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Switching Characterization of Ferrite Substrate due to Generation of Magnetostatic and Spin Waves

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Abstract- Study of switching phenomena of ferrite substrate with a normal magnetic biasing field is presented. Generally for magnetized and layered structure below the X-band of microwave range, the electromagnetic waves propagation is well described by quasi TEM waves (extraordinary waves) but for an investigation in X-band there should be an inclusion of spin wave exchange term (ω_r) in the magnetostatic wave analysis which depends upon the static internal field (H_{ex}). This term included in analysis because the wavelength of microwave approach the inter-atomic distance of ferrite material. Keeping this view in mind, the present analysis has been carried out by taking LiTiMg layer. LiTiMg ferrite has been synthesized through Solid State Reaction Technique (SSRT) and obtained electric and magnetic properties.

Further, Absorbing and Transmission power coefficients have been calculated to obtain the power loss and transmitted power through the substrate respectively. The absorbing power coefficient verifies the switching behavior of substrate for certain range of applied external magnetic field (Ho) which depends on the resonance line width parameter (ΔH) of ferrite material.

Index Terms- **Magnetostatic waves, spin wave, substituted ferrite, X-band frequency range.**

LIST OF SYMBOLS

δ = thickness of ferrite layer
α = attenuation constant
β = phase constant
β_o = propagation constant in vacuum
ε_r = dielectric constant
μ_{eff} = effective permeability
μ, κ = permeability tensor components of μ_{eff}
H_o = applied bias field
ΔH = magnetic resonance width of ferrite
ω = angular frequency of incident e-m-waves
ω_o = external magnetic field angular frequency
ω_m = internal magnetic field angular frequency
ω_{ex} = internal magnetic field angular frequency due to exchange forces
μ' = real part of permeability
μ'' = dissipative part of permeability
χ' = real part of susceptibility
χ'' = dissipative part of susceptibility
$4\pi M_S$ = saturation magnetization
t = relaxation time
θ_k = wave propagation direction
γ = gyromagnetic ratio (2.8 MHz / Oe.)

I. INTRODUCTION

In the present era of high frequency communication biased ferrite materials for microwave applications have attracted noticeable attention. Ferrite is one of the important magnetic materials which are used as in both types single and polycrystalline. Different types of polycrystalline ferrites have their specific advantages. Particularly Li substituted ferrites have high dielectric constant, low sintering temperature etc. than other substituted ferrites.

The reason behind using ferrite materials in microstrip structures is that the applied magnetic field changes the permeability and thus the electrical properties of material, which in turn, change the antenna properties. The significance of this fact is that it is possible to change the antenna characteristics through the d-c magnetic field

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applied externally. Beam steering, gain and bandwidth enhancement, RCS control, surface wave reduction, switchable and electronic tunability are some of the unique and inherent features of ferrite based microstrip antennas and arrays, which have been investigated by several investigators [1-5].

Present analysis explains the non reciprocal behavior of ferrite material under d-c biased condition with magnetostatic waves including spin wave exchange term. The reason behind the inclusion of this term is that when the incident plane waves propagate through the biased ferrite substrate at and above the X-band range then the wavelength of em-wave approach the inter-atomic distance, which arise an additional term besides quasi TEM waves, known as magnetostatic and spin wave exchange term.

II. SYNTHESIS OF SUBSTRATE

LiTiMg ferrite synthesized from the basic components of lithium ferrites. The ingredients required for the preparation of these ferrites have been calculated on the basis of chemical formula. A small amount of Mn^{3+} ion has also been incorporated in the basic composition in order to suppress the formation of Fe^{2+} ions in the ferrites and to influence megnetostriction being a John Teller ion [6]. In order to avoid Lithia at high temperature of sintering, Bi_2O_3 (0.25 wt %) has been added as sintering aid [7]. Analytical grade chemicals have been used for the preparation of the material. The stoichiometric ratio of the chemicals has been thoroughly mixed in a polypropylene jar containing the zirconium balls and distilled water has been used as a mixing agent. The presintering of the mixed powder has been carried out at ~ 750^{o}C in a box furnace and soaking time was kept 4 hours. The sieved material has been pressed in disk (antenna substrate) and toroidal shapes with the help of suitable dies and using hydraulic pressing technique at pressure of 10 ton/cm^2. The substrates and toroidals have been finally sintered at 1050^{o}C for four hours. The heating and cooling cycle of the samples has been carried out in the air atmosphere of furnace. The sintered samples so obtained have been subjected to cutting, grinding, polishing etc, in order to get specific size and shape [8].

The single-phase spinel nature of the samples has been confirmed by X-ray diffraction (XRD) patterns obtained by using Cu-K_α radiation. The microstructure studies of the sample have been carried out by scanning electron microscope (SEM). Vibrating Sample Magnetometer (VSM) has been used to determine the magnetic properties of the samples. For dielectric measurements, rectangular pellets of size 25 mm $\times$ 13 mm $\times$ 7 mm have been used. The dielectric measurements have been performed from 8 to 12 GHz by a VNA (E8263B Agilent Technology). The value of the real part of dielectric constant (ε') of the ferrite samples has been calculated using formula $\varepsilon' = Ct/\varepsilon_o A$ where 'ε_o' is the permittivity in free space, 'C' is the capacitance, 't' is the thickness and 'A' is the area of sample in square meter of specimen. The density measurement has been done by a small experiment based on Archimedes' principle. Remanence and Coercive Force have been measured by B-H loop setup applied to coiled toroid sample at 50 Hz.

Table 1: The electrical and magnetic properties of LiTiMg ferrite substrate

LiTiMg Ferrite Characteristics	Values
Magnetic Saturation ($4\pi M_s$)	2200 Gauss
Curie Temperature (T_c)	325 K
Density (ρ)	4.21grams/cm^3
Remanence Ratio	0.90
Coercivity	2.54 Oersteds
Dielectric Constant (ε)	15
Resonance Line Width (ΔH)	290 Oersteds
Loss Tangent ($\tan\delta$)	< 0.0009

The Curie temperature for the LiTiMg ferrite samples has been determined by using a simple experimental setup based on gravity effect in the laboratory. The electrical and magnetic properties of LiTiMg ferrite substrate has been experimentally calculated in laboratory which is listed in table 1.

III. THEORY

Consider a plane wave propagating in the perpendicular direction of layer with a magnetic bias field applied longitudinally. According to the theory described in [11], the waves that carry away the energy are typically "slow" electromagnetic waves that propagate along an interface between the ferrite and an adjacent material, such as a metal or a dielectric material. The slow electromagnetic waves can be analyzed using the "quasistatic approximation" (often called "magnetostatic approximation"). As a result of elasticity of the spin (magnetic) system, oscillations (precession) of the magnetic moments with the frequency of exciting force can exist and they are in resonance for the frequency equal to $\mu_o\gamma H_i$, where H_i is the internal field in the magnetic material. If these oscillations are excited in limited region of the ferrite sample, then due to elasticity of this system they will propagate with a defined velocity in the sample. This propagating disturbance represents magnetostatic and spin waves. These waves are generated when external magnetic field applied perpendicular to the magnetic vector of EM waves. MSW propagate perpendicularly on both sides to the EM wave's propagation [9-11].

If we consider the infinite- medium plane wave solution of the equations of motion including the spin wave "exchange" term and neglecting losses then permeability tensor components are:

$$\mu = 1 + \frac{\omega_r \omega_M}{\omega_r^2 - \omega^2} \quad and \quad \kappa = \frac{\omega\ \omega_M}{\omega_r^2 - \omega^2} \qquad (1)$$

The resonance frequency is now denoted by ω_r rather than ω_o, where $\omega_r = \omega_o + \omega_{ex} a^2 k^2$.

Since this interpretation of the resonance frequency does not affect the form of Maxwell`s equations because the dispersion relation also has the form as:

$$\frac{k^2}{k_o^2} = \left\{ \frac{(\mu^2 - \mu - \kappa^2)\sin^2\theta_k + 2\mu \pm [(\mu^2 - \mu - \kappa^2)\sin^4\theta_k + 4\kappa^2\cos^2\theta_k]^{1/2}}{2[1 + (\mu - 1)\sin^2\theta_k]} \right\} \qquad (2)$$

where

$$k_o^2 = -\omega^2 \epsilon \mu_o$$

Here μ and κ include the exchange term $\omega_{ex}a^2k^2$ according to equations (1) and (2). The solution of equation (2) to obtain ω as a function of k is involve three roots if we consider the limiting case of $\theta_k = 0$, $\theta_k = 90$ and for an ordinary wave, $k^2 = \omega^2\varepsilon\mu_o$.

For propagation along the direction of the d-c magnetic field, we have a solution by putting $\theta_k = 0$ in eqn. (2).

$$k^2 = k_o^2 \left\{ \frac{2\mu \pm \sqrt{4\kappa^2}}{2} \right\} = k_o^2(\mu \pm \kappa) \qquad (3)$$

$$k^2 = \frac{\omega^2}{c^2}\varepsilon_r(\mu \pm \kappa) = \omega^2\epsilon\mu_o\left(1 + \frac{\omega_M}{\omega_r \mp \omega}\right) \qquad (4)$$

Similarly for propagation perpendicular to the direction of the d-c magnetic field ($\theta_k = 90$):

$$k^2 = k_o^2 \left\{ \frac{(\mu^2 + \mu - \kappa^2) \pm [\mu^2 - \mu - \kappa^2]^{1/2}}{2\mu} \right\} \qquad (5)$$

$$k^2 = \omega^2\epsilon\mu_o \frac{(\omega_r + \omega_M)^2 - \omega^2}{\omega_r^2 + \omega_r\omega_M + \omega^2} \qquad (6)$$

This equation is biquadratic in ω, giving two roots for the extraordinary wave. The dispersion relation for ω as a function of k, for the biquadratic equation (6) is given by:

$$\omega^2 = \frac{\frac{k^2}{\epsilon\mu} + (\omega_r + \omega_M)^2 \pm \left\{ \left[\frac{k^2}{\epsilon\mu} + (\omega_r + \omega_M)^2\right]^2 - 4(\omega_r^2 + \omega_M\omega_r)\frac{k^2}{\epsilon\mu} \right\}^{1/2}}{2} \qquad (7)$$

If we plot the dispersion relation (7) then we got a curve between frequency (ω) and propagation constant (k) for a particular value of external magnetic field (H_o). The value of propagation constant (k) becomes zero twice at which the frequency known as cutoff frequency which is due to the generation of three types of waves: quasi TEM, Magnetostatic and Spin waves. Spin wave excitation is the result of exchange forces between atoms. Magnetostatic waves are of two types (A) Surface MSW (B) Volume MSW [12, 13].

A. Surface MSW: Surface magnetostatic waves are the most common and well investigated class of magnetostatic waves. These waves propagate in ferromagnetic materials magnetized in the layer plane perpendicularly to the direction of the magnetic field. The dispersion relation of surface MSW with spin wave exchange term, given as follows:

$$\omega^2 = \omega_H\,(\omega_M + \omega_r) + \frac{\omega_M^2}{2(1 + tanh^{-1}(kt))} \qquad (8)$$

Surface MSW band limits:

$$\mu_o\gamma\sqrt{H(H + M_o)} \le \omega \le \mu_o\gamma\, H\left(H + \frac{M_o}{2}\right) \qquad (9)$$

Surface MSW in metal coated ferrite:

$$\omega \le \mu_o\gamma\,(H + M_o) \qquad (10)$$

B. Volume MSW: These types of waves generally produce dominantly in the layered structure perpendicular to surface MSW propagation or magnetized layer. The dispersion relation of volume MSW with spin wave exchange term, given as follows:

$$\omega^2 = \omega_r\left[\omega_r + \frac{\omega_M}{1 + \left(\frac{m\pi}{kt}\right)^2}\right] \qquad (11)$$

Volume MSW band limits:

$$\mu_o\gamma H \le \omega \le \mu_o\gamma\sqrt{H(H + M_o)} \qquad (12)$$

IV. RESULTS AND DISCUSSION

The dispersion curve for the material has been plotted for the X band and shown in fig. 1. It is clear from curve that when ferrite substrate is magnetized the propagation constant (k) vary with frequency and the initial linear part of curve represents quasi TEM wave excitation [2] which is of very small order (10-100) in comparison of scale (10^8). The rest part of curve represents MSW and Spin wave excitation.

The absorption and transmission coefficients [11] due to the generation of MSW with spin wave in the ferrite substrate are as follow:

$$P = \frac{2\beta_o\varepsilon_r(\alpha\sin 2\beta\delta + \beta\sinh(2\alpha\delta))}{\begin{bmatrix}\beta_o^2\,\varepsilon_r^2\left((\cos\beta\delta)^2 + (\sinh(\alpha\delta))^2\right)\\ +(\alpha^2+\beta^2)\left((\sin\beta\delta)^2 + (\sinh(\alpha\delta))^2\right)\\ +\beta_o\varepsilon_r(\alpha\sin 2\beta\delta + \beta\sinh(2\alpha\delta))\end{bmatrix}} \qquad (13)$$

$$T = \frac{8(\alpha^2+\beta^2)\,\beta_o^2\varepsilon_r}{\begin{bmatrix}[4\beta^2\beta_o^2\varepsilon_r^2 + (\alpha^2+\beta^2+\beta_o^2\varepsilon_r^2)^2]\cosh(2\alpha\delta)\\ +4\beta\beta_o\varepsilon_r(\alpha^2+\beta^2+\beta_o^2\varepsilon_r^2)\sinh(2\alpha\delta)\\ -[4\beta^2\beta_o^2\varepsilon_r^2 + (\alpha^2+\beta^2-\beta_o^2\varepsilon_r^2)]\cosh(2\beta\delta)\\ +4\alpha\beta_o\varepsilon_r(\alpha^2+\beta^2-\beta_o^2\varepsilon_r^2)\sin(2\beta\delta)\end{bmatrix}} \qquad (14)$$

where

$$\alpha = \beta_o\sqrt{\left(\frac{\varepsilon_r}{2}\right)}\sqrt{\left[\sqrt{(\mu'^2 + \mu''^2)} - \mu'\right]}$$

$$\beta = \beta_o\sqrt{\left(\frac{\varepsilon_r}{2}\right)}\sqrt{\left[\sqrt{(\mu'^2 + \mu''^2)} + \mu'\right]}$$

and

$$\mu' = 1 + \chi'$$
$$\mu'' = \chi''$$

where

$$\chi' = \frac{\omega_m\,t\,(\omega_o + \omega)}{(\omega_o - \omega)^2 t^2 + 1}$$

$$\chi'' = \frac{\omega_m\,t}{(\omega_o - \omega)^2\,t^2 + 1}$$

with

$$t = \frac{2}{\gamma \times \Delta H} \quad and \quad \beta_o = \frac{\omega}{c}$$

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When the ferrite substrate is unbiased, or biased to a state where propagation constant k > 0, the fabricated microstrip devices (antennas) will transmit and receive as normal. When the ferrite is biased to the cutoff state where k < 0, incident wave will be transformed to quasi-TEM, magnetostatic waves (MSW) and spin waves. If device have single layered structure and operating in low frequency range then the the quasi TEM and surface magnetostatic waves are generated dominantly which largely absorb and attenuate the incident RF waves. Fig. 2 shows the transmission and absorption power coefficient variation with varying external DC magnetic field.

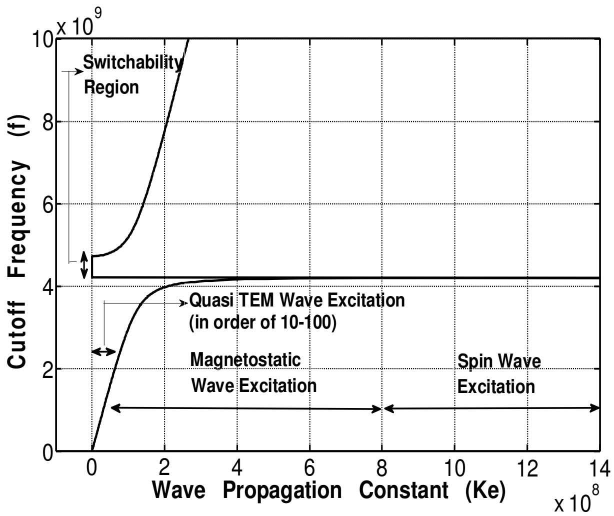

Fig. 1: Dispersion curve (f vs. k) of LiTiMg-ferrite substrate biased by 2150 Oe magnetic field in the X band.

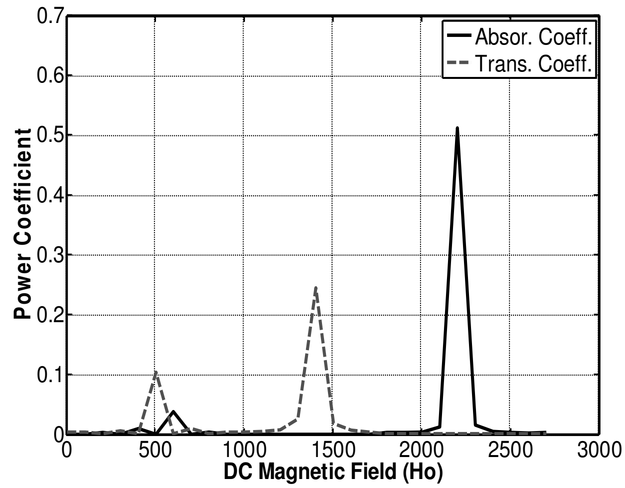

Fig. 2: Comparison of transmission (T) and absorption (P) power coefficient with the varying DC magnetic field (H_o) in the X band.

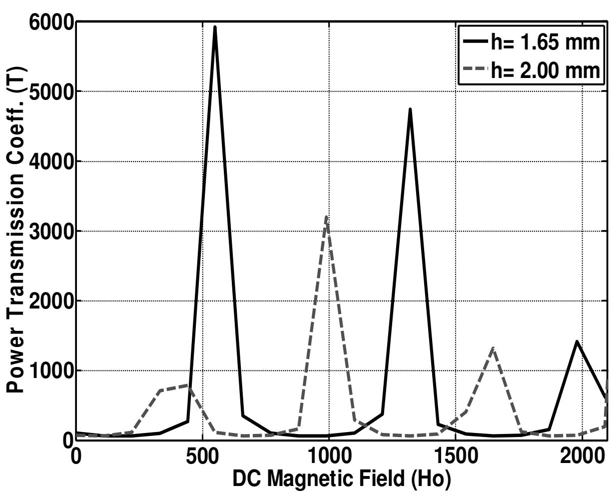

Fig. 3: Comparison of transmission power coefficient (T) for h = 2mm & 1.65mm with the varying DC magnetic field (H_o) in the X band.

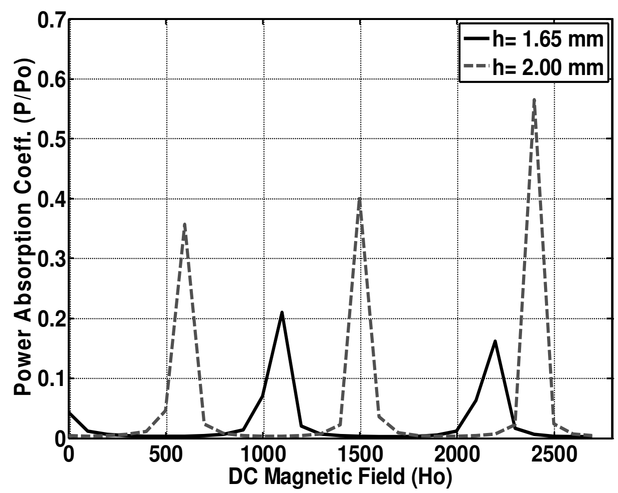

Fig. 4: Comparison of absorption power coefficient (P) for h = 2mm & 1.65mm with the varying DC magnetic field (H_o) in the X band.

From this figure it is obvious that the absorbing power is max between 2100 Oe and 2200 Oe which is in good agreement of dispersion graph fig. 1. Dispersion graph depicts the switch off state of substrate layer for cutoff frequency (f) around 4.5 GHz. Besides switchability figures 1 also shows the tunability above and below the switchability region due to dispersion effect of ferrite under external magnetic field.

The amount of absorption and attenuation can be increased by increasing the thickness of the ferrite layer. Fig. 3 & 4 depict the comparison of transmission and absorption power coefficient respectively for h = 2mm & 1.65mm with the varying DC magnetic field (H_o).

CONCLUSIONS

In the present paper, the concept of tunability and switchability of LiTiMg ferrite material is explored with the magnetostatic and spin wave propagation in the ferrite substrate in the X band. Here we have the dispersion characteristics of substrate layer of LiTiMg-ferrite under external DC-magnetic biasing. Resulted absorbing power coefficient graph has a good agreement with the dispersion relation graph of ferrite material which verify the switching behavior of LiTiMg-ferrite. It is seen from the analysis that the frequency where maximum attenuation occurs can be tuned by adjusting the bias field. It is worth to mention that the attenuation may be greater for higher frequencies, because the ferrite layer looks electrically thicker. The present integration has its own importance in view of miniaturization of microwave devices and antennas including radomes for efficient communication systems.

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