Development of Waveguide-Slot-Fed Active Integrated Antenna for Microwave Power Transmission

Kazuyoshi Nanokaichi, Naoki Shinohara, Shigeo Kawasaki, Tomohiko Mitani and Hiroshi Matsumoto

Research Institute for Sustainable Humanosphere, Kyoto University, Gokasho, Uji, Kyoto 611-0011, JAPAN
E-mail :{nanoka, shino, kawasaki, mitani, matsumot}@rish.kyoto-u.ac.jp

INTRODUCTION

Space Solar Power System (SSPS) is one of promising candidates for clean and base–load power source. To realize the SSPS economically, developments of Microwave Power Transmission (MPT) System with a huge phased array (typically 1km diameter), very accurate beam control, high overall efficiency and light weight are necessary. ISM band (2.45GHz or 5.8GHz) is supposed to be chosen as a frequency of the wireless transmission. For the microwave transmitter, which is extremely important for the SSPS, a microwave tube device and a semiconductor device are being studied. A microwave tube is characterized by its high power output, high efficiency (over 70%), high voltage operation, and low power-weight-ratio, while a semiconductor amplifier/oscillator has output power of less than 100W and efficiency of up to 50% typically. On a microwave-tube-based configuration, to match the economical SSPS system parameters: 1~2.6km antenna aperture size and 1GW output, a multi-stage power distribution network and phase shifters following to the tube device are necessary. In this configuration, losses at the power distribution and the phase shifters will reduce the total system efficiency. On the other hand, a semiconductor amplifier based SSPS configuration could be similar to conventional phased arrays (oscillator – power divider – phase shifter – power amplifier – transmit antenna) and the efficiency of the semiconductor power amplifier critical for the overall efficiency. Though the best solution has not been found yet, further study has been going on to find the best system configuration. In this paper, as one of the possible solutions for the MPT system of SSPS, Waveguide-Slot-Fed Active Integrated Antenna (AIA) system, which is a combination of a waveguide slot and the Active Integrated Antenna concept, is proposed and results of the basic study are shown.

CONCEPT OF THE WAVEGUIDE-SLOT-FED AIA

The concept of the Waveguide-Slot-Fed AIA is shown in Fig.1. Microwave power from a generator propagates into a rectangular waveguide. A waveguide slot is used for the power dividing network. Although the waveguide slot has been widely used for a radiator into free space, its low-loss, low-profile and high power handling capacity are suitable for the MPT system. The Active Integrated Antenna (AIA) concept is applied to a phase control / amplification and a radiator part. The AIA technology is an organic integration of active microwave circuits and planar antenna technology and it enables low transmission loss, compact and multifunctional MPT system. For the feeding from the waveguide to the AIA, an electromagnetic coupling is adopted because of its simple and thin layered structure. Radiated power from the AIA array is spatially combined and forms a steered microwave power beam. This system has applicability to both a microwave-tube-based system and a semiconductor amplifier based system.

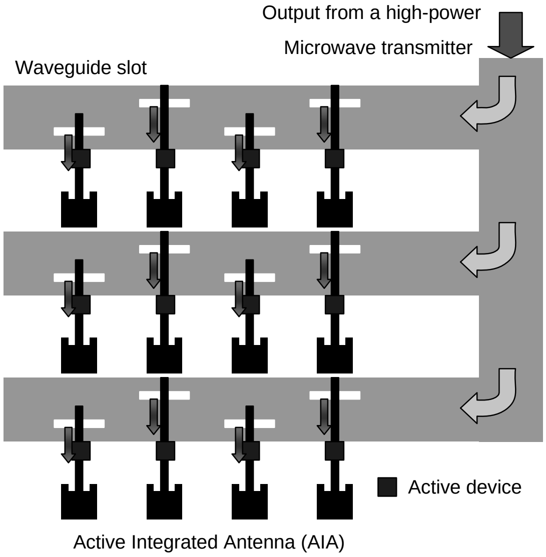
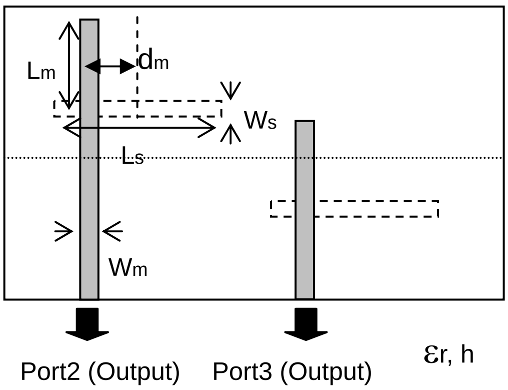


Fig.1: Concept of the Waveguide-Slot-Fed AIA

IMPROVEMENT OF THE COUPLING FACTOR

In the Waveguide-Slot-Fed AIA, the electromagnetic coupling between the AIAs and the waveguide slots should transfer the input microwave to the microstrip lines on the AIAs with minimum power dissipation. The electromagnetic coupling essentially tends to leak the microwave from the slot and the leaked microwave is radiated unnecessarily into the free space. In this study, minimization of loss at the electromagnetic coupling, in the other words, improvement methods of the coupling factor are investigated. The similar slot-to-microstrip transition has been studied in [1] [2]. In the approach proposed here, to achieve both the compact structure and better impedance matching at the electromagnetic coupling with low radiation loss, the waveguide cross section in properly tuned as well as the electromagnetic coupling structure.



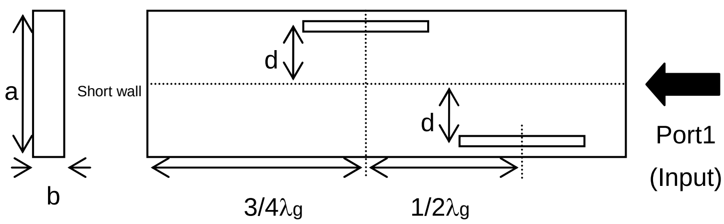


Fig.2: Parameters on the electromagnetic coupling

Fig.3: Parameters on the waveguide slot

Fig.2 and Fig.3 show the analyzed model of a simple 2-way power divider. The design frequency is 5.8GHz band. In the analyzed model, the coupling factor η is defined as follows.

$$\eta = \frac{|S_{21}|^2 + |S_{31}|^2}{1 - |S_{11}|^2} \tag{1}$$

The study is aimed at obtaining coupling factor of over 90% for high-efficiency microwave power transmission. To realize the impedance matching between the slot and the microstrip line, centered-feed method and offset-feed method are often used. By our detailed investigation which of methods is better in terms of the coupling and matching, the offset-feed method is found to be inadequate because of the higher radiation into free space. Therefore the centered-feed method is chosen in the design. As for the waveguide, the width a and the height b is varied from the standard waveguide size WR-159 (a=40mm, b=20mm) to match the slot impedance to the microstrip lines. Two types of the reduced-height waveguide dimension: type-A (a=40mm, b=1.5mm) and type-B (a=30mm, b=4.0mm) are chosen and the optimal electromagnetic coupling parameters are investigated in detail for each type. These electromagnetic simulations are performed by Ansoft HFSS. As the substrate for the microstrip lines, CGP-600 (Chukoh Chemical Industries, Ltd.) is used. This substrate has a relative dielectric constant of 2.60, a thickness of 0.8mm and a loss tangent of 0.0018. Finally optimized dimensions are : d_m=0, W_m=2.17mm, W_s=0.9mm, L_s=26mm, L_m=8.87mm, and d=19mm (type-A), d_m=0, W_m=2.17mm, W_s=0.9mm, L_s=23mm, L_m=8.87mm, and d=14mm (type-B). Coupling factor of over 90% is confirmed both type-A and type-B model in the simulation with optimized electromagnetic coupling parameters.

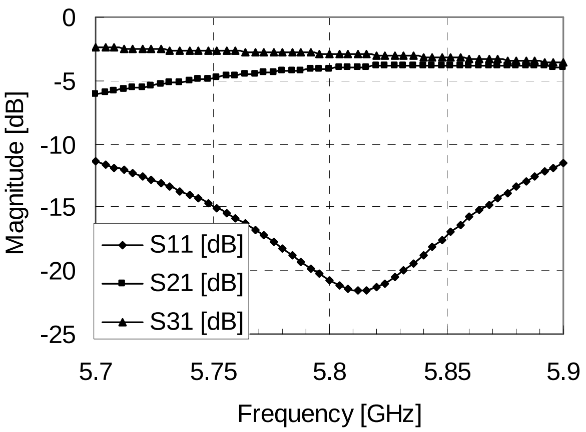


Fig.4: Measured S-parameter characteristics for type-B

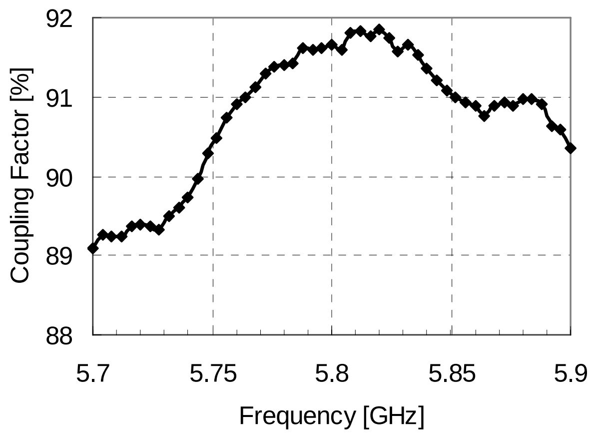
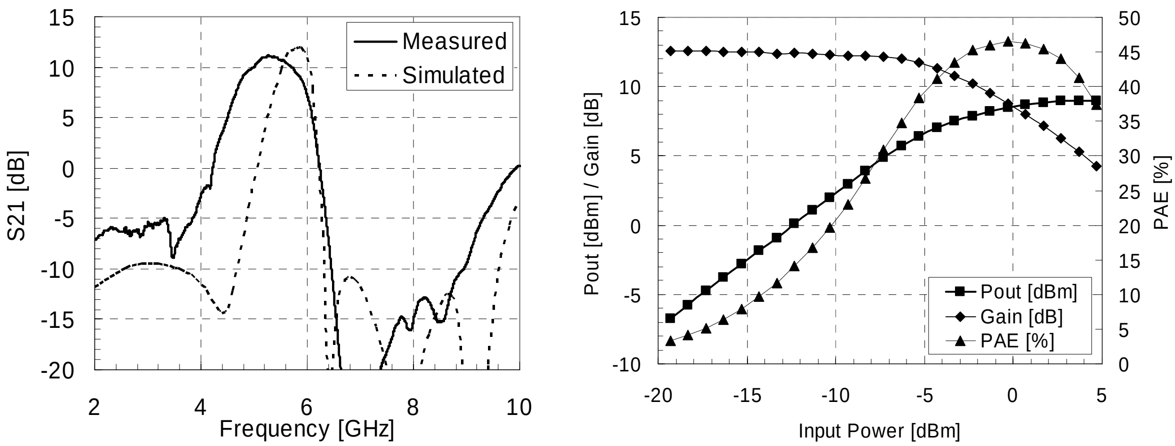


Fig.5: Measured coupling factor for Type-B

Fig.4 and Fig.5 shows measured S-parameters and the coupling factor for type-B power divider. Since the waveguide dimension of each type is not standard size, transfomer sections (quarter-wavelength type) are also designed and fabricated. Although the results shown above are including characteristics of the transformers, good agreement with the simulation is confirmed near 5.8GHz. Coupling factor of 91.6% at 5.8GHz is also achieved.

BASIC DESIGN OF AMPLIFIERS FOR THE AIA

A basic design and fabrication for amplifiers on AIA is also carried out. Amplifiers for the system need high efficiency and high power as well as compact size. In a design of the power amplifier integrated with AIA, the reduction in size is one of the important points to construct 2-dimensional, compact, and thin AIA array. Our final goal is a design of a high power MMIC, however, as a basic study, a compact amplifier with an easily-available low power HEMT device is designed and fabricated. The impedance matching circuits and the bias circuits on microstrip lines are minimized to realize the compactness. ARLON 25N substrate with a dielectric constant of 3.38 and a thickness of 0.762mm is used for the microstrip substrate. The operating point of class AB is chosen to improve the efficiency. Fig.5 shows a measured performance of the fabricated amplifier. Measured PAE (Power Added Efficiency) of the basic amplifier is 47% at 0dBm input power.



(a) Linear gain

(b) Measured output power, Gain and PAE

Fig.5: Characteristic of the fabricated basic amplifier

CONCLUTION

A Waveguide-Slot-Fed Active Integrated Antenna is proposed for high-efficiency and compact microwave power transmission system. A basic 2-way waveguide-to-microstrip power divider is designed and fabricated. As a result of the measurements, coupling factor of 91.6% is achieved sufficiently in a fabricated model. A design and a fabrication of an amplifier for the AIA part is also studied. Although the study is still in the initial stage, these results show the applicability of the Waveguide-Slot-Fed AIA for high-efficiency MPT system.

ACKNOWLEDGEMENT

This work was partially supported by a 21st Century COE Program Grant of the Estrablishment of COE on Sustainable Energy System and a joint research with Mitsubishi Heavy Industries, Ltd.

REFERENCES

[1] R. Bashirullah and A. Mortazawi, “A slotted-waveguide power amplifier for spatial power-combining applications,” IEEE Trans. Microwave Theory Tech., vol. 48, pp. 1142–1147, July 2000.

[2] X. Jiang, L. Liu, S. Ortiz, R. Bashirullah, A. Mortazawi, “A Ka-Band Power Amplifier based on a Low-Profile Slotted-Waveguide Power-Combining/Dividing Circuit,” IEEE Trans. Microwave Theory Tech., vol. 51, no. 1, pp. 144-148, Jan. 2003.