Leaky-Wave Centerline Longitudinal Slot Antenna Fed by Transversely Magnetized Ferrite

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We propose a leaky-wave slot antenna that consists of a longitudinal slot cut into the broad wall center of a ferrite-filled rectangular waveguide. The centerline longitudinal slot is excited by the TE_{10} mode of transversely magnetized ferrite waveguide, which has anti-symmetric surface current density. The electromagnetic behavior of this antenna is studied and validated numerically by the finite-element method. It is shown that the beam direction of the proposed antenna at the fixed frequency can be scanned by bias magnetic field that is attractive in such radar and measurement systems. Compared with previous work, the fabrication requirements on this structure are not critical, which enhances its potential applicability.

Index Terms—**Beam-scanning antenna, ferrite-loaded antenna, leaky-wave antenna (LWA), slot antennas.**

I. Introduction

LEAKY-WAVE antenna (LWA) is one of the common antennas used in aerospace and civilian applications. It exhibits interesting features due to its traveling-wave nonresonant nature, such as frequency beam-scanning capability and high directivity. An LWA is basically a waveguiding structure that the energy constantly leaks out when it operates in the fast-wave region ($\beta < k_0$), where β is the waveguide phase constant and k_0 is the free-space wavenumber.

The most popular structure of LWA is a rectangular waveguide with some kind of slots along its walls, for example, the straight slot that is longitudinally placed on the broad wall of the waveguide with an offset from centerline [1]. The most significant drawback of this structure is the high sidelobe level that has been solved by the multitude of techniques, such as replacing of straight slot by meandered slot [2] or tapered slot [3], and using of a ridge in the waveguide [4]. However, these techniques complicate the fabrication process.

In this paper, we present a novel leaky-wave slot antenna that consists of a normally magnetized ferrite-filled rectangular waveguide with a long slot in the center of its upper broad wall without any offset. The idea here is to excite the centerline slot in the fast-wave region using the TE_{10} mode of transversely magnetized ferrite waveguide, which has anti-symmetric surface current density. As an advantage, the beam direction of the proposed LWA can be easily scanned by changing the bias magnetic field, while in the most previous work, the capability of beam scanning is realized by a phased array structure, which suffers from high cost and large size due to the existence of expensive phase shifters [5]. Furthermore, due to slot placing at the center of wall without any offset, the sidelobe level of the proposed LWA is lower than the conventional LWA.

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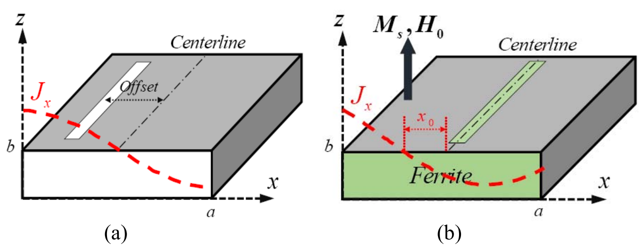


Fig. 1. (a) Geometry of the conventional straight longitudinal slot. (b) Geometry of the proposed centerline slot. Dashed red lines: surface current distribution of upper wall, J_x, in $y = 0$ plane.

It must be noted that the applications of ferrite material in slot antennas have been known to possess other useful properties, such as frequency tunability [6] and size reducing [7]. In addition, a ferrite slab has been used for the radiation beam steering of a waveguide slot array [8]. However, due to the resonant nature of this antenna, the scanning region is not wide enough.

The paper is organized as follows. Section II outlines the operation principle of a centerline slot on normally magnetized ferrite waveguide. The radiation behavior of this slot as an LWA is also described in this section. In Section III, the theory of Section II is validated by full-wave simulations, and the results are discussed.

II. Theory

A. Centerline Longitudinal Slot on Transversely Magnetized Ferrite-Filled Rectangular Waveguide

When the only dominant mode is excited in an empty rectangular waveguide, the transverse surface current density on the upper broad wall is given by [9]

$$J_x = A \cos\left(\frac{\pi}{a}x\right) \cdot e^{-j\beta y} \tag{1}$$

where A is a constant, β is the propagation constant of dominant mode, and a is the waveguide width.

As shown in Fig. 1(a), because the current distribution, J_x, has centerline symmetry in x-direction, only the longitudinal slot with an offset from centerline can radiate.

However, this offset leads to an anti-symmetric radiation for this conventional slot and increases the sidelobe level [1], [2].

Fig. 1(b) shows the antenna proposed in which a slot is etched on the upper wall center of a ferrite-filled rectangular waveguide. The ferrite is magnetized normal to the slot plane by a dc bias magnetic field H_0, which can be provided by a permanent magnet placed underneath the waveguide, where the interference with the antenna is negligible. To investigate this slot antenna, we first review the properties of the waveguide in the absence of the slot. The primary propagating mode of a rectangular waveguide, fully filled with a transversely magnetized ferrite material, is the TE_{10} mode where the modal electric and magnetic fields are, respectively, given by [10], [11]

$$\boldsymbol{E} = A_{10} \sin\left(\frac{\pi x}{a}\right) e^{-j\beta_{10} y} \hat{\boldsymbol{z}} \tag{2a}$$

$$\begin{aligned}\boldsymbol{H} = & \frac{A_{10}}{\omega\mu_0\mu_\perp}\left[\beta_{10}\sin\left(\frac{\pi x}{a}\right) - \frac{\pi}{a}\frac{\mu_a}{\mu}\cos\left(\frac{\pi x}{a}\right)\right] e^{-j\beta_{10} y}\hat{\boldsymbol{x}} \\ & + \frac{jA_{10}}{\omega\mu_0\mu_\perp}\left[\beta_{10}\frac{\mu_a}{\mu}\sin\left(\frac{\pi x}{a}\right) - \frac{\pi}{a}\cos\left(\frac{\pi x}{a}\right)\right] e^{-j\beta_{10} y}\hat{\boldsymbol{y}}.\end{aligned} \tag{2b}$$

Here, A_{10} is a constant, and μ_0 is the permeability of vacuum, and

$$\begin{aligned}\mu &= 1 + \frac{\omega_H \omega_M}{\omega_H^2 - \omega^2} \\ \mu_a &= \frac{\omega_M \omega}{\omega_H^2 - \omega^2}\end{aligned} \tag{2c}$$

denote the diagonal and off-diagonal elements of the permeability tensor of the ferrite, respectively, where

$$\omega_H = \gamma H_0, \quad \omega_M = \gamma M_s \tag{2d}$$

with M_s the saturation magnetization of the ferrite and γ the gyromagnetic ratio. Moreover

$$\mu_\perp = \mu - \frac{\mu_a^2}{\mu} = \frac{(\omega_H + \omega_M)^2 - \omega^2}{\omega_\perp^2 - \omega^2} \tag{2e}$$

where

$$\omega_\perp = \sqrt{\omega_H(\omega_H + \omega_M)}. \tag{2f}$$

Note that the TE_{10} field components do not change in the vertical (z-direction) and propagate along the guide (y-direction) with the constant [11]

$$\beta_{10} = \sqrt{\omega^2 \varepsilon_0 \varepsilon \mu_0 \mu_\perp - \frac{\pi^2}{a^2}} \tag{3}$$

where ε_0 and ε are the permittivity of vacuum and the relative permittivity of ferrite material, respectively.

The surface current density on the upper guide wall, J_s, is related to magnetic field intensity by

$$\boldsymbol{J}_s = \hat{\boldsymbol{z}} \times \boldsymbol{H} = J_x \hat{\boldsymbol{x}} + J_y \hat{\boldsymbol{y}}. \tag{4}$$

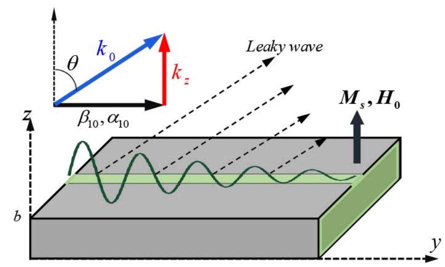


Fig. 2. Schematic of the proposed LWA.

By the substitution of (2b) in (4), the transverse surface current density in the upper wall is calculated as

$$\begin{aligned} J_x &= \frac{-jA_{10}}{\omega\mu_0\mu_\perp}\left[\beta_{10}\frac{\mu_a}{\mu}\sin\left(\frac{\pi x}{a}\right) - \frac{\pi}{a}\cos\left(\frac{\pi x}{a}\right)\right] e^{-j\beta_{10} y} \\ &= \frac{-jA_{10}}{\omega\mu_0(\mu^2 - \mu_a^2)}\rho_0 \cos\left[\frac{\pi(x - x_0)}{a}\right] e^{-j\beta_{10} y} \end{aligned} \tag{5}$$

where

$$x_0 = \frac{-a}{\pi}\arctan\left(\frac{\beta_{10} a \mu_a}{\pi\mu}\right) \tag{6}$$

$$\rho_0 = \sqrt{(\beta_{10}\mu_a)^2 + \left(\frac{\pi}{a}\mu\right)^2}. \tag{7}$$

As shown in Fig. 1(b), the current distribution at the upper wall of the ferrite rectangular waveguide, given by (5), is deviated from the center, so that the centerline longitudinal slot interrupts the flow of currents and couples the power from the waveguide modal field into the free space.

As a final point in this section, it must be mentioned that in all the above equations, the magnetic losses may be easily introduced by the replacement $\omega_H = \gamma H_0 + j\alpha\omega$, where α is the Gilbert damping constant [10], [11].

B. Leakage Radiation of Proposed Slot Antenna

Fig. 2 shows a schematic of the proposed slot structure as an LWA, where k_0 is the propagation constant in free space, β_{10} is the phase constant of ferrite-filled waveguide, and k_z is the propagation constant in z-direction. Moreover, α_{10} is the attenuation constant in direction of the waveguide, which accounts for the magnetic loss. Based on the theory of LWA, if the wave is slower than the velocity of light ($\beta_{10} > k_0$), k_z is imaginary and there is exponential decay along z. If in contrast the wave is faster than the velocity of light ($\beta_{10} < k_0$), k_z is real and there is propagation along z, which means that the leakage radiation occurs.

Fig. 3 shows the dispersion diagram obtained from (3) for a typical 20-mm-wide and 1-mm-high waveguide filled with yttrium iron garnet (YIG) ferrite material subject to a dc bias magnetic field of 1200 Oe. The diagram clearly contains a fast-wave region between the cutoff frequency of TE_{10} mode (8.33 GHz) and the transition frequency (8.52 GHz), where $\beta_{10} = k_0$. This shows that the proposed centerline longitudinal slot antenna of Fig. 2 may be used as an LWA.

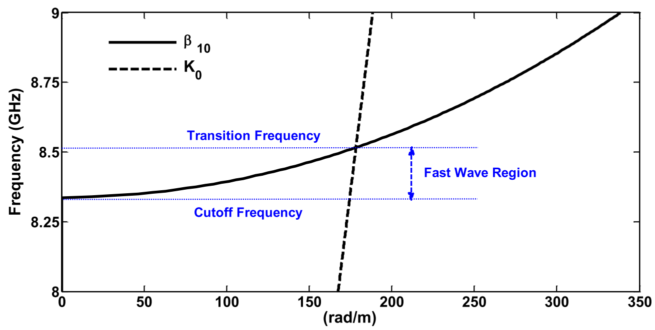
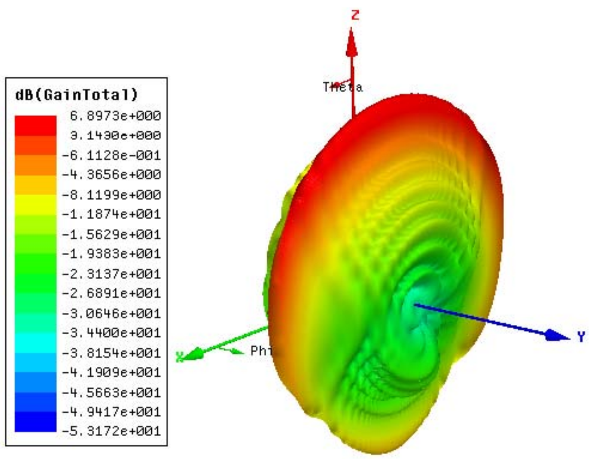
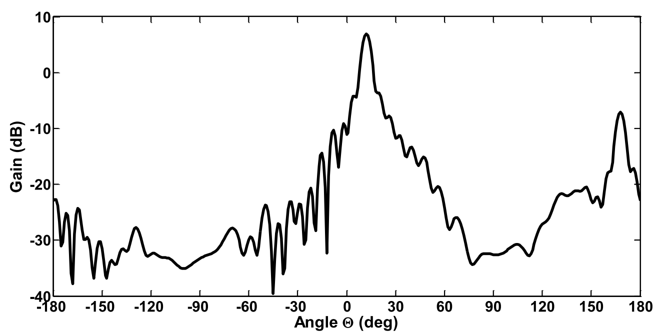


Fig. 3. Dispersion diagram calculated by (3) for typical waveguide filled with ferrite. $a = 20$ mm, $b = 1$ mm, $H_0 = 1200$ Oe, $4\pi M_s = 0.173$ T, and $\varepsilon = 15.3$.



(a)



(b)

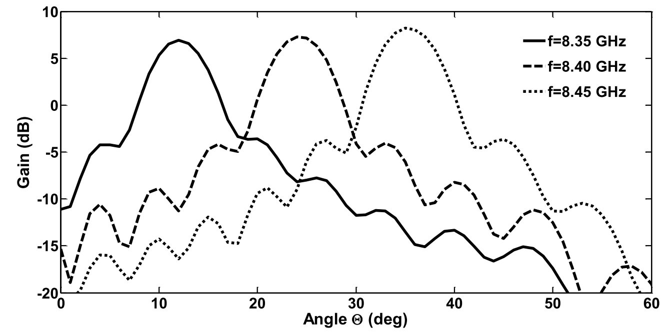
Fig. 4. Far-field radiation pattern of the proposed LWA at the frequency of 8.35 GHz. $a = 20$ mm, $b = 1$ mm, $H_0 = 1200$ Oe, $4\pi M_s = 0.173$ T, $\varepsilon = 15.3$, slot length = 400 mm, and slot width = 0.5 mm. (a) 3-D. (b) yz-plane.

With the assumption of small attenuation α_{10}, the main beam of LWA is pointed at the angle [12]

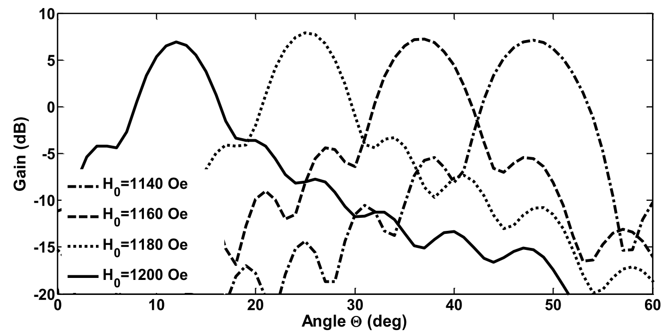
$$\theta = \arcsin\left(\frac{\beta_{10}}{k_0}\right) \tag{8}$$

where β_{10}, given by (3), has bias and frequency dependence. It means that both of the fixed-frequency bias-tuned scanning and fixed-bias frequency-tuned scanning are available in this antenna without requiring any complex phase shifter [5] or chip varactor [13]. This decreases the cost and the complexity of the fabrication process.

It is important to note that the leakage factor α_{10}, which associated with magnetic loss α, represents the amount of radiated power per unit length. If α_{10} is small, the structure must be made long before all the power has leaked out of it; therefore, the radiation aperture is large and high-directivity is obtained. In practice, an LWA is usually designed, so that its value of leakage factor allows ∼90% of the power to be radiated. The remaining power is absorbed by a matching load placed at the end of waveguide [12].



(a)



(b)

Fig. 5. (a) Frequency beam scanning and (b) magnetic bias scanning of the proposed LWA. The other design parameters are the same as given in the caption of Fig. 4.

III. Full-Wave Simulation Results and Discussion

To verify the theoretical results of the previous sections, the ferrite disk antenna of Fig. 2 is simulated by commercial software High Frequency Structural Simulator (HFSS), which utilizes the finite-element method. In all simulations, YIG ferrite with a saturation magnetization ($4\pi M_s$) of 0.173 T, magnetic line width ($\Delta H = 2\alpha\omega/\gamma$) of 5 Oe, and relative permittivity of 15.3 are used as the ferrite material. The other antenna parameters are given in the figure captions.

Fig. 4 shows the radiation pattern of the proposed LWA at the frequency of 8.35 GHz within the fast-wave region. As shown in Fig. 4, the radiation pattern is a fan beam pointed at the angle of 12°, where the analytical beam direction in (8) is 15.8°. The front-to-back ratio and sidelobe level are 10 and −16 dB, respectively. The back lobe observed is due to the use of a small waveguide width in the simulations and is decreased by increasing the width a. Compared with the conventional straight longitudinal slot reported in [1] and [2], the sidelobe level of the proposed LWA is better. This is just due to the placing of the longitudinal slot at the center of a wall in the proposed structure of Fig. 2.

Fig. 5 shows the main lobe of radiation pattern at fixed-bias versus frequency [see Fig. 5(a)] and fixed-frequency versus bias [see Fig. 5(b)], respectively. The possibility of both the frequency and bias scanning is clearly evident in these graphs.

IV. CONCLUSION

In this paper, we present a novel LWA that consists of a centerline longitudinal slot cut into upper wall of normally magnetized ferrite-filled rectangular waveguide. Using field analysis of the magnetized ferrite waveguide, radiation parameters have been calculated and validated numerically. The results obtained demonstrate a fan beam radiation pattern, which can be scanned by bias magnetic field. Compared with the conventional leaky-wave slot antenna, this structure is compact, is easy to design and fabricate, and has low sidelobe level. As such, it can be a good candidate for realizing the radiation beam scan in measurement systems, such as radars.

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