Dielectric Leaky-Wave Antenna with Planar Feed Immersed in the Dielectric Substrate

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Abstract

A dielectric leaky-wave antenna with a planar leaky-waveguide feed immersed in the substrate which permits the thicknesses of both the radiating section and the feed section to be optimized individually. As a result, low cost planar antennas with high radiation performances can be obtained in millimeter-wave and quasi-millimeter-wave bands. A design example of a 24 GHz high gain antenna and the simulated radiation characteristics will be presented.

1. INTRODUCTION

Radio systems using millimeter- and quasi-millimeter-waves, such as automotive radars, various kinds of sensor systems, fixed wireless access, or high-speed wireless LANs have been developed worldwide. As planar antennas for such applications, microstrip antennas [1], and waveguide slot antennas [2], [3] are most well known.

A dielectric leaky-wave antenna (DLWA) [4], [5] is promising candidate for these applications, because it exhibits advantages such as low-cost and low profile structure, and it performs relatively high antenna efficiency compared with microstrip antennas. In DLWAs developed so far, dielectric substrates have been excited by a rectangular waveguide [6], a parabolic reflector [5], and a waveguide slot [7]. Afterwards, a planar leaky-waveguide feed was reported [8]. It has an advantage that the entire antenna can be fabricated by only printing technology, thus low cost planar antennas in millimeter-wave and quasi-millimeter-wave bands can be realized. This antenna, however, has a problem that it cannot provide the optimal thicknesses both for the radiating- and for the feeding-sections.

In this paper we will propose a novel DLWA which has a planar feed immersed in the substrate and permit the optimal design for both section, and also show a design example and the simulated radiation performances of a 24 GHz high gain antenna.

2. DLWA WITH A FEED IMMERSED IN THE SUBSTRATE

A. Leaky-waveguide based on a microstrip line

As shown in Fig. 1, a typical DLWA consists of a dielectric substrate placed on a ground plane which is periodically loaded by parallel metallic strips in the x-direction, and a feed which excites a surface-wave of TM_{01} mode into the substrate. There are several types of feed, but from the point of view of low cost, feeds using planar transmission lines seem to be promising. A leaky-waveguide feed which consists of a microstrip line (MSL) with periodic stubs was proposed by the authors. Stub pairs are periodically arranged to the both edges of the MSL as shown in Fig. 2. Since the electric currents on a stub pair flow in the opposite direction, the radiation to the upper hemisphere due to stub pairs is suppressed, consequently the surface-wave is effectively excited into the substrate. Each stub pair is arranged with a spacing of a guide-wavelength λg, of the MSL at the center frequency. Thus the equi-phase plane of the excited waves becomes almost parallel to the MSL. In this feed, however, reflections due to each stubs are added in-phase, thus a considerable amount of reflection may occur. In order to avoid such large reflection, reflection-rejection elements are equipped as shown in Fig. 2.

Fig .3 shows an effect of the elements. It can be seen that in the case of without the elements a large reflection appears near the center frequency, 24.15 GHz, while it is improved more than 10dB by applying the reflection-rejection elements.

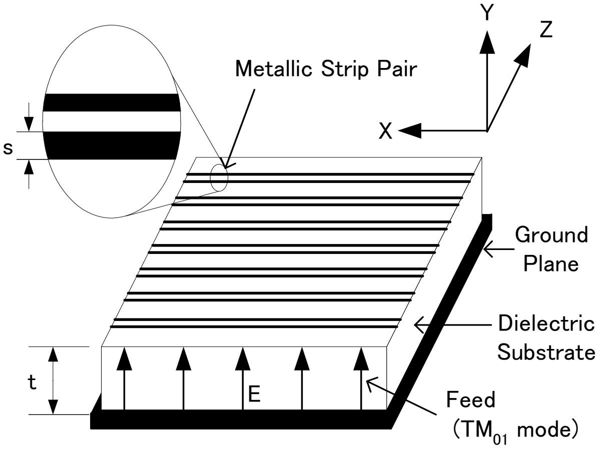

Fig. 1 Dielectric leaky-wave antenna

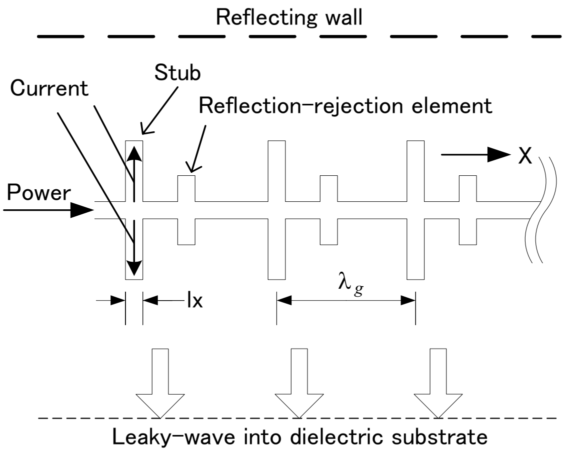

Fig. 2 Leaky-waveguide feed composed of stub-loaded microstrip line

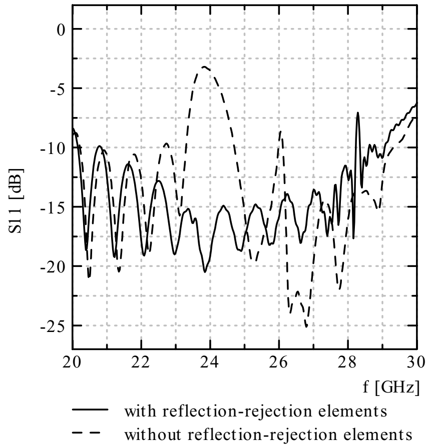

Fig. 3 Effects of reflection-rejection elements

B. Optimal thicknesses for radiating section and feed section

Although the antenna mentioned above is simple and suitable for mass-production, it is not easy to attain a high antenna efficiency, because the optimal thicknesses for the radiating section and for the feed are different. In the radiating section, the amplitude of leaky-wave generated by each metallic strip must be controlled within the range needed to obtain a desired aperture distribution. As a rule of thumb, it is known that the thickness "t" of the substrate of a typical DLWA is expressed by

$$t \approx \frac{\lambda_0}{4\sqrt{\varepsilon_s}} \qquad (1)$$

If the substrate has a thickness given by Eq. (1), we can control the leakage by adjusting the width of each metallic strips, "s", and obtain the desired aperture distribution. Fig.4 shows an example of leakage versus "s" at 24.15 GHz for two substrates with different thickness, one is t = 1.4 mm and the other is t = 0.5 mm. From this figure, we can see that in the case of t = 1.4 mm, leakages over the wide range can be obtained, while in the case of t = 0.5 mm, the leakage is limited.

On the other hand, in a MSL, large thickness causes a large unwanted leakage and deteriorates its transmission performances. In Fig. 5, leakage versus stub width, lx, is shown for two substrates of 1.4 mm thick with different height of the feed, h. In the case of h = 0.5 mm, leakage over wide range can be obtained. Contrarily, in the case of h = 1.4 mm, control of leakage is difficult particularly in the small leakage region.

From the above discussion, we propose a DLWA with an inner feed which has a leaky-waveguide printed on the surface of the inner substrate layer. This antenna can be easily manufactured using multi-layer print-circuit-board technology. By applying this technology, we can choose the optimal thickness of the substrate both for the radiating section and for the feeding section.

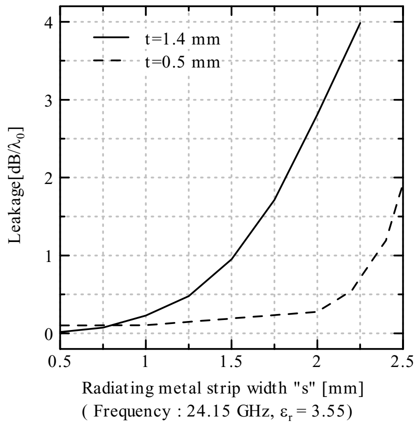

Fig. 4 Leakage control in radiating section

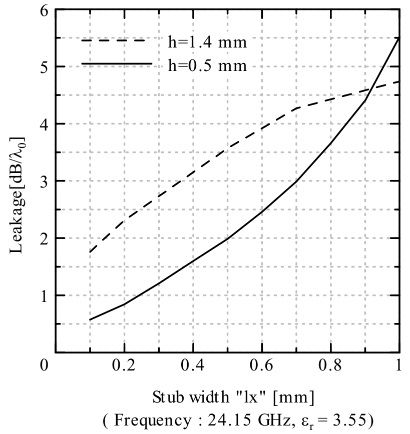

Fig. 5 Leakage control in MSL leaky-waveguide

3. DESIGN EXAMPLE OF A DLWA AND ITS RADIATION CHARACTERISTICS

We designed a 24 GHz DLWA with inner feed for a radar application and investigated the detailed radiation characteristics. As a dielectric substrate, we adopted Rogers RO4003C, a kind of resin, which provides low cost and low transmission loss in quasi-millimeter-wave band. The specifications for this antenna are summarized in Table 1. All simulations were carried out by "HFSS". Fig. 6 illustrates a decomposed structure of the antenna. On the top surface of the dielectric substrate, metallic strips forming the radiating section, and on the surface of the inner substrate layer, a MSL with loaded stubs and reflection-rejection elements forming the leaky-waveguide, are printed. Fig. 7 shows a cross-sectional view of the antenna. The signal from RF module equipped on the bottom layer is transmitted to the DLWA through a MSL and a coupling slot cut on the ground plane.

A. Planar leaky-waveguide feed

The configuration of the leaky-waveguide feed is shown in Fig. 8. The center MSL is divided into two MSL arms by a T-junction. The two arms are loaded by periodically located stubs and reflection-rejection elements. This configuration of the feed allows to avoid a beam-tilt occurred in a conventional leaky-waveguide excited at an edge. Furthermore, since the transmission line length becomes a half of that in the case of edge-feed, the transmission loss in dB becomes half. The aperture distribution along the feed is assumed to be Taylor distribution with –25 dB sidelobes. This distribution is realized by controlling the width "lx" of each stub. In actual design, first, we accumulate a lot of database of lx and leakage, and then lx of each stub is determined so that leakage may match the desired distribution.

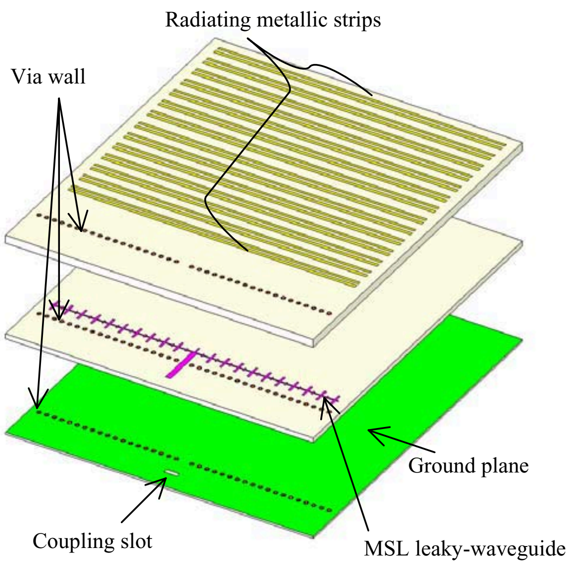

Fig. 6 Structure of the designed antenna

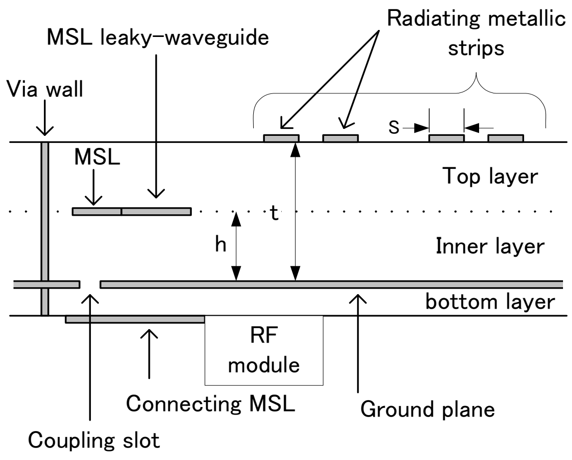

Fig. 7 Cross-sectional view of the antenna

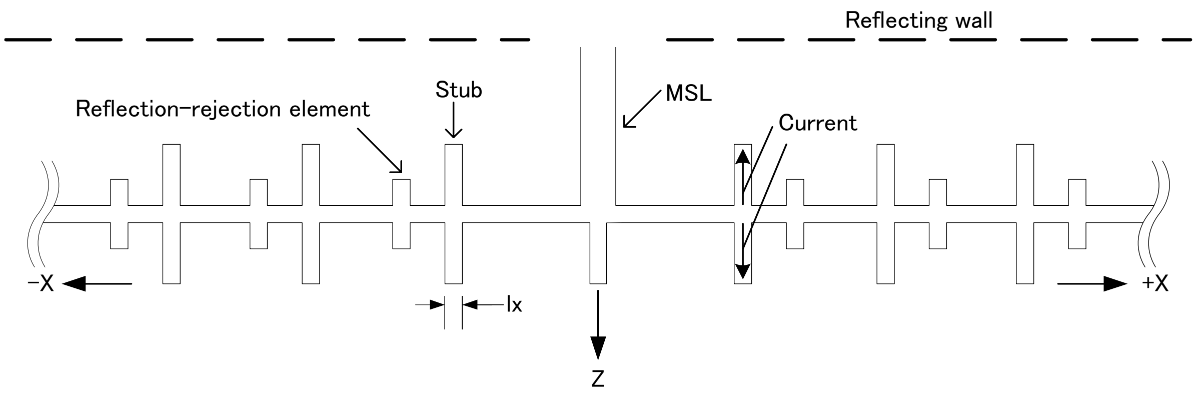

Fig. 8 Center-fed leaky-waveguide

B. Radiating section

As mentioned previously, the radiating section is configured with multiple parallel metallic strip pairs printed periodically on the surface of the dielectric substrate with thickness of 1.4 mm. Each strip pair, separated almost a quarter guide-wavelength of the TM_{01} mode of the dielectric waveguide, cancels reflections caused by the strips [5]. Furthermore, spacing between the strip pairs is slightly changed from a guide-wavelength, so that we may avoid all reflections to be added in-phase. This causes a small beam tilt from the boresight. In our case, it is approximately two degrees. The aperture is designed to have Taylor distribution with –25 dB sidelobes similarly as the feed to achieve the resulting sidelobes lower than –20 dB in the E-plane. The aperture distribution is controlled by adjusting the width of each metallic strips, “s”.

C. Performances of the antenna

In Figs. 9 and 10, the radiation patterns in the H-plane and the E-plane are shown, respectively. The half-power beam widths of these patterns are 5.6 degrees and 5.4 degrees. The sidelobes mean the desired aperture distributions are almost realized in the both planes. In Table 2 the estimated gain factors are listed. The overall antenna efficiency of 40 % is obtained including the losses of the coupling slot and the connecting MSL on the backside RF circuit board. The largest loss factor is a transmission loss of the MSL for the leaky-waveguide, and the second is a transmission loss of the dielectric substrate for the radiating section. These come from tan δ of the substrate, therefore, the choice of dielectric material is definitely important for highly efficient DLWAs.

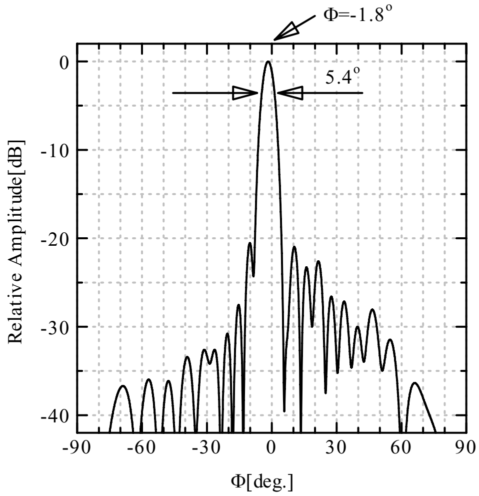

Fig. 10 Radiation pattern in the E-plane

TABLE 1: SPECIFICATIONS

Frequency	24.15 GHz ± 100 MHz
Dielectric substrate	Rogers RO4003C (ε_r = 3.55, tan δ = 0.004)
Size of radiating section	150 mm (W) × 140 mm (L)
Substrate thickness (t)	1.4 mm
Height of feed (h)	0.5 mm
Antenna Gain	> 27 dBi
Sidelobe level	< -20 dB

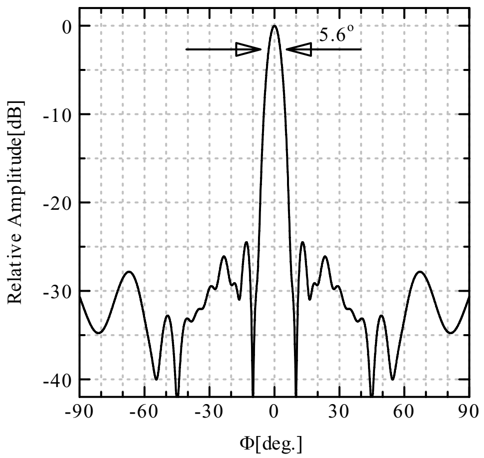

Fig. 9 Radiation pattern in the H-plane

TABLE 2: ESTIMATION OF LOSS FACTORS AND ANTENNA GAIN

	Loss factor	dB
Feed section	• Feed efficiency of leaky-waveguide (Transmission loss and residual power included)	-1.3
	• Coupling-slot loss	-0.4
	• Connecting MSL loss	-0.4
	• Input reflection loss	-0.2
	• Aperture efficiency in H-plane (-25 dB Taylor)	-0.4
Radiating section	• Radiation efficiency (Transmission loss or dielectric-guide and residual power included)	-0.8
	• Aperture efficiency in E-plane (-25 dB Taylor)	-0.4
Overall Antenna	• Total antenna efficiency	-3.9 (40.7 %)
	• 100 % antenna gain (150 × 140 mm aperture)	32.0 dBi
	• Predicted antenna gain	28.1 dBi

4. CONCLUSION

A DLWA with a planar leaky-waveguide feed immersed in the inner substrate layer, which makes optimal design possible both for radiating section and for feed section, was proposed. This technique is very effective to realize mass-productive, low cost planar antenna with moderate antenna efficiency in millimeter-wave and quasi-millimeter-wave bands. It was verified by computer simulations for a design example of 24 GHz antenna. At present, we have been developing the antenna, its result will be presented in the near future.

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