

## **28.0 Microwave and Quantum Magnetics**

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## **28.1 Microwave Hyperthermia**

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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.

The Ph.D. dissertation research of Carey Rappaport has been completed. The abstract, table of contents and conclusions are reproduced below:

## **28.2 Synthesis of Optimum Microwave Antenna Applicators for Use in Treating Deep Localized Tumors**

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Submitted to the Department of Electrical Engineering and Computer Science on May 26, 1987 in partial fulfillment of the requirements for the Degree of Doctor of Philosophy.

### **28.2.1 Abstract**

The optimal electromagnetic source distributions for depositing power at depth in biological tissue are derived and analyzed. The fundamental microwave penetration limits, against which all other applicator performance can be measured, is determined.

Focussed power patterns are computed for planar, circular cylindrical and spherical source geometries, which have as much or greater power at a centrally located tumor as in the surrounding normal tissue. Focussing is shown to increase the planar pene-

tration depth by a factor of three over a uniform source. Analysis of performance as a function of frequency shows that for smaller body parts, 915 MHz maximizes penetration without sacrificing power pattern peak resolution.

A leaky-wave antenna, the troughguide, is introduced as a flexible applicator with built-in power monitoring lines, amplitude control, and a continuous aperture with supports a distribution that is unaffected by tissue loading variations. An artificial dielectric composed of conducting spheres imbedded in boron nitride is used to match to tissue while providing surface cooling. Experiments were performed on a troughguide in conjunction with the artificial dielectric at 915 MHz radiating into simulated biological tissue. Power and temperature contours which show a localized power maximum are presented.

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Appendix A: Program Description and Listing, "SPHSUM"

Appendix B: Mathematical Derivation of Surface Current Diffraction Integral Analysis

Appendix C: Program Description and Listing, "FAZERR"

Appendix D: Program Description and Listing, "intfoc.c"

Appendix E: Program Description and Listing, "intcyl.c"

Appendix F: Program Description and Listing, "tgmatch"

Appendix G: Troughguide Power Monitoring Probe Equations

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Appendix I: Derivation of Snell's Law for Lossy Media

Appendix J: Derivation of Impedance Matching Layer Equations

Appendix K: Program Description and Listing, "CONGEN/CONTR"

References

## 28.3 Microwave Ferrites

Frederic R. Morgenthaler

The February 1988 issue of the IEEE Proceedings will be devoted, in part, to the subject of microwave ferrites. A review paper by F.R. Morgenthaler titled "An Overview of Electromagnetic and Spin Angular Movement Mechanical Waves in Ferrite Media" will be included. The abstract, table of contents, introduction and summary are reproduced below:

### 28.3.1 Abstract

We review the principal characteristics of gyromagnetic materials that are useful for microwave applications and give both the large-and small-signal models that govern wave propagation at microwave frequencies. Uniform and nonuniform plane waves in a unbounded ferrite medium are considered from the complementary view points of electromagnetics and mechanics.

Both electromagnetic ( $\vec{E}\vec{X}\vec{H}$ ) and quantum-mechanical exchange channels of power exist in such materials which can be ascribed to either waves or quasiparticles.

Regimes of wave propagation that are magnetostatic in character are shown to exist, as well as the relationships between the Walker modes of a small spheroid and the magnetostatic waves propagation in thin films.

When the power densities within these waves or modes exceeds certain thresholds, the linear model breaks down and parametric instabilities can create a form of "magnetic turbulence." We review the thresholds of such for both first - and second-order processes that involve the uniform precession mode and "parallel-pumping" process that do not.

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2. Large-Signal Model of a Magnetized Ferrite
3. Small-Signal (Linearized) Model

#### 4. Plane waves in a unbounded Ferrite Medium

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#### 10. Summary

### 28.3.3 Introduction

The desired characteristics of a magnetic material for use at microwave frequencies are:

1. Magnetic Order. A relatively high density of magnetic ions is necessary in order that the magnetic interactions be large. Strong nearest neighbor coupling leads to spontaneous magnetization below some critical temperature,  $T_c$ , which should be high enough for practical applications.

2. Very high resistivity. A large skin depth is required to allow penetration of electromagnetic energy inside the sample, where the  $\bar{h}$  field can interact with the magnetic moments.
3. Low magnetic loss. To reduce magnetic resonance damping, the magnetic ions should be weakly coupled to the lattice, therefore spin-orbit coupling effects should be small. For a given material, losses also depend upon the configuration of the magnetization and can be minimized by applying a large enough external dc magnetic field to remove all domain walls (and hence all wall resonances). It is desirable that the material saturate in a reasonable field.
4. Low elastic loss. This is important for microwave acoustic applications, but can be ignored otherwise.

Fortunately, a number of actual materials combine these properties and belong to the class termed ferrimagnetic.<sup>1</sup> These materials commonly called ferrites are oxides of the ferromagnetic metals which may also contain ions of one or more nonmagnetic atoms.<sup>1</sup> Examples are  $\text{Fe}_3\text{O}_4$  (magnetite),  $\text{BaFe}_2\text{O}_4$ ,  $\text{MnFe}_2\text{O}_4$ ,  $\text{CoFe}_2\text{O}_4$ , and  $\text{Y}_3\text{Fe}_5\text{O}_{12}$  (yttrium iron garnet). The first of these (also known as lodestone) was the first magnetic material discovered by man but is of limited importance for microwave applications because it suffers from a fairly low resistivity. The last (commonly abbreviated YIG) is of great practical importance because of its unusually low magnetic and elastic losses.

Ferrites are available in polycrystalline ceramic and single crystal forms. The former are much used in the fabrication of nonreciprocal microwave devices that operate with material wavelengths very much larger than the crystallite grain size, the latter are required for short wavelength magnetostatic wave devices and/or microwave acoustic applications because wave scattering at grain boundaries is undesirable, because it creates high attenuation.

In this review paper, we develop both large-signal and small-signal models of a rigid ferrimagnetic material that is magnetized to saturation by an external dc magnetic field. Magnetic anisotropy, quantum-mechanical exchange, and dissipation effects are included. For the linear model, and for steady-state wave propagation at frequency  $\omega$ , two complementary view points are developed. In the first, and most common, the ferrite material is “black-boxed” to yield the Polder magnetic susceptibility tensor; that constitutive law is then combined with Maxwell’s Equations. The primary emphasis is on the small-signal electric and magnetic fields,  $\bar{e}$  and  $\bar{h}$  and the waves are considered electromagnetic in character. In the second, it is Maxwell’s Equations that are “black-boxed” to yield  $\bar{e}$  and  $\bar{h}$  in terms of the small-signal magnetization  $\bar{m}$ . The primary emphasis is on the small-signal angular momentum vector associated with  $\bar{m}$  and the waves are considered as mechanical in character. Naturally, both view points lead to the same final result of waves that, in general, have both electromagnetic and mechanical characteristics; when a particular character predominates the corresponding view point is especially helpful.

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<sup>1</sup> Some authors prefer to reserve the term “ferrite” for a particular subclass of magnetic oxides, namely  $\text{MeOFe}_2\text{O}_3$  (where Me is any divalent metal ion). We make no such distinction here.

Coupling between mechanical and electromagnetic components of the wave exists because, at an atomic level, electrons that carry angular momentum also carry a magnetic moment. When the magnetic moments in a solid are parallel to one another, organized angular momentum also exists and is the basis of magnetic resonance effects in ferrites.

Because a precessing mechanical top (and thus angular momentum waves) are inherently nonreciprocal, so too are associated electromagnetic waves when the mechanical component is sufficiently strong. This fact is the underlying reason why nonreciprocal ferrite devices<sup>2</sup> such as isolators, circulators and gyrators have proved to be possible.

After developing the linearized models, we review plane wave propagation in an unbounded ferrite medium and derive the dispersion relations between angular frequency  $\omega$  and the propagation wave vector. The fields of those portions of the spectrum where mechanical properties predominate, are shown to satisfy the condition  $\nabla \times \bar{h} \cong 0$ ; these so-called magnetostatic waves are discussed in detail. In contrast, when  $\nabla \times \bar{h} \neq 0$ , the waves are primarily electromagnetic in character.

In comparatively long wave length wave regions, where quantum-mechanical exchange effects are of negligible importance, wave power is associated with the  $\bar{E} \times \bar{E}$  power flux and is governed by the normal Maxwellian boundary conditions on  $\bar{E}$  and  $\bar{H}$  when the wavelengths are sufficiently short, power is also carried by exchange mechanisms and additional boundary conditions are required.

Based upon the linearized-model, we formulate small-signal energy, power and stress, momentum conservation laws. An alternative interpretation to the wave description is given in terms of quasiparticles. At the macroscopic continuum level, the connection between photons, magnons and waves is provided by energy-momentum considerations. After the boundary conditions on both static and rf fields are considered, the magnetostatic modes of small spheroids are discussed with particular attention being given the family of modes that contain the uniform precession, or Kittel resonance. magnetostatic surface waves of a rectangular thin film are shown to be directly related to that family of modes; they provide an explanation of field-displacement modes; they provide an explanation of field-displacement nonreciprocity. Forward and backward volume waves propagating in such films are also reviewed.

Coupling between the linear modes of a saturated ferrite occurs because the total magnetization vector is conserved; this leads to nonlinear frequency mixing and parametric instabilities that cause a type of magnetic turbulence that can limit the amplitude of the linear response. Such indirect first- and second-order instabilities involve the linear susceptibility between an applied rf field and some mode (commonly the uniform precession) which nonlinearly pumps unstable spin waves. These processes are reviewed along with first-order “parallel-pumping” processes that directly couple an applied rf magnetic field to unstable spin waves or other magnetostatic modes. A particle interpretation of parametric instabilities, concludes this review of basic microwave resonance and propagation effects in ferrite media.

### 28.3.4 Summary

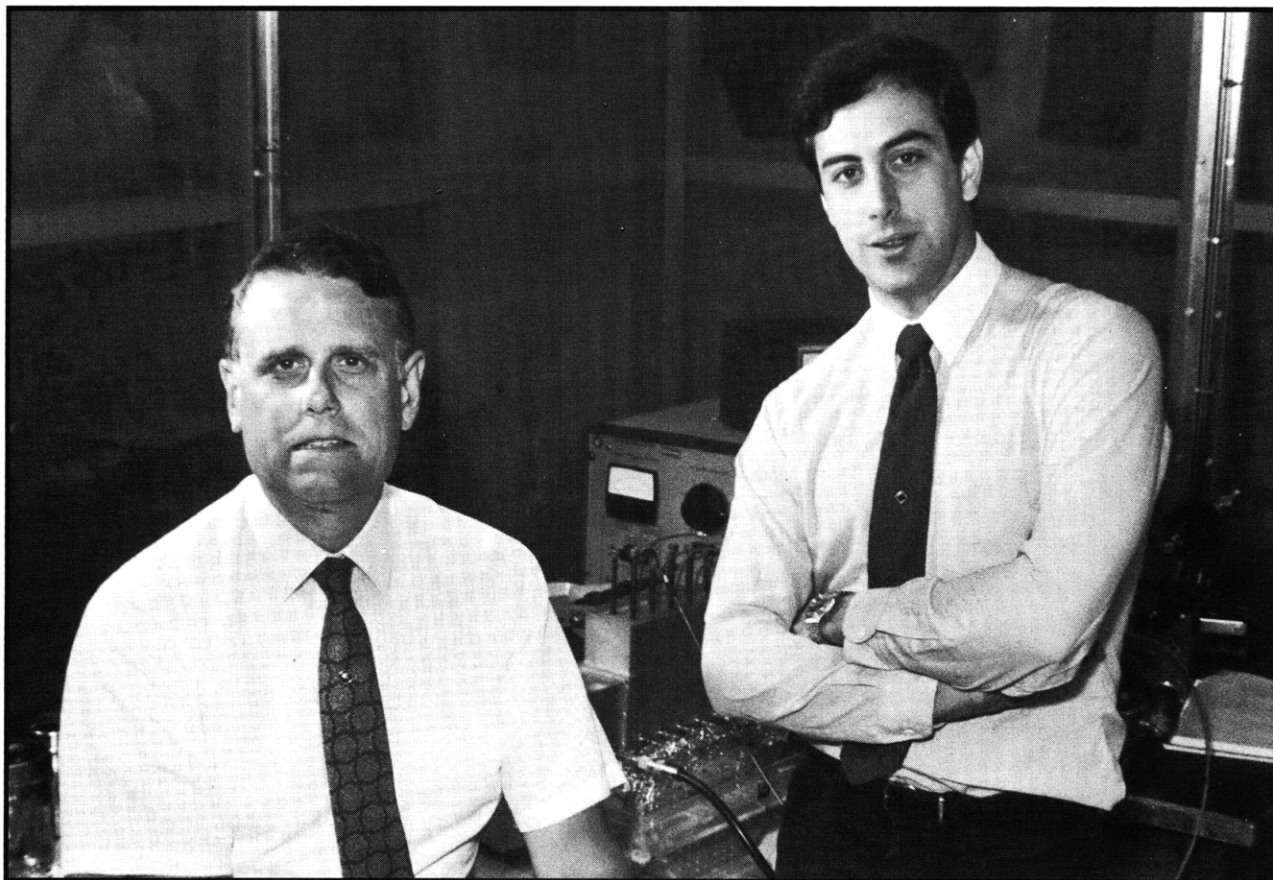
We have reviewed the underlying large-signal model of a rigid magnetically-saturated (single-domain) ferrite medium and used it to develop the linearized equations that govern the small-signal model. Uniform and non-uniform wave propagation in an infinite medium was derived from both electromagnetic and mechanical view points; the mechanical view points; the latter is especially useful for dealing with magnetostatic wave regimes.

Power-energy and momentum theorems revealed the connection between wave and quasi-particle representations.

Magnetostatic Walker modes in small ferrite ellipsoids were discussed with special attention given to the Kittel uniform precession mode.

Both volume and surface magnetostatic wave propagation in thin films were also considered.

Finally, high power effects cause by parametrically unstable spin wave were reviewed and a unified treatment of first and second-order thresholds and parallel pumping thresholds was presented.



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