# 12. Microwave and Quantum Magnetics

**Academic and Research Staff**

*Prof. F.R. Morgenthaler, Prof. R.L. Kyhl[2], Dr. T. Bhattacharjee, D.A. Zeskind*

**Graduate Students**

*M. Borgeaud, L. Hegi, C.M. Rappaport, N.P. Vlannes*

## Objective

Our objective is to develop an understanding of electromagnetic, magnetostatic, and magnetoelastic wave phenomena and to employ them to create novel device concepts useful for microwave signal-processing applications. We are especially interested in developing novel device concepts for the millimeter wavelength portion of the electromagnetic spectrum.

## 12.1 Millimeter Wave Magnetics

*Frederic R. Morgenthaler, Robert L. Kyhl, Dale A. Zeskind*

The Microwave and Quantum Magnetics Group within the M.I.T. Department of Electrical Engineering and Computer Science and the Research Laboratory of Electronics recently began a research program aimed at developing coherent magnetic wave signal processing techniques for microwave energy which may form either the primary signal or else the intermediate frequency (IF) modulation of modulation of millimeter wavelength signals.

We are currently waiting for renewed Army support so that we can reactivate and continue this research program.

## 12.2 New Techniques to Guide and Control Magnetostatic Waves

*National Science Foundation (Grant 8008628-DAR)*
*Joint Services Electronics Program (Contract DAAG29-83-K-0003)*
*U.S. Army Research Office (Contract DAAG29-81-K-0126)*
*Frederic R. Morgenthaler, Dale A. Zeskind, Larry Hegi*

We have recently reviewed[1,2] our early interest and work[3-5] in controlling magnetostatic waves and modes in thin ferrite films by means of spatial gradients in the effective dc bias that depends upon

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[2]Emeritus

applied field, magnetic anisotropy and saturation magnetization.

Special emphasis has been given to a bias that varies in magnitude and/or direction while maintaining an orientation transverse to the propagation direction. Both rectangular and circular film geometries have been studied when the bias is either normal (forward-volume wave) or parallel (surface-wave) to the film.

An especially interesting case exists when the orientation of an in-plane bias is changed so as to alter the propagation direction of magnetostatic surface waves. Experimental confirmation of the basic idea has previously been reported by Stancil and Morgenthaler[6] and has very recently been extended by Stancil[7] to the case of a high Q surface wave ring-resonator that shows considerable device promise.

The analysis of mode propagation in bias gradient environments is complicated by the fact that even weak gradients can cause large changes in the rf susceptibility tensor whenever the components of the latter are very near resonance. Therefore, although there are regimes in which perturbation theory is very valid, there are those in which it is decidedly not.

In an invited paper to be published in Circuits, Systems and Signal Processing, Morgenthaler first develops a very general mathematical formulation applicable to ferrite films of both cartesian and circular geometries when the effective bias is normal to the film plane and conducting ground-planes may be present. All of the special cases, previously studied,[8] are embraced by the new theory.

Next, we consider the comparatively simple case of modes or waves without thickness variations and review how weak gradients can control the basic frequency dispersion and how larger gradients can sometimes create what are in effect "microwave domains" of the rf magnetization residing in a single domain environment of the static-equilibriummagnetization. Such "virtual-surface" modes[5] are predicted to have very large microwave energy densities associated with their "microwave-domain walls".

Continuing, we separate the ground planes, that were used to justify the consideration of modes without thickness variation, and discuss the three-dimensional modes of both a rectangular strip with finite width and a circular disk of finite radius. At first, the bias is kept uniform but then width (or radial) variations are added to reveal (through numerical solutions of the differential equations) how even weak gradients can sometimes cause major adjustments in the transverse mode patterns. Such gradient-induced field displacement effects are shown to be highly nonreciprocal and may have important ramifications for developing new types of microwave MSW devices.

An effective particle density $\hat{n}$ is defined (that includes the effects of fringing fields) such that its integration over the ferrite volume yields the total magnetostatic mode energy. Plots of $\hat{n}$ as a function of transverse coordinate provide valuable insight into the mode properties.

Finally, we show how the new analysis complements and extends our coupled-integral equation approach to solving boundary value problems when the in-plane bias (surface wave geometry) is a function of the width coordinate. This is done by simply interchanging width and thickness parameters in the new theory which then allows one to consider surface-wave propagation when there are thickness (but not width) variations in the effective bias. For a thin film such variation would come from thickness gradients in either the saturation magnetization or magnetic anisotropy (or both) and thus the modified theory can also treat the case of multiple graded layers with or without dielectric spaces between them.

**References**


1. F.R. Morgenthaler, "Novel Devices Based upon Field Gradient Control of Magnetostatic Modes and Waves," FERRITES: Proceedings of the International Conference, Japan, September-October 1980, pp. 839-846.
2. F.R. Morgenthaler, "Field Gradient Control of Magnetostatic Waves for Microwave Signal Processing Applications," Proceedings of the 1981 RADC Microwave Magnetics Technology Workship, June 10-11, 1981; F.R. Morgenthaler, "Workshop on Application of Garnet and Ferrite Thin Films to Microwave Devices," Session FC, Third Joint Intermag — Magnetism and Magnetic Materials Conference, Montreal, Canada, July 1982; N.P. Vlannes, "Investigation of Magnetostatic Waves in Uniform and Nonuniform Magnetic Bias Fields with a New Induction Probe," Third Joint Intermag — Magnetism and Magnetic Materials Conference, Montreal, Canada, July 1982.
3. D.A. Zeskind and F.R. Morgenthaler, "Localized High-Q Ferromagnetic Resonance in Nonuniform Magnetic Fields," IEEE Trans. Magn. MAG-13, 5, 1249-1251, September 1977.
4. F.R. Morgenthaler, "Magnetostatic Waves Bound to a DC Field Gradient," IEEE Trans. Magn. MAG-13, 5, 1252-1254, September 1977.
5. F.R. Morgenthaler, "Bound Magnetostatic Waves Controlled by Field Gradients in YIG Single Crystal and Epitaxial Films," IEEE Trans. Magn. MAG-14, 5, 806-810, September 1978.
6. D.D. Stancil and F.R. Morgenthaler, "Guiding Magnetostatic Surface Waves with Nonuniform In-plane Fields," J. Appl. Phys. 54, 3, 1613-1618 (1983).
7. D.D. Stancil, private communication paper presented at the 1983 Conference on Magnetism and Magnetic Materials, Pittsburgh, Pennsylvania, November 1983.
8. F.R. Morgenthaler, "Nondispersive Magnetostatic Forward Volume Waves under Field Gradient Control," J. Appl. Phys. 53, 3, 2652-2654 (1982).


## 12.3 Optical and Inductive Probing of Magnetostatic Resonances

*Joint Services Electronics Program (Contract DAAG29-83-K-0003)*

*Frederic R. Morgenthaler, Nickolas P. Vlannes, Robert L. Khyl*

Having finished development of the new induction probe that measures microwave magnetic field patterns of magnetostatic waves in LPE-YIG thin films, Nickolas Vlannes turned to making operative the optical probe based upon a Spectra Physics 125 laser tuned to the 1150 nonometer wavelength.

## 12.4 Magnetostatic Wave Dispersion Theory

*Joint Services Electronics Program (Contract DAAG29-83-K-0003)*
*Frederic R. Morgenthaler*

Larry Hegi has been carrying out theoretical and experimental determinations of the frequency dispersion of magnetostatic wave guides in the form of thin film rectangular strips of various width to thickness ratios when the external magnetic bias is either uniform of spatially nonuniform. He has written a report that includes sections on

- Measuring Dispersion The Antenna Finite Width Technology Fabrication Procedures

A paper based upon the S.M. Thesis of D.A. Fishman was published in the Journal of Applied Physics, June 1983. The abstract follows:

> The velocity of energy circulation associated with the uniform precession mode in a ferrite sphere is studied. Specifically, the effect of the boundary conditions imposed by a concentric conducting spherical cavity is considered for the uniform precession magnetic resonance mode of a yttrium–iron–garent (YIG) sphere. Theoretical analyses show that there is a critical ratio between the radius of the ferrite sphere and the conducting cavity where the energy velocity of the uniform precession mode approaches zero. Spin wave instabilities, as a result of the nonlinear coupling of the uniform precession mode to spin wave excitations are brought on if the rf–energy density expected to decrease the amount of incident power required for the onset of spin wave instability have been observed as a function of the cavity radius. The experimental cavity consists of two conducting partial hemispheres, one on each side of the YIG sphere.

**References**

1. D.A. Fishman and F.R. Morgenthaler, "Investigation of the Velocity of Energy Circulation of Magnetostatic Modes in Ferrites," J. Appl. Phys. 54, 6 (1983).

## 12.5 Magnetoelastic Waves and Devices

*Joint Services Electronics Program (Contract DAAG29-83-K-0003)*
*National Science Foundation (Grant 8008628-DAR)*
*Frederic R. Morgenthaler, Maurice Borgeaud*

The evolution of the magnetoelastic delay line has progressed gradually over a period of the last twenty years. In 1961, Schlömann[4] first proposed the possibility of spin wave excitation in nonuniform magnetic fields. In 1963, this effect was experimentally verified by Eschbach.[5,6] He showed that the excited spin waves propagated in the direction of decreasing magnetic field until their wavelengths matched those of elastic waves. As that value of wavelength (or corresponding magnetic field), most of the spin waves appeared to convert to elastic waves. This connection between conversion point and magnetic field, also verified by Strauss[7] in 1965, led both Strauss and

Schlömann[8,9] to propose the magnetically tunable delay line.

Since the proposal in 1965, a variety of magnetically tunable delay lines have been designed with limited success. To electromagnetically excite the spin waves in the YIG rod, designs utilizing thin wire coupling antennas,[1,10] stripline cavity resonators,[11] and more recently thin film antennas[2,3] have all been tried. Most designs have also had specific nonuniform field shapes imposed by either ferrimagnetic geometry[12,13] or auxiliary pole pieces designed into the housing.[1-3] In almost all of the previous attempts at producing linear delay with frequency in YIG delay lines, the focus has been on synthetizing a linear axial magnetic field.[1,2] However, no reason exists why a nonlinear axial magnetic field cannot also be used to obtain the desired delay function. Wadsworth[3] proved it by achieving insertion losses of 30 dB over a bandwidth of 500 MHz. The advantage of removing the unnecessary constraint of linearity from the axial magnetic field profile gives an extra degree of freedom which can be used to attempt to lower insertion loss and increase bandwidth.

Delay lines which were built by Itano[2] and Wadsworth[3] used a highly polished surface of the rod to get a reflection in the elastic region. These devices suffered because the input and output antennas lay in the same plane and were not very well electrically isolated.

### References

1. F.R. Morgenthaler and A. Platzker, "Magnetic Field Synthesis Procedures for Magnetostatic and Magnetoelastic Devices," Proceedings of the 1978 International Symposium on Circuits and Systems, New York, May 1978, pp. 574–578.
2. L.M. Itano, "Microwave Delay Line with Thin Film Antennas," Technical Report 43, S.M. Thesis, Microwave and Quantum Magnetics Group, Massachusetts Institute of Technology, August 1981.
3. A.K. Wadsworth, "Improvements in the Design of Microwave Magnetoelastic Delay Lines," Technical Report 46, S.M. Thesis, Microwave and Quantum Magnetics Group, Massachusetts Institute of Technology, January 1982.
4. E. Schlömann, "Advances in Quantum Electronics," (Columbia University Press, New York, 1961) p. 437.
5. J.R. Eschbach, "Spin Wave Propagation and the Magnetoelastic Interaction In Yttrium Iron Garnet," Phys. Rev. Lett. 8, 9, 357–359, May 1962.
6. J.R. Eschbach, "Spin Wave Propagation and the Magnetoelastic Interaction in Yttrium Iron Garnet," J. Appl. Phys. 34, 4, 1298–1304 (1963).
7. W. Strauss, "Elastic and Magnetoelastic Waves in Yttrium Iron Garnet," Proc. IEEE 53, 10, 1485–1495 (1965).
8. E. Schlömann, "Generation of Spin Waves in Nonuniform DC Magnetic Fields. I. Conversion of Electromagnetic Power Into Spin Wave Power and Vice Versa," J. Appl. Phys. 35, 1, 159–166 (1964).
9. E. Schlömann, "Generation of Spin Waves in Nonuniform DC Magnetic Fields. II. Calculation of the Coupling Length," J. Appl. Phys. 35, 1, 167–170 (1964).
10. E. Schlömann, R.I. Joseph, and T. Kohane,"Generation of Spin Waves in Nonuniform Magnetic Fields with Applications to Magnetic Delay Lines," Proc. IEEE 53, 10, 1495–1507 (1965).
11. B.A. Auld, J.H. Collins, and D.C. Webb, "Excitation of Magnetoelastic Waves in YIG Delay Lines," J. Appl. Phys. 39, 3, 1598–1602 (1968).
12. H. Dotsch, "Magnetoelastic Delay Lines with Linear Dispersion," J. Appl. Phys. 43, 4, 1923 (1972).

13. R.W. Kedzie, "Magnetostatic Mode Propagation in Axially Magnetized YIG Rod Containing a Turning Point," J. Appl. Phys. 39, 6, 2731–2734 (1968).

## 12.6 On the Electrodynamics of a Deformable Ferromagnet Undergoing Magnetic Resonance

*National Science Foundation (Grant 8008628-DAR)*
*Joint Services Electronics Program (Contract DAAG29-83-K-0003)*
*Frederic R. Morgenthaler*

The energy-momentum tensor of a deformable ferromagnet is developed using the Chu formulation of electrodynamics which we reviewed in an invited paper presented in Paris during July 1983 at the Mechanical Behavior of Electromagnetic Solid Continua Symposium. It is shown that when the magnetization is undergoing ferromagnetic resonance, the new tensor differs from that of conventional theory, principally because large-signal linear momentum due to spin precession can appear in the rest-frame of the solid. Under transient conditions, the time rate of change of that momentum leads to predictions of an altered net force even when the ferromagnet is acting as a rigid body.

## 12.7 Microwave Hyperthermia

*Frederic R. Morgenthaler, Tushar Bhattacharjee, Carey M. Rappaport*

Our understanding of both physics and physiology is challenged in trying to optimize techniques for heat production and for the thermometry associated with Hyperthermia modalities used in connection with cancer therapy.

Fundamental considerations are based on designing proper microwave applicators which must be able to handle the microwave power required to raise the temperature of the tumor. They must also minimize the amounts of microwave power being delivered to the healthy tissue or being radiated into free space.

## 12.8 Synthesis of Microwave Applicators

*National Institutes of Health (Grant 1 P01 CA31303-01)*
*Frederic R. Morgenthaler, Carey M. Rappaport, Tushar Bhattacharjee*

We have recently given consideration to radiating trough waveguides as a possible microwave applicator for the delivery of hyperthermia. The asymmetric geometry shown in Fig. 12–1 was first discussed in 1958 by Rotman and Naumann.[1]

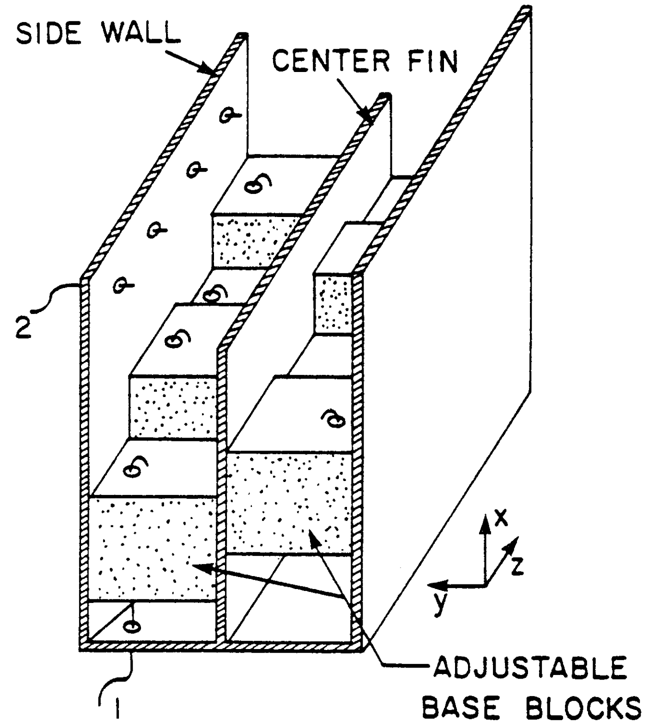


**Figure 12-1:** Trough Waveguide with alternating base asymmetry and field sampling probes (1 → H field, 2 → E field).

Being a leaky wave transmission line, it radiates in the x–direction as it guides waves in the z–direction. It can be derived either from a symmetric bisection of a strip line carrying the 1st higher order TE mode or from the folding of a slotted rectangular waveguide carrying $TE_{01}$ mode. The base asymmetry supports an asymmetric radiating mode. The complex transcendental equation solution has been derived from the equivalent circuit for the asymmetric trough waveguide using the transverse resonance technique. The derivation includes the reflection due to the finite length of the guide and also the effect of the finite thickness of the fin in the trough guide geometry. Programs have been written which solve such geometries from both analysis and synthesis points of view. For example, one can calculate the dimensions of a troughguide with a specified complex propagation constant $\gamma$ or the $\gamma$ can be determined from a particular known geometry.

An experimental model has been designed and built to investigate the trough waveguide performance. Intended for use at 915–2450 MHz, this applicator will focus power in synthetic muscle phantom material. As a single unit with an aperture of 2½" by 8½", it is a building block for either a planar array — where several troughs are placed next to one another; or for a cylindrical array — where axial troughs would radiate into a phantom in the center.

The asymmetry of the test model is adjustable. The base is formed by blocks which can be finely displaced vertically. Note the alternating block heights in Fig. 12–1. This provides for 180° phase reversals, allowing configurations of aperture as a Fresnel lens. The Fresnel zone width was chosen to maximize power in muscle phantom at a depth of one wavelength at 915 MHz.

A major concern of this applicator is monitoring radiated power. Electric and magnetic field probes sample the total forward and backward waves at each block section. Combining the outputs from these probes gives power guided by the trough waveguide.

To investigate the cylindrical applicator configuration, software has been written which calculates the radial ($\hat{r}$) and axial ($\hat{z}$) field distribution produced by E-field sources on a finite cylindrical section. Given the dielectric characteristics of a medium and the frequency, field intensity is plotted as a function of radius or length. The radial impedance ($Z_r$) can also be calculated. Typical results for an infinitely long cylindrical aperture are shown in Fig. 12-2 for muscle tissue and frequencies 433, 915, 2450 MHz.

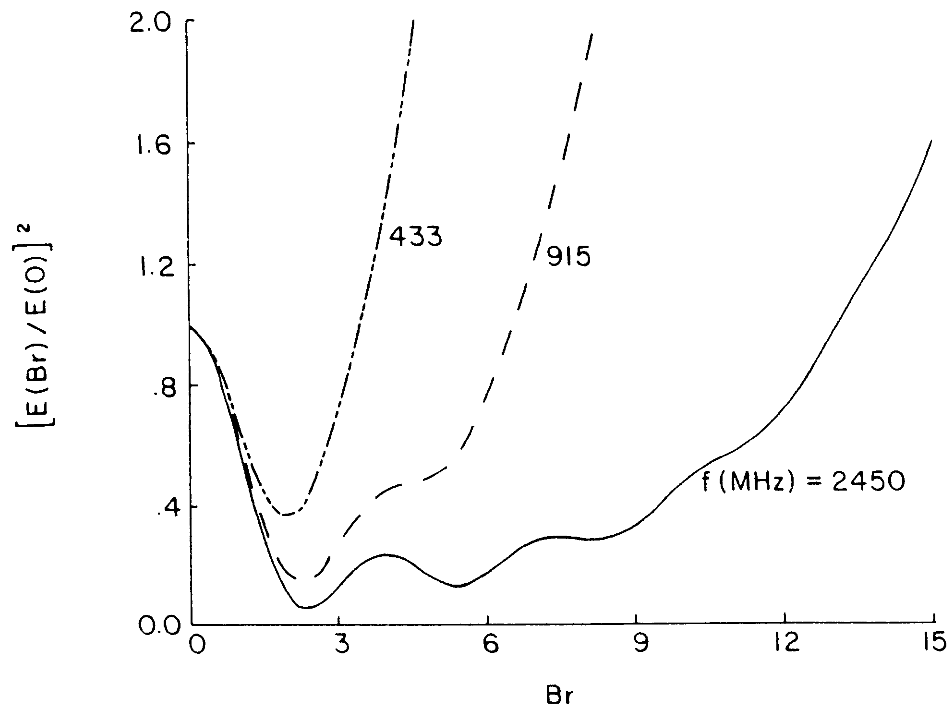


**Figure 12-2:** Relative power absorption for an infinite cylinder of muscle tissue

## References

1. W. Rotman and S.J. Naumann, "The Design of Trough Waveguide Antenna Arrays," AFCRC-TR-58-154, June 1958.

## Publications

Borgeaud, M., "An Improved Two-port Magnetoelastic Delay Line," S.M. Thesis, Department of Electrical Engineering and Computer Science, M.I.T., January 1984.

Morgenthaler, F., "On the Electrodynamics of a Deformable Ferromagnet Undergoing Magnetic Resonance," Proceedings of the IUTAM-IUPAP Symposium on Mechanical Behavior of Electromagnetic Solid Continua.

Morgenthaler, F. and T. Bhattacharjee, "Design of Annual Arrays to Contol Microwave Power Deposition in Biological Tissues," poster paper presented at the Hyperthermia Workshop at IEEE MTT-S International Microwave Symposium, May 3l-June 3, 1983.

Fishman, D.A. and F.R. Morgenthaler, "Investigation of the Velocity of Energy Circulation of Magnetostatic Modes in Ferrites," J. Appl. Phys. 54, 6 (1983).

Melcher, J.R., "Analytic Solutions to the Bioheat Equation in a Cylindrical Geometry," S.B. Thesis, Department of Electrical Engineering and Computer Science, M.I.T., May 1983.

Stancil, D.D. and F.R. Morgenthaler, "Guiding Magnetostatic Surface Waves with Nonuniform In-plane Fields," J. Appl. Phys. 54, 3 (1983).

Morgenthaler, F.R., "Field Gradient Control of Magnetostatic Waves for Microwave Signal Processing Applications," Proceedings of the 1981 RADC Microwave Magnetics Technology Workshop, June 10-11, 1981, RADC In-house Report, January 1983.

Morgenthaler, F.R., "Control of Magnetostatic Waves in Thin Films by Means of Spatially Nonuniform Bias Fields," Circ. Syst. Sig. Proc., to be published.