Near-Field Leaky-Wave Focusing Antenna With Inhomogeneous Rectangular Waveguide

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Abstract: The near field leaky-wave focusing antenna using the inhomogeneous rectangular waveguide is proposed and a design method is presented. The height of broad-wall of waveguide is inhomogeneous to obtain focusing effect at a desired position. In the antenna design, a relation between the phase constant of traveling wave and the height of broad-wall of the waveguide is derived. Simulation results and measured results at Ka-band are presented to validate the proposed design method.

Keywords: Focusing antennas, near-field antennas, leaky-wave antennas, waveguide antennas

Classification: Antennas and propagation

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1 Introduction

The imaging technology that can detect dangerous items in clothes using non-contact / non-invasive manner is needed at airports and seaports. One of the main reasons is that the many dangerous items are miniaturized, easy to be concealed in clothes. In order to detect or to obtain images of dangerous objects in clothes, it is necessary to focus electromagnetic wave on a specific position of the surface of a human body. Recently, the technologies for microwave-focusing in the near field are drawing attention in various applications such as the imaging, the thermotherapy [1], WPT (wireless power transfer) [2], RFID reader [3]. In most cases, the handy type imaging device with compact structure is desired. In the case of the focal plane imaging, lens antennas or reflector antennas are used to obtain high resolution of images. However, these antennas are not suitable for compact devices because weight and size of the lens and the reflector are usually a big problem, especially in the application of handy type imaging device. In this paper, a waveguide leaky-wave antenna (LWA) is designed to address this problem.

LWA is one of traveling wave antennas having characteristics that the radiation direction is changed as the frequency changes which are useful to change the focusing position without using a dielectric lens or a metal reflector. In the previous studies, the focusing LWAs have been proposed in [4]-[7]. In [4], the structure of the radiating grating elements is designed to obtain focusing effect. In [5], the desired phase difference for the focusing is obtained by changing the distance between the focal point and the slot elements located on the curved substrate integrated waveguide. In [6], the location of radiating slot elements are designed to obtain the desired phase distribution. This LWA is effective for handy type devices from the view point of it's low weight. The rectilinear LWA in [7] adjusts the slit width and the position of slit on the dielectric to obtain the desired phase distribution, however, the experimental study was not provided.

In this paper, the phase constant distribution of leaky waves is controlled by changing the height of broad-wall of a rectangular waveguide inhomogeneously, and with homogeneous structure of the radiating slot elements. The structure is simple and easy to fabricated. The design concept and principle of focusing effect using a waveguide LWA are shown in section II. Our research was first reported in [8] which showed the focusing effect by simula-

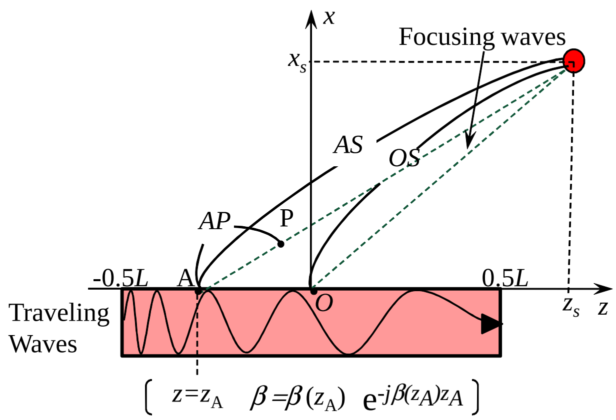


Fig. 1. Principle of focusing effect. As phase constant $\beta(z)$ gradually changes, leaked radiations are focused in near field.

tions. In section III, the design method to obtain focusing effect at desired point in the near field is presented. In section IV, experimental results of our proposed antenna are shown and the conclusion of this paper is shown in section V.

2 Concept

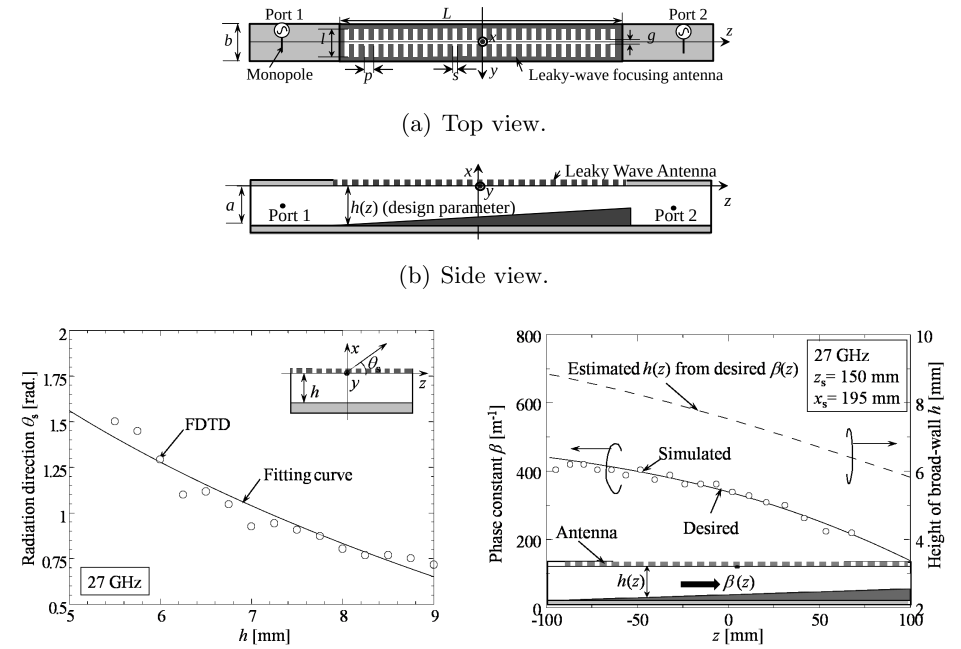
A waveguide LWA is a kind of a traveling wave antenna. Eq. (1) shows the relationship between phase constant β of the traveling wave in the waveguide and a radiation direction θ_s is

$$\theta_s \text{ [rad.]} = \cos^{-1}\frac{\beta}{k_0} \tag{1}$$

where k_0 is the wave number in vacuum. The radiation direction depends on the phase constant. Also, the phase constant depends on the frequency. Generally the phase constant and a wave number are constant for a fixed frequency, the radiation direction is constant and leaked waves become a plane wave. In order to perform imaging using a waveguide LWA, leakage radiations are required to be focused in the near field at a fixed frequency. One method to focus leaked waves in the near field is to change the phase constant of the traveling wave along the waveguide with changing the height of broad-wall of waveguide, gradually. Detail of the structure are discussed in the next section. Fig. 1 shows a principle of focusing effect. A traveling wave is excited from the end point of the waveguide LWA. In order to focus at a desired point S in the near field, the distribution of phase constant $\beta(z)$ of the traveling wave should be the desired distribution.

3 Design method

In this section, the design method to obtain the focusing effect at a desired point in the near field is discussed. As shown in Fig. 1, the desired focus point and the desired phase constant distribution are indicated as S(z_s, x_s)



(a) Top view.

(b) Side view.

(c) Relation between height of broad-wall of waveguide h and radiation direction θ_s

(d) Desired and simulated phase constant distribution $\beta(z)$ when designed focus point is S(z_s, x_s)=(150 mm, 195 mm). Height distribution $h(z)$ is obtained by using Eq. (7).

Fig. 2. Simulation model and design procedure of focusing LWA.

and $\beta(z)$. Providing a distance OS from origin O (z=0) to focal point S and a distance AS from a certain point A (z=z_A) on the surface of LWA (-0.5 $L \leq z \leq$ 0.5 L), the distance AP is given by

$$\mathrm{AP} = \mathrm{AS} - \mathrm{OS} = \sqrt{(z_s - z_A)^2 + {x_s}^2} - \sqrt{{z_s}^2 + {x_s}^2}. \tag{2}$$

The phase difference corresponding to distance AP is defined as

$$\Delta Phase(z_A) = k_0 \mathrm{AP}. \tag{3}$$

Furthermore, the phase difference and the phase constant $\beta(z)$ can be expressed in an integral form as

$$\Delta Phase(z_A) = \int_0^{z_A} \beta(z) dz. \tag{4}$$

Therefore, the phase constant distribution in the range of (-0.5 $L \leq z \leq$ 0.5 L) is expressed by the following equation as

$$\beta(z) = \frac{d}{dz} \Delta Phase(z). \tag{5}$$

Fig. 2(a) and Fig. 2(b) shows the simulation model of the waveguide LWA, and each parameters of the proposed antenna are a=8.5 mm, b=4 mm, g=1 mm, l=4 mm, s= 1 mm, p=3 mm and L=200 mm. $h(z)$ is design parameter. The design frequency is set as 27 GHz. The antenna has slot arraying on the narrow-wall surface of a rectangular waveguide. The structure of LWA part is based on the waveguide slot array proposed in [9]. A monopole located at Port 1 excites TE_{10} mode with cutoff frequency of f_c=$c/2a$=17.7 GHz, then the design frequency is in the propagation mode. In order to obtain the relation between the radiation direction and the height of the broad-wall h, the radiation patterns were evaluated using FDTD analysis. Fig. 2(c) shows the simulated radiation direction indicated as circle marks, when height of the broad-wall h is changed. The radiation directions decrease by increasing the height of broad-wall h. In Fig. 2(c), a fitted curve using logarithmic function is obtained, and the relation between the height of broad-wall h and the radiation direction is derived as

$$h\,[\mathrm{mm}] = e^{2.616-0.645\theta_\mathrm{s}\,[\mathrm{rad.}]}. \tag{6}$$

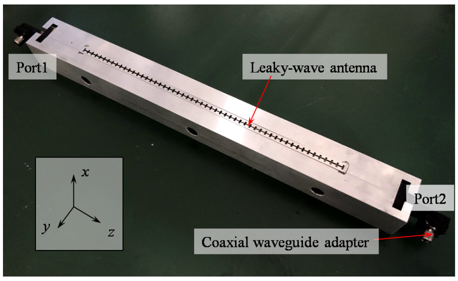
Substituting Eq. (1) into Eq. (6), the expression of the relation between the phase constant $\beta_(z)$ and the height of broad-wall h can be derived as

$$h\,[\mathrm{mm}] = e^{2.616-0.645\cos^{-1}\frac{\beta}{k_0}}. \tag{7}$$

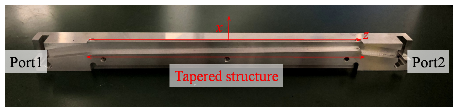
Using Eq. (7), it is possible to design the inhomogeneous height distribution $h(z)$ from the desired phase constant distribution obtained by Eq. (5). Fig. 2(d) shows the desired phase constant distribution, and the designed height of broad-wall distribution $h(z)$ by using Eq. (7) when the focusing point is selected as S(150 mm, 195 mm) at 27 GHz. Furthermore, the simulated phase constant distribution is the result of designed height of broad-wall distribution $h(z)$. The desired phase constant distribution gradually decreases as z increases. The designed height distribution of broad-wall also decreases as z increases, gradually. Also, the simulation result of phase constant distribution roughly agrees with desired values. In this paper, the height h is changed along the waveguide to obtain desired phase constant distribution, however, the cutoff frequency also changes. In this design, the frequency 27 GHz is not in the cutoff frequency region in the designed height range of 5.5 mm to 8.5 mm.

4 Experiment

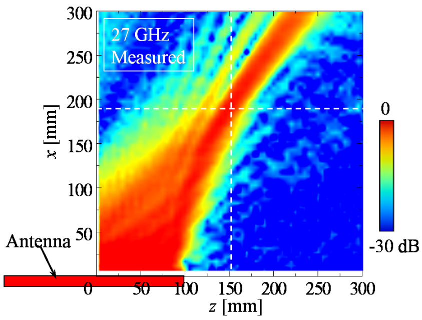
This section describes the measured results of designed focusing antenna. Fig. 3(a) shows the birds view of fabricated leaky-wave focusing antenna. LWA composed of an aluminum plate with a large number of slots was provided on the narrow-wall of the waveguide. Fig. 3(b) shows the inside view of fabricated antenna. The height of the broad-wall was set to the distribution $h(z)$ in Fig. 2(d). The travelling wave was excited at Port 1. Port 2 was terminated by 50 Ω.The near-field distribution was measured. An open ended waveguide (receiving antenna) was moved in xz-plane. The measurement area was $0\,\mathrm{mm} \leq z \leq 300$ mm, $10\,\mathrm{mm} \leq x \leq 300$ mm, with at 5 mm intervals. Fig. 3(c) and Fig. 3(e) shows measurement result at 27 GHz and 29 GHz. In Fig. 3(c), the focusing effect at roughly the design point (the dashed lines intersection, S(150 mm, 195 mm)) was observed. In Fig. 3(e), the focusing effect was also observed, and the focused area moved about 30 mm in $+z$



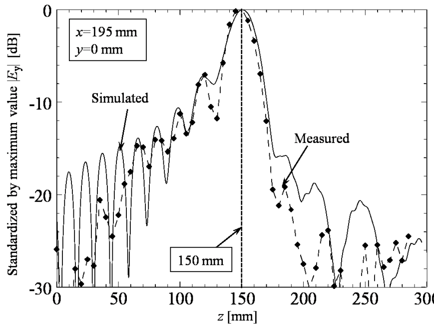
(a) Fabricated leaky-wave focusing antenna, birds view.



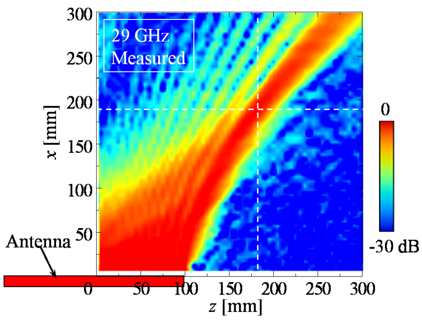
(b) Fabricated leaky-wave focusing antenna, side view.



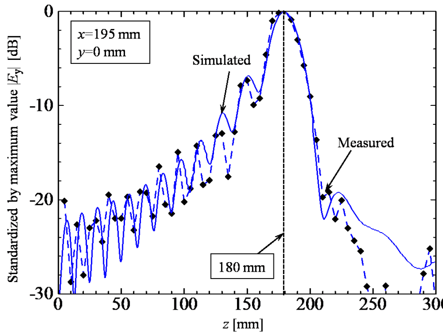
(c) Mesured result at 27 GHz.



(d) Line distribution x=195 mm at 27 GHz



(e) Measured result at 29 GHz.



(f) Line distribution x=195 mm at 29 GHz

Fig. 3. Measure electric field $|E_y|$ distribution at 27 GHz and 29 GHz.

direction. Fig. 3(d) and Fig. 3(f) shows the $|E_y|$ transverse line distribution (x=195 mm). In Fig. 3(d), the maximum value was obtained at the desired position (z_s=150 mm), and it was found that there is a focal region. Both of In Fig. 3(d) and in Fig. 3(f), good agreement were observed in the depth and the width of focus and the sidelobe levels with the simulation results.

5 Conclusion

The near field leaky-wave focusing antenna using the inhomogeneous rectangular waveguide and its design method was proposed. Inhomogeneous distributions of the phase constant of traveling wave and the height of broad-wall of waveguide were provided to obtain focusing effect at a desired position. The fabrication of the leaky-wave focusing antenna was performed at 27 GHz. The focal region of simulation and measurement were roughly agreed with the desired position and the focal area moved with changing frequency.