PROPAGATION AND RADIATION CHARACTERISTICS OF GYROTROPIC OPEN STRUCTURES IN THE PRESENCE OF SOURCES

Paolo Baccarelli, Carlo Di Nallo, Fabrizio Frezza, Alessandro Galli, and Paolo Lampariello

Electronic Engineering Department - “La Sapienza” University of Rome, Italy

Abstract

In this work a comprehensive investigation is carried out for a significant class of open structures with gyrotropic substrates concerning the effective capability to propagate and radiate power in the presence of suitable feeders. In our previous analyses of such structures [1,2], various situations were identified where peculiar nonreciprocal propagation and radiation behaviors could occur. On this ground, we wish to emphasize here important aspects of the excitation problem (e.g., the directional features of the radiation, gain and efficiency, etc.), which can affect the practical performance of the components. Thus, by means of new powerful and simple theoretical procedures, it is possible to develop fundamental investigations that provide qualitative and quantitative information in order to use such devices either as waveguiding structures or as leaky-wave type radiators.

I. Introduction

As is known, anisotropic media such as ferrites enrich the possibilities of achieving uncommon electromagnetic behaviors, allowing anisotropic and nonreciprocal waveguiding [3-5] or radiative [6,7] performances.

In our previous analyses [1,2], original and interesting phenomena have been emphasized as regards the guiding and the radiative effects in basic topologies showing nonreciprocal characteristics, such as a transversely-magnetized ferrite layer on a ground plane (see, as a reference, Fig. 1 of [1,2]).

In this case, some exotic behaviors have been found in certain situations due to the particular anisotropic properties of propagation and radiation. Specific regions of interest have been identified, where the effective permeability assumes rather low values (less than unity) and, for suitable choices of the physical parameters involved, both guided and radiated powers show strong nonreciprocal features. It has also been shown that these effects could be explained efficiently by evaluating the dispersion behavior of an ‘anomalous’ mode having complex characteristics [1,2] (see Fig. 2 of [2]).

Even though these original features are undoubtedly attractive, the possibility of advantageous applications has carefully to be evaluated in practice. The present analysis is therefore focused on the ‘realistic’ aspects related to the use of such structure in the presence of feeding elements: i.e., the effective excitation of guided and radiated power in connection with the source location, the efficiency of radiation, the capability of reaching high directivity, the dramatic influence of ohmic losses, and so forth. The simple but rigorous theoretical procedures introduced here, in conjunction with the quantitative results achieved, give precious knowledge for the practical use of these anisotropic substrates in waveguiding or radiating components.

II. Background: propagation and radiation features of the structure

We will then focus our attention on the basic gyrotropic structure consisting in a simple grounded ferrite slab (‘GFS’) of width *w*, transversely biased by a magnetostatic field in the same direction of a current line source of strength J_o (two-dimensional problem). The basic structure and the operation conditions considered here are still those ones presented in Fig. 1 of [1,2], where also the medium parameters can explicitly be found.

For suitable choices of the parameters involved, as those ones fixed in [1,2], the nonreciprocity effects can be found first in a unidirectional propagation that can occur in certain frequency ranges. Such guidance has various nonconventional properties with exotic forward/backward behaviors, as also visible from the dispersion curve of the proper real branch of the anomalous mode (Fig. 2 of [2]).

In these situations, for such an open structure, the radiative effects may anyway assume an outstanding importance. The accurate determination of the radiation characteristics requires the evaluation of the excitation problem due to the presence of the line source, achieved here through a suitable extension of the transmission-line formalism for nonreciprocal structures [8].

It has been noted that, when the other parameters are properly chosen, a frequency ‘window’ exists where a pointed-beam radiation is scannable continuously in wide angular ranges from one endfire to the other through broadside. We have also emphasized that the prediction of this unusual radiative feature is achievable in a simple and efficient way by examining carefully the nature of the complex solutions of the structure [2]: it can be seen that, in such situations, the radiation is strongly dominated by a single leaky-wave contribution. In particular, the so-called ‘forward’ radiation can be rephrased through the complex *improper* branch of the anomalous mode ($-1<\beta/k_o<0$ curve of Fig. 2 in [2]), while the so-called ‘backward’

0-7803-4471-5/98/$10.00 (c) 1998 IEEE

radiation can be rephrased through the complex *proper* branch ($0<\beta/k_o<1$ curve of Fig. 2 in [2]). The normalized phase and leakage constant are thus representative of the pointing angle and the beam width, so that the radiation characteristics may easily be predicted in terms of leaky waves.

The practical aspects related to the excitation problem involving both propagation and radiation effects in such structures will be examined in detail next.

III. Nonreciprocity and directivity of radiation

One fundamental property of the structure under investigation is that it is possible to reach quite narrow radiated beams that are scannable in wide angular forward/backward ranges with a simple isotropic line source placed in a single ferrite layer.

It should be reminded that such radiation presents nonreciprocal characteristics, that is for a fixed frequency the power is transmitted at a certain angle but is received from a direction that is symmetrical with respect to the broadside direction. This property has been confirmed quantitatively by considering the power transferred by an external elementary source placed at variable angles with respect to an internal receiving probe.

The possibility of achieving scannable narrow beams has been investigated here referring to a transverse-resonance approach [9,10], properly extended to nonreciprocal structures via [8]. In these cases the maximum voltage transfer from the incident wave is optimized considering the resonance condition as a function of the angle with a probe placed at the interface. Due to space limits, we prefer to avoid here any detailed description of the theoretical procedures developed in this case, just furnishing some main reference expressions that can immediately strengthen the physical understanding of the results achieved. The directional patterns are derivable on the basis of a formulation extending that one for the isotropic case; for the far-field amplitude of the electric field as a function of the observation angle θ we can write (neglecting a common contribution due to the cylindrical-wave factor):

$$\left|E_y(\theta)\right| = J_o Z_o \Big/ \sqrt{1+R^2 \big/ (\mu_e \cos\theta)^2}$$

$$R = \frac{\mu_2}{\mu_1}\sin\theta + \sqrt{n_e^2 - \sin^2\theta}\,\cot\!\left(k_o w \sqrt{n_e^2 - \sin^2\theta}\right),\ n_e = \sqrt{\varepsilon_r \mu_e}$$

where k_o and Z_o are the wavenumber and the characteristic impedance of vacuum, while the medium parameters have been reported in [1,2] Fig. 1.

The comparisons with an equivalent grounded dielectric layer with a standard isotropic magnetic characteristic show the notable improvement of the directivity for the GFS. The zeroing of the *R* factor gives the angular resonance condition (when the resonance condition is satisfied, as a function of different angles or frequencies, it is seen that the far-field amplitude assumes a fixed maximum value, given by $J_o Z_o$). The *R* factor is also responsible of the nonreciprocal transmitting/ receiving behavior: due to the anisotropic permeability terms (first addendum related to μ_2/μ_1), *R* assumes different values even for symmetrical direction with respect to broadside (since the angle θ changes its sign). The increasing of directivity for GFS may easily be interpreted through the presented equations, if we remind that in the region of interest the values of the effective permeability μ_e are substantially less than unity.

A typical result is represented here in Fig. 1. In a single-layer isotropic structure there is no effective possibility of focusing power, while very narrow pointed beams are achievable in the GFS, as optimized here for two different frequency values both in the forward and in the backward quadrant.

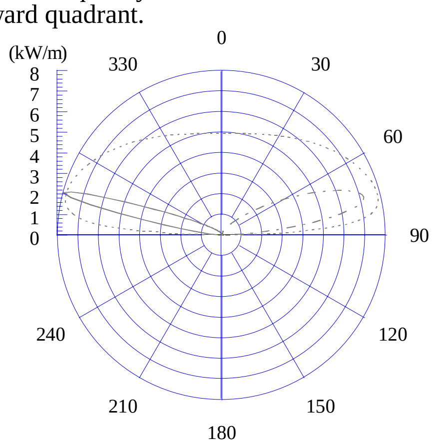

Fig. 1 - Directivity properties of the GFS compared to an equivalent isotropic structure: radiated power vs. observation angle in polar form. The two directional backward/forward beams for the GFS are chosen at ±75° (with respect to broadside) at the frequencies of 11.36 and 12.65 GHz respectively (the equivalent grounded dielectric slab is optimized at 12.44 GHz).

In general, it is known that the directivity (i.e., the radiation intensity in a particular direction with respect to that one of an isotropic radiator) can be influenced by various factors (source location, etc.). A representative situation for the GFS is shown in Fig. 2, where the maximum of directivity is calculated as a function of frequency, for different source locations. Inside the radiation window, the directional properties appear not much dependent on frequency or, equivalently, on the pointing angle. Also the variations of directivity with the source position are rather limited here.

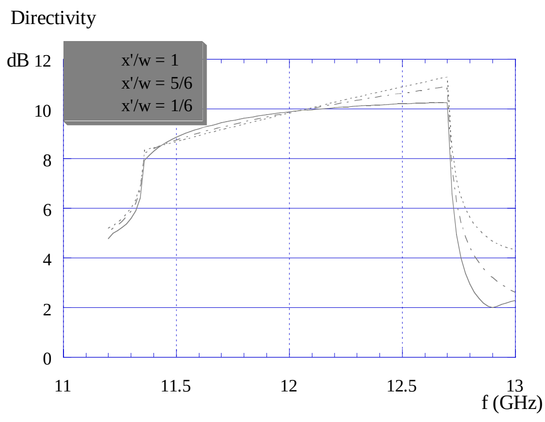

Fig. 2 - Directivity of the GFS as the frequency varies for a current-line excitation placed at different positions along *x*.

It is important to point out that the highly-directional features of the GFS can be explained well considering the leaky-wave contributions: in fact it results that, for low values of the effective permeability, the leaky wave strongly dominates the radiation. In this case, for wide angular ranges, there is an excellent agreement between the basic features of the radiated power (direction and width) as obtained through the resonance condition of the transmission-line method (see above equations, etc.) and the features of the forward/backward leaky-wave beam as obtained through the complex improper/proper wave-number as a function of frequency (the notable agreement concerning the calculation of the pointing angle against frequency in the two cases has been checked quantitatively).

It is interesting to note that a clear description of such propagation and radiation features can be achieved also by means of suitable ray optics considerations. In this case, by considering the transmission and the reflection of guided and leaky waves, suitable extensions have to be considered in connection with the intrinsic nonreciprocal nature of the problem: following the approach described in [8], reflection and transmission coefficients have been found whose expressions depend on the orientation of the propagation direction.

The choice of the physical parameters for a correct synthesis of these anisotropic radiators is much more complicated if compared to the isotropic cases. Anyway, it is seen that the procedures above outlined strongly facilitate the design of a structure acting as a leaky-wave antenna: simple criteria can be derived to properly choose the parameters involved in connection with specified requirements.

IV. Excitation of guided and radiated powers: gain and efficiency

In addition to these aspects, the actual possibility of achieving a gain enhancement is analyzed by evaluating the efficiency of such radiators, considering both the power properly radiated in the far field and the power carried away by the excitable guided modes.

Evaluations of the radiated and guided power have been led in order to optimize gain, thus identifying the most advantageous positions of the source element inside the structure. The radiated power has been derived by integrating the far field as a function of the observation angle θ over the half space above the layer. The guided power has been derived by calculating the residues of the excitable guided modes and then the relevant power flow along positive or negative *z*. Again, careful analyses are necessary due to the nonreciprocity of the problem.

Typical patterns of the amount of the total power delivered by the source, and of the relevant guided and radiated contributions, are illustrated in Fig. 3, as a function of frequency and for different positions of the source. Power is quantified for a unit-strength current line. Out of the radiation window, corresponding to the complex branches of the anomalous mode, a drastic reduction of the radiated power is seen. On the contrary, the contribution of guided powers tends to increase.

For practical radiation purposes it is important to quantify the gain, which describes the capability to concentrate radiation with respect to the total power accepted by the antenna (the ratio between gain and directivity giving the efficiency). A result for gain as a function of frequency for different source location is presented in Fig. 4.

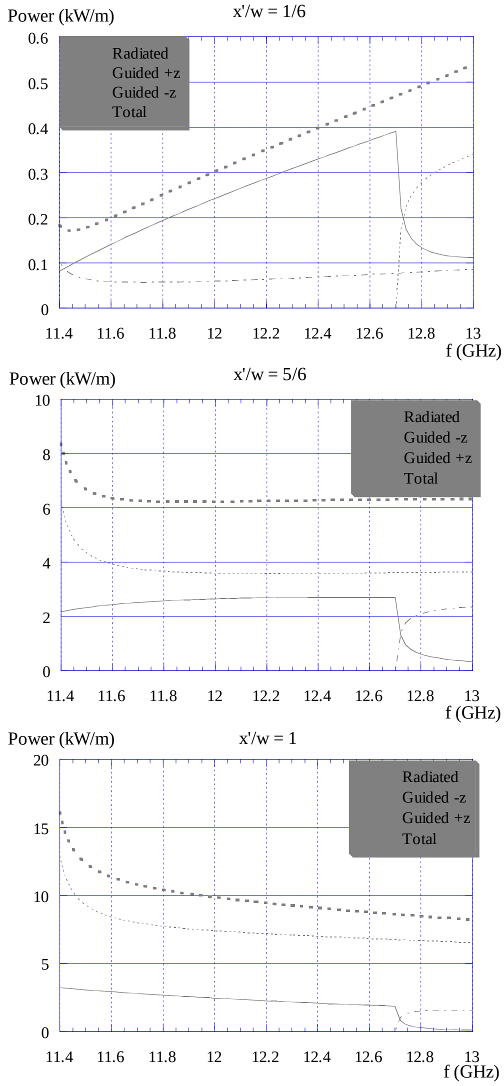

Fig. 3 - Behaviors of the guided, radiated, and total powers excitable by a unit-strength line source located at different places as a function of frequency *f*.

It is interesting to note that different conditions can generally exist for the optimization of the directivity, the amount of radiated power, and the gain. For instance, the location of the current line on the interface presents the pleasant characteristics of a maximum of directivity and of an almost constant gain as a function of frequency or scanning angle: in this case, however, in conjunction with high radiated powers, a rather large amount of the guided power has to be accepted, which reduces efficiency. If higher gains are aimed it is more convenient to locate the source inside the layer: in this case, even though the amount of radiated power is reduced with respect to the previous position, the efficiency is maximized (a stronger reduction of guided power occurs).

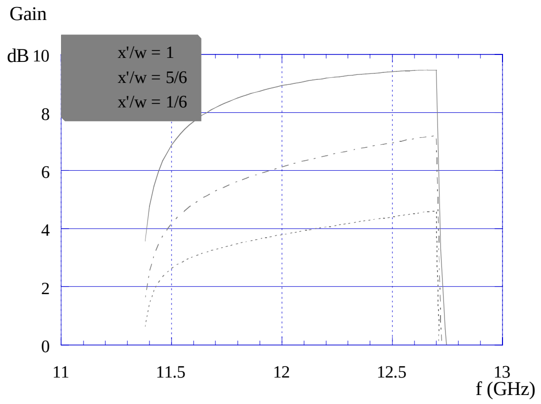

Fig. 4 - Behavior of the gain of the GFS vs. frequency *f* in the radiation window for different source locations.

By deriving the field configurations of the anomalous mode, strongly nonreciprocal shapes (evanescent/ stationary type) are verified for the 'direct' ($\beta/k_o>0$) and the 'reverse' ($\beta/k_o<0$) branches. The analysis of the field patterns furnishes an immediate interpretation of which are the most suitable locations of the source to efficiently excite guided or radiated power, in complete agreement with the discussed results concerning directivity and gain.

V. Conclusion

Various fundamental points can be fixed as a conclusion of the studies on this representative class of nonreciprocal structures, which are briefly summarized here.

a) Open waveguides such as GFS present regions of strong nonreciprocity for both propagation and radiation, as a rather complicated function of several physical parameters: it is seen that the analysis and the design techniques can be strongly simplified with the introduction of suitable theoretical procedures (equivalent transmission-line approach, transverse resonance techniques, leaky-wave phrasing, ray optics, etc.).

b) The main effects can be connected to a single anomalous mode, having various real/complex proper/ improper branches. Interesting effects are related to low values of the effective permeability. Nonreciprocal guidance is linked to very different field configurations (evanescent/stationary) and power transport properties. Particular phenomena have also been found where forward/backward/forward propagation can occur at the same time. The radiative properties are particularly interesting since frequency windows exist where a simple current line placed in a single layer can produce pointed-beam radiation scannable angularly in a complete way. Alternatively, the same scanning features of the radiation beam are obtainable by suitably changing the biasing magnetic field.

c) The transmission and reception of power occur in different directions symmetrical to broadside. The improper/proper complex branches of the anomalous mode dominate the forward/backward quadrant radiation, as confirmed by a transverse-resonance approach. Ray optics considerations can suitably be extended too from the isotropic case. Such information is very useful for straightforward design of radiating structures.

d) The directivity of the beams does not change much with the source position. The actual capability of focusing power has anyway to be checked in conjunction with the efficiency of the structure, also considering the excitation of guided power that adversely affects the gain. The knowledge of the field configurations facilitates the prediction of the guidance and radiation effects as a function of the source location.

e) The ohmic losses in the media have practical consequences on the propagation and radiation as well. Basic modifications from the ideal case have to be taken into account: in fact, a number of ideal behaviors related to the lossless case disappear when realistic permeability parameters are considered. Careful analyses should be considered to guarantee the validity of the theoretical model for the problem under investigation. The limits of this paper cannot allow further discussions on this argument here.

A complete knowledge for the practical use of anisotropic substrates in the presence of sources is thus available. The theoretical procedures facilitate the physical understanding of the basic electromagnetic phenomena and give the practical tools for efficient analysis and synthesis of novel microwave devices.

References

[1] P. Baccarelli, C. Di Nallo, F. Frezza, A. Galli, and P. Lampariello, "Anomalous propagation, loss and radiation effects in open waveguides with gyrotropic media," *IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 283-286, 1996.

[2] P. Baccarelli, C. Di Nallo, F. Frezza, A. Galli, and P. Lampariello, "The role of complex waves of proper type in radiative effects of nonreciprocal structures," *IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 491-494, 1997.

[3] A. S. Omar and K. Schunemann, "Complex and backward-wave modes in inhomogeneously and anisotropically filled waveguides," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-35, pp. 268-275, March 1987.

[4] C.-K. C. Tzuang and J.-M. Lin, "On the mode-coupling formation of complex modes in a nonreciprocal finline," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-41, pp. 1400-1408, Aug. 1993.

[5] V. N. Ivanov, S. I. Tolstolutskiy, and A. G. Shchuchinskiy, "Surface modes in a flat waveguide filled with ferrite-dielectric material," *Radio Eng. Electronic Phys.*, pp. 21-25, 1982.

[6] I. Y. Hsia and N. G. Alexopoulos, "Radiation characteristics of Hertzian dipole antennas in a nonreciprocal superstrate-substrate structure," *IEEE Trans. Antennas Propagat.*, vol. AP-40, pp. 782-790, July 1992.

[7] J. L. Tsalamengas and N. K. Uzunoglu, "Radiation from a dipole in the proximity of a general anisotropic grounded layer," *IEEE Trans. Antennas Propagat.*, vol. AP-33, pp. 165-172, Feb. 1985.

[8] C. Di Nallo, F. Frezza, A. Galli, and G. Gerosa, "A convenient transmission-line formulation for wave propagation in typical ferrite structures," *IEEE Trans. Magn.*, vol. MAG-32, pp. 3228-3236, July 1996.

[9] D. R. Jackson and N. G. Alexopoulos, "Gain enhancement methods for printed circuit antennas," *IEEE Trans. Antennas Propagat.*, vol. AP-33, pp. 976-987, Sept. 1985.

[10] D. R. Jackson and A. A. Oliner, "A leaky-wave analysis of the high-gain printed antenna configuration," *IEEE Trans. Antennas Propagat.*, vol. AP-36, pp. 905-910, July 1988.