THE ROLE OF COMPLEX WAVES OF PROPER TYPE IN RADIATIVE EFFECTS OF NONRECIPROCAL STRUCTURES

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Abstract

Structures of open type based on gyrotropic substrates have shown interesting nonreciprocal radiation characteristics, recently investigated in terms of leaky waves. This subject is studied further in this work, on the basis of accurate theoretical procedures. Our attention is particularly focused on the identification and the interpretation of original forward/backward beam-scanning properties due to isotropic current sources. The contributions to the radiation of excitable proper (or spectral) leaky waves, till now quite disregarded in such type of open structures, is emphasized and discussed as concerns its physical meaning. This analysis makes it possible a quite simple, complete, and effective interpretation of the radiative features in devices that may find application as unconventional antennas.

I. Introduction

Radiation effects related to the nonreciprocal properties of components employing anisotropic materials (ferrites, etc.) assume outstanding importance both for applications in specific antennas and for control of interference problems in integrated circuits.

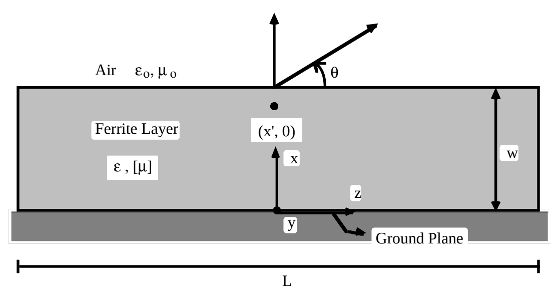
The study presented here, on the basis of a previous analysis on a significant class of gyrotropic planar structures [1], intends to give novel useful information as concerns the identification of uncommon radiative effects and the possible prediction and physical explanation in terms of leaky waves of both improper and proper type.

II. Background

For the class of nonreciprocal structures of our interest (see, e.g., Fig. 1), it is known that the complex eigen-solutions can be isolated in single pairs that are of the type (k_z,k_z^*) (where $k_z=\beta-j\alpha$, with $\beta>0$, $\alpha>0$) [2], lying on only two of the four k_z-plane quadrants (due to nonreciprocity, the opposite pair $(-k_z,-k_z^*)$ does not generally exist). As particularly regards the complex solutions of proper type, they have already been discussed widely for anisotropic waveguides of closed type [3,4], where it is confirmed that they do not transfer real power, contributing to reactive phenomena of power storage only.

When nonreciprocal waveguides of open type are considered, in addition to improper (or nonspectral) complex solutions, which in certain cases can provide a valid interpretation in describing radiation [1], proper (or spectral) complex solutions may be present as well. The role played by this last kind of solution in the evaluation of the field for such structures is extremely important, even though rather complicated and not investigated much [5].

We will examine here, based on quantitative and qualitative considerations, in which way such proper complex modes can efficiently contribute to the field in the presence of exciting sources. Unlike closed anisotropic or particular open isotropic structures [5], we will show that such proper complex solutions do not necessarily describe reactive phenomena, but, on the contrary, they may represent very well situations where peculiar radiative phenomena occur.



$$[\mu] = \mu_o[\mu_r] = \mu_o \begin{bmatrix} \mu_1 & 0 & -j\mu_2 \\ 0 & 1 & 0 \\ j\mu_2 & 0 & \mu_1 \end{bmatrix}, \begin{cases} \mu_1 = 1+\dfrac{\omega_m\omega_o}{\omega_o^2-\omega^2} \\ \mu_2 = \dfrac{\omega\,\omega_m}{\omega_o^2-\omega^2} \end{cases} \quad \omega_o = -\gamma H_o, \ \omega_m = -\frac{\gamma}{\mu_o} M_o, \ \gamma\text{, gyromagnetic ratio}$$

Fig. 1 - A representative open anisotropic structure where nonreciprocal radiation effects may occur: a grounded transversely-magnetized ferrite layer (static field along y) with a current-line source (along y and placed at $x=x'$ and $z=0$). Basic choice of the physical parameters: $\varepsilon_r=10$; static magnetic field $H_{oy}=(1/4\pi)\ 10^6$ A/m; magnetization $M_o=0.3$ Wb/m^2; width $w=6$ mm; length along z $L=60$ cm; source location $x'=5$ mm.

III. Methods of analysis

The basic structure under investigation is a representative nonreciprocal open waveguide, constituted by a transversely-magnetized ferrite layer on a ground plane, as resumed in Fig. 1. The fundamental properties shown by this guide can be recognized also in other similar open planar structures based on anisotropic layers [6].

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We consider here the radiative effects of a current-line source directed along the magnetization direction (y in our reference system), expressible as $\boldsymbol{J} = J_{oy}\,\delta(x\text{–}x')\,\delta(z)\,\boldsymbol{y_o}$ (see Fig. 1, where the source location is inside the layer, close to the interface and symmetrically along z, i.e. at $z=0$). A realistic structure will be examined by considering in particular the radiative properties for a layer of width w and of a "long" but finite length L along z.

Different methods have been developed in order to determine the field radiated by the source. As is known, it is possible to obtain the radiation pattern by means of the field generated on the aperture interface through a Fourier-transform type integral [5,7].

For this evaluation, we have first carried out a rigorous procedure based on a spectral-domain approach. The spectral dyadic Green's function of the structure has been achieved with a novel direct method employing an appropriate extension of the transmission-line formalism, which allows us to profitably apply the transverse-resonance technique [8]. In this way, by means of careful analyses concerning the integral evaluation on the complex k_z plane, it is possible to derive numerically a reference quantification of the radiated field.

In addition, a simplified form of this numerical evaluation may be quite useful, considering the analogous infinitely-long structure: in this case, the radiation pattern does not take into account the diffraction effects due to truncation but does give a quick evaluation of the beam characteristics. In fact, in this case, it is possible to express in a closed form the reference integral expression.

Moreover, according to classical approaches [5,7], an alternative to the continuous-spectrum evaluation is achievable in a simple analytical form that allows us to isolate the often significant contribution due to leaky-wave poles k_z, calculating their residues.

Results on the radiation patterns (calculable through the three different approaches briefly outlined above) will be discussed in the next sections, allowing us to describe interesting properties of nonreciprocal structures.

IV. Characteristic propagation properties

To analyze the radiation properties of the structure of Fig. 1 it is useful to consider the links with the eigenvalue spectrum of the waveguide. The basic dispersion properties of the grounded ferrite layer have already been analyzed extensively, and its radiation characteristics due to the presence of a current-line source, parallel to the magnetization direction, have been investigated in part in [1] as concerns with the role of improper complex modes.

In particular, it has been noticed that a fundamental *TE* mode, that for its various rather uncommon characteristics we have called "anomalous," assumes a specific importance for many aspects. We show here that further interesting radiative properties may derive in connection with a complete study of such a mode.

The strongly nonreciprocal dispersive behavior of this anomalous mode is reported in Fig. 2, where the pattern of the normalized phase constant β/k_o vs. frequency f is shown for a suitable choice of the other physical parameters (see Fig. 1 captions).

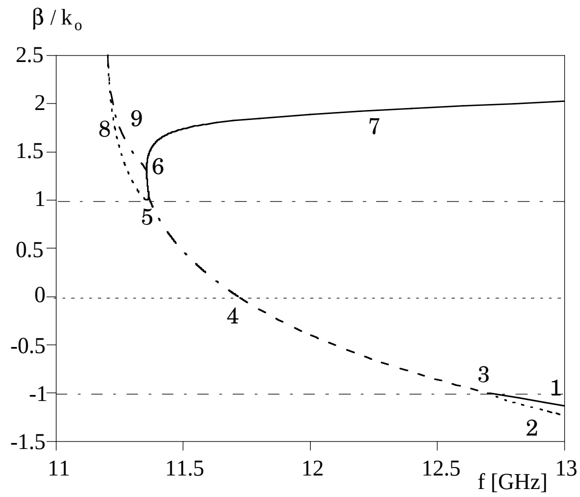

Fig. 2 - Dispersive behavior of the "anomalous" mode: various branches (proper/improper, real/complex) for the normalized phase constant β/k_o vs. frequency f.

Due to space limits, the results presented here refer only to the lossless case. We remind that, in such type of structures, ohmic losses in the ferrite can deeply change both the dispersion behaviors for phase and leakage and the mode-coupling phenomena, globally affecting the radiation patterns. Anyway, in the presence of low losses, the basic properties shown here remain substantially valid.

This modal information, joined to a careful analysis through the steepest-descent representation, gives us the possibility of finding new complete interpretations of peculiar phenomena in the structures of interest.

V. Forward radiation and improper leaky waves

We examine in detail the radiation properties of the structure of Fig. 1. From Fig. 2 it can be seen that, as frequency decreases, the "reverse" ($\beta/k_o<0$) proper real (or guided) mode (branch coming from point 1 to point 3) becomes improper complex (from around point 3 to 4) passing through a standard small transition region (not visible in Fig. 2). The improper real branch coming from point 2 to 3 has no practical importance.

Conversely, it has been noted that, since the anomalous mode is the dominant one in this range (usually said "isotropic region" [1]), when the condition for leakage is satisfied ($-1<\beta/k_o<0$ for the reverse mode), the improper complex branch 3-4 does have a physical meaning and may contribute to the most part of the radiated field, which is at an angle θ in one quadrant. In our convention here we consider angles measured from the positive z axis (see Fig. 1): thus, for the reverse branch of the anomalous mode, the power in the layer will flow attenuated along $-z$ and the power in the air will leak out at an angle in the quadrant given by $90°<\theta<180°$: for simplicity, since in this case the guided and radiated powers flow in "concordant" directions ("forward" radiation), we will refer to the $90° < \theta < 180°$ region also as the "forward" quadrant.

By varying for instance the frequency, for specific choices of the parameters, it is thus possible to have scannable radiated beams that in the 3-4 zone find interpretation through the improper complex mode (around point 3 we are close to the endfire $\theta = 180°$, and by decreasing frequency towards point 4 the beam approaches progressively the broadside $\theta = 90°$).

A typical behavior of the far-field "forward" radiation pattern for the structure of Fig. 1 is presented in Fig. 3a, with a value of frequency fixed inside the 3-4 zone. The calculations have been led both in the rigorous integral form for the realistic finite-length structure (solid lines), and for infinite-length structure (dashed lines), and also in the approximation of the leaky-wave contribution (dashed-dotted lines). It can be seen that in these situations the agreement between the complete radiated field and the leaky-wave evaluation is very good, so that the leaky pole of the anomalous mode strongly dominates the radiation effects. The performances of the pointed beam are quite good and are related to the achievable values of the leakage constant, which can be rather low. The length of the structure for such situations is anyway sufficient to reduce diffraction effects (L has been chosen to have around *90%* of radiated power for the mean value of the leakage in the range of interest), as shown also by the comparison with the radiation for infinite length.

VI. Backward radiation and proper leaky waves

We have seen so far that in the "forward" quadrant there is the possibility of scannable pointed beams which can well be represented with the single leaky-wave pole of the anomalous mode. By continuing the analysis of the radiation effects, original interesting behaviors may be found also in regions where proper complex branches exist. Usually, complex proper branches are related to reactive phenomena. We show here that, on the contrary, such branches can be excited singularly and are representative of leakage phenomena as well, effectively explaining peculiar anisotropic radiation behaviors in these structures.

When the curve of β/k_o of the anomalous mode changes the sign and becomes "direct," ($\beta/k_o > 0$) from the careful analysis of the transverse and longitudinal eigenvalues, we can observe that the branch 4-5 becomes complex proper (Fig. 2). We mention also that, for certain choices of the physical parameters, such proper complex mode can then be coupled (bifurcation around point 5) with the direct guided branch (5-6-7). The other branches starting from this guided mode, one (5-8) improper real, the other (6-9) still proper complex, do not assume physical importance for radiation (the condition for leakage is anyway maintained for the direct mode only when $0 < \beta/k_o < 1$, then only for the 4-5 branch).

Based on the previous theoretical approach, we have investigated further the radiation properties of our structure. As frequency is reduced, entering the 4-5 region where the anomalous mode changes its nature and becomes complex proper, we can observe that the radiation is continuously scanned and varies its pointing angle inside the $0° < \theta < 90°$ quadrant, the broadside $\theta = 90°$ being around point 4 (at *11.72 GHz* in our simulation) and the endfire $\theta = 0°$ around point 5. It is thus seen that in the range of the proper complex branch of the anomalous mode, power inside the layer still flows attenuating in the $-z$ direction, but in the outside air region the same power amount will leak out in an opposite direction, i.e., in the quadrant given by $0° < \theta < 90°$ (a quantitative proof of this complete power transfer is achievable numerically). Since in this case the guided and radiated powers flow in "discordant" directions ("backward" radiation), we will refer to the $0° < \theta < 90°$ region also as the "backward" quadrant.

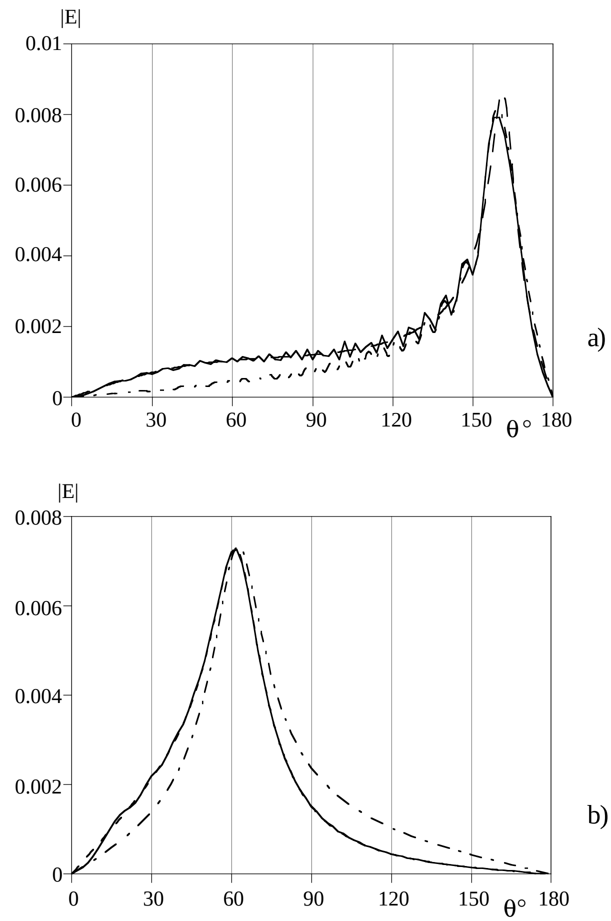

Fig. 3 - Forward/backward radiation as a function of frequency: comparisons between the complete numerically-evaluated field (solid), the field for infinitely-long structure (dashed), and the field due to the improper/proper leaky pole of the anomalous mode (dashed-dotted): a) "forward" radiation in the improper region ($f = 12.6$ GHz); b) "backward" radiation in the proper region ($f = 11.5$ GHz).

A radiation pattern in this range has been calculated in Fig. 3b for a fixed frequency through the usual different approaches (finite-length structure, infinite structure, leaky-wave contribution). It can thus be verified that the radiation in the "backward" quadrant may still be strongly dominated by the complex proper pole, which has therefore an important physical meaning, as it was in the "forward" quadrant for the complex improper pole.

As endfire directions are closely approached, a certain deterioration of the directionality of the pointed beam may be found, and the agreement between radiation field and leaky waves is anyway worsened, as is typical approaching transition regions where the condition for leakage is no longer satisfied. In such cases, generally the leaky pole gives no longer useful convergent representation of the field, and space waves assume increasing importance.

Also, as already said, the ohmic effects can deteriorate the ideal behavior of the radiation patterns, particularly towards the backward region (here the attenuation constant due to dissipation becomes higher as frequency decreases).

From an application-oriented viewpoint, it should be observed that the radiation features of such a structure (which is of a very simple "uniform" type) appear worthy of interest since it is possible to achieve pointed beams with a very large angular scanning close to both the endfire directions (changing continuously through broadside as well), and with amplitudes that are quite constant in all the directions. A global polar diagram of radiation patterns vs. frequency is shown in Fig. 4. It is shown that an excellent pencil-beam scanning is achievable in rather reduced frequency ranges (about *150°* in *1.3 GHz* in our case).

Similar investigations have been extended also to explain the radiation properties in other similar nonreciprocal planar structures already considered in the literature [6]. The relevant results confirm the correctness of our approaches and give generality to our considerations.

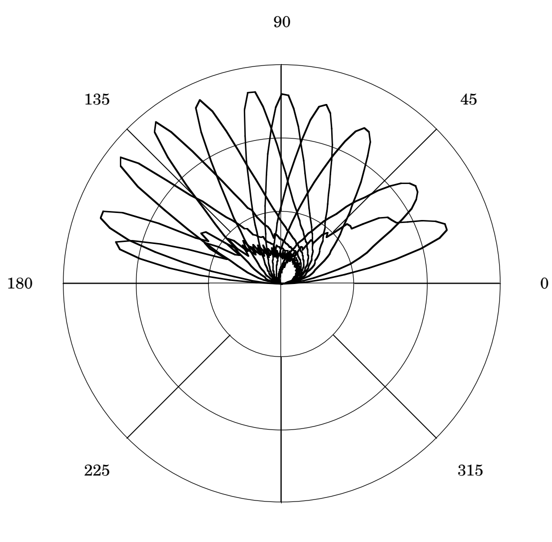

Fig. 4 - Polar diagram of the complete pointed-beam scanning as the frequency is varied. The clockwise beam scanning (from "forward" to "backward" region) is obtained for frequency decreasing as follows: *f=12.7, 12.6, 12.4, 12.2, 12, 11.8, 11.72, 11.6, 11.5, 11.4, 11.37 GHz.*

VII. Conclusion

Representative types of open anisotropic nonreciprocal uniform structures have accurately been analyzed as concerns with uncommon radiation effects and their relations with complex waves. Some main results may be emphasized from our analysis:

a) with a simple isotropic (bidirectional) source it is possible to achieve strongly asymmetric (monodirectional) pointed-beam radiation patterns, with angles variable by frequency or magnetization;

b) the beam scanning for these uniform-type structures is shown to occur not only in the "forward" quadrant but also in the "backward" one, changing continuously from one endfire to the other through broadside;

c) whilst radiated fields in the "forward" quadrant may be represented in a highly convergent way by means of improper complex modes, radiated fields in the "backward" quadrant may suitably be rephrased in terms of complex eigensolutions of proper type, that are singularly excitable and give power leakage in an opposite direction to that of internal propagation.

The choice of parameters can deeply vary such radiation effects. Even though the material losses can adversely affect the performances, the properties of the achievable pointed beams may be quite interesting for original leaky-wave antennas. The procedures of analysis and design for such applications are greatly clarified and simplified on the basis of the present interpretation.

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