Effect of Warm Ionized Plasma Medium on Radiation Properties of Four Elements Microstrip Antenna Array Printed on Ferrite Substrate

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(Received on 21 July, 2009)

This paper describes theoretically the radiation properties of four element microstrip antenna array printed upon a typical ferrite substrate $Ni_{1.062}Co_{0.o2}Fe_{1.948}O_4$ in the presence of normal dc magnetic bias field. In lossless isotropic warm plasma, this array antenna geometry excites both electromagnetic (EM) and electroacoustic plasma (P) waves in addition to nonradiating surface waves. In the absence of an external magnetic field, the EM – mode and P-mode can be decoupled into two independent modes, the electoacoustic mode is longitudinal while the electromagnetic mode is transverse. Far zone electromagnetic mode and plasma mode radiation fields are derived using vector wave function technique and pattern multiplication approaches. The results are obtained in both plasma medium and free space .Some important antenna parameters such as radiation patterns, radiation conductance and directivity are plotted for different values of plasma to source frequency.

Keywords: Microstrip Antenna Array, Ferrite, Plasma Medium

Introduction

Microstrip antennas are proved useful for application on spacecrafts and mobile handsets due to their lightweight, small size, better aerodynamic properties and compatibility to get integrated with host objects. In past years, extensive research on different geometries of microstrip antennas under different conditions has been carried out to improve their inherent low bandwidth and low directive gain [1].

Ferrite and other magnetic materials have been extensively used in several microwave devices such as phase shifters, isolators, circulators, tunable filters, delay lines etc. Ferrite materials basically have a significant amount of anisotropy at microwave frequencies [2].This anisotropy induces on applying external dc magnetic field and brings about nonreciprocal behavior in them. Availability of low cost commercial ferrite substrates and recent advances in thin film technology has attracted noticeable attention of scientific community in the development of microstrip antennas on ferrite substrates [3-4].

The high dielectric constant of the ferrite substrate reduces the antenna dimensions and when biased with DC magnetic field, the antenna exhibits a number of novel properties. These include frequency tuning agility, the generation of circular polarization, reduction of surface waves and radar cross-section control. Microstrip antenna mounted on aerospace vehicles encounter plasma medium during their voyage in space, as a result of which radiation properties are altered significantly. This change is caused due to the generation of electroacoustic waves in addition to electromagnetic waves [5-7].

This paper reports theoretical work carried out to investigate the radiation properties of four element microstrip antenna printed upon a typical ferrite substrate $Ni_{1.062}Co_{0.o2}Fe_{1.948}O_4$ by considering the presence of dc magnetic bias field normal to the direction of propagation of electromagnetic waves. Several radiation characteristics of four element microstrip antenna array are analyzed theoretically by applying cavity modal based modal expansion technique. Design requirement and substrate characteristics considered for this theoretical analysis are listed in table 1.

TABLE I: Design requirement and characteristics of $Ni_{1.062}Co_{0.o2}Fe_{1.948}O_4$.

Design frequency (f)	1.0GHz
Relative permittivity (ε_r)	14.78
Dielectric loss tangent	0.0005
Magnetic loss tangent	0.005
Applied DC magnetic bias field (H_o)	$6.37\times10^5 A/m$
Saturation magnetization $(\mu_o M_s)$	0.3T

Theoretical Considerations

Microstrip antennas printed on ordinary non-magnetic dielectric substrate with a single feed point have a single linearity polarized resonance mode. By applying two orthogonal feeds with 90 phase difference, a microstrip antenna will again have a single dominant resonance mode but can radiate circularly polarized waves. The use of magnetized ferrite substrate in place of dielectric substrate however leads to quite different results, since it can support various guided modes in different conditions. When direction of magnetization is normal to the direction of propagation of electromagnetic waves, two plane wave modes namely ordinary (O) and extraordinary (E) modes exist. The propagation constant in this case is still given by

$$\delta = \alpha + j\beta = j\omega\sqrt{\varepsilon_o\varepsilon_r\mu_o\mu_{eff}}\ldots\ldots \quad (1)$$

The ordinary wave is similar to plane wave in a dielectric slab polarized transversally to the biasing direction with phase constant [8].

$$\beta_O = \frac{2\pi f_r}{c}\sqrt{\varepsilon_r}\ldots\ldots \quad (2)$$

However extraordinary wave is a transverse electric mode polarized parallel to the biasing direction with phase constant:

$$\beta_E = \frac{2\pi f_r}{c}\sqrt{\varepsilon_r\mu_{eff}}\ldots\ldots \quad (3)$$

The effective permeability of a magnetized substrate material (μ_{eff}) is given by [9]:

$$\mu_{eff} = \frac{\mu^2 - K^2}{\mu} \ldots\ldots \tag{4}$$

With

$$\mu = 1 + \frac{\omega_o\omega_m}{\omega_o^2 - \omega_m^2} \quad \text{and} \quad K = \frac{\omega\omega_m}{\omega^2 - \omega_m^2} \ldots . \tag{5}$$

Here ω_o and ω_m are the precession and forced precession frequencies respectively and are defined as:

$$\omega_o = \mu_o\gamma H_o \quad , \quad \omega_m = \mu_0\gamma M_s \quad \text{and} \quad \omega = 2\pi f$$

Applied dc magnetic bias field (H_o) and saturation magnetization $(\mu_o M_s)$ are considered in Amper/meter (A/m) and Tesla (T) units, respectively.

When μ_{eff} is negative, the extraordinary wave is decaying even if the material is loss-less. The frequency range for negative μ_{eff} is $\sqrt{\omega_0(\omega_o+\omega_m)} \leq \omega \leq (\omega_o+\omega_m)$.

The geometry and coordinate system of four element microstrip antenna array of rectangular microstrip patch antenna are shown if figure (1).

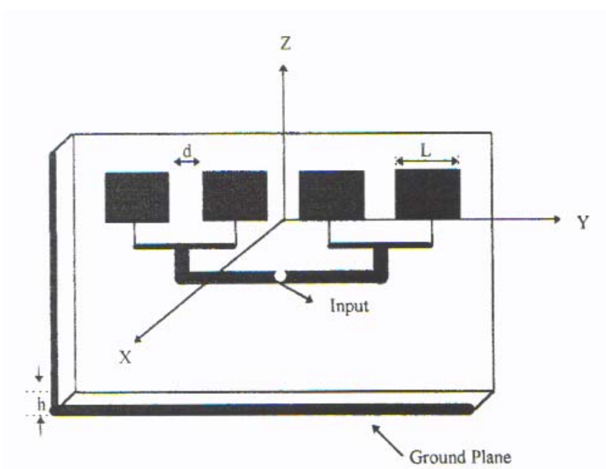

FIG. 1: Geometry and coordinate system of four element microstrip antenna array.

In microstrip antenna array each patch is excited in a same phase and amplitude by corporate microstrip line feed connected to the edge of the radiating slot [10].

Radiation Field Expressions

Using hydrodynamic theory and vector wave function technique [11-12], the total far field of electromagnetic mode and plasma mode of the linear array are obtained as:

EM mode:

$$(E_\phi)_T = \frac{-jV_o\beta_e L}{\pi}\frac{e^{-j\beta_e r}}{r}\sin\theta\frac{\sin(\frac{\beta_e h}{2}\cos\theta)}{(\frac{\beta_e h}{2}\cos\theta)}\frac{\sin(\frac{\beta_e L}{2}\sin\theta\sin\phi)}{(\frac{\beta_e L}{2}\sin\theta\sin\phi)} \cos(\frac{\beta_e L}{2}\sin\theta\cos\phi)\frac{\sin 2(\beta_e d\sin\theta\sin\phi)}{\sin\frac{1}{2}(\beta_e d\sin\theta\sin\phi)} \ldots\ldots \tag{6}$$

And in plasma mode:

$$(E_P)_T = \frac{V_o L}{\pi}\left(\frac{1-A^2}{A}\right)\left(\frac{c}{\upsilon_o}\right)\frac{e^{-j\beta_p r}}{r} \sin\theta\frac{\sin(\frac{\beta_p h}{2}\cos\theta)}{(\frac{\beta_p h}{2}\cos\theta)}\frac{\sin(\frac{\beta_p L}{2}\sin\theta\sin\phi)}{(\frac{\beta_p L}{2}\sin\theta\sin\phi)} \cos(\frac{\beta_p L}{2}\sin\theta\cos\phi)\frac{\sin 2(\beta_p d\sin\theta\sin\phi)}{\sin\frac{1}{2}(\beta_p d\sin\theta\sin\phi)} \tag{7}$$

Where

$$A = (1 - \frac{\omega_p^2}{\omega^2}) \quad , \quad \beta_e = \beta_o A \quad , \quad \beta_p = \left(\frac{c}{\upsilon_o}\right)\beta_e$$

β_e,β_p are the propagation constants in electromagnetic mode and plasma mode respectively and $A$is the plasma parameter.

Radiated Power

The radiated power in the EM mode is obtained by integrating the Poynting vector over a large sphere. In our case study:

$$P_e = \frac{A}{2z_o}(\frac{\beta_e L V_o}{\pi})^2 I_1 \ldots . \tag{8}$$

Where

$$I_1 = \int_0^{\frac{\pi}{2}}\int_0^{2\pi}[\frac{\sin(\beta_e\frac{h}{2}\cos\theta)}{(\beta_e\frac{h}{2}\cos\theta)} \frac{\sin(\beta_e\frac{L}{2}\sin\theta\cos\phi)}{(\beta_e\frac{L}{2}\sin\theta\cos\phi)}\sin\theta\cos(\beta_e\frac{L}{2}\sin\theta\cos\phi) \frac{\sin 2(\beta_e d\sin\theta\sin\phi)}{\sin\frac{1}{2}(\beta_e d\sin\theta\sin\phi)}]^2\sin\theta d\theta d\phi$$

Similarly $P_p$is obtained as

$$P_p = \frac{L^2\beta_p V_o^2}{\pi^2\varepsilon_o\omega\, z_o}(\frac{1-A^2}{A^2})\, I_2 \ldots . \tag{9}$$

Where

$$I_2 = \int_0^{\frac{\pi}{2}}\int_0^{2\pi}[\frac{\sin(\beta_p\frac{h}{2}\cos\theta)}{(\beta_p\frac{h}{2}\cos\theta)}\frac{\sin(\beta_p\frac{L}{2}\sin\theta\cos\phi)}{(\beta_p\frac{L}{2}\sin\theta\cos\phi)} \cos(\beta_p\frac{L}{2}\sin\theta\cos\phi) \frac{\sin 2(\beta_p d\sin\theta\sin\phi)}{\sin\frac{1}{2}(\beta_p d\sin\theta\sin\phi)}]^2\sin\theta d\theta d\phi$$

The EM mode radiation conductance is given by:

$$G_e = \frac{2P_e}{V_o^2} \ldots . \tag{10}$$

And the plasma mode radiation conductance is given by:

$$G_p = \frac{2P_p}{V_o^2} \ldots \tag{11}$$

The directive gain of the antenna in plasma medium can be expressed as:

$$D = \frac{4\pi U(\theta,\phi)}{P_e} \ldots . \tag{12}$$

Where, $U(\theta,\phi)$ is the radiation intensity in (θ,ϕ) direction. The expression for directive gain of four element array

$$D = \frac{4\pi S}{I_1}$$

Where

$$S = \left[\frac{\sin(\beta_e \frac{h}{2}\cos\theta)}{(\beta_e \frac{h}{2}\cos\theta)} \frac{\sin(\beta_e \frac{L}{2}\sin\theta\cos\phi)}{(\beta_e \frac{L}{2}\sin\theta\cos\phi)} \sin\theta\cos(\beta_e \frac{L}{2}\sin\theta\cos\phi)\frac{\sin 2(\beta_e d\sin\theta\sin\phi)}{\sin 0.5(\beta_e d\sin\theta\sin\phi)}\right]^2$$

Using equations (8) and (9), the radiation efficiency of a ferrite-based four element microstrip antenna array inside plasma medium is expressed as:

$$\eta = \frac{P_e}{P_e + P_p} \times 100\,\% \ldots. \qquad (13)$$

The value of radiation conductance , directive gain and efficiency of four element microstrip antenna array is computed for different values of plasma parameter with$H_o = 6.37 \times 10^5 A/m$and plotted in figures (2,3,4 and 5) respectively.

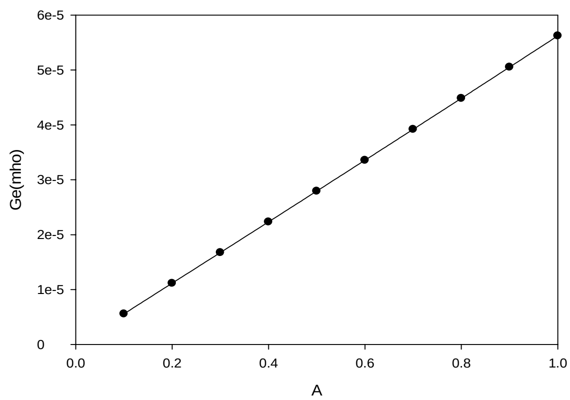

FIG. 2: Radiation conductance in EM mode for different A and $H_o = 6.37 \times 10^5 A/m$

Conclusion

The radiation properties of four element linear microstrip antenna array printed upon a typical ferrite substrate $Ni_{1.062}Co_{0.o2}Fe_{1.948}O_4$ have been studied by considering the presence of dc magnetic bias field normal to the direction of propagation of electromagnetic waves It is observed that the radiation conductance (G_e) of four element array is more than that of single element for all the plasma frequency. It is maxima in free space and decreases on increasing plasma frequency. It is found that when microstrip antenna is biased the directivity and the efficiency are improved as compared to an unbiased case. Our results are consistent with the results reported by Yang [2]. Finally, it is concluded that the four element microstrip antenna array has unique radiation

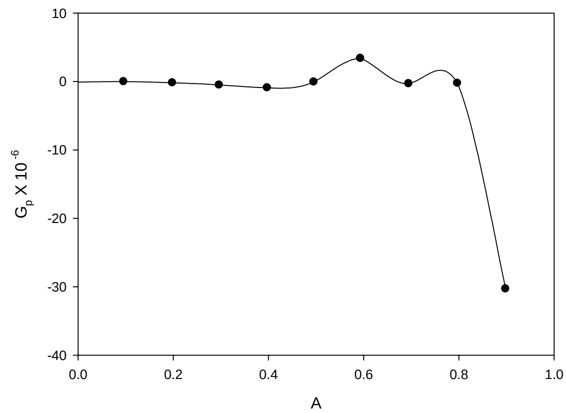

FIG. 3: Radiation conductance in P-mode for different A and $H_o = 6.37 \times 10^5 A/m$

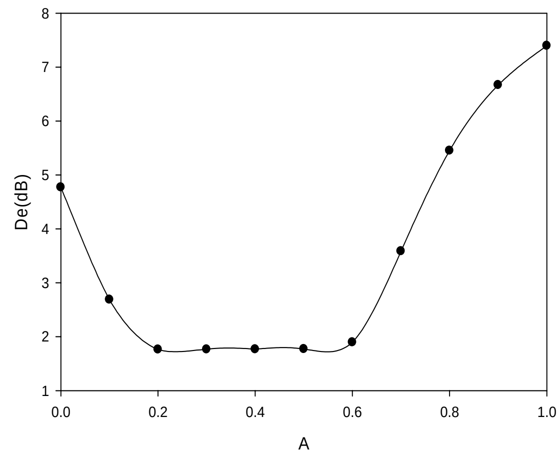

FIG. 4: Directivity in EM mode for different A and $H_o = 6.37 \times 10^5 A/m$

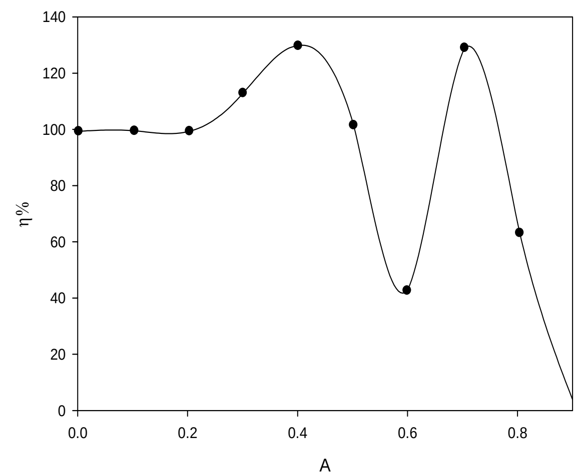

FIG. 5: Efficiency of four element microstrip antenna in EM mode for different A and $H_o = 6.37 \times 10^5 A/m$

properties and can be employed in applications where high gain and narrow beam-width are required. The results of the present study are useful, particularly for space vehicles because such type of linear array can be mounted on the flat surface as well as on the curved surface of the space vehicles.

Acknowledgments

This research project (N0.90081)has been financially supported by Deanship of Scientific Research, King Faisal University, Saudi Arabia

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