INTERACTION OF MICROWAVES WITH FERRIMAGNETIC LAYERED STRUCTURES

by

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S.S. Gupta

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ABSTRACT

The present thesis is devoted to the study of the interaction of microwaves with ferrimagnetic layers. The total reflection of electromagnetic waves from biased ferrimagnetic interface has been investigated from the point of view of energy flow and ray propagation. An expression for the lateral shift has been derived. The nonreciprocal phase shift has been explained in terms of the occurrence unequal lateral shifts when the rays are incident from the opposite sides to the normal. This study leads to a phenomenological ray model for attenuated total reflection.

We have presented electromagnetic analysis of surface wave propagation on a thick, transversely magnetized ferrimagnetic slab, accounting for the effect of the finite width of the slab. The domain of validity of earlier analyses has been established.

A theoretical study of the power flow and energy distribution of guided magnetostatic bulk and surface waves in a dielectric-layered structure has been carried out, neglecting losses. The equivalence of energy velocity and group velocity has been established. Useful numerical results and conclusions regarding the power flow, energy distribution and nondispersive

delay characteristics have also been presented.

A ray optic analysis has been carried out to investigate magnetostatic bulk wave propagation in a ferrimagnetic slab/film. Dispersion relations are obtained for different configurations. Several results regarding power flow in delay lines are explained with the help of this model. The ray model analysis has also been extended to the case of transversely magnetized slab of a hexagonal planar magnetoplumbite. The group delay time obtained from ray optic and rigorous analyses have been compared numerically; good agreement between the two is obtained.

PREFACE

In the last decade, there has been a renewed interest[1-8] in the study of the interaction of microwaves with ferrimagnetic layered structures. The reason for this is the potential applications of such investigations to a variety of novel devices for microwave signal processing (with magnetic waves guided by ferrimagnetic layers). It is well known that biased ferrimagnetics are strongly dispersive in the vicinity of ferromagnetic resonance[9]. For biasing fields of reasonable strength, the resonance frequency lies in the microwave region of the electromagnetic spectrum. Hence, biased ferrimagnetics generally exhibit strong dispersion at microwave frequencies. This leads to characteristic frequency dependence of phase and group velocities which is well suited for the various microwave devices[5,6,9-15].

An indepth study shows that the characteristic features of the interaction of microwaves with ferrimagnetics are brought about by the existence (in ferrimagnetics) of permanent magnetic dipoles (spins) which are coupled by means of various interactions, such as, exchange interaction[16,17](direct or indirect), dipolar interaction[18], spin-orbit interactions[9], etc. A magnetic disturbance can propagate in this system of coupled spins, thus, leading to the socalled spin waves. These spin waves are highly dispersive and are characterized by phase velocities ranging from the speed of sound to the speed of light[1]. The response of ferrimagnetics to a microwave field (electromagnetic or elastic) depends on the coupling of the field to the spin waves. In the region where the phase velocities of electromagnetic and spin waves are comparable, the coupled waves are called magnetostatic. On the other hand, the region where the phase velocities of elastic waves and spin waves are comparable, the coupled waves are called magnetoelastic[1]. Ignoring the elastic wave branches, a typical dispersion curve for an unbounded medium is shown in Figure 1. While the upper branch corresponds purely to fast electromagnetic waves and is of little practical interest, the lower branch contains[9,19] electromagnetic (I), dipolar (II) and spin wave (III) regions. This branch has been greatly explored to fabricate a variety of devices, such as delay lines, filters, resonators, loaded waveguide, phaseshifters, isolators, circulators, etc.

The earliest fabricated delay devices were based on magnetostatic and magnetoelastic waves in rods, discs and plates[2]. After the demonstration[20] of the propagation magnetostatic waves in a YIG sample, a large number of investigations were reported on signal processing devices[21-28] for pulse compression, storage, variable delay, delay cum isolation, etc. In spite of the numerous theoretical

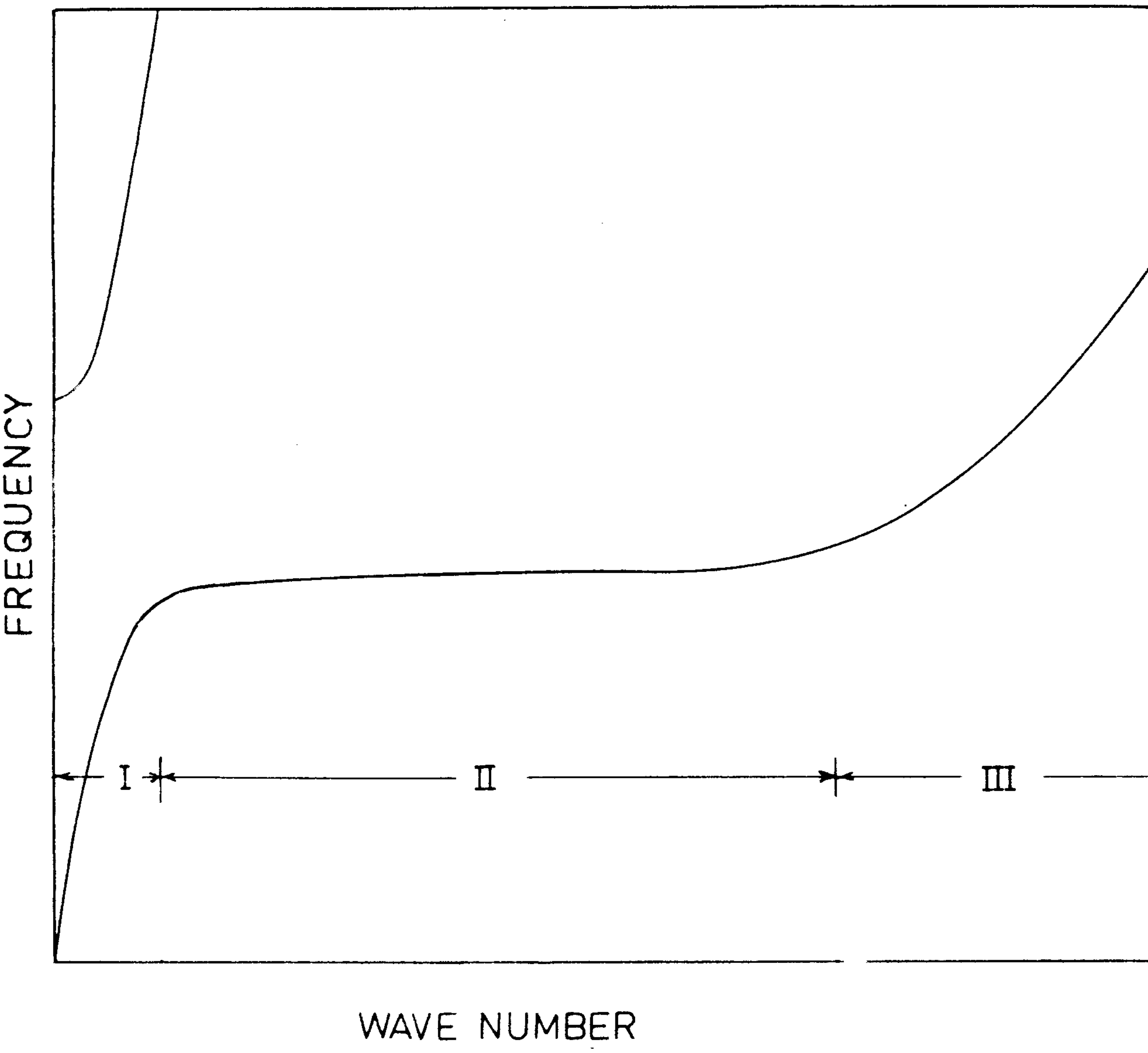

Fig.1 Qualitative dispersion curve.

and experimental investigations, the delay devices using rods, discs and plates could not meet the system requirements, mainly because of the focussing effects due to inhomogeneous internal magnetic field arising on account of non-ellipsoidal geometry of the material sample[2]. In recent years, this difficulty has been overcome after the growth of high quality epitaxial ferrimagnetic films[29-31] on non-magnetic substrates. The aspect ratio of films being large ($\sim$1000), the internal dc field is more or less uniform which leads to suppression of the lens effects associated with non-uniform internal dc fields in rods, discs and thick plate. Thus, modern magnetostatic wave devices, viz., delay lines, filters, resonators, convoluers, etc. make use of thin ferrimagnetic layered planar structures.

The operation characteristics of the aforementioned devices depend critically on a large number of parameters[32-41], viz., dc magnetic field, wave frequency, thicknesses, widths and relative positions of the various layers, couplers, etc. As such, an empirical approach to the design of these devices is unlikely to yield the desired characteristics. Detailed analysis is required to predict the microwave propagation characteristics for each configuration.

In recent years, numerous analyses[42-53] of microwave propagation characteristics in ferrimagnetic layered planar structures have been published. The usual method of analysis consists of obtaining rigorous or quasistatic solution of Maxwell's equations subject to appropriate boundary conditions. While this approach is quite successful, it does not provide sufficient physical insight of the associated phenomena. The present thesis lays particular stress on the physics of the interaction of microwaves with ferrimagnetic layers. Specifically, the author has resorted to energy and power flow approach to investigate the interaction of microwaves with ferrimagnetics and the application of this study to guided waves in ferrimagnetic layered planar structures. Apart from providing the necessary physical insight, such an approach has led to new results which have been reported in this thesis.

A chapterwise summary of the thesis is as follows:

Chapter-I: Microwave Reflection at Dielectric-Ferrimagnetic Interface

This chapter presents the investigation of the reflection of electromagnetic waves from biased ferrimagnetics, from the view point of energy flow and ray propagation. Renard's analysis[54] of reflection from dielectrics has been generalized to study the lateral shift of an electromagnetic beam reflected from a ferrimagnetic half space, magnetized transverse to the plane of incidence. The nonreciprocity of total reflection has been explained in terms of unequal lateral shifts, when the rays are incident from opposite sides to the normal. It has been shown that the lateral shift can be positive as well as negative and is finite at normal incidence. This study leads to a phenomenological ray model for attenuated total reflection from a ferrimagnetic medium. The results can also be useful in ray modelling of guided waves as well as for open resonator measurements of linewidth in the millimeter wave region.

Chapter-II: Surface Wave Propagation on a Thick Ferrimagnetic Slab

This chapter presents an electromagnetic analysis of magnetic surface wave propagation associated with a thick, transversely magnetized ferrimagnetic slab. The effect of transverse variation of the wave field has been taken into account; this leads to hybridization of TE and TM modes. Using the interface model, a general dispersion relation has been obtained which reduces to the well known limiting forms. The numerical results indicate restricted validity of the earlier analyses. Specifically, for any realistic set of parameters, the propagation of magnetic surface wave on a ferrimagnetic substrate in X-band can be satisfactorily described only by the present analysis.

Chapter-III: Power Flow and Energy Distribution of Magnetostatic Bulk and Surface Waves in Dielectric Layered Structure

A theoretical study is presented of power flow and energy distribution of guided magnetostatic bulk and surface waves in a dielectric layered structure consisting of a ferrimagnetic layer, sandwitched between free space and grounded dielectric. The analysis has been carried out for a hexagonal planar magnetoplumbite from which the results for isotropic ferrimagnetics follow as a special case. Two configurations have been investigated in which the dc magnetization is either perpendicular to the ferrimagnetic layer or within the plane of the layer (transverse to the direction of propagation). Starting from the generalized Poynting theorem for dispersive media, the expressions for power flow per unit area and energy density have been derived under the magnetostatic approximation. It is seen that, in the case of isotropic ferrimagnetics, the power flow in the dielectric and ferrimagnetic regions occurs in mutually opposite directions. But, the net power flows in the direction of phase propagation. The velocity of time averaged energy flow has been shown to be equal to the group velocity, which establishes the consistency of magnetostatic approximation with the general principles of wave propagation.

On the other hand, for slabs/films of hexagonal planar magnetoplumbites, practically all permutations regarding the directions of power flow in different regions are possible depending on the orientation of the hard axis and of the dc magnetization. Useful numerical results and conclusions regarding the delay characteristics have also been presented.

Chapter-IV: Ray Optic Approach to Magnetostatic Bulk Wave Propagation in a YIG Film Delay Line

This chapter presents a ray optic approach to magnetostatic bulk wave propagation in a normally magnetized YIG film. The dispersion relation is obtained using the method of transverse resonance^{55}. The lateral shift due to reflection at the boundaries has been obtained from energy analysis. The path of the rays has been traced from which an approximate expression for the group delay time has been obtained. It is seen from the numerical results that, for the first order mode, the agreement between this approximate expression for the delay with the rigorous one is satisfactory except near the lower cut off. In the case of higher order modes, the two compare satisfactorily throughout the frequency range of guided waves. Several conclusions drawn in chapter III are physically explained on the basis of this model.

Chapter-V: Ray Model of Non-reciprocal Bulk Wave Propagation in a Slab of Hexagonal Planar Magnetoplumbite

In this chapter, the author has generalized the ray optic approach to the case of a transversely magnetized

Zn_2Y planar magnetoplumbite. The model explains the existence of guided bulk waves in spite of the transverse magnetization. The occurrence of forward as well as backward wave modes for different orientations of the hard axis has also been explained by tracing the path of rays for each configuration. The nonreciprocity of the modes for the grounded slab configuration is explained in terms of non-reciprocal reflection at the ferrimagnetic-dielectric interfaces. The delays obtained from ray optic and rigorous analyses have also been compared in the case of grounded ferrimagnetic slab/film. It is seen that the agreement between the ray optic and rigorous calculations is excellent in the case of backward mode. In the case of the forward wave modes, the agreement is quite satisfactory except for the first order mode. Even for the first order mode, the agreement is satisfactory far from the cut off region.

The aforementioned work has resulted in the following publications/communications:-

1. Physics of Microwave reflection at a dielectric-ferrite interface, Physical Review B, Vol.19, pp.5403-5412 (1979).
2. Theory of Magnetic Surface Wave Propagation on a Thick YIG Slab, ~~Communicated~~ to J.Appl.Phys. (1980). Accepted

3. Power flow and energy distribution of magnetostatic bulk waves in dielectric-layered structure, J.Appl.Phys. ~~(In Press 1979).~~ 50 (11), pp.6697-6699 (1979).

4. Power flow and energy distribution of magnetostatic surface waves in a dielectric-layered structure, Communicated to Appl.Phys. (1979).

5. Ray optic approach to magnetostatic bulk wave propagation in a YIG film delay line, Accepted ~~Communicated to~~ IEEE Trans. MTT (1980).

6. Ray model of non-reciprocal bulk wave propagation in a slab of hexagonal planar magnetoplumbite, Communicated, 1979.

REFERENCES

1. B.A.Auld, in *Appl.Solid State Science*, Vol.2, Ed. R.Wolfe, (Academic Press, N.Y. and London, 1971), pp.2-106.

2. J.H.Collins, J.D.Adam and J.M.Owens, *Solid State Devices*, (Conf. Series No.15, The Institute of Physics, London, 1972), pp.83-126.

3. J.H.Collins and F.A.Pizzarello, Int. J.Electron., *34*, pp.319-351, 1973.

4. W.L.Bongianni, Microwave J. *17(1)*, 49, 1974.

5. F.J.Rosenbaum, in *Advances in Microwaves*, Vol.8, Eds. L.Young and H.Sobol (Academic Press, N.Y.1974), pp.203-294.

6. J.Helszajn, *Nonreciprocal Microwave Junctions and Circulators* (J.Wiley and Sons; N.Y., 1975).

7. J.D.Adam and J.H.Collins, Proc. IEEE *64*, pp.794-800, 1976.

8. J.H.Collins, J.M.Owens, and C.V.Smith, Jr. Proc. Ultrasonic Symp., pp.541-552, 1977.

9. B.Lax and K.J.Button, Microwave Ferrites and Ferrimagnetics, (McGraw Hill, New York, 1962).

10. J.Helszajn, *Principles of Microwave Ferrite Engineering*, (Wiley-Interscience, London, 1969).

11. R.A.Waldron, *Ferrites: An Introduction for Microwave Engineers* (D.Van Nostrand Company Ltd. London, 1961).

12. A.G.Gurevich, *Ferrites at Microwave Frequencies* (Boston Technical Publishers, Inc., Massachusetts,USA, 1965).

13. W.H.Von Aulock and Clifford E.Fay, *Linear Ferrite Devices for Microwave Applications* (Academic Press, New York, 1968).

14. R.F.Soohoo, *Theory and Applications of Ferrites* (Prentice-Hall, Inc., Englewood Cliffs, N.J., 1960).

15. P.J.R.Clarricoats, Microwave Ferrites, (John Wiley and Sons, Inc., New York, 1961).

16. P.W.Anderson, in Solid State Physics Vol.14, Eds. F.Seitz and D.Turnbull, (Academic Press, N.Y., 1963), pp.99-214.

17. P.W.Anderson, in Magnetism Vol. I. Ed. G.T.Rado and H.Suhl, (Academic Press, N.Y., 1963).

18. W.H.Von Aulock, Handbook of Microwave Ferrite Materials, (Academic Press, N.Y., 1965).

19. B.A.Auld, J.Appl.Phys. 31, 1642, 1960.

20. F.A.Olson and J.R.Yaeger, IEEE Trans. MTT 13, 63, 1965.

21. J.H.Collins and G.G.Neilson, Electron.Lett. 1, 234, 1965.

22. B.A.Auld, J.H.Collins and D.C.Webb, J.Appl.Phys. 39, 1598, 1968.

23. E.K.Kirchner, F.A.Olson and G.E.Bennett, J.Appl. Phys. 39, 489, 1968.

24. L.K.Brundle and N.J.Freedman, Electron.Lett. 4, 132, 1968.

25. D.E.Kaplan, R.M.Hill and G.F.Hermann, J.Appl.Phys. 40, 1164, 1969.

26. J.D.Adam, Electron.Lett. 6, 718, 1970.

27. J.D.Adam, J.H.Collins, and J.M.Owens, Electron. Lett. 8, 229, 1972.

28. J.B.Merry and J.C.Sethares, IEEE MAG. 9, 527, 1973.

29. J.E.Mee, J.L.Archer, R.H.Meade and T.M.Hamilton, Appl.Phys.Lett. 10, 289, 1967.

30. R.C.Linares, J.Crystal Growth 3, 4443, 1968.

31. H.J.Levensteen, S.Licht, R.W. Landorf and S.L.Blank, Appl.Phys.Lett. 19, 486, 1971.

32. J.H.Collins, J.D.Adam and J.M.Owens, AIP Conf. Proc. 10, pp.150-154, 1972.

33. W.L.Bongianni, J.Appl.Phys. 43, 2541, 1972.

34. J.C.Sethares and M.R.Stiglitz, IEEE Trans.MAG 10, 787, 1974.

35. R.G.Newburg, P.Blacksmith, A.J.Budreau and J.C.Sethares, Proc. IEEE 62, 1621, 1974.

36. Z.M.Bardai, J.D.Adam, J.H.Collins and J.P.Parekh, AIP Conf. Proc. 34, pp.268-270, 1976.

37. N.D.J.Miller, Phys.Status Solidi (a) 37, 83, 1976.

38. N.D.J.Miller and D.Brown, Electron.Lett. 12, 209, 1976.

39. C.G.Sykes, J.D.Adam and J.H.Collins, Appl.Phys.Lett. 29, 388, 1976.

40. H.J.Wu, C.V.Smith, J.H.Collins and J.M.Owens, Electron. Lett. 13, 610, 1977.

41. J.P.Castera, IEEE Trans. MAG 14, 826, 1978.

42. R.W.Damon and J.R.Eshback, J.Phys.Chem.Solids 19, 308, 1961.

43. S.R.Seshadri, Proc. IEEE 58, 506, 1970.

44. D.F.Vaslow, Proc.IEEE 61, 142, 1973.

45. C.Vittoria and N.D.Wilsey, J.Appl.Phys. 45, 414, 1974.

46. A.K.Ganguly and D.C.Webb, IEEE Trans.MTT-23,998,1975.

47. J.C.Sethares, T.Tsai, and I.Koltunov, RADC-78-78, April 1978.

48. N.C.Chang, S.Yamada and Y.Matsuo, Wave Electronics 2, 341, 1976.

49. M.Bini, P.L.Filetti, L.Millanta and N.Rubino, J.Appl.Phys. 47, 3209, 1976.

50. T.Yukawa and Jun-ichi Ikenoue, Jun-ichi Yamada and K.Abo, J.Appl.Phys. 49, 376, 1978.

51. T.W.O'Keeffe and R.W.Patterson, J.Appl.Phys. 49, 4886, 1978.

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