CHAPTER I

Introduction.

The last two decades have witnessed tremendous technological strides in the development of minaturized microwave components and modules using microstrip transmission lines [1-10]. The need for small size, highly reliable low cost microwave circuitry with improved reproducibility is the demand of the day in hybrid microelectronics industry. This need has stimulated studies in the development of Microwave Integrated Circuits (MIC).

Microwave hybrid integrated circuits for a wide variety of applications are generally manufactured by thin and thick film techniques on a suitable substrate [11-12]. Thin film technique involves the vacuum deposition of a thin film by evaporation or sputtering. The vacuum deposited film adheres to substrates by a chemical bond which requires smooth substrate of surface finish better than 5 μinch. The conductor pattern is usually defined by etching using photolithographic technique. An important development in the field of electronic components has been the introduction of thick film materials since midsixties [13-15]. Thick film process involves printing of paste through a screen on ceramic substrate and subsequent firing of the film. Although thin film has been the dominant technology for MIC, thick film technique can provide significant cost advantages over thin film circuits. The applicability of thick film technology for hybrid microwave integrated circuits has been investigated [16-19] 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 poor RF conductivity of thick film conductors and inferior line definition inherent in 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 [20-22].

Hybrid microwave integrated circuitry needs the development of different reciprocal and nonreciprocal MIC components. Nonreciprocal MIC components are conventionally fabricated on ferrimagnetic substrate utilizing gyromagnetic effect. As these substrates have a relatively high dielectric constant at microwave frequencies, fabrication of complete microwave circuits or subsystem on a single ferrimagnetic substrate is feasible [23]. In this case the d.c. magnetic fields needed to obtain nonreciprocal action of some components influence the properties of other reciprocal components and active devices [24,25]. As an alternative, ferrimagnetic materials are inserted in dielectric substrates using Arc Plasma Spray (APS) [26], RF sputtering technique [27]; d.c. magnetic field is applied locally to get the nonreciprocal action. A major disadvantage of the APS process is the high temperature during deposition. RF sputtering involves operations in vacuum and is inherently costly.

A cost-effective technique for realizing nonreciprocal ferrimagnetic devices in planar form is to use thick film ferrimagnetic pastes which can be screen printed on alumina or other substrates employing thick film technique. Thick layers of ferrimagnetic material grown using fired film technology are useful in realizing the UHF and microwave integrated circuits as they readily permit combination of magnetic and non-magnetic components on the same substrate.

Till 1972, not much attention has been devoted to the development of thick film ferrimagnetic pastes, although comprehensive studies have been made on thick film conductive, dielectric and resistive pastes. The basic problem in making a ferrimagnetic paste is to find a suitable ferrite/YIG composition which permits firing in the range of 800-1000°C, has microwave magnetic properties close to those of bulk material and gives with appropriate binders, good adherence to alumina substrates and is compatible with other commercially available resistive, conductive and dielectric pastes. Reports available on ferromagnetic pastes in midseventies show promising results in the fabrication of delay lines and filters [28,29]. So a research program was initiated to study the applicability of ferrimagnetic pastes for realization of microwave nonreciprocal devices like isolators, circulators, phase shifters etc. Investigations made include development of ferrimagnetic pastes using Mg-Mn, Mn-Ni, Li-ferrites, their characteristics and device performance [30-34].

In recent years there has been an extensive development of ferrimagnetic garnets which have found widespread applications in microwave devices because of their excellent material properties. The remarkably low resonance linewidth, high resistivity, low dielectric and magnetic loss tangent of Yttrium Iron Garnet (YIG) have made the material extremely popular in microwave industry [35-37]. It was therefore considered worthwhile to examine the possibility of using microwave ferrimagnetic garnets for making low loss ferrimagnetic pastes and realization of planar nonreciprocal microwave components using the YIG pastes.

Chapter II of the dissertation is devoted to the development of thick film YIG paste, the evaluation of physical, electrical and magnetic properties of YIG paste and their microwave application [38]. Since relatively thick layers of YIG film are generally required for MIC applications, YIG paste formulation differs from conventional thick film inks. Viscosity, particle size and vehicle used in the paste formulation have been optimized to get the proper rheological characteristics of the YIG paste. Compatibility of the YIG paste developed with other commercially available thick film compositions such as resitive, conductive, dielectric paste has been studied. For useful application of the YIG film in MIC's, its property should have to be close to bulk materials. During the growth of the YIG film no pressure can be applied. So for the densification of the fired films, bismuth oxide has been used as a flux, and for good adhesion to alumina substrate proper amount of glass has been added during the development of

YIG paste. Excess amount of these additives modifies the microwave properties of the film. The effects of addition of bismuth oxide and glass to YIG have been studied to optimize the amount of bismuth oxide and glass. Microstrip transmission lines made on such YIG films have been tested for the loss in order to see the feasibility of microwave application of the paste so developed.

The electric and magnetic properties such as dielectric constant, saturation magnetization, resonance linewidth, permeability etc. of the YIG films grown are to be known for their application in microwave devices. The conventional microwave methods [39,40] for the measurement of saturation magnetization, dielectric constant etc. cannot be used in case of YIG film since these methods need highly polished and pressed slabs or spheres of YIG. Alternatively, dielectric constant and saturation magnetization could be determined by ring resonator technique [41]. Accordingly a test pattern has been screen printed on the YIG film and the parameters have been measured by noting the resonance frequencies for consecutive modes. The dispersion characteristics of microstrip ring resonator has also been measured. All these measurement have been taken by varying the applied magnetic field.

The pastes developed have been used for realizing edge guided wave isolators. Edge guided waves (EGW) [42] separate forward and reverse waves on opposite edges of a relatively wide transmission line on ferrite substrate magnetized perpendicular to the ground plane. By applying a resistive film on one edge of the transmission line, it is possible to design a component with highly directional properties [43-46]. Thick film YIG pastes, developed and characterized as discussed in the previous section, have been utilized for realizing such planar isolators. Reciprocal meander line phase shifters have been fabricated using YIG paste and the results are given in this section.

Microstrip coupled lines find many uses in realization of microwave filters and directional couplers. The parameters involved in determining their performances are the even mode and odd mode characteristic impedances and phase constants. These may be computed from a knowledge of even- and odd-mode capacitances of parallel coupled lines which are determined from variational series based on conformal transformations [47-50]. However, there are no simple relations available for finding the parameters involved in the design. An alternative approach to design may be formulated making use of the knowledge of the capacitive and inductive coupling coefficients in coupled lines [51-54]. Unfortunately here again straightforward formulae are not available.

Chapter III aims at finding empirical relations describing the variation of both inductive and capacitive coupling coefficients with physical dimensions of the lines and electrical parameters of the substrates [55]. The functional relationships are based on the physical mechanism of coupling in microstrip lines. These relations permit ready application in design of coupled systems realized on dielectric and ferrimagnetic substrates. The values of capacitive and inductive coupling coefficients computed from the proposed empirical relations are compared with those obtained from the work of Bryant and Weiss [56], Napoli and Hughes [57]. These empirical relations have been utilized to design the microstrip couplers using thin film technique on alumina and ferrite (TT G113) substrates. The performances of the couplers were measured and compared with theoretically computed values following Krage and Haddad [52].

Non-identical line directional couplers embedded in an inhomogeneous medium have drawn considerable interest due to their potential applications as microwave circuit elements such as filters, transformers, impedance matching networks etc. [58-62]. The normal mode parameters of non-identical coupled lines namely, mode voltage ratio of the two lines, normal mode impedances of the two lines and mode velocities are essential to study the properties and characteristics of the non-identical coupled circuits for applications at microwave frequencies.

Chapter IV deals with the evaluation of normal mode parameters of non-identical microstrip coupled lines. The normal mode parameters are usually determined from the capacitances and inductances of the microstrip lines which are found by solving Laplace equation for the quasi-TEM case and the Helmholtz equation for the dispersive case [63-64]. In the present work the method described to calculate the normal mode parameters of non-identical microstrip coupled lines, uses the values of capacitive and inductive coupling coefficients rather than capacitance and inductance values [65]. The expressions for coupling coefficients described in Chapter III have now been modified to enable calculation of the normal mode parameters of non-identical microstrip coupled lines. Values of normal mode parameters thus computed from quasistatic approach have been compared with those obtained by Tripathi and Chang [64]. Non-identical line microstrip couplers have been realized on alumina substrate and the experimental results are compared with theoretical values. The principal advantage of the proposed method is that one can readily calculate the normal mode parameters from the values of dimensional ratio of the lines and electrical parameters of the substrate material.

High directivity microstrip directional coupler is an important device in the design of a microwave system with integrated circuitry and a considerable effort has been directed to the problem of realizing such a coupler in planar form. The directivity of microstrip coupler is normally low due to the inequality of phase velocities of the even- and odd-mode [1,54]. Techniques which have been put forward for improving the directivity of microstrip couplers include wiggling the adjacent edges of the pair of coupled lines [66], serpentine coupler [67], transverse slotting and use of dielectric overlay [68-73]. It has been reported that the directivity may be improved by adding small capacitance between the coupled lines [74-75] or by use of additional coupled lines [76].

Chapter V describes a method of obtaining a substantially higher directivity in microstrip version using non-identical coupled lines with complex terminations. A theoretical analysis of such a coupler taking into account the effects of port impedances have been presented. The expressions given in this chapter enable one to calculate coupling and directivity for any terminating impedance of the coupler. Directivities of non-identical and identical microstrip coupler have been computed for different combinations of the terminating impedances at different ports. Use of non-identical coupled lines with complex terminating impedances at different ports has considerable effect on the directivity of microstrip couplers [77,78]. The impedance behaviour of a variety of bends and discontinuities has been examined. The inductive reactance at the ports may be realized by connecting short sections (length $\ll$ guide wavelength) of narrow line at the end of the coupled section which are connected to the input/output 50 ohm lines. The performance of the microstrip couplers for the coupled section where the ratio of the width of the auxiliary line to the width of the main line is unity, one half or two have been compared and the effects of terminating impedances at various ports of the couplers have been determined experimentally.

MIC filters find many applications in microwave circuitry. Filters using stepped impedance resonators, edge coupled filters and elliptical filters are the popular forms of MIC filters. Tapped line filters offer space and cost saving advantages over conventional filter types because the first and last end sections of the filters are eliminated [79-80]. In some cases of parallel coupled line filters, the coupling of the end sections is so tight that the physical realization becomes impractical, the same filter can still be realized by tapping.

The impedance matrices [81] of a single section coupled microstrip structure with specific terminations and tapped input/output points have been described in Chapter VI. Image impedance and transfer function of the structure have been derived. Cut-off region of the filter was found out from the image impedance and a design curve was drawn using inductive and capacitive coupling coefficients which are related to the line parameters. Design parameters such as gap spacing, width of lines, length of the coupled region, tapping point for a specified filter characteristics have been optimized. Tapped line filters have been fabricated on alumina substrate using thin film technique and tested to verify the design procedure. A computer aided design procedure for tapped line filter has been discussed.

A ferrimagnetic phase shifter is an important MIC component. Meander line phase shifter using YIG paste has been described in Chapter II. A helical phase shifter is expected to offer large differential phase shift because of slow wave propagation through helix. A microstrip helix may be fabricated with ease using ferrimagnetic pastes. For preliminary study, a helix embedded in YIG film was fabricated on alumina substrate using thick film technique. The magnetic medium is latched in azimuthal direction by sending current through strip conductors inside helix. An analytical study of such a helix phase shifter in planar form has been undertaken. The structure of the microstrip helix may be approximated from a helix in elliptic cylindrical guide where the minor axis of the ellipse cross-section is very small compared to the major axis.

Propagation characteristics of nonreciprocal cylindrical helix phase shifters have been investigated by Suhl and Walker, Hair [82,83]. The conventional solutions of these problems involve mathematical functions for which extensive tables are not available. In some cases when the cross-section of the ferrite toroid of helix phase shifter is different from circular, the analytical solution of the wave equations using available mathematical functions becomes very difficult. An alternative approach is to solve these problems using Finite Element Method (FEM) [84,85]. This appears to be a comparatively easier means for obtaining meaningful results.

In Chapter VII, finite element analysis of circular cylindrical and elliptic cylindrical helix ferrite phase shifters has been described. A computer program has been developed to solve these problems using FEM and the results of 'normal', 'inverted' and 'ferrite embedded' helix ferrite phase shifter in circular cylindrical geometry have been presented.

Chapter VIII gives a summary of the conclusions of the present investigation and the scope of future work.