High-Efficiency W-Band Electroforming Slot Array Antenna

Dong-yeon Kim, Youngjoon Lim, Hee-Sung Yoon, and Sangwook Nam

Abstract—**A W-band 8×8 slot array antenna is proposed and fabricated by electroforming for high-precision manufacturing. The external mutual coupling between radiating shunt slots is compensated for input impedance matching and a uniform field distribution. The overall antenna aperture area is $473.1\ \mathrm{mm}^2$ with slot spacings of 2.8 and 2.64 mm in the transverse and longitudinal direction, respectively. The measured maximum gain is 26.8 dBi and the corresponding antenna efficiency is 81.9% at 94 GHz. The measured impedance bandwidth when the VSWR is less than 2.0 (-10 dB) is 8.3%, with a range from 89.9 to 97.6 GHz.**

Index Terms—**Electroforming, high efficiency, millimeter wave antenna, waveguide slot array antenna, W-band.**

I. Introduction

Waveguide slot array antennas are excellent candidates for high-efficiency millimeter-wave radiating systems due to their low transmission loss. In addition, the robust and low-profile features make them useful in various applications such as satellite communications, military radar systems, and indoor high-speed data transfer systems despite their narrow impedance bandwidth stemming from standing-wave excitation as well as the serial radiating/coupling slot elements along radiating/feeding waveguide in array.

Various studies of millimeter-wave antenna designs have been conducted for designs characterized by their high efficiency, low cost, ease of integration, and high reproducibility. Microstrip antennas are typically advantageous in terms of the cost of production and their lightweight features. However, transmission line losses increase especially for millimeter-wave applications. To suppress the reflection from each radiating element, a microstrip comb-line antenna was investigated using reflection-canceling slit structures [1]. The maximum antenna efficiency obtained was 55.0% at 76.5 GHz. In order to suppress the feeding network losses of microstrip antennas, "substrate integrated waveguide" (SIW) or "postwall waveguide" slot array antennas have been suggested and applied for different operating frequencies [2]–[4]. A 12×12 planar slot array antenna for 60 GHz was developed for use on a single printed-circuit board (PCB), achieving high radiation efficiency of approximately 68% [2]. At 76 GHz, the measured efficiency of a postwall waveguide slot array antenna was less than 50% due to the aperture efficiency loss and reflection loss [3]. In addition, a SIW monopulse slot array antenna was designed for 94 GHz operation [4]. It was found that the dielectric loss from the feeding network is considerable and that unintended etching errors for radiating slots distort the aperture field distributions severely in terms of their amplitude and phase due to the relative permittivity of the PCB. Meanwhile, hollow-waveguide slot array antennas have been designed and fabricated by a process involving the diffusion bonding of laminated thin metal etching plates for operation at 60 and 94 GHz [5], [6]. The maximum antenna efficiencies were 83.6% and 60.0% at 61.5 and 93.7 GHz, respectively, based on respective aperture efficiencies of 93.7% and 69.0% in the absence of dielectric losses. It is clear that the simple and typical hollow-waveguide slot array antenna structures are significantly more efficient within a given aperture area than other types of antennas, even if there is a narrow bandwidth for impedance and patterns that is in inverse proportion to the number of radiating and coupling slots.

In this communication, a standing-wave excited double-layer W-band 8×8 slot array antenna is designed and fabricated using an electroforming process in an effort to minimize the transmission line losses and enhance the reproducibility. First, the internal waveguides and several coupling slots are formed by mandrels made of aluminum. Next, the high conductive metal is coated on the mandrel through electrodeposition in a plating bath, and then the mandrel is chemically resolved [7]. This electroforming technique had been applied for millimeter-wave antenna manufacturing such as corrugated horn antennas [8]. The target gain of the proposed antenna is more than 25 dBi with uniform distribution and the maximum gain of 26.8 dBi is achieved with the help of the electroforming. The antenna design was conducted using a full-wave simulator from CST MWS [9] and compared with measurement results.

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II. 8×8 Slot Array Antenna Structure

The proposed double-layer 8×8 slot array antenna is shown in Fig. 1. All radiating waveguides are fed by centered coupling slots that are located between radiating and feeding waveguides. The input power injected by an E-bend transition is split by a T-junction both ways at equal amounts with minimal reflection. All radiating waveguides are separated by a wall with a thickness of 0.8 mm. The width (a_1) and height (b_1) of the radiating waveguides are set to 2.0 and 1.0 mm, respectively. Considering the width of the radiating waveguides and the thickness of the walls, the slot spacings are $0.878 \cdot \lambda_0$ and $0.828 \cdot \lambda_0$ in x- and y-directions, respectively. It is expected that narrower slot spacings can be achieved if a more accurate manufacturing technique is used.

The crossed feeding waveguide is located under the radiating waveguides and shunt-to-series coupling slots are arrayed on the upper side with a constant offset value from the center line with a half guided-wavelength spacing for a uniform field distribution, as shown in Fig. 1(b). Unlike series-to-series coupling slots with perfect magnetic conductor (PMC) walls [10], shunt-to-series coupling slots are applied and terminated with a simple one-quarter guided-wavelength stub of a feeding waveguide. These shorter open-circuit stubs can reduce the "blockage" or the existence of "slot-free regions" when these subarrays are aligned side by side and create a large-array antenna. Moreover, the tapered distribution design on the radiating slots is not necessary due to the extended slot spacing between subarrays as applied in [11]. In order to locate all radiating waveguides at standing wave peaks of a feeding waveguide, the width (a_2) of the feeding waveguide used here is set to 1.94 mm.

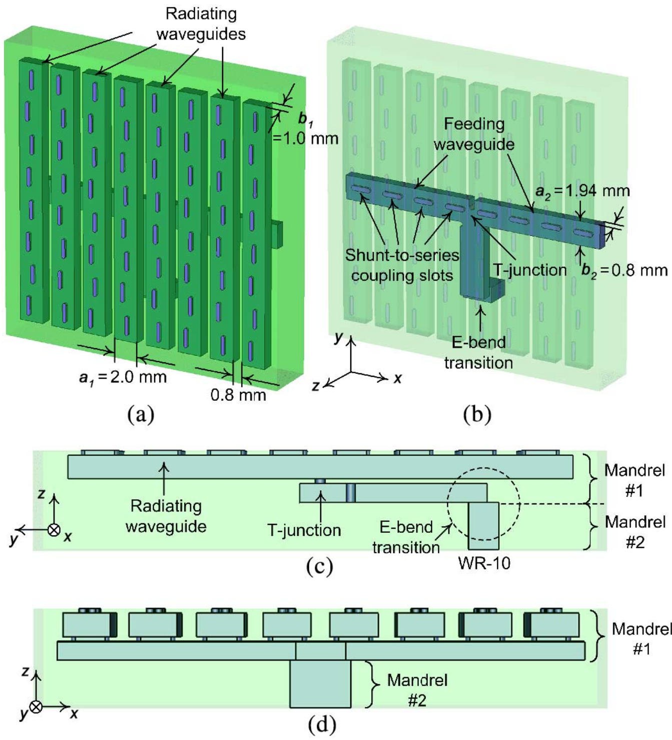

Fig. 1. Proposed 8 × 8 slot array antenna. (a) Radiating shunt slots located on radiating waveguides. (b) Shunt-to-series coupling slots between radiating and feeding waveguides. (c) Side view (*yz*-plane). (d) Side view (*zx*-plane).

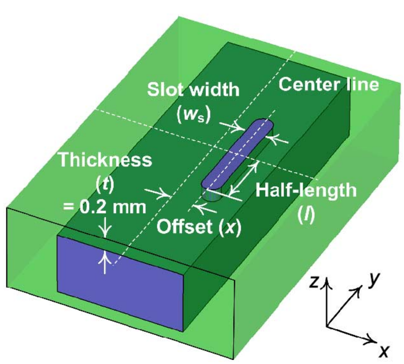

Fig. 2. Single-shunt-slot module for admittance extraction.

A. Self-Admittance of a Single-Shunt-Slot Module

The width (w_s) and thickness (t) of the radiating shunt slots are set to 0.3 and 0.2 mm, respectively, to widen the fractional bandwidth. Both edges are designed with rounded ends for accurate fabrication, as depicted in Fig. 2. Self-admittance extraction from a single-shunt-slot module was conducted using the two-port S-parameter results, specifically the length and the offset [12]. To compensate for the external mutual coupling effects from active admittances, the normalized conductance (G/G_r) and susceptance (B/G_r) by the resonant conductance (G_r) of an isolated single-slot module were obtained using a full-wave EM simulator. The normalized loci for several offsets are similar especially around the resonant length (l_r), and they can be substituted for curve fitting, as shown by the solid lines in Fig. 3. In addition, the curves pertaining to the resonant length and resonant conductance to offset variation are obtained to satisfy the input matching and field distributions. The whole iteration process was conducted by MATLAB as described in [12].

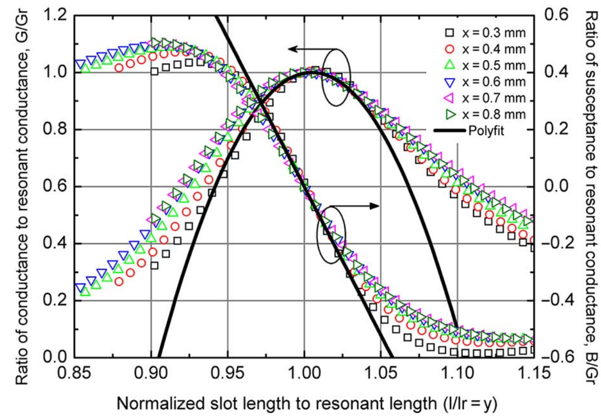

Fig. 3. Normalized resonant conductance (G/G_r) and susceptance (B/G_r) in terms of the length and the offset.

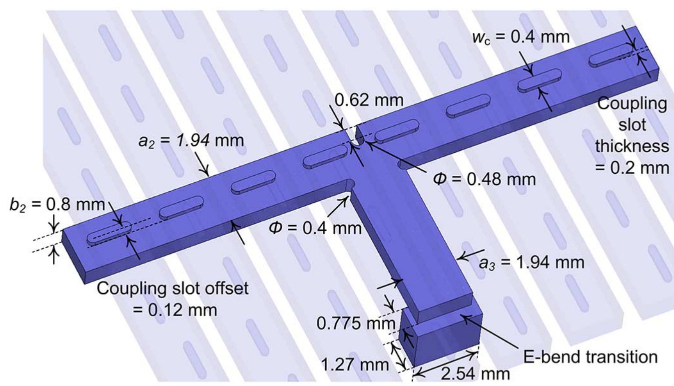

Fig. 4. Feeding network and optimized values.

B. T-Junction and E-Bend Transition

The total impedance bandwidth of a slot array antenna is dependent on the main radiators and feeding network, including a transition structure for measurements or interconnections. Also, simpler and wideband feeding networks are advantageous when seeking to adjust the operation frequency, especially for millimeter-wave antennas. The conventional T-junction, which applies a symmetrical window with a septum, was employed for the corporate feeding network in order to minimize reflections [5]. Considering the sensitivity required during the fabrication precision for W-band operation, the edges of the septum and obstacles parallel to the electric field are rounded, as shown in Fig. 4. The optimum values for the T-junction and E-bend transition are obtained for minimal reflections from a full-wave simulator and confirmed as depicted in Fig. 5. The two elements of a feeding network were designed independently for a center frequency of 94 GHz. As a result, the optimized reflection coefficient bandwidths when VSWR <1.22 (-20 dB) are ranged from 87.6 to 103.8 GHz (16.9%) and from 76.6 to 102.4 GHz (28.9%) for the T-junction and E-bend transition, respectively. The impedance bandwidth of the combined total feeding network ranges from 88.4 to 98.4 GHz (10.8%).

III. Fabrication and Experimental Results

The 8 × 8 slot array antenna is electroformed at one time using a single mandrel combined mandrel #1 and #2 as shown in Fig. 1(c) and (d). The mandrel #1 consists of radiating and feeding waveguides including coupling slots. Mandrel #2 indicates a vertical waveguide consisting E-bend. The fabricated antenna is shown in Fig. 6. The

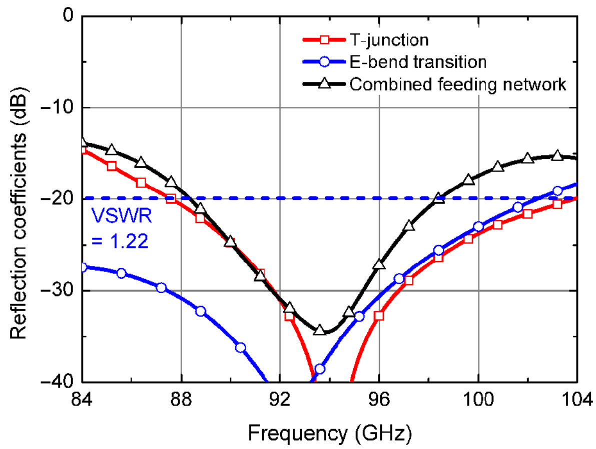

Fig. 5. Reflection coefficient results for the feeding network.

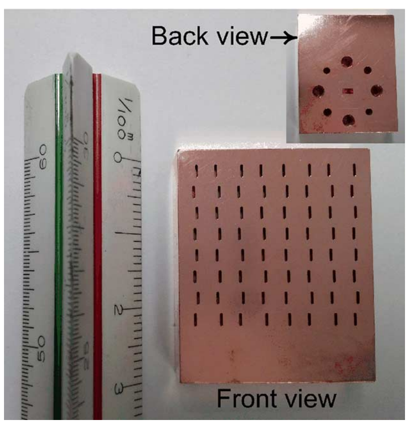

Fig. 6. 8×8 slot array antenna fabricated by an electroforming process.

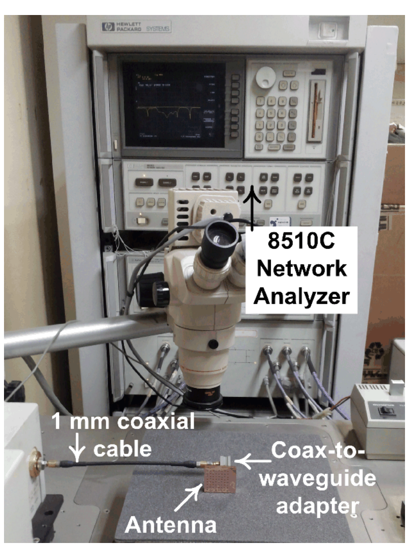

Fig. 7. Set-up for reflection coefficient measurement.

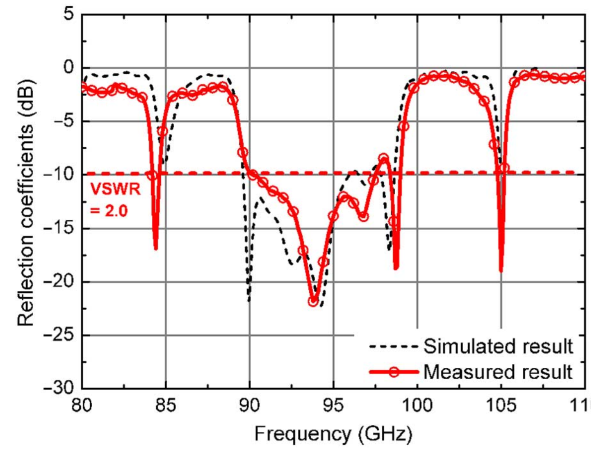

Fig. 8. Simulated and measured reflection coefficients.

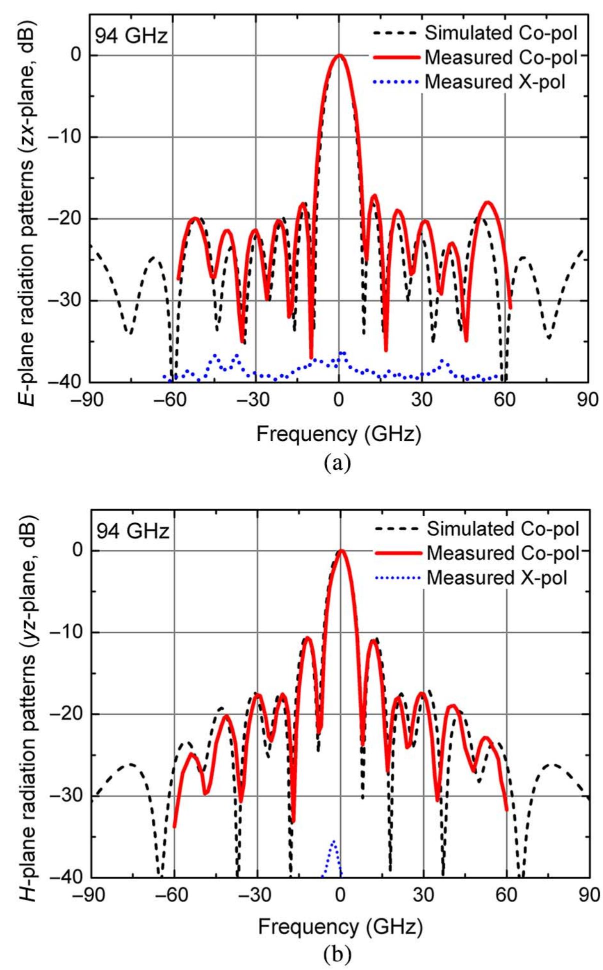

Fig. 9. Simulated and measured radiation patterns at 94 GHz. (a) E-plane. (b) H-plane.

proposed antenna is made of copper, and the conductivity is high at 5.8×10^7 S/m for low conductor loss [6]. The aperture area is $473.1\ \mathrm{mm}^2$, as calculated by $(N_x \times d_x) \times (N_y \times d_y)$, where N_x, N_y and d_x, d_y are the number of slots and spacings in the x- and y-directions, respectively. In addition, the total antenna thickness is 7.2 mm. As shown in the back view of Fig. 6, there are alignment pins and screw holes that are used to assemble a coax-to-waveguide (WR-10) adapter for measurements.

The reflection coefficient was measured using the 8510C network analyzer from Agilent HP, as shown in Fig. 7. The results of the simulated and measured reflection coefficients are shown in Fig. 8. The measured minimal reflection was detected at $-21.3\,\mathrm{dB}$ at a center frequency of 94 GHz, and the overall measured locus is in

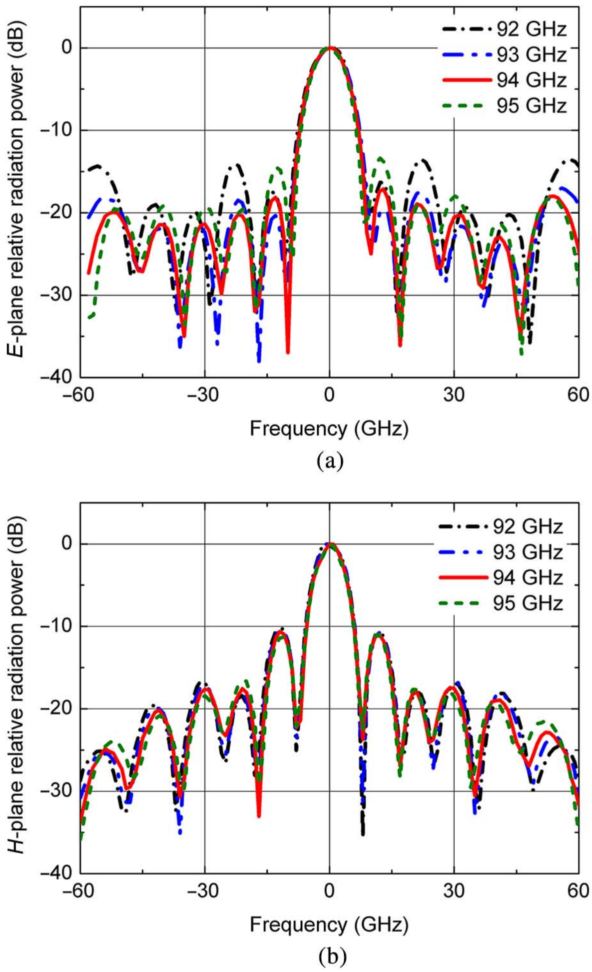

Fig. 10. Measured radiation pattern results for different frequencies. (a) E-plane. (b) H-plane.

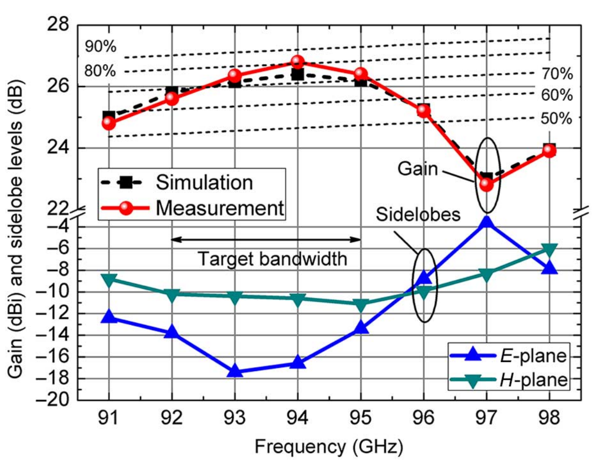

Fig. 11. Gain, antenna efficiency, and sidelobe levels of the proposed antenna.

good agreement with the simulation. The simulated and measured impedance bandwidths when VSWR <2.0 ($-10\,\mathrm{dB}$) are from 89.6 to 97.4 GHz (8.3%) and from 89.9 to 97.6 GHz (8.3%), respectively.

Radiation patterns were measured in an anechoic chamber at EMTI [13]. The relative power levels were plotted at a center frequency of 94 GHz from -60 to 60 degree for the E- and H-planes, as shown in Fig. 9. It was found that both measured radiation patterns are quite similar to the simulation results. The normalized radiation patterns for different frequencies for the E- and the H-plane are plotted in Fig. 10. It is shown that the sidelobe levels for the E-plane radiation patterns range from -19.4 to $-13.4\,\mathrm{dB}$, whereas those for the H-plane patterns are constant.

The frequency characteristics for gain, antenna efficiency, and sidelobe levels are summarized in Fig. 11. The measured maximum gain is 26.8 dBi at 94 GHz and the corresponding antenna efficiency is 81.9% for a given aperture area. However, the sidelobe levels for H-plane are increased to $-10\,\mathrm{dB}$ that need improvement for precise uniform aperture distribution.

IV. Conclusion

An 8×8 slot array antenna is proposed and fabricated by an electroforming process. In order to broaden the impedance bandwidth of the total array antenna, the width and thickness of the radiating and coupling slots are considered along with the feeding network. In addition, all edges of the slots, including the fine feeding structures, are designed with rounded ends to alleviate fabrication error and avoid a shift in the operating frequency. As a result, the measured reflection coefficient is very close to the simulated result, with an acceptable level of error tolerance even for W-band operation. The maximum realized gain is 26.8 dBi with a high efficiency of 81.9% at 94 GHz. In addition, the operating bandwidth from 92 to 95 GHz (3.2%) is evaluated with respect to 2-dB gain, sidelobe level, and input impedance, simultaneously. This communication offers and verifies a good antenna solution fabricated by an electroforming process for high efficient millimeter-wave radiating systems.

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