A Millimeter-wave 8-element Double Slot Array Antenna for High Gain Beam-forming

Yosuke sato, Kazuya Fujita, Hirokazu sawada, Hiroyuki, Nakase, and Shuzo Kato
Research Institute of Electrical Communication, Tohoku University
2-1-1 Katahira, Aobaku, Sendai, Miyagi, Japan

Abstract- **For practically portable millimeter-wave communication systems, an antenna needs to have high gain and to be small footprint. This paper proposes a novel high gain and small size beam-forming antenna of 8-element array double slot antenna. The heuristic computer simulations show thirteen unique beam shapes have the antenna gain of 13.5dBi and +/- 36degree steering coverage. The 8-element double slot array antenna is fabricated for performance validation, and measured results show the 13.5 dB gain with +/- 33 degree antenna steering coverage. Thus, the proposed 8-elemetn double slot beam-forming antenna with discrete (90 degree step) phase shifters is practically applicable for portable terminals in Super Broad Band Wireless Communications Systems.**

I. INTRODUCTION

In order to realize multi Gbps communications, millimeter-wave communication systems [1] have been attracting attention. The IEEE802 standards committee has created 60GHz WPAN standard since the 60GHz band is unlicensed in many countries (59-66GHz in Japan and 57-64 GHz in USA [2,3]). IEEE802.15.3c (60GHz WPAN) [4] completed standardization in September 2009, and IEEE802.11ad (60GHz WLAN) standardization [5] is currently in progress. In the 802.15.3C standard and 802.11ad standard draft, beam-forming/steering antenna technologies [6, 7] are considered to obtain a high antenna gain and also offset the shadowing loss of obstacles by using reflected waves. Thus beam-forming antennas are sure to become the key technology of indoor millimeter-wave communications systems. The phased array antenna technology [8] is suitable for implementing the beam-forming antenna. However, the large insertion loss of the RF phase shifter is a significant barrier to implement phased array antennas in the millimeter-wave band communication systems [9]. Therefore a beam-forming antenna with discrete phase shifters was proposed to reduce the insertion loss. In the previous research [10], we have developed the antenna gain of the 4-element slot array antennas with discrete 90 degree step phase shifters was 10 dBi with 62 degree of steering coverage gain. In this paper, a double slot antenna has been proposed to increase the antenna gain and keep the antenna size small enough for a portable terminal. In order to verify the proposed double slot antenna performance, the 8-element double slot array antenna with 90 degree phase step phase shifter is simulated and then measured. The results show the proposed double slot antenna is good for a potable terminal in Super Broad Band Wireless Communications Systems.

This paper organized as follows. Section II describes the proposed double slot antenna. The simulated characteristics of 8-element array beam-forming antenna with discrete phase shifters are described in Section III. The developed antenna characteristics are shown in Section IV. Section V summarizes the proposed double slot array antenna.

II. DOUBLE SLOT ANTENNA

The proposed double slot antenna is shown in Fig.1. The antenna is fed by a micro strip line (MSL). The input signal is divided in half with a U-shape divider. Each divided signal is coupled to slot antenna respectively, and radiates in Z-axis direction shown in Fig. 1. In order to increase antenna gain, a reflector is set under the double slot antenna. The substrate is fluoroplastic with copper clad laminates (CGN-500 fabricated by CHUKOH CHEMICAL INDUSTRIES, LTD). The substrate permittivity in 60 GHz band is 2.17, and the dielectric tangent is 0.0009. The slot antenna length is 2mm, and the width is 0.1mm. The micro strip line width is 0.25mm and its impedance is 75ohm to match antenna input impedance.

The designed double slot antenna characteristics are shown in Fig. 2. The characteristics are simulated by electromagnetic simulator (HFSS v12.1). The maximum gain is 9.3dBi. The beam width with 8.3dBi, which is 1dB lower than peak gain, is 51 degree from -29 to 22 degree. The double slot antenna gain increases 3dB from the single slot antenna one [10] and the beam width is almost the same. From the input reflection characteristics, the band width under -10dB of S11 is 8 GHz from 56GHz to 64GHz. In other word, rhe relative band width is 13 % and the band width is wide enough for millimeter-wave communication systems.

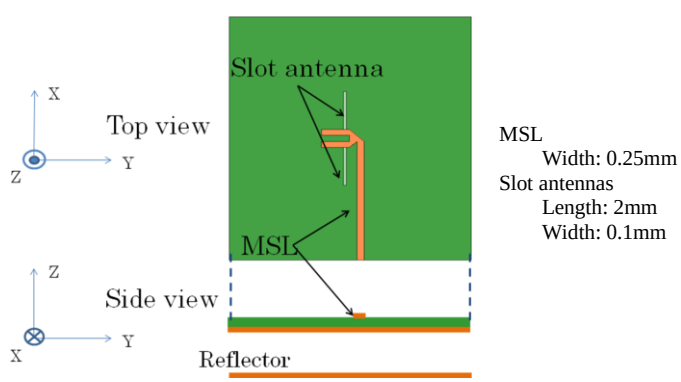
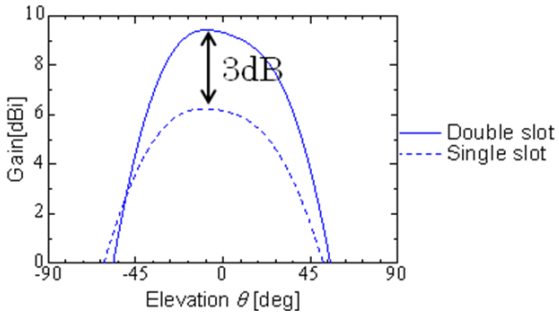
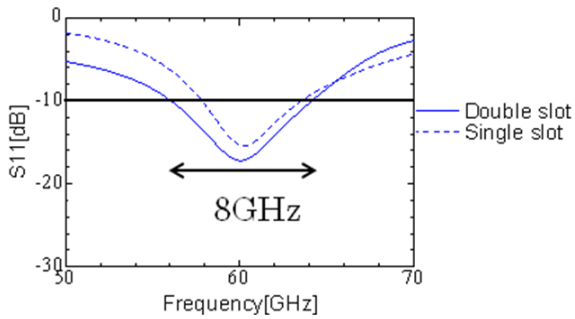


Fig. 1 Double slot antenna



(a) Directivity



(b) Reflection

Fig. 2 Characteristics of double slot antenna (simulation results)

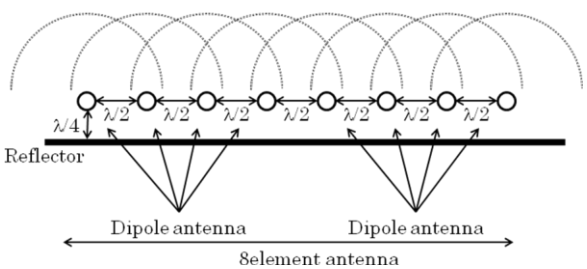


Fig. 3 Simulation modes of 8 element array beam-forming antenna

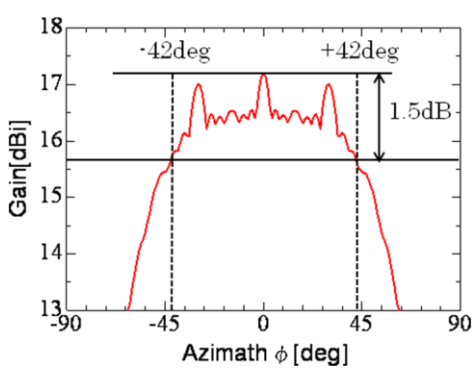


Fig. 4 Gain envelope of eight element array beam-forming antenna (simulation result)

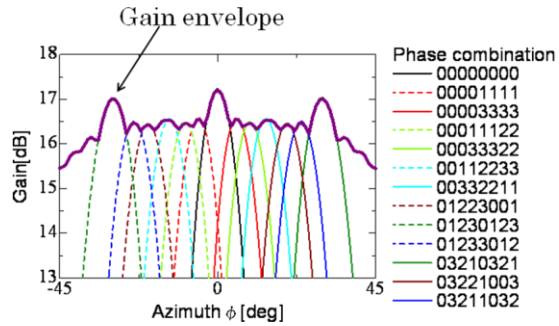


Fig. 5 Phase combination of 8 element array beam-forming antenna (simulation results)

Table. 1 Phase combination

Phase	Assigned number
0°	0
90°	1
180°	2
270°	3

III. Eight Element Array Antenna with Discrete Phase Shifter

A. *Finding beam patterns*

As mentioned earlier, the phase resolution of discrete phase shifter is set to 90 degree step throughout in this paper. The important parameter in designing beam-forming antenna is to find out how many and what are beam-patterns out of 4^8 possible patterns regulated 90 degree phase step. For this purpose, a dipole antenna with metal reflector instead of the proposed double slot antenna is used for simulation simplicity as shown in Fig. 3. The separation from each antenna element from reflector was λ/4 (λ is a free space wave length). Eight antenna elements were sequentially placed with λ/2 separation. In this simulation, the mutual coupling is not considered since the mutual coupling effect for phase combination selection process was negligibly-small [10]. The antenna gain has been calculated by the total of radiated electrical field vectors from each element. The envelope shape of all simulated beam patterns is shown in Fig. 4. The peak gain is 17.2dBi with 84 degree of steering coverage from -42 degree to +42degree. The beam steering coverage was considered within the range of 1dB less than the peak gain, since this beam pattern will be used for the link budget of beam forming system. For the phase combination selection process, the similar beam patterns were removed to reduce the number of phase combinations.

Eventually, the number of unique beam patterns was 13 as shown in Fig. 5. The phase combination is expressed by assigning the numbers for each phase value which are defined in table 1 such as the numbers of 0, 1, 2 and 3 for the phase values of 0, 90, 180, and 270 degree respectively. For example, the phase combination 00332211 means that the phases of antenna A and B are 0degree, the antenna C and D are 270degree, the antenna E and F are 180degree, and antenna G and H are 90degree.

B. Double slot antenna

By using the calculated phase combinations found in previous section A to the proposed double slot antenna, the 8-element double slot array antenna was designed to verify its antenna performance. The designed double slot array antenna is shown in Fig. 6. Each antenna element is sequentially placed with λ/2 separation. The reflector is set under the antenna with λ/4 separation. The simulated beam patterns of the double slot antenna are shown in Fig. 7. The antenna gain was 15dB with 67 degree of beam steering coverage from -34 to 33 degree. When the peak gain of a single double slot antenna is set to the same peak gain of 8-element double slot array antenna as shown in Fig. 9 (a), the gain difference is 7.7dB. Although the simulation with dipole antennas shown in Fig. 4 did not include the mutual coupling between antenna elements, the gain variation in the simulation results including mutual coupling agree with these of the dipole antenna simulation results well.

IV. Antenna Design and Measurement

For simplicity, the beam patterns in only positive angle side were examined since the beam patterns in Fig. 7 have some symmetry with a 0.5dB lower gain in negative angle side than the positive side. The designed 8-element double slot array antenna is shown in Fig. 8. The discrete phase shifters were fabricated by fixed delay lines and these were connected to the 8-port power divider, and the micro strip line was connected to the coaxial connector for feeding. The reflector was made of metal block, and it was scraped off like a cavity to accommodate antennas. The simulated beam patterns are shown in Fig. 9. In comparison with the beam patterns of Fig. 7(a) without the phase shifter and the power divider, the 1.5dB gain was decreased. This reduction comes from the insertion loss of phase shifter. The beam steering coverage in positive angle side was 36degree. So, the coverage in both sides could be estimated at 72degree. As show in Fig. 10, the reflection characteristics were changed from Fig. 7 (b). These differences were caused by phase shifter's reflection. However, the reflections $|S_{11}|$ at 60GHz ware under -10dB, and these reflections were practically small for communication systems.

A. Measurement results

The measurement results are shown in Fig. 11. In the Fig. 11 (a), the maximum gains of each beam pattern are 2-4dB lower than simulation results in Fig. 9.

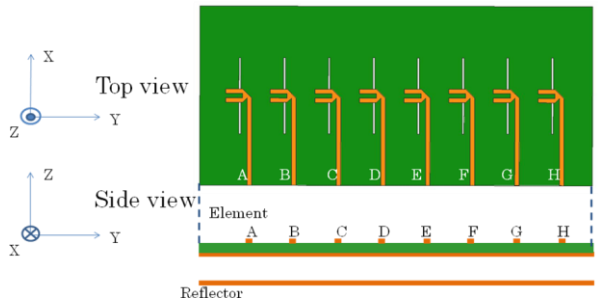
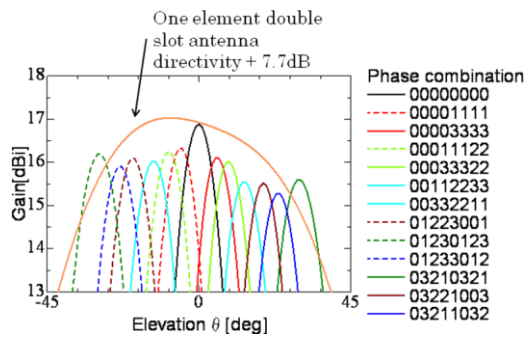
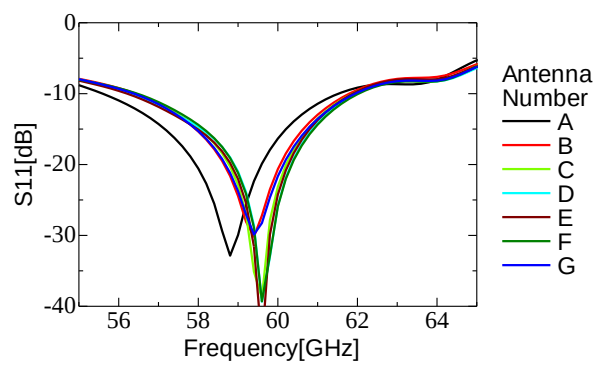


Fig. 6 Eight-element double slot array antenna



(a) Beam patterns



(b) Reflections

Fig. 7 Characteristic of 8-element double slot array antenna (electromagnetic simulation results)

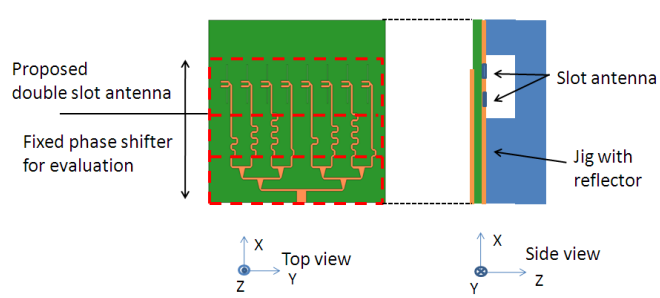


Fig. 8 Eight-element double slot array antenna with fixed phase shifter

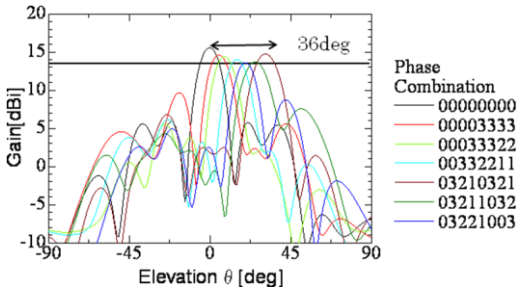


Fig. 9 Beam patterns of 8-element beam-forming antenna with fixed phase shifter (electromagnetic simulation)

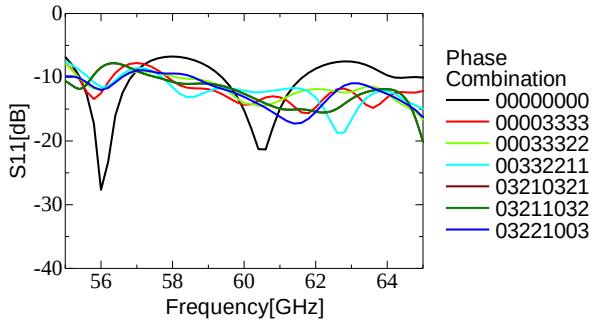
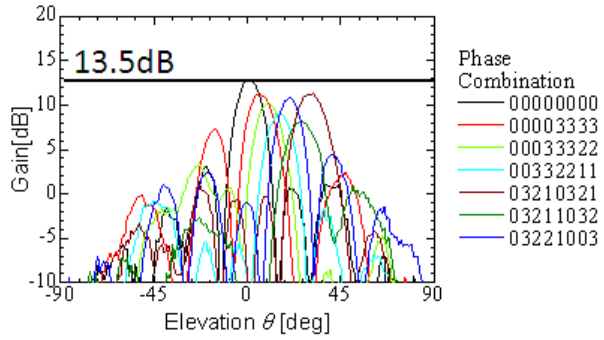
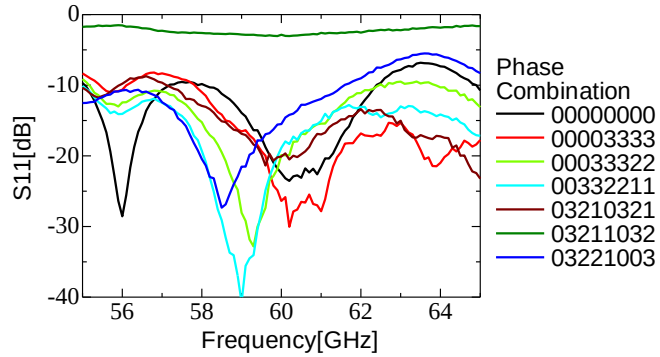


Fig. 10 Reflections of 8-element beam-forming antenna (electromagnetic simulation)

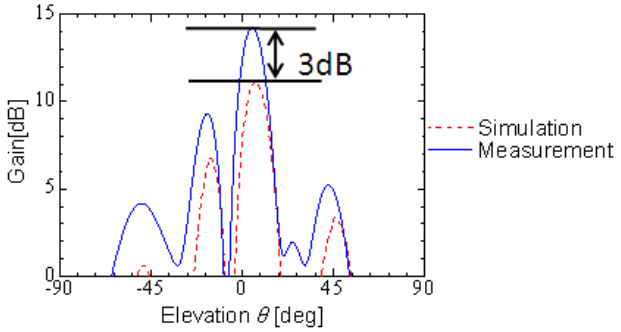


(a) Beam patterns

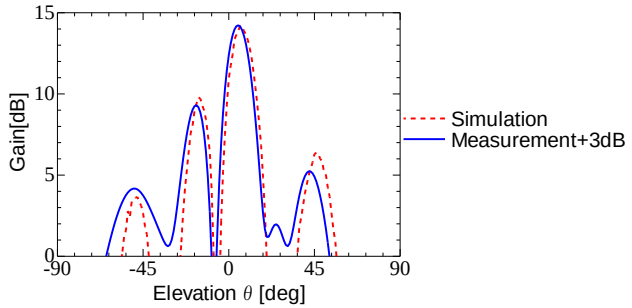


(b) Reflections

Fig. 11 Characteristic of 8-element double slot array antenna (measurement)



(a) Comparison between simulation and measurement (Phase combination 00003333)



(b) Comparison between simulation result and corrected measurement result (Phase combination 00003333)

Fig. 12 Loss consideration in measurement

The gain reduction in measurement results was examined. As an example, the phase combination of 00003333 was examined. The comparison between simulation and measurement results are shown in Fig. 12. In Fig. 12 (a), the peak gain of measurement result is 3dB smaller than simulation one. However, when this reduction is corrected like Fig. 12 (b), the beam shape is almost the same. This means the gain reduction was caused by loss increase. The beam patterns with 3dB loss correction are shown in Fig. 13. In the Fig. 13, the antenna gain was 13.5dB with 33degree in positive angle side. Thus the coverage in both sides is estimated at 66degree. Furthermore, the corrected measurement results were almost same as simulation results. For this reason, the designed double slot array beam-forming antenna is suitable for implementing in millimeter-wave communication systems since the antenna size is small (5mm * 20mm) and the gain is high (13.5dB).

B. Loss analysis

The loss analysis results are shown in Fig. 14. As Fig. 2 (a) shows, the one double slot antenna element gain is 9.3dB. Thus the gain of 8-element double slot array antenna is estimated as 18.3dB theoretically since +9dB gain increases by the array effect of 8-element. However, the measured gain was 11.3dB as shown in Fig. 12, and it is 7dB lower than the theoretical gain. This 7dB gain reduction has been analyzed, and resulting

the following: (1) gain variation by discrete phase shifter (1dB), (2) loss by mutual coupling (1dB), (3) loss by fixed phase shifter (2dB) , (4) loss by fabrication errors (3dB). The detail of fabrication errors were estimated to consist of reflection at connector (less than 1dB), effect of size errors (0.3dB~1.3db), conversion loss at connector (0.5dB~1dB), and the loss of conductor loss (0.5dB~1.5dB). When this antenna is implemented in the actual communication system, the loss of fixed phase shifter can be removed since the antenna is connected to RF phase shifter chips. The future work is performance validation of a beam-forming antenna connected with phase shifter chip.

V. Conclusion

This paper has proposed the double slot antenna as high gain and small size antenna suitable for practical portable terminals in millimeter-wave communication system. The heuristic computer simulations have shown the 13 unique beam patterns are enough for 8-element array beam-forming antenna beam control. The Eight-element double slot array antennas with the calculated phase combination have been fabricated and measured for performance validation. The measured results agree with simulation results, and show the gain of designed 8-element beam-forming antenna is a 13.5 dBi with 66 degree of antenna steering coverage and the size of one is small (5mm”20mm). Thus the proposed double slot antenna is good enough to be used for beam-forming antenna in millimeter-wave communication systems.

Acknowledgment

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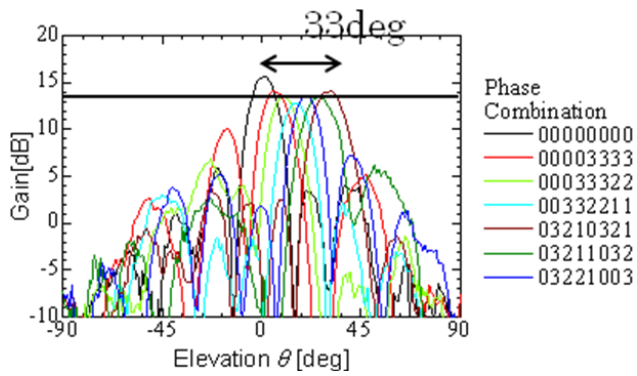

Fig. 13 Corrected beam patterns of 8-element double slot array antenna (corrected measurement result)

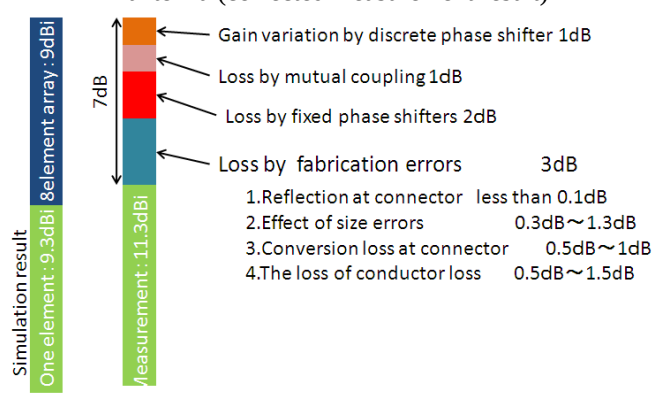

Fig. 14 Consideration for loss cause