

## XIII. MICROWAVE AND QUANTUM MAGNETICS

### Academic and Research Staff

Prof. F.R. Morgenthaler  
Prof. R.L. Kyhl

Dr. T. Bhattacharjee  
D.A. Zeskind

### Graduate Students

D. Fishman  
L. Hegi

L.M. Itano

D.D. Stancil  
N.P. Vlannes

F.R. Morgenthaler

Our objective is to develop an understanding of magnetostatic and magneto-elastic wave phenomena and to employ them to create novel device concepts useful for microwave signal-processing applications.

Several years ago, work at M.I.T. by Zeskind and Morgenthaler, and subsequently, Cooley proved the feasibility of efficiently coupling, with microstrip lines, to very high-Q tunable microwave resonances in rectangular slabs and disks of single-crystal yttrium iron garnet (YIG).

Our interpretation of these resonances (potentially useful for microwave filtering) is that localized magnetic-mode patterns are formed in which the resonant energies are guided or confined by regions of dc magnetic-field gradient within the crystal. In the first experiments such gradients arose naturally from the nonuniform-shape demagnetizing fields; in subsequent work, we have created prespecified gradients with shaped pole pieces designed by field-synthesis techniques.

This work has two motivations. First, we want to learn whether or not it is feasible to create a multiplicity of tunable, high-Q resonances within the same crystal, whether all at the same frequency or separated by preset amounts. Such a structure could serve as an integrated magnetostatic filter circuit. Second, renewed interest in magnetostatic waves for signal-processing applications in the frequency ranges above L-band (where surface acoustic wave (SAW) device fabrication is difficult) has prompted us to inquire whether frequency dispersion, group velocity, and mode energy distribution can be controlled in a practical manner.

(XIII. MICROWAVE AND QUANTUM MAGNETICS)

1. MAGNETOSTATIC MODES BOUND BY DC H-FIELD GRADIENTS

Joint Services Electronics Program (Contracts DAAG29-78-C-0020 and  
DAAG29-80-C-0104)

United States Air Force (Contract F19628-79-C-0047)

Frederic R. Morgenthaler, Robert L. Kyhl, Tushar Bhattacharjee,  
Dale A. Zeskind, Daniel D. Stancil

Our interest in controlling magnetostatic waves and modes by means of dc field gradients dates from the experimental observation of localized high-Q resonance in single-crystal yttrium iron garnet (YIG) reported by Zeskind and Morgenthaler.<sup>1</sup> These and subsequent experiments have recently been reviewed in an invited paper<sup>2</sup> presented at the Third International Conference on Ferrites held September 29-October 2, 1980 in Kyoto, Japan. We also have extended our previous theoretical treatment<sup>3</sup> of two-dimensional magnetostatic modes of single-domain thin ferrite circular disks or annular rings, when the dc magnetic field is normal to the plane and varies radially.

In the absence of a radial gradient, all of the modes of a solid disk have circularly polarized rf h-fields with zero volume divergence. These modes are strongly influenced by the magnetic pole distribution on the edge of the disk and the rf energy becomes progressively concentrated near the rim as the mode index increases.

The volume divergence of certain modes can change so dramatically that selective localization or expulsion of the energy occurs. The sense of polarization can also reverse. In certain cases, the volume divergence of the rf magnetization can become infinite (in the lossless-exchangeless approximation) at a certain interior radius,  $r_x$ . The magnetic pole distribution at this "virtual-surface" thus resembles that of a true surface and can serve to guide and localize the mode.

Such modes have now been reanalyzed in terms of the polarization factor of the rf magnetization. Analytic solutions of that factor are continuous through the "virtual-surface" and are given for the two-dimensional modes associated with special field profiles. Consideration of the radial impedance vs dc field plane provides a great deal of insight into the character of both boundary-dominated and gradient-dominated modes.

(XIII. MICROWAVE AND QUANTUM MAGNETICS)

The rf field patterns for a typical mode are shown in Fig. XIII-1 in which the "virtual-surface" is shown as a dotted circle. All three fields rotate synchronously at the mode frequency.

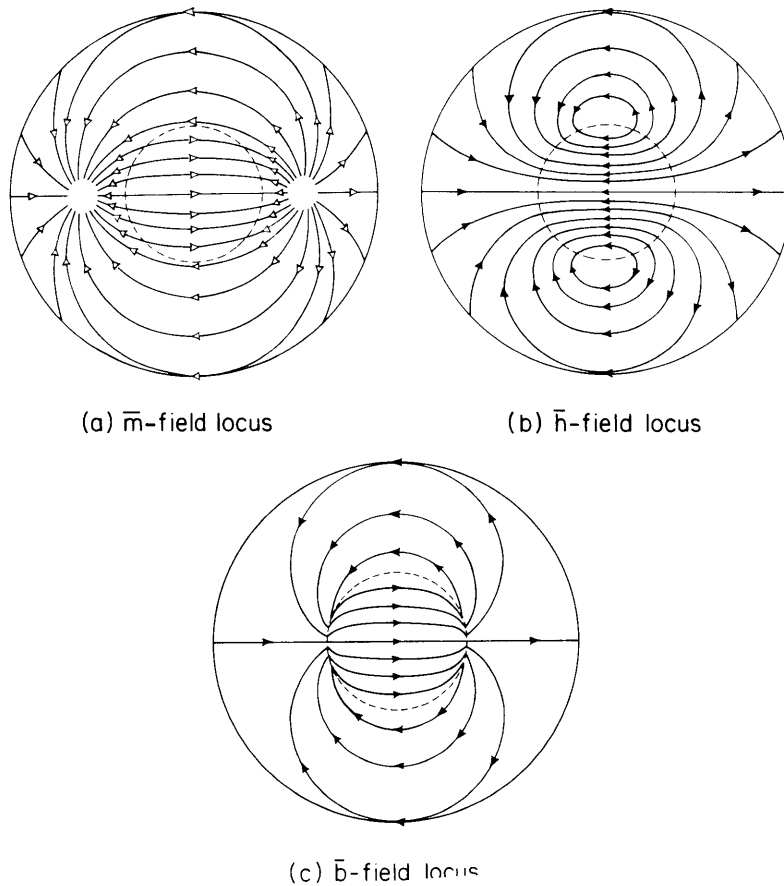


Fig. XIII-1. Loci of  $\bar{m}$ -,  $\bar{h}$ -, and  $\bar{b}$ -field lines for the lowest order "virtual-surface" mode when  $H_z(r)/M = 0.3 + 1.095 (r/R)^4$ . All patterns rotate at the mode frequency  $\omega$ . The "virtual-surface" (shown dotted) occurs at  $r/R = 0.385$ .

Notice that the rf magnetization reverses direction in passing through the critical radius constituting, in effect, a "microwave domain" with a 180-degree rf "domain wall."

The role of exchange at a "virtual-surface" has been discussed by Morgenthaler<sup>4</sup>

(XIII. MICROWAVE AND QUANTUM MAGNETICS)

and recently by Stancil<sup>5</sup> in a paper presented at the 1980 Intermag Conference held in Boston during April. The effects of magnetic loss on the spin-wave component of the mode potential and the effect on the overall mode pattern have also been treated.<sup>6</sup>

In the absence of both exchange and loss, the magnetostatic potential has a logarithmic singularity at the critical radius. Consequently, the radial  $\bar{h}$ -field and tangential  $\bar{b}$ -field will there become infinite. Either exchange or loss will remove the singularity. The cusps in the  $\bar{b}$ -field are similarly removed making finite all the rf fields and energy densities.

References

1. D.A. Zeskind and F.R. Morgenthaler, "Localized High-Q Ferromagnetic Resonance in Nonuniform Magnetic Fields," IEEE Trans. on MAG, Vol. MAG-13, No. 5, September 1977.
2. F.R. Morgenthaler, "Novel Devices Based upon Field Gradient Control of Magnetostatic Modes and Waves," 3rd International Conference on Ferrites, Tokyo, Japan, September 29-October 2, 1980.
3. F.R. Morgenthaler, "Bound Magnetostatic Waves Controlled by Field Gradients in YIG Single Crystals and Epitaxial Films," IEEE Trans. on MAG, Vol. MAG-14, September 1978, pp. 806-810.
4. F.R. Morgenthaler, "Two-Dimensional Magnetostatic Resonances in a Thin Film Disk Containing a Magnetic Bubble," presented at the 1978 Conference on Magnetism and Magnetic Materials, Cleveland, Ohio, November 14-17, 1978.
5. D.D. Stancil, "Magnetostatic Waves in Nonuniform Bias Fields Including Exchange Effects," IEEE Trans. on MAG Conference Proceedings, September 1980.
6. F.R. Morgenthaler, "Synthesis of Magnetostatic Waves and Modes Using Nonuniform Bias Fields," 1980 Ultrasonics Symposium, Boston, November 1980, to be published in Conference Proceedings.

2. OPTICAL DETECTION OF MAGNETOSTATIC RESONANCES

Joint Services Electronics Program (Contracts DAAG29-78-C-0020 and  
DAAG29-80-C-0104)

Nickolas P. Vlannes, Frederic R. Morgenthaler

The doctoral thesis of N.P. Vlannes will attempt optical detection of localized magnetostatic resonances in thin LPE films of YIG. At infrared frequencies, the magneto-optical response of YIG can be modeled by a dielectric tensor that is

### (XIII. MICROWAVE AND QUANTUM MAGNETICS)

dependent upon magnetization. Thus one can probe for the characteristics of the magnetization.

The experimental setup comprising a Spectra Physics 125 Laser tuned to 1150 nm with lens elements for focusing the beam and optical detectors capable of responding to 2-GHz modulation rates is essentially complete.

A list of our goals follows.

1. Design and construction of an optical probing system to examine the microwave magnetization of magnetostatic modes of YIG;
2. Design and construction of an induction probing system to sense fringing microwave magnetic fields;
3. Use of the probing systems to probe for the respective rf fields of YIG, particularly under nonuniform bias-field conditions;
4. Conduct experiments on the effects of different antenna geometries and antenna orientations relative to the YIG substrate in regard to signal processing character and field patterns;
5. Test the microwave magnetic effects of various nonuniform bias fields induced by varied-magnet pole-piece geometries.

### 3. MODE SYNTHESIS

United States Air Force (Contract F19628-79-C-0047)

Daniel Fishman, Frederic R. Morgenthaler

Nonuniform magnetic bias field can control magnetostatic waves and modes in ferrite thin films. Gradients in either the field magnitude, direction or both can be employed to synthesize wave or mode spectra to prespecified characteristics.

Parameters affected include frequency, rf energy distribution, impedance, velocity of energy circulation, and the threshold governing the onset of nonlinear effects due to parametrically unstable spin waves.

The important case of a thin-film disk that is surrounded by free space and magnetized to saturation along the normal to its plane was analyzed in the 1980 Intermag Conference Proceedings<sup>1</sup> for the conditions of weak-to-moderate radial gradients or arbitrary form:

(XIII. MICROWAVE AND QUANTUM MAGNETICS)

$$H_z(r) \sim A + \sum_{n=1}^{\infty} B_n r^{2n}.$$

The non-"virtual-surface" modes analyzed are quasi-two-dimensional in that the rf magnetization is assumed to be without appreciable thickness variation; the fringing magnetic fields are, of course, three-dimensional because the disk is surrounded by free space.

The results allow one to synthesize modes with prespecified characteristics, such as frequency, energy distribution, velocity of energy-circulation impedance level, and power threshold for nonlinear behavior.

If it is desired to create a spectrum with the resonance frequencies separated by prespecified amounts or if one wishes to control the velocity of energy circulation  $V_{\phi}^E$  of individual modes, the independent constants  $B_n$  can be adjusted and the required field  $H_z(r)$  synthesized.

Control of  $V_{\phi}^E$  not only affects the group delay of signals propagating through the mode but also the total energy,  $E$ , of the mode in terms of the signal power  $P_{\phi}$ .

The normally slow energy circulation that occurs when  $B_n = 0$  can either be speeded up or slowed down. In the latter event, the direction of net power flow can even be reversed. Near the balance point where  $V_{\phi}^E = 0$ ,  $E$  becomes very large, for a fixed value of  $P_{\phi}$ . Because nonlinear behavior, due to parametric spin-wave instabilities, occurs when the energy density of the mode reaches a critical value, it follows that the threshold power of the limiting level should be gradient-controllable.

It is useful to realize that  $V_{\phi}^E$  can be forced to be independent of  $m$  over some range of  $m$ . This also suggests that magnetostatic plane-wave propagation can be made precisely nondispersive over a predetermined bandwidth.

In Fig. XIII-2, we give the theoretical curves that result from forcing  $V_{\phi}^E$  to be constant for the first three modes ( $m = 1,2,3$ ) by means of  $B_1, B_2, B_3$ .

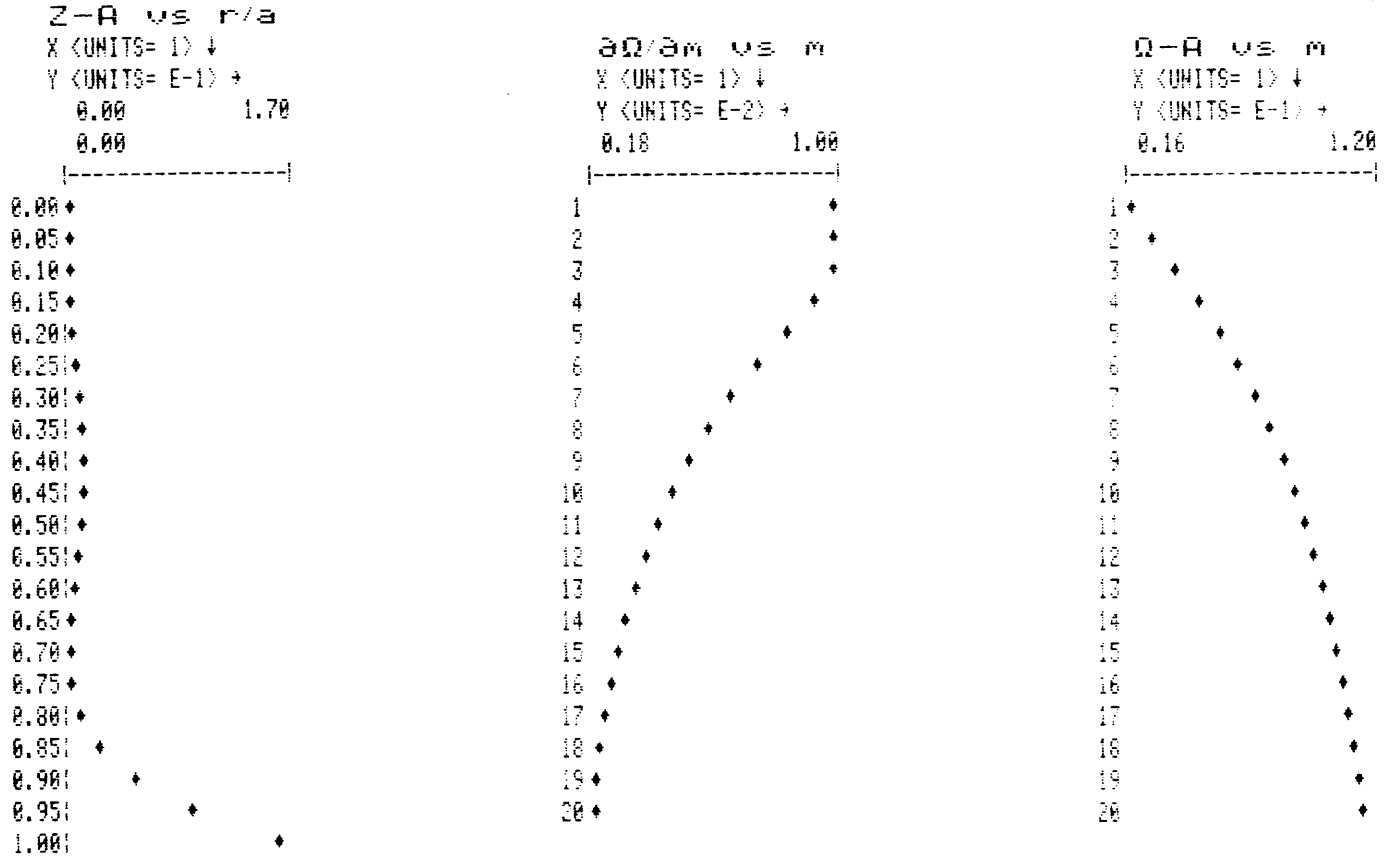


Fig. XIII-2. The normalized mode frequency (a) and prespecified energy frequency (b) both plotted vs mode number, together with the required field profile (c) plotted vs radius.

(XIII. MICROWAVE AND QUANTUM MAGNETICS)

References

1. F.R. Morgenthaler, "Synthesized Magnetostatic Resonances in a Nonuniformly Biased Thin Disk without Conducting Boundaries," IEEE Trans. on MAG Conference Proceedings, September 1980.

4. NEW TECHNIQUES TO GUIDE AND CONTROL MAGNETOSTATIC WAVES

United States Air Force (Contract F19628-79-C-0047)

Joint Services Electronics Program (Contracts DAAG29-78-C-0020 and DAAG29-80-C-0104)

Daniel D. Stancil, Frederic R. Morgenthaler, Dale A. Zeskind

The prospect of guiding magnetostatic waves is of considerable interest because of possible device applications. Such guided waves might be used to increase the delay time realizable on a given-size sample by meandering the path, or to make a resonator by guiding the waves along a closed loop. In addition, controlling the coupling between adjacent waveguides could make possible signal-routing devices such as directional couplers.

Guiding magnetostatic surface waves (MSSWs) is complicated by the fact that MSSW propagation is only possible in one direction on a given surface when the applied in-plane bias field is uniform; turns of  $90^\circ$  would normally require conversion to backward-volume waves.

It should be possible to overcome this difficulty by employing gradients that arise from a change in the direction of the bias field. As an example, consider a YIG film that is covered with permalloy containing a slot of controlled width. If the permalloy is at a different magnetostatic potential on either side of the slot,

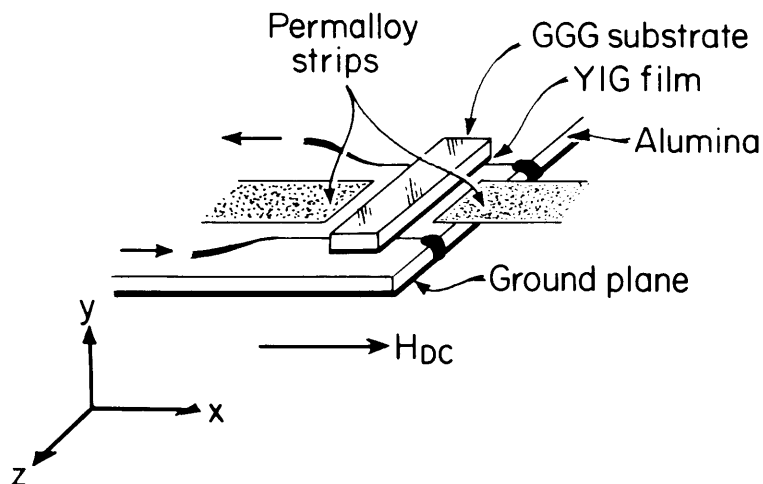


Fig. XIII-3. Basic experimental configuration.



(XIII. MICROWAVE AND QUANTUM MAGNETICS)

the dc magnetic field will be parallel to the film in the region underneath the slot but normal to the film surface in those portions directly underneath the permalloy.

The in-plane fields permit magnetostatic surface wave propagation; the normal fields do not.

Therefore the surface-wave energy should be localized under the air-filled slot rather than under the conducting permalloy; eddy-current dissipation is thereby minimized.

Notice also that if the entire field is normally directed, the surface wave disappears completely. Taken together, these factors should allow novel control

of the surface-wave channel. Notice, too, that the width of the slot will strongly affect the speed of propagation and more than one slot can be placed side-by-side to provide coupled-wave possibilities. The slots can be curved or even meandered with the in-plane field automatically adjusting direction to maintain the surface-wave conditions. Such curved paths can be closed themselves to form resonant tracks that are single or multiple.

As a first step toward evaluating this approach, we have conducted preliminary experiments and have recently reported<sup>1</sup> the observation of magnetostatic surface waves (MSSWs) in a rectangular YIG film placed between strips of permalloy and in the plane of the strips. In such a configuration, shown in Fig. XIII-3, the dc magnetic field between

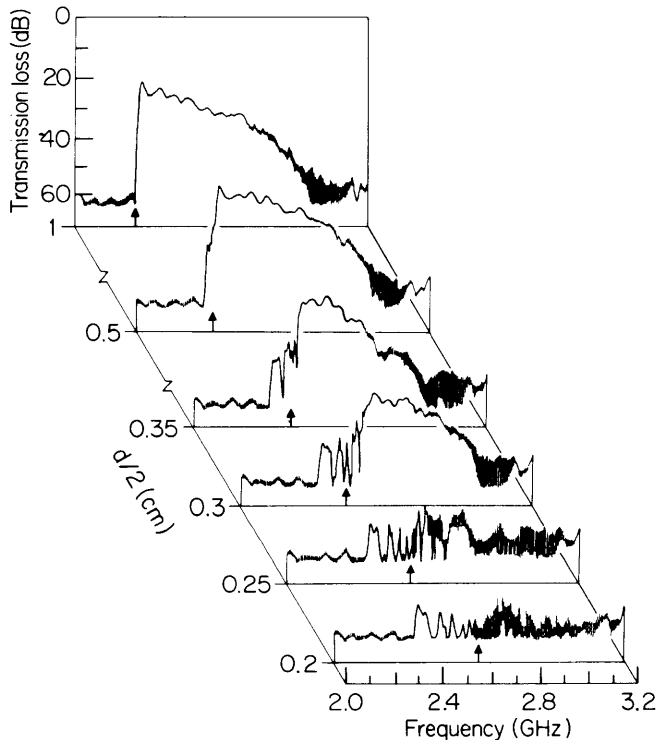


Fig. XIII-4.

MSSW transmission spectra as a function of the spacing between permalloy strips. The fine structure near the high-frequency end is due to interference with the EM feed-through.

(XIII. MICROWAVE AND QUANTUM MAGNETICS)

the permalloy strips is primarily in-plane with a minimum halfway between the strips. In the presence of such a gradient, a series of discrete modes appears below the low-frequency end of the continuous MSSW band as shown in Fig. XIII-4. We report here the results of pulse-time-delay measurements indicating that these modes travel several times faster than normal MSSW modes, in agreement with previous cw measurements.

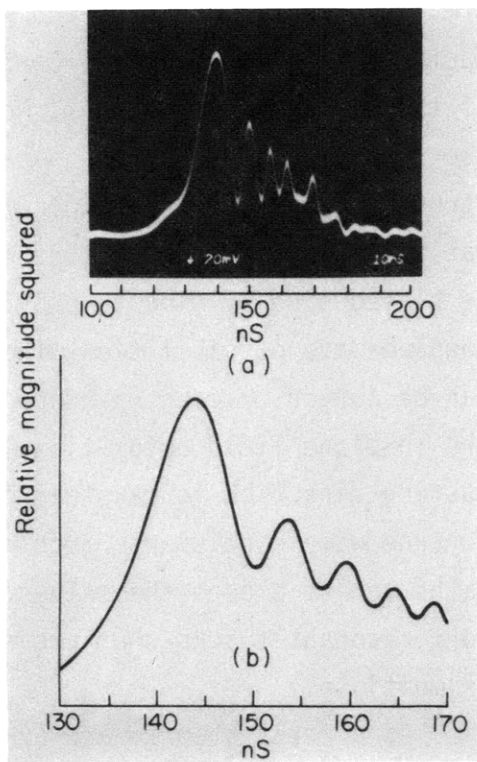


Fig. XIII-5.

Surface wave precursors. (a) Precursor due to leading edge of a pulse centered at 2.000 GHz with  $H = 300$  Oe and bottom of the band measured to be 2.388 GHz. Nominal film thickness  $s = 5$  microns. (b) Theoretical precursor based on  $H = 300$  Oe,  $4 M_S = 2122$  G,  $s = 3.19$  microns, and  $L = 1$  cm.

We also reported<sup>2</sup> the experimental observation of MSSW precursors in both uniform and nonuniform fields. An approximate theory for the precursors in a uniform field has been developed which agrees well with the measurements. The comparison is shown in Fig. XIII-5.

## (XIII. MICROWAVE AND QUANTUM MAGNETICS)

### References

1. D.D. Stancil and F.R. Morgenthaler, "Magnetostatic Surface Modes in a Thin Film with Nonuniform In-Plane Fields," IEEE Trans. on Magnetics, Vol. MAG-16, No. 5, September 1980.
2. D.D. Stancil and F.R. Morgenthaler, "The Effects of Nonuniform In-Plane Fields on the Propagation Characteristics of Magnetostatic Surface Waves," 1980 Ultrasonics Symposium, November 1980, to be published in Conference Proceedings.

### 5. MAGNETOSTATIC WAVE-DISPERSION THEORY

United States Air Force (Contract F19628-79-C-0047)

Joint Services Electronics Program (Contracts DAAG29-78-C-0020 and  
DAAG29-80-C-0104)

Frederic R. Morgenthaler, Tushar Bhattacharjee, Daniel D. Stancil

In our prior analyses of nonuniform magnetostatic modes in thin films, the bias field was assumed to be directed normal to the plane and the modes considered were quasi-two-dimensional in that thickness variations of the rf magnetization were ignored. This restriction conformed to the geometry of several experimental configurations but our most recent studies<sup>1</sup> have involved films with nonuniform in-plane bias and, consequently, we have now developed a general theory, based upon coupled-integral equations, that can deal with surfacelike modes in one or more concentric thin-film rings when the bias and any material nonuniformities (such as variation of the saturation magnetization) are purely radial. We have also treated the analogous integral equations based upon Cartesian coordinates for film configurations that involved one or more rectangular strips. Exchange effects and thickness variations of the bias field and material parameters are not included in the model but, because surface-wave character is expected, such variations of the rf fields are permitted.

The boundary conditions required at the film surfaces are built directly into these equations; the transverse conditions enter through the components of the Polder susceptibility tensor.

The equations govern a very wide range of physical situations. For example, coupling between modes circulating on two concentric annular rings spaced by an air gap can be handled as can the analogous problem involving two ferrite strips.

Computer algorithms for numerical solutions of this class of eigenfrequency

(XIII. MICROWAVE AND QUANTUM MAGNETICS)

problem are currently being developed.

References

1. F.R. Morgenthaler, "Magnetostatic Surface Modes in Nonuniform Thin Films with In-Plane Bias Fields," 26th Conference on Magnetism and Magnetic Material, Dallas, Texas, November 1980.

6. MAGNETOELASTIC WAVES AND DEVICES

United States Air Force (Contract F19628-79-C-0047)  
Joint Services Electronics Program (Contracts DAAG29-78-C-0020 and  
DAAG29-80-C-0104)

Frederic R. Morgenthaler, Leslie M. Itano

A microwave yttrium-iron-garnet (YIG) delay line can be made to provide linearly dispersive delay with instantaneous bandwidth in excess of 1 GHz in C-band. The dispersion of the device is based on the properties of spin and elastic waves in magnetically biased YIG, a ferrimagnetic material. In particular, linear dispersion can be achieved by first specifying a particular dc magnetic-field profile along the axis of a YIG rod, and then designing the necessary pole pieces with the aid of a computer.

The first generation of thin-film antennae were fabricated, but the results were disappointing. A second set of designs is currently being processed, and modifications of the test fixture are being made that are expected to increase the focusing of the magnetostatic backward wave into the magnetoelastic beam. The hoped-for result will be an increase in coupling efficiency and consequent reduction in the insertion loss of the magnetoelastic wave signal.