GENERATION OF MICROWAVE ULTRASONICS WITH FERROMAGNETIC THIN FILM TRANSDUCERS

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ABSTRACT

Acoustic waves at 9.07 Qc have been generated in thin ferromagnetic films of nickel and monel. The phonon pulses are produced upon spin-wave or ferromagnetic resonance by a magnetostrictive coupling. Both transverse and longitudinal waves have been observed at several angles of magnetic field with respect to film surface. The acoustic spectrum has been studied as a function of magnetic field and compared with a spin-wave absorption spectrum also run on each film. The applicability of various surface pinning models to the results of the individual films is discussed. And the feasibility of this method of generation for use in other acoustic studies is examined and found favorable.
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I. INTRODUCTION

It is the purpose of this thesis to report on an experimental investigation of a new technique for generating acoustic waves at microwave frequencies conducted by the author. Thin (2000A-10,000A) ferromagnetic films of nickel and monel, vacuum deposited onto the ends of optically polished and parallel ruby rods, were utilized as resonant magnetostrictive transducers. Radio-frequency pulses at 10 Gc were converted into acoustic pulses at the same frequency upon satisfying the conditions for ferromagnetic or spin-wave resonance within a microwave cavity. After reflection from the far end of the ruby rod and return to the film, the sound waves excited an rf "echo" in the cavity by the reverse effect.

The first work reported on this technique was that of Bommel and Dransfeld\(^1\) in 1959, who succeeded in generating 1-Gc acoustic waves in a quartz rod with an 18,000A-thick nickel film. The film was situated adjacent to and parallel with the center post of a re-entrant cylindrical cavity, in such a manner that the rf magnetic field was parallel to the film surface. A large dc magnetic field was imposed perpendicular to the surface; and, at a value of the dc field roughly equal to that for ferromagnetic resonance, an acoustic pulse was observed to be generated. The authors attributed the
effect to a magnetostrictive coupling which related a uniform
precession of the magnetization in the film to a stress
ellipsoid also precessing about the dc magnetic field. If
the direction of the dc field is normal to the film, it can
be shown that, at ferromagnetic resonance, the surface will
undergo a rotational shear motion around the dc field and
the film will emit circularly polarized sound waves into the
quartz on which it is plated.

The range of frequency was extended to 10 Gc in 1961 by
Pomerantz(2), who observed discrete peaks of phonon power,
not only at values of the dc field corresponding to ferro-
magnetic resonance, but also at several other values below
the main line in magnetic field. A spin-wave-absorption
spectrum analysis of the permalloy films used revealed a
definite correlation between phonon-power peaks and discrete
spin-wave-resonance absorption lines. Earlier theoretical
work by Kittel(3), and experimental verification by Seavey
and Tannenwald(4), had shown that the pinning of spins at
the film surface will allow the excitation of standing spin
waves by a uniform rf magnetic field. Only those spin waves
are excited for which the film thickness is an odd number of
half wavelengths long.

Pomerantz's experiment further purported to prove a
direct relation between magnetostriction and the observed
magnon-phonon interaction. By coating half of a rod with a permalloy composition of known zero magnetostriction and the other half with a composition with a large static magnetostrictive constant, he was able to observe the difference in transducing potency. Within the range of experimental sensitivity, no spin-phonon coupling was present in the former while the latter exhibited a rather large effect. This certainly seemed to support the proposed connection. Furthermore, when spin-wave resonance was excited electromagnetically in the two samples, they exhibited approximately the same amplitudes and linewidths. This naturally led to the conclusion that, since the magnitude of the spin-phonon interaction was so drastically different in the two compositions, this mechanism could not be responsible for the observed linewidths.

More recent work by Seavey\(^{(5)}\) has presented contradictory evidence on the above points. Not only was he able to generate quite strong acoustic waves with 83-17 permalloy (zero magnetostriction composition), but certain discrepancies appeared in correlating phonon peaks in a one-one fashion, with spin-wave-resonance lines.

Seavey's experiments and those of Lewis, Phillips and Rosenberg\(^{(6)}\) have also exhibited the feasibility of generating longitudinal waves and various admixtures of longitudinal and
transverse acoustic waves for directions of the magnetic field other than normal to the film surface. In particular, the parallel alignment case has been well investigated and appears to give easily interpretable results.

Interest in the generation of coherent lattice vibrations of definite frequency and polarization at microwave frequencies has developed in a number of current fields of research. As indicated above, the generation process itself can act as a sensitive probe of the strength and nature of the spin-lattice interaction in ferromagnets. The question of relaxation mechanisms in ferromagnets and antiferromagnets is yet unclear in many instances. In the field of paramagnetic resonance, where the spin-phonon interaction is known to be the dominant relaxation mechanism, a great deal of information has already been gained on the magnetoelastic coupling through resonant absorption from microwave phonons at the Larmour frequency. Phonon-phonon interactions are presently being studied in a number of crystals by measuring the attenuation, as a function of temperature, of acoustic waves. In addition, Pomerantz has used magnetostrictively generated 10 Gc sound waves to study electronic relaxation in semiconductors. This marks the first application of this technique of generation to an independent branch of study.

The other competing process for generation at these
frequencies depends upon the piezoelectric effect and has been used successfully in a number of experiments \( ^9 \). Seavey \( ^5 \) has investigated the relative efficiencies of the two processes and found them to be approximately equal at the present state of the art. However, there seems to be room for substantial improvement in the magnetostrictive case.

The study of thin films has recently come into its own as a separate and quite important branch of research \( ^{10} \). The proper film preparation technique is perhaps the most essential step in producing a successful transducer and will be discussed at length in a following section.

The present study was undertaken with two major ends in view: 1) The development and perfection of this technique was considered desirable for use in microwave acoustic studies already in progress at this laboratory. Problems encountered in bonding piezoelectric transducers to substrates of interest and undesirable characteristics of most of these bonds, particularly at low temperatures, has indicated the desirability of a different approach. 2) As an interesting branch of study in its own right, magnetostrictive generation at these frequencies has been very little studied, and much further investigation is indicated before a full understanding of the phenomenon is acquired.
II. Theory

The interaction of acoustic vibrations with spin waves in ferromagnetic media has been treated by Akhiezer, Kittel and Abrahams, Seavey and others. A good review of the quantum treatment is presented by Akhiezer, Baryakhtar and Kaganov. These treatments are generally concerned with ferromagnetic relaxation in bulk materials and yield strong interaction between a single phonon and a single magnon only when both energy and linear momentum are conserved. It is to be expected that the latter requirement might well be violated in the case of thin films. Near the surface of the material there is no translational invariance normal to the film, so that linear momentum need not be conserved in this direction. Thus, for films of thickness comparable to magnon or phonon wavelength, one might expect interactions between spin waves and acoustic waves of equal frequency but different wavelengths. This is what has been observed experimentally and will be assumed in what follows.

The conditions for spinwave resonance were originally derived by Kittel. The classical equation of motion for a macroscopic magnetic moment in a magnetic field is given by:

\[ \frac{\partial \bar{M}}{\partial t} = \gamma \bar{M} \times \mathbf{H}_{\text{eff}} - \frac{\bar{M}}{T} \]  \hspace{1cm} (2.1)
where \( \chi \) is the gyromagnetic ratio, \( M \) is the saturation magnetization of the film and the last term accounts for the familiar Bloch-Bloembergen phenomenological damping. In the type of experiment being discussed, \( H_{\text{eff}} = H_{\text{ext}} + H_{\text{de}} + h_{\text{ex}}^\text{eff} + h_{\text{rf}} \).

\( H_{\text{de}} \) is the demagnetization field given by \((-4\pi M)\) for direction of magnetization normal to the film surface. The term \( h_{\text{ex}} \) is commonly referred to as the exchange-anisotropy term and is given by \( h_{\text{ex}} = \frac{2A}{M^2} \sqrt{\bar{m}} \), where \( A = 4JS^2/a \) is the spin-wave constant, a function of \( J \), the exchange integral, and "a", the lattice constant. This term contains all of the distinctive features of the spin-wave approximation, corresponding to an effective field at a spin site due to an additional exchange interaction between a spin and its non-parallel nearest neighbors. The non-alignment in this approximation takes the form of a sinusoidal variation of spin direction, the classical angle between any two adjacent spins being very small (16).

The assumption of \( e^{i(kz - \omega t)} \) dependence for \( m \), the microwave magnetization, yields a solution to Eq. (1), neglecting the relaxation term and without the rf field, which is just a precession about the applied dc field with frequency

\[
\omega = \chi (H - 4\pi M) + 2A \chi K^2/M
\]

(2.2)

This is the familiar Kittel relation for spin-wave precession in the case where \( K \) and \( H \) are both perpendicular to the film
surface. The excitation of these spin waves by a uniform rf field was shown by Kittel\(^{(2)}\) to be dependent upon a surface pinning effect. The effects of "pinning" on either one or both surfaces of a thin film were investigated by Seavey\(^{(17)}\), and the experimental results confirm the fact that pinning occurs on both surfaces. This imposes a condition on the possible values of \(K\), giving \(K = \rho \pi /L\), where \(L\) is film thickness and \(\rho\) an odd integer. More recently Kooi, Holmquist and Wigen\(^{(18)}\) have presented experimental evidence which shows surface pinning to be caused by an oxide layer.

In the case of a cubic crystal, the magnetoelastic energy density takes the form:\(^{(19)}\)

\[
U = \frac{b_1}{M^2}(M_x^2 e_{xx} + M_y^2 e_{yy} + M_z^2 e_{zz})
\]

\[
+ \frac{b_2}{M^2} (M_x M_y e_{xy} + M_y M_z e_{yz} + M_z M_x e_{zx})
\] \(2.3\)

where \(M\) is the magnetization, \(b_1\) and \(b_2\) are the magnetostrictive constants and \(e_{ij}\) is a strain component. It is assumed that, for a polycrystalline thin film, the axes of the demagnetizing ellipsoid coincide with the suitably averaged crystallographic axes. From Figure (1)

\[
M_x = m_x
\]

\[
M_y = M \cos \alpha + m_1 \sin \alpha
\]

\[
M_z = M \sin \alpha - m_1 \cos \alpha
\] \(2.4\)
where \( m_1 \) and \( m_2 \) are the microwave magnetizations and \( \alpha \) is the angle between the film normal and the M direction. The following equations of motion result for propagation in the y direction (normal to the film surface) when Eqs. (2.4) are used in (2.3).

\[
\frac{\partial^2 u}{\partial y^2} - \frac{1}{\nu^2} \frac{\partial^2 u}{\partial x^2} = -\frac{b_2}{C_{yy} M} \cos \alpha \frac{\partial m_x}{\partial y} - \frac{b_2}{C_{yy} M^2} \sin \alpha \frac{\partial(m_x m_y)}{\partial y} \tag{2.5}
\]

\[
\frac{\partial^2 v}{\partial y^2} - \frac{1}{\nu^2} \frac{\partial^2 v}{\partial x^2} = \frac{b_1}{(c_{12} + 2c_{44}) M} \sin 2\alpha \frac{\partial m_y}{\partial y} - \frac{b_1 \sin \alpha}{(c_{12} + 2c_{44}) M^2} \frac{\partial^2 m_y}{\partial y^2}
\]

\[
\frac{\partial^2 w}{\partial y^2} - \frac{1}{\nu^2} \frac{\partial^2 w}{\partial x^2} = \frac{b_2}{C_{yy} M} \cos 2\alpha \frac{\partial m_x}{\partial y} - \frac{b_2}{2C_{yy} M^2} \sin 2\alpha \frac{\partial^2 m_y}{\partial y^2}
\]

The terms involving \( \partial m/\partial x \) or \( \partial m/\partial y \) are driving terms for the sound waves at the precession frequency. The quadratic terms on the right have a \( 2\omega \) dependence and are smaller by a factor of \( m/M \).

It will be noticed that for \( \alpha = 0 \) and 90°, only transverse modes will be generated and that the longitudinal driving term is a maximum for \( \alpha = 45° \).

In the neighborhood of spin-wave-phonon crossover (equal \( K \) and \( \omega \)), the full set of coupled magnetoelastic equations must be solved in order to find the displacement components. Seavey (13) has shown that the full solution yields three modes of propagation instead of the usual two. Each mode is a mixture...
of electromagnetic (uniform precession, $K = 0$ mode), spin-wave and phonon excitations, with one of these types usually predominating in a given mode. At crossover, the magnetic and elastic components of the two latter modes are equal and they exchange character, the elastic mode becoming predominantly magnetic and vice versa on the other side.

Far enough away from crossover, the case of interest here, the amount of admixture may be ignored and the magnetic and elastic equations solved separately\(^{(5)}\). In the case of the elastic equations ($2.5$), the $\nabla \bar{m}$ terms will be regarded as spin-wave driving terms for the acoustic waves, and will exhibit the same resonance condition and dispersion relation ($2.2$) as in the uncoupled case.

The solutions to the inhomogeneous wave equations ($2.5$) can be obtained by a Green's function method similar to that used by Jacobsen\(^{(20)}\) for piezoelectric generation. Assuming an acoustical match between film and substrate and neglecting terms in $2 \omega$, the $u$-component displacement is:\(^{(5)}\)

$$u = \int_{y}^{\infty} G(y, y') \left[ -\frac{b_\alpha}{c_m H} \cos \alpha \frac{\partial \rho_{\alpha}}{\partial y'} \right] dy'$$

(2.6)

The Green's function $G(y, y')$ is the sum function for a direct wave and one reflected from $y' = 0$. Thus, since

$$G(y) = \frac{1}{2K_p} e^{-iK_y y}$$
\[ G(y, y') = G(y-y') + G(y+y') = \frac{1}{k} \cos K_p y' e^{-iK_p y} \quad (2.7) \]

and

\[ u = -\frac{i b_2 \cos \alpha}{K_p C_{44} M} \left[ \int_0^d \frac{dm}{dy} \cos K_p y \ dy \right] e^{-iK_p y} \quad (2.8) \]

Phonon generation is thus given by the integral across the film thickness of the magnetic field gradient weighted by the \( \cos K_p y \) factor from the Green's function (5).

In the uniform precession case, \( \frac{dm}{dy} = 0 \) throughout the film interior and generation occurs only at the surfaces. Then

\[ \frac{dm}{dy} = m_0 \left[ \delta(y) - \delta(y-d) \right] \]

and

\[ u = \frac{-i b_2 \cos \alpha}{K_p C_{44} M} (1-\cos K_p d)m_0 \quad (2.9) \]

When the dc magnetic field is parallel to the film (\( \alpha = 90^\circ \)) \( u = v = 0 \) and

\[ w = \frac{-i b_2}{K_p C_{44} M} (1-\cos K_p d)m_0 \quad (2.10) \]

Phonon power flow can be computed from considering \( P_{ac} = U_e v_t \), \( U_e \) being the elastic energy and \( v_t \) the wave velocity, and becomes, for \( \alpha = 90^\circ \),

\[ P = \frac{b_2 v_t}{\alpha C_{44}} \left( \frac{m_0^2}{M} \right)^2 (1 - \cos K_r d)^2 \quad (2.11) \]
and, for $\alpha = 0^\circ$,

$$P = \frac{b_2}{2} \frac{\nu_2}{C_{y y}} \left( \frac{m_0}{M} \right)^2 \left( 1 - \cos k_y d \right)^2$$  \hspace{1cm} (2.12)

where $m_0$ is the amplitude of the circularly rotating microwave magnetization, generating a circularly polarized phonon.

In the spin-wave-resonance case, a similar calculation yields ($\alpha = 0$)

$$P_{nc} = \frac{b_2}{2} \frac{\nu_2}{C_{y y}} \left( \frac{I}{M} \right)^2$$  \hspace{1cm} (2.13)

where

$$I = \int_0^d \frac{dm}{dy} \cos k_y y \ dy$$  \hspace{1cm} (2.14)

and where $\frac{dm}{dy}$ is a sinusoidal function, and generation takes place throughout the interior of the film. Interference between the two terms in the integral can be expected to shift the phonon-power peak associated with a given spin-wave-resonance line off the line by as much as 40 oe at $x$-band. This interference is illustrated in Fig. 2a for a film $3/4$ of a phonon wavelength thick. In the uniform precession case, Fig. 2b, all of the power emerges from the $y = 0$ surface. Destructive interference occurs for waves originating at the $y = d$ surface. For films an odd number of $1/2$ phonon wavelengths thick, the maximum power is generated and, for even numbers, destructive interference cancels all generation.
FIG. 2a ACOUSTIC INTERFERENCE - SPWR - $d = 3/4 \lambda_p$

FIG. 2b INTERFERENCE - FMR $d = 3/4 \lambda_p$
Figures (2a) illustrate the interference for a spin-wave mode. The $\frac{dm}{dy}$ term is given by $\sin K(y=d/2)$, where $K = \sqrt{\frac{M}{2A}} (\frac{\omega}{\gamma} - H)$, and the Green's function weighting factor by $\cos 3\pi/2 y/d$. In the direction of decreasing $H$, the positive contributions grow at the expense of the negative. If resonance occurs at $H = H_3$, the maximum power generation will then be shifted to a slightly lower $H$ value by this interference effect\(^{(5)}\).

Thus, we can expect a quite distinctive dependence of the power-generation versus magnetic field, upon the film thickness. The constructive interference which can be expected to occur for equal phonon and magnon wavelengths (crossover) should produce a quite noticeable effect if the point of crossover coincides with an allowed spin-wave mode.
III. Experimental Procedure

A. Film Preparation

It would be expected that the requirements for a thin film to be a good transducer should be that it be flat, continuous, parallel sided, homogeneous, free from contaminants and adsorbed gases, and as near in physical characteristics to the bulk material as possible. Films of nickel and other high melting point metals with these characteristics have become available in recent years with the refinement of high vacuum evaporation techniques. This was the method chosen for the present investigation.

An essential ingredient for successful plating with nickel appears to be the maintenance of high substrate temperature during deposition(21). Electron microscope studies of early stages of film formation indicate that deposition begins with small three dimensional nuclei dispersed over the layer, even for an average thickness of less than one atomic layer(22). Nucleation proceeds by addition to already established nuclei and by growth of the larger at the expense of the smaller. Both lateral growth in the plane of the film and vertical growth normal to the surface are important. Among the factors determining the growth of the film structure are: cleanliness and regularity of the substrate surface, mobility of atoms and groups of atoms on the substrate surface, residual
gas atoms, and the rate of evaporation. It is found that high melting point atoms, such as nickel, have low surface mobility and tend to form small microcrystals. Unless the vacuum is exceptionally good (<10^{-7} \text{ mm}), the rate of arrival of residual gas atoms will be comparable to that of the nickel, and the resulting structure will be a rather porous one, composed of many small microcrystals combined with adsorbed gases. Such films have been studied and shown to exhibit properties quite different from the bulk material and to be discontinuous for film thicknesses up to 500\text{A}. Heating the substrate to temperatures of the order of 300\text{°C} serves several purposes. In addition to "baking out" the surface of any adsorbed gases or other contaminants, it increases the mobility of nickel atoms on the surface, aiding in lateral agglomeration and the early development of a continuous film. On the other hand, evaporations performed by Pomerantz in 1963 in vacuums of 10^{-10} \text{ mm} and at substrate temperatures of 500\text{°C}, produced epitaxial films consisting of discrete, well separated islands of nickel. This effect is quite common in lower melting point metals such as silver, where well oriented single crystals grow with orientation normal to the surface at temperatures only slightly above room temperature. At the pressures utilized in this experiment (10^{-5} \text{ mm}) this problem would not appear to be pertinent. Substrate
temperatures of approximately 350°C were maintained during evaporation.

The evaporation technique itself presented certain serious problems. Nickel combines with all three of the commonly used heating elements, tungsten, tantalum and molybdenum to form alloys with lower melting points than that of the nickel itself (1455°C)\(^\text{(25)}\). Attempts to vacuum-plate nickel from resistively heated tungsten boats were not successful due to rapid dissolution of the boat and contamination of films by tungsten. Likewise, similar attempts using carbon crucibles yielded carbon contaminated films. By far the cleanest method of vacuum-plating materials appears to be electron bombardment. This technique requires no crucible, using the sample rod as an anode with a 1500V potential between itself and an electron-source tungsten cathode. Electrons accelerated through the potential drop produce sufficient heating upon striking the anode to melt it. Unfortunately, one must maintain a molten zone without severing the anode for a considerable period of time before evaporating enough material to produce films of the desired thickness. The vapour pressure of nickel at 1510°C is 10\(^{-2}\) mm and, at a vacuum pressure of 10\(^{-5}\) mm, it requires several hours to plate a film of 5000Å thickness. This is much too slow a rate of deposition at these pressures and involves a much higher rate of incidence
on the surface of residual gas atoms than of nickel. Both the zone refining technique of maintaining a molten zone in the center of the rod and that of suspending a molten drop on the end required continuous monitoring to avoid "losing the zone" and proved unsatisfactory for the above reasons.

The method which finally proved successful was that of induction heating of the sample from an alumina crucible. Recrystallized alumina (alundum) refractory crucibles have been used for some time in high melting point metal evaporation and yield extremely low contamination depositions (26, 27). A Lepel T-20-3 20kw induction furnace supplied the current to the coils surrounding the sample. Heating is produced by eddy currents induced in the nickel sample, and adequate temperatures (1600°C-1700°C) are easily obtainable for producing a suitable rate of deposition.

The experimental evaporation apparatus is pictured in Figure 3. The alundum crucible containing the nickel sample rested on a quartz cylinder, which served to thermally insulate it from the floor of the pyrex container. The design of the container itself was empirically derived after a straight wall design proved unsatisfactory, due to the induction heating of nickel deposited on the container walls and resultant fracture. The small tail at the bottom facilitates good coupling between the small sample and the coils which are
FIG. 3 VACUUM PLATING APPARATUS
snugly wound around it. The bulge above serves to remove the walls immediately adjacent to the crucible from the region of rf magnetic field and, thus, avoid inductive heating. The brass substrate holder is located directly 20 cm above the sample. It is supported by stainless-steel tubing between two vertical brass supports and is tightly wound with a glass-cloth-insulated tantalum-wire heater. A copper-constantan thermocouple is attached to the holder for temperature measurement, and a microscope slide holder is attached along side the substrate holder to facilitate film thickness measurements to be discussed in the following section. The shutter between sample and substrate is controlled by a magnet outside the container.

The initial and perhaps most important step in thin film preparation is the thorough cleaning of the substrate surface. The substrate was first cleansed of grease films etc. by a standard acid "glass cleaner"\(^{(28)}\), followed by dilute nitric acid. The final step was a mechanical cleaning with a prepared chalk solution\(^{(29)}\), and, after rinsing in distilled water, drying with a chalk powdered cotton swab. Recent work indicates that ultrasonic cleaning may well be the most reliable\(^{(29)}\). However, the above method has proved quite satisfactory.

After both substrate and slide were cleansed, they were
carefully inserted into their respective holders, without direct contact by human hand. The system was pumped down to 10^{-6} \text{ mm Hg}, by an oil diffusion pump and the substrate baked out at a temperature of 350\textdegree C for a period of 4-6 hours. With the shutter in place, the nickel was inductively heated to a temperature of 1000\textdegree C and held at this temperature for 2 hours in order to outgas the nickel and crucible. At these elevated temperatures, the lowest attainable vacuum was 10^{-5} \text{ mm}. As the temperature was raised to the melting point of nickel, the pressure rose to 10^{-4} \text{ mm} and a glow discharge was struck and held for several minutes. The efficacy of a glow discharge in thoroughly cleaning glass surfaces by ion bombardment has been investigated by several authors and is an established technique in film production for interferometer applications^{30}. After allowing sufficient time for the system to pump back down to 10^{-5} \text{ cm} and after evaporating nickel for a few minutes to boil off impurities, the shutter was removed and the temperature elevated to approximately 1600\textdegree C. The rate of evaporation is estimated to have been approximately 500\text{A} per minute, a figure somewhat below that desired, but unfortunately the maximum obtainable with the low-pumping-speed vacuum system utilized.

Considerable improvement could be derived from the employment of a more efficient vacuum system capable of
maintaining the system at pressures of $10^{-7}$ mm or better during evaporation. Techniques for epitaxial growth of single crystal nickel films on heated substrates at pressures of $10^{-9}$ mm have been reported and are, by now, well established\textsuperscript{(31)}. Such films should provide a decided improvement in transducer quality. It is felt, however, that under the conditions of the present experiment, substrate temperature was the most crucial variable. Elevated temperature largely eliminated adsorbed gases from the marginal vacuum conditions and facilitated uniform film growth. After evaporation was completed, the temperature was maintained at $350^\circ$C for several hours in vacuo for additional annealing and outgasing.

Monel films, containing only 60\% Ni, presented somewhat less of a problem, as they could be rapidly evaporated from a tungsten boat before too much alloying took place. Otherwise, much the same technique was utilized. High substrate temperatures were additionally requisite in this case to counteract the effects of fractional distillation, which certainly took place. It is estimated that the entire monel sample was evaporated in 5 secs.
B. Pulse Generation Apparatus

As indicated in section II, a microwave magnetic field of as large an intensity as possible and of sufficient homogeneity over the face of the film is required for the generation of phonons. For this reason, a rectangular cavity operating in the TE\,101 mode was selected. The experimental arrangement and field configuration are pictured in Figure 4. A ruby rod, with the ends polished optically flat to within $1/4\,\lambda$ of Na light and parallel to within $0.1^\circ$, has the end plated with the transducer pressed against the far wall of the cavity by a polystyrene holder. At the center of the wall, where the film is located, the field intensity is a maximum being given by:

$$H_x = -j \frac{E_0}{\eta} \frac{\lambda}{2d} \sin \frac{n x}{a}.$$  

This gives a field intensity constant to $0.1\%$ over the area of the $0.1"$ dia. rod.

For maximum conversion of power, the Q of the cavity should be as large as possible. However, for best echo resolution, a short, $1/2$ microsecond pulse, was utilized, requiring a fairly wide bandwidth. The cavity used in these experiments had a loaded Q of 4,000 at 4°K giving a 2.5 Mc bandwidth at 10 Gc. This is a somewhat smaller bandwidth than anticipated due to an over-estimation of the effect of the ruby and polystyrene on the cavity Q. The cavity was constructed of brass and silver-plated. A movable sapphire
FIG. 4 MICROWAVE TE101 CAVITY
rod was inserted in the end and provided cavity tuning over a range of about 40 Mc. The resonant frequency was 9.075 Gc at 4°K and 9.28 Gc at 80°K with the tuning plunger all the way out of the cavity. Coupling was accomplished through a small iris window and was essentially unity at 4°K.

A schematic of the experimental apparatus is shown in Figure 5. Power is supplied by an RK6229 tuneable magnetron capable of delivering 1/2 microsecond pulses at 400 watts. The solid state equivalent of a thyratron modulator, utilizing Shockley 4-layer diodes, was used to power the magnetron. Attenuators following the magnetron were inserted to avoid possible cavity breakdown and were essential for reducing the power level below the T-R tube breakdown level during cavity tuning. Pulses were fed into the cavity through a circulator. Acoustic pulses generated in the film by the rf pulse returned to the film after reflection from the far end of the rod and re-excited an rf "echo" in the cavity. For a rod length of .562 cm, echo separation was 4.8 microseconds and 2.5 microseconds for transverse and longitudinal acoustic waves respectively. A reflected pulse followed by an echo train was then directed by the circulator through a Bomac 1B63A T-R tube. At the power levels used, the tube was broken down by the reflected pulse, strongly attenuating the power transmitted to the receiver. A fast recovery time
FIG. 5 BLOCK DIAGRAM OF PHONON SPECTROMETER

- Klystron
- Local Oscillator
- ISOLATOR
- IF AMPLIFIER
- SAMPLING INTEGRATOR
- SERVO-RETER
- MAGIC TEE
- 20DB DIRECTIONAL COUPLER
- IN23MR X-TALS
- IN23E
- PRECISION ATTENUATOR
- MATCHED LOAD
- ISOLATOR
- MAGNETRON PULSER
- SWEEP GENERATOR
- MAGNET POWER SUPPLY
- DELAYED TRIGGER
- TECHTRONIX 545A SCOPES
- GATE IN
- SAMPLE CAVITY
of 2 microseconds was required of the tube in order that the first longitudinal echo be passed unattenuated. This requirement was well satisfied up to the highest power levels attainable.

The precision attenuator following the T-R tube was incorporated to permit relative measurement of echo pulse heights to be made. The detection scheme was basically just a superheterodyne system followed by a pulse sampling integrator and a chart recorder. The local oscillator signal from the Varian X-13 klystron was combined with the incoming signal in a balanced mixer, designed to cancel out local oscillator noise caused by frequency modulation of the klystron. The 60 Mc i.f. signal was then directed to a Tridea model 10A amplifier with a 10 Mc bandwidth. The output of the video stage of the i.f. amplifier was used as the input to the gate tube of the pulse sampling integrator.

All pulse timing was initiated from a 545A Tektronix oscilloscope. The scope trace was triggered by its own 1 kc square wave calibrated output signal. The "gate A" output, consisting of a positive pulse triggered simultaneously with the scope trace, was used to trigger the magnetron pulser. A signal from the "delayed output" terminal, and controlled by the delay time multiplier control, was then used to trigger an E-H pulser, which, in turn, provided a gate signal for the
the pulse sampling detector. With the use of a type "M" 4-trace preamp, it was then an easy matter to vary the timing of the gate pulse, with the delay time multiplier control, to coincide with the particular echo of interest as displayed on the output from the i.f. amplifier.

The gated amplifier was thus on only during the time of the echo pulse of interest. The signal plus noise is then integrated in an RC network of time constant 10 secs. The random noise averages out to zero, while the signal, which is present with nearly constant amplitude during the gate time, averages to some dc level. This dc signal is then sent to a Texas Instruments Servo-riter.

Unfortunately, the output to the Servo-riter is not a linear function of pulse height. The signal recorded must then be calibrated by some means. For this purpose, the signal was attenuated by the precision attenuator in varying steps and the chart calibrated in db of attenuation in this manner. This is far from an optimum technique. Seavey has successfully used a calibrator pulse, which is mixed with the signal in such a manner as to give an absolute measurement of echo amplitude\(^{(5)}\).

The dc magnetic field was supplied by placing the cavity between the pole pieces of a Harvey-Wells magnet with a 12" gap. The maximum field attainable with the standard Harvey-
Wells power-supply was 6300 gauss. Unfortunately, fields of the order of 9000 gauss are necessary to investigate the entire spin-wave spectrum of nickel.

All pulse experiments were carried out at 4°K in a liquid helium bath and contained in a standard double-dewar cryogenic arrangement. Stainless-steel wave guide was used to minimize the heat-leak. It was found that, at full power, (400 watts) helium was boiled off at the rapid rate of 2-3 liters per hour. This can be alleviated by reducing the pulse repetition rate from 1kc to 60 cps.
C. **Spin-Wave-Resonance Spectrometer**

As indicated in section II, it is of considerable interest to know the spin-wave spectrum of the film being studied. With this information it may be possible to identify individual phonon-power peaks with corresponding spin-wave-absorption lines.

The spectrometer used in this study was identical with the standard electron-spin-resonance spectrometer. The same cavity was used in this as in the acoustic experiment. In fact, the same considerations apply as discussed in the previous section. The only difference in the two experiments lies in the fact that, here, we are using a continuous wave, vice pulse, at much lower power levels, to look at the absorption from the rf field in the cavity caused by the same resonant transition which generated the acoustic pulse.

A schematic of the spectrometer is shown in Figure 6. The X-13 klystron was stabilized to the sample cavity by a variation of the standard Pound microwave discriminator. Details of design of the stabilization system are discussed by Hemphill (32). A small low-frequency modulation field is superimposed upon the larger dc field. As the latter is slowly swept through a resonance condition, the reflected power from the cavity is modulated with an amplitude proportional to the derivative of the absorption line at the
FIG. 6 BLOCK DIAGRAM OF SPWR SPECTROMETER
superimposed frequency. A straight crystal detection is followed by a narrow-band amplifier centered at the modulation frequency. The signal to noise ratio is further improved by then directing the signal to a phase-sensitive detector, which also supplies the modulator signal. The dc output from the detector is then proportional to the derivative of the absorption line and is plotted as a function of magnetic field by the Texas Instruments Servo-riter.
D. Film Thickness Measurement

Accurate measurement of film thickness is requisite for identification of the various spin-wave modes, since the propagation vector $K = p \pi / L$. ($L$ is film thickness and "p" an integer). Of the many techniques applied to this problem, interferometric methods have yielded the most satisfactory results. Deviations from bulk densities and the small (micro-gram) weights involved make weighing impractical. Tolansky has developed a widely used method involving the multiple-beam interference of light, resulting in a Fizeau fringe pattern, which is shifted upon passage over a step in the film. A variation of this technique, due to Stern, and requiring fewer sensitive adjustments of optical elements, has been utilized. The method depends upon silver-modified Newton's rings.

A fire-polished microscope slide, prepared identically with, and adjacent to, the substrate during film deposition is used in the measurement. A narrow (1 mm) groove is first made in the film by removing the nickel down to the glass substrate with a dull metal scribe, care being taken to avoid scratching the glass. The entire slide is then covered with a 1000A layer of silver. It is then placed beneath a partially transparent convex lens, silvered to a 500A thickness, as shown in Figure 7. Light from a mono-
chromatic source is made to pass through the lens and is viewed upon reflection from the microscope slide with a metallurgical type microscope. The resultant fringe pattern is illustrated in Figure 8 and consists of fine dark circles, modified Newton's rings, on a bright background. The shift caused in passage over the step in the film is shown in this diagram, the radii of the circles due to reflection from within and without the step being designated $r_{ks}$ and $r_k$ respectively.

The various geometrical parameters of interest are designated in Figure 9. "$R$" is the radius of curvature of the lens and "$s$" the step height. From this figure, it is easy to see that interference minima will occur for regions not over the step when $d+e = 1/4(2k+1)\lambda$, $(k=0,1,2\cdots)$. And, over the step, the condition becomes $d+e+s = 1/4(2k+1)\lambda$, $k=0,1,2\cdots)$. Using the relation, $d = R-(R^2 - r_k^2)^{1/2} \approx r_k^2/2R$, and, after various algebraic manipulation, the desired expression for $s$ is obtained: $s = \lambda(r_k^2 - r_{ks}^2)/2(r_k^2 + 1 - r_k^2)$. This relates the step height to the wave length of the light and the radii of the fringe pattern.

The silverings of slide and lens were accomplished by vacuum deposition from a tungsten boat at a pressure of $10^{-5}$ mm Hg and with substrates at room temperature. Film thicknesses were estimated by weighing of silver prior to evaporation.
FIG. 7 SCHEMATIC OF THICKNESS MEASUREMENT APPARATUS

FIG. 8 FRINGE PATTERN

FIG. 9
and are only order of magnitude estimates. It is important only to insure that the silver on the slide is opaque to avoid phase shift of the reflected light\(^{(30)}\). The sole purpose of the silver on the lens is to sharpen the fringes for more accurate measurement\(^{(31)}\). The maximum reflectivity which will still allow sufficient transmission for fringe observation is desired. Thus, the proper lens coating is largely determined by the intensity of the light source.

Two different light sources were employed in these experiments. A Hg arc with green filter produced a nearly monochromatic line of \(\lambda = 5460\) A, while the thallium source produced a more closely monochromatic light at \(\lambda = 5350\) A. The Hg source had a quoted relative intensity 10 times that of the thallium and was thus better adapted to the requirements of this measurement. Fringes were observed with an American Optical Metallograph with magnifications of 50X and 100X. Measurements were made from photographs of the patterns shown in Figure 10. The results of these measurements will be discussed in a later section.
FIG. 10 MODIFIED NEWTON'S RINGS

NICKEL FILM
IV. RESULTS

A. Nickel Films

Generation of acoustic waves at 9.07 Gc was first accomplished in a nickel film plated upon a ruby rod by the techniques described above. An array of echoes produced with the dc magnetic field perpendicular to the film surface is shown in Figure 11. The spacing between echoes is 4.8 microsecs, which corresponds quite accurately with the calculated time which it takes for a transverse wave to travel twice the length of the rod along the ruby c-axis. The fact that the velocity of propagation along this pure mode axis is approximately twice that of transverse waves for longitudinal waves makes the character of the echoes quite easy to determine.

Transverse waves generated with the magnetic field parallel to the film surface are pictured in Figure 12 and are characteristically weaker, in keeping with theoretical prediction, by an estimated factor of 100 from the perpendicular case. Comparable acoustic power generation occurred at angles of $28^\circ$ and $34^\circ$ with respect to film normal. Pure longitudinal waves were observed only for the $34^\circ$ angle and were not at all detectable at $0^\circ$ or $90^\circ$. Simultaneous generation of longitudinal and transverse waves was observed.
FIG. 11 TRANSVERSE WAVES H-NORMAL

FIG. 12 TRANSVERSE WAVES H-PARALLEL

FIG. 13 LONGITUDINAL WAVES
at some angles. Figure 13 shows longitudinal mode echoes barely visible above the noise level.

These qualitative features seem to agree quite well with the predictions based upon Equations 2.5. In particular, the maximum of longitudinal power at \( \alpha = 34^\circ \) is as expected. The maximum at \( \alpha = 45^\circ \), obtained by considering \( \partial m/\partial y \) to be independent of angle, will be shifted toward \( 0^\circ \) by the fact that the microwave magnetization, \( m \), increases as the dc magnetic field for resonance approaches the perpendicular orientation (\( \alpha = 0^\circ \)). Absence of longitudinal echoes at \( 0^\circ \) and \( 90^\circ \) is as predicted from Equation 2.5.

Film thickness measurements, necessary for more quantitative analysis, were taken from Figure 10. The fringe displacements caused by passage over the step in the film are easily discernible at the center of the photograph and represent a shift of almost a whole fringe. Measurement and application of the analysis described in the previous section gives a value of film thickness \( s = 2200A \pm 300A \). The excessive width of the dark fringes in these photographs accounts for the rather large degree of uncertainty in the measurement. Much of this is merely due to poor photographic technique, the fringes being visually much sharper. Also, improved filtering of the Hg source could be expected to help matters. However, it has been verified that the major source
of broadening was due to the low reflectivity and poor quality of the silvered surface of the lens. The width of the fringes in the photograph is quite normal for unmodified Newton's rings. It is the multiple-beam interference effect, produced by the silvered surfaces, which leads to a drastic reduction in width and which makes this method feasible for highly accurate measurements. Subsequent improvement of silvered surfaces has yielded widths of less than .5 mm with x 50 magnification. Unfortunately, this improvement had not been incorporated at the time of this measurement. It should be noted that, for film thicknesses of greater than 2700Å, there is some ambiguity involved in this technique, since the fractional shift can be accurately measured, but the number of integral fringes shifted cannot be determined. This can be easily resolved by weighing with a sensitive chemical balance.

From the relation, \( H_r = 4\pi M + \omega/\chi - 2AK^2/M \), for spin-wave resonance, we find that the resonance condition for the \( K = 0 \), uniform precessional, mode occurs at 9300 gauss. This assumes the accepted bulk saturation magnetization value, \( M \), for nickel of 505 gauss. The various higher order spin-wave modes will then be arrayed in ascending order below this value toward \( H = 0 \). Assuming complete pinning of spins at the surfaces, \( K^2 = p^2 \pi^2/L^2 \), and only odd integral values
of p would show resonance. On the other hand, for the dc field parallel to the film surface, \( \omega/\gamma = \left[ H_r (H_r + 4\pi M) \right]^{1/2} \) gives a K=0 value of \( H = 1155 \) gauss, and spin-wave modes are similarly separated below this value by \( 2AK^2/M \). It was then to be expected that acoustic generation peaks would be observed in an array as the magnetic field was swept from zero to these respective maximum resonance values and that there would be no echoes above. Observation, in this particular experiment, of the entire spectrum for the perpendicular case was severely hampered by a limitation of the magnitude of the magnetic field obtainable to 6500 gauss. Subsequent extension of this range to 7500 gauss still fell considerably short of the fundamental mode at 9300 gauss. However, it was hoped that some of the higher order modes would be sufficiently strong at these lower fields to produce detectable phonon-power conversion.

The echoes shown in Figure 11 were obtained at 6500 gauss. There was no detectable generation below 6000 gauss. A spin-wave-absorption experiment was run on this same film and a plot of absorption versus magnetic field is shown in Figure 14. This curve corresponds quite well with the observed variation of phonon power with magnetic field. The relatively broad, structureless spin-wave-resonance line centered at 6750 gauss is contrasted with the sharp EPR line caused by the 1-2
FIG. 14  NICKEL SPIN WAVE ABSORPTION

Hₚ PERPENDICULAR
transition in the ruby rod substrate. Since only one phonon peak and one SPWR line were observed, it was not, at this point, possible to determine the order of the spin wave causing the effect or to calculate the value of the exchange constant, $A$, obtainable from measurement of the distance between consecutive lines. Indeed, it is not clear whether this is one single line or a group of closely spaced, unresolved lines.

Further information is afforded by considering results for $H$ parallel to the film surface ($\alpha = 90^\circ$). The echoes shown in Figure 12 attained a maximum value at 1700 gauss. A detailed phonon spectrum was not, however, obtained for this case. The corresponding spin-wave spectrum was run and is shown in Figure 15. Three discernible spin-wave-absorption peaks are in evidence and one ruby line at 1875 gauss. It is regrettable that the ruby line obscures a quite interesting portion of the spectrum. One fact is, nevertheless, quite obvious, that both phonon and SPWR spectrums extend appreciably above the expected maximum of 1155 gauss. Assuming then a revised resonance field of 1650 gauss in keeping with the highest discernible absorption peak, the resonance relation then gives us a saturation magnetization $M=300$ gauss. If we now apply this value to obtain a revised $H_r$ for the uniform mode in the perpendicular case, we find a value of 6720 gauss, which fits remarkably well the observed absorption peak at 6750 gauss. The fact that extension of the magnetic field to 7500 gauss
FIG. 15 NICKEL SPIN WAVE ABSORPTION SPECTRUM - $H_r$ PARALLEL
revealed no other resonances supports the contention that the single observed resonance at 6750 gauss is indeed the main, K=0, line and not a higher order mode as was first supposed. The question as to whether it is composed of several unresolved lines is yet undetermined. This result coincides with that of a similar study performed by Pomerantz, Freedman, and Suits \(^{(23)}\). They found that in films grown at high substrate temperatures (\(>400^\circ\text{C}\)) and in ultrahigh vacuum (\(<10^{-9}\ \text{mm Hg}\)) the ferromagnetic resonance occurred at 6900 gauss. Efforts to explain this by planar stresses in the film, which caused lowering of M through magnetostriction, proved unsatisfactory. Electron microscope studies of these films indicated that they were in the form of discrete, well separated islands of nickel. The effect was then explained by the change in the demagnetization factors from those of a plane to those appropriate for ellipsoidal islands.

The poorer vacuum (\(2x10^{-5}\ \text{mm Hg}\)) and 350\(^\circ\text{C}\) temperature used in the present experiment makes it questionable whether the above argument would be applicable. It is possible that the substrate temperature could have risen appreciably during the plating process to over 400\(^\circ\text{C}\). But, the fact that appreciable transducing efficiency was obtained from this film leads one to believe that the film was continuous and reasonably flat and that a more likely explanation would come from
the presence of a considerable amount of adsorbed gases throughout its interior. This point will be further developed in connection with the monel film.

It is interesting to investigate the ordering of the three discernible spin-wave-absorption peaks in Figure 14.

<table>
<thead>
<tr>
<th>Peak Number</th>
<th>H</th>
<th>H_p - H_{p+1}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1625</td>
<td>140</td>
</tr>
<tr>
<td>2</td>
<td>1485</td>
<td>395</td>
</tr>
<tr>
<td>3</td>
<td>1090</td>
<td></td>
</tr>
</tbody>
</table>

If we assume a quadratic ordering i.e. \( K^2 = p^2 \pi^2 / L^2 \) and a distance of mode \( p \) from the \( K=0 \) mode given by, \(-2AK^2 / M\), or, \(-2Ap^2 \pi^2 / L^2 M\), the separation between modes \( p \) and \( p-1 \) should be \( (2p+1)2A \pi^2 / L^2 \). Elimination of \( p \) from the equations for the two adjacent mode separations above gives:

\[ 2A \pi^2 / ML^2 = 130. \]

And, using the previously discussed values for \( L \) and \( M \), gives us a value for the exchange constant \( A = 0.94 \times 10^{-6} \text{erg cm}^{-1} \), as compared with Nose's value of \( 0.75 \times 10^{-5} \text{erg cm}^{-1} \) at room temperature. This provides a value for the exchange integral \( J = 11.8 \times 10^{-14} \text{erg} \). A large source of error in this measurement is that of the film thickness determination. However, more crucial is the lack of any real justification for assuming that these three peaks are consecutive modes. At best, a large number of well
resolved modes would be necessary to lend any credence to this measurement. In Seavey's work\(^{(17)}\), for instance, it was necessary to assume the damping of several modes intermediate to the observed ones to explain the results consistently. Also, the assignment of even mode numbers to some of the peaks is in violation of the assumption of complete pinning at the surfaces. In fact, recent experiments\(^{(18,35,36)}\) have called into serious question the complete pinning model and the quadratic ordering of the modes. It is clear that a great deal more information would be required concerning the actual pinning conditions in the individual films and the proper identification of the spin-wave modes observed before quantitative calculations such as this can be taken seriously. It is also interesting to note that the appearance of the middle peak was a quite sensitive function of angle (a change of .5° caused disappearance).

A second nickel film, prepared in the same manner, showed many of the same features and will be discussed only generally. For parallel alignment, a single transverse echo appeared with a maximum height at 1050 gauss, and no appreciable structure to the resonance line shape was observed. This value is more in keeping with the expected bulk value magnetization for nickel. Maximum acoustic generation occurred at angles approximately 12° either side of the parallel and perpendicular
alignment, and the variation with respect to angle was remarkably symmetrical about these points. No explanation of this behavior has been attempted. It is quite obvious that the transducing properties of these films are a strong function of several other individual film properties and will be difficult to reproduce.
B. Monel Films

The other material studied in this investigation was monel, an alloy primarily of Ni and Cu in the approximate respective proportions of 65% and 29% and with small (~1%) concentrations of Fe, Mn, Si and C. This material was suggested for study by its early use in non-resonant low-frequency type magnetostrictive transducers. Its relatively low saturation magnetization of 120 gauss inspired the hope that its entire spectrum could be studied within the limitations of our equipment. Furthermore, its excellent corrosion-resistant properties make it particularly adaptable to experiments carried out at 4°K, subsequent warming to room temperature, and recooling, where constant properties are required.

Echoes from acoustic pulses generated at 9.07 Gc are shown for the parallel and perpendicular cases respectively in Figures 16 and 17. The main echo peaks in both cases come from transverse waves, but longitudinal echoes do appear in the perpendicular case at several values of the magnetic field. Simultaneous generation of longitudinal and transverse waves at an intermediate angle is illustrated in Figure 18. The exceptionally clean, symmetrical character of these echoes and their very closely exponential decay for the perpendicular case is quite encouraging for application to acoustic attenu-
FIG. 16 TRANSVERSE WAVES H-PARALLEL

FIG. 17 TRANSVERSE WAVES H-NORMAL

FIG. 18 MIXED WAVES
ation measurements. This is quite an improvement over the general run of echoes generated by the piezoelectric effect, where bonding problems often create "ringing" effects. To the best of my knowledge, this is the first work reported on this effect in monel.

A plot of acoustic power versus magnetic field is shown in Figure 19 for perpendicular alignment. Apparent immediately is the anomalously strong peaking of the generation at high magnetic fields. The maximum at 7000 gauss is considerably above the expected edge at 4500 gauss. The three sharp dips in the otherwise broad structure are caused by absorption in the ruby when EPR transitions are induced by the acoustic wave through the spin-lattice interaction. The strong absorption evident indicates the feasibility of using this technique of generation in spin-lattice interaction studies, which have so far relied upon piezoelectric transducers.

The ratio of power out to power in was estimated in the perpendicular case as $5 \times 10^{-8}$. This was slightly worse than the factor of $10^{-7}$ for the first nickel film. Both films showed a lowering of efficiency by $10^{-2}$ for the parallel generation. This is comparable with, but slightly inferior to, the conversion efficiency of the best piezoelectric transducers used in this laboratory. Seavey$^{(5)}$ has calculated theoretical power output factors based upon Equations 2.11-2.14.
FIG. 19 MONEL PHONON SPECTRUM
for the permalloy films used in his experiments and compared them with similar calculations for piezoelectric transducers. While the actual conversion of electromagnetic to acoustic energy is better by a factor of 100 for the magnetostrictive generation, the superior "filling factor" in the re-entrant cavity used with quartz transducers is far more effective in concentrating the electromagnetic energy in the volume occupied by the transducer. It is felt that a more efficient cavity design would improve thin film generation to a position of considerable superiority.

The absence of any provision for making accurate absolute-power measurements in this experiment forbids a quantitative determination of the dynamic magnetostrictive interaction responsible for this effect. Information on this matter could be derived from the constant $b$ in Equations 2.11-2.14. Before this is possible, however, a far more satisfactory determination of the actual pinning conditions on spin waves and identification of the individual modes will be necessary. Better resolution of individual phonon modes and line width measurements, such as those of Pomerantz$^{(2)}$, would permit an estimate of the extent to which interaction with the lattice contributes to relaxation of spin systems in ferromagnets.

Figure 20 is a plot of spin-wave absorption versus magnetic field for the monel film. Here again, the strong
FIG. 20  MONEL SPIN-WAVE-ABSORPTION SPECTRUM

H-KILOGAUSS  ABSORPTION
narrow peaks are all caused by transitions in the ruby. The extreme complexity of this spectrum is due to a number of factors. Hyperfine structure of the ruby lines probably accounts for much of the detail surrounding each main line. The thickness of the monel film itself was approximately 1 micron. Since the separation of the modes depends upon \( l/L^2 \), this would account for an extremely close spacing of individual lines. In fact, assuming a value for \( A \) equal to that of Ni gives a variation with magnetic field of only 3.5 \( p^2 \) gauss. However, even at values of the magnetic field far down the spectrum, where spacings should be appreciable, there does not appear to be anything recognizable as a \( p^2 \) dependence. In fact, the only regularity noticeable in peaks appreciably removed from the ruby lines is a roughly uniform spacing for many of them. This would correspond to a breakdown of the complete pinning model and is in keeping with a new model proposed by Wigen, Kooi and Shanabarger\(^{35} \), which will be discussed in the next section. The gross features of the curve seem to indicate appreciable absorption from spin waves at the same points, 3550 gauss and 7000 gauss, at which the acoustic maxima occurred. Again, the fact that the ruby lines appear in precisely these most interesting regions and obscure much of the spin-wave spectrum is unfortunate. However, the absorption spectrum does not show anything like the extreme,
but broad, peaking evident in the phonon spectrum. This would indicate that the latter is due to some more gross resonance feature than the strength of the individual spin-wave resonances. The possibility exists that the coincidence of phonon and magnon wavelengths at one of these points might lead to either an increased strength of interaction or merely constructive interference between waves generated in different parts of the film. The former possibility was predicted by Kittel\(^\text{(38)}\) and has been looked for without success by Seavey\(^\text{(5)}\). However, previous investigations were carried out in thinner films and the point of coincidence may not have fallen at a point occupied by an allowed spin-wave mode.

The anomalous upward shift in both of the monel spectrums cannot be explained by the mechanism previously invoked to justify the downward shift in the nickel spectrum. The fact that fractional distillation of the alloy upon evaporation would cause an increase in the percentage of Cu, would also cause an opposite shift from that observed. Pomerantz, Freedman and Suits\(^\text{(23)}\) also found this upward shift in nickel films grown at lower substrate temperatures (<400°C) and in vacuums of 10\(^{-5}\) mm Hg. Electron microscopy showed the films to be continuous, and the effect was well accounted for by the presence of large compressive stresses. The fact that the nickel and monel films were prepared by different procedures, the
latter being evaporated much more quickly at a lower substrate temperature, would account for the difference in properties.
V. CONCLUSIONS

Perhaps the most conspicuous feature of the present work is the highly individual behavior of the resonant magnetostrictive generation in the films studied. Obviously, isolation of the various factors influencing this behavior would be highly desirable. Knowledge of film structure, composition, amount and distribution of adsorbed gases, stresses, saturation magnetization, magnetic domain structure, thickness, and static magnetostrictive constants would all enlighten a thorough research program on many of the points brought up in the previous section. By far the most crucial question posed is that concerned with the nature of the boundary conditions (or pinning) imposed upon spin-wave modes. This problem has attracted increasing attention in recent months. The work, previously mentioned, by Wigen et al.\(^{(35)}\) demonstrated experimentally that boundary conditions were imposed by surface regions in which the magnetization differs from that in the body of the film. Under most conditions the resonance frequency of the uniform precession mode in this surface layer will differ from that in the body of the film, and since the spins are exchange coupled at the interface, the excitation of the uniform precession mode of oscillation will be suppressed. However, those spin-wave modes that satisfy the appropriate boundary conditions at the interface can exist.
There is then a dynamic pinning at this interface. This model was generalized by Portis\(^{(39)}\) to a case in which the volume magnetization is non-uniform and parabolic in dependence throughout the thickness of the film. This leads to a spin-wave spectrum which is uniformly spaced for the lowest modes and which approaches quadratic dependence only for the higher modes. Clearly, the variation of the magnetization will depend drastically upon structural properties and gas absorption throughout the film. Such a model could fit the general features of the monel-film spectrum. Obviously, much further investigation of this matter is indicated.

As a useful device, the magnetostrictive transducer has been demonstrated by this experiment to be quite practicable for various studies in microwave acoustics. Considerable improvement afforded by better cavity design and the use of materials with larger magnetostrictive effects is indicated.
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