Analysis and Design of V-Band Radial Line Slot Array Antenna Fed by a Rectangular Waveguide

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ABSTRACT **— A single-layered radial line slot array (SL-RLSA) antenna etched on a substrate and fed by a rectangular waveguide is presented in the 60GHz band. The design curves are obtained by an efficient electromagnetic coupling analysis using Ewald Sum technique and Shanks' transformation. The antenna has rectangular waveguide feed structure using a rectangular waveguide-to-radial line transition. The prototype antenna of 10cm-diameter was tested and the gain of 31dBi and the efficiency of 38% were measured at 60GHz.**

I. INTRODUCTION

High-gain planar antennas are important elements in wireless LANs and collision avoidance radar systems in the millimeter wave band. The RLSA antenna was proposed as a candidate for these requirements with high efficiency. Since the analysis model, from which the information about couplings through slots can be obtained, and design procedures have been well developed already in the 12GHz band [1], several types of RLSA antennas have been designed easily [2]. But, in the coupling analysis of these RLSAs, the efficiency from the viewpoint of numerical analysis has not been emphasized, so there is a practical difficulty in convergence behavior in the evaluation of the Green's functions. Also, the use of the coaxial cable with coaxial-to-radial line transition as a feed structure in existing RLSA antennas made these antennas more lossy, expensive, and difficult to handle in the millimeter wave band. This paper summarizes the proposed efficient method of analyzing the slot coupling and proposes new planar feeding method suitable at 60GHz band. Fig. 1 shows the structure of prototype antenna to be designed.

II. EFFICIENT ANALYSIS OF SLOT COUPLING

The slot coupling characteristics should be analyzed in RLSA for its design. The previous analysis [1] used a waveguide model with a periodic boundary condition on its narrow walls and periodically arranged slots on its wide wall. The magnetic field integral equation and two dyadic Green's functions for each region are derived and the

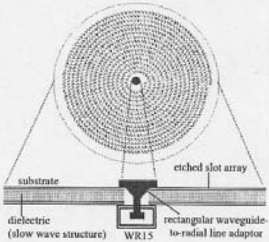


Fig. 1. SL-RLSA antenna with proposed adaptor

method of moments is used. For the rectangular waveguide region, the Green's function is a two dimensional series, which is quite slowly convergent. In our analysis, Green's function is expanded in terms of image series. The series is the superposition of the free-space periodic Green's functions, which can be efficiently calculated using the Ewald sum technique as follows [3-5].

$$G_{WG} = G_{WG1} + G_{WG2}$$

$$G_{WG1} = \sum_{m=0}^{\infty}\sum_{n=0}^{\infty} \frac{\varepsilon_m \varepsilon_n}{4ab\gamma_{mn}} f(k_{x_m}, x, x') h(k_{y_n}, y, y') \times \left\{ \frac{\exp[\gamma_{mn} Z] erfc[\gamma_{mn}/2E + ZE]}{\gamma_{mn}} + \frac{\exp[-\gamma_{mn} Z] erfc[\gamma_{mn}/2E - ZE]}{\gamma_{mn}} \right\}$$

$$G_{WG2} = \frac{1}{4\pi} \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} \sum_{i=0}^{1} A_i \times \frac{\mathrm{Re}[\exp(jkR_{i,mn}) erfc(R_{i,mn}E + jk/2E)]}{R_{i,mn}} \quad (i = 0,1)$$

, where

f, h: sinusoidal functions

a, b: width and height of waveguide cross section

E: control parameter in the Ewald sum method

$$R_{0,mn} = \sqrt{(x - x' + ma)^2 + (y - y' + 2nb)^2 + (z - z')^2}$$

$$R_{1,mn} = \sqrt{(x - x' + ma)^2 + (y + y' + 2nb)^2 + (z - z')^2}$$

$$\gamma_{mn} = \sqrt{k_{x_m}{}^2 + k_{y_n}{}^2 - k^2}$$

$$k_{x_m} = \frac{2m\pi}{a}, k_{y_n} = \frac{n\pi}{b}$$

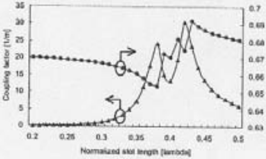
$$\varepsilon_i = \begin{cases} 1, i = 0 \\ 2, i > 0 \end{cases}$$

$$Z = |z - z'|$$

$$A_i : \pm 1$$

As a result, exponential convergence is achieved with increasing the number of summation terms. Similarly, some acceleration method is required for the effective calculation of the free-space Green's function series in the half space region. We used Shanks' transformation which transform the sequence of partial sums of slowly convergent infinite series into the new one which converges quickly toward the exact value [6]. In addition to the accelerations of the two Green's functions, two different kinds of basis functions, the entire domain basis function and the sub-domain one, are used together to maximize the efficiency of numerical analysis and to extract singularities. That is to say, in filling impedance matrix in method of moments, non-self term is calculated using entire basis function expansion of magnetic current because there are no singularities. But, since entire basis function cannot be used for the self-term due to the difficulties in extracting singularities, the current is expanded using the roof-top basis functions through the piecewise linear approximation of the entire domain basis function. With the help of this sub-domain basis function, we can use the well-known analytical integral formulas in computing the part related to singularities and numerical integrations in computing the other part, respectively. It can be shown that the proposed analysis method leads to a reduction in computational effort and time with better accuracy. Fig. 2 shows the coupling characteristics of the slots etched on the substrate.

Fig. 2. Calculated coupling characteristics of slots



III. DESIGN OF RECTANGULAR WAVEGUIDE FEEDER

In the usual RLSA antennas, the power is fed by the coaxial feed at the center of the radial waveguide [2]. But this type of feed cannot be easily used in millimeter wave band because coaxial cable is lossy, and the adaptors are expensive and fragile in that band. Therefore, most of mm-wave tranceivers have their input/output ports with standard rectangular waveguides. For these reasons, we got an idea from the commonly used coaxial-to-waveguide transition and applied it directly to rectangular waveguide-to-radial line transition. The mechanism of power transfer by our adaptor is as follows. First, the input power is coupled from rectangular waveguide to upper substrate. Next, the coupled power is gradually changed into a radially outward traveling wave by the inclined shape of the adaptor and finally radiates through slots. The optimum dimensions of the adaptor were determined using commercial field simulators assuming the absence of etched slot array. The structure of the proposed transition was already shown in Fig. 1, and the symmetric field distribution after the transition by the adaptor was checked through the simulations as shown in Fig. 3.

IV. FABRICATION AND MEASUREMENT RESULTS

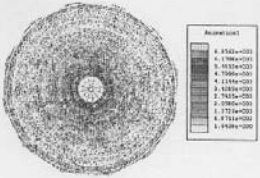


Fig. 3. Field distribution after transition. (top view)

A prototype RLSA antenna with a new feed structure is fabricated and tested as shown in Fig. 4. We use a substrate (dielectric constant of 2.2) on which the pattern of slots is chemically etched for easy manufacturing contrary to the conventional type of RLSA. The measured reflection in Fig. 5 shows satisfactory return loss of about −14dB around 60GHz. The ripple in Fig. 5 is due to the existence of etched slots that cannot be considered in simulations. Fig. 6 shows the measured far-field radiation pattern (-20° ~ +20° only). The beam pattern is reasonably symmetrical and reveals the first side lobe level of −14dB and the 3dB beam width of 4°. Also, the cross polarization level was about −14dB and high-gain of 31dBi (38% of efficiency) was measured.

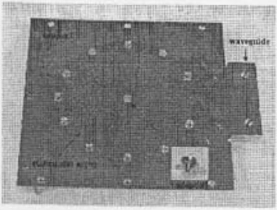


Fig. 4. Photograph of fabricated antenna

V. CONCLUSIONS

We have presented the design of RLSA antenna etched on a substrate which is fed by rectangular waveguide at 60GHz. By using two different kinds of accelerating techniques and exploiting two different kinds of basis functions, the coupling characteristics of slot array was analyzed exactly and rapidly. Also, we replaced the coaxial feeder with the rectangular waveguide by using the simple adaptor in feed structure, which has less loss and can be easily connected to most of millimeter wave transceivers. The designed antenna showed good performances.

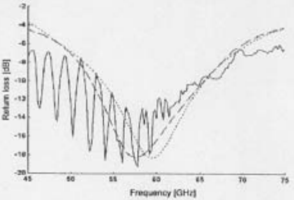


Fig. 5. Reflection of the feeder. (Dashed line: simulation using HFSS; dotted line: simulation using Microwave Studio; solid line: measurement)

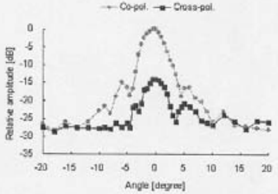


Fig. 6. Measured antenna radiation pattern.

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