Diverging/Focusing of Electromagnetic Waves by Utilizing the Curved Leakywave Structure: Application to Broad-Beam Antenna for Radiating Within Specified Wide-Angle

Isao Ohtera, *Member, IEEE*

***Abstract*—In this paper, a new "broad-beam antenna" for radiating electromagnetic energy in a specified wide angular region is proposed, utilizing the "curved leakywave structure." This structure consists of the leakywave structure curved physically and longitudinally into the form of an equi-angular spiral. The expression of the radiation field from this structure is given, the effects of various geometrical parameters on the radiation properties is discussed numerically for the design of the broad-beam antennas, and a simple experiment is also performed to verify the beam broadening by the proposed method. The concept in this paper may be easily applied to any leakywave structure such as a periodic dielectric antenna and a leaky nonradiative dielectric (NRD)-guide antenna for millimeter-wave application.**

***Index Terms*—Beam broadening, curved leakywave structure, leakywave antenna.**

I. Introduction

RECENTLY, the use of millimeter-wave spectrum in many applications has attracted interest. For using this spectrum in different fields, development of the antennas suited for each purpose is desired. For example, the future Wireless Local Area Network (WLAN) will require transmitting-/receiving-antennas with a wide responding angle, as the case may be. So far, the radiation pattern with the specified broad beamwidth has had to be achieved using the complex and elaborate array design.

In this paper, a new "broad-beam antenna" utilizing the "curved leakywave structure [1]–[3]" is proposed, which is easy to design for any beamwidth.

Generally, while the leakywave structure has some features such as a low profile, structural simplicity, good matching with the feed transmission line, and a feasibility for frequency scanning, this structure has an essentially asymmetric radiation pattern due to intrinsic nonuniform field distribution on it. All the features are delivered to the curved leakywave structures. Especially the asymmetry (such as the sloped radiation pattern), neglected in the conventional leakywave structure with narrow beam, will be a serious problem in the use as broad-beam antennas.

Manuscript received March 11, 1998; revised March 22, 1999.

The author is with the Tohoku Institute of Technology, Taihaku-Ku, Sendai, 982-8577 Japan.

Publisher Item Identifier S 0018-926X(99)07065-9.

The curved leaky-wave structure addressed in this paper may give the solutions for improving the average slope of the pattern as well as for broadening arbitrarily the beamwidth in terms of some structural parameters.

Following, the method for focusing and diverging the leakywave is described based on the geometrical optics and the radiation fields from the curved leakywave structure are given. Furthermore, the effects of various structural parameters on the radiation properties are also discussed numerically, including the broadening of beamwidth and the leveling off the broad-beam top of the radiation pattern. The result is very useful for obtaining the appropriate design parameters of the broad-beam antennas.

The proposed design may be applied for any leakywave structure such as a dielectric grating antenna [4] and a leaky NRD-guide antenna [5] for millimeter-wave application.

II. Focusing/Diverging of Electromagnetic Waves by the Curved Leakywave Structures

A. Interpretation Based on Geometrical Optics

It is well known that when the transmission lines for propagating the micro-/millimeter-waves have periodic or continuous discontinuities along the axis, they radiate leakywaves. Such leakywave radiation can be explained by means of the geometrical optics as "all of rays are emitted parallel to each other at a certain angle," as shown in Fig. 1(a).

Focusing/diverging of these parallel rays may be realized in at least two ways, as shown in Fig. 1(b) and (c). In Fig. 1(b), by gradually changing the propagation constant along the axis, parallel rays are emitted to converge at or diverge from one point. However, it is generally difficult to get the propagation constant in closed form.

Another one is shown in Fig. 1(c) in which focusing/diverging for leakywave can be achieved by curving it physically along the axis. This method, which is proposed in this paper, is based on the simple concept that by curving the structure into an "equi-angular" spiral, taking note of the "equality" of emitting angle, they converge at or diverge from the pole of the equiangular spiral. Here, it is assumed that the curvature is gradual and small so as not to affect the emitting angle or the phase constant. As a result, it turns out that this

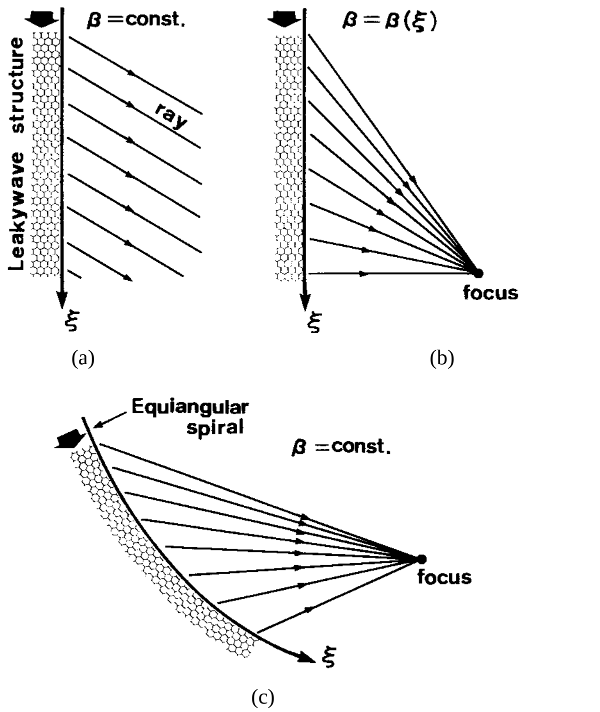

Fig. 1. Schematics on focusing of leakywave. (a) Typical leakywave structure. (b) Focusing by varying phase constant. (c) Focusing by curved leakywave structure.

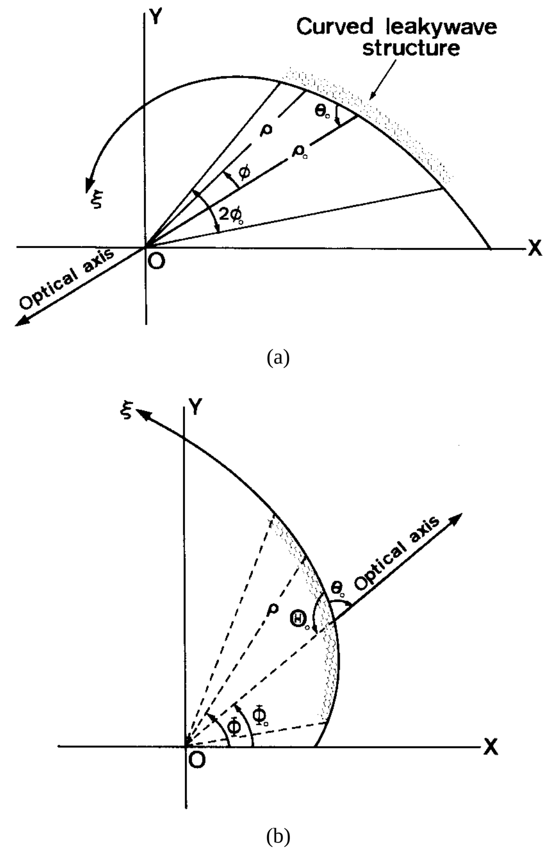

Fig. 2. Schematics on diverging/focusing by equi-angular spiral curved leakywave structures. (a) Focusing type. (b) Diverging type.

method is very useful and simple for focusing/diverging the electromagnetic waves.

Both types of focusing and diverging are shown schematically in Fig. 2(a) and (b). In this paper, we assume leakywave structures designed for radiation in the forward direction. But including the backward radiation in the periodic structure, either of the structures of Fig. 2 is acceptable for focusing and diverging.

The equi-angular spiral is represented in the polar coordinates (ρ, ϕ) and the rectangular coordinates (x, y) as follows:

$$\begin{aligned} \rho &= \rho_0 \exp(-\phi \cot \Theta_0) \\ \phi &= \Phi - \Phi_0 \\ \xi &= \sec \Theta_0(\rho_0 - \rho) \\ x &= \rho \cos \Phi \\ y &= \rho \sin \Phi. \end{aligned} \tag{1}$$

In (1) and Fig. 2 is the angular coordinate from the x axis, Φ_0 the off-set angle (the angle between the x axis and the optical axis), ρ_0 the length of radius on the optical axis (the equivalent focal length), $2\phi_0$ the angular aperture, and ξ the distance along the equi-angular spiral from the intersection with the optical axis. Moreover, Θ_0, which is the intrinsic constant in the "equi-angular" spiral, is the anti-clockwise angle between the radius and the tangential line and it is given in terms of the emitting angle of rays θ_0 as follows:

$$\Theta_0 = \begin{cases} \theta_0; & \text{Focusing} \\ \pi - \theta_0; & \text{Diverging.} \end{cases} \tag{2}$$

The emitting angle θ_0 is determined from the phase constant β through $\theta_0 = \cos^{-1}(\beta/k)$, where k is the free-space wave number. The shape of equi-angular spiral, namely, the curve of leakywave structure, can be decided uniquely by any set of three parameters including $\rho_0, \phi_0, \theta_0, \Theta_0$ and the length of the curved leakywave structure ξ_0.

Then, θ_0 is in the region $0 < \theta_0 < \pi/2$. Corresponding to $\theta_0 = \pi/2$ and 0, the equi-angular spiral degenerates to a circle with radius ρ_0 and a half-line on the optical axis, respectively.

B. Radiation Fields from Curved Leakywave Structure

The coordinates system is shown in Fig. 3. The curved leakywave structure is in xy plane and the origin coincides with the pole of the equi-angular spiral. Then, it is assumed that the height of the guide is small compared to the wavelength.

In general, fields distributed on the leakywave structure based on the dielectric strip such as a dielectric grating antenna [4] and a leaky nonradiative dielectric (NRD) guide antenna [5] are hybrid. However, for the dielectric grating antenna, the tangential magnetic field H_z parallel to the ground plane contributes mainly to the radiation, while for the leaky NRD guide and the longitudinal slotted waveguide, the tangential electric field E_z is the main contributor. As a matter of convenience, we shall designate the former *horizontal-polarization-type* leakywave structure, and the latter the *vertical-polarization-type* one.

The radiation fields for each type of curved leakywave structures are given as, through the simple approach on the

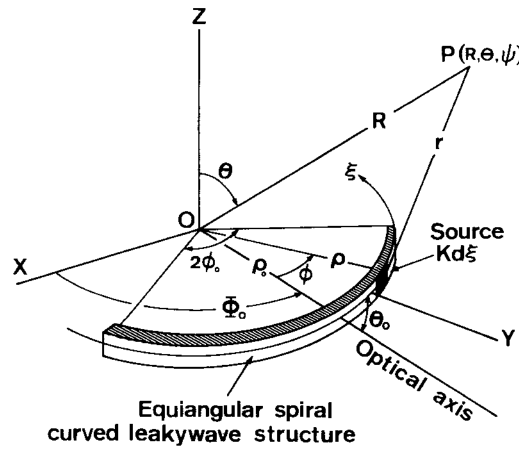

Fig. 3. Coordinates system.

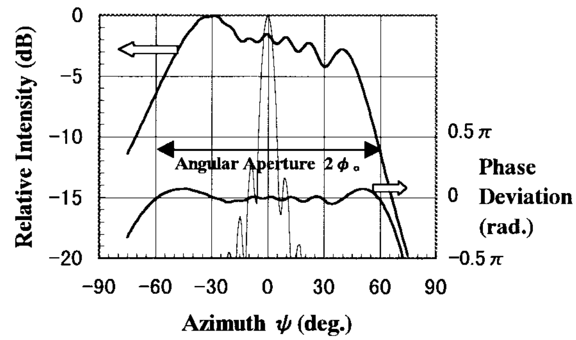

Fig. 4. An example of radiation pattern of broad-beam antenna ($\alpha\lambda = 0.1, \theta_0 = 66°, \xi_0 = 10\lambda$). A fine line is the pattern of the linear leakywave antenna with the same parameters.

Phase Center of Radiation Field

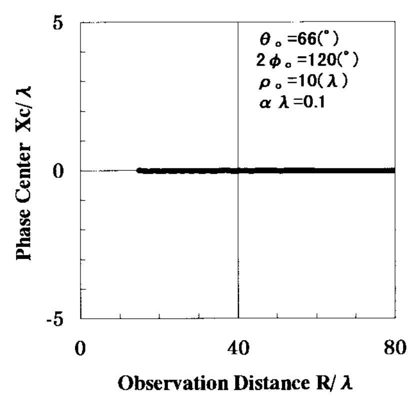

Fig. 5. Phase centers of the broad-beam antenna as a function of observation distance.

radiation problem [2],[3]

$$E_0(R,\psi) = -\frac{jk}{4\pi}\int_\xi E_s(\xi)\frac{e^{-jkr}}{r} \cdot \left\{\frac{R}{r}\sin v - \frac{\rho}{r}\sin(\psi - \Phi + v)\right\} d\xi \quad (3)$$

the H-plane pattern for the *vertical-polarization type* and

$$E_\psi(R,\psi) = -\frac{jk}{4\pi}\sqrt{\frac{\mu}{\varepsilon}}\int_\xi H_s(\xi)\frac{e^{-jkr}}{r} \cdot \left\{\sin v - \left(\frac{R}{r}\cos v - \frac{\rho}{r}\cos\theta_0\right)\frac{\rho}{r}\sin(\psi - \Phi)\right\} d\xi \quad (4)$$

the E-plane pattern for the *horizontal-polarization type*. Here $E_s(\xi)$ and $H_s(\xi)$ are field distributions on each type. Then

$$r = \{R^{-2}R\rho\sin\theta\cos(\psi - \Phi) + \rho^2\}^{1/2} \quad (5)$$

$$v = (\pi - \Theta_0) - (\psi - \Phi) \quad (6)$$

and Θ_0 is related to the emitting angle of rays θ_0 through (2).

The terms $\{\ \}$ in (3) and (4) mean how the source $d\xi$ faces to the field point P and it is a factor corresponding to "inclination factor" in Huygens–Fresnel refraction theory [6]. For $R \to \infty$, the factor degenerates to $\sin v$.

The above expressions can be applied to both of focusing and diverging types of the curved leakywave structure. The radiation properties on the focusing type have been described in previous papers [1], [2]. In the following, the diverging type is mainly discussed in relation to the design for the broad-beam antenna.

III. Numerical Discussions for Radiation Properties of Broad-Beam Antennas

A. Radiation Pattern

A radiation pattern of standard leakywave antennas has, in general, narrow half-power beamwidth in the principal plane, while it is asymmetrical to the optical axis due to the intrinsic nonuniform field distribution.

Fig. 4 shows the typical radiation patterns for the curved and linear dielectric grating antennas, which are calculated through (4). It is assumed for simplification that the magnetic field distribution along the guide is $H_s(\xi) = e^{-(\alpha + j\beta)\xi}$. And $\alpha\lambda = 0.1$ and $\theta_0 = 66°$ for calculation are obtained from Schwering and Peng [4, Fig. 11], assuming that these parameters do not change along the curved guide, where α is the attenuation constant and λ the free-space wavelength.

Asymmetry, especially the average slope of the amplitude pattern, which can be neglected for the linear structure, is very serious and disadvantageous in using the curved structure for the broad-beam antenna.

On the other hand, the phase pattern is nearly uniform within the angular aperture $2\phi_0$. This is inferable from that the phase centers and the radiation patterns of the curved leakywave structure are little dependent on the observation distance, as shown in Figs. 5 and 6, respectively. Here "the center of curvature of equi-phase plane on the optical axis [7], [8]" used conventionally is inadequate as the phase center, so the method [7] based on the least squares method is used to calculate that.

Another factor affecting the radiation properties is the ripple on the amplitude pattern. This effect may be reduced practically by using longer structure or by processing appropriately the terminals to be matched.

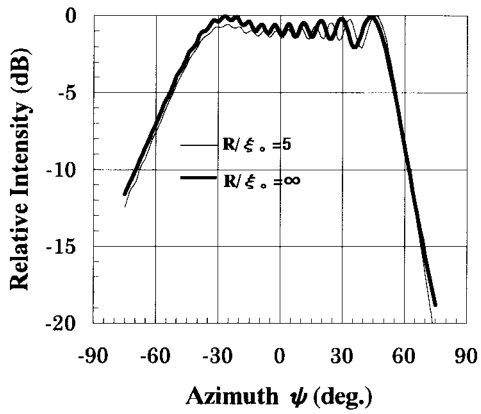

Fig. 6. Near- and far-field radiation patterns ($\alpha\lambda = 0.06, \theta_0 = 55°, 2\phi_0 = 120°, \xi_0 = 13.35\lambda$).

B. Optimization of Radiation Patterns

The optimization in relation to asymmetry of radiation patterns is very important in the practical design of the broad-beam antennas and may be achieved by improving the average slope of the pattern.

In the equi-angular curved leakywave structure, the power radiated per unit angle can be affected by various parameters $\theta_0, \alpha, \xi_0, 2\phi_0,$ and ρ_0. So the leveling off the broad-beam top of the radiation pattern, namely the flat pattern, can be achieved approximately by controlling the gradient of the angular power density near the optical axis, via these parameters. This concept is described in the Appendix. In the result, we have the definite conditions to achieve the flat pattern in relation to optimization of the broad-beam antennas as follows:

$$\Lambda_0 = 2\alpha\rho_0 - \cos\theta_0 = 0 \tag{7}$$

or

$$\frac{\rho_0}{\lambda} = \frac{\beta}{4\pi\alpha} \tag{8}$$

$$\alpha\xi_0 = \sinh(\phi_0 \cot\theta_0). \tag{9}$$

Equations (8) and (9) are alternatives to (7), modified via the relation between the parameters.

Fig. 7 shows the gradient of the power distribution at $\phi = 0$ as function of the emitting angle θ_0. The cut-in figures are the radiation patterns with the parameters corresponding to the marking on the curve. It is explicitly found that a flatter pattern can be obtained according to the above condition.

Improving the average slope of the pattern depends on not only θ_0, but the other parameters as well. The curves in Fig. 8 show the relation between the parameters under the flat pattern condition. Thus, θ_0 has to be decided taking account of the angular aperture $2\phi_0$ and the attenuation $\alpha\xi_0$.

Fig. 9 shows an example for the theoretical E-plane radiation pattern with appropriate parameters satisfying (7). The parameters $\alpha\lambda = 0.06$ and $\theta_0 = 55°$ are obtained again from Schwering and Peng [4, Fig. 11]. The amplitude pattern is flat and symmetric relative to the optical axis and compared with that in Fig. 4.

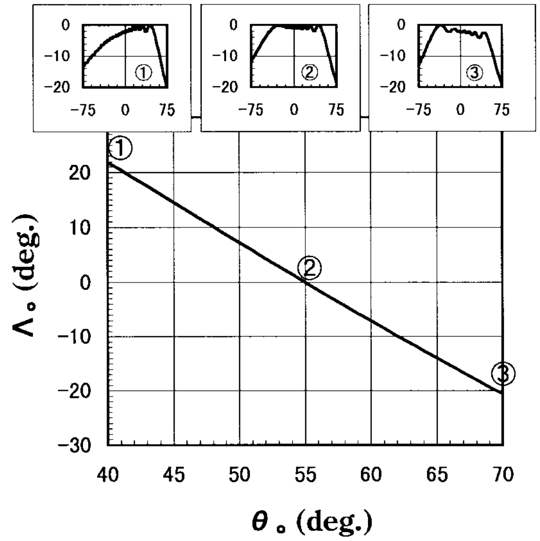

Fig. 7. Gradient of aperture distribution at $\phi = 0$ as a function of $\theta_0 (\alpha\lambda = 0.06, \xi_0 = 13.35\lambda)$.

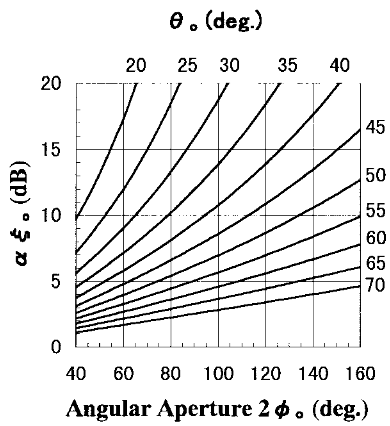

Fig. 8. Condition for leveling off the broad-beam top.

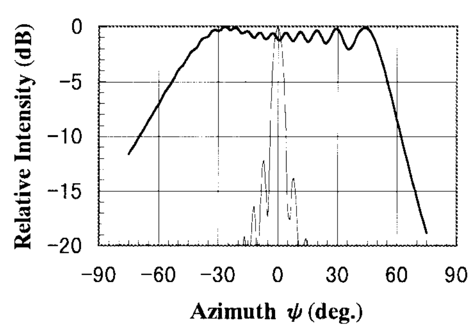

Fig. 9. Radiation pattern with appropriate parameters ($\alpha\lambda = 0.06, \theta_0 = 55°, \xi_0 = 13.35\lambda$). A fine line is the pattern of the linear leakywave antenna with the same parameters.

C. Broadening of Beamwidth

The half-power beamwidth of the radiation pattern depends directly on the angular aperture $2\phi_0$ of the curved leakywave structure. Fig. 10 shows the calculated half-power beamwidth under the flat-pattern condition mentioned above. The half-power beamwidth increases monotonically with the angular aperture $2\phi_0$. This means that the broadening of beamwidth

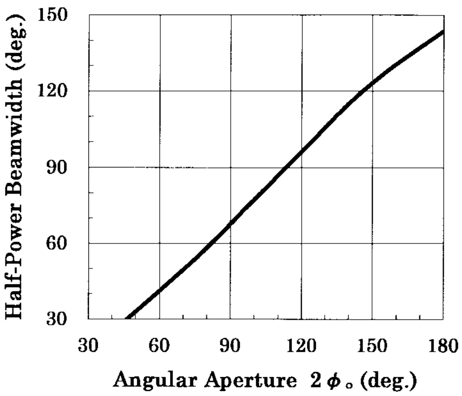

Fig. 10. Beam broadening ($\alpha\lambda = 0.08, \theta_0 = 60°, \xi_0 = 10\lambda$).

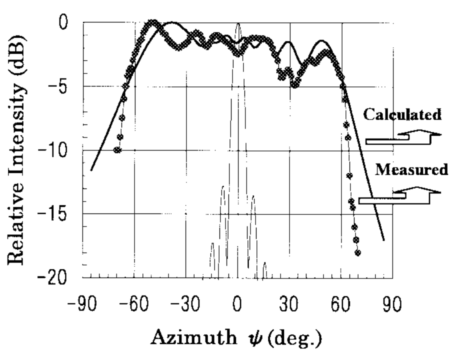

Fig. 11. Measured patterns of curved leaky NRD guide ($\alpha\lambda \sim 0.068, \theta_0 \sim 71°, \xi_0 \sim 10\lambda, 2\phi_0 \sim 140°$). A fine line is the pattern of the linear leakywave antenna with the same parameters.

can easily be realized through only the angular aperture, i.e., the curving of the structures.

To verify the beam-broadening technique, the radiation pattern of a curved leaky-wave structure was measured in the principal plane at 10 GHz and shown in Fig. 11. This leakywave structure is a type of leaky NRD guide [5] consisting of the curved grating dielectric strip in two semicircular parallel metal plates. The strip height $a = 0.46\lambda$, the strip width $b = 0.42\lambda$, the grating period $d = 0.2\lambda$, the groove width $d_1 = 0.14\lambda$, and the groove depth $t = 0.17\lambda$ were used for the strip structural parameters, respectively. Teflon was used as the dielectric material. Then, as the parameters for the curved structure, $\xi_0 = 10\lambda$ and $2\phi_0 = 140°$ were also used as well as $\theta_0 = 71°$ and $\alpha\lambda = 0.07$ obtained from measurement.

The beam broadening could be demonstrated, but the flat pattern not be achieved because the used parameters did not satisfy completely the condition (7). In addition, the ripple on the pattern increased a little as compared with the calculated one because of mismatching with the terminal. Consequently the practical design will require the appropriate parameters satisfying (7) and the richer matching with the terminals.

IV. Conclusion

In this paper, a new "broad-beam antenna" utilizing the "curved leakywave structure" is proposed, which is easy to design for any beamwidth and to integrate with many millimeter-wave transmission lines. Radiation fields from this leakywave structure are given and the effects of various geometrical parameters on the radiation properties are discussed numerically.

This antenna possesses all of the features of the standard leakywave antennas, including not only a low profile and structural simplicity and a compatibility with the feed transmission line, but an asymmetry on the radiation pattern due to intrinsic nonuniform field distribution. Then, a simple expression is given for optimizing the asymmetry and it is demonstrated numerically that the flatness on the radiation patterns may be improved significantly by one of the configuration parameters, "equi-angle of spiral θ_0." Moreover, it is found that the broadening of beamwidth can also be obtained by another parameter—"angular aperture $2\phi_0$."

In addition, this curved structure possesses the advantage that its phase center and radiation pattern are little dependent on the observation distance, unlike the aperture antennas such as the horn antenna. This is very useful in practice in relation to the use in the near region and the measurement of the pattern.

The proposed design may readily be applied to any leakywave structure, including a periodic dielectric antenna and a leaky NRD-guide antenna for millimeter-wave application. Consequently, this design is directly compatible with these guides and may be well suited for integrated design.

Appendix

The power radiated per unit length along the leakywave structure is given as

$$\begin{aligned} p_r(\xi) &= 2\alpha P(0)\exp(-2\alpha\xi) \\ \xi &= \rho_0 \sec\theta_0\{\exp(\phi\cot\theta_0) - 1\} \end{aligned} \tag{A.1}$$

where $P(0)$ is input power, and α is the attenuation constant. Then the power radiated per unit angle can be also written as

$$p_r(\phi) = p_r(\xi)\frac{d\xi}{d\phi}. \tag{A.2}$$

The gradient of $p_r(\phi)$ near $\phi = 0$ (the optical axis) is

$$\Lambda_0 = \left.\frac{dp_r(\phi)}{d\phi}\right|_{\phi=0}. \tag{A.3}$$

Thus, for achieving the flat radiation patterns, it is required that $p_r(\phi)$ must be stationary near $\phi = 0$; that is,

$$\Lambda_0 = 0. \tag{A.4}$$

As a result, we have the definite conditions (7)–(9) for optimizing the radiation pattern of the broad-beam antennas.

References

[1] I. Ohtera, "Focusing properties of a microwave radiator utilizing a slotted rectangular waveguide," *IEEE Trans. Antennas Propagat.*, vol. 38, pp. 121–124, Jan. 1990.

[2] I. Ohtera and H. Ujiie, "Focusing properties of leaky-microwave from equiangular spiral slotted rectangular waveguide," *Trans. Inst. Electron., Inform. Commun. Eng.*, vol. J74-B-**?**, no. 2, pp. 55–63, Feb. 1991.

[3] I. Ohtera, H. Ujiie, and T. Yoneyama, "A Paraboloid antenna fed by the equiangular spiral-bent slotted waveguide," *Trans. Inst. Electron., Inform. Commun. Eng.*, vol. J76-B-**?**, no. 2, pp. 86–95, Feb. 1993.

[4] F. K. Schwering and S. T. Peng, “Design of dielectric grating antennas for millimeter-wave applications,” *IEEE Trans. Microwave Theory Tech.*, vol. MTT-31, pp. 199–209, Feb. 1983.

[5] K. Maamria, T. Wagatsuma, and T. Yoneyama, “Leaky NRD guide as a feeder for microwave planer antennas,” *IEEE Trans. Antennas Propagat.*, vol. 41, pp. 1680–1686, Dec. 1993.

[6] M. Born and E. Wolf, *Principles of Optics*, 5th ed. Oxford, U.K.; Pergamon, 1975.

[7] I. Ohtera and H. Ujiie, “Phase center of conical horn antennas,” *Trans. Inst. Electron., Inform., Commun. Eng.*, vol. 58-B, no. 2, pp. 76–83, Feb. 1975.

[8] ——, “Nomographs for phase centers of conical corrugated and TE_{11}-mode horns,” *IEEE Trans. Antennas Propagat.*, vol. AP-23, pp. 858–859, Nov. 1975; reprinted in Antenna Handbook, Y. T. Lo and S. W. Lee, Eds. New York: Van Nostrand Reinhold, 1988, pp. 8.76–8.80.

Isao Ohtera (M’80) received the B.E. degree from the Department of Electronics, Yamagata University, Yamagata, Japan, in 1966.

Since 1966, he has been with the Department of Communication Engineering, Tohoku Institute of Technology, Japan, as an Associate Professor. He has been engaged in research of reflector and leakywave antennas. His current interests are in microwave/millimeter-wave antennas for wireless (W)LAN.

Mr. Ohtera is a member of the Institute of Electronics, Information, and Communication Engineers of Japan.