Low-Frequency Dispersion Features of a New Complex Mode for a Periodic Strip Grating on a Grounded Dielectric Slab

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***Abstract*—In this paper, novel behavioral features are found for the propagation and radiation of a class of periodic structures often employed in various microwave passive devices and antennas, i.e., a periodic metallic strip grating placed on a grounded dielectric slab. At low frequencies, the dispersion features of the fundamental TE mode are completely different when the grating structure is almost closed, as compared to when it is almost open, that is, when the ratio of the strip width (s) to the grating period (p) is close to unity or close to zero. As is discussed here, this difference led to initially puzzling behavior as the ratio s/p was varied, and the behavior became clear only after a new improper complex (leaky) modal solution was discovered. This paper presents the results of a systematic parametric study of the dispersion features of the new mode in relation to the occurrence of leaky and bound regimes of the fundamental TE mode and also yields information on what ranges of the physical parameters can provide values of phase and leakage (attenuation) constants suitable for a class of practical leaky-wave antennas.**

***Index Terms*—Leaky waves, leaky-wave antennas, periodic structures, planar waveguides.**

I. Introduction

PERIODIC structures have been employed in electromagnetics in a wide range of applications (e.g., filters, gratings, traveling-wave tubes, particle accelerators, leaky-wave antennas, phased arrays, and frequency-selective surfaces), thanks to their characteristic waveguiding and radiative properties [1], [2]. With regard to radiating periodic structures, periodically modulated transversely open waveguides form the basis of a significant class of leaky-wave antennas, whose radiative features are directly related to the dispersion behavior of the modes (Bloch waves) supported by the basic structure [3], [4]. Their operation is based on the existence, in certain frequency ranges, of at least one axially fast spatial harmonic, each fast harmonic giving rise to a radiated beam which is scanned angularly by varying the frequency of operation [3], [4].

In this paper, we focus the attention on a significant two-dimensional (2-D) open periodic structure, constituted by a periodic metal-strip grating at the interface between air and a grounded dielectric slab, as depicted in Fig. 1. Different leaky-wave antennas based on the periodically modulated grounded slab, which offer interesting radiative performances, have been studied in the past (see, e.g., [5]–[9]). The dispersion features of the modes supported by this structure have been investigated numerically and experimentally by many authors (see, e.g., [10]–[12]), both in the guided regime and in the leaky regime due to radiation from the spatial harmonic of order $n = -1$. More recently, based on the multimode transverse network representation developed in [13], the spectral-gap regions have been investigated [14] for the cases of one and two radiating spatial harmonics.

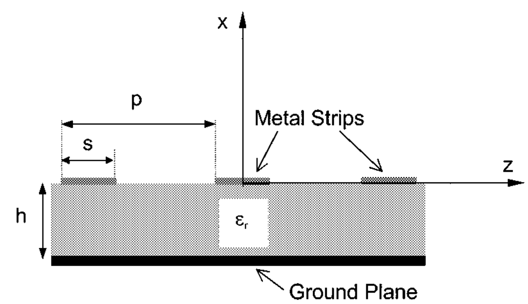

Fig. 1. The periodic open structure treated here: strip grating on a grounded dielectric slab.

Instead of examining the guiding and radiating behaviors of the $n = -1$ space harmonic, as was done in all previous studies, we analyze in this paper the low-frequency properties of the basic TE mode supported by the metal-strip grating, and the related leakage phenomena due to radiation from the fundamental ($n = 0$) space harmonic. The present analysis shows that, at low frequencies, rather involved and unexpected dispersion behaviors can be found, which are strongly dependent on the ratio s/p between the strip width (s) and the period (p). It is shown that when we follow customary analytical procedures we find that a leaky mode is present when the strips are wide and fill up most of the period (s/p close to unity), but that when the strips are narrow (s/p small) the leaky mode appears to be absent. This surprising result produces something of a mystery, since it implies that a more open structure will not radiate, whereas a more closed one will, which is, at the least, the opposite of what one would expect.

This mystery was resolved when we discovered a new, previously unknown, leaky complex solution, whose physical meaning varies with s/p. This new solution makes clear in what ways reactive and radiative phenomena may occur, affecting

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the practical performance of this class of periodic structures. By slowly varying the values of s/p, and displaying the results in the Brillouin diagram (k_0p/π versus β_0p/π, where β_0 is the fundamental-harmonic phase constant) and in the dispersion plot (β_0/k_0 and α/k_0 versus frequency f, where α is the attenuation or leakage constant, which is the same for all the spatial harmonics), we can follow the evolution of the solutions and see clearly how the physical behavior changes.

The paper is organized as follows. In Section II, we describe the transverse resonance technique that has been adopted here to obtain the dispersion equation of the grating, and we review the relevant spectral properties of the spatial harmonics. In Section III, the low-frequency properties of the grating are examined and explained in terms of the new (leaky) improper complex mode. A parametric analysis of the dispersion properties of the new mode is presented in Section IV, where indications are also given on some physically useful ranges of geometrical parameters in order to obtain efficient radiation. Finally, in Section V, conclusions are presented on the various results of this study.

II. Background and Full-Wave Analysis

The structure in Fig. 1 is 2-D, so that an arbitrary electromagnetic field can be decomposed into a set of TE and TM modes which can exist independently. The TE polarization is particularly useful in the application of the grating as a constituent of leaky-wave antennas, since it offers the possibility of limiting the structure along the y direction with metal walls without disturbing the field, and it can be easily excited by means of a rectangular waveguide partially filled with dielectric.

The fundamental TE mode studied here has its electric field linearly polarized in the y direction (parallel to the metal strips), while the magnetic field vector lies in the xz plane. This mode can be seen either as a perturbation of the TE_1 mode supported by a grounded dielectric slab (GDS), the perturbation being represented by the metal strips, or as a perturbation of the TE_1 mode of a dielectric-filled parallel-plate (DPP) waveguide, the perturbation being represented by the apertures on the upper metallic plate.

The dispersion diagrams (β/k_0 and α/k_0 versus f) for these two unperturbed modes are shown in Fig. 2. Their behaviors below cutoff are very different, since the DPP mode reaches its cutoff when $\beta/k_0 = 0$ and becomes evanescent for lower frequencies (the continuous line with triangles represents its attenuation constant), while the GDS mode reaches its cutoff when $\beta/k_0 = 1$ and becomes an improper real mode without physical meaning for lower frequencies (the dotted line represents its phase constant). As will be explained in the next section, a qualitative change in the low-frequency behavior has also been found in the dispersion features of the mode supported by the periodically loaded structure, as the ratio s/p is varied continuously.

The dispersion analysis has been performed here by means of the transverse resonance technique, based on a rigorous transverse multimode network representation of the metal-strip grating at the interface between two different dielectrics [13], [15]. The transverse network model of a TE mode propagating

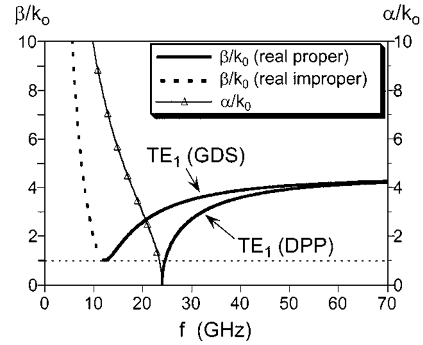


Fig. 2. Dispersion diagrams (β/k_0 and α/k_0 versus frequency f) for the TE_1 mode of the GDS and for the TE_1 mode of the DPP waveguide. Parameters: $\varepsilon_r = 20$, $h = 0.14$ cm. Conventions adopted here and in Figs. 4–11 for the normalized phase constant: solid line: proper, dotted line: improper real, continuous line with black dots: improper complex; convention adopted for the normalized attenuation constant: continuous line with triangles. The dots and the triangles are used in the latter cases to identify the curves and do not represent specific data points.

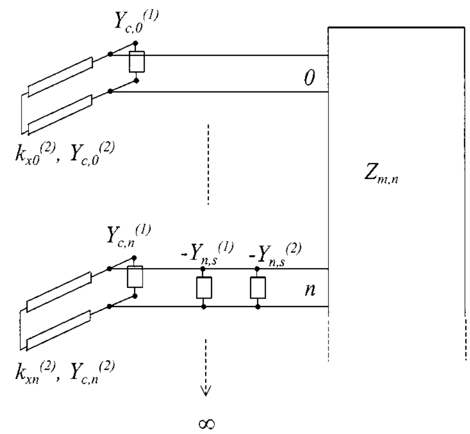


Fig. 3. Multimode transverse equivalent network for a TE mode propagating along the structure shown in Fig. 1.

in the longitudinal (z) direction along the metal-strip grating on a grounded slab is represented in Fig. 3. The propagation in the transverse (x) direction of each space harmonic, the infinite sum of which constitutes the Floquet expansion of the total field, is modeled by an equivalent transmission line. The propagation in the transverse direction within the dielectric slab is modeled by a finite length of transmission line, terminated by a short circuit due to the presence of the backing ground plane; the propagation in air is modeled by an infinite (matched) transmission line. The elements $Y_{n,s}$ are the static values of the characteristic admittances for each of the lines and are very simple in form [13]. The coupling network Z_{mn} is characterized by an impedance matrix, whose elements are available in a simple closed form and are independent of frequency and longitudinal wavenumber, except for a multiplicative constant [15]. The approximate dispersion equation is obtained by retaining a finite number of spatial harmonics and imposing the condition of resonance on the finite transverse network thus obtained. A small number of harmonics is generally sufficient to achieve a good accuracy (for the structures considered here, orders from $n = -8$ to $n = +8$ have been used).

Since we are interested in finding both real and complex waves, the dispersion equation has been solved in the complex plane, employing a numerical routine based on the secant method. In the process of root search, the spectral properties of the space harmonics involved have to be carefully taken into account. The transverse wavenumber of each harmonic in the air region has two possible determinations, one corresponding to a field attenuating exponentially at infinity (the proper determination) and the other diverging exponentially at infinity (the improper determination) [4]. The dispersion equation is thus defined on a Riemann surface with a denumerably infinite number of sheets, because there are an infinite number of space harmonics. As the frequency is varied, a solution can migrate from one sheet to another, with a consequent change in the spectral character of one or more spatial harmonics of the modal solution.

III. Different Dispersive Behaviors at Low Frequencies and Interpretation in Terms of a New (Leaky) Complex Mode

The aim of our analysis here is to characterize the fundamental TE mode supported by the grating over the full range of values for the s/p ratio between the strip width (s) and the spatial period (p). A qualitative change will be shown to occur in the dispersion properties of the mode supported by the grating as the s/p ratio is varied: for a basically closed structure (values of s/p close to unity), the bound mode becomes leaky at low frequencies due to radiation from the fundamental ($n = 0$) spatial harmonic, while for a basically open structure (low values of s/p) the proper bound mode becomes improper real at low frequencies, and no radiation occurs.

Part of the following results will be displayed by means of the Brillouin diagram, with axis variables $\beta_0 p/\pi$ and $k_0 p/\pi$. Thanks to the horizontal periodicity of the diagram, only the vertical strip with $0 < \beta_0 p/\pi < 2$ will be represented, with the explicit indication of the first bound-mode triangle.

The Brillouin diagram for a basically closed structure is shown in Fig. 4 (the physical parameters are $s/p = 0.6$, $\varepsilon_r = 20$, $h = 0.14$ cm, $p = 0.338$ cm). In this case, the proper bound mode (solid line) crosses the left side of the triangle at about 22.0 GHz and enters a leaky regime where the $n = 0$ space harmonic (continuous line with black dots) is improper complex, but physical. The leaky mode is fast and, therefore, has physical meaning, down to very low frequencies (until it again crosses the triangle boundary). The dispersion behavior for this case corresponds to what we would expect.

In the Brillouin diagram in Fig. 5, the case is presented for a basically open structure, with $s/p = 0.4$; the other parameters are the same as those in Fig. 4. The $n = 0$ space harmonic, shown as a solid line, is proper real and bound inside the triangle. As the frequency is lowered, the solution becomes improper real at the tangency point with the left side of the triangle at 19.56 GHz. The solution bends toward the inside of the triangle for lower frequencies (dotted line), and it has no physical meaning; at 16.62 GHz, it becomes tangent to the right side of the triangle, where the $n = -1$ harmonic becomes improper,

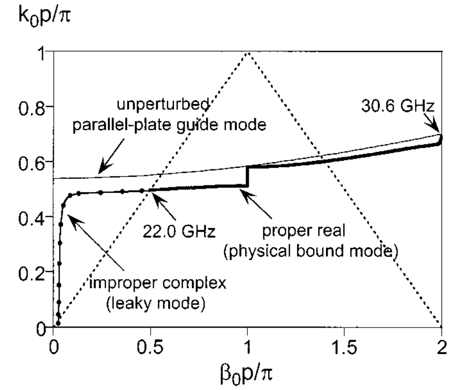


Fig. 4. Brillouin diagram ($k_0 p/\pi$ versus $\beta_0 p/\pi$) for the periodically loaded structure in Fig. 1 with $s/p = 0.6$. The other parameters are $\varepsilon_r = 20$, $h = 0.14$ cm, $p = 0.338$ cm. This structure may be considered as basically closed.

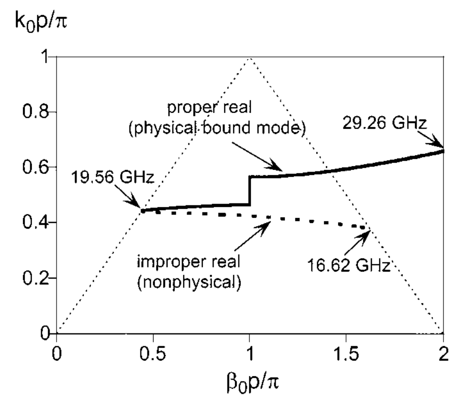


Fig. 5. Same parameters as in Fig. 4, but with $s/p = 0.4$. This structure may be considered as basically open.

and, by further lowering the frequency, the solution remains inside the triangle and always remains nonphysical.

We can, therefore, see from Figs. 4 and 5 that a leaky-mode solution is present outside of the triangle in Fig. 4, but not in Fig. 5, implying that radiation can occur when $s/p = 0.6$, but not when $s/p = 0.4$. Such behavior seems rather mysterious, particularly since $s/p = 0.4$ corresponds to a more open structure. One might think that the structure near one s/p limit resembles that of a series of strips while near the other s/p limit it resembles a series of slots, but that is not the situation here. We see here that radiation occurs for larger values of s/p, but none at all when s/p is small. Such performance is counterintuitive and suggests that something is missing.

We have investigated the details of the transition from the basically open structure to the basically closed one, with a particular concern for the algebraic multiplicity of the solutions, which is to be maintained as the frequency is changed in any given configuration. We then found that a new, previously unknown, complex improper mode generally exists, which permits a consistent view of the above-mentioned transition [16].

In Fig. 6(a), a Brillouin diagram for the same structure as the one for Fig. 5 ($s/p = 0.4$) is shown in a more restricted frequency range. The continuous curve with black dots represents the new improper complex mode, which has been found to be an additional solution for the $n = 0$ spatial harmonic and

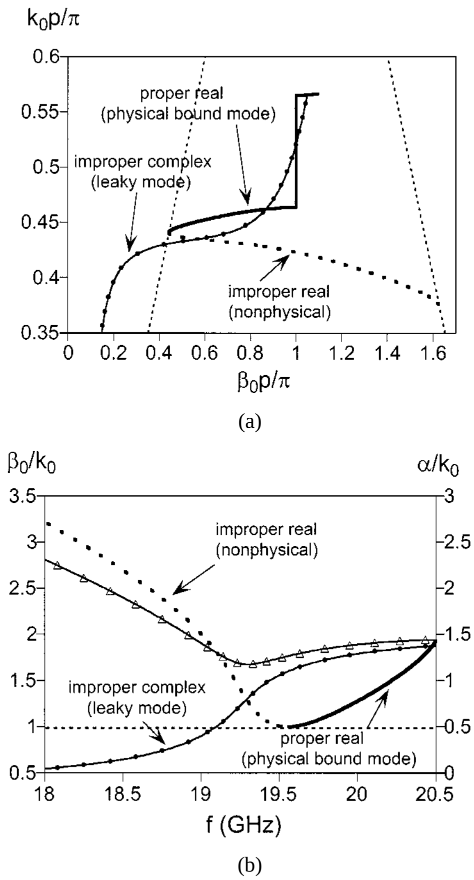


Fig. 6. Case of Fig. 5 ($s/p = 0.4$), but including the new complex solution, shown dash-dotted. (a) Brillouin diagram. (b) Corresponding dispersion diagram. The continuous curve with triangles represents the α/k_0 value for the new leaky mode.

was not present in the diagram in Fig. 5. This mode has been obtained with the improper determination of the fundamental ($n = 0$) space harmonic, and it has physical meaning in the fast-wave region outside the bound-mode triangle. Therefore, it gives rise to leakage, even though the value of the leakage constant is very large, so that the power would be radiated away in a very short distance. This new solution is nonphysical inside the triangle.

The dispersion diagram (β_0/k_0 and α/k_0 versus frequency f) corresponding to Fig. 6(a) is shown in Fig. 6(b). The portion of the new improper complex mode outside the triangle in Fig. 6(a) lies below the $\beta_0/k_0 = 1$ line in Fig. 6(b), where the solution is fast so that the leaky mode is physical. For values above that line (at higher frequencies), the solution is nonphysical. The value of α/k_0 is high, with its minimum at the frequency for which the phase constants of the improper real and improper complex solutions (both nonphysical) are equal.

If the ratio s/p is increased, the minimum in the attenuation constant of this improper complex mode becomes sharper, and its value decreases. Interestingly, this minimum occurs systematically at the frequency at which the phase constants of the new mode and of the guided mode (or of its improper real low-frequency continuation) are equal, as in Fig. 6(b). The leakage constant ultimately reaches zero for a certain value of the s/p ratio. By further increasing s/p, a qualitative change in the dispersive features of the structure occurs: the complex improper solution is no longer continuous and it splits into two separate improper complex branches, joined by a real improper branch.

This can be seen in Fig. 7(a), which is a Brillouin diagram for the same structure as that for Fig. 4 ($s/p = 0.6$). It is also shown clearly in Fig. 7(b), which presents the corresponding dispersion diagram. In Fig. 7(b), we may also see that the algebraic multiplicity of the solutions is maintained as frequency varies and that there are three real branches in the frequency region between the ranges where the two complex solutions exist. (We should remember that each complex solution has its complex conjugate solution, with the same value of β_0/k_0.)

The details of the transition region at forward endfire of the $n = 0$ space harmonic is shown in the enlarged plot in Fig. 7(c). The complex branch (on the left side, shown as a continuous curve with black dots) is a physical leaky mode and is the leaky branch already plotted in Fig. 4; it enters the bound-mode triangle at about 22 GHz (exactly at 21.965 GHz) and then splits into two improper real solutions (at 21.980 GHz). The left one of these [in Fig. 7(c)] reaches the side of the triangle (at 21.996 GHz) and then becomes the real proper branch already plotted in Fig. 4. The right improper real solution in Fig. 7(c) bends upwards with a decreasing slope until it merges [see Fig. 7(a)] with another real improper branch at 22.19 GHz (where the slope of the curve is zero): as seen in Fig. 7(a), the complex solution (nonphysical leaky mode) inside the triangle originates at this splitting point. The transition region between the fast complex solution and the proper bound mode has the typical shape already known for similar kinds of open guiding structures [4], [17].

We have shown above that, for smaller values of s/p, the new improper complex mode remains as a single continuous solution as frequency varies. The portion at lower frequencies (corresponding to the region outside of the triangle in Fig. 6(a), for $s/p = 0.4$) represents a physical leaky mode, but, as seen, it does not connect directly with the bound mode inside the triangle. On the other hand, for larger values of s/p, this solution breaks into two parts, and the part for lower frequencies [outside the triangle in Fig. 7(a), for $s/p = 0.6$] becomes identical with the leaky-mode portion outside the triangle in Fig. 4, which is a (complex) continuation of the bound-mode solution inside the triangle. In a limited sense, therefore, the new solution can be viewed as an evolution from the known leaky-mode solution in Fig. 4. However, this evolution requires knowing that the solution has two parts, and the existence of the second part, which is improper complex and nonphysical, was not previously known. Then, of course, one must know that when s/p is decreased these two separate parts will join, etc. None of this was known or suspected before, so it is valid to state that this previously unknown and unreported solution is new.

The presence of this mode also allows the constancy of the algebraic multiplicity of the solutions of the dispersion equation to be maintained when the frequency and the geometrical parameters are varied continuously.

The detailed evolution of the new mode for this structure as s/p is varied over a wide range is described in the following section.

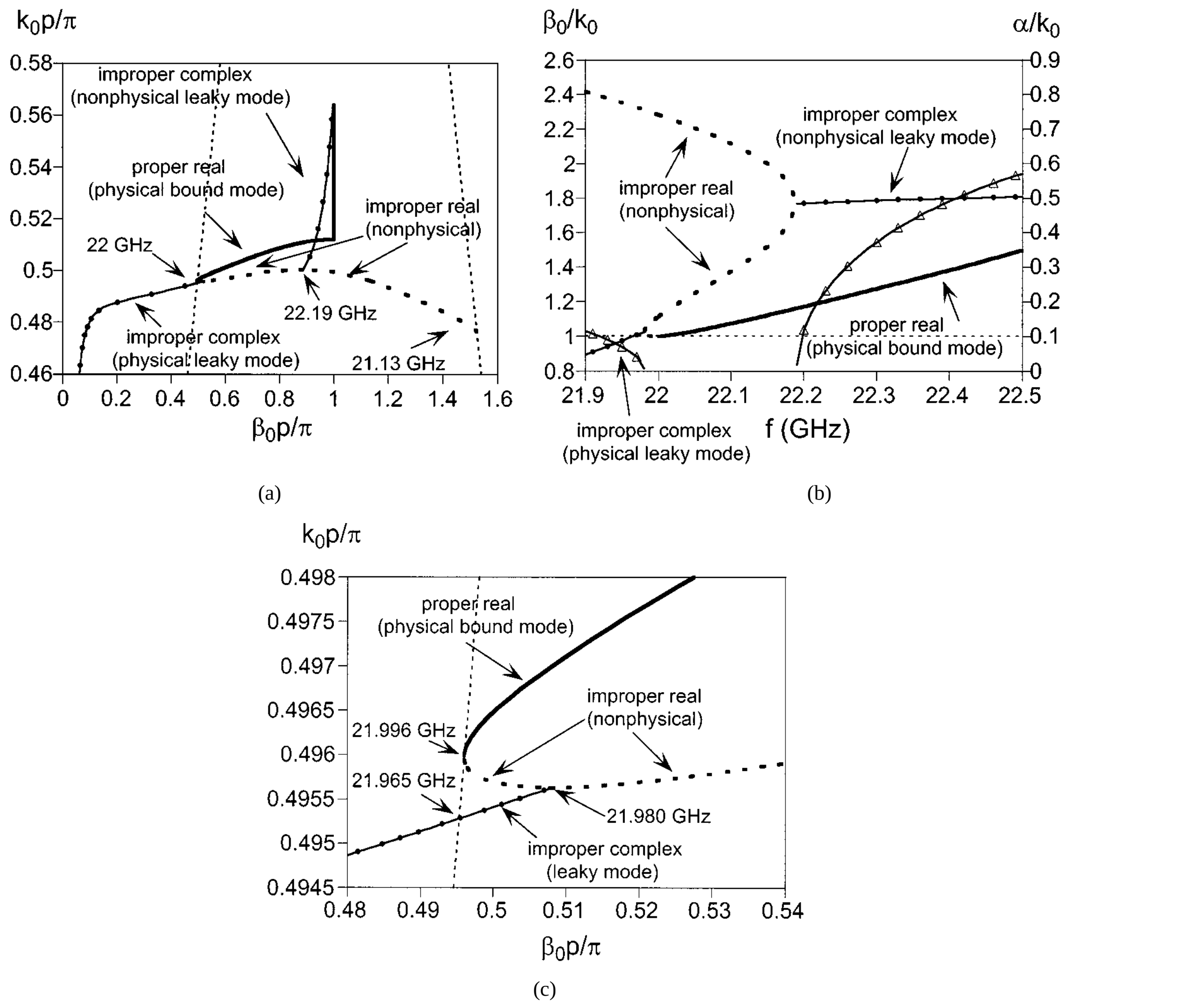


Fig. 7. Case of Fig. 4 ($s/p = 0.6$), but including the new complex solution, shown with a continuous line with black dots. (a) Brillouin diagram with additional nonphysical solution. (b) Corresponding dispersion diagram. The new solution is now seen to be split into two separate portions. (c) Details of the transition region at forward endfire of the $n = 0$ radiating space harmonic, showing the behavior of the spectral gap there.

IV. Parametric Analysis of the New Complex Mode

A. The Effects of Varying the Ratio Between the Strip Width and the Spatial Period

The first set of results concerns the changes in the low-frequency dispersion features of the structure for various geometrical configurations.

In Fig. 8, a set of dispersion diagrams of the fundamental harmonic of the new improper complex mode is shown, for a grating with physical parameters as in Figs. 4–7 ($\varepsilon_r = 20$), for a wide range of values of the s/p ratio (from 0.2 to 0.8). It is seen from Fig. 8 that, for low s/p values, this new improper complex mode is an independent solution of the dispersion equation, which exists in addition to the fundamental TE mode. For $s/p = 0.2$, the normalized phase constant β_0/k_0 is always greater than unity, so that the mode has no physical meaning, and it will, therefore, not leak any physical power. Again, at the frequency for which the phase constant matches that of the improper real solution of the fundamental TE mode, the relevant curve of the attenuation constant changes its slope.

By increasing s/p to 0.4, the mode becomes physical over a wide frequency range, even though its attenuation constant is always very high, with a minimum at the above-mentioned phase-match frequency. By further increasing the value of the s/p ratio, the minimum of the attenuation constant is lowered and it becomes sharper.

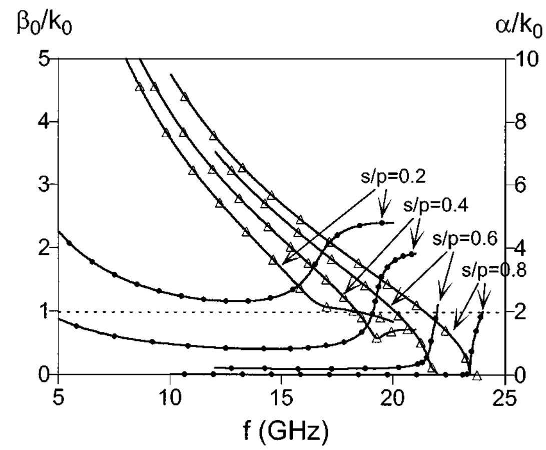


Fig. 8. Parametric analysis for a structure with the same parameters as in Fig. 4, for different values of s/p. Dispersion diagrams for s/p ranging from 0.2 to 0.8.

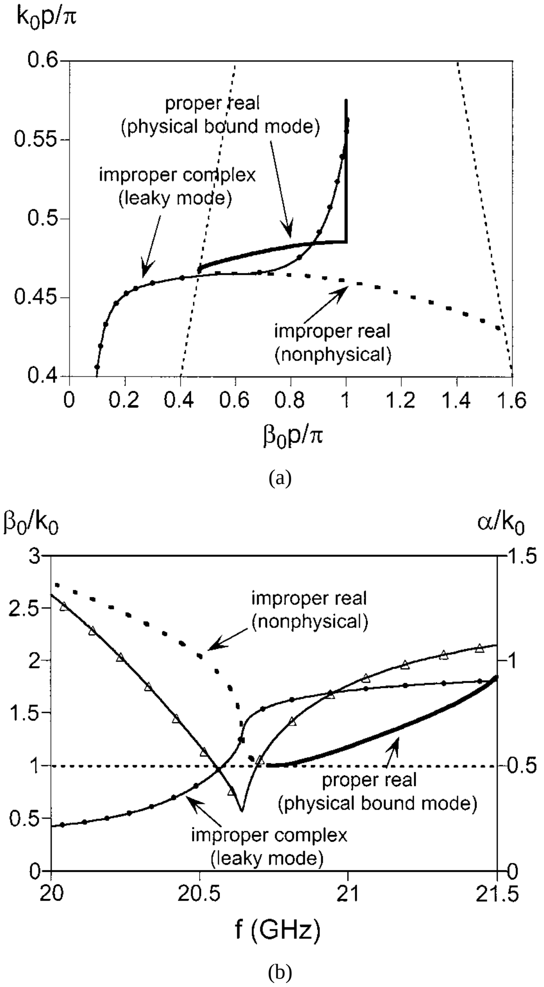


Fig. 9. Results for $s/p = 0.5$, to show behavior intermediate between those for $s/p = 0.4$ (Fig. 6) and $s/p = 0.6$ (Fig. 7). The other parameters are the same as those in Fig. 4. (a) Brillouin diagram. (b) Corresponding dispersion diagram.

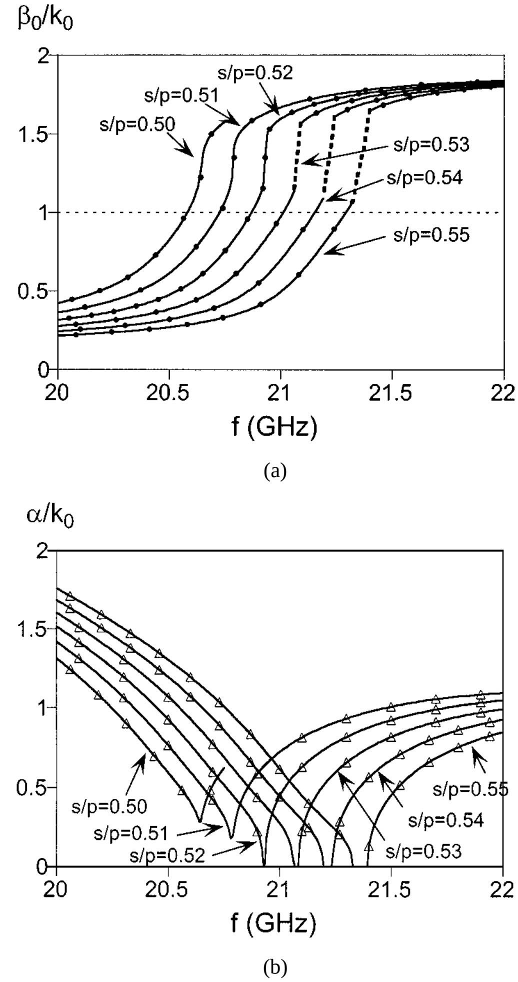


Fig. 10. The dispersion behavior of the new complex mode as the s/p ratio is increased from 0.50 to 0.55. (a) Normalized phase constant. (b) Normalized attenuation constant. These results show the details of the transition from a single continuous complex solution to the splitting into two separate complex branches, one physical and the other nonphysical.

In agreement with the remarks above, it was shown in the previous section for the dispersion diagram in Fig. 6(b) (for $s/p = 0.4$) that the curve for α/k_0 for the new leaky mode had a minimum at the frequency for which the crossing occurs between the β_0/k_0 values for the new leaky mode (when nonphysical) and the nonphysical improper real mode of the original TE mode. It was also pointed out that, when the value of s/p is increased, this minimum in α/k_0 becomes sharper, eventually going to a null. After a further increase, the new mode is no longer continuous, but splits into two separate complex branches, connected by an improper real branch. Then, for $s/p = 0.6$, Fig. 7(b) demonstrated such a splitting into two separate branches.

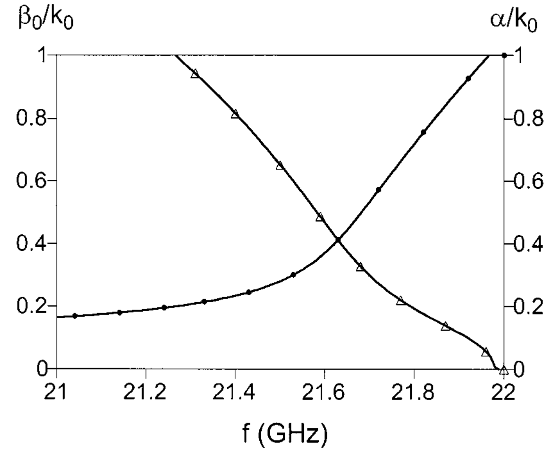
For some value of s/p between 0.4 and 0.6, therefore, the dispersion behavior should exhibit a null in α/k_0 at the crossing of the phase constants mentioned just above. We selected the value $s/p = 0.5$ to determine the behavior for that intermediate value, and the results are presented in Fig. 9(a) and (b). It is seen in Fig. 9(b) that the minimum is much closer to a null than that shown in Fig. 6(b) for $s/p = 0.4$, but has not quite reached it, and that the crossing in the phase constants appears at that frequency to have a common inflection point and approximately the same tangent. This behavior is in agreement with our expectations.

In order to pinpoint the s/p value for which the null actually appears, and also to observe how the splitting of the new mode into separate branches occurs, the dispersion curves shown in Fig. 10(a) and (b) were calculated for β_0/k_0 and α/k_0, respectively. These curves are for the new mode only, and the s/p values range from 0.50 to 0.55. From the α/k_0 results [see Fig. 10(b)], we can readily see that the null occurs for $s/p = 0.52$. As s/p increases, we may observe the evolution from a minimum to a null, and then watch as the splitting widens between the two separate complex branches.

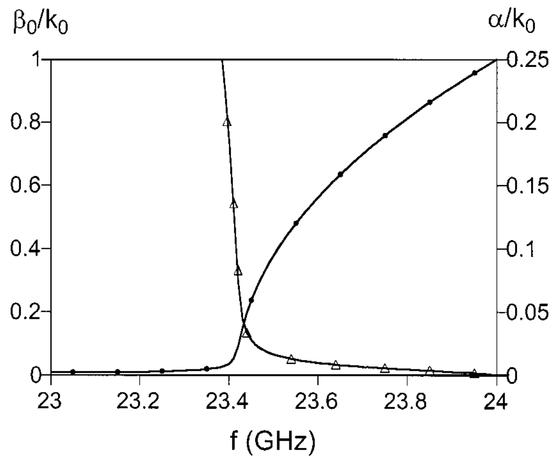
After the complex mode splits into two separate complex branches, the lower (and physical) part of it is no longer a separate solution, but represents instead the low-frequency leaky continuation of the fundamental TE mode (already seen in Fig. 4 for the case $s/p = 0.6$).

B. Identification of Useful Physical Ranges for Leaky-Wave Antenna Applications

We may also ask if there are parameter ranges for which the values of β_0/k_0 and α/k_0 are suitable for narrow-beam



(a)



(b)

Fig. 11. Examples of possible useful ranges for application to leaky-wave antennas: dispersion diagram of the new improper complex (leaky) mode for parameters as in Fig. 4 with: (a) $s/p = 0.6$ and (b) $s/p = 0.8$. Case (b) permits narrow-beam radiation over a wide angular range.

leaky-wave antennas. It should be noted that, in most cases, especially for low values of the s/p ratio, the new complex mode has a very high attenuation constant over the whole frequency range for which the mode is fast (and, therefore, has physical meaning). Our analysis has led to the identification of cases where efficient radiation through the fundamental ($n = 0$) harmonic can be achieved by employing basically closed structures. For suitable choices of the parameters, the attenuation constant can be sufficiently low to permit a narrow-beam scan over a wide angular range.

In Fig. 11(a), an enlarged plot of a portion of the dispersion diagram for a structure as in Fig. 4 with $s/p = 0.6$ is presented. The attenuation constant increases rapidly as frequency decreases, so that it has rather impractical values unless very wide beams are desired. By increasing the value of s/p, the situation changes, as shown in Fig. 11(b) for $s/p = 0.8$. In this case, the curve of the attenuation constant flattens and lowers, so that a useful range of frequency values can be obtained for which a narrow directive beam can scan in the forward quadrant over a wide angular range.

As an example, for a leaky-wave antenna whose length is selected (as is customary) so that about 90% of the power is radiated, we may calculate from the data in Fig. 11(b), using simple approximate expressions [5], that for $f = 23.6$ GHz the beam angle is about 34° from broadside, and the beamwidth is about 3.5°.

V. Conclusion

We have systematically investigated the low-frequency behavior of the fundamental TE mode of a typical periodically loaded open structure, a metal-strip grating on a grounded dielectric slab, which is often used at microwave frequencies for filtering and radiating applications.

With respect to the use of this structure as a leaky-wave antenna, all previous designs have based the radiation on the $n = -1$ space harmonic, for which the frequency must be above that for the first stopband of the periodic structure. Our investigation is concerned with the performance at low frequencies, for which the radiation is provided by the fundamental ($n = 0$) space harmonic. It turns out that, for most ranges of strip width relative to the period, the leakage (or attenuation) constant is too high to be practical. For an almost-closed structure, however, as shown in Section IV-B, it is possible to obtain, for suitable choices of the geometrical parameters, values of the phase and leakage constants that permit narrow-beam scan over a wide angular range. A specific example is presented.

Early in the investigation we came across some results that were initially puzzling. By following the customary analytical procedures, we determined that when the strips were wide (producing an almost-closed structure) radiation was obtained at low frequencies from the $n = 0$ space harmonic, as expected. When the strips were narrow, however, resulting in an almost-open structure, no radiation was found. This result was counterintuitive, producing something of a mystery.

This mystery was resolved when we discovered a new, previously unknown, leaky mode. With this new additional solution, radiation was found for almost all ranges of strip widths, and the transition from the almost-closed case to the almost-open one became clear. The paper shows the evolution from one limiting case to the other in a systematic way, explaining the important role played by nonphysical solutions in the process. This discovery of the new mode, and the explanation of its role in the physical behavior of the $n = 0$ space harmonic as the strip width changes, forms an important contribution to the understanding of the basic behavior of this class of periodic structures.

References

[1] R. E. Collin, *Field Theory of Guided Waves*. New York, NY: IEEE Press, 1991, ch. 9.

[2] C. Elachi, “Waves in active and passive periodic structures: A review,” *Proc. IEEE*, vol. 64, pp. 1666–1698, Dec. 1976.

[3] A. A. Oliner and A. Hessel, “Guided waves on sinusoidally-modulated reactance surfaces,” *IRE Trans. Antennas Propagat.*, vol. 7, pp. S201–S208, Dec. 1959.

[4] A. Hessel, “General characteristics of traveling-wave antennas,” in *Antenna Theory*, R. E. Collin and F. J. Zucker, Eds. New York, NY: McGraw-Hill, 1969, ch. 19.

[5] A. A. Oliner, “Leaky-wave antennas,” in *Antenna Engineering Handbook*, 3rd ed, R. C. Johnson, Ed. New York: McGraw-Hill, 1993, ch. 10.

[6] M. Guglielmi and G. Boccalone, "A novel theory for dielectric-inset waveguide leaky-wave antennas," *IEEE Trans. Antennas Propagat.*, vol. 39, pp. 497–504, Apr. 1991.

[7] M. Guglielmi and D. R. Jackson, "Broadside radiation from periodic leaky-wave antennas," *IEEE Trans. Antennas Propagat.*, vol. 41, pp. 31–37, Jan. 1993.

[8] M. Ghomi, B. Lejay, J. L. Amalric, and H. Baudrand, "Radiation characteristics of uniform and nonuniform dielectric leaky-wave antennas," *IEEE Trans. Antennas Propagat.*, vol. 41, pp. 1177–1185, Sept. 1993.

[9] J. A. Encinar, "Mode-matching and point-matching techniques applied to the analysis of metal-strip-loaded dielectric antennas," *IEEE Trans. Antennas Propagat.*, vol. 38, pp. 1405–1412, Sept. 1990.

[10] R. A. Sigelmann, "Surface waves on a grounded dielectric slab covered by a periodically slotted ground plane," *IEEE Trans. Antennas Propagat.*, vol. AP-18, pp. 379–388, May 1970.

[11] J. Jacobsen, "Analytical, numerical and experimental investigation of guided waves on a periodically strip-loaded dielectric slab," *IEEE Trans. Antennas Propagat.*, vol. AP-15, pp. 672–676, Sept. 1967.

[12] F. H. Bellamine and E. F. Kuester, "Guided waves along a metal grating on the surface of a grounded dielectric slab," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 1190–1197, July 1994.

[13] M. Guglielmi and A. A. Oliner, "Multimode network description of a planar periodic metal-strip grating at a dielectric interface—Part I: Rigorous network formulations," *IEEE Trans. Microwave Theory Tech.*, vol. 37, pp. 534–541, Mar. 1989.

[14] S. Majumder, D. R. Jackson, A. A. Oliner, and M. Guglielmi, "The nature of the spectral gap for leaky waves on a periodic strip-grating structure," *IEEE Trans. Microwave Theory Tech.*, vol. 45, pp. 2296–2306, Dec. 1997.

[15] M. Guglielmi and H. Hochstadt, "Multimode network description of a planar periodic metal-strip grating at a dielectric interface—Part III: Rigorous solution," *IEEE Trans. Microwave Theory Tech.*, vol. 37, pp. 902–909, May 1989.

[16] P. Burghignoli, P. Baccarelli, F. Frezza, A. Galli, P. Lampariello, and A. A. Oliner, "The nature of the radiation at low frequencies from a class of periodic structures," in *Proc. 30th European Microwave Conf.*, Paris, France, Oct. 2000, pp. 349–352.

[17] A. Hessel and A. A. Oliner, "Mode-coupling regions in the dispersion curves of modulated slow wave antennas," *IEEE AP-S Int. Symp. Dig.*, pp. 104–108, 1963.

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