Making the bond consisted of laying the transducer on a minute speck of the bonding fluid placed on the end of the LiF specimen, and, with a toothpick, tapping the transducer very lightly to achieve a homogenous film which would be as thin as possible without forming air voids (detected by the presence of color bands or fringes), and, of emphatic importance, which would render the faces of the transducer and LiF specimen exactly parallel to each other (Sec. III-6). The lower viscosity DC 200 Fluid seemed to be slightly superior to the higher in all respects. In one run DC 33 Grease (heavy) was used. This material appeared to give an echo pattern superior in quality but inferior in number of echos to that of the DC 200 Fluid

(Figs. 8 & 9). The reason for this is not known. The best room temperature echo pattern was obtained with a bond of "Decalin" (decahydro-naphthalene). Due to its very high volatility, however, its preservation depended upon immediate reduction in temperature. Several attempts to do this were unsuccessful and use of this material was discontinued. It was found that the "tapping" method of making bonds, described above, excelled over "wringing" or pressing the transducer onto the specimen. At best, making bonds is more of an art than a science, a trial-and-error process which warrants a separate detailed study.

4. The LiF Specimens

In this project three specimens with long axis parallel, respectively, to the [100], [110] and [111] crystallographic axes (Fig. 5) were oriented, and cut to the dimensions 1/8" x 1/8" x 11/16" on a diamond wheel saw from a single crystal of high purity LiF obtained from the Harshaw Chemical Co. of Cleveland, Ohio. The work was done by Mr. J. P. Hannon of this Laboratory. The [100], [110] and [111] axes which were found by standard X-ray techniques are, respectively, the axes of four-fold, two-fold and three-fold symmetry. They are, furthermore, those axes of cubic crystals along which pure longitudinal modes in the megacycle range may be propagated.[20, 21] The cross sectional dimensions of the specimens were chosen as the maximum tolerable with respect to disruption of the electric field (Sec. II-1), and the minimum allowable for polishing the ends flat and parallel. The length was so chosen to be the minimum necessary, considering the velocity of sound in LiF (Sec. III-7), for good separation of echos. Polishing of the ends of the specimens was performed by the Adolf Meller Co. of Providence, Rhode Island who guaranteed a flatness of one-quarter wavelength of sodium vapor light ($\lambda \approx 6 \times 10^{-5}$ cm), and a parallelism of four seconds of arc. (This subject is treated further in Sec. III-6). Plastic deformation which undoubtedly occurred during the aligning, cutting, polishing and general handling of the specimens is not quantitatively considered in this project. The curves of attenuation vs frequency for three runs made at room temperature over a period of a few weeks, however, are noted in Fig. 10 to differ only by a small but progressive rise in attenuation. This may reflect some plastic deformation introduced by handling. The specimens were not annealed prior to polishing. Since it was thought that annealing might damage the end faces with respect to flatness and/or parallelism, no heat treatment was attempted after polishing.

Although some early exploratory tests were made on the [100] and [110] specimens, only one very small echo was ever observed at room temperature for the [100] crystal, while two or three could be obtained for the [110] crystal, and four, five or six for the [111] crystal at room temperature. Because several echos are required for analysis, and since at least one or two "good" echos should be present for evaluation of the bond before the temperature is lowered, no runs were made on the [100] or [110] specimens. That the order of increasing attenuation for these variously oriented specimens is, in fact, [111] , [110] , [100] , is reported by Merkulov,[16] and by Papadakis,[19] and is discussed in terms of the Granato-Lücke dislocation model[22] in Sec. III-4. A decrease in attenuation, assumed by an increase in size and number of echos in a middle range of temperature between room temperature and liquid air temperature, was observed for the [100] crystal. This phenomenon is considered further in Sec's. II-5 and III-5.

5. Temperature Dependence

A standard liquid helium double dewar system was used to maintain the cavity at 4.2° K for low temperature tests. Prior to the addition of liquid helium the jacket of this dewar was evacuated, and an outer dewar was filled with liquid air. Due to this vacuum the temperature of the specimen decreased to that of liquid air, about 80° K, slowly enough for changes in the echo pattern to be observed. Differences in temperature between the specimen and thermocouple due to the difference in environment (Fig. 3) was assumed to be small and was neglected. A copper-constantan thermocouple, with a Leeds & Northrup Type K-2 Potentiometer, Model 706557, and a Honeywell Galvonometer, Model 104WIG, was used to measure the temperature down to that of liquid air. Since this method becomes rapidly less accurate at lower temperatures, and since attenuation varies very fast with temperature in a region between 20° K and 75° K, its use was discontinued after the addition of liquid helium. This subject is treated in detail in Sec. III-5.

6. Apparatus (Fig. 4)

A pulse of microwave energy, 8-10 μ sec in duration, from an Airborne Instruments Laboratory Power Oscillator, Model 124, was sent through an isolator to a Diode Switch designed by Dr. P. L. Donoho and built by Messrs. B. R. Breed and R. T. Haase of this laboratory. In the Switch a bias pulse from an E-H Research Laboratories Pulse Generator, Model 131, selected a "flat" portion (region having reached steady state conditions) of the power pulse and so shortened it to about 1 μ sec. Both the Power Oscillator and the "bias" Pulse Generator were triggered by an 8-10 μ sec pulse from a Hewlett-Packard Pulse Generator, Model 212A, which was also used to synchronize the Hewlett-Packard Oscilloscope, Model 175A. While one part of the Switch was open to receive the power pulse and transmit it via a stainless-steel coaxial cable to the Cavity, the other part was closed to exclude this large "transmitted" power from the "receiver" elements (Local Oscillator, Mixer, IF Amplifier). There existed, however, a "leakage" problem, common in microwave circuits, such that some of the transmitted pulse passed directly through the Switch and into the Receiver. This was alleviated in part by attaching an Arra Switch, Model 7752B, to the input of the Diode Switch. Microwave power, reflected from the Cavity, passed back through a Directional Coupler where a small portion was sent into a Dual Trace Vertical Amplifier on the Oscilloscope where it could be monitored to facilitate optimum coupling of the Cavity, while most of the signal was sent directly back to the Diode Switch. From here the reflected power (the echos), entered a 30 Mc mixer where it combined with another microwave signal (30 Mc different from that of the echos) from a General Radio Local Oscillator, Model 1218A. The echos, which had been merely an amplitude-modulated envelope of a kilomegacycle carrier wave, were then sent on a 30 Mc carrier wave to the IF Amplifier. Since this Amplifier had been part of an aircraft radar receiver it was assumed to be a very non-linear device, i.e. small echos would be amplified more than large echos. For this reason the Oscilloscope display of echos, believed to portray a false picture of relative echo heights was treated in the following manner by an Arra Variable Attenuator, Model 2-3414-30. Marking the height of a given echo, #n, by means of a Mosley X-Y Recorder, Model 2D-2, echo #(n-1) was "brought down" to this level by turning a micrometer plunger on the Variable Attenuator. Curves of micrometer readings vs attenuation in decibels were constructed for a frequency range of 600 Mc to 1900 Mc. This method of determining relative heights of echos, plus the construction of the calibration curves was a tedious process and represented a great expenditure of time and labor. Careful comparison of data taken both by this method, and by merely measuring heights of the echos on a photograph taken from the Oscilloscope revealed negligle difference. The Amplifier was thereby considered sufficiently linear to warrant use of the "direct measurement" method. From the Amplifier, whose gain was measured to be 75 db, the echo train was sent to the Dual Trace Vertical Amplifier of the Oscilloscope. The Display Scanner, a relatively recent innovation, is a plug-in unit for the Oscilloscope and provides an output which transforms high-speed phenomena by means of high density sampling techniques to a continuous presentation on the X-Y Recorder. Had the critical tuning of the Cavity not tended to drift in time, this method of recording an echo pattern (which required about one minute) would have been the best. Quite frequently, however, an echo pattern, excellent in other respects, deteriorated almost as soon as it was "tuned-in". In practically all cases, therefore, echo trains were recorded with a Polaroid camera.

III. THEORETICAL, DISCUSSION AND RESULTS

1. The Material

Lithium fluoride is a cubic ionic crystal with lithium and fluorine ions occuping alternate lattice sites in three dimensions. The structure is not technically simple cubic since it violates Bravais' definition of a space lattice (a given point must have the same surroundings as any other point), but it may be properly considered a super-lattice of two interpenetrating face centered cubic systems, one of lithium atoms, the other of fluorine atoms (Fig. 5B).[23] Properties of LiF that make it favorable for the study of acoustic absorption are as follows:[24]

a) non-conductor, so negligible electron-electron, electron-phonon or electron-stress wave interaction;
b) non-hygroscopic;
c) simple lattice structure and unusually perfect after growth from melt;
d) readily cleavable (along $\{100\}$ planes) with negligible distortion;
e) hard enough to be handled with simple precautions, yet slightly plastic at room temperature.

This material is therefore valuable for studying how dislocations originate, how dislocation loops move under the influence of a stress wave and by what internal friction mechanisms in general energy is absorbed from a stress wave.

Attenuation of acoustic waves in non-conducting solids is due essentially to the action of thermal phonons (both a viscocity and a thermal conductivity loss), to lattice defects (viz. dislocation loops), to charged particles (viz. the ions themselves) and to electron spins (if a paramagnetic impurity is present).[11, 25, 26]

2. The Dislocation Model

The model assumed for this project is that of Koehler[27] and of Granato and Lücke[20, 22] (Fig. 6), whereby the motion of edge type dislocations[28] which are "pinned down" by impurity atoms is treated for the case of a periodic external stress, and may be compared to the problem of the forced damped vibration of a stretched string. The model leads to a hysteretic, frequency-independent, strain-amplitude dependent damping of the periodic stress throughout a wide frequency range including the kilocycle region,[27] and to a frequency dependent, strain-amplitude independent damping which is calculated for low damping to have a maximum in the high megacycle region.[20, 22] The former of these two types of loss will not be considered further in this paper.

It is assumed that the pure single crystal contains, even without deformation, a network of dislocations and that for a large enough concentration of impurity atoms a network of dislocations is further pinned into shorter loops by these impurities. Considering the high frequencies used in this project it is also assumed that there is neither "breakaway" from pinning points, nor is there sufficient time during a half cycle for a loop to reach the maximum displacement corresponding to the same stress applied statically. For low damping maximum attenuation will therefore occur when the displacement of the dislocation loop and the elastic stress wave are exactly $\pi/2$ radians apart.[20]

According to Koehler,[27] when the frequency of oscillation exceeds the low kilocycle region, impurities cannot follow the vibrating stress (diffusion being a very slow process at and below room temperature) and therefore secure the dislocation line at periodic pinning points. The intervening section of line then oscillates under the influence of the stress on its slip plane and in the slip direction[28] (Figs. 5A & 6). For LiF the slip planes and slip directions are, respectively, the $\{110\}$ type planes and the $\langle 1\bar{1}0\rangle$ type directions.[17, 19, 24, 29, 30] The applied normal stress, σ, is resolved into a shear stress, τ, acting normal to the dislocation line on the slip planes in the slip directions. When the latter is $\tau_o \cos \omega t$ the equation of motion of the pinned dislocation loop is:[22, 27]

$$A\frac{\partial^2 \xi}{\partial t^2} + B\frac{\partial \xi}{\partial t} - C\frac{\partial^2 \xi}{\partial y^2} = \tau_o b \cos \omega t$$

where these terms, in order of decreasing influence are, according to Koehler:

C term on the left	$\equiv$	restoring force per unit length
External force term on the right	$\equiv$	shear force per unit length
B term on the left	$\equiv$	damping force per unit length
A term on the left	$\equiv$	inertial force per unit length

and $C \equiv$ tension tending to decrease length of loop

$= 2Gb^2/\pi(1-\nu)$ [22, 27]

$B \equiv$ damping constant

$= 16 \times 10^{-4}$ gm/cm/sec [31]

See also Refs 14 - 1×10^{-4} for Ge
20 - 5×10^{-4} for Cu; etc.
25 - 7×10^{-4} for LiF
27 - 0.5×10^{-4} for Cu (considered low)
31 - 8×10^{-4} for Cu

$A \equiv$ effective mass of dislocation per unit length

$= \pi \rho b^2$ [22, 27]

$\tau_o \equiv$ magnitude of resolved shear stress

$b \equiv$ interatomic distance, or Burgers vector

$= 2.83 \times 10^{-8}$ cm [25]

$\rho \equiv$ density of LiF

$= 2.6$ gm/cm^3 [15]

$G \equiv$ shear modulus for the slip systems

$$= \left[S_{44} + 4(S_{11} - S_{12} - \tfrac{1}{2}S_{44})\right]^{-1} (l^2 l'^2 + m^2 m'^2 + n^2 n'^2)^{-1}$$

$= 3.46 \times 10^{11}$ dyne/cm^2 [15, 32]

where l, m, n, direction cosines between $[1\bar{1}0]$ and the axes of a unit cube

and l', m', n', direction cosines between (110) and the faces of a unit cube

$\nu \equiv$ Poisson's ratio

$$= \frac{e_{(001)}\ [001]}{e_{(110)}\ [1\bar{1}0]} = \frac{S_{12}\ \sigma_{(110)}\ [1\bar{1}0]}{\frac{1}{2}(S_{11}+S_{12}+S_{44})\ \sigma_{(110)}\ [1\bar{1}0]} = -0.258$$

$e \equiv$ strain on the given planes and directions

Although the above relations would apply approximately to screw dislocations, these are not considered here because it is assumed that interaction of dislocations with each other is negligible, and because screw dislocations are not pinned by impurity atoms.[22, 27]

3. Attenuation and the Logarithmic Decrement

The damping of the oscillating stress wave is described by the decrement:

$$\Delta = \frac{\text{energy lost per cycle}}{2(\text{total vibrational energy of the specimen})}$$

which is the mechanical counterpart of the electrical quantity, Q (described in Sec. II-1), so that $Q\Delta = \pi$. Attenuation and decrement are related by $\alpha = \Delta/\lambda$ which is in units of nepers or decibels per unit length, and $\lambda = v/f$. The symbols λ, v and f are, respectively, wavelength, velocity and frequency of the acoustic wave. Since Δ increases with the first power of frequency in the megacycle region it would be expected that α should increase with the square of the frequency.[20] Merkulov,[16] Granato and Lücke,[20] Granato and

Truell,[14] and Papadakis[19] have found, in support of the foregoing, that for several materials tested in the range 15 - 200 Mc, $\alpha \propto f^n$ where $n \leq 2$. They do not suggest that this exponent would change at higher frequencies. It was determined from the room temperature curves of Fig. 10 that above about 1200 Mc α is nearly proportional to the frequency squared, while in Fig. 12 Δ is about linear with frequency. The constants of proportionality for $\alpha \propto f^2$ and for $\Delta \propto f$ are, respectively, 0.3×10^{-18} and 0.25×10^{-12}.

There is good agreement between Merkulov,[16] and Papadakis[19] on the constant of proportionality for $\alpha \propto f^2$ from data which they obtained at room temperature on NaCl in the frequency range from 15 - 200 Mc. Merkulov's value of the constant ($\alpha/f^2 \approx 1 \times 10^{-18}$ for the [111] direction) yields an $\alpha \approx 1.21$ nepers/cm at 1100 Mc in LiF. This is a factor of about four higher than the mean room temperature $\alpha \approx 0.3$ nepers/cm shown in Fig. 10. This discrepancy can be resolved by realizing that in the expression $\alpha \propto f^n$, $n \leq 2$[14, 16, 20, 25] and may be 1.95, for example. In the latter case the room temperature data of Fig. 10 is an excellent extrapolation of Merkulov's data. This conclusion is the same despite the fact that Fig. 10 considers only the second and third echos, between which the attenuation is considered to be greater than the true attenuation (Sec. III-6). If the data of the present project has merely confirmed that $\alpha \propto f^n$, then a resonant dislocation maximum has been neither proved nor disproved.

Dislocations, on the other hand, as discussed in Sec. III-4, are not expected to contribute to α for longitudinal waves in the [111] direction. From Granato and Lücke,[22] nevertheless, for small damping where the frequency of maximum attenuation, ω_m, is that of the resonant frequency, ω_o, $f_o = \frac{1}{2\pi L_i}\sqrt{C/A} \approx 1 \times 10^9$ cps if $L_i \approx 10^{-4}$ cm for very pure material (Fig. 6). Also for $\omega_m = \omega_o$, $\alpha = \Omega\Lambda 4G^{\frac{1}{2}}b^2p^{\frac{1}{2}}/\pi^2B$ where Ω is the orientation factor and Λ is the total length of movable dislocation line per unit volume. The orientation factor, which accounts for the orientation of the individual slip system to the propagation and polarization of the acoustic wave, is found as in Sec. III-4. Using the values for LiF given above, and assuming that $\Lambda \approx 10^6$ cm/cm^3 for "good" material, $\alpha \approx 2.5 \times 10^{-7} \frac{\text{nepers}}{\text{cm}} \times 10^5$ cm = 0.025 nepers for this specific 0.17 cm^3 specimen. But a typical α of 0.02 nepers/cm from Fig. 11 multiplied by 3.66 cm, twice the length of the specimen, is 0.073 nepers. These must be regarded as coincidental, however, since the data of Fig. 11 are for longitudinal waves in the [111] direction, where Ω would be small or zero.

The value of B used above was calculated at room temperature by Suzuki et al.[31] using the Granato-Lücke model.[20, 22] This value is thought to vary with both temperature[25] and frequency[27] as discussed elsewhere in this thesis, and with irradiation[31] and loop length.[20] Variation in B may account for the irregular shape of the low temperature curves in Figs. 10, 11 and 12. The specific contour of all curves in these figures may be considered due to the small range of frequency they cover (Fig. 1), as mere experimental variations in data points which would be "smoothed out" if several orders of the frequency spectrum were presented. They are significant, however, in that the data shown in Figs. 10 & 11 were found to be reproducible for a given set of conditions, and that the attenuation and the decrement for the room temperature curves of Figs. 10 & 12 are, respectively, proportional to the frequency squared, and linear with frequency.

Suzuki et al., however, assumed that the Granato-Lücke model was an over-damped system.[31] This means that they considered their value of $B = 16 \times 10^{-4}$ gm/cm/sec to be large (although it is not much larger than other values (Refs. 14, 20, 25, 31), and that $\omega_m = A\omega_o^2/B$ occurs not at ω_o, but at frequencies progressively less than ω_o with increasing B. They have, in fact, determined a broad peak in $\Delta \approx 2 \times 10^{-3}$ nepers around 6 Mc. This work was done at room temperature with a deformed crystal of LiF oriented in the [100] direction, and using a value of $L_i = 10^{-4}$ cm. The calculated value of $f_m = A\,\omega_o^2/2\pi B = \pi C/2L_i^2 B \approx 23$ Mc for large B then compares roughly with this value, and compares exactly with Suzuki's value of f_m for an irradiated crystal.

Merkulov explains a regression from the $\alpha \propto f^2$ law dependence as being due to diffraction effects at the transducer as well as to a possible diffusive scattering.[17] His "regression" occurs below 40 Mc. At 20 Mc, in fact, his value of $\Delta \approx 10^{-4}$ nepers is only one order of magnitude less than Suzuki's Δ at the same frequency. Likewise, Papadakis reports a diffraction dominated attenuation in NaCl below 50 Mc, with adherence to the $\alpha \propto f^2$ law above 50 Mc.[19]

Koehler also discusses the distribution of loop lengths (upon which the amount of plastic strain is sensitively dependent) as a function of impurity concentration, and concludes with a statement that both the damping constant, B, and the shear required for plastic deformation increase as the time for deformation decreases.[27] Of the dislocation loops themselves there is a distribution function which decreases exponentially with increasing loop length.[22, 27] It has been found that Δ, which depends on the fourth power of the loop length, is more sensitive to long loops (low concentration of impurities).[22] It may therefore be said that attenuation, which is proportional to the area swept by the moving dislocation line, will be higher in the case of low concentration of impurities. It is assumed that network pinning prevents the loop lengths, and hence Δ, from becoming excessive in high purity materials. For the high purity LiF used here, however, relatively long loops which in turn implied a relatively low resonant frequency and attendant high Δ, was assumed. This assumption is supported by experimental evidence obtained by Granato and Lücke.[20]

It is necessary to digress at this point to discuss the concept of attenuation. In considering two echos, V_n and V_{n-1}, where V is the echo height in volts (Figs. 7, 8 & 9):

$$\alpha = \text{attenuation in decibels}$$

$$= 20 \log_{10}(V_{n-1}/V_n)\,\text{db where } V_{n-1} > V_n$$ [10, 33]

Since echos #n and #(n-1) are adjacent:

$$\alpha = 20/\left[n-(n-1)\right] \log_{10}(V_{n-1}/V_n)\ \text{db/echo}$$

But each echo represents a path for the acoustic stress wave of 2ℓ cm where ℓ is the length of the specimen:

$$\alpha = 20/2\ell \log_{10}(V_{n-1}/V_n)\ \text{db/cm}$$

The amplitude of the modulated echo pattern (Fig. 8) can be described by:

$$h = (10^{-\alpha' x})\left[-f(x)\right]$$

where $h \equiv$ vertical dimension at any point

$\alpha' \equiv$ absorption coefficient which is proportional to α, the attenuation in db/cm

$x \equiv$ horizontal dimension in cm (or echos)

$f(x) \equiv$ modulating function

But if $h = V_{n-1}/V_n$ = the relative height of two adjacent echos, and V_{n-1} is normalized to be equal to unity, then:

$$\log_{10}(V_{n-1}/V_n) = -\alpha' x - \log_{10} f(x)$$

$$20 \log_{10}(V_{n-1}/V_n) = \left[-\alpha' x - \log_{10} f(x)\right] 20$$

$$-\text{db} = \left[-\alpha' x - F(x)\right] 20$$

$$\text{db}/2\ell = \left[\alpha' x + F(x)\right] 20/2\ell$$

But $\text{db}/2\ell = d/dx\ \text{db}$

= slope of the individual echo heights, as $x \rightarrow 0$, at any given position on the curve.

$$\frac{\alpha' \not{x}}{2\ell} 20 = 20\alpha' = \alpha$$

= the true attenuation, or exponential decay, and is the peak-to-peak decay (Fig. 8 and Sec. III-6).

$$\frac{F(\not{x})}{2\ell} 20$$ = the difference slope which for the set of echo patterns in Fig. 8 was found to increase directly with frequency at a rate of about 1 db/cm in 520 Mc.

Although the decibel is a more convenient unit to use (e.g. 20 db corresponds to a voltage loss of 10, and to a power loss of 100) the decrement is defined in terms of natural logarithms,[32] so α is expressed as nepers/cm instead of as db/cm. Conversion is made by the expression:[33]

$$\alpha\ \text{db/cm} = 8.686\,\alpha\ \text{nepers/cm}$$

4. The Stress

The shear stress, τ , actually applied to a segment of dislocation line tending to bow it into a loop is an elusive quantity to calculate. According to Granato and Lücke, the component of dislocation displacement in phase with the applied stress contributes to a change in velocity of the wave, while the component out of phase leads to the attenuation and to a change in the modulus.[20, 22] Changes in velocity and modulus other than those due to temperature are small and are not considered in the present paper. The shear stress in question, however, is resolved into the slip systems (Figs. 5A & 6) from the normal stress, σ , applied to the end face of each of the three LiF specimens by the relation:

$$\tau_{ij} = \sigma_{\alpha\beta}\, l_{i\alpha}\, l_{j\beta}$$

where $i = \{110\}$ type planes

$j = \langle 1\bar{1}0 \rangle$ type directions

$\alpha =$ (100), (110) and (111) planes containing the respective end faces of the specimens

$\beta =$ [100], [110] and [111] directions containing the respective axes of the specimens

$l =$ direction cosines

By use of this relation it was found that there is no shear resolution onto any slip system for $\sigma_{(111)\,[111]}$, that $\sigma_{(100)\,[100]}$ and $\sigma_{(110)\,[110]}$ can each be resolved onto four of the six slip systems, and that $\sigma_{(100)\,[100]}$ gives a resolved shear about twice that of $\sigma_{(110)\,[110]}$. This calculation is supported by reports of Merkulov,[16] of Granato and Truell,[14] of Papadakis[19] and of Alers.[34] The magnitude of the applied normal stress $\sigma_{(\ )[\ ]}$ furthermore must be determined from the magnitude of the oscillator pulse (about 10 - 15 watts) which is severely reduced before it is actually applied to the LiF lattice. This reduction is due to losses in the electronic components (about 3 db), the coaxial lines, the cavity, the transducer (30 - 60 db),[11, 18, 26] the bond and the transducer-bond-specimen interfaces. Considering the gain of the amplifier ($\sim$75 db), and that the highest echos (before becoming saturated) were about 20 volts (Figs. 8 & 9), the shear stress actually applied to the dislocation lines can be regarded as a "perturbation" for which only a rough estimate is attempted here.

The 10 watt pulse, transmitted for 1 μsec (Sec. II-6) can be assumed from the foregoing to be attenuated about 70 db between the pulse generator and the specimen. It is applied to the face of the 1.83 cm long specimen through a transducer 1/16" in diameter. The energy density for the first echo is, therefore:

$$\frac{\text{Energy}}{\text{Volume}} = \frac{(10\ \text{watts})(1\times10^{-6}\,\text{sec})(10^{7}\,\frac{\text{erg}}{\text{joule}})}{(2\times1.83\,\text{cm})\pi\left(\frac{1}{32}\,\text{in}\times2.54\,\frac{\text{cm}}{\text{in}}\right)^2}\times10^{-7} = 1.35\times10^{-4}\ \frac{\text{erg}}{\text{cm}^3}$$

But the energy density is equal to $\sigma^2/2E$ where Young's Modulus,[15, 32]

$$E = \left[S_{11} - 2\left(S_{11}-S_{12}-\tfrac{1}{2}S_{44}\right)\right]^{-1}\left(l^2m^2+m^2n^2+n^2l^2\right)^{-1} = 12.2\times10^{11}\ \frac{\text{dyne}}{\text{cm}^2}$$

so that:

$$\sigma = \sqrt{2E(\text{En.Den.})} = \sqrt{2(12.2\times10^{11})(1.35\times10^{-4})\left(1\,\frac{\text{dyne cm}}{\text{erg}}\right)} = 1.82\times10^{4}\ \frac{\text{dyne}}{\text{cm}^2}$$

If the shape of the dislocation loop of Fig. 6B is considered parabolic and is reduced to a rectangular average of displacement, $\bar{y}$, then it can be shown that:[27]

$$\bar{y} \approx \frac{\sigma L_i^2}{7 G b}\Omega = \frac{(1.82\times10^{4}\ \frac{\text{dyne}}{\text{cm}^2})\,(10^{-4}\,\text{cm})^2\ \Omega}{7\,(3.46\times10^{11}\ \frac{\text{dyne}}{\text{cm}^2})(2.83\times10^{-8}\,\text{cm})} = 0.27\ \text{Å}$$

which is about 0.1(b) if the orientation factor were unity. From the relation $\tau_{ij} = \sigma_{\alpha\beta}\, l_{i\alpha}\, l_{j\beta}$, however, the Ω's corresponding to $\sigma_{(100)}$ [100] , $\sigma_{(110)}$ [110] and $\sigma_{(111)}$ [111] are respectively, (2/3)(0.5), (2/3)(0.25) and zero, where the factor 2/3 accounts for the fact that only four of the six slip systems are active. Therefore, to a first approximation, $0.01(b) < \bar{y} < 0.1(b)$ except for the [111] specimen. Since $\tau = \tau_0 \cos \omega t$, and since ω is in the strain amplitude independent region[22] as discussed earlier, even with all other factors being favorable to a large displacement, there is not time during a half cycle for $y \longrightarrow y_{max}$. A displacement of $y \approx 0.01(b)$ is therefore a reasonable estimate for the maximum bowing of the dislocation loop.

5. Interaction Between the Stress Wave and the Specimen

Attention is now turned to the nature of the wave inside the LiF specimen. Dislocation loss has been discussed, and thermoelastic loss (heat arising from the acoustic compression-rarefaction concept absorbs energy from the wave by conduction of heat from hot to cold parts of the specimen) is small for longitudinal waves, especially at very low temperatures, and is zero for shear waves.[14, 17, 19, 25] The effect of phonon viscosity is considered to be the greatest cause of acoustic damping,[25] and since phonons are the heat of the solid, it was decided for this project to suppress this source of attenuation by operating at 4.2^{o} K, the temperature of liquid helium. Pinning of dislocations, furthermore, is more effective at low temperatures.[22]

The effect which suppression of phonons has on attenuation is adequately demonstrated by the sharp decrease in curves of α vs T at a temperature near but below that of liquid air, to about the same low value of α regardless of frequency.[1, 11, 13, 21, 25, 26] From an early theoretical treatment by Akhiezer,[35] and from theoretical and/or experimental reports in more recent literature[1, 11, 13, 14, 16, 17, 19, 20, 21, 25] the general shape of the α vs T curves for non-conductors has been established (Fig. 13). Above the Debye temperature[36] α is independent of T and is proportional to f^2, while at lower temperatures (around 60^{o} K; Fig. 13) α is inversely proportional to T (although the last effect disappears at higher frequencies)[13, 21, 25, 37] and remains proportional to f^2 (Fig. 13). At a sufficiently low temperature the number of phonons becomes few enough so that the frequency of their collisions decreases to about that of the acoustic wave. The attenuation then decreases rapidly over a narrow temperature range (at about 50° K for quartz at 1 Mc; higher temperature for higher frequency) and is relatively independent of frequency. Below about 10° K, α is very low and is independent of both T and f. Akhiezer's account reasons that the acoustic wave disturbs thermal phonons from their equilibrium Planck distribution which is regained during a relaxation time, τ, by random interphonon collisions. In relaxing to their equilibrium distribution, the phonons absorb energy from the wave directly by converting acoustic energy to heat energy,[25, 35] and indirectly due to the damping of dislocations as they move in the "phonon gas".[25] Mason suggests that the cause of damping of dislocations is associated with the phonon viscosity, and states that the dislocation damping constant, B, is proportional to the inverse of the relaxation time, τ, at low temperatures.[25] Since τ becomes very large at low T,[25, 37] and the elastic moduli increase only slightly,[15] it appears that dislocations <u>may</u> be an unimportant absorption mechanism at liquid helium temperature for any direction of propagation. It may be proper, in fact, to consider as dislocation damping only the elastic problem, and dislocation-phonon interaction as part of the phonon absorption phenomenon.

Since the majority of the present experiments was carried out at 4.2° K, it can be concluded that the absorption mechanisms given earlier, those due to lattice defects, in spite of the lower B, are the most significant here. Of special note is that any low-temperature frequency dependence, which can be deduced from Figs. 10, 11 & 12, is necessarily due to such mechanisms, and varies neither as the frequency squared nor linearly with frequency. The residual absorption at very low temperatures, in fact, has been noticed to vary in quartz over a factor of two from about 0.1 to 0.2 of the high temperature absorption from specimen to specimen.[1] The temperature dependent absorption, furthermore, varies less than 20%, if at all, suggesting that residual absorption is more structure sensitive than temperature-dependent absorption. From Fig. 10, α increases by a factor of three or four between 4.2° K and room temperature in LiF. With respect to the region where α varies with temperature, the conclusion of Woodruff and Ehrenreich is noteworthy.[37] They find that the attenuation is equal to the product of three factors, one proportional to ω^2, one equal to the thermal conductivity times the temperature, and one the inverse tangent of $(2\,\omega\tau)$ divided by $(2\,\omega\tau)$. In the temperature-dependent region the product of the curves of the last two factors would determine the <u>shape</u> of the absorption characteristic as shown relatively in Fig. 13 A & B. When multiplied by the first term, ω^2, the shape of the α curve is as in Fig. 13C. This phenomenon has been demonstrated.[1, 13, 21, 25] It is qualitatively supported in the present experiment. As mentioned in Sec. II-4, a few "good" echos were obtained for both the [100] and the [110] crystals in the middle range between, but not at, room and liquid air temperatures. (At higher frequencies as in Fig. 13, this effect would be expected to disappear.) Just why echos in this project appeared to be attenuated to about the same extent at both room and liquid air temperature, with a low point in attenuation in between, is not explained by the foregoing. A possible "rocking" of the transducer as the viscosity of the bond was increasing could have had some complicated effect. It is significant, however, that at liquid helium temperature for neither the [100] nor the [110] crystal could an improvement in echo pattern over that at liquid air temperature be obtained. Now the orientation factor of these two crystals is <u>not</u> zero, and the residual attenuation (as mentioned above) seems to be very structure sensitive. It is possible, therefore, that dislocation damping, regardless of possible reduction in B at low temperature, is great enough to preclude observing the large change in α below liquid air temperature as shown in Fig. 13.

6. Parallelism

It has been demonstrated that α is a sensitive function of dislocation density in a metal[31, 39] and in alkali halides.[16, 17, 31, 40, 41] With regard to the density of dislocations, it is known that these originate upon plastic deformation of the specimen, but that a certain time lapses before they become pinned.[16, 17, 40]

It may therefore be concluded that an acoustic absorption experiment made just after deformation would show a great increase in the damping of sonic waves.[16, 17, 24, 39] It was originally intended in the present project to make measurements comparing α vs f curves determined before and after deformation of the specimen. But of the methods effective in plastic deformation to create dislocations (bending about an axis perpendicular to the long axis of the specimen, shearing of a long side relative to the opposite side, twisting around the long axis, compression stress between two long sides), all seemed likely to cause either breakage of the specimen or disturbance in the parallelism of the end faces or both.

Lack of parallelism of the ends of the specimen becomes increasingly critical with increasing frequency. It is the most severe of four factors causing the exponential decay of the echos to be modulated[21, 38] (Fig. 8). Other factors are diffraction, bounded wave propagation and poor flatness. In this project lack of parallelism is attributed to six conditions, the result of which would be a vector summation giving an <u>effective</u> angle of non-parallelism. This angle is composed of (1) the four-second tolerance in polishing, (2) the fifteen-minute tolerance in aligning the physical axis with the crystallographic pure-mode axis when cutting the specimens, (3) an unknown angle between the face of the transducer and the end-face of the specimen, (4) an unknown angle introduced by the optical method of polishing which, due to inhomogenieties in the rod, may have caused differences in optical path length over the cross-section, (5) a possible "wedge angle" of the elastic properties of strain fields due to elastic inhomogenieties[11, 38] and (6) non-alignment of the specimen axis with the electric field. Clearly the angle due to the third, fourth, fifth and sixth of these factors would be extremely difficult to determine, while the angle due to factors three, five and six most certainly changes from one run to the next.

According to Jacabsen,[21] the maximum allowable effective angle of non-parallelism, if the first n echos are to be free from modulation, is $\beta \approx \lambda/2nD$ where λ is the wavelength of the acoustic wave and D is the diameter of the transducer. (This is one of two reasons that the diameter of the transducer was made equal to one-half of rather than equal to, the side of the face of the specimen. The other reason is mentioned later.) The velocity of compressional wave in LiF in the [111] direction at 4.2° K is, from a method to be discussed, 0.77 cm/μ sec. At a frequency of one kilomegacycle, therefore,

$$\lambda = v/f = \frac{0.77\times10^{6}\ \mathrm{cm/sec}}{10^{9}\ \mathrm{sec}^{-1}} = 7.7\times10^{-4}\ \mathrm{cm}$$

(The lattice, therefore, appears as a continuum to the acoustic wave, while the spacing of dislocations, 10^{-3} cm, compares to the wavelength.) The transducer was 0.16 cm in diameter, so that if the first twenty echos were to be unmodulated

$$\beta = \frac{7.7 \times 10^{-4}\,\mathrm{cm}}{2 \times 20 \times 0.16\,\mathrm{cm}} \approx 10^{-4}\,\mathrm{rad} \approx 25\,\mathrm{sec},$$

an angle which, from the evidence of Fig. 8 was not obtained. Fig. 9, however, despite the <u>slight</u> modulation of the nearly perfect exponential decay, indicates that a fortunately small vector sum apparently was obtained for the effective angle of non-parallelism in that run. Values of the angle of non-parallelism which cause such modulation as is shown in Fig. 8 are discussed by Jacobsen,[21] by Truell and Oates,[38] and by Rowell.[11] Rowell believes that the effective angle of non-parallelism must be less than 6' for echos to be seen at all at f = 1 kMc, while Truell and Oates insist that β = 0.01" is the maximum tolerable angle for the same frequency. An important point of controversy arises with Jacobsen's concept of a modulation free pattern of echos for the first n echos, and with Rowell's requirement for the presence of even the first echo. This point, in brief, is that echos <u>not</u> present can produce the impression that the echos which <u>are</u> present do, in fact, represent the true attenuation. Inspection and comparison of Figs. 7 & 8 show that where the attenuation is high and only a few echos are present (i.e. at high temperature and at the high and low ends of the frequency spectrum here examined) the first modulation peak does not appear. In those cases where several modulation peaks are present (for Figs. 8C, E, F & G where four such peaks were visible on the oscilloscope) the first few echos do decay exponentially but with too high a value of α . Since energy is certainly not created in the LiF specimen, it is the maxima (also seen to decay exponentially in Fig. 8) which describe the true attenuation. This conclusion is supported by Mason and McSkimin.[4] Whether one should strive for the extreme dimensional tolerances described by Truell and Oates, or be content with peak-to-peak attenuation data is not resolved here. That the two methods do not yield exactly the same results, however, is seen by comparing the upper two curves with the lower two curves in Fig. 11. The upper curves yield an $\alpha \approx 0.045$ nepers/cm in the frequency range measured, while the lower ones give an $\alpha \approx 0.015$ nepers/cm. It is also curious to note that the echo patterns of Fig. 9 give a peak-to-peak attenuation (to the extent peaks can be discerned) which has a logarithmic plot parallel to that of the attenuation of the first few <u>unsaturated</u> echos. According to Jacobsen[21] the mechanism by which non-parallelism causes modulation is that when the wave vector makes an angle β with the normal to the face of the transducer, the next half of the wave front begins to drive a portion of the face 180° out of phase with the remainder. As β increases, with increasing number of reflections, the net piezoelectric polarization will go through a series of maxima and minima, i.e. modulate the decay envelope. Since β is proportional to λ , it is also proportional to 1/f, so that the position of the modulation peaks with respect to a given echo number should vary with frequency in the same run. This phenomenon can be seen in Fig. 8 where the first two maxima and the first two minima "recede" slightly in echo number at higher frequencies. It has been qualitatively observed in this laboratory that at 10 kMc, modulation peaks have about the same spacing as the echos themselves. The minima, then, occur when a "non-equilibrium" ratio of compression-to-rarefaction half wave fronts pass across the transducer face during the reception of a given echo.

7. Bounded Guide Propagation, Flatness, Velocity

Two other causes of modulation not considered significant at the high frequencies of this project, where the wavelength is much less than the dimensions of the system, are diffraction and bounded wave propagation.[21] Because the LiF specimen is definitely a bounded guide, however, this interesting concept is worthy of a short discussion. If the whole face of the specimen is considered as a vibrating membrane and is driven as a piston source (entire surface displaced uniformly), several modes, each a successively higher order Bessel function, and each with a slightly different phase velocity, will be propagated.[4, 21] This follows from a Fourier analysis of the axial displacement as a function of a transverse axis. A plane wave connects all atoms displaced to their maximum value at the same time, i.e. those in phase. The value of this displacement is, for the first mode, zero at the specimen edges, finite at the center, and approximates a Bessel function. All modes can be resolved into smaller longitudinal waves which produce transverse waves on reflection from the walls of the specimen. The transverse waves absorb energy from the primary longitudinal wave to produce out-of-phase secondary longitudinal waves. In this project, for whatever advantage could be gained, a transducer with a diameter half the length of one side of the specimen face was used, in an effort to excite only the fundamental mode. For cases where this source of loss might be important, it would be an interesting project to design a reentrant post (Figs. 2 & 3) whose end was so shaped as to produce an electric field which would excite only the fundamental mode in the specimen. That the travelling modes are Bessel functions assumes vibrating circular membranes. This assumption is compromised by the condition that the cross section of the LiF specimen was square. Excellent treatments of stress waves in solid cylinders are given by McSkimin[42] and by Redwood.[43]

Flatness, although not directly related to modulation, is important in achieving maximum signals and should be within $\frac{1}{2}$ a sonic wavelength.[21] The flatness was within $\frac{1}{4}$ wavelength of sodium vapor, or about $\frac{1}{4} \times 6000$ Å $= 1.5 \times 10^{-5}$ cm, while $\frac{1}{2}$ the sonic wavelength ([111] specimen at 1 kMc, 4.2° K) was $\frac{1}{2}(v/f) = \frac{1}{2}\,\frac{0.77 \times 10^6}{10^9} = 38 \times 10^{-5}$ cm. The flatness tolerance was therefore more than satisfied.

The equations for acoustic wave velocity used in this project, after Mason,[44] are as follows:

$$v_{long.} = (c_{11}/\rho)^{1/2} \qquad \text{along the [100] direction}$$

$$v_{long.} = [(c_{11} + c_{12} + 2c_{44})/2\rho]^{1/2} \qquad \text{along the [110] direction}$$

$$v_{long.} = [(c_{11} + 2c_{12} + 4c_{44})/3\rho]^{1/2} \qquad \text{along the [111] direction}$$

where ρ is the density of LiF. It is not the purpose here to derive these, but it might be pointed out that they apply to any cubic crystal, and that of the six-by-six matrix of elastic moduli, c_{ij}, where $\sigma_i = \sum_{j=1}^{6} c_{ij} e_j$, only three independent ones remain for cubic crystals like the alkali halides. These are $c_{11} = 11.12 \times 10^{11}$, $c_{12} = 4.20 \times 10^{11}$ and $c_{44} = 6.28 \times 10^{11}$ dynes/cm^2 for LiF at 300° K, and are $c_{11} = 12.46 \times 10^{11}$, $c_{12} = 4.20 \times 10^{11}$ and $c_{44} = 6.49 \times 10^{11}$ dynes/cm^2 at 4.2° K. Many different values of the moduli are offered in the literature,[25, 36, 45] but those of Briscoe and Squire,[15] since they were obtained by an ultrasonic measuring technique, are used in this thesis. Although shear distortion can cause changes in the elastic moduli,[25] none other than

$c_{44} \neq \frac{1}{2}(c_{11} - c_{12})$ is considered here. (From Kittel, crystals which are completely isotropic and which satisfy the Cauchy relation, $c_{44} = c_{12} = (1/3)c_{11}$, have but two independent moduli.)[36] According to Huntington, $c_{44} < \frac{1}{2}(c_{11} - c_{12})$ for most of the alkali halides.[45] In the case of these substances the shear distortion associated with c_{44} leaves the distance between nearest neighbors unaltered in the first order. For this reason that part of the internal energy per unit cell arising from the interaction of the overlapping closed shell of neighboring ions, makes only a small contribution to c_{44} but a substantial one to $\frac{1}{2}(c_{11} - c_{12})$. For LiF, however, where the small size of the alkali Li^+ ion causes the most intimate contact to be between the halide F^- ions along $\langle 110 \rangle$ directions, $c_{44} > \frac{1}{2}(c_{11}-c_{12})$. From the foregoing equations and values of elastic moduli, the velocities in cm/μsec of longitudinal acoustic waves in LiF are:

	300° K	4.2° K
v_ℓ (100) [100]	0.65	0.69
v_ℓ (110) [110]	0.73	0.76
v_ℓ (111) [111]	0.75	0.77

IV. CONCLUSIONS

Two definite restrictions in obtaining good data for this sort of experiment are the bonding material and method of making the bond, and the design of the reentrant cavity. Separate research on finding a suitable material for bonds (Sec. II-3) and on securing (and possibly preserving) good bonds is essential. Also, due to the great power losses in the system (Fig. 3 and Sec. III-4), greater attention should be given to designing a cavity which will maximize the electric field at the transducer.

Although LiF is ideal for the study of dislocations (Sec. III-1), its high attenuation of acoustic waves in the kilomegacycle region appears to render it unsatisfactory for this type of experiment. As is generally reported in the literature, attenuation is proportional to the frequency squared well above liquid helium temperature, and is independent of frequency near and at 4.2° K. In spite of a reduction, however, in the damping constant with decreasing temperature (Sec. III-5), dislocations should be the important (although small) attenuating mechanism at 4.2° K. But from the results of the present study dislocation damping is considered sufficiently high to prevent meaningful data in the [100] and [110] crystals at any temperature (Secs. II-4 & III-5), and insignificant in the [111] crystal due to low orientation factor (Sec. III-4). There is no indication of what sort of dependence exists between α and f at 4.2° K, if any. Observation of any such dependence would apparently depend upon an extremely well controlled experimental technique.

Using the values of B, C, and b of Sec. III-2, σ and Ω of Sec. III-4, f = 1 kilomegacycle, $L_i = 10^{-4}$ cm and neglecting the mass term in Koehler's equation,[25, 27] this author estimates the damping term to be 25×10^{-4} dyne/cm and the restoring term to be 25×10^{-5} dyne/cm. Koehler's suggestion that damping may be negligible is therefore invalid, while Suzuki's statement that the model is an overdamped system is supported. In this case ω_m, as in Sec. III-3, is probably much lower than ω_o. If, however, $f_m \approx 23$ Mc, the peak exists in a frequency region low enough for the $\alpha \propto f^2$ law to be less valid because of diffraction and diffusion losses.[17, 19] The values of Δ, both absolute and relative, of Suzuki et al. ($\Delta = 2 \times 10^{-3}$ nepers at 5 Mc in the deformed crystal; $\Delta = 3 \times 10^{-4}$ nepers at 20 Mc in the irradiated crystal) may therefore need to be modified in comparing them to data of higher frequencies. In referring to Fig. 10 the left-hand "tail" of the room temperature curves can be considered to be the high-frequency trailing edge of Suzuki's dislocation peak. Since the long right-hand sides of these curves correspond to the $\alpha \propto f^2$ law, it can be concluded that the effect of dislocations has been passed. The dislocation effect is apparently just a hump on the phonon viscosity dominated $\alpha \propto f^2$ curve.

If enough echos can be obtained for several modulation peaks to be observed, parallelism in the low kilomegacycle region need not be a crucial matter (Sec. III-6). Determination of α by peak-to-peak measurements, however, turns out to be a somewhat less accurate method than theoretically possible, and a minimum angle of non-parallelism should be sought.

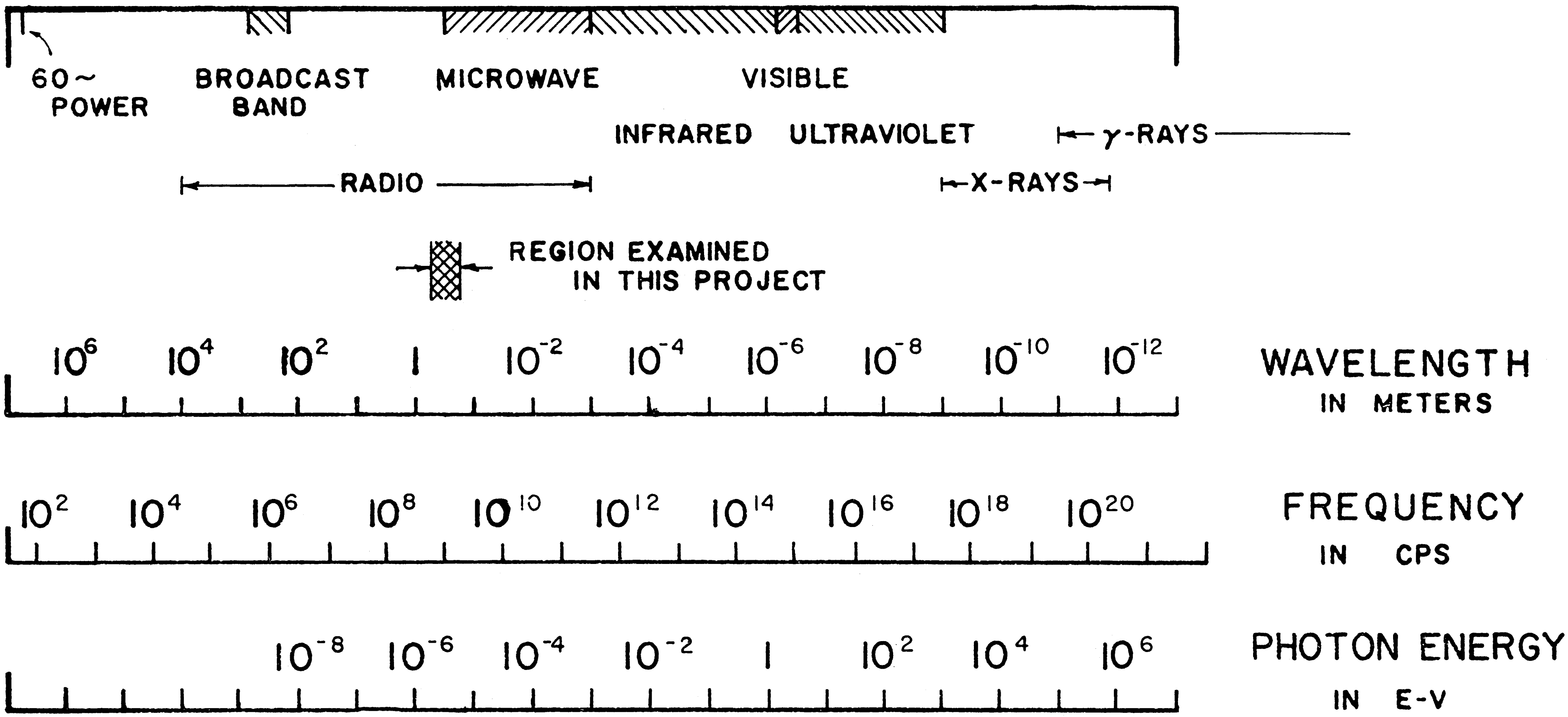
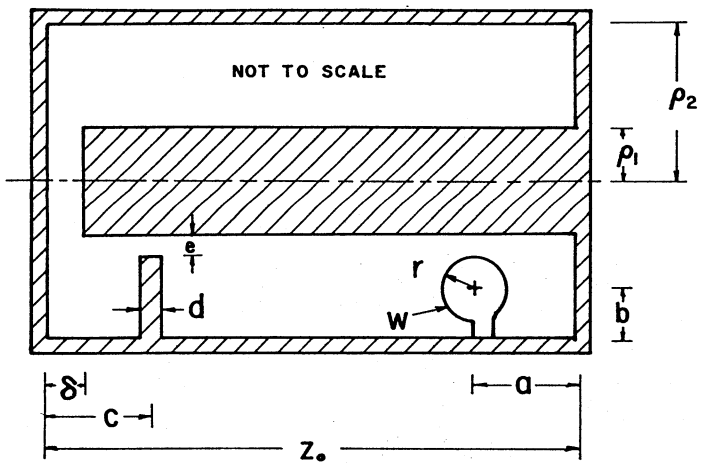


FIGURE 1

ELECTROMAGNETIC SPECTRUM



TUNABLE CAVITY

$Z_o \approx 1.50''$ VARIABLE
$\rho_1 = 0.25''$
$\rho_2 = 0.75''$
$\delta \approx 0.01''$ VARIABLE
$r = 0.125''$
$a = 0.375''$
$b = 0.25''$
$w = 0.062''$ DIAM.

FIXED CAVITY

$Z_o = 1.875''$
$\rho_1 = 0.125''$
$\rho_2 = 0.687''$
$\delta \approx 0.005''$
$r = 0.125''$
$a = 0.50''$
$b = 0.125''$
$c = 0.50''$
$d = 0.125''$
$e \approx 0.03''$ VARIABLE
$w = 0.031''$ DIAM.

FIGURE 2

CAVITY DIMENSIONS

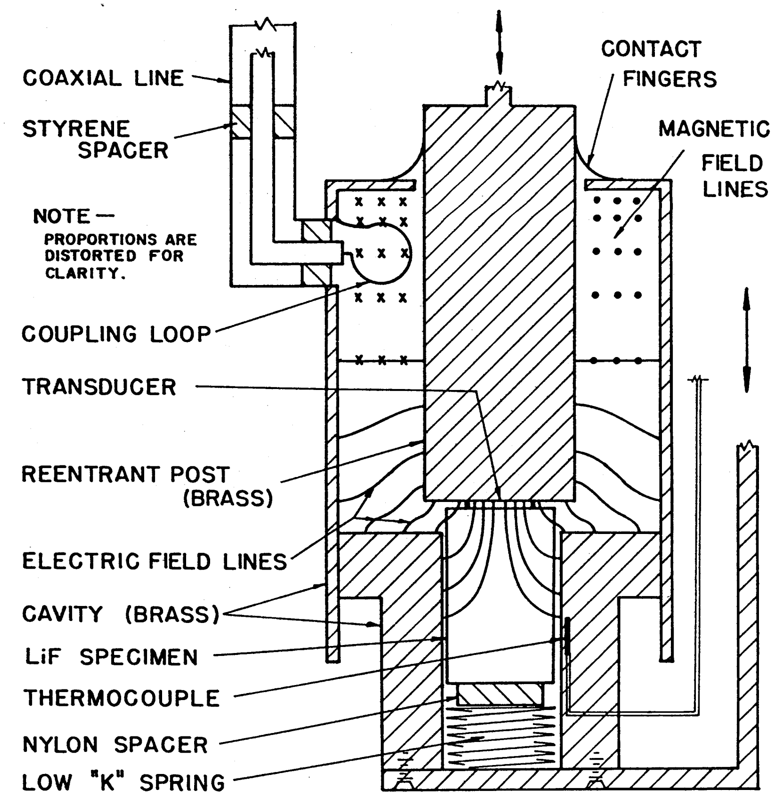


FIGURE 3

LiF SPECIMEN IN SITU
WITH FIELDS SHOWN IN REGIONS
OF HIGHEST DENSITY

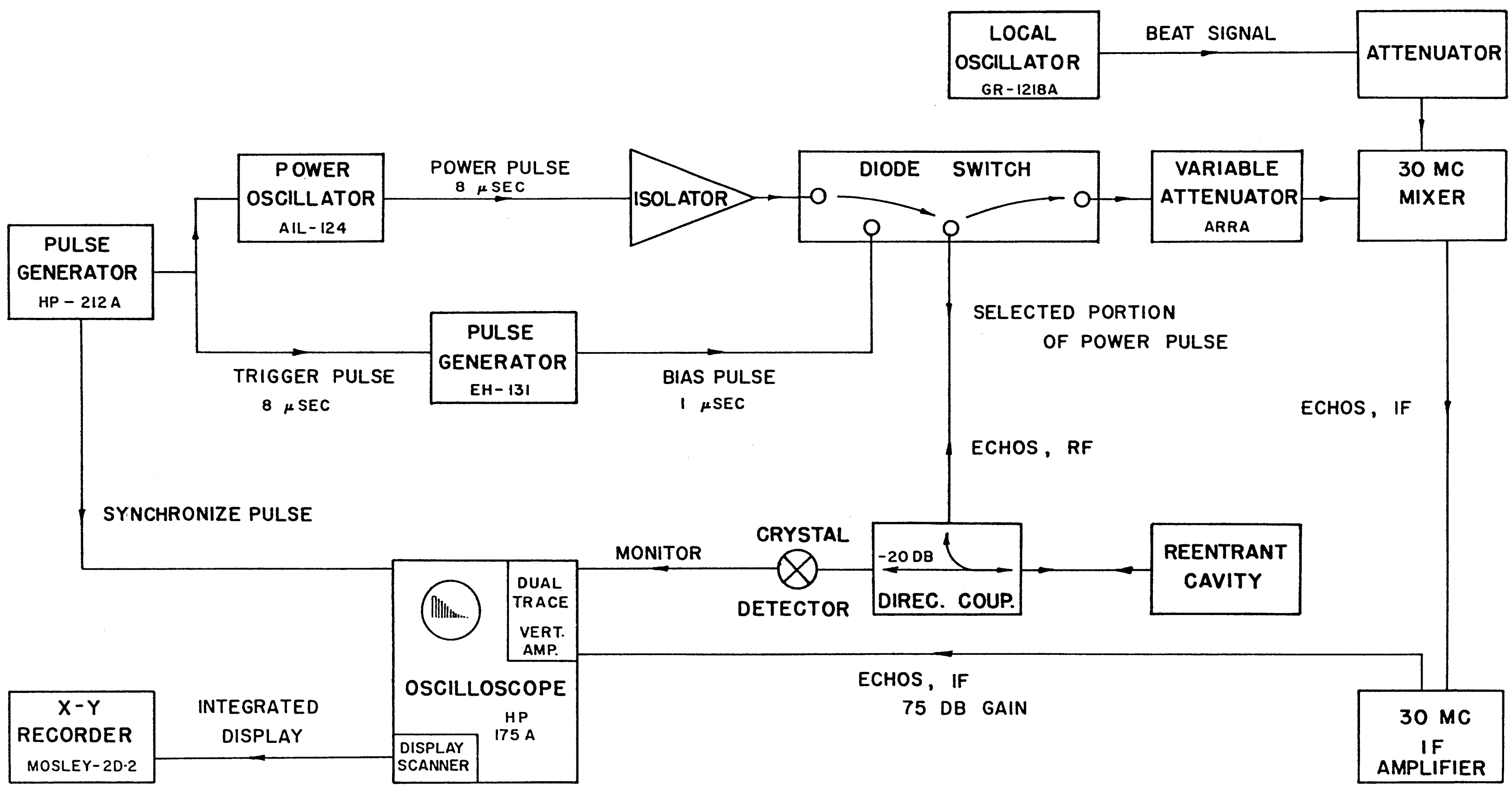


FIGURE 4

BLOCK DIAGRAM OF APPARATUS

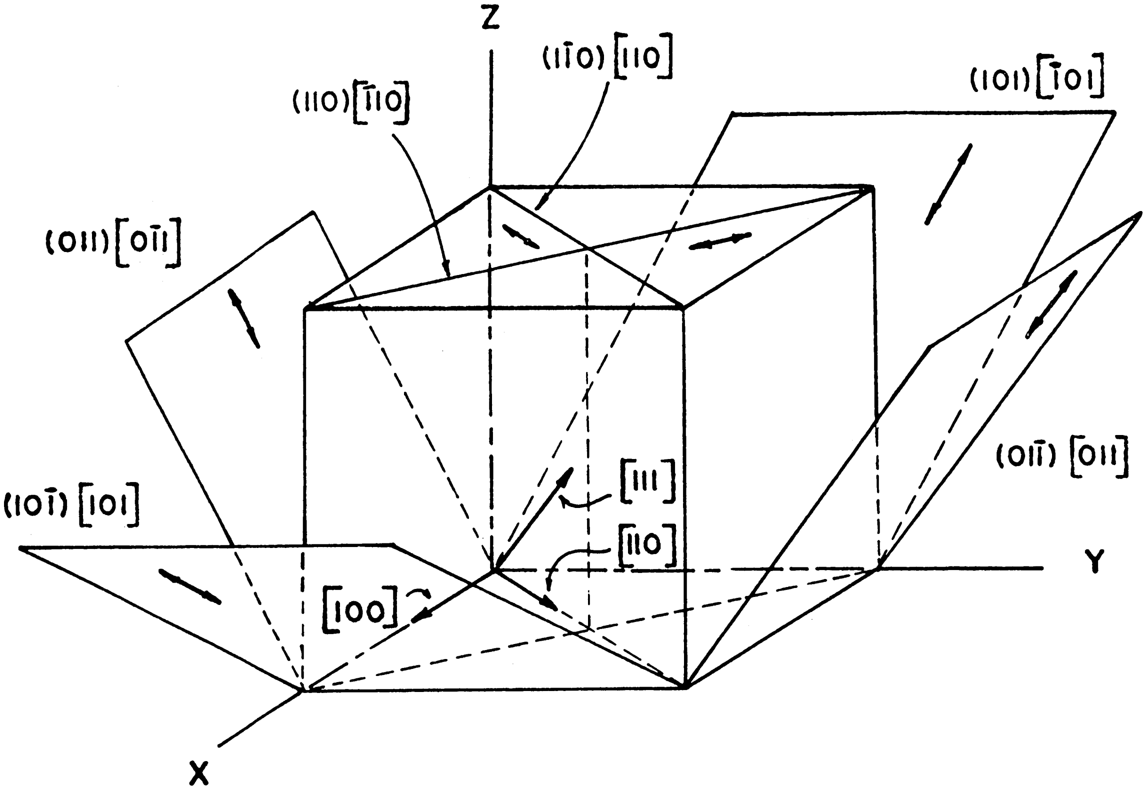


FIGURE 5A

UNIT CUBE SHOWING SIX {110} TYPE SLIP PLANES WITH THE ⟨11̄0⟩ TYPE SLIP DIRECTIONS SHOWN BY DOUBLE ARROWS

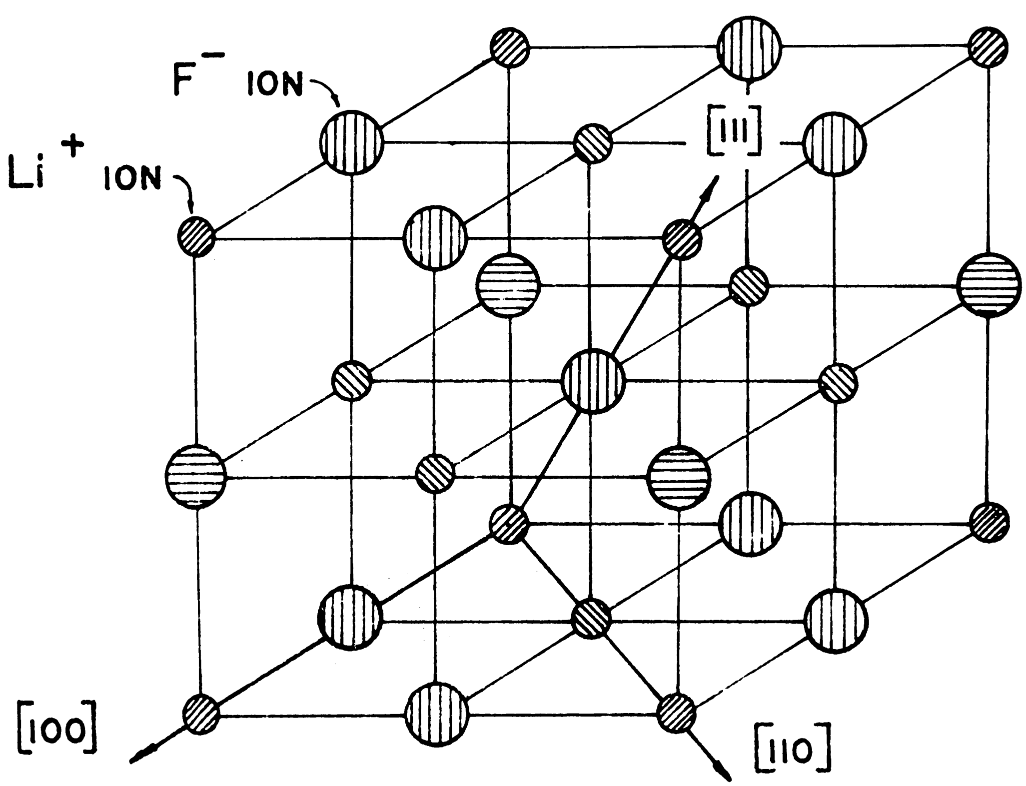
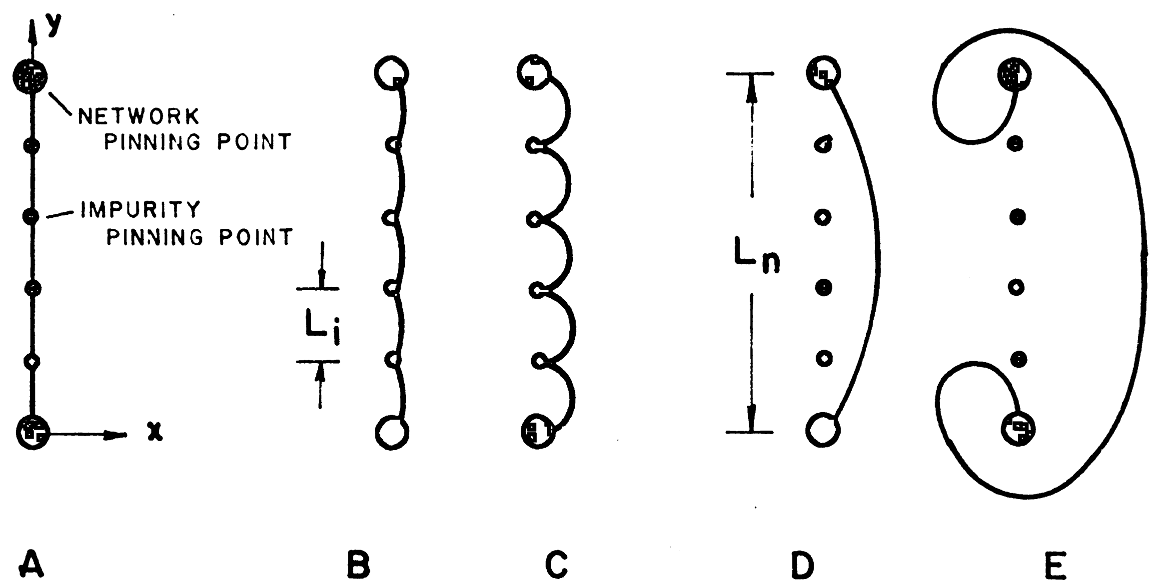


FIGURE 5B

FCC SUPER-LATTICE OF LiF

LOW STRESS FIELD HIGH STRESS FIELD



INCREASING STRESS, τ, IN $\langle 1\bar{1}0\rangle$ DIRECTION, ON $\{110\}$ PLANE, THE PLANE OF THIS FIGURE.

THE CONFIGURATION SHOWN IN "B" IS THAT ASSUMED FOR THIS PROJECT.

FIGURE 6

GRANATO-LÜCKE PINNING MODEL

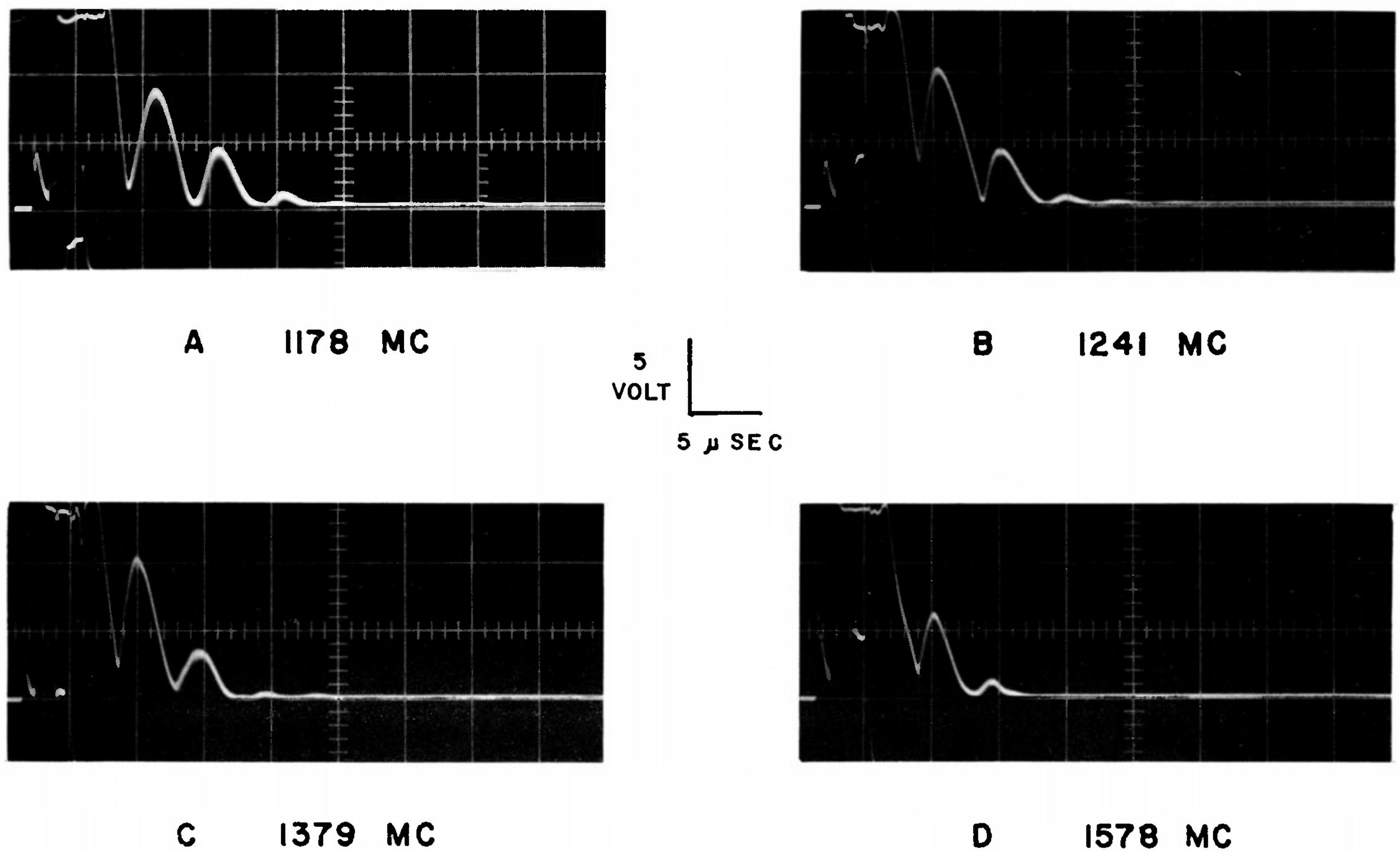
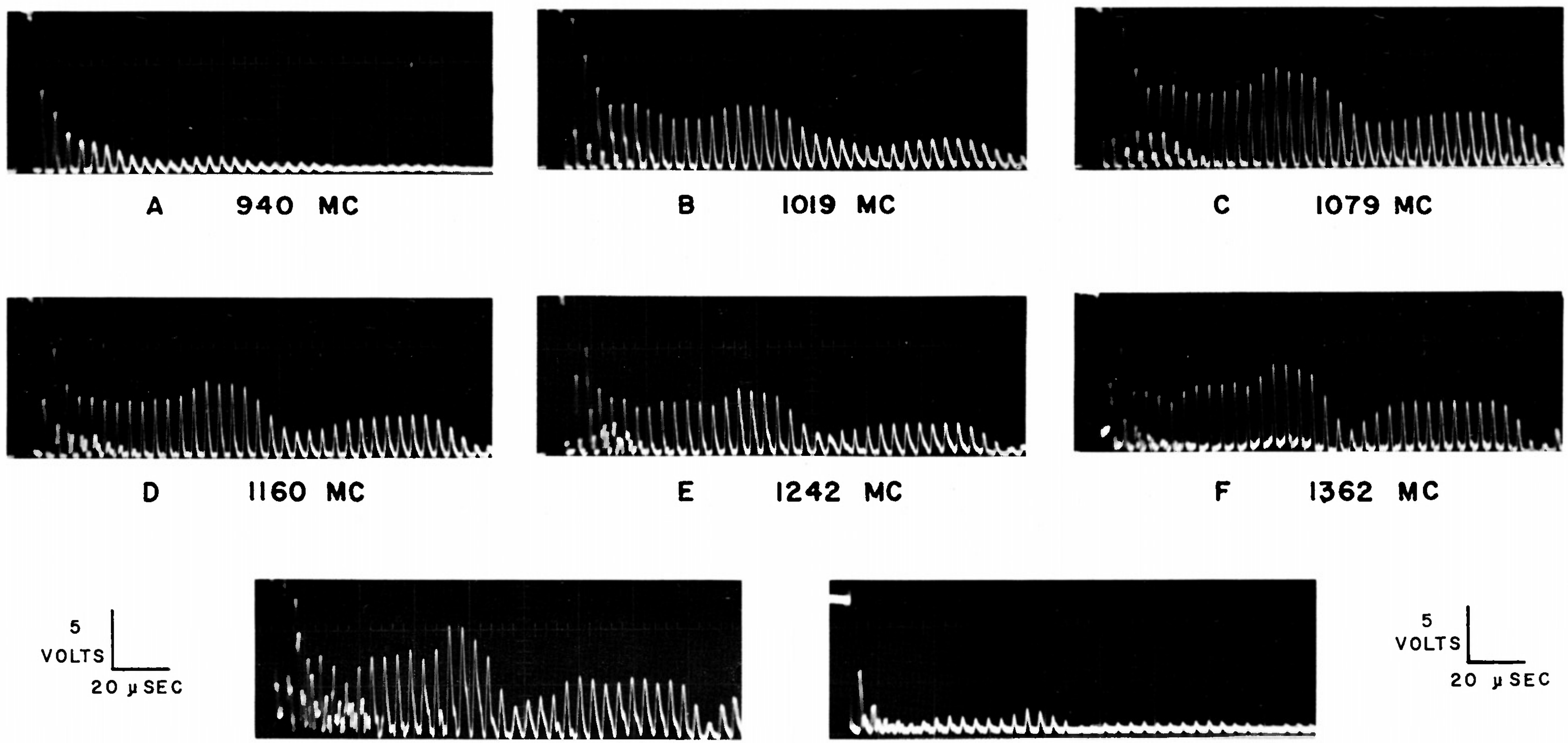


FIG - 7 ECHO PATTERNS OF LONGITUDINAL WAVES IN THE [111] DIRECTION OF LiF SINGLE CRYSTAL ; ROOM TEMPERATURE, DC 1.0M 200 BOND, 1/16" TRANSDUCER (REF. FIG. 10)



G 1482 MC

H 1752 MC

FIG-8 ECHO PATTERNS OF LONGITUDINAL WAVES IN [111] DIRECTION OF LiF SINGLE CRYSTAL; 4.2°K, DC 1.0M 200 BOND, 1/16" TRANSDUCER (REF. FIGS. 10 & 11)

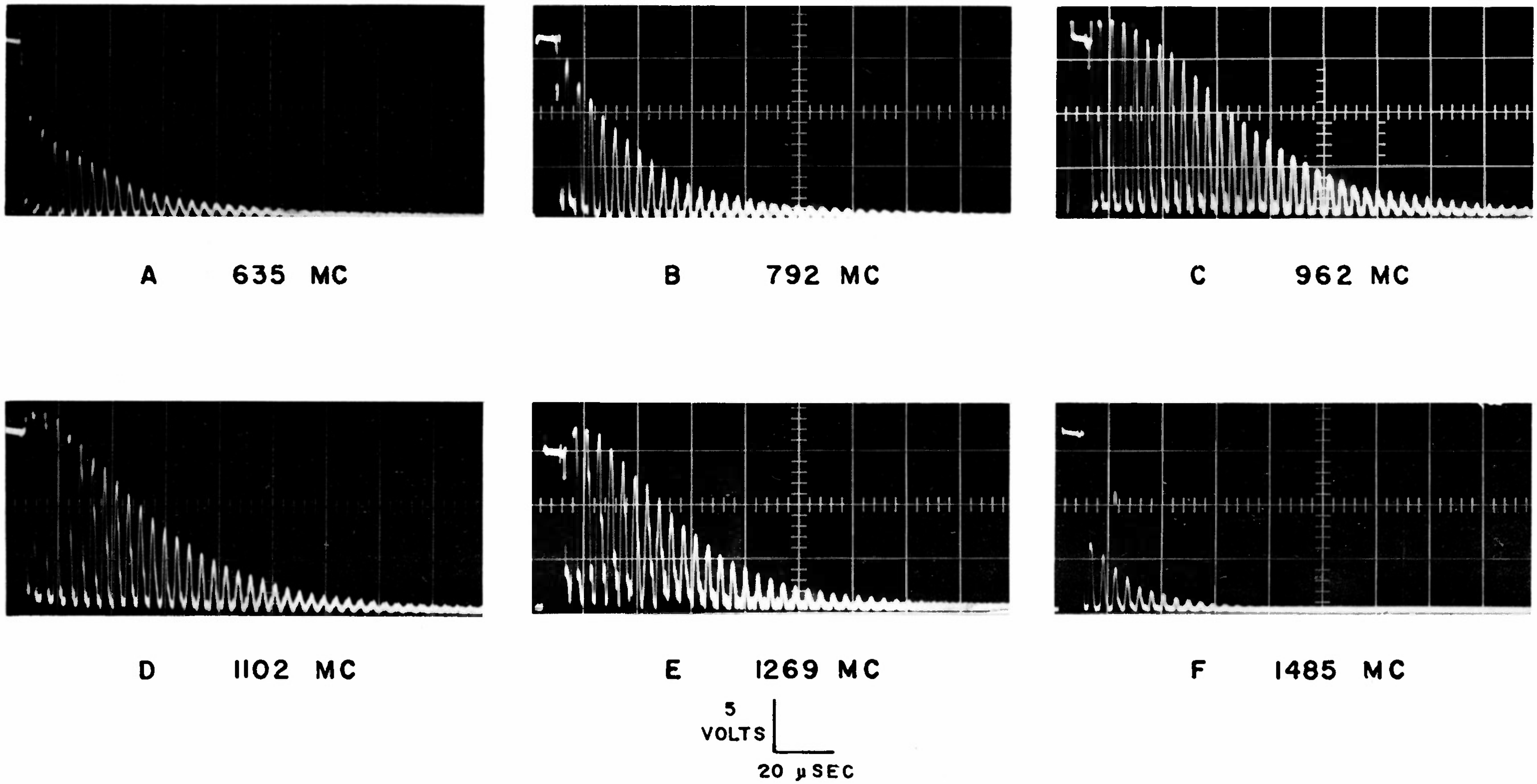


FIG- 9 ECHO PATTERNS OF LONGITUDINAL WAVES IN [111] DIRECTION OF LiF SINGLE CRYSTAL ; 4.2°K, DC 33 BOND, 1/16" TRANSDUCER (REF. FIG. 11)

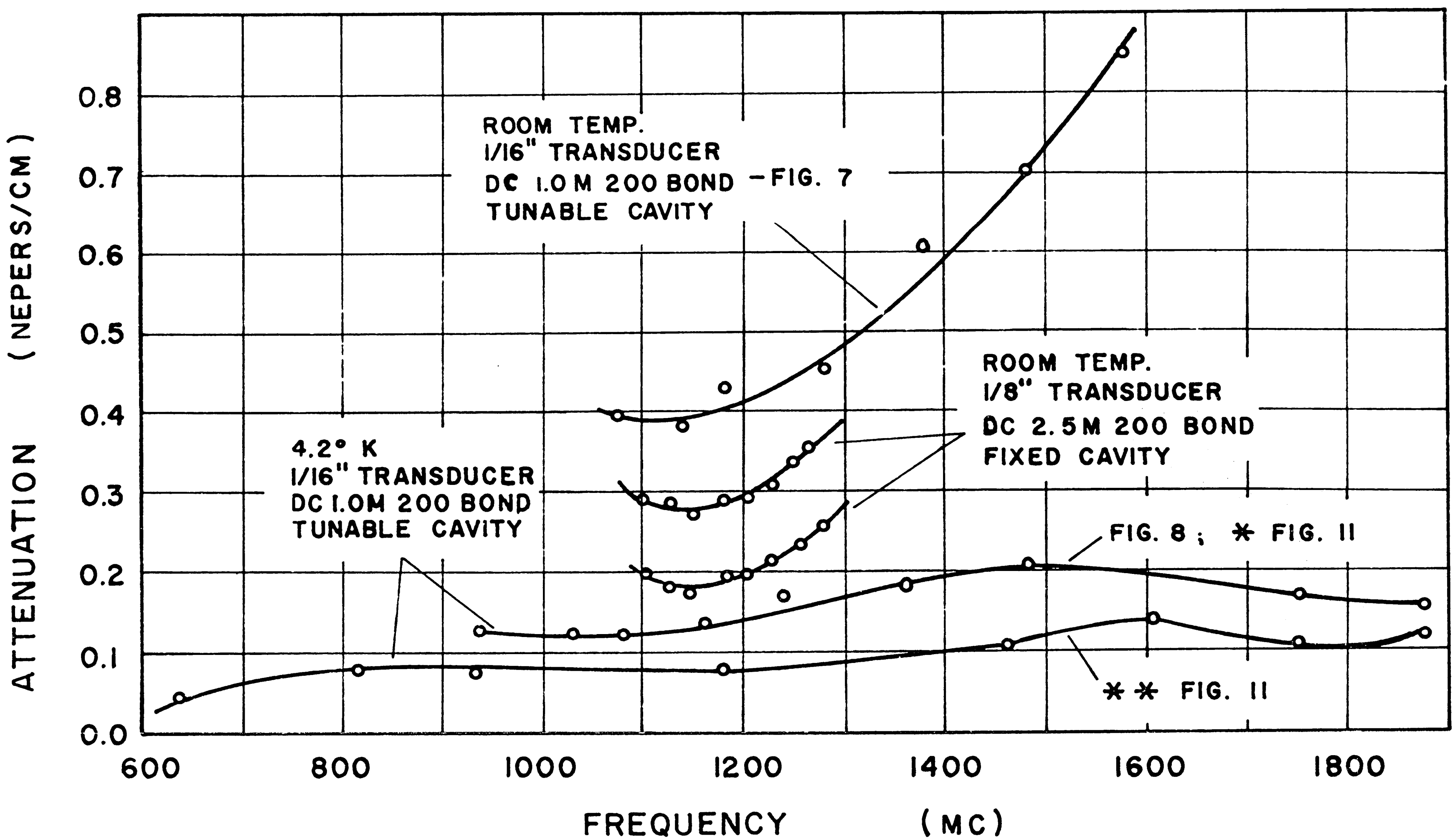


FIG. 10 NATURAL ATTENUATION BETWEEN THE 2nd AND 3rd ECHOS OF LONGITUDINAL WAVES IN THE [111] DIRECTION OF LiF SINGLE CRYSTAL

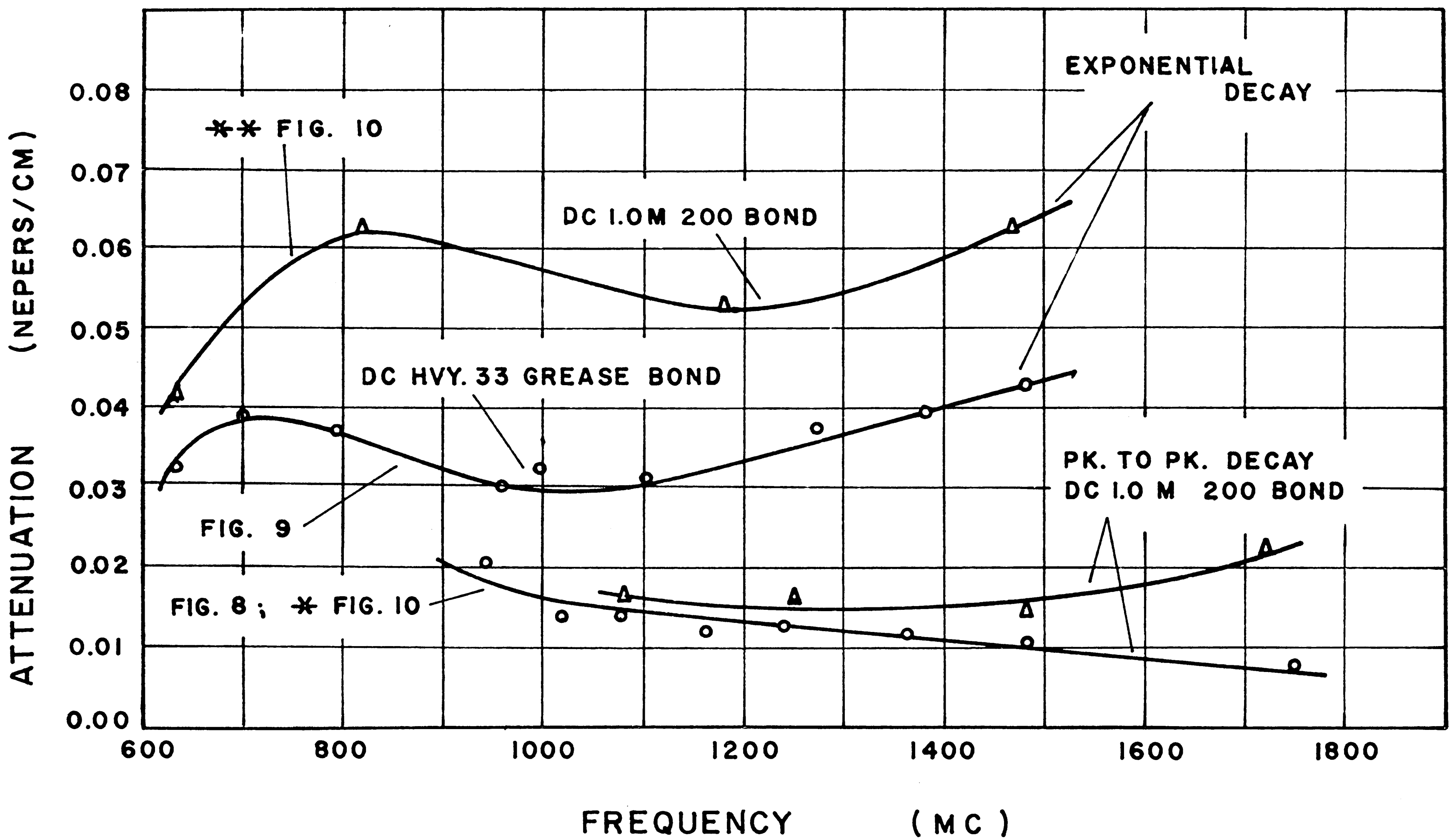


FIG. 11 NATURAL ATTENUATION OF LONGITUDINAL WAVES IN [111] DIRECTION OF LiF SINGLE CRYSTAL; 4.2°K, TUNABLE CAVITY, 1/16" TRANSDUCER

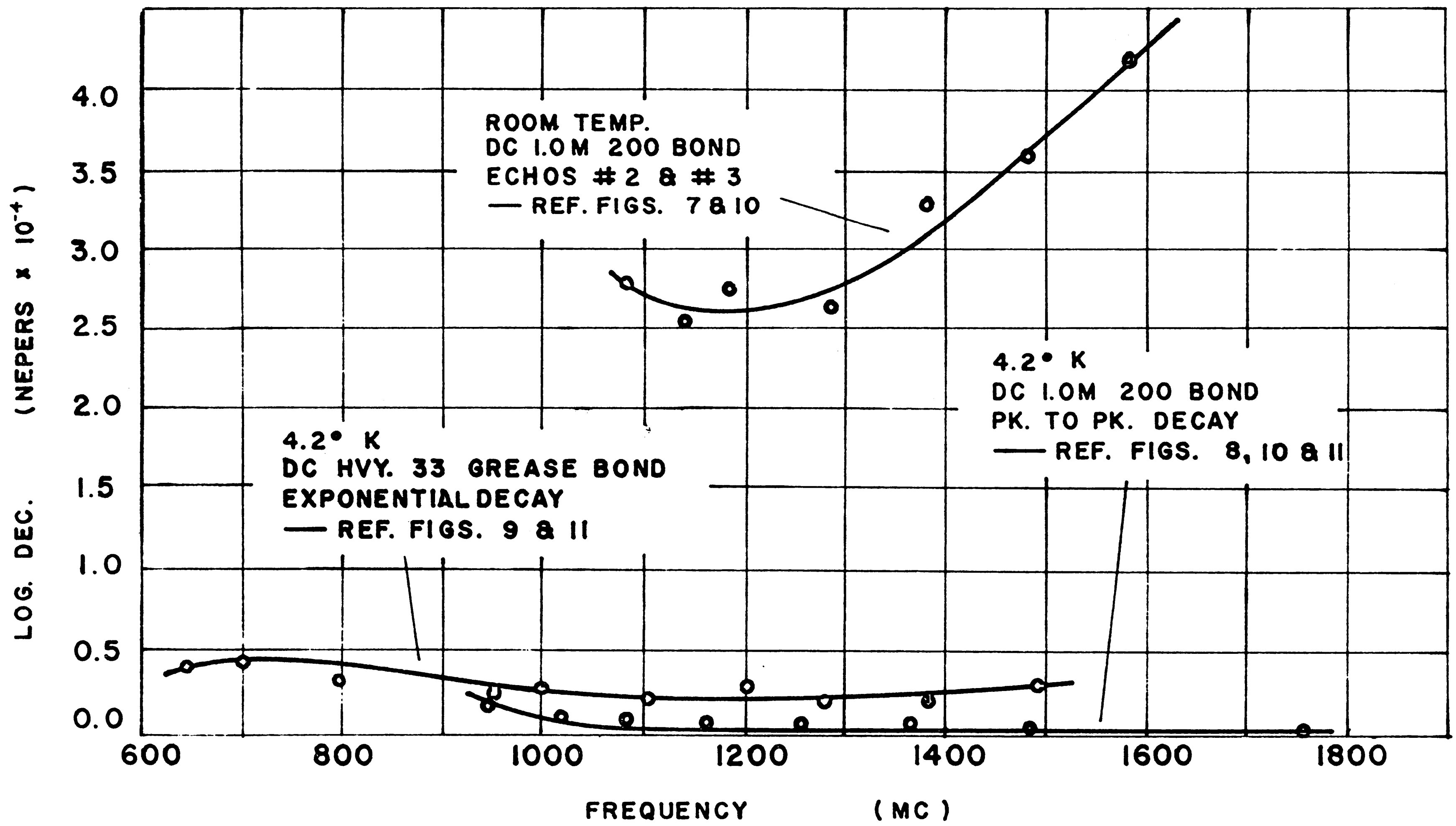


FIG. 12 — LOGARITHMIC DECREMENT OF LONGITUDINAL WAVES IN [111] DIRECTION OF LiF SINGLE CRYSTAL; TUNABLE CAVITY, 1/16" TRANSDUCER

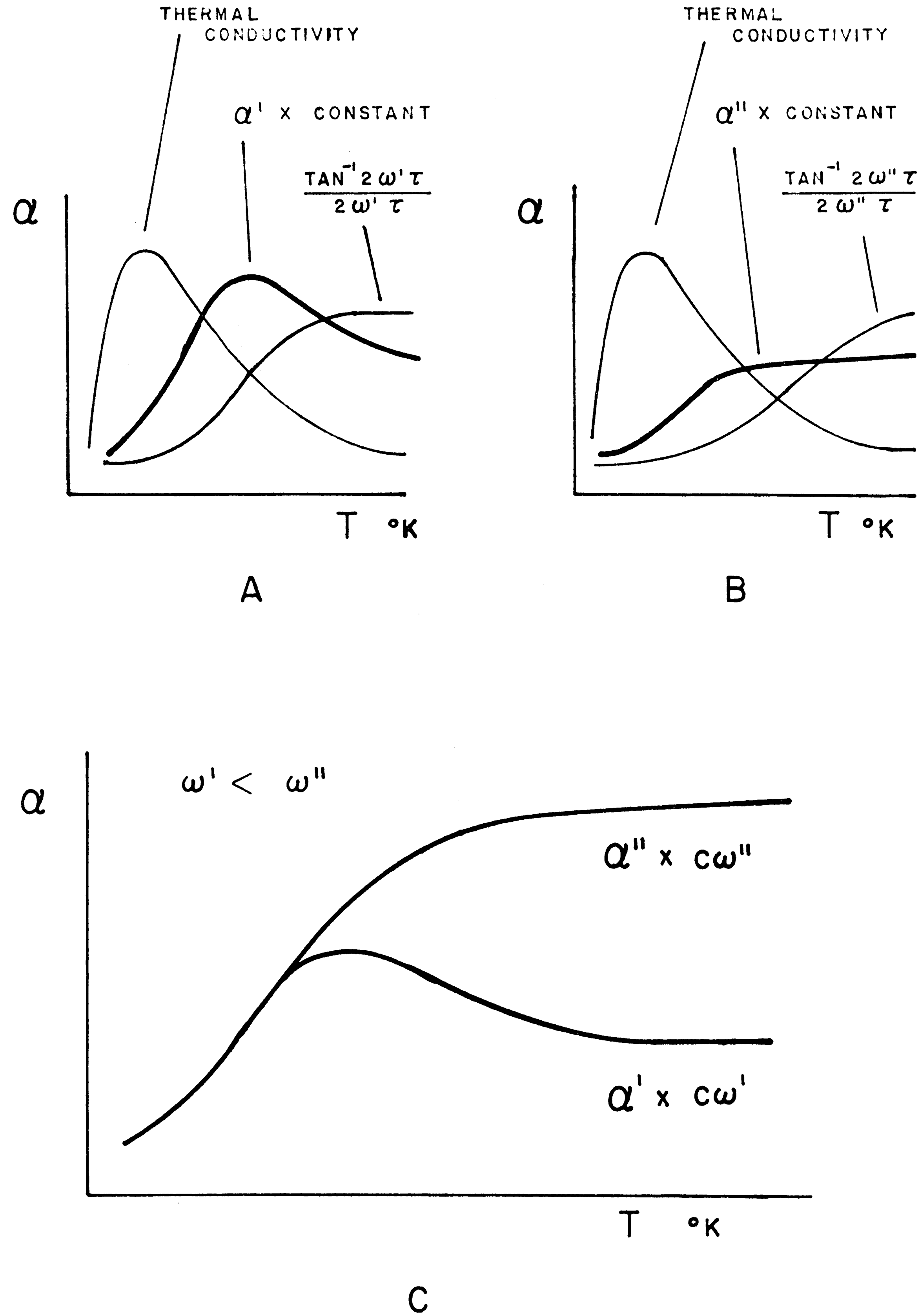


FIG. 13 — **VARIATION OF THE α VS. T CURVE WITH FREQUENCY**

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