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Magnetically Scannable Leaky Wave Antenna

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Abstract

This paper discusses the electronically scanning characteristics of a Leaky-Wave Antenna by means of controlling the real part of the leaky-mode complex longitudinal propagation constant at a fixed frequency. The structure is based on a standard rectangular waveguide section with a series of slots cut along its broad wall and loaded with a transversely-magnetized ferrite slab parallel to the narrow wall and extending along the full height of the guide. The beam steering in this configuration is achieved by a combination of two mechanisms namely the variation of the internal magnetization of the ferrite slab and its position. A rigorous theoretical analysis of the electromagnetic field propagating inside the loaded waveguide is followed. By numerically solving the transcendental equation for the leaky-mode phase constant of such LWA the associated propagating modes can be obtained. A parametric analysis of the permeability tensor and the position of the slab shows a ~50° beam deflection from near broadside toward ± endfire direction. The relevant radiation patterns are also calculated proving the scanning performance of the antenna. A good input match (<-30dB) was observed for the different positions of the ferrite slab.

1. Introduction

Leaky wave antennas (LWA) exhibit interesting characteristics such as inherent fast frequency-scanning response, high directivity and large bandwidth [1-5]. These features make them excellent candidates for modern wireless communication systems. It is common for LWAs to be realized using conventional waveguides where some cuts has been performed to allow the energy to leak as the wave is propagating along its longitudinal direction [1-2]. In this sense, LWAs are a type of traveling wave antennas. For a general understanding of the radiating mechanism of LWAs the propagation wave number of the leaky-mode is studied [3-4]. Due to the leakage, this is complex with a phase constant β (imaginary part), and a leakage constant α (real part). By controlling α and β of the leaky-mode one can engineer their radiation pattern and frequency-scanning performance [4-5].

Despite of these advantages, for several applications such as i.e. satellite communications systems, where a narrow frequency band is required, a LWA with a fixed-frequency of operation is most desirable. In this sense, other scanning mechanisms need to be considered. Several authors have proposed the use of composite right- and left-handed (CRLH) metamaterials with some sort of reconfigurable mechanism [6] including ferrite structures [7-8], ferroelectric (FE) substrates [9], tunable composites [10] and/or metasurfaces [11].

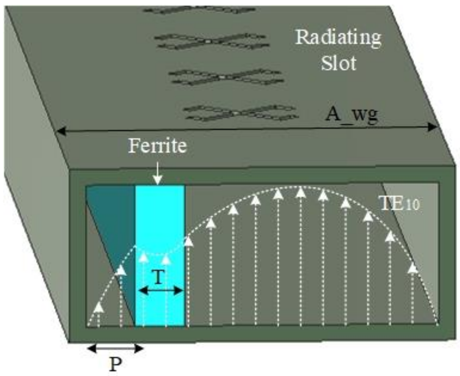

Figure 1. Slotted Leaky-wave Antenna (LWA) loaded with a transversely-magnetized ferrite slab together with their equivalent TE_{01} electric field mode lines.

In this work, the effect of loading a LWA based on waveguide technology with a ferrite slab is revisited. A standard rectangular waveguide (RWG) section with a series of slots cut along its broad wall is taken as an example. The RWG is loaded with a transversely-magnetized ferrite slab parallel to the narrow wall and extending along the full height of the guide. The waveguide and the slab are assumed to be lossless. The permeability tensor can be easily controlled through the use of a dc magnetic bias field, which changes the resonant frequency of ferrite (i.e. permeability properties). The position of the ferrite slab also alters the dispersion of the leaky-mode inside the waveguide. Both effects are combined for the first time in order to increase the beam steering capability of the structure in Figure 1, from near broadside towards ± end-fire.

2. Theoretical Analysis of a Rectangular Waveguide loaded with a ferrite slab

In the next section a rigorous theoretical analysis of the TE_{m0} modes propagating inside the loaded waveguide is presented. The structure in Figure 1 is considered where P can be varied. In the ferrite slab Maxwell's equations can be written as:

$$\nabla \times \vec{E} = -j\omega[\mu]\vec{H}$$
$$\nabla \times \vec{H} = j\omega\varepsilon\vec{E} \qquad (1)$$

where $[\mu]$ is the permeability tensor of Polder for $\hat{y}$ bias and calculated as shown in (2).

$$[\mu] = \begin{bmatrix} \mu & 0 & -j\kappa \\ 0 & \mu_0 & 0 \\ j\kappa & 0 & \mu \end{bmatrix} \qquad (2)$$

The elements of the permeability tensor refer to the permeability of the ferrite material with $\kappa = j\mu_0 \frac{\omega\omega_m}{\omega_0^2-\omega^2}$ where ω_m is the *gyrotropic* frequency, ω_0 is the *Lamor* frequency and $\mu_0 = 4\pi 10^{-7}$. Considering the two-dimensional structure of Figure 1, it can be seen that the transverse electric (TE) mode exhibits sensitivity to the dc magnetic field. For TE_{m0} modes it is known that E_z=0 and $\frac{\partial}{\partial y} = 0$, we will treat this mode with field components H_x, H_z, and E_y. From (1) the expression of the wave equation for E_y in the air region as well as within the ferrite slab can be found in terms of the cut-off wavenumber in air and in the ferrite slab respectively (3).

$$\left(\frac{\partial^2}{\partial x^2} + k_f^2\right)E_y = 0 \quad k_f^2 = \omega^2\mu_{eff}\varepsilon - \beta^2$$
$$\left(\frac{\partial^2}{\partial x^2} + k_a^2\right)E_y = 0 \qquad k_a^2 = k_0 - \beta^2 \qquad (3)$$
$$H_z = \frac{j}{\omega\mu\mu_{eff}}\left(\kappa\beta E_y + \mu\frac{\partial^2 E_y}{\partial x^2}\right)$$

where $\mu_{eff} = \frac{(\mu^2-\kappa^2)}{\mu}$ and k_a and k_f are the horizontal eigenvalues in the air and ferrite regions. By matching E_y and H_z at the boundaries (i.e. x=P and x=P+T) as well as enforcing the boundary condition at the walls of the waveguide (i.e. x=0 and x=A_wg) a transcendental equation for the propagation constant, β, can be found (4).

$$\begin{aligned} \boldsymbol{A}^2 + \boldsymbol{B}^2 - \boldsymbol{C}cot(k_aP)\left(\boldsymbol{A}cot(k_fT) + \boldsymbol{B}\right) \\ - \boldsymbol{C}^2cot(k_aP)cot(k_fH) \\ - \boldsymbol{C}cot(k_aH)\left(\boldsymbol{A}cot(k_fT) - \boldsymbol{B}\right) \\ = 0 \end{aligned} \qquad (4)$$

Here $A = \frac{k_f}{\mu_{eff}}$, $B = \frac{\kappa\beta}{\mu\mu_{eff}}$, $C = \frac{k_a}{\mu_0}$ and $H = A_{wg} - (P+T)$ and can easily be solved numerically.

3. Dispersion analysis

In the following, the imaginary part of the complex longitudinal propagation constant (phase constant) of the excited leaky-wave mode in the antenna is determined. According to the well-known leaky-wave scanning law Eq. (5), this antenna scans the entire space in the *yz* plane as ω varies from $-k_0/c$ to $+k_0/c$. From the phase, the angle of maximum radiation, θ_m, (measured from the broadside direction) can be approximately determined using (5)

$$sin\left(\theta_m(\omega)\right) = \frac{\beta(\omega)}{k} \qquad (5)$$

Without loss of generality, here a ferrite slab of $Y_3Fe_5O_{12}$ (Yttrium iron garnet) with thickness 1.5mm is used. The slab characteristics are: $4\pi M_s$~1800G, where M_s is the saturation magnetization), $\omega_0=\gamma\mu_0 H_0$ where H_o is the static magnetic field and γ is the gyromagnetic ratio of the electron ($\gamma=1.759x10^{11}$ C/Kg). The ferrite slab is positioned within a standard empty waveguide WR-42 and the position varies from 0 (i.e. ferrite slab against the vertical wall of the waveguide) to a maximum of 2.5mm. By solving the transcendental equation (4), the leaky-wave modes associated to this structure are determined. Figure 2 show the phase constant of the leaky-wave mode vs. frequency for different values of the relative permeability of the ferrite slab and position. As can be seen, as the permeability increases the value of β increases. In fact, higher values of the permeability will cause the phase velocity of the propagating mode to decrease which in turn causes the value of β to increase. Conversely, as the ferrite slab is moved closer to the center of the waveguide the phase constant decreases. The distortion of the microwave fields in the presence of the ferrite material is sketched in Figure 1 for position P. The distortion increases sharply with increasing P. In the limit P~A_wg the field intensity will decrease rapidly outside the ferrite. A combination of both effects can be carried out in order to obtain a larger range of variation in β and therefore a larger scanning angle of the antenna. For this example the range of β correspond to 117-369.3 rad/m at 22GHz.

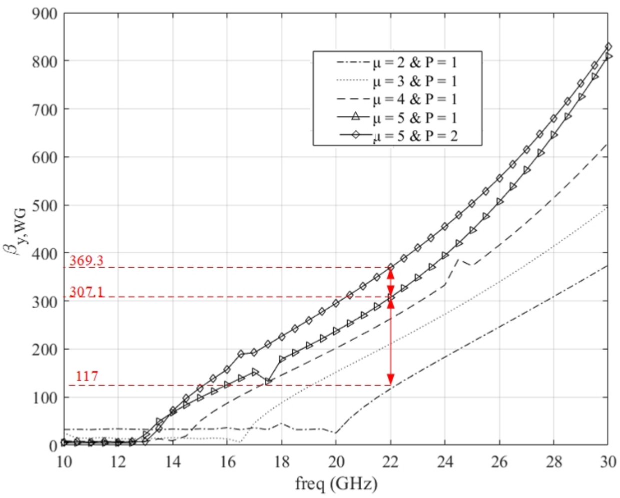

Figure 2. Frequency dispersion curve for the LWA depicted in Figure 1 for varying permeability (μ_r=1 to 5) and varying position (P=1 to 2.5mm).

4. Radiation Pattern of LWA

In the following, the effective radiation in the presence of a real source and considering the permeability tensor in (2) is analyzed next. The normalized radiation patterns of the antenna illustrated in Figure 1 for the two limit scanning angles corresponding to μ_r=5 and P=1mm and μ_r=2 and P=2.5mm at 22GHz are shown in Figure 3. Here can be seen that by simply modifying the applied external field to the ferrite slab, to achieve the required permeability, and the position of the slab we are able to scan the antenna beam from near broadside toward $\pm$ endfire direction.

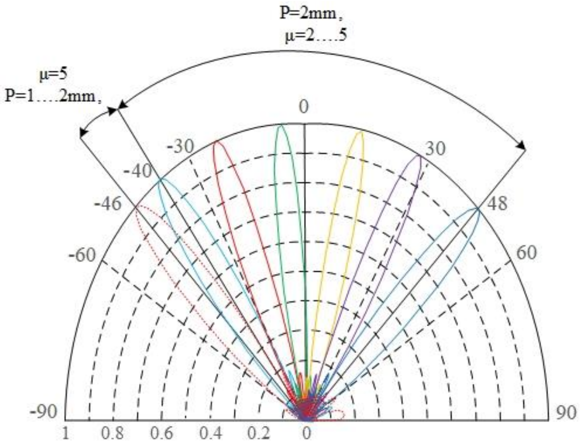

Figure 3. Radiation pattern for the LWA depicted in Figure 1 for varying permeability (μ_r=2 to 5) and varying position (P=1 to 2.5mm).

As a representative example the reflection coefficient of the LWA depicted in Figure 1 when the ferrite slab is positioned at P=1mm and μ_r=2 is shown in Figure 4. The antenna is well match at the frequency of interest with S11~-30dB.

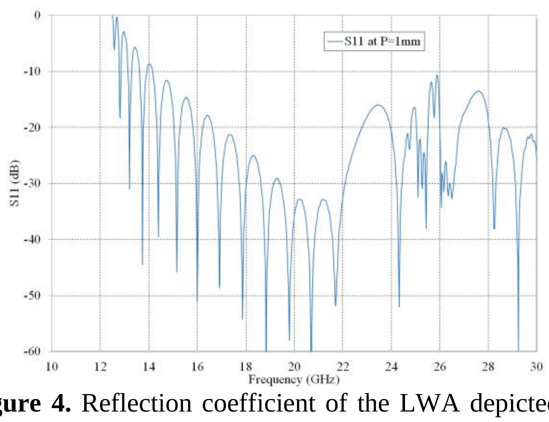

Figure 4. Reflection coefficient of the LWA depicted in Figure 1 for P=1 and μ_r=2.

5. Conclusions

The study presented in this paper includes the radiation properties of leaky-wave antennas based on ferrite loaded waveguide technology. Initially the theoretical analysis corresponding to such structure is presented. Due to the non-reciprocal properties of ferrites, it has been shown that practical isotropic sources can give unidirectional pointed beams that are scannable by varying the magnetization in wide angular ranges. A scanning range of $\pm$50° at 22GHz

6. References

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