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Comparative study of radiation characteristics of polarized switchable microstrip triangular Patch array antenna

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Abstract

A comparative study of radiation characteristics of a polarized switchable microstrip planar array of triangular patch antenna printed on synthesized LiTiMg ferrite substrate with a normal magnetic bias field has been done and reporting here. Radiation patterns and some important characteristics of proposed array antenna have been compared with the same geometry printed on RT-duroid and silicon. 61% miniaturization and high quality factor are some advantages of using LiTiMg ferrite compare to RT-duroid. With the biasing of external magnetic field perpendicular to the ferrite substrate arise some tunable behavior which has been elaborated by the generation quasi TEM, magnetostatic and spin waves. In this analysis spin wave exchange term (ω_r) which depends upon the static internal field (H_{ex}), has also included in the dispersion formula because the wavelength of microwave approach the inter-atomic distance of ferrite material which is the main cause of generation of spin waves in such types of layered structures.

Keywords: substituted Li ferrite, magnetostatic and spin waves, microstrip array antenna, X-band frequency range

1. Introduction

In recent years, biased ferrite material for microstrip antenna structures has attracted noticeable attention. Ferrite is one of the important magnetic materials which are used as in both types single and polycrystalline. Some novel characteristics of polycrystalline ferrite over normal dielectric material make it very useful in microwave antenna applications. Different types of polycrystalline ferrites have their specific advantages as Li substituted ferrites has high dielectric constant, low sintering temperature etc. than other substituted ferrites. The integration of ferrite technology into microstrip printed circuit antenna has numerous advantages and potential applications. The reason for 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 changes the antenna properties. The significance of this is that it is possible to change the antenna characteristics through the DC magnetic field 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 discussed by numbers of investigators for the C-band and S-band but not for the X-band [1-6].

In the present paper, the study of tunable antenna with the concept of generation of the magnetostatic and spin wave has been developed by taking a 4×4 array of triangular patches printed on LiTiMg ferrite substrate in an X band (10 GHz.) of microwave frequency range.

2. Array Structure

The array geometry is shown in fig. 1. It consists of 16 identical elements of equilateral side length *'s'* printed on LiTiMg ferrite substrate of thickness *'h'*. The dielectric constant and saturation magnetization ($4\pi M_s$) of substrate is 15 and 2200 Gauss respectively. Out of many feeding techniques, coaxial feeding has been preferred due to the consideration of impedance matching. The electrical and magnetic properties of LiTiMg ferrite substrate has been experimentally calculated in laboratory which is listed in table 1.

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)	4.21 grams/cm^3
Remanence	0.90
Coercivity	2.54 Oe.
Dielectric Constant (ε)	15
Resonance Line Width (ΔH)	290 Oersteds
Loss Tangent ($\tan\delta$)	< 0.0009

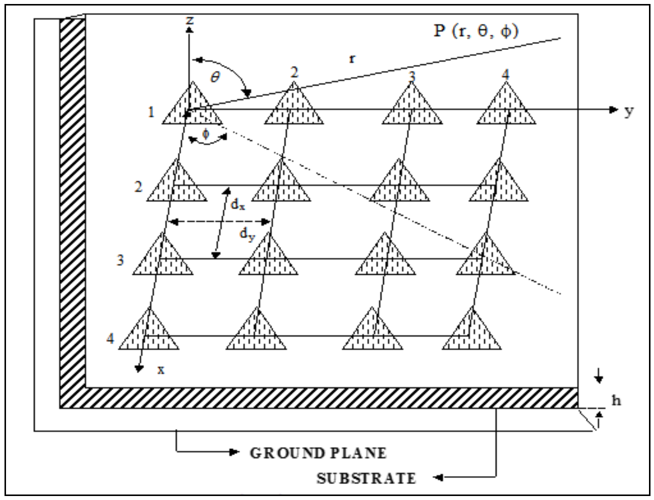

Fig 1: Geometry of 4×4 array microstrip triangular patch antenna

3. Theory

Consider a plane wave propagating in the perpendicular direction of slab with a magnetic bias field applied longitudinally. 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 and γ is a gyromagnetic ratio (2.8 MHz / Oe.). 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 [7-9].

If we consider the infinite medium plane wave solution of the equations of motion including the spin wave "exchange" term and neglecting losses then the dispersion relation for ω as a function of *k* is given by:

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

Where

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

If we plot the dispersion relation (1) 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 [9].

3.1 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.

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

Surface MSW band limits:

$$\mu_o \gamma\,\sqrt{H(H + M_o)} \leq \omega \leq \mu_o \gamma\, H\left(H + \frac{M_o}{2}\right) \qquad (3)$$

Surface MSW in metal coated ferrite:

$$\omega \leq \mu_o \gamma\,(H + M_o) \qquad (4)$$

3.2 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:

$$\omega^2 = \omega_r\left[\omega_r + \frac{\omega_M}{1 + \left(\frac{m\pi}{kt}\right)^2}\right] \qquad (5)$$

Volume MSW band limits:

$$\mu_o \gamma H \leq \omega \leq \mu_o \gamma \sqrt{H(H + M_o)} \qquad (6)$$

4. Result and discussion

The dispersion curve for the material has been plotted and shown in fig. 2. It is clear from the 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 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. Spin wave excitation is the result of exchange forces between atoms. According to Fig. 2 the absorbing power due to the MSW generation is in a particular limit. This particular limit depends upon the thickness of substrate, Resonance Line Width *(ΔH)* and external magnetic field orientation. Here obtained results are simulated and are in close agreement with results available in the literature. The dimensions of each element of antenna are calculated by following equations:

$$s = \frac{2c}{3 f_r \sqrt{\varepsilon_{eff}}} \qquad (7)$$

The above equation is based on the Cavity model. Using the pattern multiplication approach and neglecting mutual coupling between the elements, the normalized form of the array factor for the present geometry is obtained and given below:

$$AF = 0.0625 \frac{\sin\{2(kd_x \sin\theta \cos\varphi + \beta_x)\}}{\sin\{0.5(kd_x \sin\theta \cos\varphi + \beta_x)\}} \times \frac{\sin\{2(kd_y \sin\theta \sin\varphi + \beta_y)\}}{\sin\{0.5(kd_y \sin\theta \sin\varphi + \beta_y)\}} \qquad (8)$$

The total fields of the present array geometry can be expressed by the field of single element multiplied by array factor. Thus the far zone expressions for 4×4 planar array triangular patch microstrip antenna are obtained as follow [10, 11]:

$$E_\theta = -j\,\eta_o \omega[-F_X \sin\varphi + F_Y \cos\varphi] \qquad (9)$$

$$E_\varphi = j\,\eta_o \omega[-F_X \cos\theta \cos\varphi + F_Y \cos\theta \sin\varphi] \qquad (10)$$

$$R_E(\theta) = \left(|E_\theta|^2 + |E_\varphi|^2\right) \times AF = \eta_o^2 \omega^2[(|F_Y|^2 + |F_X|^2)(\cos\theta)^2] \times AF \qquad (11)$$

$$R_H(\theta) = \left(|E_\theta|^2 + |E_\varphi|^2\right) \times AF = \eta_o^2 \omega^2[(|F_X|^2 + |F_Y|^2)(\cos\theta)^2] \times AF \qquad (12)$$

In the above far field equations wherever the propagation constant *(k)* is placed, it is replaced by the following expression.

$$k_\pm = \omega^2 \epsilon \mu_o \frac{(\omega_r + \omega_M)^2 - \omega^2}{\omega_r^2 + \omega_r \omega_M + \omega^2}^{1/2} \qquad (13)$$

The polarization of antenna can be adjusted by the propagation constant listed in table 2. The parameters related to patch characterization have been calculated for triangular patch array antenna for three conditions: unbiased dielectric substrate, unbiased ferrite and biased ferrite respectively, listed in table 3. With the help of these parameters and mathematical software (Mathworks MatLab 7.1), a comparison of right hand circular polarized (RHCP) radiation patterns of microstrip triangular patch array antenna for RT-duroid, Silicon and Ferrite (with external biasing field $H_o = 0$ & *1500 Oe*) as a substrate. The value of $R(\theta,\varphi)$ have been computed by taking source frequency $f = 10$ *GHz*, RHCP propagation constant $k = K_+$ and height $h = 1.65$ *mm*. For the array, the element separation $d_x = d_y = \lambda/2$ cm and progressive phase excitation is $\beta_x = \beta_y = 0$.

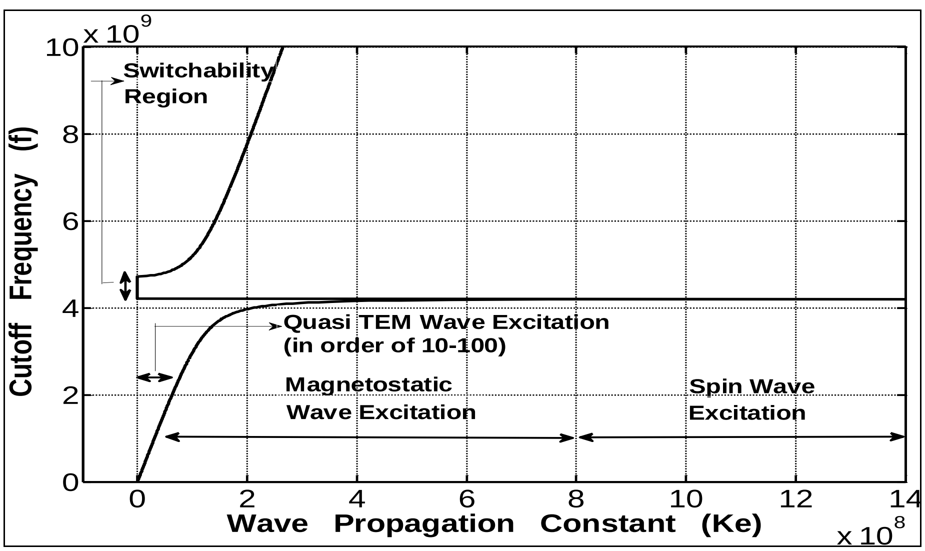

Fig 2: Dispersion curve (f Vs. K_e) of LiTiMg for incident plane wave perpendicular to biased substrate, magnetized by 1500 Oe magnetic field in the X band.

Table 2: Antenna`s function based on the propagation of extraordinary waves.

Extraordinary Wave Propagation with Propagation Constant	Antenna Function
Negative μ_{eff}	Off
Positive μ_{eff} with k_+	Radiate with RHCP
Positive μ_{eff} with k_-	Radiate with LHCP

Table 3: Comparison of Antenna`s parameters for Unbiased and biased case

Parameters	RT duroid Unbiased ($\varepsilon_r = 2.33$)	Silicon Unbiased ($\varepsilon_r = 13$)	Ferrite Unbiased ($\varepsilon_r = 15$)	Ferrite Biased ($\varepsilon_r = 15$)
Eff. Side Length (s)	14.22 mm	6.07 mm	5.48 mm	5.48 mm
Eff. Die. Const. (ε_{eff})	2.43	10.85	12.92	12.92
Reso. Frequency (f_r)	9.00 GHz	9.98 GHz	10.14 GHz	10.14 GHz
Total Imped. (Z_{in})	181.27 ohms	268.83 ohms	265.88 ohms	265.88 ohms
Admittance (Y)	0.028 mhos	0.019 mhos	0.019 mhos	0.019 mhos
Quality Factor (Q)	5.7285	25.22	29.93	29.93
Bandwidth (BW)	7.13 %	1.62 %	1.36 %	1.36 %
Directivity (D)	13.60 dB	11.61 dB	11.12 dB	11.12 dB
Radiation Power (P_r)	14.00 mW	9.29 mW	9.40 mW	9.40 mW

5. Conclusions

The use of biased LiTiMg ferrite material as substrate for triangular patch array antenna reveals many important factors in comparison of other substrate materials like RT-duroid and Silicon. The switching and tunability characteristics of antenna can be evident from the dispersion curve of LiTiMg ferrite material which shows that there is a propagating and non-propagating region. There is a frequency range bounded by limits, namely cutoff limit or resonance limit which is about at 4.2 GHz to 4.5 GHz. In this cutoff limits where μ_{eff} *or* k is negative, the em-waves are highly attenuating and therefore the antenna is effectively off as radiator. Some salient features of this array geometry are summarized as follow:

The 61% miniaturization has been calculated between the geometries, printed on RT-duroid and ferrite substrate. The geometrical reduction has also been calculated between RT-duroid and silicon as substrate is 57% while 9.7% between silicon and ferrite as substrate for the same microstrip triangular array geometry. This whole study concluded that ferrite is a better option for compact antennas with additive advantage of surface wave reduction which gives accuracy and preciseness.

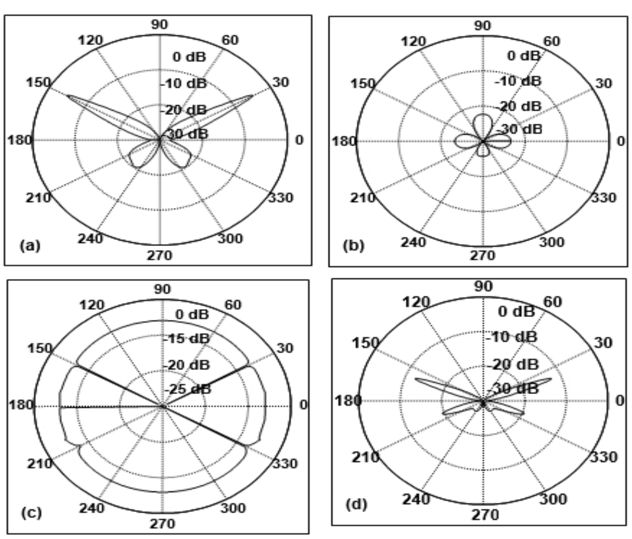

Fig 3: Comparison of RHCP radiation patterns of triangular patch microstrip array antenna for external biasing field **(a)** $H_o = 0$ Oe with TR-duroid substrate, **(b)** $H_o = 0$ Oe with Silicon substrate, **(c)** $H_o = 0$ Oe with Ferrite substrate, **(d)** $H_o = 1500$ Oe with Ferrite substrate.

If we compare antenna geometry for silicon and ferrite of approx. same dielectric constant ($\varepsilon_r = 15$) as a substrate, the radiation pattern is more directive in nature but have almost same directivity with negligible differences with rest of parameters without external field biasing. Comparison between biased and unbiased antenna array radiation pattern, shows that on biasing, the radiation pattern gaining the scanning characteristics with narrow beamwidth & low directivity.

The overall comparison among all four cases concluded that the inclusion of ferrite as a substrate at the place of silicon is better in point of view of miniaturization and the suppression of surface wave excitation. On the other hand under external biasing condition the radiation of array antenna becomes directive in nature as well as polarizibility & switchability also arise which is very helpful for tracking & scanning antenna systems for space and cellular communication.

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