Analysis and Measurement of NRD-Guide Leaky Wave Coupler in *Ka* Band

Dow-Chih Niu, Tsukasa Yoneyama, *Fellow, IEEE,* and Tatsuo Itoh, *Fellow, IEEE*

***Abstract*—A new structure for an NRD-guide directional coupler is developed. This structure combines two NRD guides and a dielectric slab guide in order to utilize a leakage mechanism for coupling. The coupling depends on this leaky mechanism, but not on field interactions as in a conventional proximity coupler. A theoretical formula is presented. The field along the NRD guide and the decay constant are measured at *Ka* band (35 GHz) and compared with the theoretical data. Reasonable agreement exists between the measured data and theoretical data.**

I. Introduction

A necessary component for many millimeter-wave systems is a directional coupler, which can distribute power at a specified ratio between two waveguides. The coupling mechanism of a conventional proximity coupler is due to the interaction of the exponentially decaying field between the two waveguides, and hence the coupling is sensitive to the gap distance and the length of coupler.

Many authors have studied coupling characteristics of the conventional couplers for different dielectric waveguide structures by using the coupled mode theory developed by Miller [1]. Marcuse [2] provided an approximate but accurate expression for the coupling coefficient of dielectric waveguides. Arnaud provided a formula just involving the line integrals. This formula has been shown to be identical with Marcuse's formula, but is easier to apply [3]. Yoneyama and Nishida have proven that this expression also is valid for a conventional NRD-guide coupler [4].

In many applications, strong coupling (<6 dB) is necessary. For a conventional coupler, the gap distance for a strong coupler is not easily realized. This problem becomes more serious at higher frequencies at which structural dimensions are smaller. Many methods have been proposed to solve this problem, such as change of dielectric materials or use of sophisticated circuit configurations. Nevertheless, this problem cannot be solved effectively and economically.

Oliner and Peng [5], [6] have written two companion papers that discuss the leakage phenomena in detail; a rigorous mathematical formulation in Part I, and the physical effects of leakage of dielectric waveguide in Part II. Leakage phenomena take place in many different dielectric waveguides and transmission line structures. Many studies about this topic have been carried out. Usually, the leakage phenomena can cause a problem in millimeter-wave and microwave circuit design. On the other hand, it is possible to make use of such phenomena to realize novel components.

A novel directional coupler that depends on leaky waves was suggested by Oliner and Peng [7]. Because the coupling is dependent on the leaky wave, the physical separation between two waveguides to be coupled is not a dominant factor. This leaky wave coupler can be realized easily by an appropriate design. A leaky wave coupler was first realized by Yoneyama and Nishida [8]. This coupler was made of two inverted strip dielectric waveguides coupled through a multimode waveguide between them. Miller's theory of coupling [1] was applied to analyze this coupler, and the solution was transformed by a complex contour integral into an expression which clearly reveals the leaky wave contribution.

The nonradiative dielectric waveguide (NRD guide) is a newly proposed dielectric waveguide [9]. The NRD guide has an interesting feature in that the discontinuity can be made reactive rather than resistive. The design equation can be obtained by rigorous analysis. Combining the leakage concept and NRD guide structure, a new directional coupler is proposed in the present paper. It consists of two NRD guides coupled through a dielectric slab between them.

In this paper, two different variations of this structure have been made and measured. For the first structure [Fig. 1 (a)], the space between the upper and lower metal plate is filled. For the second structure [Fig. 1(b)], a dielectric slab guide with a partial height is placed between the two NRD guides. Good performance can be obtained for the first structure. A theoretical deviation for the decay constant is presented for the first structure by using the coupled mode theory. Finally, the measured data are compared with the theoretical data. Agreement between the measured and theoretical data is found reasonable.

II. Theory

For a coupler involving two monomode guides coupled by a multimode guide, the field intensity in the primary

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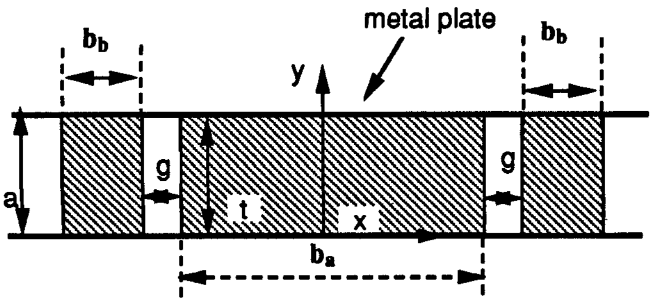
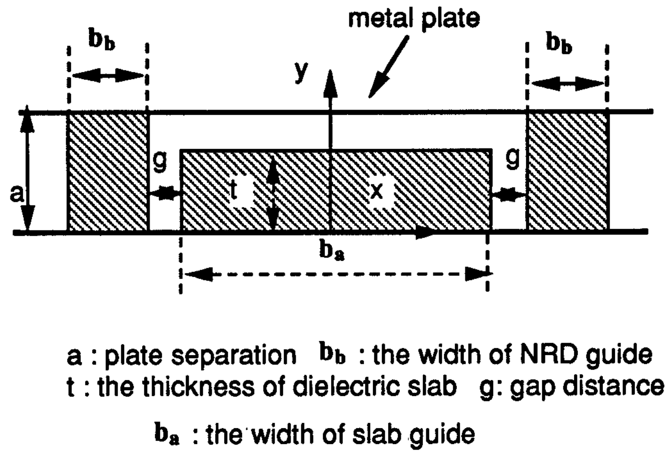


(a)



(b)

Fig. 1. (a) Cross-sectional view of the first structure of NRD-guide leaky wave coupler. (b) Cross-sectional view of the second structure of NRD-guide leaky wave coupler.

guide and in the secondary guide can be written as [8]

$$u_p = \exp(-\alpha z)\theta(z) - 2\alpha(z - 2\pi/\Delta\beta) \cdot [1 - \alpha(z - 2\pi/\Delta\beta)] \exp[-\alpha(z - 2\pi/\Delta\beta) - j2\pi(\beta_0 - \beta)/\Delta\beta]\theta(z - 2\pi/\Delta\beta) + \cdots \tag{1}$$

$$u_s = -2\alpha(z - \pi/\Delta\beta) \exp[-\alpha(z - \pi/\Delta\beta) - j\pi(\beta_0 - \beta)/\Delta\beta]\theta(z - \pi/\Delta\beta) + \cdots \tag{2}$$

$$\alpha = \pi * C_c^2/\Delta\beta \tag{3}$$

$$z_1 = \pi/\Delta\beta \tag{4}$$

where θ is the step function, α is the decay constant, and z_1 is the field build-up distance in the secondary guide. In the derivation of this equation, the phase constant in the NRD guide is assumed to be β (monomode guide) and the phase constants in the slab guide are assumed to be distributed uniformly with an interval $\Delta\beta$ around β_0 (multimode guide). Furthermore, a constant coupling coefficient between the two modes, one in the NRD guide and another in the slab guide, is assumed. If the coupling coefficient C_c and $\Delta\beta$ can be obtained, the decay constant can be calculated by (3).

For the first structure of this coupler, the coupling coefficient between the NRD guide and the slab guide (as shown in Fig. 2) is the same as the coupling coefficient of a conventional NRD-guide coupler with an asymmetric structure. By means of the perturbation theory, Marcuse [2] provided an approximate but accurate expression to calculate the coupling coefficient of a conventional coupler. This formula involves a surface integral over the cross section of dielectric waveguide. A formula just involving line integrals has been derived by Arnaud [3], based on Lorentz's reciprocity theorem and perturbation theory. These two formulas were proven to be, in fact, identical, although Arnaud's formula is much easier to use than Marcuse's formula. Arnaud's formula for the coupling coefficient can be written as

$$C_c^2 = C^2/P_aP_b \tag{5}$$

where

$$C = 1/2 \int_0^a (E_{ay}H_{bz} + E_{az}H_{by} - E_{by}H - E_{by}H_{ay})\, dy$$

$$P_a = \int_0^a dy \int_{-\infty}^{\infty} dx\, (E_a \times H_a.\hat{z})$$

$$P_b = \int_o^a dy \int_{-\infty}^{\infty} dx\, (E_b \times H_b.\hat{z}).$$

In (5), $\hat{z}$ denotes the unit vector along the z direction, (E_a, H_a) are the fields in the slab guide in the absence of the NRD guide, and (E_b, H_b) are the fields in the NRD guide in the absence of the slab guide. The quantity C can be interpreted as being the field interactions between the NRD guide and the slab guide. P_a and P_b are the power in the NRD guide and in the slab guide, respectively. By using Arnaud's formula for the asymmetric structure (as shown in Fig. 2), the equation of coupling coefficient between any two LSM modes, one in the NRD guide and the other in the slab guide, can be written as

$$C_c = K \exp - [(p_a + p_b)g/2] \tag{6}$$

where

$$K = \sqrt{p_a p_b q_a^2 q_b^2 \epsilon_r^2 (p_a + p_b)^2 [(m\pi/a)**2 + \beta_a\beta_b]^2 / (4\beta_a\beta_b h_a^2 h_b^2 r1 r2)}$$

$$h_a^2 = \epsilon_r k_0^2 - q_a^2$$

$$h_b^2 = \epsilon_r k_0^2 - q_b^2$$

$$r1 = [(q_a^2 + \epsilon_r^2 p_a^2)(p_a b_a/2) + (p_a^2 + q_a^2)\epsilon_r]$$

$$r2 = [(q_b^2 + \epsilon_r^2 p_b^2)(p_b b_b/2) + (p_b^2 + q_b^2)\epsilon_r].$$

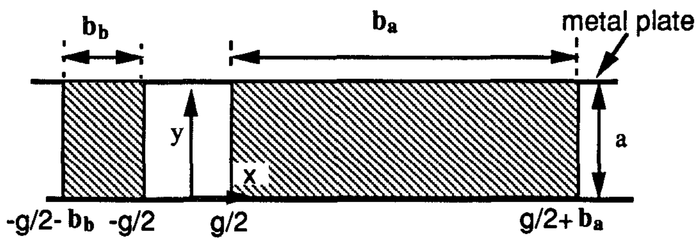


Fig. 2. Structure of asymmetric coupler for calculating coupling coefficient.

In the above equations, g is the gap distance, b_a is the width of the slab guide, and b_b is the width of the NRD guide; also, β_a, q_a, and p_a (and β_b, q_b, and p_b) are the propagation constant, the transverse phase constant, and the transverse decay constant in the slab guide (and NRD guide).

When coupling occurs ($\beta_a = \beta_b$), the phase constants q_a, p_a, and β_a in the slab guide are equal to q_b, p_b, and β_b in the NRD guide. Equation (6) can be simplified to

$$C_c = K \exp(-pg) \tag{7}$$

where

$$K = \epsilon_r p^2 q^2 / (\beta \sqrt{r1\, r2})$$

$$r1 = [(q^2 + \epsilon_r^2 p^2)(pb_a/2) + (p^2 + q^2)\epsilon_r]$$

$$r2 = [(q^2 + \epsilon_r^2 p^2)(pb_b/2) + (p^2 + q^2)\epsilon_r]$$

where β, p, and q are the propagation constant, the transverse phase constant, and the transverse decay constant in both the NRD guide and the slab guide, and are determined by the characteristic equations.

$$q \tan(qb_a/2) = \epsilon_r p \tag{8}$$

$$q^2 + p^2 = (\epsilon_r - 1)k_0^2. \tag{9}$$

When the width of the slab guide (b_a) is large enough, there exist the following relations:

$$\beta \Delta \beta + q \Delta q = 0 \tag{10a}$$

$$\Delta q = -\frac{\pi}{b_a}. \tag{10b}$$

Therefore, $\Delta \beta$ can be described as

$$\Delta \beta = \pi q / (\beta b_a). \tag{10c}$$

By using (3), (7), (10), the expression of decay constant can be written as

$$\alpha = [2\epsilon_r^2 p^3 q^3 \exp(-2pg)] / \{[(\epsilon_r - 1)^2 \beta][k_0^2 + (\epsilon_r + 1)p^2]t1\} \tag{11}$$

where

$$t1 = \{\epsilon_r k_0^2 + [k_0^2 + (\epsilon_r + 1)p^2]pb_b/2\}.$$

Note that the decay constant in (11) is independent of the width of the slab guide. This implies that the coupling is not modal coupling, but it occurs through a leaky wave coupling.

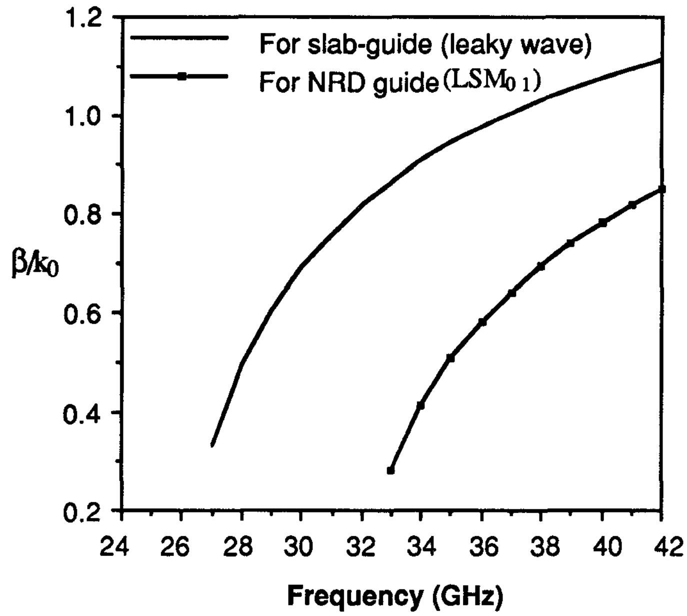


Fig. 3. Dispersion curve of the leaky wave in the slab guide and dispersion curve of dominant mode in NRD guide.

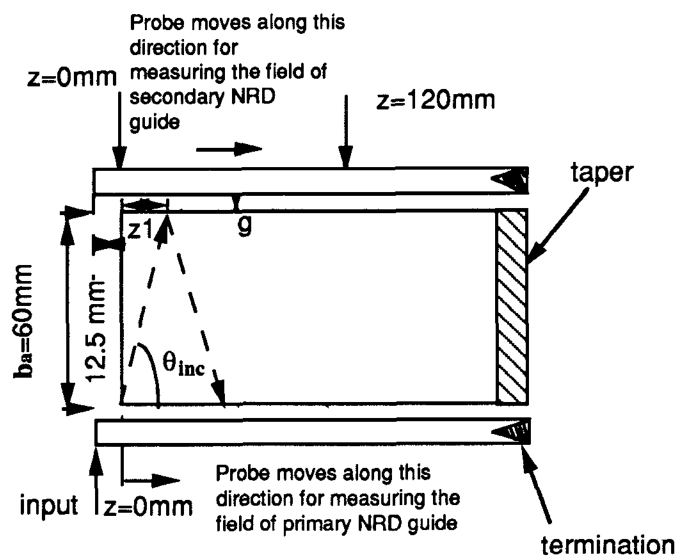
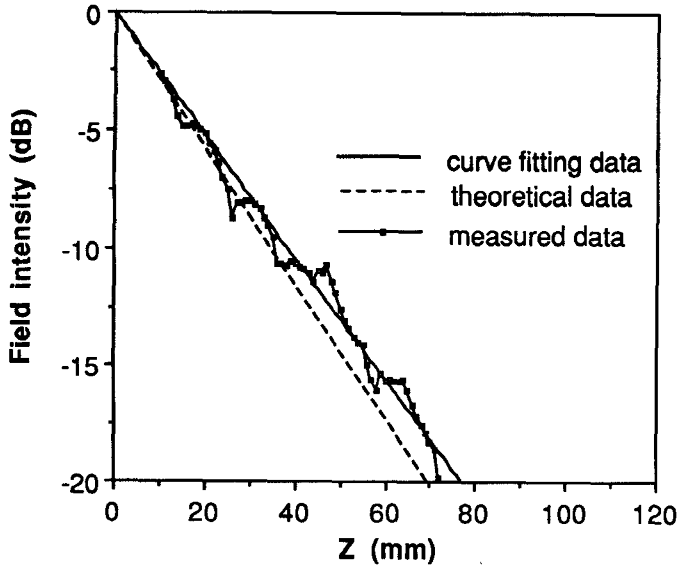


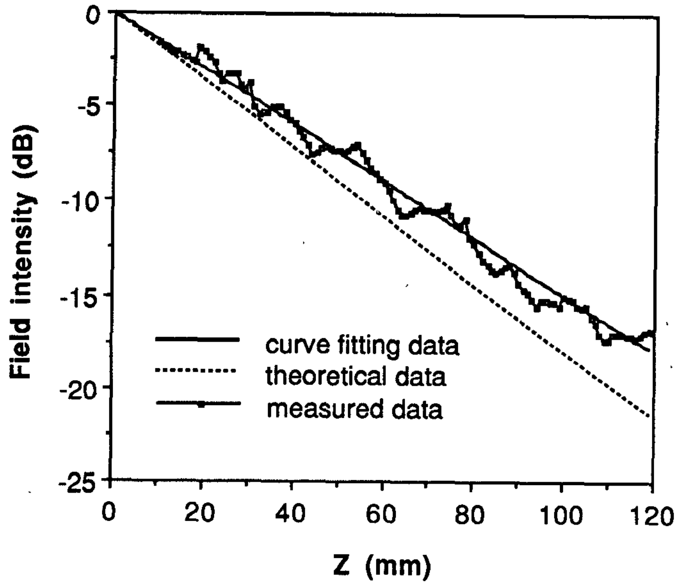
Fig. 4. Structure of measurement for the leaky wave coupler.

III. Measurement Setup and Dispersion Curve

Two different variations of this structure have been made and measured (see Fig. 1). For the first structure (fully filled structure), the space between the lower and the upper metal plates is completely filled by Teflon with $\epsilon_r = 2.04$ $a = 4$ mm, $b_a = 60$ mm. For the second structure (partially filled structure), a dielectric slab with $\epsilon_r = 2.04$, $a = 4$ mm, $t = 2.4$ mm, $b_a = 60$ mm is placed between the two NRD guides with $\epsilon_r = 2.04$, $a = 4$ mm, $b = 3.5$ mm. Both LSE and LSM modes can exist in the slab. The LSM_{01} mode is the dominant mode in the NRD guide, where the mode indexes refer to x and y directions in order. Due to the similar field distribution, the LSM modes in the slab guide have a larger contribution in the total coupling than the LSE modes. In the present case,



(a)



(b)

Fig. 5. (a) Field intensity of primary NRD guide for the first structure $g = 1.5$ mm. (b) Field intensity of primary NRD guide for the first structure $g = 2.0$ mm.

the phase constant of the leaky wave can be written as

$$\beta_s = \sqrt{k_0^2 \epsilon_r - \left(\frac{\pi}{a}\right)^2} \tag{12}$$

where a is the height of the NRD guide and q is the transverse phase constant in NRD guide. The meaning of this formula is that the total effect of leakage can be regarded as a leaky wave propagating along the incident angle (θ_{inc}) in the slab. The theoretical dispersion curve of the leaky wave (β_s/k_0) in the slab guide and the dispersion curve of the dominant mode ($LSM_{0,1}$) in the NRD guide are shown in Fig. 3.

The setup of the experiment for leaky wave coupling is shown in Fig. 4. There are two semi-rigid coaxial cables, each with one end connected to an HP 8510 network analyzer, and the other end without any connector (just keeping the center conductor as a probe). The probes are placed at a small fixed distance from each side of the NRD guide. Each cable is fixed onto an adjustable sliding table. The sliding table can move smoothly along the primary and secondary NRD guides with the minimum interval of 0.5 mm. By using this experimental setup, the field intensity along the NRD guide can be measured. In order to reduce the reflected waves, the end of the slab is tapered and the resistive films are placed at the end of the NRD guides.

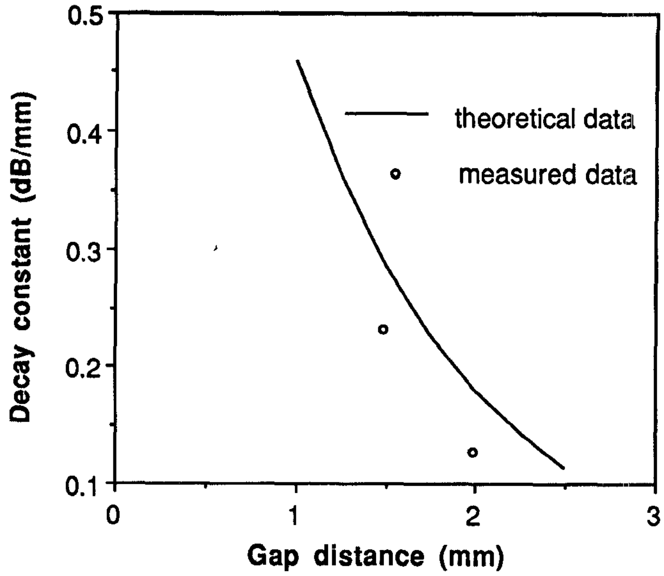


Fig. 6. Theoretical and experimental decay constants versus gap distances.

The field build-up distance z_1 is the distance indicating the position where the leaky wave first reaches the secondary guide with an angle θ_{inc}. From (4) and (10b), the field build-up distance is given by

$$z_1 = \pi/\Delta\beta = \beta b_a/q \tag{13}$$

where b_a is the width of the dielectric slab, and β and q are the propagation constant and the transverse phase constant for the NRD guide. The incident angle θ_{inc} for the leaky wave (as shown in Fig. 4) can be obtained by

$$\tan(\theta_{\text{inc}}) = b_a/z_1 \tag{14}$$

where z_1 is the field build-up distance and b_a is the width of the slab guide. For the first structure, the field build-up distance is 38.3 mm and the incident angle is 57.4°.

IV. Decay Constant and Coupling

The amplitude of the first term of (1) can be regarded as an expression of the field intensity along the primary NRD guide. The field intensity $a_1(z)$ can be described by the following equation [8]:

$$a_1(z) = \exp(-\alpha z) \tag{15}$$

where α is the attenuation constant and z is the distance along the NRD guide. When expressed in decibels, a straight line can be obtained for the field intensity. The

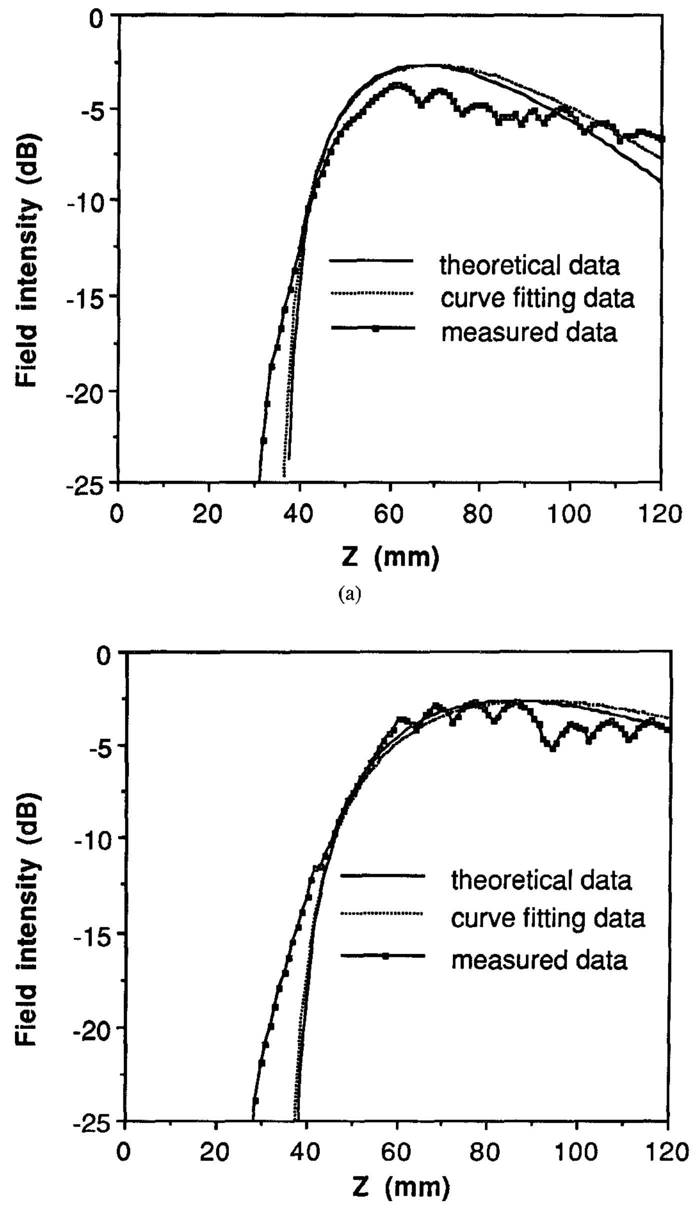


Fig. 7. (a) Field intensity of secondary NRD guide for the first structure $g = 1.5$ mm. (b) Field intensity of secondary NRD guide for the first structure $g = 2.0$ mm.

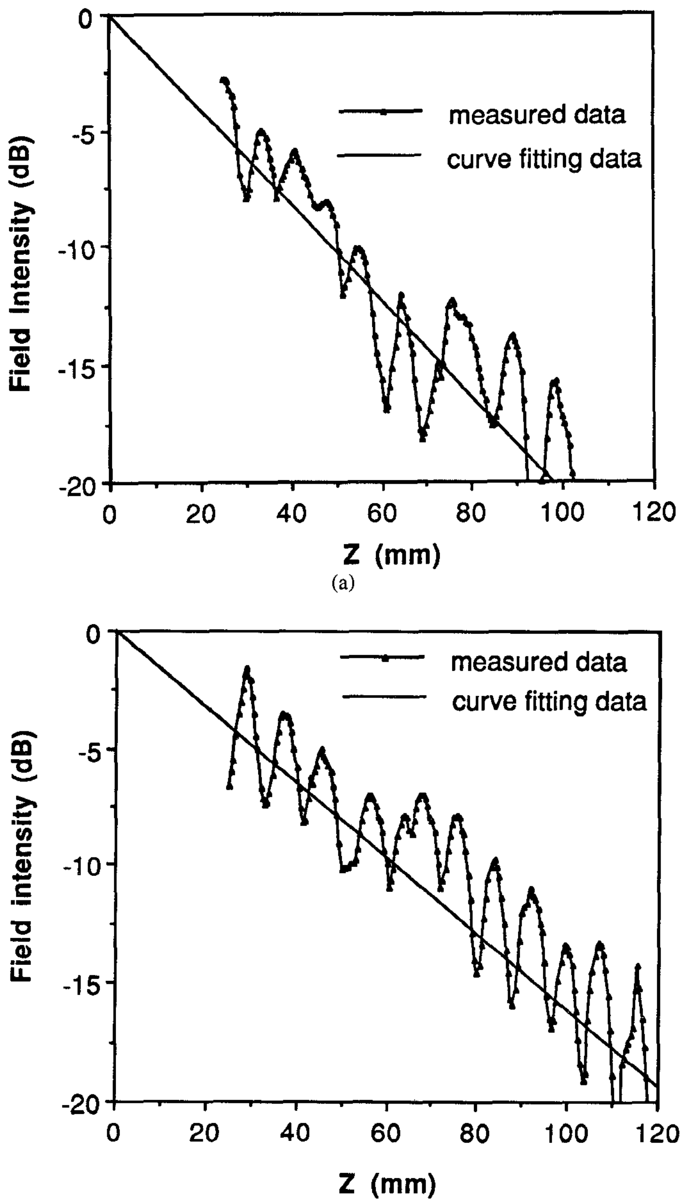


Fig. 8. (a) Field intensity of primary NRD guide for the second structure $g = 1.5$ mm. (b) Field intensity of primary NRD guide for the second structure $g = 2.0$ mm.

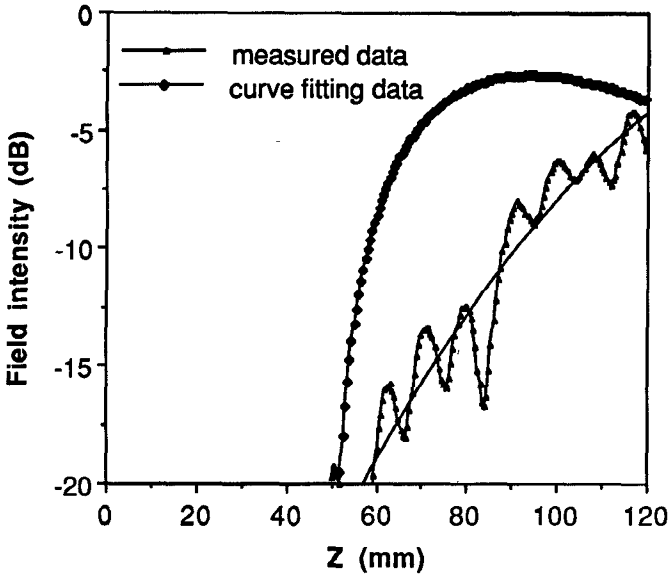
measured curves of the first structure with different gap distances g($g = 1.5$ mm and $g = 2.0$ mm) are shown in Fig. 5 (a) and (b). In these figures, the field decays as z increases. Although there are ripples in these curves, a straight line can be obtained by curve fitting. Then, the experimental decay constant can be determined from this straight line. By using the theoretical decay constant computed from (11), the theoretical curve can be plotted in the same figure.

The theoretical decay constants for different gap distances are presented together with experimental data in Fig. 6. The difference between theoretical data and experimental data is about 10–15%. By considering our experimental setup, we concluded that the difference is mainly a result of inaccuracy in alignment between the NRD guide and the slab guide, such as the small error existing in the gap distance between the NRD guide and the slab guide, as well as the distance between the probe and NRD guide not being parallel. Each of the inaccuracies could cause considerable error in the measurement of the decay constant.

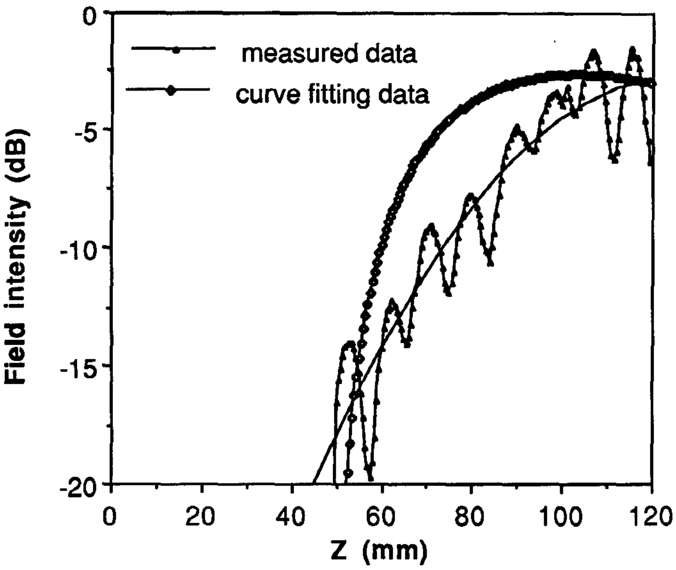
The amplitude of the first term of (2) can be regarded as an expression of the field intensity along the secondary NRD guide. The field intensity $a_2(z)$ can be described by the following equation [8]:

$$a_2(z) = 2\alpha(z - z_1) \exp(-\alpha(z - z_1)) \qquad (16)$$

where α is the decay constant and z_1 is the field build-up distance in Fig. 4. We evaluated $a_2(z)$ from (16) by using the decay constant α obtained by curve fitting and calcu-



(a)



(b)

Fig. 9. (a) Field intensity of secondary NRD guide for the second structure $g = 1.5$ mm. (b) Field intensity of secondary NRD guide for the second structure $g = 2.0$ mm.

lated from (11). The measured field intensity curves of the first structure with different gap distances are shown in Fig. 7 (a) and (b). In each figure, the measured data, the curve fitting line, and the theoretical curve are presented. Good performance of the coupler can be obtained.

V. Discussion

For the second structure, the measured field intensity and the curve fitting data along the primary and secondary NRD guide with different gap distances are shown in Figs. 8 and 9. In comparing Fig. 5 with Fig. 8, we note that there are larger ripples in these curves for the second structure than for the first structure. The reason is that there is a better match in the field distribution between the NRD guide and the dielectric slab guide for the first structure, because no larger discontinuity exists between the NRD and the dielectric slab guide.

In Fig. 9, there exists a big difference between the measured and the curve fitting data for the second structure. Agreement is much better for the first structure, as seen in Fig. 7. There are two reasons for the larger discrepancy between the curve fitting and measured curves for the second structure. First, the large discontinuity between the NRD guides and the slab guide may affect smooth energy transition. Second, according to Oliner [10], [11], the NRD guide with an air gap between the metal plate and the dielectric strip will radiate very easily. Radiation can be generated in this vertically asymmetric structure. On the other hand, for the first structure, there is a better match in the field profile between the NRD guide and the slab, and furthermore, the radiation is less likely to be generated in a fully filled structure. Hence, the curve fitting data are much closer to the measured data in this case.

VI. Conclusion

This paper described a new structure for an NRD guide directional coupler. This new structure combines two NRD guides and a dielectric slab. Because the coupling is due to the leakage mechanism and not to the interaction of the field, the distance between the two NRD guides is not critical, although the two NRD guides and the slab guide must be arranged in parallel. This leaky wave coupler can be manufactured more easily.

A formula based on the coupled mode theory for the calculation of the decay constant has been presented. Two different variations of this leaky wave coupler have been demonstrated. The field intensity along primary and secondary NRD guides and the decay constant have been measured and compared with theoretical data. Reasonable agreement exists between measured and theoretical data.

References

[1] S. E. Miller, "Coupled wave theory and waveguide applications," *Bell Syst. Tech. J.*, pp. 661–718, May 1954.

[2] D. Marcuse, "The coupling of degenerate modes in two parallel dielectric waveguides," *Bell Syst. Tech. J.*, vol. 50, pp. 1791–1816, July–Aug. 1971.

[3] J. A. Arnaud, "Transverse coupling in fiber optics, Part 1: Coupling between trapped modes," *Bell Syst. Tech. J.*, vol. 53, pp. 217–224, Feb. 1974.

[4] T. Yoneyama, N. Tozawa, and S. Nishida, "Coupling characteristics of nonradiative dielectric waveguides," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-31, pp. 648–654, Aug. 1983.

[5] A. A. Oliner, S. T. Peng, T. Hsu, and A. Sanchez, "Guidance and leakage properties of a class of open dielectric waveguides: Part I—Mathematical formulations," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-29, pp. 843–855, Sept. 1981.

[6] ——, "Guidance and leakage properties of a class of open dielectric waveguides: Part II—New physical effects," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-29, pp. 855–869, Sept. 1981.

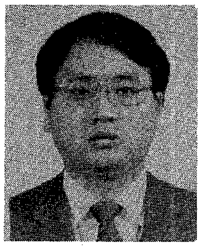
[7] E. W. Hue, S. T. Peng, and A. A. Oliner, "A novel leaky-wave strip waveguide directional coupler," presented at the Topical Meet. Integrated and Guided Wave Opt., Salt Lake City, UT, paper WD2, Jan. 1978.

[8] T. Yoneyama and S. Nishida, "Dielectric waveguide coupling by leaky wave," in *Proc. Int. Symp. Microwave and Commun.*, India, Dec. 1981, pp. 185–190.

[9] —, "Nonradiative dielectric waveguide for millimeter-wave integrated circuits," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-29, pp. 1188–1192, Nov. 1981.

[10] A. Sanchez and A. A. Oliner, "A new leaky waveguide for millimeter wave using nonradiative dielectric waveguide—Part I: Accurate theory," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-29, pp. 737–747, Aug. 1987.

[11] H. Qing, A. A. Oliner, and A. Sanchez, "A new leaky waveguide for millimeter wave using nonradiative dielectric waveguide—Part II: Comparison with experimental," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-29, pp. 748–752, Aug. 1987.



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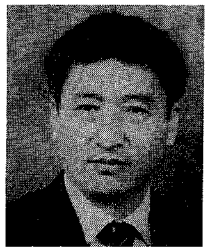
Tsukasa Yoneyama, photograph and biography not available at the time of publication.



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Dr. Itoh is a member of the Institute of Electronics and Communication Engineers of Japan, Sigma Xi, and Commissions B and D of USNC/URSI. He served as the Editor of IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES for 1983–1985. He serves on the Administrative Committee of the IEEE Microwave Theory and Techniques Society. He was Vice President of the Microwave Theory and Techniques Society in 1989 and President in 1990. He is the Editor-in-Chief of IEEE MICROWAVE AND GUIDED WAVE LETTERS. He was the Chairman of USNC/URSI Commission D from 1988 to 1990 and is the Vice Chairman of Commission D of the International URSI.