Properties of Guided Modes on Open Structures Near the Cutoff Region Using a New Version of Complex Effective Dielectric Constant

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***Abstract*—Radiation region for open guiding structures is known to be further divided into antenna- and reactive-mode regions, and there is no clear cutoff point defined between the two regions. For a leaky-wave antenna, it is crucial that the antenna is designed to operate in the antenna-mode region so as to increase radiation efficiency, whereas in integrated circuits, the leakage should be suppressed to avoid unwanted coupling among circuits. Therefore, a reasonable definition of the two above-mentioned mode regions is necessary. In this paper, we propose a simple, but good alternative to define these two regions by means of a new version of complex effective dielectric constant, where the complex nature is due to leakage rather than dielectric or metal losses, as is customary. With the new approach, the reactive-mode region is found to be consistent with the conventional concept, and our results are similar to those in the literature. The present technique, however, helps in a better understanding of the results in a much easier way. Furthermore, we find for the first time that the attenuation constant in the deep reactive-mode region can be divided into two separate parts, one is due to the cutoff effect, while the other is caused by the leakage effect. Simple closed-form expressions are derived to determine the two kinds of effects. One can, therefore, gain some insight into the leakage effect in the reactive-mode region. A nonradiative-guide leaky-wave antenna is then investigated as a showcase and low radiation efficiency is observed in the reactive-mode region.**

***Index Terms*—Antenna mode, complex effective dielectric constant, guided waves, leakage effects, nonradiative waveguide, open structure, reactive mode.**

I. Introduction

LEAKY-WAVE phenomena have been used in antenna design for a long time [1]. With the recent emergence of low-loss waveguiding structures, many leaky-wave antennas based on such guides that possess a number of inherent merits were proposed for practical applications, especially in the millimeter-wave range [2]–[8]. To cope with the design requirements of leaky-wave antennas, Oliner and his co-workers developed some useful theoretical model [9]. With the recognition of power leakage from printed-type transmission lines, such as microstrip lines, slot lines, and coplanar waveguides, the leaky-wave phenomenon has attracted more and more attention in connection with RF and millimeter-wave integrated circuits (ICs). It may cause some headaches such as signal power loss and crosstalk interference [10], [11]. Once excited, the leaky mode radiates power into the fundamental guided-wave mode of the background structure. This guided-wave field may then interact with other transmission lines or circuit components, resulting in undesirable power loss, crosstalk, and package effects, which can ruin the performance of the circuit in question unless the leakage effects are well understood and controlled beforehand.

More and more guiding structures have been found to be subject to leakage in a certain frequency range. The purpose of leakage investigation for antenna applications and ICs is, however, quite different. In the former case, the leakage is highly desired, whereas in the latter case, the leakage is undesirable and should be suppressed [12], [13]. Nevertheless, whether the leakage is to be enhanced or suppressed, its characteristics should be studied and *a priori* knowledge is required.

It is well known that the guidance region of higher order modes in a microstrip-line is divided into the following three subregions with decreasing frequency:

1) bound-mode region;
2) surface-wave region;
3) radiation-mode region [14].

Although it is made for a microstrip antenna, this distinction is apparently also suitable for other guiding structures, except that there exists no surface-wave region in some cases such as the nonradiative guide (NRD-guide) [2]. Modal behavior at the transition from bound to leaky state has already been studied in the literature [15]. Oliner has pointed out that the mode in the radiation region with a large attenuation constant is reactive. Therefore, it is natural for Lin and his co-workers to divide the radiation region further into the antenna- and reactive-mode regions [16]. In [16], Lin and Sheen have also claimed that there is no clear point to distinguish the reactive-mode region from the antenna-mode region, as leakage exists physically in the whole radiation region [14]. Compared to the transition from bound to leaky states, modal properties between the current two regions of interest have not yet been studied much. This is probably due to the difficulty of determining a critical point to separate them, even though a critical point is clearly defined between the bound

Manuscript received June 31, 1999; revised May 23, 2000. This work was supported by the National Science Foundation of China under Project 69871026, by the Research Grant Council of Hong Kong under the Competitive Earmarked Research Grant Project 9040371, and by the Natural Sciences and Engineering Research Council of Canada under a Strategic Grant Scheme.

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Publisher Item Identifier S 0018-9480(02)04044-9.

and leaky regions. However, a further investigation into the two regions is significant. The reason is twofold. First, a guiding structure used as an antenna should operate safely in the antenna-mode region so that its high radiation efficiency can be guaranteed. Second, an IC should operate in the bound region or in the deep reactive-mode region in order to eliminate or decrease the leakage effect as much as possible. Deep below cutoff is used since, in most cases, there is no pure evanescent region without any associated leakage.

Thus far, the transition from the reactive- to antenna-mode region was investigated only for the microstrip-line leaky-wave antenna [16]–[18]. In [16], Lin *et al.* defined the reactive-mode region as a frequency region, in which the imaginary power is larger than the real power guided along the propagation direction. They also found that the frequency point, where the attenuation constant is equal to the phase constant, is almost the same as the point where the normalized propagating imaginary power equals one. Nevertheless, two neat questions were not clearly answered there, i.e., 1) why the reactive-mode region is so defined and 2) why the frequency point where the attenuation constant is equal to the phase constant is always nearly the same point where the imaginary power is equal to the real part. We will see later that the role of the imaginary power is essentially the same as that of the attenuation constant. Also, in the reactive-mode region, neither the attenuation constant, nor the imaginary power alone can provide us much information about the leakage. It is the purpose of this paper to find a simple way to give a reasonable alternative definition of the reactive-mode region and to get more meaningful information about the leakage in this region.

In this paper, we propose a simple, but good alternative definition of the reactive-mode region by means of the concept of a complex effective dielectric constant, where the complex nature is due to leakage, not to dielectric or metal losses, as is customary. This concept will be shown to have a number of technical merits. First, it is very simple and also consistent with the conventional definition of the reactive-mode region, thus it is easy to be understood. Second, our definition based on the complex effective dielectric constant is surprisingly consistent with that defined in [16]. Third, the concept can give a simple qualitative explanation to the second aforementioned question, i.e., why the point where the attenuation constant is equal to the phase constant is always nearly the same point where the imaginary part of power equals the real part. Finally, the concept can be used to distinguish the contributions of reactance and of leakage to the attenuation constant in a qualitative sense. Furthermore, the attenuation constant in the deep reactive-mode region can even be quantitatively divided into two separate parts considering the cutoff effect and leakage effect, respectively, which makes it possible for us to gain some qualitative or quantitative knowledge of the leakage in this region.

In Section II, the concept of a complex dielectric constant is given, and details are discussed as to define the reactive-mode region. A qualitative information about the leakage is then obtained and the attenuation constants due to the cutoff and leakage effects are determined, respectively, in a closed form for the deep reactive-mode region. Subsequently, an NRD-guide leaky-wave antenna is considered as an example and the approach of obtaining its complex effective dielectric constant is briefly discussed in Section III. In Section IV, results are described and low radiation efficiency is observed from the leakage-related attenuation constant in the reactive-mode region.

II. Concept of a Complex Effective Dielectric Constant

Among the parameters characterizing a leaky-wave antenna, the attenuation and phase constants are two of the most important ones, and they must be determined accurately beforehand either theoretically or experimentally. With the two parameters in hand, we can easily construct the complex effective dielectric constant without any further complicated calculations as follows:

$$Er - jEi = (\gamma/k_0)^2 = \left((\beta - j\alpha)/k_0\right)^2. \tag{1}$$

Wave propagation in the z-direction is assumed to follow $e^{-j\gamma z}$. This definition is obviously the same as the usual effective dielectric constant, which is very familiar to microwave engineers. Notation Er and Ei are used herewith to denote the real and negative imaginary parts of the complex effective dielectric constant, respectively. As we know, in a conventional metallically closed waveguide, $\alpha = 0$ and $\beta > 0$ when above cutoff, whereas $\beta = 0$ and $\alpha > 0$ when below cutoff. Therefore, the reactive region can be defined by either $\alpha > 0$ or $\beta = 0$. Er is also greater than zero when above cutoff and less than zero when below cutoff with Ei always being zero. Therefore, we can also determine the reactive region as $Er < 0$. The standard NRD-guide operating is also above or below cutoff. In a leaky-wave antenna, however, it is more complicated. Since β and α are always positive as long as the leakage exists, the previous definition using α or β then becomes impracticable when leakage exists. Furthermore, the leakage in the reactive-mode region cannot be determined solely from the attenuation constant because both the leakage and reactance contribute to the attenuation constant. However, no such difficulties will occur if the latter definition is used. That is to say, $Er = 0$ is still a suitable alternative to distinguish the antenna- and reactive-mode regions when leakage exists. Apparently, this choice will be very good when a small leakage is involved. We will see later that Ei contains the information about the leakage in the reactive-mode region, and the cutoff effect, which contributes mainly to Er, has no direct relation to Ei in that region. In this way, $Er = 0$ is used to separate the antenna- and reactive-mode regions in our analysis, and Ei is used to help us determine the leakage effect in the reactive-mode region, which will be discussed below.

Let us consider the example of an NRD-guide leaky-wave antenna, as shown in Fig. 1. First, let us begin with a standard NRD-guide without an air gap (i.e., $t = 0$), and assume that the exponential factor along the z-direction be expressed as $e^{-j\gamma z}$ with $\gamma = \beta - j\alpha$. It is well known that α varies from a positive real β to zero, and then to a complex value having only the imaginary part $-j\alpha$, when the eigenmode operates from the propagation region to the cutoff region, with its trajectory path in the complex plane described in Fig. 2(a). In parallel,

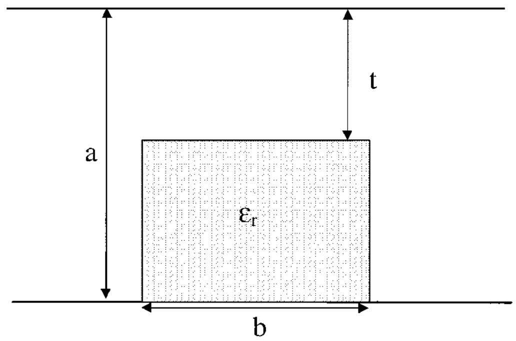

Fig. 1. Cross-sectional view of an NRD-guide leaky-wave antenna, which is showcased as an example for the proposed approach on the basis of the concept of complex effective dielectric constant.

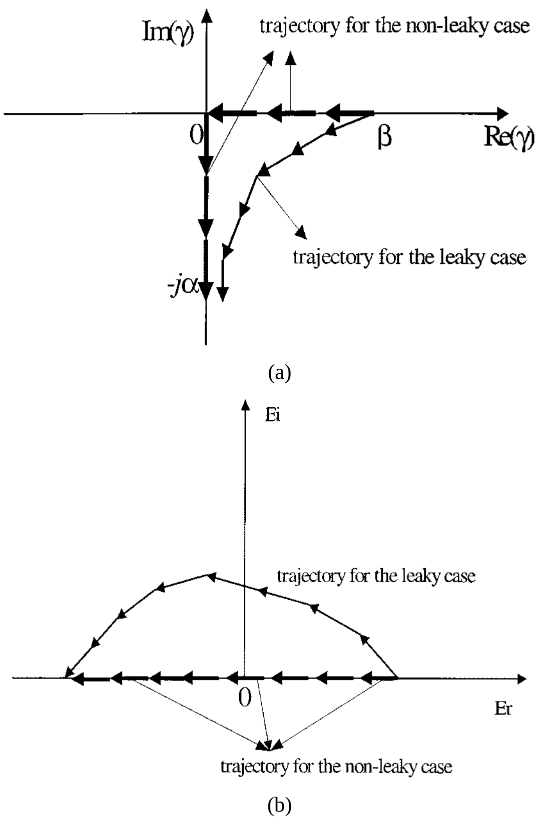

Fig. 2. Description of the modal properties in the complex plane. (a) Trajectory path of the propagation constant when the mode operates from the guided-wave state to the evanescent state. (b) Trajectory path of Ei–Er curves for the leaky and nonleaky cases when the mode operates from the guided-wave state to the evanescent state.

γ^2 just varies from a positive real to zero and then to a negative real value. That means when there is no leakage, the trajectory path of γ^2 will never be apart from the horizontal axis in the Ei–Er diagram because, in this case, Ei is always equal to zero. However, when t increases away from zero with suitably chosen geometric parameters, the guide starts to leak power along the transverse direction that will make the Ei–Er curve deviate from the horizontal axis, as indicated in Fig. 2(b). As the dielectric is assumed to be lossless and the conductivity of metallic plates is assumed to be infinite, it is obvious that the deviation of the Ei–Er curve from the horizontal axis is totally due to the leakage effect. Therefore, we can get some qualitative knowledge of the leakage from Ei.

From the above discussion, it suggests that the region, where the real part of complex effective dielectric constant is less than zero, be a suitable alternative definition for the reactive-mode region. In the following, we will see that our definition is surprisingly identical to that defined in [16], and the complex effective dielectric constant can also help us to understand qualitatively other aspects.

When the real part is equal to zero, we have from (1)

$$-jEi = (\beta - j\alpha)^2 / k_0^2 \tag{2}$$

which yields $\beta = \alpha = k_0\sqrt{Ei/2}$. Hence, the critical point to separate the reactive-mode region from the antenna-mode region, according to the current definition, is the crossing point of the β and α curves, which is the same as that used in [16]. Lin and Sheen defined in [16] the critical point as the one where the imaginary part of the power propagating toward the propagation direction is equal to the real part. They also pointed out that it is almost the same as the point where the attenuation constant is equal to the phase constant. They obtained that result after having carried out a complicated calculation. In this study, we find that the concept of a complex effective dielectric constant can give a simple qualitative explanation over their concluding remarks. It is known that along the propagation direction, the space can be viewed as the one filled homogeneously with a medium having a dielectric constant equal to the effective dielectric constant. Unlike the practical complex dielectric constant, the negative imaginary part of the current one is due to the leakage instead of the dielectric loss. Therefore, the space is uniform in the propagation direction, and its effective characteristic impedance can simply be formulated by

$$Z = \sqrt{\frac{\mu_0}{\varepsilon_0(Er - jEi)}} = \frac{\eta_0 k_0}{\beta - j\alpha} = \eta_0 k_0 \frac{\beta + j\alpha}{\beta^2 + \alpha^2}. \tag{3}$$

If we do not mind whether the reactance is inductive or capacitive, we can then deduce qualitatively that the ratio of the imaginary part of power to the real part is equal to α/β. One can then see that: 1) when the mode is bound ($\beta > 0$, $\alpha = 0$), the power transmitting toward the propagation direction is real and there is no imaginary part and 2) when the mode goes into the antenna-mode region, α increases, and the imaginary power begins to increase. Here, we should note that increasing the imaginary power is caused by the leakage effect instead of others, just as the emergence of α is due to the leakage. When the mode runs into the reactive-mode region, we can see that α increases rapidly, as does the imaginary power, and most of the power is, therefore, stored, resulting in a large power reflection to the feeding structure, as shown in [16] and [17] for microstrip line leaky-wave antennas. The ratio of the imaginary part of power to the real part is qualitatively depicted in Fig. 3 for both leaky and nonleaky cases. We can now see that the role of the imaginary power is essentially the same as that of the attenuation constant. The attenuation constant alone cannot give much information about the leakage in the reactive-mode region and neither can the imaginary power.

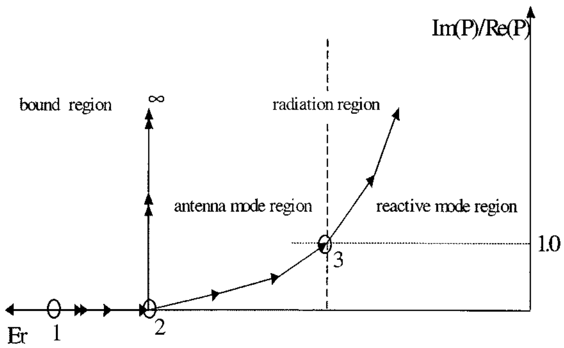

Fig. 3. Trajectory path of the ratio of the imaginary power to the real one for the leaky and nonleaky cases. ►► for the nonleaky case (from O_1 to O_2 then to ∞), ► for the leaky case (from O_1 to O_2 to O_3 to the reactive-mode region) and the radiation region for the leaky case becomes a pure evanescent region for the nonleaky case with $\mathrm{Im}(P)/\mathrm{Re}(P)$ always being ∞.

Also in the deep reactive-mode region (Ei is much less than $|Er|$), one can further divide the attenuation constant into two parts using the complex effective dielectric constant; one is on the basis of the cutoff effect, while the other is on the leakage effect. Leakage properties in this region can be approximately obtained as follows. From (1), we have

$$\beta - j\alpha = k_0\sqrt{Er - jEi}. \tag{4}$$

Since Ei is much less than $|Er|$, the square root can be expanded into a Taylor series as

$$\sqrt{Er - jEi} = -j\sqrt{|Er|}\left[1 + \frac{1}{8}\left(\frac{Ei}{Er}\right)^2 - \frac{5}{128}\left(\frac{Ei}{Er}\right)^4\right] + \sqrt{|Er|}\left[\frac{1}{2}\frac{Ei}{|Er|} - \frac{1}{16}\left(\frac{Ei}{|Er|}\right)^3\right] + \text{c.c.} \tag{5}$$

Neglecting the higher order terms leads to approximate expressions for the phase and attenuation constants

$$\beta = k_0\frac{Ei}{2\sqrt{|Er|}} \tag{6}$$

$$\alpha = k_0\sqrt{|Er|}\left(1 + \frac{Ei^2}{8Er^2}\right) = \alpha_c + \alpha_l \tag{7}$$

with

$$\alpha_c = k_0\sqrt{|Er|} \quad \alpha_l = k_0\frac{Ei^2}{8|Er|\sqrt{|Er|}}. \tag{8}$$

In (8), α_c, related to the cutoff effect, is independent of Ei, and α_l, due to the leakage effect, heavily depends on Ei. From (8), we note that, as expected, if there is no leakage, α_c is exactly the same as the conventional one. The leakage effect also really enhances the attenuation constant. From (6) to (8), we have

$$\frac{\alpha_l}{\alpha_c} = \frac{Ei^2}{8Er^2} = \frac{\beta^2}{2\alpha_c^2} \approx \frac{\beta^2}{2\alpha^2}. \tag{9}$$

Since β stays small and α increases rapidly as we go further into the reactive-mode region, this expression directly shows us that the ratio α_l/α_c becomes smaller and smaller very rapidly as we enter further into the reactive-mode region. With (7) and (9), we get an approximate expression for α_l as

$$\alpha_l \approx \frac{\alpha\beta^2}{\beta^2 + 2\alpha^2}. \tag{10}$$

Considering that β is much small than α, (10) can be simplified further as follows:

$$\alpha_l \approx \frac{\beta^2}{2\alpha}. \tag{11}$$

An approximation for the leakage contribution to the attenuation constant is now obtained just using β and α.

III. Calculation of the Complex Effective Dielectric Constant

To obtain the complex effective dielectric constant, as discussed above, one should first calculate the propagation constant, which is always required in the design or analysis for a leaky-wave antenna. A number of ways are available to do so. In our analysis, a combining method of a multimode network technique with a mode-matching method is used [19]. In Fig. 1, the structure can be divided into an air-filled parallel-plate region and partially dielectric-filled planar region. In each region, electric and magnetic fields are derived in terms of a superposition of longitudinal section electric (LSE) and longitudinal section magnetic (LSM) modes. Matching tangential fields leads to the formulation of modal coupling parameters, and then a dispersion equation is obtained with the concept of transversely cascaded network. Finally, the complex propagation constant can easily be obtained by solving the resulting transcendental dispersion equation.

IV. Numerical Examples

In this section, the concept of a complex effective dielectric constant is detailed to model characteristics of the NRD-guide leaky-wave antenna shown in Fig. 1. Fig. 4 gives leakage properties of the antenna as the width of the dielectric slab varies for various normalized heights of the NRD-guide strip. The dots in Fig. 4(c) are calculated results given in [2]. Oliner has indicated that a rapid increase of the attenuation constant is due to the cutoff effect, and the nature of attenuation in the vicinity of cutoff changes from radiative to primarily reactive. From Fig. 4(a), we note that when $t/\lambda_0 = 0.0$, Ei is always zero, as there is no leakage; therefore, the curve fits exactly with the horizontal axis. When t/λ_0 is increased to 0.04, the Ei–Er curve starts to go up gradually apart from the horizontal axis, meaning the appearance of leakage. From Fig. 4(b), one can also see that when t/λ_0 becomes large, the leakage effect (Ei) becomes large; however, after t/λ_0 reaches 0.2, it decreases. Physically speaking, this is quite true because when t increases to a, the guide becomes a parallel-plate guide, and there is no leakage, as the separation of the two parallel plates is less than one-half of the free-space wavelength. The curves of Ei indicate that the

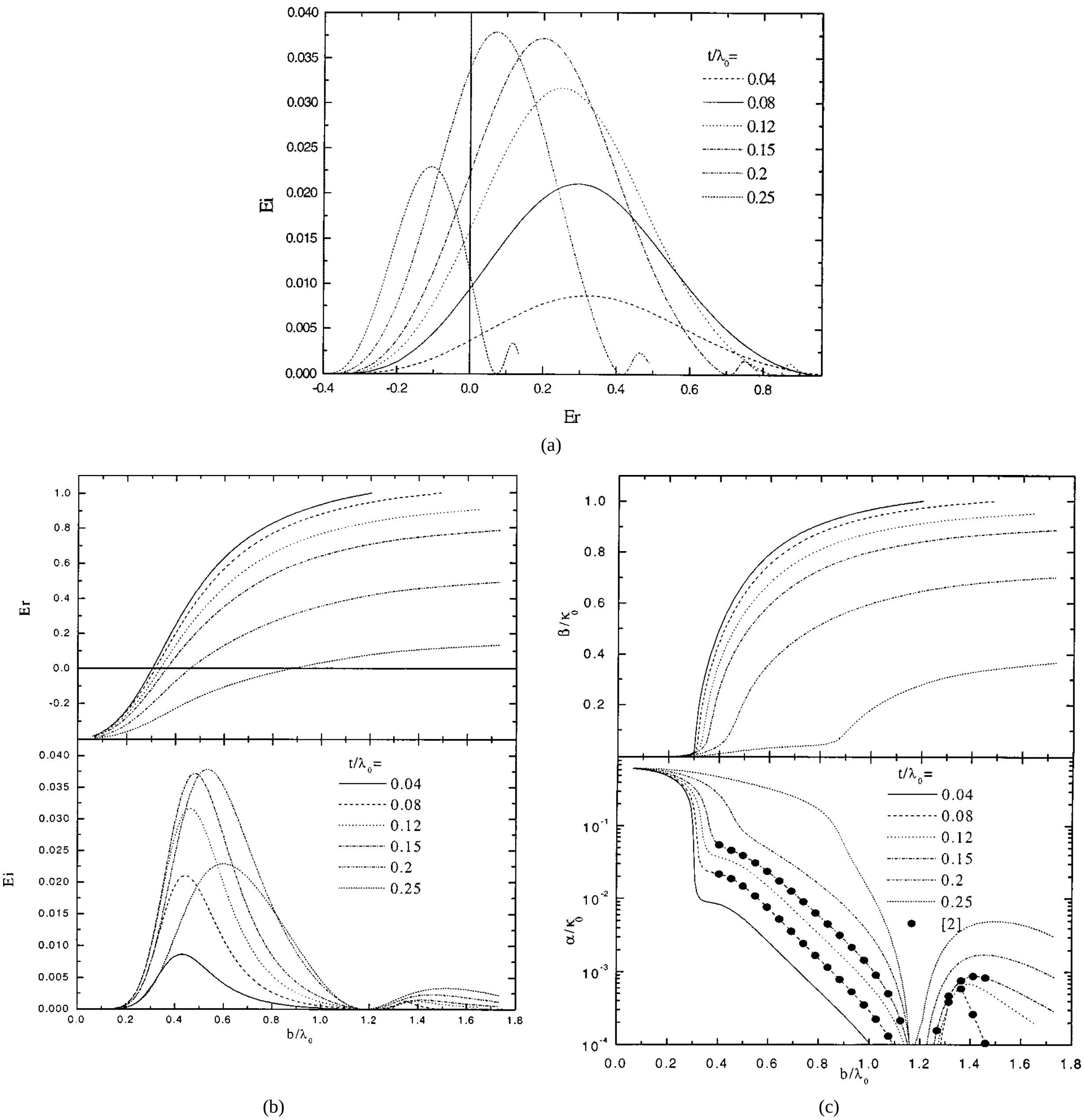

Fig. 4. Parametric effects of the NRD-guide antenna geometry including b/λ_0 on the leakage properties versus t/λ_0 with $a/\lambda_0 = 0.423$ and $\varepsilon_r = 2.56$. (a) Ei–Er diagram. (b) Real and negative imaginary parts of the complex effective dielectric constant. (c) Attenuation and the phase constants.

largest leakage occurs in the case when t/λ_0 and b/λ_0 are close to 0.2 and 0.55, respectively, which cannot be obtained from the attenuation curves. When t is fixed and b is zero, the attenuation constant is very large and it is totally due to the cutoff effect. As b increases when t is fixed, the leakage appears and increases gradually, whereas the attenuation decreases. In the vicinity of the cutoff, the normalized phase constant changes rapidly, as shown in Fig. 4(c), and reaches near 0.18 for $t/\lambda_0 = 0.2$ when Er is zero. From these figures, one can observe that, in the vicinity of $Er = 0$, the curves of the attenuation constant always undergo a sharp change.

Fig. 5 presents parametric variations of radiation characteristics of the antenna as a function of the thickness of an air gap, which was proposed for antenna application in [2], and has been used for antenna array in [20]. When t/λ_0 is less than 0.16, we obtain the same attenuation constant curves as given in [2]. A further increase of the air-gap thickness, however, makes the antenna operate below cutoff, as described in Fig. 5(a), which generates a large attenuation constant with a very low radiation efficiency. From the attenuation curves, it is very hard to determine the air-gap thickness for which the leakage gets its maximum, whereas Ei reveals such properties. Fig. 5(b) presents calculated results for the complex effective dielectric constant. The Ei curves suggest that the maximum leakage in the case of $b/\lambda_0 = 0.4, 0.6, 0.8$ takes place in the vicinity of 0.15, 0.2, 0.225, respectively. Beyond that, the attenuation constant increases further with increasing the thickness of the air gap, whereas the leakage reduces. In Fig. 5(c), (7) and (8) are used to calculate the attenuation parts due to the cutoff and leakage effects. We note from this figure that, in the deep

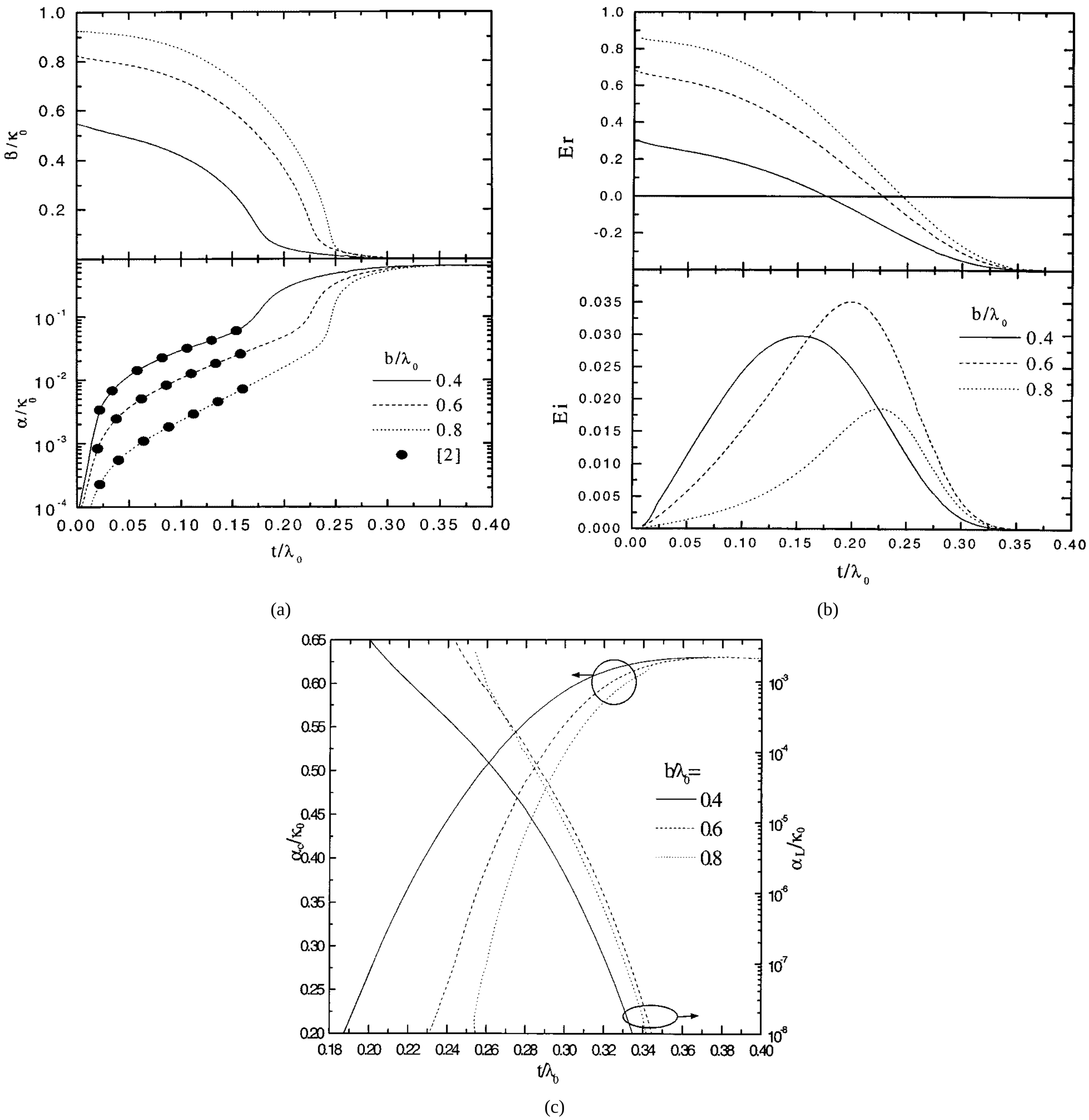

Fig. 5. Parametric effects of t/λ_0 on the leakage properties of the NRD-guide antenna with various values of b/λ_0 with $a/\lambda_0 = 0.423$ and $\varepsilon_r = 2.56$. (a) Attenuation constant and the phase constant. (b) Real and negative imaginary parts of the complex effective dielectric constant. (c) α_c and α_L in the reactive-mode region.

reactive-mode region, the attenuation caused by the leakage is much less pronounced than that caused by the cutoff effect; therefore, the radiation efficiency in this region is very low. As t/λ_0 is larger than 0.3, the attenuation caused by the leakage is negligible for all the different b/λ_0. Looking into the curves plotted in Fig. 5, we find out that using $Er = 0$ to separate the antenna- from the reactive-mode region will help the designer to make a leaky-wave antenna operate in the antenna-mode region with a high radiation efficiency. Although the concept of a complex effective dielectric constant has been applied in this paper only to the NRD-guide leaky-wave antenna, it is also applicable to many other leaky-wave structures.

V. Conclusion

A novel concept of a complex effective dielectric constant has been developed and used to define the antenna- and reactive-mode regions for open dielectric guiding structures. It overcomes the blurry concept of an attenuation constant from which one cannot obtain any knowledge about the leakage in the below-cutoff region. Compared to other available techniques in the literature, this concept has been shown to be much simpler and easier. Systematic analysis has been presented with a number of results generated from a combined numerical approach in the modeling of NRD-guide leaky-wave structures.

Our study indicates that the proposed approach can effectively assist the designer to make sure that a leaky-wave antenna operates in the antenna-mode region with high radiation efficiency, and it also generates qualitative knowledge about the leakage effect in the reactive-mode region.

ACKNOWLEDGMENT

The authors would like to acknowledge thoughtful comments and suggestions made by one of the reviewers.

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Prof. Luk is a Fellow of the Chinese Institute of Electronic and the Institution of Electrical Engineers (IEE), U.K. He is a member of the Electromagnetics Academy. He was the Technical Program chairperson of the Progress in Electromagnetics Research Symposium (PIERS 1997), Hong Kong, and the general vice-chairperson of the 1997 Asia–Pacific Microwave Conference, Hong Kong. He was the recipient of the 1994 Japan Microwave Prize presented at the Asia–Pacific Microwave Conference, Chiba, Japan. In 1995, his completed CERG project rated excellent. He received the prestigious Croucher Foundation Senior Research Fellowship in Hong Kong SAR in 2000. He also received the Applied Research Excellence Award from the City University of Hong Kong for his contributions in the development of patch antennas for wireless applications.