A Novel Leaky NRD Guide with a Double-Layer Dielectric Slab

Xiang-yin Zeng, Kwai-man Luk, *Senior Member, IEEE*, and Shan-jia Xu, *Senior Member, IEEE*

***Abstract*—A new leaky nonradiative dielectric guide with a double-layer dielectric slab is investigated in this paper by combining a multimode network theory with a mode-matching method. Numerical results show that proper selection of the permittivities can vary the leakage constant over a wide range. A leakage constant larger than 10% of free-space wavenumber can be obtained easily without entering the cutoff region. Leaky-wave antennas with shorter length and medium gain can thus be developed. In addition, the present leaky guide possesses the advantages of simple fabrication and physical stability. Extensive numerical results are provided to guide the antenna designs.**

***Index Terms*—Leaky-wave antenna, millimeter wave, NRD guide.**

I. Introduction

VARIOUS leaky-wave antennas based on nonradiative dielectric (NRD) guide [1] have been proposed for use in millimeter-wave range because of its inherent low-loss property. One of the antennas proposed by Oliner [2] has a dielectric slab routed close to the open end of the metallic plates while still maintaining the vertical symmetry of the NRD guide. Other designs break the vertical symmetry of the NRD guide by introducing some kinds of asymmetry. As a result, a net vertical electric field is produced and leakage occurs in the form of a TEM wave in the parallel-plate's region propagating away from the dielectric slab obliquely, thus making the propagation constant complex. An air gap between the dielectric slab and one of the metal plates was introduced by Oliner *et al.* [3] to form a kind of leaky-wave antenna. It makes the fabrication very easy and the antenna is kept simple. Besides, a rigorous theoretical method was established to generate design guides. Later, a trapezoidal slab NRD guide leaky-wave antenna was proposed by Yoneyama *et al.* [4], and a rigorous analysis of it appeared in [5]. In 1993, Maamria *et al.* proposed a leaky NRD guide based on a periodic array of grooves on the upper surface of the dielectric slab [6]. An approximate coupled-mode theory was used to get the complex propagation constant. In order to make the slab fixed precisely, groove NRD guide leaky-wave antenna was proposed [7].

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As is known, leaky-wave antennas are usually high-gain antennas with a length of the order of $20\lambda_0$ to $100\lambda_0$. In some wireless applications, antennas with medium gain are required. A medium-gain ($\sim$ 10 dBi–20 dBi) antenna cannot be too long. To make the antenna shorter while still keeping most of the energy radiated, the leaky-wave antenna should have a strong leakage. From the literature, it seems that, to obtain strong leakage, metallic discontinuity must be introduced, such as the microstrip leaky-wave antenna [8] and the groove NRD guide leaky-wave antenna. Also, the metallic grating has stronger leakage than dielectric grating [9]. The leaky NRD guide with an air gap does achieve a large attenuation constant when the air gap is large. However, as mentioned in [10], a large air gap may push the guide into the reactive-mode region, in which the large attenuation constant is mainly due to the cutoff effect rather than leakage effect; thus, the radiation efficiency is low. Thus, the question may arise: "Can a leaky-wave guide, without metallic discontinuity involved, achieve a large leakage constant without the risk of entering the reactive-mode region?" It is the purpose of this paper to propose a new leaky NRD guide fulfilling such requirements.

In this paper, instead of using a single dielectric slab, as in the conventional designs, a modified leaky NRD guide with two dielectric layers, as shown in Fig. 1, is presented. Since the two dielectric slabs are rectangular in shape, they can be fabricated precisely without difficulty. A rigorous multimode network combining the mode-matching technique as established in [5] is used to find out the phase and leakage constants characterizing the structure. Numerical results show that by choosing the parameters of the guide properly, a wide range of leakage can be achieved.

II. Structure of the Leaky Double-Layer NRD Guide

The antenna shown in Fig. 1 is apparently derived from the air-gap leaky-wave antenna proposed by Oliner *et al.* [3]. Different from the air-gap case, however, proper selection of the parameters of the present general two-layer leaky NRD guide makes it possible to achieve higher leakage without entering the reactive-mode region.

Fig. 2 shows the leakage properties of the air-gap case. Results in [3] are included for comparison. One can observe that the attenuation constant increases with air-gap thickness due to the increase of leakage. However, when the air gap becomes too thick, the efficiency of the antenna will be very low, even though the attenuation constant is large. As there is no clear watershed to separate the reactive- and antenna-mode regions [10], the antenna may have the risk of entering the reactive-mode region when large leakage is achieved by just increasing the air

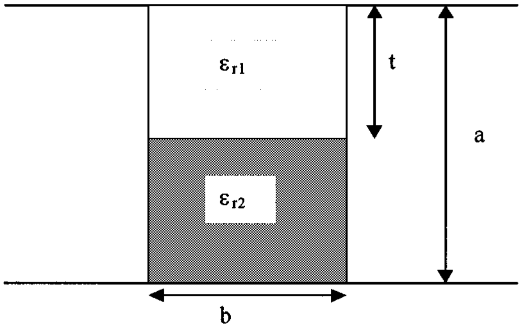

Fig. 1. Geometry of the two-layer leaky NRD guide.

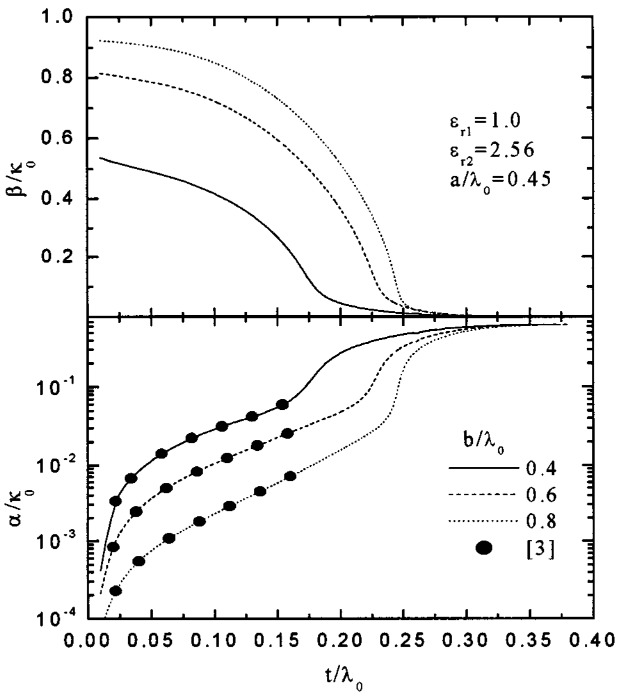

Fig. 2. Parametric effects of t/λ_0 on the leakage properties of the air-gap leaky NRD guide for a comparison.

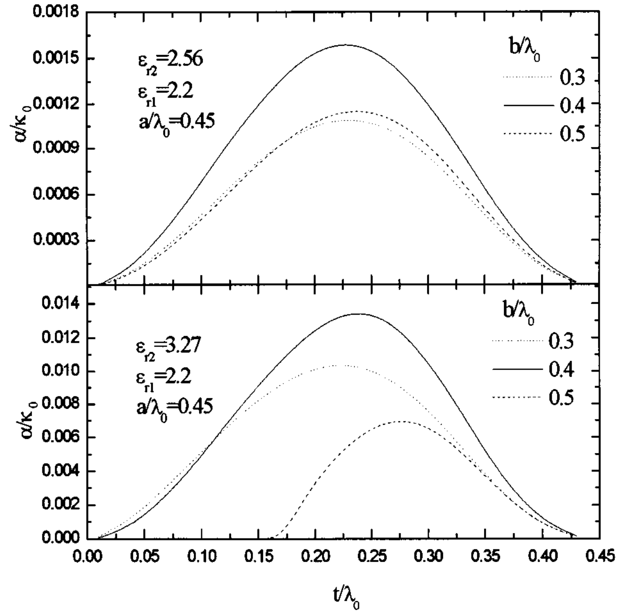

Fig. 3. Variation of the leakage constant with t/λ_0 for a small leakage case.

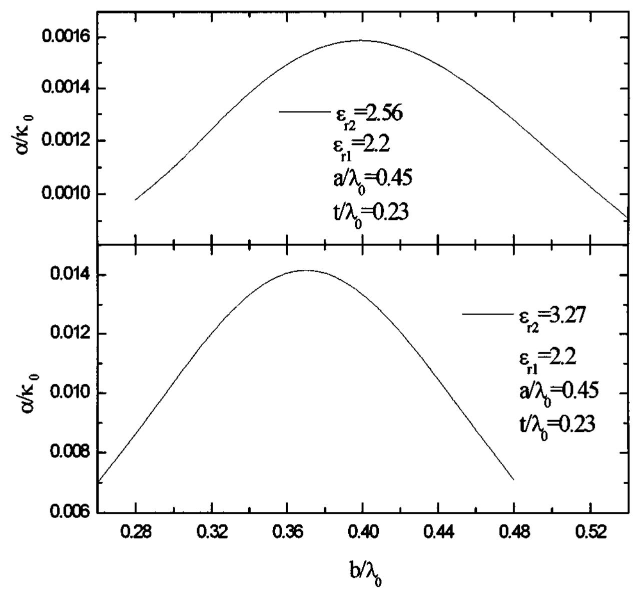

Fig. 4. Variation of the leakage constant with the dielectric slab width for a small leakage case.

gap. To fully utilize the advantages of the antenna, the air gap is replaced by another dielectric slab. Suitably choosing the dimensions of the antenna will make it far away from the reactive region, thus, high efficiency can be guaranteed. In addition, the use of a dielectric slab instead of an air gap also makes the antenna physically stable and, therefore, more practicable.

III. Design Guideline for Small Leakage Case

Usually, leaky-wave antennas operate with a normalized leakage constant α/k_0 in the order of 10^{-3}–10^{-2}, resulting in a narrow beam with high gain. In this section, we will discuss the characteristics of the present antenna and its theoretical design guidelines when small leakage is required. Fig. 3 presents variation of the leakage constant with the thickness of the upper dielectric slab, which has a small value of dielectric constant. This figure clearly shows that no leakage occurs, as expected when $t = 0.0$ or $0.45\lambda_0$, which correspond to standard NRD guide cases. However, these features fail to be revealed in Fig. 2 where an air gap is introduced because, in that case, the leakage constant is mixed with the attenuation constant caused by the cutoff effect when the thickness of the air gap is large. Therefore, one can safely say that the replacement of the air gap with a suitable dielectric slab makes the antenna work far away from the reactive-mode region. Also, from Fig. 3, one can observe that the leakage will reach the maximum when t is close to half of the separation of the two metal plates if b is not large. In other words, when b is small, two dielectric slabs of almost equal thickness will achieve maximum leakage. This is a very important guideline for the antenna design. Thus, in Fig. 4, the effect of the dielectric slab width is studied with $t = 0.23\lambda_0$ selected. The maximum leakage is obtained when the width of the dielectric slab is equal to $0.4\lambda_0$ and $0.36\lambda_0$ for $\varepsilon_{r2} = 2.56$ and $\varepsilon_{r2} = 3.27$, respectively. In Figs. 3 and 4,

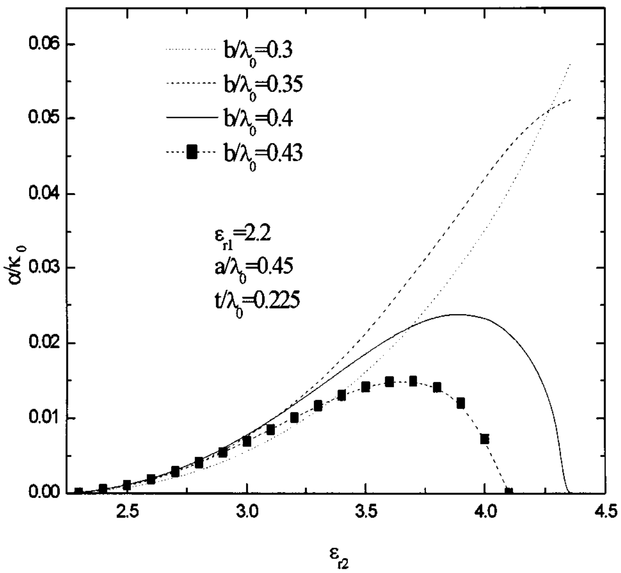

Fig. 5. Plot of the leakage constant versus ε_{r2} for a small leakage case.

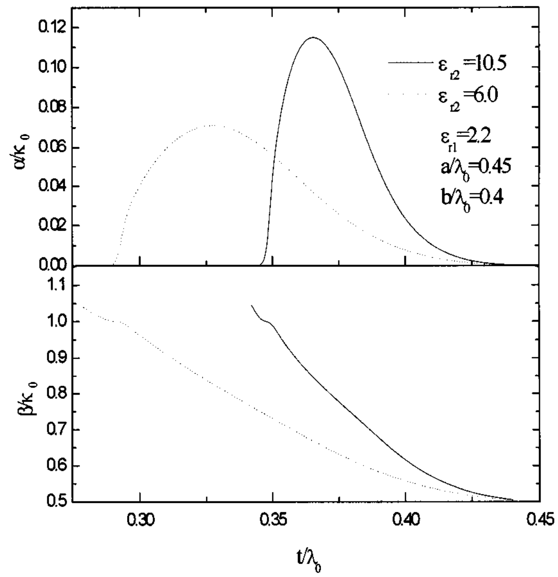

Fig. 6. Parametric effects of t/λ_0 on the leakage properties for large leakage case.

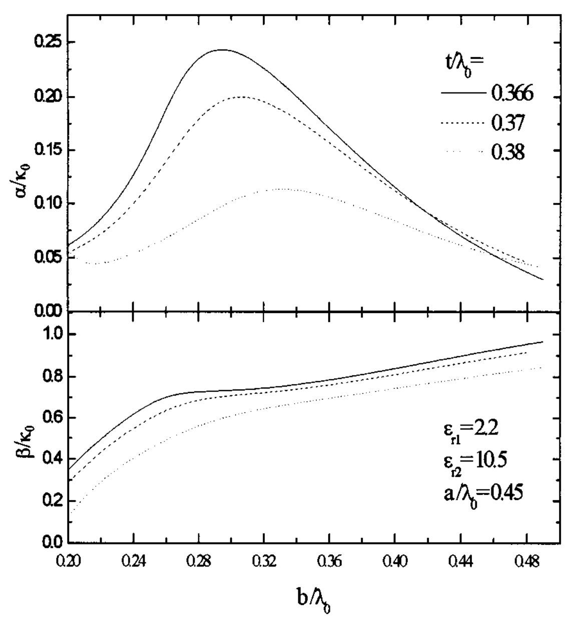

Fig. 7. Effect of dielectric slab width on the leakage properties for large leakage case.

the maximum leakage for the case $\varepsilon_{r2} = 3.27$ is found to be almost one order of magnitude higher than that for the case $\varepsilon_{r2} = 2.56$.

Since there is a large difference between the maximum leakage for the cases with $\varepsilon_{r2} = 2.56$, and $\varepsilon_{r2} = 3.27$, the effect of ε_{r2} on the leakage constants is then studied in Fig. 5. Some curves are found to increase initially and decrease for further increase of the dielectric constant. It is because the leaky-wave mode transforms to the bound mode and, thus, no leakage occurs. The trend of the curves indicates that using a higher dielectric constant can achieve stronger leakage and, in order to make sure that it will not enter the bound mode region, the width of the slab should be smaller with the increase of the dielectric constant.

A useful guideline for the antenna design can be obtained from the results of Figs. 3–5. When ε_{r2} is less than 3.0, the maximum leakage of the antenna will approximately occur when the thicknesses of the two dielectric slabs are nearly identical and the width of the slab is around $0.4\lambda_0$. Further increase of ε_{r2} will make the maximum leakage occur at smaller dielectric slab width, e.g., $0.36\lambda_0$ for the case $\varepsilon_{r2} = 3.27$. Since too small slab width will make the guide physically unstable, ε_{r2} should not be too large.

IV. Methods to Achieve Large Leakage

In some applications, antennas with medium gain are required, thus, the antenna should be made shorter. To meet such a requirement, leaky-wave antennas with large leakage should be used if reasonable beamwidth is needed. It is known that, to make 90% of the incident power radiated, the electrical length of a leaky-wave antenna is governed by the following expression:

$$\frac{L}{\lambda_0} \approx \frac{0.18}{\alpha/k_0} \tag{1}$$

where L is the antenna length, λ_0 is the free-space wavelength, α is the leakage constant, and k_0 is the free-space wavenumber. It is observed that the normalized leakage constant α/k_0 should be as high as 0.18 if the length for the leaky-wave antenna is one free-space wavelength. This section will show how to get such a large leakage without entering the reactive-mode region, while still keeping the antenna simple and strong.

To achieve strong leakage, a high dielectric constant should be used for the lower dielectric layer. However, unlike the implication in Fig. 5, the dielectric slab width is maintained large to make the antenna physically stable, while choosing a small thickness of the dielectric slab with higher dielectric constant. This arrangement is more robust and, at the same time, a very large leakage constant can be obtained by adjusting the thickness of the dielectric slab. Fig. 6 shows that larger leakage can be obtained with the use of higher dielectric constant and small thickness. When the dielectric constant is selected, the thickness of the slab can be used to vary the leakage constant over a wide range. For $\varepsilon_{r2} = 10.5$, the normalized leakage constant α/k_0 can be as large as 0.11 when its thickness is about $0.084\lambda_0$ (or t is about $0.366\lambda_0$), and the radiation angle is at about 60°. Fig. 7 plots the effect of dielectric slab width on the leakage and phase constants. A normalized leakage constant larger than 0.1 is obtained. The large variation of the normalized leakage constant from 0.001 to 0.2 suggests many potential applications of the present two-layer leaky NRD guide.

V. Conclusion

A double-layer leaky NRD guide has been proposed in this paper, and extensive numerical results have been given for the design of both small and large leakage cases. It is found that the replacement of the air gap with a dielectric slab maintains the antenna to be simple and, at the same time, makes the antenna physically stable. Besides, a very large leakage constant can be achieved without entering the reactive-mode region. The large variation of the leakage constant makes it suitable for various applications.

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