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Wide-band scanned array of microstrip antenna on ferrite substrate

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Abstract : Calculated results for the radiation pattern characteristics, band width, directive gain and radiation conductance of a 4 × 4 planar array of circular patch microstrip antenna designed on YIG ferrite substrate are presented at 10 GHz. It is shown that a wide-band antenna characteristics can be obtained by proper selection of progressive phase excitation difference among the antenna elements. This array geometry also offers good scanning capabilities with higher directive gain

Keywords : Microstrip array, ferrite, wideband

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1. Introduction

Recent advancement of thin film technology has motivated the use of ferrite materials in microwave and millimeter wave integrated circuits. Applications of ferrite substrate in designing of scanning arrays has become increasingly important. An attractive feature of ferrites is that the material characteristics are nonreciprocal and electronically tunable. The high dielectric constant of ferrite reduces the antenna dimensions and when biased with dc magnetic field the antenna exhibit a number of novel properties including frequency tuning agility, generation of circular polarization and reduction in radar cross section [1-4]. In this communication the use of YIG ferrite in designing a 4 × 4 planar array of circular patch microstrip antenna geometry has been investigated extensively at 10 GHz. Unique antenna characteristics including wide bandwidth, beam steering and gain enhancement have been described.

2. Theory

The array geometry and its co-ordinate system is shown in Figure 1.

It consists 16 identical elements of radius 'a' designed on YIG ferrite substrate with $4\pi M_s = 1780$ Gauss, $\varepsilon_r = 15$, $\mu_r = 18.2$, thickness $h = 0.16$ cm. Each patch can be excited by a microstrip transmission line connected to the edge or by a co-axial line from the back at the plane $\phi = 0$. Several investigators have considered the patch as a cavity which acts as a disc resonator. In such a geometry TM_{mn} mode with respect to z-axis are excited. The subscripts n and m are the mode numbers associated with x and y-directions respectively.

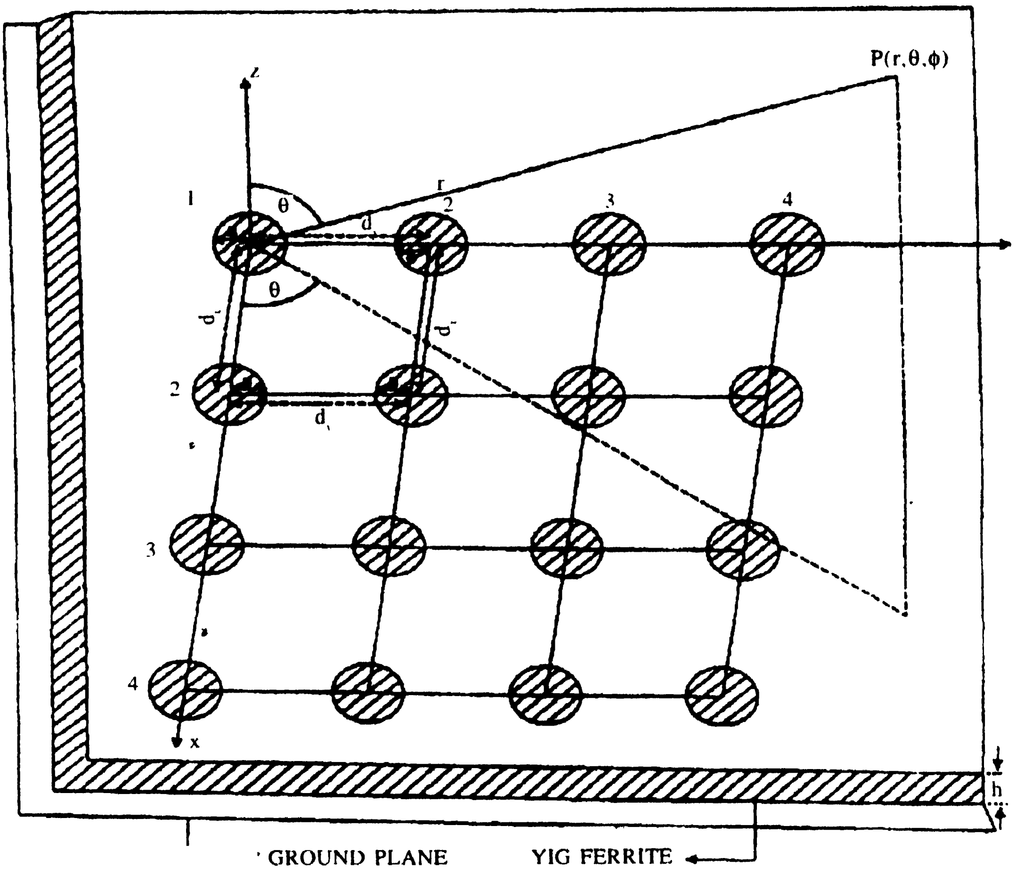

Figure 1. Array geometry and coordinate system of 4 × 4 element planar array of circular patch microstrip antenna on YIG ferrite

The total fields of the present array antenna can be expressed by the fields of a single element positioned at the origin multiplied by a factor which is referred as the array factor. This method is widely known as pattern multiplication approach[5]. Since the entire array is taken as uniform, the normalized form of array factor (AF) is obtained and may be written as,

$$AF = 0.0625 \frac{\sin\left\{2(Kd_x \sin\theta\cos\phi + \beta_x)\right\}}{\sin\left\{0.5(Kd_x \sin\theta\cos\phi + \beta_x)\right\}} \times \frac{\sin\left\{2(Kd_y \sin\theta\sin\phi + \beta_y)\right\}}{\sin\left\{0.5(Kd_y \sin\theta\sin\phi + \beta_y)\right\}} \quad (1)$$

Here, we have developed a theory of planar phased array antennas in which, the radiation from an array can be scanned directly by controlling the phase excitation difference between the elements *i.e.* the maximum direction can be oriented in any direction, by changing the phase excitation difference β_x and β_y between the elements. Thus, following procedure described in references [4] and [5] and neglecting coupling [6] between the elements, the far-zone field expressions for 4 × 4 element planar array of circular patch microstrip antenna are obtained as follows :

$$E_{\theta t} = j^n \frac{VaK_0}{2} \frac{e^{-jk_0 r}}{r} \cos n\phi \frac{\sin(K_0 h \cos\theta)}{(K_0 h \cos\theta)} \times$$

$$\left\{J_{n+1}(K_0 a \sin\theta) - J_{n-1}(K_0 a \sin\theta)\right\} \times \text{array factor.} \tag{2}$$

Similarly,

$$E_{\phi t} = j^n \frac{VaK_0}{2} \frac{e^{-jk_0 r}}{r} \cos\theta \sin n\phi \frac{\sin(K_0 h \cos\theta)}{(K_0 h \cos\theta)} \times$$

$$\left\{J_{n+1}(K_0 a \sin\theta) + J_{n-1}(K_0 a \sin\theta)\right\} \times \text{array factor.} \tag{3}$$

where

$E_{\theta t}$, $E_{\phi t}$	=	Components of total electric field vector for EM wave,
K_0	=	Phase propagation constant for EM wave,
β_x, β_y	=	Progressive phase excitation difference along x and y directions respectively,
J_{n+1}	=	$(n + 1)$ th order Bessel's function of first kind,
J_{n-1}	=	$(n - 1)$ th order Bessel's function of first kind,
V	=	edge voltage at $\phi = 0$,
λ_0	=	free space wave length,
a	=	radius of each circular patch,
h	=	thickness of dielectric substrate.

Value of 'a' is obtained using the characteristic equation for the resonant frequency (f_r) as

$$f_r = \frac{Ck_{nm}}{2\pi a \sqrt{\varepsilon_r \mu_r}}, \tag{4}$$

where $k_{nm} = 1.84118$ ($n = 1$ and $m = 1$), integer n corresponds to the order of the Bessel function and the integer m represents the m-th zero of the function $(K_1 a)$. For any given frequency the mode corresponding to $n = m = 1$ has the minimum radius and is known as the dominant mode.

Field patterns :

The total field pattern $R(\theta, \phi)$ is generally obtained from the relation

$$R(\theta, \phi) = \left|E_{\theta t}\right|^2 + \left|E_{\phi t}\right|^2 . \tag{5}$$

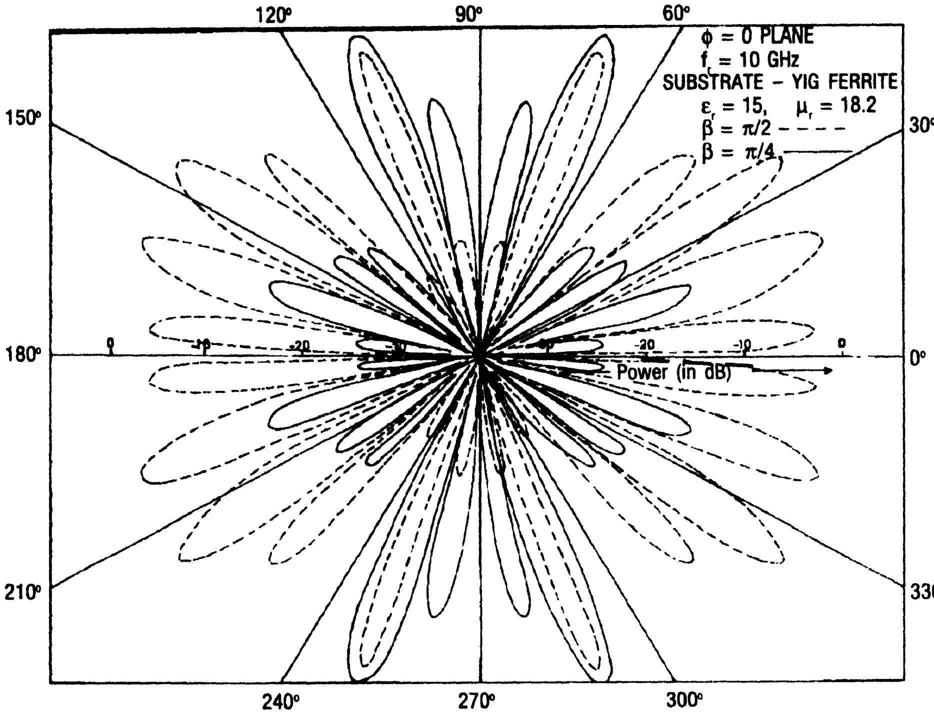

Figure 2. Variation of $R(\theta, \phi)$ for 4 × 4 element planar array of circular patch microstrip antenna for $\phi = 0$ plane and $\beta = \pi/2$ and $\pi/4$.

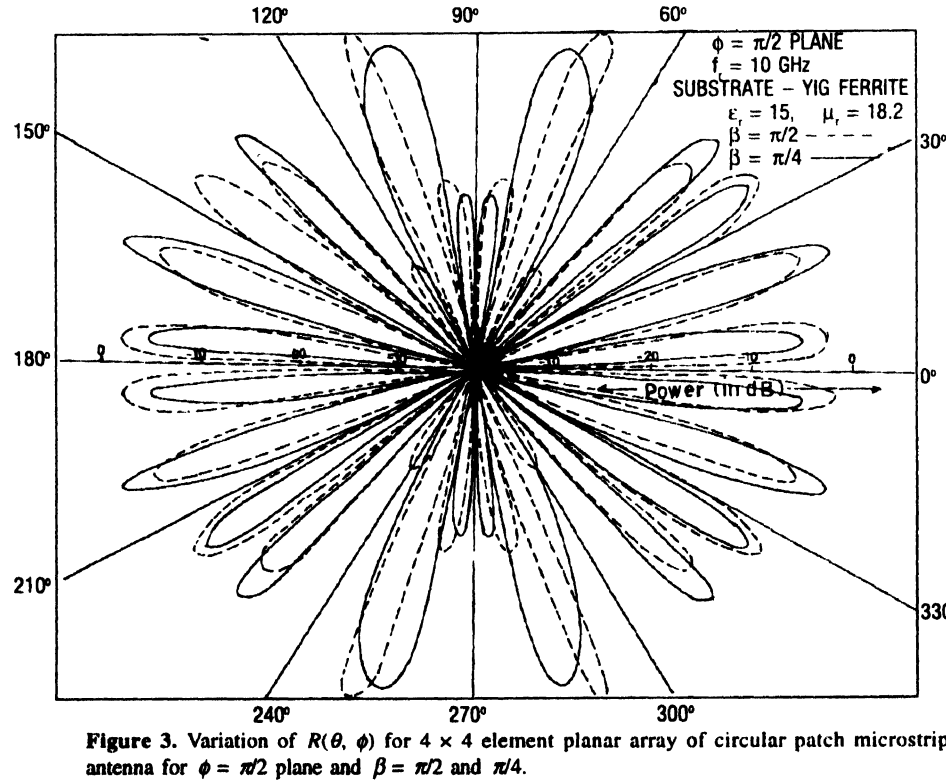

Figure 3. Variation of $R(\theta, \phi)$ for 4 × 4 element planar array of circular patch microstrip antenna for $\phi = \pi/2$ plane and $\beta = \pi/2$ and $\pi/4$.

The $R(\theta, \phi)$ has been computed for two values of progressive phase excitation difference *i.e.* $\beta_x = \beta_y = \pi/2$ and $\pi/4$ and a case taking source frequency $(F_r) = 10$ GHz, $a = 5.3 \times 10^{-2}$ cm. $\varepsilon_r = 15$, $\mu_r = 18.2$, $h = 0.16$ cm. and the element separation $d_x = d_y = 0.5\ \lambda_0 = 1.5$ cm. The calculated results are plotted in two different planes *i.e.* $\phi = 0$ and $\phi = \pi/2$ and shown in Figures 2 and 3.

It is observed from the figures that pattern of array antenna are directive in nature and provide simultaneously large number of beams. It is also found that on the variation of progressive phase excitation difference among the elements, the position of main beam and the secondary beams are scanned and the direction of maximum radiation is shifted. We have measured different pattern characteristics of array geometry for $\beta_x = \beta_y = \pi/2$ and $\pi/4$ which are given in Table-1.

Table 1. Measured values of pattern characteristics of array geometry

S No.	Pattern Characteristics	$\phi = 0$ plane		$\phi = \pi/2$ plane	
		$\beta_x = \beta_y = \pi/2$	$\beta_x = \beta_y = \pi/4$	$\beta_x = \beta_y = \pi/2$	$\beta_x = \beta_y = \pi/4$
1	HPBW (major lobe)	4^0	5^0	5^0	4^0
2.	Direction of max radiation (major lobe)	35^0	70^0	70^0	20^0
3	First null beam width	12^0	14^0	8^0	13^0
4	HPBW (first minor lobe)	6^0	4^0	6^0	9^0
5	Direction of max. radiation (first minor lobe)	21^0	80^0	5^0	75^0
6	SLL (dB)	-1.0	-9 5	-2 0	-2.5
7	Total shift (major lobe)	35^0		50^0	
8	Total shift (first minor lobe)	59^0		70^0	

Radiation conductance :

By integrating the Poynting vector over a large sphere, the expression for radiation conductance of the array geometry may be expressed as [4]

$$G = \frac{2P_r}{V^2}, \tag{6}$$

where P_r is the radiated power by the antenna and may be written as follows :

$$P_r = A\int_0^{2\pi}\int_0^{\pi} \frac{\sin^2(K_0 h\cos\theta)}{(K_0 h\cos\theta)^2} \times \frac{\sin^2\{2(Kd_y \sin\theta\sin\phi + \beta_y)\}}{\sin^2\{0.5(Kd_y \sin\theta\sin\phi + \beta_y)\}}$$

$$\times \frac{\sin^2\{2(Kd_x \sin\theta\cos\phi + \beta_x)\}}{\sin^2\{0.5(Kd_x \sin\theta\cos\phi + \beta_x)\}} \left\{\cos^2 n\phi\left[J_{n+1}(K_0 a\sin\theta) - J_{n-1}(K_0 a\sin\theta)\right]^2\right.$$

$$\left. + \cos^2\theta\sin^2 n\phi\left[J_{n+1}(K_0 a\sin\theta) + J_{n-1}(K_0 a\sin\theta)\right]^2\right\} \times \sin\theta d\theta d\phi. \tag{7}$$

where

$$A = \frac{j^{2n} a^2 K_0{}^2 V^2 e^{-2jk\omega r}}{2048\eta},$$

$$V_0(\text{edge voltage}) = hE_0 J_n(K_0 a),$$

$$\eta\ (\text{free space impedence} = 120\pi.$$

Directive gain :

The directive gain of an antenna in a given direction is defined as the ratio of the radiation intensity (U) in that direction to the average radiated power P_r. It is expressed as [4]

$$D_g = \frac{4\pi U}{P_r}. \tag{8}$$

Therefore,

$$D_g = \frac{4\pi m_e}{I}, \tag{9}$$

where

$$I = \int_0^{2\pi}\int_0^{\pi} m_e \sin\theta \, d\theta d\phi, \tag{10}$$

and $$m_e = R(\theta,\phi) = \left|E_{\theta t}\right|^2 + \left|E_{\phi t}\right|^2.$$

$$m_e = \frac{\sin^2(K_0 h\cos\theta)}{(K_0 h\cos\theta)^2} \times \frac{\sin^2\{2(Kd_x \sin\theta\cos\phi + \beta_x)\}}{\sin^2\{0.5(Kd_x \sin\theta\cos\phi + \beta_x)\}}$$

$$\times \frac{\sin^2\{2(Kd_y \sin\theta\sin\phi + \beta_y)\}}{\sin^2\{0.5(Kd_y \sin\theta\sin\phi + \beta_y)\}}$$

$$\times\Big\{\cos^2 n\phi\left[J_{n+1}(K_0 a\sin\theta) - J_{n-1}(K_0 a\sin\theta)\right]^2$$

$$+\cos^2\theta\sin^2 n\phi\left[J_{n+1}(K_0 a\sin\theta) + J_{n-1}(K_0 a\sin\theta)\right]^2\Big\}. \tag{11}$$

Bandwidth :

The bandwidth of the antenna is calculated as [7]

$$BW = \frac{F_r}{Q_T}, \tag{12}$$

where Q_T is the total quality factor which is given as

$$\frac{1}{Q_T} = \frac{1}{Q_R} + \frac{1}{Q_C} + \frac{1}{Q_d}. \tag{13}$$

For simplification, dielectric loss and copper loss are considered to be negligible, hence the bandwidth is

$$BW = \frac{1}{Q_R}. \tag{14}$$

The Q_R factor of a microstrip antenna is calculated using the relation

$$Q_R = \frac{\omega_0 W_T}{P_r} = 2\pi f_r \frac{W_T}{P_r}. \tag{15}$$

Here, W_T is the total stored energy obtained as follows :

$$W_T = \frac{1}{2}\varepsilon_0 \varepsilon_r h \int_v |E_z|^2 \, dv, \tag{16}$$

where $E_Z = E_0 J_1 (K\rho) \cos n\phi$ is a z component of electric field in the substrate.

The values of radiation conductance, directive gain and bandwidth have been calculated for the array geometry using above expressions for two different values of progressive phase excitation *i.e.* $\beta_x = \beta_y = \pi/2$ and $\pi/4$ by taking same input parameters. The integral involved in eq. (7) has been solved using numerical method [8]. The calculated values are given in Table 1. It is observed from the table that there is a significant changes in the values of bandwidth, directive gain and radiation conductance on variation of progressive phase excitation difference among the elements of array geometry. The present array geometry designed on YIG ferrite substrate provides a large bandwidth *i.e.* 24.8% and higher gain of 23.10 dB at $\beta_x = \beta_y = \pi/4$. These results are significantly better than recent results reported by Staraj *et al* [9] and Yang [2].

3. Discussion and conclusion

Figure 2 and 3 show the radiation pattern of the array geometry for two values of $\beta_x = \beta_y = \pi/2$ and $\pi/4$. It is observed that patterns are directive in nature and provides simultaneously large number of beams. The position of mainbeam is being steered by 30° in $\phi = 0$ plane and 50° in $\phi = \pi/2$ plane on changing the progressive phase excitation difference. Measured values of pattern characteristics are given in Table 1 and the calculated values of bandwidth, directive

Table 2. Calculated values of radiation conductance and directive gain of array geometry.

S No.	Antenna parameters	Phase excitation difference	
		$\beta_x = \beta_y = \pi/2$	$\beta_x = \beta_y = \pi/4$
1	Band width (BW) (%)	9 6	24.8
2.	Directive gain (D_g) (dB)	6.4	23.1
3.	Radiation conductance (G) (Mho)	$0.449 \times 10^{-}$[illegible]	1.14×10^{-5}

gain and radiation conductance of the array geometry are given in Table-2. It can be seen from the tables that there is a significant change in the values of antenna parameters with respect to change in progressive phase excitation difference between the antenna elements. A wide-band characteristics with a band width of 24.8% is achieved of the geometry for YIG ferrite for a case when $\beta_x = \beta_y = \pi/4$.

Some salient features of this array geometry are summerised as :-

(i) The size of antenna is considerably reduced when designed on YIG ferrite. This remarkable reduction in size of array geometry would certainly have wide utility to create miniaturization of antenna system, which has potential application in space communication as well as in cellular communication.

(ii) The splitting and steering of main beam into number of intensified beams can be observed with the application of ferrite substrates, which in turn shifts the position of principal maxima and secondary maxima on changing the progressive phase excitation difference.

(iii) Due to scanning effect the array geometry provides a low value of side lobe level (SLL) about –9.5 dB for $\beta_x = \beta_y = \pi/4$, which is also an essential requirement with considerable importance in many applications [10].

It can be concluded that the 4 x 4 planar circular patch microstrip array printed on YIG ferrite substrate has novel characteristics. It is shown that the bandwidth and directive gain is strongly dependent on the progressive phase excitation difference between the elements. The highest of bandwidth and directive gain is obtained for $\beta_x = \beta_y = \pi/4$.

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