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Wideband 4×8 Array Antennas with Aperture Coupled Patch Antenna Elements on LTCC

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Abstract

We proposed a 4×8 array antenna with aperture-coupled patch antenna elements. The antenna was designed for 60 GHz operation and fabrication on the low-temperature cofired ceramic(LTCC) substrate($\epsilon_r=5.8$). The feedline with the stub was designed to enhance the radiating element bandwidth and the transition characteristics between the waveguide (WG) and microstrip line(MSL). Through the optimization of the antenna and feedline geometry, the antenna gain and the performance of the 10 dB bandwidth were 20.2 dBi and 13 % up, respectively. The measured results agreed with the simulated ones.

Key words : System on Package, 60 GHz Array Antennas, Wideband Antenna.

I . Introduction

There is rapid growth demand for high-speed data transmission in wireless communications and for the miniaturization of components in high-frequency operation leads to facilitate the development of hardware and software for next-generation telecommunications. In particular, for unlicensed millimetre-wave bands such as 60 GHz(all over the world), this growing demand has attracted the attention of both the research and industrial fields. The wide bandwidth allows the creation of communication and sensing systems that can easily support transmission rates above 1 Gbit/s^{[1],[2]}.

The concept of system-on-package(SOP) has been developed to meet the requirements of system miniaturization. SOP implies a high integration of components, consisting of a system based on multilayer technology. The multilayer packaging technologies for SOP are necessary, and LTCC technology is used as the essential multilayer technology; it has become a popular technique for the production of highly integrated modules. These technologies are spot-lighted for their flexibility and diversity in realizing an arbitrary number of layers^[3].

Several types of the waveguide to microstrip-line transition have been reported. Array antennas, consisting of 16 parasitic microstrip antennas, have been discussed in ref. [4]. The antenna has characteristics of high gain and wide bandwidth. For the integration with other components of the system and for feeding of the antenna power, a rectangular type waveguide is used. The primary

issue of this paper places the focus on the design of the feedline transition between waveguide(WG) and microstrip-line(MSL).

For the given conditions, the most suitable type of transition was waveguide to microstrip-line probe transition, where the micro-stripline extends into the waveguide through an aperture in the broad wall^{[5],[6]}. In this solution, the critical view of transition is the aperture in the waveguide broad wall. Apertures should be made as small as possible to minimize the influence on the fields (E, H) that propagate inside the waveguide. On the other hand, the waveguide wall has a finite thickness and plays an essential role as the second ground plane for the inserted microstrip line. Hence, a stripline area with the length equal to the thickness of the waveguide was created. The effect was more significant at high frequencies where the wavelength of the signal became smaller. The reason for the effect may be explained as follows; in the wall-aperture area of the small waveguide, there are actually two transitions: waveguide to stripline(SL) transition and stripline to microstrip-line(MSL) transition.

Transition by two transition media must provide impedance matching between the two transitions lines that maximizes the coupling instead of minimizing reflections. In addition to the impedance matching, a transition must provide an efficient field transition from one medium to another one by smooth and gradual change within the physical boundary conditions. To achieve a field and an impedance matching, step-by step transition or continuous taper transition is mainly used^[7].

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The main idea of this paper is to make the field transition more efficient for the waveguide to microstrip-line transition, by dividing the transition into three separated transitions, including waveguide to strip-line transition; strip-line to embedded microstrip-line transition, and embedded microstrip-line to microstrip-line transition.

Another complicated issue that was solved during the research that led to this paper was the packaging of all the transitions, and finally, integration with the microstrip antenna [8]–[10]. The authors of this paper designed and fabricated a 4×8 array antenna with aperture-coupled patch elements and waveguide to microstrip-line transition to obtain high gain and wide bandwidth.

II. Waveguide to Microstrip Line Transition

As shown in Fig. 1, rectangular waveguide(WG) to strip-line transition(SL) consisted of the WG being attached to the LTCC multilayer structure with SL. The LTCC structure under the WG was designed to realize effective energy transition. The number of layers is limited by the fabrication processes and should be appropriate to the number of layers for other nodes in the same system-of-package(SOP). For the described transition, the number of layers was seven (7) and the thickness of each layer was 0.1 mm, with a relative permittivity of the LTCC layer $\epsilon_r=5.9$, and tangent loss of the LTCC layer $\tan \delta =0.001$. In a simple way it can be thought that the SL has been inserted into the WG broad wall through the aperture. The vertical aperture size is equal to the SL thickness corresponding to impedance of 50 Ω. The WG part below SL forms the input section and the part under SL forms the short circuit section. The part of the SL inserted into the WG is the rectangular patch. The critical parameters for effective energy transition are patch dimensions and the size of the WG short circuit section.

The structure of the short circuit section was formed by adding three LTCC layers with metal covers on the

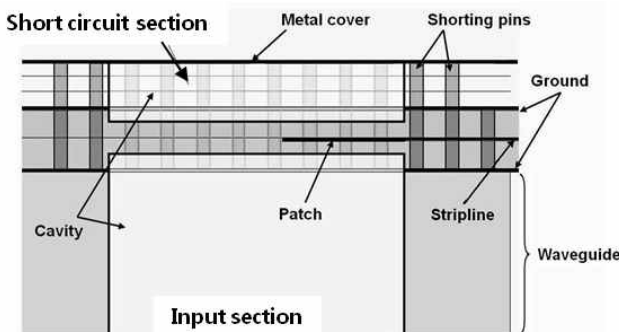


Fig. 1. Waveguide to strip-line transition side view.

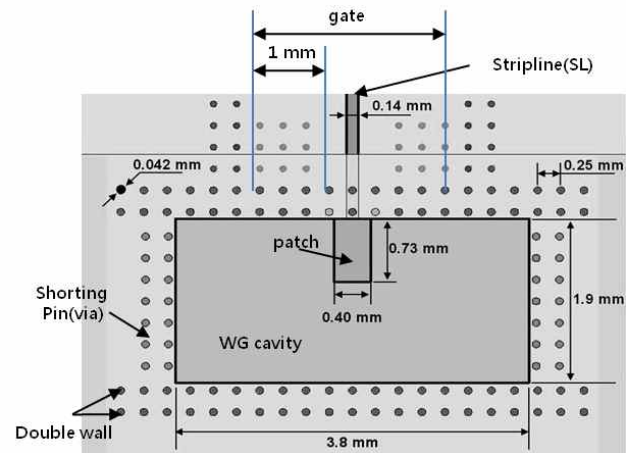


Fig. 2. Waveguide to strip-line transition top view.

tops(see Fig. 1). In all layers, the cavity of the WG length and width were made. Shorting pins were fabricated between adjacent metal layers through the LTCC layers. Metal layers and a double wall of pins simulated the metal walls. The arrangement of short circuit section pins is shown in Fig. 2.

Input and short circuit sections were in spaced alignment and the SL was in the gap between the two sections. The SL included ground planes on either side and apertures of the same size and shape as the WG cavity were cut into the ground planes. Between the input and short circuit sections, a double wall of pins simulated the continuation of the WG walls. Good simulation results have been achieved for the gate that has the four pin period size, which is 1 mm. The shorting pins wall has been extended to prevent surface waves and has four periods size, in total, from the WG wall, which is 1 mm(see Fig. 2).

The dimensions of SL, patch, WG and shorting pins are shown in Fig. 2 also. Full-wave simulation scattering parameters related to designed transition are shown in Fig. 3.

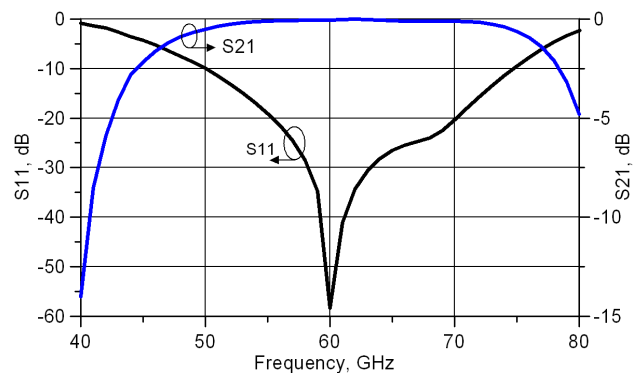


Fig. 3. Transition scattering parameters.

The proposed SL to embedded microstrip line(EMSL) transition is shown in Fig. 4. The SL part and the EMSL part were positioned on the same level. EMSL ground, substrate and feedline were common for both types of feeding. 4 LTCC layers formed a substrate with the thickness of 0.4 mm. The unique difference between two types of feedlines is that the SL has one more additional ground. The idea of the transition is to make a smooth shape cutting at the SL ground near the feedline in order to minimize return loss and to make energy transition effective. It is recognized also that along SL, the wall of shorting pins must play an important role to suppress the parallel plate modes. The most evident solution is to make round-shaped ground corners and to place shorting pins near the corners. Full-wave simulation, however, shows that this variant is not satisfactory.

The study described here proposed ellipse-shaped ground cutting and the view of this cutting type is shown in Fig. 4. The distance between the feedline and the shorting pins wall is fixed and represents the ellipse minor radius. The core variable to control for transition matching is the ellipse major radius.

EMSL impedance is approximately 60 Ω. Then, impedance mismatching can be compensated by the ellipse-shaped cutting. Transition dimensions are shown in Fig. 4.

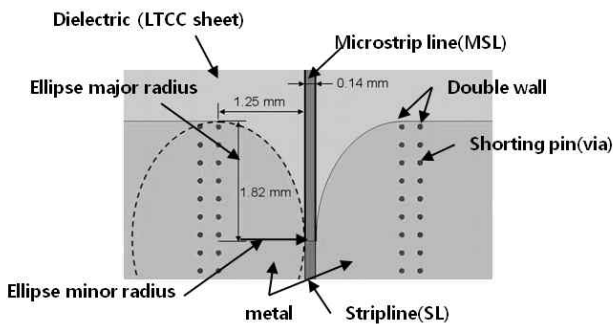


Fig. 4. Strip-line to embedded microstrip line transition (top view).

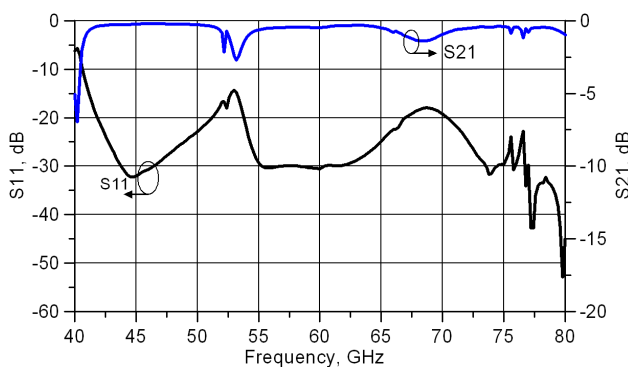


Fig. 5. Transition scattering parameters of EMSL.

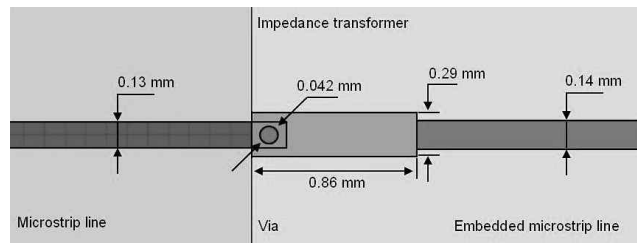


Fig. 6. Embedded microstrip line to microstrip line transition (top view).

Full-wave simulation scattering parameters for the designed transition are shown in Fig. 5.

The geometry of the proposed embedded microstrip line to microstrip line transition is shown in Fig. 6. MSL substrate thickness equals one LTCC layer with thickness of 0.1 mm. Then, EMSL substrate thickness equals 4 LTCC layers with thickness of 0.4 mm.

Two types of feedline have a common ground plane. MSL connects to the EMSL by means of via and via height is one LTCC layer. Impedance of MSL is about 60 Ω. The Quarter-wave impedance transformer has been used to compensate impedance difference between EMSL and MSL.

Dimensions of the EMSL to MSL transition are shown in Fig. 6 and full-wave simulation scattering parameters above transition are shown in Fig. 7.

After each separate transition was designed, all of them were assembled together and to form complex WG to EMSL transition. The top view of the complex transition is shown in Fig. 8. Full-wave simulation scattering parameters for the designed complex WG to EMSL transition are shown in Fig. 9. The designed complex transition shows wide bandwidth characteristics, about 38 % greater, compared to the central frequency.

III. The Aperture-Coupled Patch Antenna Structure

We have designed the antenna with optimized band-

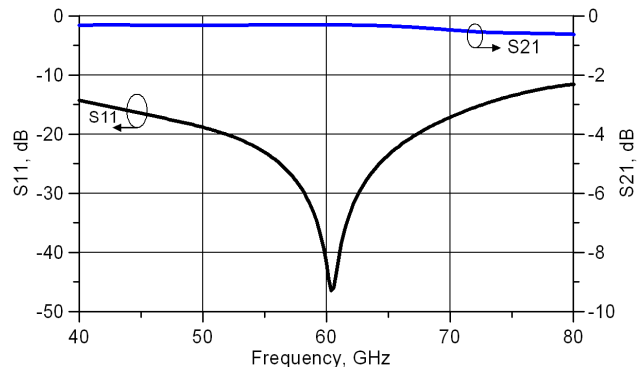


Fig. 7. Transition scattering parameters.

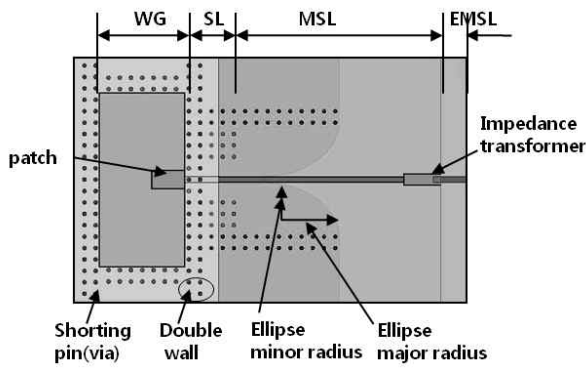


Fig. 8. Assembled transition(top view).

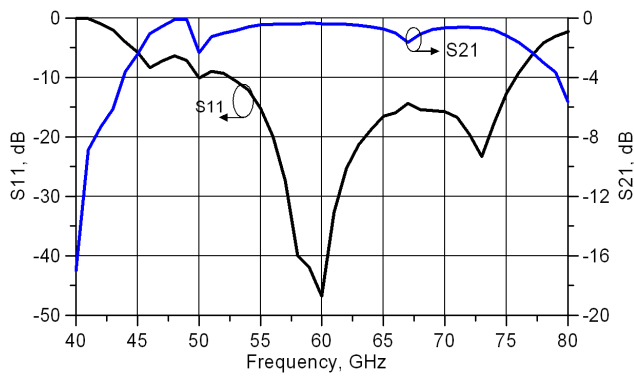


Fig. 9. Complex transition scattering parameters.

width, gain, side lobe level, cross polarization radiation, etc. The bandwidth is the key element to realize a high-speed data transmission and to implement a general-purpose antenna. A step-by-step optimization was carried out during the antenna design processes. Firstly, the aperture-coupled patch size and the distance between patch and feedline were optimized using the adjustment of the substrate thickness. As parameters have been changed within a broad range, the optimization to find the optimal parameters was performed using full-wave simulation software. The concept and core elements of the proposed aperture-coupled patch antenna are shown in Fig. 10.

The proposed antenna structure had three-layer LTCC substrates and the layer thicknesses were hm , hf , and hp from bottom to top, respectively. A microstrip feedline arranged the patch antenna through an aperture slot in a ground.

The aperture-coupled patch antenna element had a rectangular structure. To control the feed-line impedance about 50Ω , a set of parameters, which greatly influenced the antenna characteristics, such as substrate thickness, slot size, embedded microstrip stub length, and patch size, were optimized. In particular, to enhance the bandwidth of radiating elements, the feed-line with the stub was

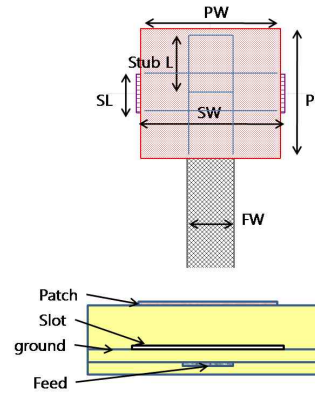


Fig. 10. The concept of the proposed aperture-coupled patch antenna elements.

designed and, in consideration of all of the antenna elements, array antennas with spacing, $d=2.3 \text{ mm}=0.45 \lambda_0$ at 60.5 GHz (where λ_0 is the wavelength in free space), were completed, as shown in Fig. 11. Table 1 shows the array antenna's physical dimensions, such as patch width (PW) of $720 \mu\text{m}$ and length (PL) of $685 \mu\text{m}$. The quarter-wave transformer with length ($tl1$, $tl3$) and width ($tw1$, $tw3$) was used for impedance matching of antennas. The feed width (FW) and the height of each layer were $234 \mu\text{m}$ and $100 \mu\text{m}$ respectively. On the basis of the single antenna structure, the array antennas were designed as shown in Fig. 11.

IV. Simulation and Measurement

On the basis of the previous physical dimensions, return loss was simulated using Ansoft HFSS/designer. The design parameters were optimized to improve the characteristics of the transition (S_{21}) and return loss (S_{11}). The performance of the antennas was measured by an Anritsu 37169A vector network analyzer. Simulated and

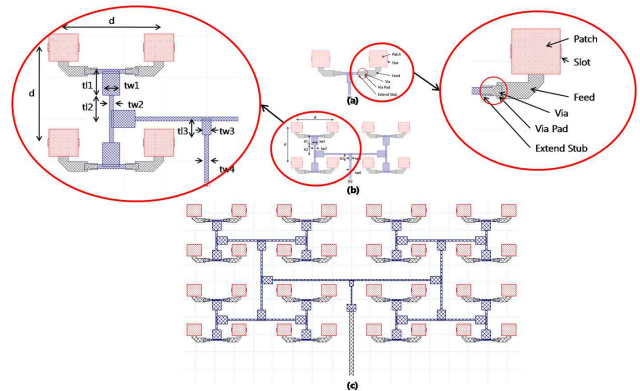


Fig. 11. The designed array antenna geometry including the feedline with stub. (a) 1×2 array antenna, (b) 2×4 array antenna, (c) 4×8 array antenna.

Table 1. Array antennas physical dimension.

Parameters	Size(mm)
Patch length(PL)	0.685
Patch width(PW)	0.72
Feed width(FW)	0.234
Slot length(SL)	0.231
Slot width(SW)	0.75
Stub length(Stub L)	0.32
Transformer width1(tw1)	0.446
Transformer width2(tw2)	0.214
Transformer width3(tw3)	0.446
Transformer width4(tw4)	0.214
Transformer length1(tl1)	0.575
Transformer length2(tl2)	0.575
Transformer length3(tl3)	0.575
Via diameter	0.1
Via pad	0.147
Extend stub	0.224
Antenna element spacing(d)	2.3
Height of each layer thickness	0.100

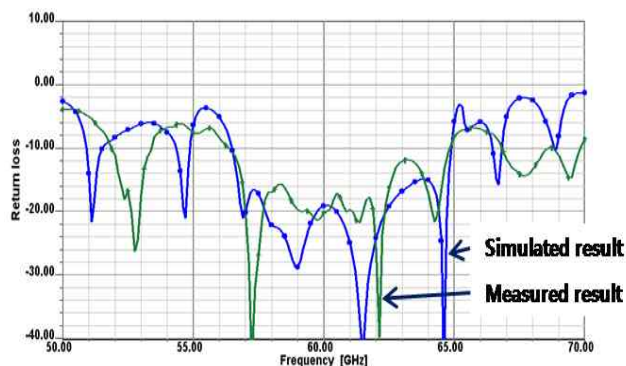


Fig. 12. The return loss for 4×8 the array antennas.

measured results are shown in Fig. 12. Especially, Fig. 13 and Fig. 14 represent the normalized radiation pattern of the 4×8 antenna array in E-plane and H-plane respectively. According to these results, it can be seen that the bandwidth of 10-dB return loss is about 13 % up for the central frequency range(from 57 to 65 GHz) and the gain is about 20.2 dBi. The side-lobe level was lower than -15 dB in the H-plane and -18 dB in the E-plane respectively. The half power beam width was about 8° in the E-plane and 14.5° in the H-plane, respectively. The gains of the antennas were about 20.2 dBi in the frequency range(from 57 to 65 GHz).

The radiation pattern of H-plane has a small asymmetry because of the side lobes. These results could be sur-

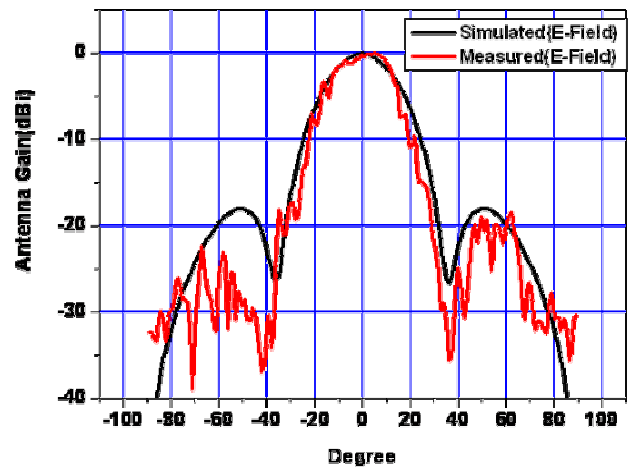


Fig. 13. The normalized radiation pattern(E-field) for the array antennas.

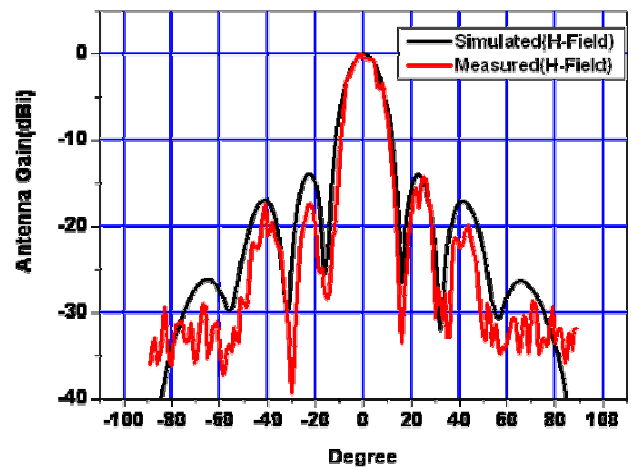


Fig. 14. The normalized radiation pattern(H-field) for the array antennas.

mised to be the result of the mutual coupling and asymmetry of the radiating patches connected with the fabricated feed network. The measured results are in a good agreement with simulated results. In the measured radiation pattern a noise was added because the measurement environment was not completely shielded. Fig. 15 shows the gain and cross polarization of the array antenna. The cross-polarization level was lower than -22 dBi for the broadside direction and the antenna gain was higher than 20.2 dBi.

Fig. 16 shows the front view and back view of the fabricated array antenna. The front view of the array antenna shows a simple design with the 4×8 array patch antenna. Several components such as the microstrip line (MSL) to embedded MSL(EMSL) transition, EMSL to strip-line(SL) transition and SL to waveguide(WG) transition are integrated on its back side. Specially, SL to

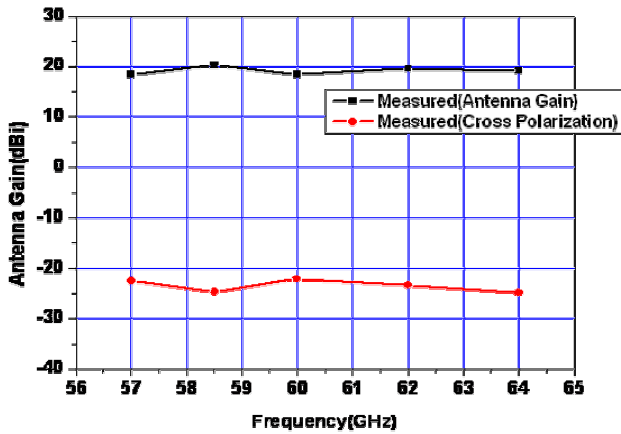


Fig. 15. The gain and cross polarization for the array antennas.

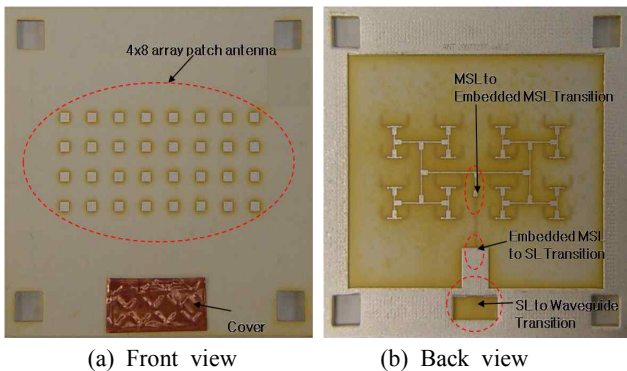


Fig. 16. Fabricated array antennas.

WG transition connected with WR-15 is used to measure the radiation pattern and return loss.

V. Conclusions

The array antenna, based on LTCC substrate, operating at 60 GHz was designed using full-wave simulation software. The wideband aperture-coupled patch antenna was proposed. The feed-line connected with the patch elements had a stub to broaden the bandwidth of the patch. After the optimization and the fabrication of array antennas with proposed antenna geometries, the measured results agreed well with the simulated ones. The fabricated array antennas on the LTCC substrate had a 20.2 dBi gain the 13 % up return loss bandwidth. The array antennas can be used in high speed wireless communications at the 60 GHz band.

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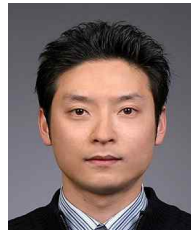
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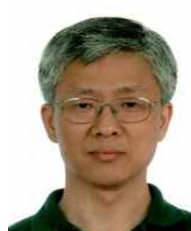
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