Short Papers

Radiation and Leakage Characteristics of Transverse Slot in NRD-Guide Operating in LSE_{00} Mode

Xiang-yin Zeng, Kwai-Man Luk, and Shan-jia Xu

***Abstract*—Characteristics of a transverse slot in the upper plate of a nonradiative dielectric guide operating in the dominant LSE_{00} mode have been analyzed. A fundamental radiation phenomenon due to the open property of the guiding structure is observed theoretically. It is found that the propagation direction of the leakage covers the whole angular spectrum in the plane parallel to the metallic plates. Explanation to its physical existence is given. A simple, but efficient method is developed to determine its angular power density. Numerical computation shows that the leakage is substantially high when the slot is near resonance.**

***Index Terms*—NRD-guide, slot antenna, transverse radiation.**

I. Introduction

Slots have been widely used in antenna applications and integrated circuits (ICs). Design of slot antenna or array fed by open/semiopen guiding structures, e.g., nonradiative dielectric (NRD) guide slot antenna and array [1], [2], is mainly based on the previous work of slot arrays in a closed rectangular waveguide. However, a major difference between them did not attract much attention before, i.e., only the dominant mode is assumed to propagate in a closed rectangular waveguide, while it is not true for an open guiding structure. When feeding by a closed guide, the incident energy will be converted to the reflected, transmitted, and slot radiation part on encountering the slot discontinuity, while the situation is more complicated in the case of an open guiding structure. Firstly, it is difficult, if not impossible, to make all the other modes below cutoff, except the operation mode. Secondly, energy leakage along the transverse direction may exist due to the potential excitation of radiation modes. Thirdly, for an NRD-guide operating in the commonly used LSM_{01} mode, the dominant mode (LSE_{00}) and the first higher order mode (LSE_{01}) may be excited when an inclined slot is cut, and their intensities may accumulate in slot arrays. The excitation of the undesirable modes may degrade the array performance due to their different phase velocities from the operation mode. On the other hand, today, the slot is widely used to couple energy between guiding structures in millimeter-wave ICs. When an NRD-guide is concerned in such circuits [3], [4], the above phenomenon may occur, which may cause crosstalk or energy loss. To the best of the authors' knowledge, no paper has reported on the transverse radiation phenomenon caused by the slot in either antenna applications or ICs of NRD-guides.

In this paper, characteristics of a transverse slot cut in an NRD-guide, shown in Fig. 1, operating in the dominant LSE_{00} mode are investigated (designated as the *H*-guide in [5] and [6]). Emphasis is placed on the discussion of the physical existence of the transverse radiation and its evaluation. To determine the detailed information of the transverse radiation, the structure is boxed by symmetrically placing two electric walls far from the dielectric slab. The continuous angular power spectrum of the transverse radiation is obtained from the discrete angular power spectrum of the boxed NRD-guide after a reasonable discretization-to-continuation procedure.

Manuscript received April 13, 2000. This work was supported by the Research Grant Council, Hong Kong, under Competitive Earmarked Research Grants Grant 9040371 (CityU 1145/98E).

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Publisher Item Identifier S 0018-9480(02)05224-9.

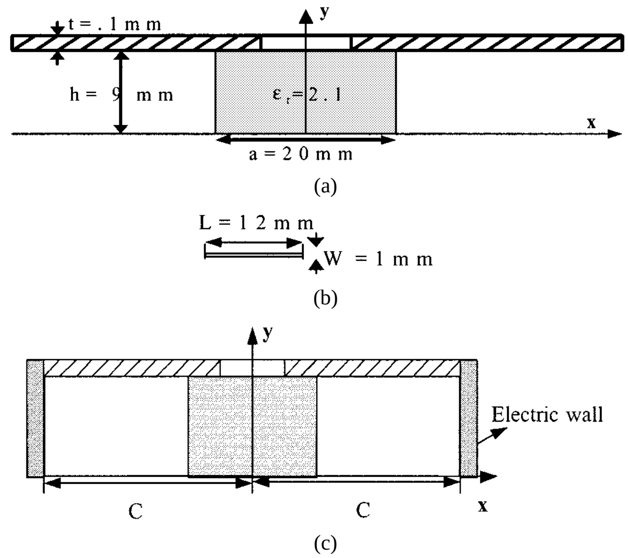

Fig. 1. Geometries of the NRD-guide and the corresponding boxed NRD-guide. (a) Cross section of the NRD-guide. (b) Top view of the NRD-guide. (c) Cross section of the boxed NRD-guide.

II. Transverse Radiation Phenomenon and Its Determination

To analyze the transverse radiation due to the slot cut, a moment-method formulation is established, taking the wall thickness into consideration. Details can be found in [6] and [7]. The electric fields on the slot apertures are then used to calculate the reflection coefficient and the radiation efficiency of the slot in Section II-A. Computational result shows that new leakage phenomenon occurs, with the explanation of its physical existence given in Section II-B. The total energy carried by the radiation modes is calculated in Section II-C, where the angular power density is determined by boxing the guide. Finally, a further discussion is presented in Section II-D.

A. Computational Point-of-View

With the electric fields in the two apertures of the slot cavity obtained, the reflection coefficient of the dominant mode can be obtained [8] as follows:

$$B = \frac{\int_{\text{slot}} \left(\vec{E}_l \times \vec{H}_x\right) \cdot \hat{n}\, ds}{2\int_{s_1} \left(\vec{E}_t \times \vec{H}_t\right) \cdot \vec{z}\, ds} = \frac{\int_{\text{slot}} \left(\vec{E}_l \times \vec{H}_x\right) \cdot \hat{n}\, ds}{2\,\dfrac{\beta_g}{\omega\mu_0} \int_{s_1} f^2(x)\, ds} \tag{1}$$

and the formula of the slot radiation efficiency is

$$\eta_{\text{slot}} = \frac{\int_s \vec{E}_u \times \left(\tilde{G}_o \cdot \left(\vec{E}_u \times \hat{n}\right)\right)^* \cdot \hat{n}\, ds}{\int_s \vec{E}_y \times \vec{H}_x^* \cdot \vec{z}\, ds} \tag{2}$$

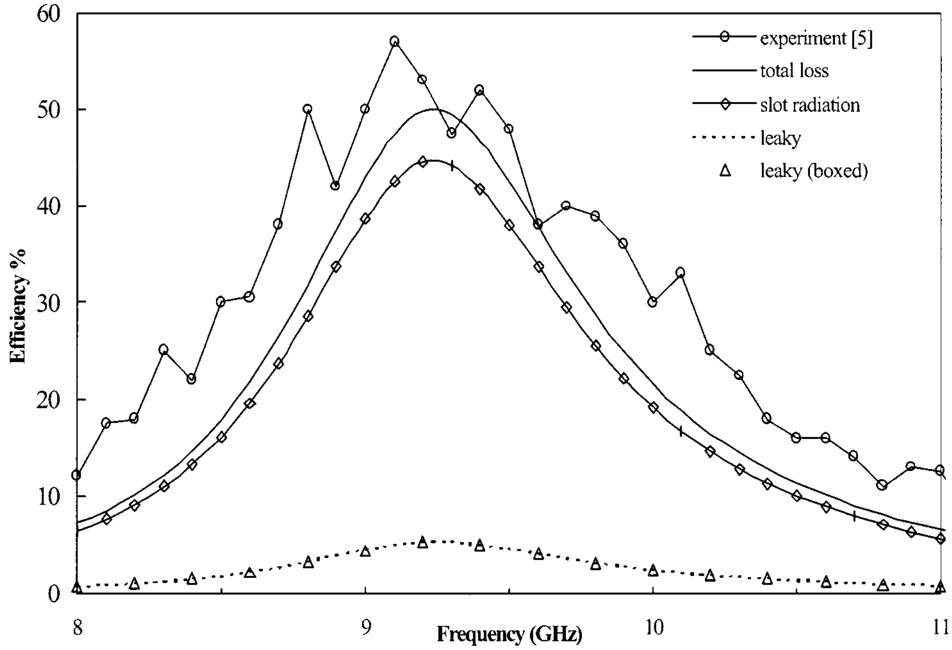

Fig. 2. Plot of the calculated normalized power of the total loss, slot radiation, and side leakage with a comparison to experimental results.

where $\tilde{G}_o$ is the dyadic Green's function in the half free space, $\hat{n}$ is the normal direction of the upper slot aperture toward the outside, and $*$ denotes the complex conjugate. The total power lost on encountering the slot discontinuity is the difference between the incident power and the sum of the power carried by reflected and transmitted dominant modes so the total lost power normalized by the incident one is

$$\boldsymbol{\eta}_t = 1 - |B|^2 - |1 - B|^2. \tag{3}$$

The computed frequency-dependent η_t and $\eta_{\rm slot}$ are plotted in Fig. 2, where experimental data [5] is also shown. From [5, eq. (36a)], we know that the experimental result is the total lost power η_t rather than $\boldsymbol{\eta}_{\rm slot}$. The experimental result is calculated using the measured reflection coefficients, which were found not to have as good an accuracy as one can see from the measured voltage standing-wave ratio (VSWR) in [5, Fig. 5]. That makes us fail to get a good agreement between the η_t curve and the experimental data. Unlike the case of the closed waveguide-fed slot radiator, however, Fig. 2 shows that $\boldsymbol{\eta}_t$ is not equal to $\boldsymbol{\eta}_{\rm slot}$. Instead, it is slightly larger than $\eta_{\rm slot}$. The difference between them clearly indicates that power is being coupled to higher order leaky modes of the NRD-guide.

B. Physical Point-of-View

First, let us have a look at the modal property of an NRD-guide. It is known that the modes in an NRD-guide, similar to a layered dielectric slab, can be divided into LSE and LSM modes [9]. Both the LSE and LSM modes consist of some discrete surface modes and continuous radiation modes. When a slot is cut in the upper plate, an equivalent magnetic current is established in the slot apertures. From the mechanism of mode excitation [10], we know that this equivalent magnetic current with a cosine-like distribution near resonance will excite not only some surface modes, but also some continuous radiation modes. For the present case, only LSE modes can be excited due to the orthogonality of LSE and LSM modes. Apparently owing to the condition $a < \lambda_0/2$, the leakage (transverse radiation) arising from the slot in the NRD-guide is in the form of a TEM parallel-plate mode in the air-filled regions. Thus far, we know that it is the excitation of the LSE radiation modes that cause $\eta_{\rm slot}$ to be slightly smaller than η_t. In the following, we will try to find out the angular power density of the excited LSE radiation modes.

C. Evaluation of the Continuous Radiation Modes

First, let us determine the total power carried by the excited LSE radiation modes, which will obviously cover the whole angular spectrum. Similar to the calculation of the slot radiation, the total scattered power between the two parallel plates can be formulated as

$$P_{\rm sca} = \frac{1}{2}\int_s \overline{E}_l \times \left(G_{xx}^h \cdot \left(\overline{y} \times \overline{E}_l\right)\right)^* \cdot \left(-\overline{y}\right) ds \tag{4}$$

with $\boldsymbol{G}_{xx}^h$ given in [6]. The transverse radiation between the two parallel metallic plates, propagating away from the dielectric slab, can be obtained by subtracting the scattered power carried by the dominant surface mode from the total scattered power between the parallel plates. Thus, the ratio of the transverse radiation power to the incident power is

$$\eta_{\rm leaky} = \frac{P_{\rm sca}}{\frac{1}{2}\int_s \overline{E}_y \times \overline{H}_x^* \cdot \overline{z}\, ds} - 2|B|^2. \tag{5}$$

From the view of energy conservation, one can deduce that

$$\eta_t = \eta_{\rm slot} + \eta_{\rm leaky}. \tag{6}$$

Fig. 2 shows the plot of $\boldsymbol{\eta}_t$, $\boldsymbol{\eta}_{\rm slot}$, and $\boldsymbol{\eta}_{\rm leaky}$, and a calculation confirms the above energy conservation relation. However, detailed characteristics of the transverse radiation cannot be obtained in this way.

As is known, it is very difficult to handle the continuous spectrum of the radiation modes from both a mathematical and physical point-of-view [9]. Here, a boxing technique is used, i.e., two metallic plates are placed symmetrically far away from the dielectric slab to close the NRD-guide. This procedure will then convert the continuous

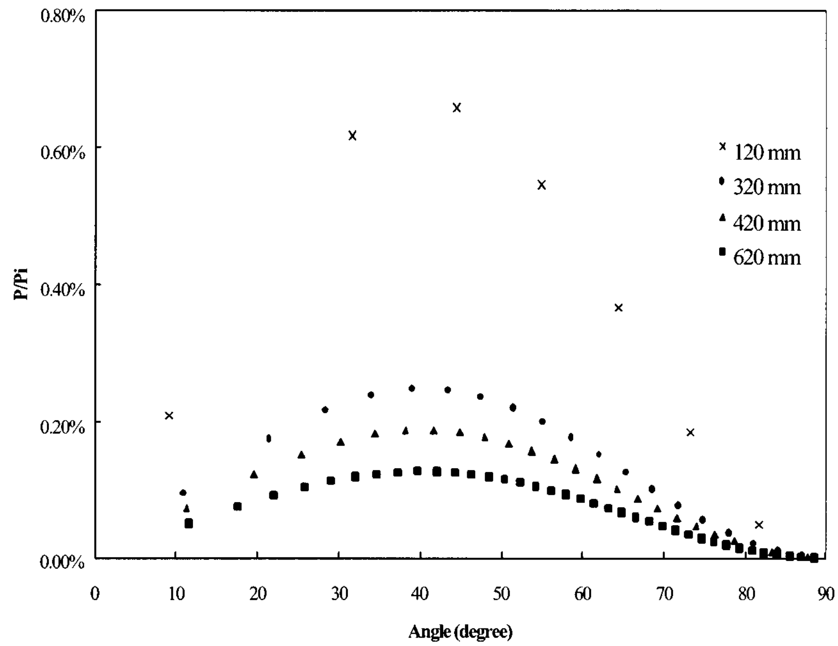

Fig. 3. Normalized power carried by each forward propagation mode with c as a parameter, with the angle formed by the mode's propagation vector in the air region and the x-axis.

LSE radiation modes of the NRD-guide into discrete LSE_{n0} propagation modes of the boxed one. With the increase of the distance between the dielectric slab and the two additional plates, we expect the characteristics of the slot in the boxed NRD-guide to approach the actual one. To calculate the characteristics of the slot in the boxed NRD-guide by use of the moment method, a suitable Green's function is derived, following the procedure in [6]. It has the same formula as [6, eq. (9)], but with a different expression for G_{mx} as follows:

$$G_{mx} = \frac{-U}{jq_{2m}} \frac{Ue^{-jq_{2m}a}\cos q_{2m}(x-x_0) - \overline{U}\cos q_{2m}(x+x_0)}{U^2 e^{-jq_{2m}a} - \overline{U}^2 e^{jq_{2m}a}} \tag{7}$$

with

$$U = q_{1m}\cos q_{1m}\left(\frac{a}{2}-c\right) + jq_{2m}\sin q_{1m}\left(\frac{a}{2}-c\right)$$
$$\overline{U} = q_{1m}\cos q_{1m}\left(\frac{a}{2}-c\right) - jq_{2m}\sin q_{1m}\left(\frac{a}{2}-c\right).$$

Calculated efficiency for the boxed NRD-guide is also plotted in Fig. 2. No significant discrepancy exists between results of the ideal and boxed cases, as long as the two added plates are too far away to influence the operation surface mode. For the boxed NRD-guide when the dimension c (half of the distance between the two added metallic plates) is large, many propagating modes (LSE_{n0}) can exist, and the backward and forward scattering coefficients of the nth propagating modes are

$$B_n = -C_n = \frac{\int_{\mathrm{slot}}\left(\vec{E}_l \times \vec{H}_{2n}\right)\cdot \hat{n}\, ds}{2\int_{s_1}\left(\vec{E}_{tn}\times\vec{H}_{tn}\right)\cdot \vec{z}\, ds}. \tag{8}$$

Thus, the normalized forward and backward power by the incident power can be obtained as follows:

$$\overline{P}_n = \frac{P_n}{P_{\mathrm{inc}}} = \frac{|B_n|^2 N_n}{N_{\mathrm{inc}}} \tag{9}$$

where N_n is the normalization factor for the nth propagating mode defined by

$$N_n = \frac{1}{2}\int_{s_1}\left(\vec{E}_{tn}\times\vec{H}_{tn}\right)\cdot\vec{z}\, ds \tag{10}$$

and N_{inc} is for the incident surface mode. The propagating angle for each LSE_{n0} mode is defined as the angle formed by the propagation vector in the air region and the x-axis, i.e., $\theta_n = \arcsin(\beta_{gn}/k_0)$. Fig. 3 plots the normalized forward power carried by different propagating modes, identified by their propagating angle as defined above, with c being 120, 320, 420, and 620 mm, and the frequency is fixed on 9.2 GHz near resonance. Apparently, to get useful information for the continuous radiation modes, a procedure should be established to convert the discrete power to a continuous angular power spectrum. From coupled-mode theory, we can expect that the continuous radiation modes caused by the slot discontinuity, which have propagation directions near that of a discrete LSE mode (say, the LSE_{n0} mode) will have a strong coupling with the LSE_{n0} mode in the boxed guide. Thus, it is very natural to expect that the power carried by the continuous radiation modes in the actual NRD-guide will be converted to the discrete LSE mode in the boxed one having a nearest propagation direction. Considering this, we assume, without loss of generality, that the power carried by the forward nth propagating mode of the boxed NRD-guide is the total power in the actual continuous radiation angular spectrum at the direction θ_n with an angular width equivalent to $\Delta\theta_n = ((\theta_n - \theta_{n-1})/2) + ((\theta_{n+1} - \theta_n)/2)$, thus the normalized power density in the direction θ_n becomes $\overline{P}_n/\Delta\theta_n$. With the increase of the parameter c, more propagating modes in the boxed NRD-guide will occur, and the maximum angular width $\Delta\theta_n$ will decrease. This decrease makes the above assumption more reliable and, therefore, makes the normalized power density approach to the actual one. Fig. 4 presents the convergent property. When c tends to infinity, the boxed NRD-guide tends to the actual one, which makes it reasonable to say that the convergent normalized power density is the actual one we want. It shows that when c is greater than ten wavelength, the calculated normalized power density will be a good approximation to the actual one. However, a very large c should be chosen in order to

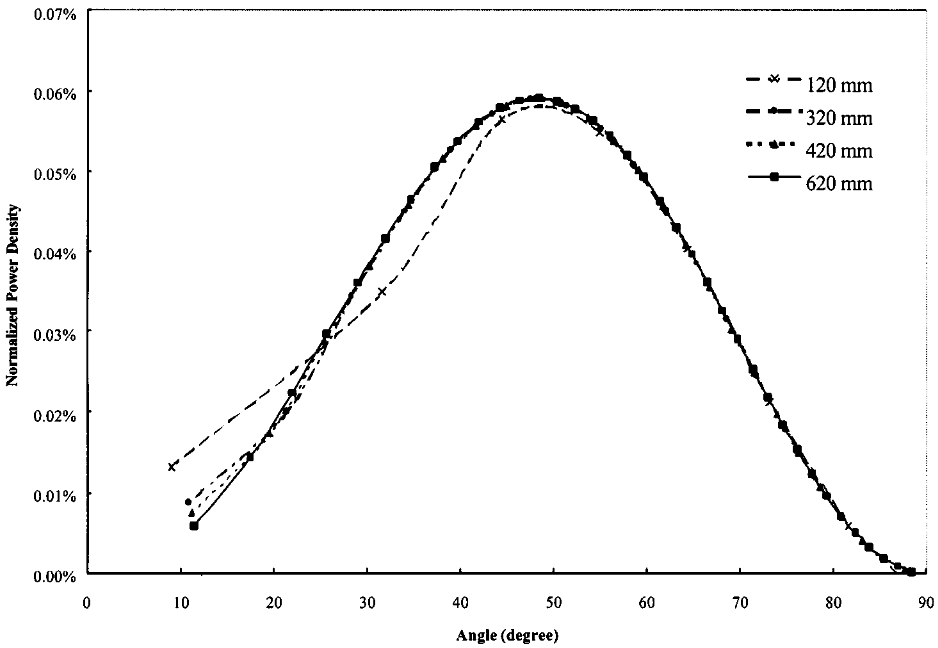

Fig. 4. Convergence behavior of the calculated normalized forward angular power density after a discretization-to-continuation procedure with dimension c as a parameter, with the angle defined by the propagation direction in the air region and the x-axis.

plot the angular power spectrum in the range from 0° to 10°. Since the power in that range is minor compared with the total transverse radiation power, a curve fitting will be better than choosing a very large c. Due to the symmetry of the structure, the normalized backward power density is the same as that for the forward. Thus, the normalized power density in the whole angular spectrum is obtained.

D. Further Discussion

The mechanism for higher order leaky-mode loss in NRD-guide containing a radiating slot has been identified and explained. However, Kisliuk and Axelrod failed to find it in their experiment [5]. In [5], they pointed out that no significant change in the values of the reflected and transmitted waves was detected when the measurements were repeated with metallic screens mounted across the side gaps of the guide. Our computation for the VSWR in the actual and boxed NRD-guide (not shown here) also confirms this. The calculation in Fig. 4 shows that most energy of the excited LSE_{n0} radiation modes propagates with a large angle with the x-axis, forming a zigzag path between the two added electric walls. Therefore, the energy that can return to the slot position after boxing the guide and, thus, interacts with the slot discontinuity, is insignificant. This explains why there is no significant change for the reflected and transmitted dominant modes after boxing the guide. Also, the small power density of the continuous radiation modes will make them hard to detect.

III. Conclusion

The transverse radiation due to a transverse-center slot cut on an NRD-guide upper plate has been investigated by using the method of moment. Physical existence of the new phenomenon is explained and a boxing technique used to determine the angular distribution of the normalized power carried by the transverse radiation modes has been presented. Angular power distribution of the unwanted radiation power will be helpful for both the antenna design and circuit design when such a guiding structure is involved.

References

[1] J. A. G. Malherbe, "The design of a slot array in nonradiative dielectric waveguide—Part I: Theory," *IEEE Trans. Antennas Propagat.*, vol. AP-32, pp. 1335–1340, Dec. 1984.

[2] Ghosh, N. Simons, L. Shafai, A. Ittipiboon, A. Petosa, and M. Cuhaci, "Characterization of an NRD slot for the design of an NRD based slot array," in *IEEE Antennas Propagat. Symp.*, 1998, pp. 1405–1408.

[3] L. Han, K. Wu, and R. G. Bosisio, "An integrated transition of microstrip to nonradiative dielectric waveguide for microwave and millimeter-wave circuits," *IEEE Microwave Theory Tech.*, vol. 44, pp. 1091–1096, July 1996.

[4] K. Wu and L. Han, "Hybrid integration technology of planar circuits and NRD-guide for cost-effective microwave and millimeter-wave applications," *IEEE Microwave Theory Tech.*, vol. 45, pp. 946–954, June 1997.

[5] M. Kisliuk and A. Axelrod, "Theoretical and experimental study of a novel H-guide transverse slot antenna," *IEEE Microwave Theory Tech.*, vol. MTT-33, pp. 428–433, May 1985.

[6] K. M. Luk, X. Y. Zeng, and S. J. Xu, "Spectral-domain Green's function of magnetic type for NRD guides and H-guides," *IEEE Microwave Theory Tech.*, vol. 47, pp. 1975–1981, Oct. 1999.

[7] R. W. Lyon and A. J. Sangster, "An efficient moment method analysis of radiating slots in thick-walled waveguide," *Proc. Inst. Elect. Eng.*, pt. H, vol. 128, pp. 197–205, 1981.

[8] S. Silver, Ed., *Microwave Antenna Theory and Design*. ser. MIT Rad. Lab. Series. New York: McGraw-Hill, 1949, vol. 12.

[9] N. C. Di, F. Frezza, A. Galli, P. Lampariello, and A. A. Oliner, "Properties of NRD-guide and H-guide higher-order modes: Physical and nonphysical ranges," *IEEE Microwave Theory Tech.*, vol. 42, pp. 2429–2434, Dec. 1994.

[10] R. E. Collin, *Field Theory of Guided Waves*. New York: IEEE Press, 1991.