CHAPTER 1

Introduction.

In microwave device development there is a strong trend towards realizing the conventional waveguide components in microstrip/stripline form for hybrid microwave integrated circuits with device performance equalling or surpassing that of waveguide device. Microwave hybrid integrated circuits for a wide variety of applications are generally manufactured by thin and thick film techniques on a suitable substrate.

In MIC applications use of ferrimagnetic substrates is conventional as these provide both transmission and gyromagnetic functions. Ferrimagnetic substrates may be operated at self remanance to provide latching or digital operations and above resonance for nonreciprocal devices such as isolators, circulators etc. As ferrimagnetic substrates have a relatively high dielectric constant at microwave frequencies, fabrication of the complete microwave circuit or subsystem on a single ferrimagnetic substrate is also feasible / 1 /.

However, satisfactory performance of the circuit or subsystem cannot be achieved by developing the entire circuit on a ferrimagnetic substrate, because the presence of the dc magnetic field required to obtain the nonreciprocal action may affect the function of other components and active devices / 2,3 /. As an alternative, ferrimagnetic inserts in dielectric substrates have been used where dc magnetic field is applied locally to obtain the nonreciprocal action. Various methods, such as Arc Plasma Spray / 4-6 / , RF sputtering / 7,8 / have been used for deposition of ferrimagnetic films over a desired location. Arc Plasma Spray (APS) makes possible the fabrication of complex ferrite/dielectric composite structures suitable for use as substrates for microwave integrated circuits. One major disadvantage of the APS process is its high temperature during deposition. Furthermore APS is not suitable for many applications where the circuits are prefabricated.

RF sputtering of magnetic oxides is of special interest in view of possible application in storage devices. RF sputtering can be used to grow thin films but it involves operations in vacuum and is inherently costly. One must therefore look for a simple method of growth of ferrite/YIG films.

An important development in the field of electronic components has been the introduction of screened and fired (thick film) materials since the midsixties. It is well known that thick film circuits can provide significant cost advantages over thin film circuits. The applicability of thick film technology for hybrid microwave integrated circuits has been investigated / 9-12 / and found suitable upto X-band provided higher losses compared to those in thin film devices can be tolerated. The higher loss is due partly to the poor rf conductivity of the thick film conductors and inferior line definition inherent of thick film fabrication. The advent of new fritless and low frit thick film conductor pastes has made possible great improvements in the loss characteristics of screen printed thick film microwave integrated circuits / 13,14 /. Thick film technology uses conductive, resistive, dielectric and optoelectronic thick film inks which are screen printed onto the substrate to make the circuit. While extensive studies have been made on thick films resistive, conductive and dielectric pastes, not much attention has been paid to the formulation of thick film ferrimagnetic inks. Electro-Science Laboratories, USA introduced in early seventies a thick film ferromagnetic paste / 15 /. This has been used for making delay lines and filters. In view of the limited amount of studies upto 1975 and the encouraging results reported /16,17 / concerning potential applications in thick film integrated circuits, a research program was initiated to investigate whether ferrimagnetic films, grown using thick film technique, can be satisfactorily used for the fabrication of devices such as delay lines and filters in the VHF/UHF frequencies.

For microwave applications commonly used ferrites are Mg-Mn, Mn-Ni and Li-ferrites for their attractive microwave properties such as high saturation magnetization, low dielectric loss tangent, moderate linewidths and high resistivity. These ferrite systems were considered for use in the fabrication of thick film ferrimagnetic pastes. For hybrid microwave circuit applications the ferrimagnetic paste is used to grow on a dielectric substrate (e.g., alumina) coated with a layer of conductor. This conductor layer and the ferrimagnetic film together with a suitable strip conductor on the top of the film will provide the necessary microstrip configuration needed for specific applications

The ferrimagnetic film, conductor layer and strip conductors are all fabricated using screen printing and firing technique.

To be useful ferrimagnetic films have the same properties as those of the bulk materials. High density is achieved in bulk ferrimagnetic substrates by adding appropriate flux and applying pressure during fabrication. In ferrimagnetic films no pressure can be applied during growth. Also for good adhesion to alumina substrates some amount of glass must be added. This increases the porosity as well as modifies the microwave properties of the film. It has been shown that addition of a small amount of bismuth oxide increases density and improves microwave properties of lithium ferrites / 18,19 /.

For microwave applications, a relatively thick ferrimagnetic film is generally required and hence the paste formulation differs from that of conventional screen printing inks. The rheological characteristics of the thick film inks are dependent on the viscosity, particle size, and the vehicle used during paste formulation.

Proper exploitation of the ferrimagnetic films grown in developing microwave devices necessiates the knowledge of the magnetic and dielectric properties such as saturation magnetization ($4\pi M_s$), ferromagnetic linewidth (ΔH), dielectric constant (ε_r) and loss tangent ($\tan\delta_e$). Various measurement techniques are available / 20-22 / and require a sample in the form of an accurately polished pressed slab or polished sphere, the fabrication of which is quite tedious. It is not possible to make a sphere from ferrimagnetic paste and therefore existing microwave methods / 23,24 / of measurement cannot be applied. A technique using a ring resonator / 25 / has been employed to measure the dielectric constant and saturation magnetization of the ferrimagnetic films.

The present study is mainly concerned with the development of suitable thick film ferrimagnetic pastes and evaluation of their physical, electrical and magnetic properties. Special attention has been paid to the use of thick film ferrimagnetic pastes developed for the fabrication of nonreciprocal microwave components such as isolators, circulators, phase shifters and couplers in microstrip configuration. In wide ferrite microstrips with dc magnetization perpendicular to the ground plane, the rf energy concentrates at one edge of the strip conductor for forward propagation and at the opposite edge for reverse propagation. This has been termed in the literature as Edge Guided Wave propagation. The potentiality which edge guided waves offer for the development of nonreciprocal components has led us to study the applicability of thick film technique for fabrication of such devices.

Chapter 2 is concerned with the paste development and various physical properties. At the initial phase of the program, various methods of preparation of ferrite powders such as Mg-Mn, Mn-Ni and lithium ferrites have been used in our laboratory. It has been found that the preparation technique based on decomposition of solidified solution of organometallic salts / 26 / is indeed very suitable for these ferrite systems as ferrite powders are then obtainable at low temperature / 27,28 /. This method has also the advantage that the ferrites obtained are porous powders and can be ball milled easily.

The basic problem in making a ferrimagnetic paste is to find a ferrite/YIG composition which permits firing in the temperature range of 800-950^{o}C, has microwave magnetic properties close to those of the bulk material and gives, with appropriate binders, good adherence to alumina substrates and other commercially available resistive, conductive and dielectric pastes.

Thick film ferrimagnetic pastes have been formulated by adding various amounts of electronic glass composition TGC-120 / 29 / to investigate the adhesion of the film to alumina substrates with a bottom conductor to be used as ground plane. For the preliminary investigations, the bottom conductor material was chosen to be Palladium-Silver ESL:9635 / 30 / which is a low cost material and the silver migration is relatively low.

Compatibility of the ferrimagnetic pastes developed with other commercially available thick film compositions such as resistors, conductors and dielectric has been studied. To study the usefulness of the pastes developed at microwave frequencies, microstrip transmission lines were screen printed using silver paste Transene Type 200 /31 / on the fired ferrite film and transmission loss was measured over the frequency range from 2-12 GHz. It has been found that the transmission loss for a wide microstrip line (width/height = 10) in case of Mg-Mn and Mn-Ni ferrites is almost twice that in case of lithium ferrites (supplied by Solidstate Physics Laboratory, Delhi) / 32 /. The transmission loss also increases with the amount of glass added. The relatively low transmission loss in case of lithium ferrite led us to think that lithium ferrite could be a good contender for thick film ferrimagnetic pastes. The effects of addition of glass and bismuth oxide to lithium ferrite have been studied /28 / to optimize the amount that should be added during the formulation of the thick film ferrimagnetic paste. It has been found that the addition of bismuth oxide improves densification and increases resistivity of the lithium ferrite but the addition of glass causes a reduction of the resistivity. The effect of introducing a dielectric layer between the ferrimagnetic film and the ground plane has also been studied for lithium ferrite system. It is also of interest to compare the performance of the ferrimagnetic films to that of the bulk substrate. For the purpose, it was necessary to fabricate similar devices on both substrates and films grown using thick film technique.

In recent years there has been extensive development of ferrimagnetic garnets which have found widespread applications in microwave devices because of their generally excellent dielectric properties and low loss. YIG powders and substrates were not available in the country in the initial phase of the work. On our request M/s. Electro-Science Laboratories, Inc., USA formulated on an experimental basis an YIG paste using Trans-Tech G-113 YIG powder /33 /. Throughout the course of investigation this YIG paste (ESL:EX:2002) has been used.

Chapter 3 details the microwave characterization of the ferrimagnetic films deposited by using ferrimagnetic pastes. The study is confined to lithium ferrite and YIG pastes.

The electrical and magnetic properties of the ferrimagnetic films grown using thick film technique have been studied. In the low frequency range, spiral inductors have been used to measure the permeability. Thick film capacitors have been used to measure the low frequency dielectric constants and loss tangents. In the course of the investigation the suitability of the ferrimagnetic films grown has been assessed by comparing the performances of these films with bulk substrates almost at every stage of development. For the measurement of dielectric constant (ε_r) and saturation magnetization ($4\pi M_s$) ring resonator technique has been employed. The test pattern has been screen printed on ferrimagnetic film and dielectric constant has been measured by determining two consecutive resonant frequencies, while for the measurement of the saturation magnetization the same structure is subjected to an external magnetic field transverse to the ground plane. The band stop filter technique / 25,34 /, using a microstrip transmission line on fired films to be evaluated, has been utilized for the determination of the resonance linewidth (ΔH).

The interest in theoretical and experimental analysis of electromagnetic waves supported by planar structures containing ferrite-dielectric materials has grown in the last few years together with the progress in the technology of microwave microstrip components. The wave propagation on a ferrimagnetic slab has been investigated under different boundary conditions / 35-38 /. Composite planar waveguiding structures consisting of dielectric and/or ferrite media can be conveniently fabricated using thick film ferrimagnetic pastes and dielectric pastes / 32 /. Since the ferrite-dielectric composite medium is a relatively new waveguiding structure little is known about its characteristics such as its dispersion diagram, attenuation, and magnetic behaviour.

In Chapter 4 the theory of propagation in the homogeneously biased media has been reviewed and propagation characteristics in an inhomogeneously biased, two region, composite ferrite parallel plane waveguide has been presented. The structure consists of two ferrite slabs placed side by side between two infinite perfectly conducting planes with bias magnetization perpendicular to the ground plane. The ferrites are taken to be lossy and are loaded on one side by a lossy material. The effect of the lossy material has been modelled by using a semi-infinite lossy region. The resulting boundary value problem is solved exactly and the propagation characteristics in the media have been presented. Special attention has been paid to the capabilities of this configuration to model a nonreciprocal isolator.

In Chapter 5 Edge Guided Wave (EGW) propagation characteristics /39-43 / for different geometries of the waveguiding structures and various types of edge loadings have been discussed. The effect of variation of strip conductor width, internal magnetic field on the performance characteristics of edge guided mode isolators/circulators has been presented. Thick film techniques have been employed for the fabrication of isolators and circulators. The lithium ferrite and YIG pastes (ESL:EX:2002) have been utilized to develop the EGW isolators / 32,44 /. The performance of such isolators depends on three factors - width of the strip conductor, resistive loading and applied dc magnetic field. Experiments have been carried out over the frequency range from 2-12 GHz to investigate the effects of the variation of the various parameters. Different resistive edge loadings have been applied in an attempt to determine the optimum loading condition.

An EGW circulator may be considered to be a combination of three EGW isolators, with resistively loaded part placed in the common central region. Circulators have been fabricated both on bulk substrates as well as on ferrite/YIG films. The performance characteristics such as isolation, insertion loss and return loss have been measured over the frequency range from 2-12 GHz / 45 /.

de Santis and Pucci / 46 / reported that while broad band isolators can be constructed readily using EGW principle, broad band circulators are not feasible. Our experimental results however show that a minimum 15 dB isolation bandwidth of 6 GHz is achievable in case of EGW circulators on YIG substrates. Favourable agreement of the experimental results with the theoretically obtained values has been obtained; the theoretical computations have been carried out following Talisa and Bolle / 47,48 /. The performance of three port edge guided wave circulators has been compared with those of other types of MIC broad band Y-junction circulators / 6,49 /.

In Edge Guided Wave phase shifters, nonreciprocal phase shift may be obtained by asymmetric reactive loading of the two edges of a wide transmission line fabricated on ferrimagnetic film. The operation of the device depends on electrical asymmetry attained through structural asymmetry, viz., the dielectric materials introduced on the two sides of the ferrite have widely different permittivities.

In Chapter 6 the applicability of thick film technique for fabrication of nonreciprocal EGW differential phase shifters has been studied. High permittivity thick film dielectric pastes are commonly used for low frequency applications and permittivity data for these pastes are not readily available at microwave frequencies. For the purpose of the present work the dielectric constants of the dielectric pastes have been measured at microwave frequencies using resonator technique.

Differential phase shifters have been fabricated / 50 / using YIG paste, and various dielectric pastes have been used for asymmetric loading of the wide transmission line. The performance characteristics have been measured in the frequency range from 4-12 GHz. The effects of variation of the applied magnetic field and the dielectric constant of the capacitively loaded side on differential phase shift, insertion loss and bandwidth have been studied.

A dual directional coupler using edge guided waves has also been fabricated / 44 /. A wide transmission line is used as the main line, the auxilliary lines are narrow lines printed on either side of the main line on the same substrate. The dual feature is achieved because of the field displacement phenomenon. The coupler can be switched from one auxilliary line to the other by reversing the direction of the applied magnetic field. Dual directional couplers have been fabricated on ferrimagnetic substrates and also on ferrite films. The coupler performances have been measured over the frequency range from 4-12 GHz and are presented in Chapter 6.

Chapter 7 summarizes the results obtained and discusses the potential applications of thick film ferrimagnetic pastes.