Beam Squint Using Integrated Gyrotropic Phase Shifter

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Abstract − Gyrotropic planar phase shifters are widely used to control the radiation properties of phased array antennas. The design and performance of a microstrip array antenna with integrated ferrite phase-shifter are described. Calculated tunable differential phase shift and simulated beam scanning properties of the linear phased array antenna are presented and corroborated with measured results.

I. INTRODUCTION

The revolution in PCB techniques and the recent availability of low loss and commercially viable microwave ferrites have renewed the interest in printed antennas on ferrite substrate. When magnetized, ferrite substrates offer greater agility in controlling the beam steering and pattern shaping characteristics of the microstrip array antennas [1, 2]. The high dielectric constant of the ferrite brings a reduction in the antenna dimension [3] and the inherent anisotropy and non-reciprocal behavior of this media is often used to achieve frequency tuning and polarization diversity [4]. In this paper, a microstrip array antenna with integrated phase shifter is realized on a transversely magnetized planar ferrite substrate. Tunable progressive phase shift is achieved by varying the magnetic bias that changes the permeability of ferrite material, which in turn changes the phase velocity, hence, the insertion phase of the propagating microwave signal. Analytical methods are used to calculate the tunable differential phase shift of the microstrip phase shifter, integrated with the four-way Wilkinson type array feeder. Commercial CAD software is used to analyze the impedance matching and the beam scanning properties of the designed microstrip linear phased array antenna. The simulated responses are verified using the measured results, obtained from a vector network analyzer and an antenna measurement system.

II. METHOD OF ANALYSIS

The parallel plate waveguide has long been used to study the electromagnetic wave propagation in planar microstrip structures [3]. An analytical method is used here to predict the phase shift properties of an externally magnetized ferrite filled parallel plate waveguide. In the presence of a transversely applied biasing magnetic field, the gyromagnetic behavior of ferrite material is described by its tensor permeability,

$$[\mu_r] = \begin{bmatrix} \mu & 0 & -j\kappa \\ 0 & \mu_z & 0 \\ j\kappa & 0 & \mu \end{bmatrix} \qquad (1)$$

where

$$\mu = 1 + \frac{\gamma^2 (H_0 - MN) M}{\gamma^2 \left(H_0 - MN\right)^2 - f^2}, \qquad \kappa = \frac{\gamma M f}{\gamma^2 \left(H_0 - MN\right)^2 - f^2} .$$

The symbol 'H_0' is the external biasing field, 'f' is the signal frequency, 'γ' is the gyromagnetic ratio, 'M' is the magnetization, and 'N' is the demagnetization factor of the planar (μ_z=1) ferrite material. Thus, for a lossless and transversely (y-directed) magnetized ferrite filled parallel plate waveguide, substituting the tensor permeability ($[\mu_r]$) and the boundary conditions into Maxwell's equation, the derived characteristic equation can be written as,

$$\frac{-\beta^2 + K_0^2 \varepsilon_r}{-\beta^2 + K_0^2 \mu \varepsilon_r} \left\{ -\beta^2 \mu + K_0^2 \mu \varepsilon_r \mu_{eff} \right\} = \left\{ \left(2m+1\right) \frac{\pi}{d} \right\}^2 \qquad (2)$$

where, '$2d$' is the separation between plates, '$K_0 = \omega\sqrt{(\mu_0 \varepsilon_0)}$', '$\mu_{eff} = (\mu^2 - \kappa^2)/\mu$' and '$m$' determines the mode of operation. Since the resonance conditions in magnetized ferrites are associated with singular value of effective permeability ($\mu_{eff} \rightarrow \infty$), this analysis is restricted to modes operating at magnetic bias below resonance region.

III. DESIGN AND RESULTS

The phase-constant (β) and the external bias field (H_0) solution of equation (2) is plotted in Fig. 1, for a ferrite filled parallel plate structure. Note the sharp changes in the insertion phase near the resonance region, where β can be tuned significantly by slightly varying the biasing field. While designing the ferrite based microstrip integrated array feeder, Pucels analytical expressions [5]

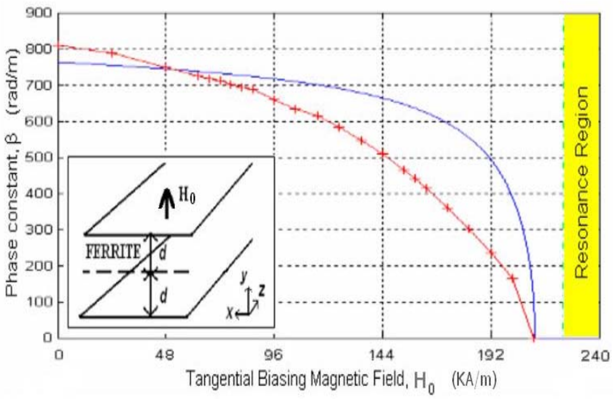
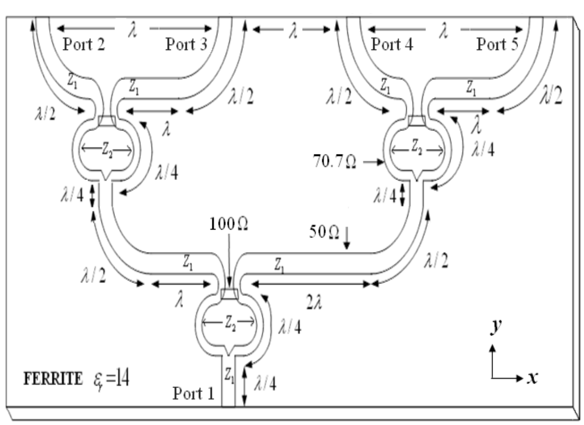


Fig. 1. Tunable phase constants for parallel plate waveguide filled with transversely magnetized ferrite at *f*=10GHz. (*M_s=63 KA/m, ε_r=14, ΔH=10 Oe, d=0.2mm).*

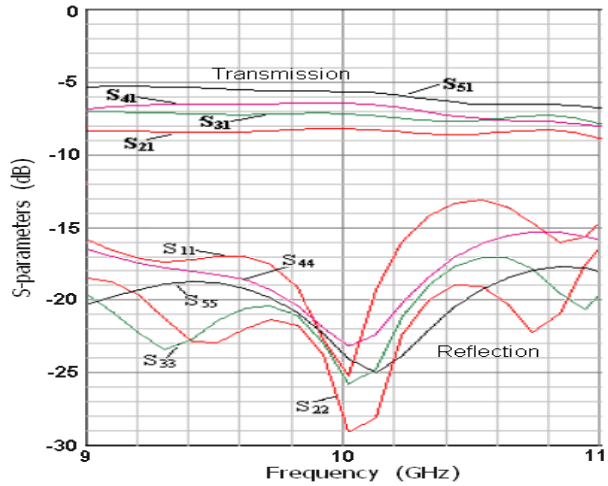
are used to calculate the required microstrip parameters. Figure 2 (a) shows the integrated array feeder, designed to provide 360° progressive phase shift on an unbiased (H_0=0 KA/m) ferrite substrate. The spacing in x-axis is carefully selected to provide adequate space for realizing radiating patches that generate a broadside radiation.

The scattering parameters of the array feeder are plotted in Fig. 2 (b). Note that the reflection (S_{11}, S_{22}, S_{33}, S_{44}) and isolation (not shown) parameters exhibit acceptable responses (below -20dB), whereas the transmission parameters (S_{21}, S_{31}, S_{41}, S_{51}) display unequal amplitudes of the patch excitation signals. Since the excitation amplitudes also depend on the external biasing field, this apparent disadvantages of the ferrite substrate can be exploited to design a non-uniform phased array antenna, which requires a different excitation amplitude and phase for each radiating element.

Figure 3 superimposes the simulated and experimental reflection responses ($|S_{11}|$) of the 4-element linear array antenna based on dielectric-ferrite composite substrate. The picture of the fabricated antenna is also shown in the inset of Fig. 3.



(a)



(b)

Fig. 2. (a) Ferrite based integrated array feeder to provide 360° progressive phase shift. (b) Reflection and transmission responses of the 4-port array feeder.

Note that a quarter wavelength transformer is used to match the impedance of the radiating patches with array feeder. Although the array antenna is designed to operate at 10 GHz, the discrepancy between these responses is mainly due to computational and fabrication related limitations. Since basic microstrip array is inherently a narrow band device, the impedance bandwidth for the designed antenna array is observed to be 6.5%. The radiation properties of the antenna also exhibited acceptable responses, such as, gain of 14 dB, beam-width of 28° and main-to-side lobe ratio of -16 dB.

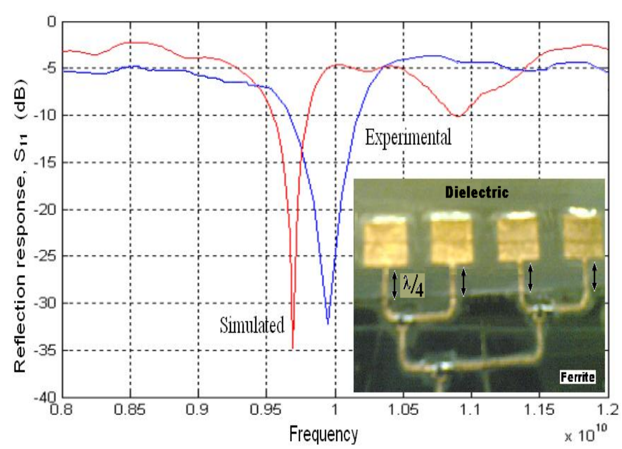
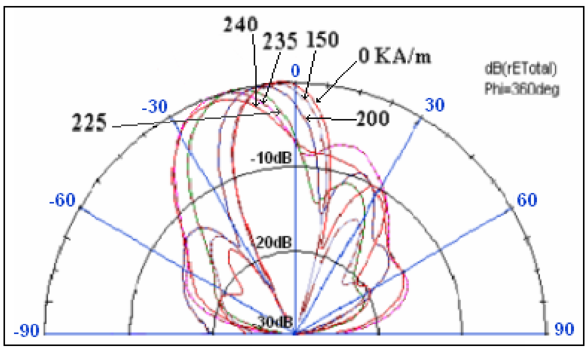


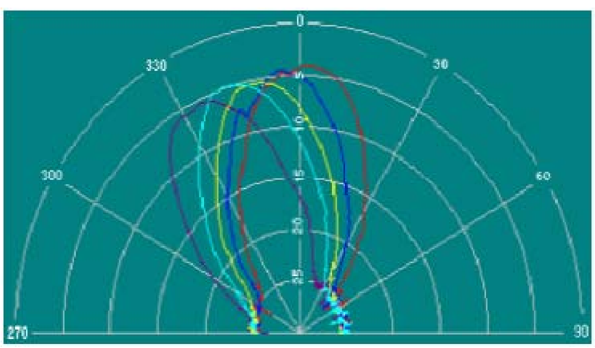
Fig. 3. Simulated and experimental reflection responses of the un-magnetized 10 GHz, 4-element composite linear array antenna (shown in the inset of the figure).

The beam scanning properties of the array antenna is shown in Fig. 4. The simulated angles of the squinted main beam for six different magnetic biases are shown in

Fig. 4 (a), and related measured results are shown in Fig. 4 (b). Note that for magnetic biases up to 150 KA/m, the main beam is steered by a very small angle ($\approx 3^0$). But, when the biasing field is increased from 200 KA/m to 240 KA/m, the main beam is observed to squint by 23^0, where the beam directions are observed at -7^0, -14.5^0, -19.7^0 and -22.5^0 degrees for external basing fields of 200 KA/m, 225 KA/m, 235 KA/m and 240 KA/m, respectively. Although increasing magnetic fields produces sharp beam scanning, it also biases the ferrite material close to lossy ferrimagentic resonance. So a compromise is essential between the acceptable losses and the required sharp changes in progressive phase shift that leads to larger angle of the beam squint.



(a)



(b)

Fig. 4. (a) Simulated and (b) Measured radiation response of the ferrite based 4-element linear array for six specific external magnetic bias (in y-axis).

IV. CONCLUSION

A linear phased array antenna based on composite dielectric-ferrite substrate is presented. The tunable insertion phase of the integrated microstrip phase shifter is investigated. Steep phase variation is observed near ferromagnetic resonance region, although the amplitudes of the patch excitation signals are observed to be unequal. The radiation response demonstrated significant beam squint for a small variation of magnetic bias and without major degradation of the antenna properties.

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REFERENCES

[1] J. C. Batchelor, *et. a.l*, “Scanned microstrip arrays using simple integrated Ferrite phase shifters,” *IEE Proc. Microwave Antennas Prop.*, vol. 147, no. 3, pp. 237-241, 2000.

[2] A. Henderson and J. R. James, “Magnetized microstrip antenna with pattern control,” *Electronics Letter*, vol. 24, no. 1, pp. 45-47, 1988.

[3] D. M. Pozar, “Radiation and scattering characteristics of microstrip antennas on normally biased ferrite substrates,” *IEEE Trans. Antennas Propagation*, vol. 40, no. 9, pp. 1084-1092, 1992.

[4] P. J. Rainville and F. J. Harackiewiz, “Magnetic tuning of a microstrip patch antenna fabricated on a ferrite file,” *IEEE Microwave and Guided Wave Letters*, vol. 2, pp. 483-485, 1992.

[5] R. A. Pucel and D. J. Masse, “Microstrip propagation on magnetic substrates- Part1: design theory,” *IEEE Trans. Microwave Theory and Tech.*, vol. 20, no. 5, pp. 304-308, 1972.

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