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Japan's Project for the Research and Development of Active Phased Array Antennas for Practical Applications

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Review

This paper presents Japan's enterprising project to develop the active phased array antenna (APAA) for practical applications. The objectives are to realize the cost reduction, small volume and light weight of APAAs at K-band frequency. The key technologies for those purposes are partial drive of an array, Monolithic Microwave Integrated Circuits (MMIC), a phase shifter with Radio Frequency-Micro Electro Mechanical System (RF-MEMS) switch and relevant control circuits, and system integration of all devices. The structure and the research and development (R&D) schedule of the project are explained. The results of R&D activities so far are also described.

Key words: Japan's project, Active phased array antennas, Cost reduction, Beam scan, Partial drive of an array, MMIC, Phase shifter with RF-MEMS

1 INTRODUCTION

Recently, microwave frequencies have been forecasted to become tighter due to the rapid growth of communication systems in the world. In order to overcome this situation, the frequency band from 6 GHz to 30 GHz which is called high microwave band is promoted for positive utilization by the Ministry of Internal Affairs and Communications (MIC) in Japan [1, 2]. Main applications are assumed to be mobile systems, satellite communications and wireless LAN. One of the promising key technologies for those systems is active phased array antennas (APAA) which have excellent features in the radiation beam control.

Phased array antennas (PAA) have been vigorously utilized in radars. On the other hand, there were many attempts to use phased array antennas in communications due to the agility in the beam control [3], but most of them were not put into practical uses. The main reasons of their failure may be as follows:

(1) high cost
(2) large weight and size
(3) power consumption in an antenna
(4) narrow angular coverage of beam scanning.

The items (1) and (2) are most critical though the items (3) and (4) may not be so in some types of communication systems.

In Japan, a new project for research and development has been started in collaboration of several organizations in order to realize practical APAAs which can be used in communications or public welfares. This paper describes the objectives, technical problems, organizations and schedule of the project.

2 OBJECTIVES AND STRUCTURE OF THE PROJECT

An example of APAA in conventional radar is, as shown in Figure 1, composed of radiators, transmitters and receivers (TR), a combiner to be interfaced with a modulator and demodulator, and transmission lines to connect a TR models and a combiner. A radiator is attached with a TR. The type and number of radiators are determined to realize the antenna gain, radiation pattern, weight and size, power consumption which are required by an application system. For example, the PAA in SPY-1 radar for Aegis is said to have 4,350 radiators in an aperture of 3.7 m diameter. The longest transmission line is about 2 m in this case.

Beam scan is accomplished by phase shifters which are imbedded in the transmission- and reception-paths. The phase shifters are controlled according to the desired direction of the antenna beam. The phase shift value is different for each

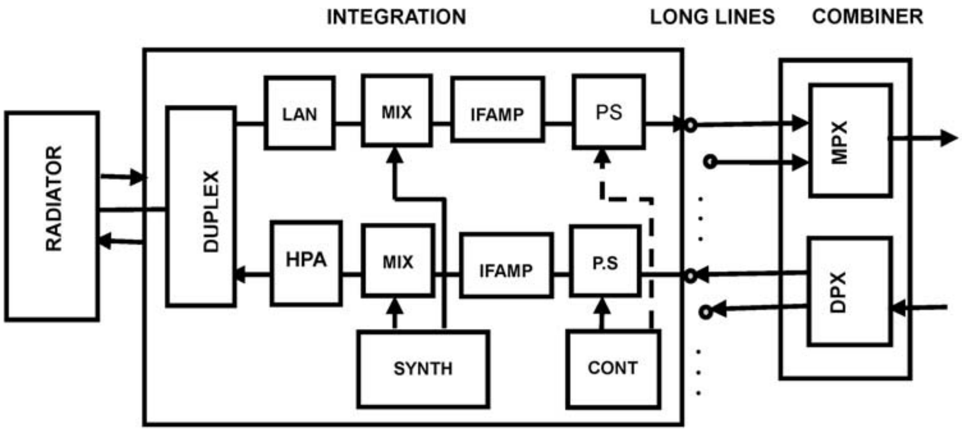


Fig. 1 Configuration of a Unit in a Conventional APAA

TR in general. If the frequency is different between the transmission- and reception-paths, the phase shifters should be driven with different voltages.

For practical application of APAA, the cost should be drastically reduced by less than one-tenth. In order to accomplish the cost reduction, we chose the following objectives for the basic technologies:

(1) The reduction of driven elements in an array antenna due to positive utilization of element coupling.
(2) Development of Monolithic Microwave Integrated Circuits (MMIC) and integration with radiating elements.
(3) Radio Frequency-Micro Electro Mechanical System (RF-MEMS) switch for a phase shifter.
(4) Development of beam control circuits.

As many difficulties may appear in pursuing the objectives, we expect a situation to make a compromise between the realizable level of technology and the required level by a system. Without this kind of compromise, really practical systems can not be synthesized. In this sense, the study of applications or systems is indispensable. The system with APAA will be verified at RF level at least in this project.

According to the above-mentioned objectives, the R&D project was organized with correspondent groups as shown in Table 1. The R&D activity is planned to be carried out for 4 years. The former 2 years are dedicated for rather fundamental research with a side look at practical applications. The latter 2 years are used for realization of practical systems which could be utilized for services or businesses.

The objective goal is held up for each year as follows:

– 2006 Trial manufacturing of APAA around 6 GHz.
– 2007 Trial manufacturing of APAA around K-band.
– 2008 Realization of practical APAA for car uses.
– 2009 Realization of practical APAA for maritime uses, and application study for airplane and space.

Table 1 **Structure of the Project and Responsibilities**

Group	Responsibility
Japan Aerospace Exploration Agency	Radiator, Array structure
Kyoto University	Amplifier, MMIC, Phase shifter
University of Tokyo	Switch in RF-MEMS technology
Japan Radio Co., Ltd	System, Application

3 CONCEPT AND KEY TECHNOLOGIES

In order to realize the cost reduction of agile antennas for practical applications, we analyzed effective factors, relevant technologies and concrete means to solve problems. The resultant roadmap is summarized in Figure 2. The means or key techniques are linked to the antenna, RF circuits and control.

The outlook of the antenna may be as shown in Figure 3. On the front of the reflector, four radiating elements are installed in this case. But only two elements are driven with a driving voltage though the reaming two elements are passive. On

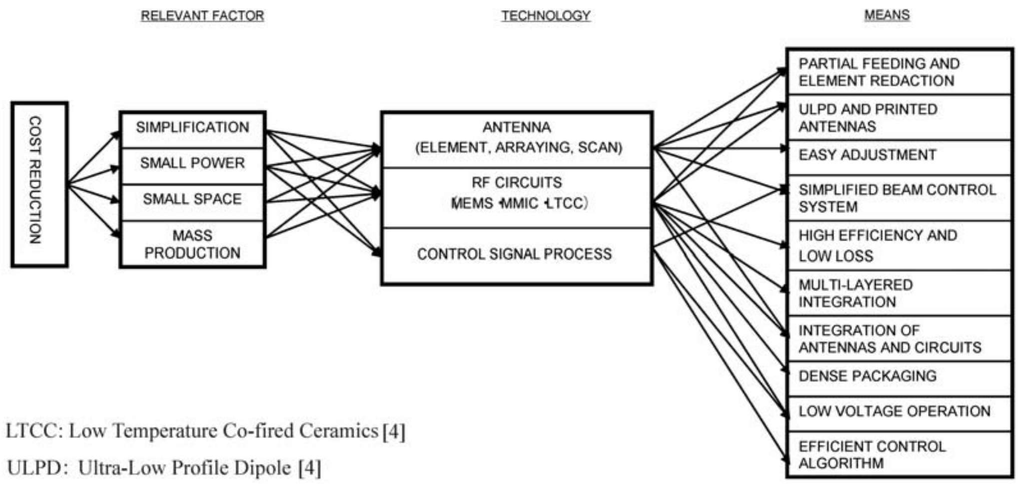


Fig. 2 Road Map of Cost Reduction

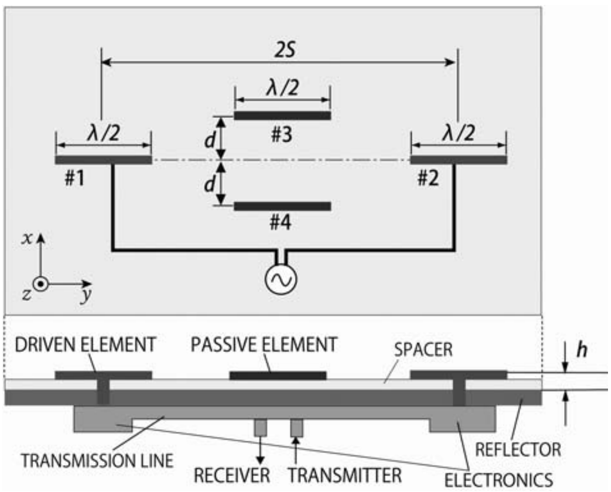


Fig. 3 Concept of an Active Phased Array Antenna

the back side of the reflector, electronic circuits are installed at the correspondent locations to the radiating elements. All electronic circuits are connected and combined at the input and output port of the antenna. The technical features are as follows:

(1) The number of driven radiators is reduced without serious degradation of principal characteristics.

(2) The driven radiator is integrated with a TR.

(3) The TR is installed in a small package with MMIC technology.

(4) As the phase shifter operates at frequency higher than 10 GHz, RF-MEMS at RF is required for a switching device instead of a PIN diode or a HEMT device.

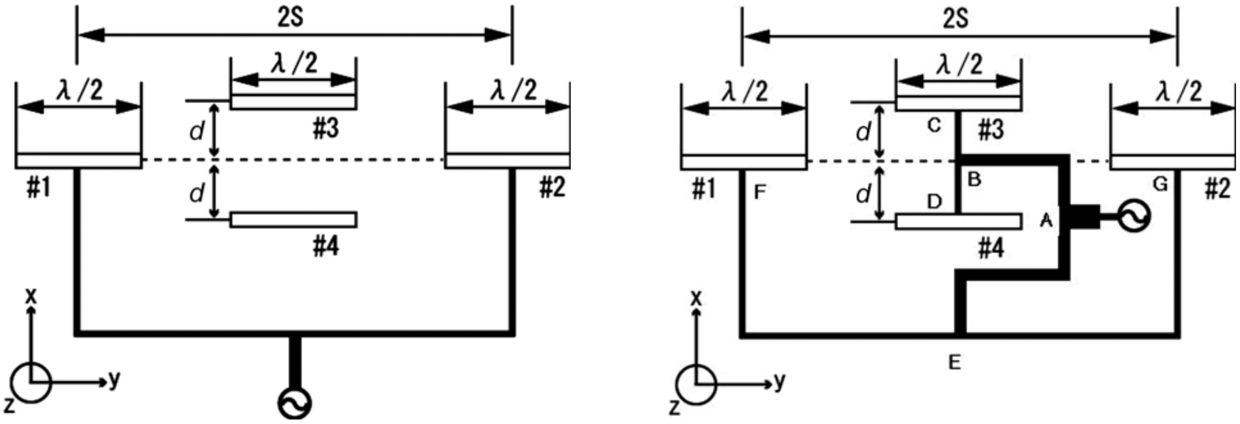
4 ACHIEVEMENTS

4.1 Antennas

In a conventional APAA, almost all radiators were fed by an amplifier and a phase shifter. One of technical issues is the coupling between radiator elements: the malignant effect to input impedance and pattern. However, it has been shown that driven elements can be replaced by undriven or passive elements without serious degradation of antenna characteristics according to the elaborate design [5]. This situation which may be called partial driving is accomplished by the positive utilization of element coupling.

An APAA with partial driving technique is shown in Figure 3 in Section 3. It was revealed theoretically and experimentally that the radiated field from the driven elements (#1, #2) propagates to and scattered by the passive elements (#3, #4). If the height h and the separations s and d are chosen properly, the directly radiated field from #1 and #2 and the scattered field from #3 and #4 are added in phase in the far field. The ratio of the un-driven element number to the total element number is defined as the cutback ratio, and is 0.5 in the case of Figure 3 with an infinite reflector [6].

Possible circuits to distribute a microwave to each radiator element are shown for the fully driven and partially driven cases in Figure 4 (a) and (b), respectively. In Figure 4(b), the lines are drawn for simplification purpose, so that the lengths are incorrect: The lengths should satisfy AB = AE, BC = BD = EF = EG in the actual case. As the driven elements are reduced half in number, the feeding circuit behind the reflector can be much



(a) Partially driven case (b) Fully driven case

Fig. 4 Feeding Circuit

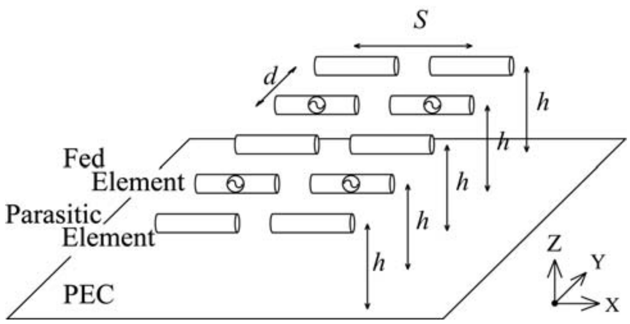


Fig. 5 Configuration of a Partially Driven Array Antenna with a Cutback Ratio of 0.6

simplified to give the same antenna gain. Especially, the chances of a circuit cross-over are apparently reduced much.

At a branch point, a line which is closer to the power source is connected with two lines which are closer to the radiating elements. In order to make a good impedance matching, the line width in the source side should be double that in the radiator side because the impedance is almost inversely proportional to the line width. Therefore, the number and complexity of branch points are much reduced in the partially driven case.

A high-power radiating system needs amplifiers to amplify a seed microwave and to feed the driven elements at a desired power level. For this purpose, two amplifiers are sufficient in the partially driven case though four amplifiers are required in the fully driven case.

The later study revealed the possibility of the cutback ratio of 0.6 or even more [7]. The partially driven array antenna in Figure 5 has only four driven elements out of ten elements. If the parameters h, s and d are properly chosen, the antenna gain is 18.5 dBi which is almost equal to the gain of fully driven array antenna with ten elements, namely 18.2 dBi.

4.2 MMIC

The TRs are attached to the backside of the reflector in correspondence to the radiator elements.

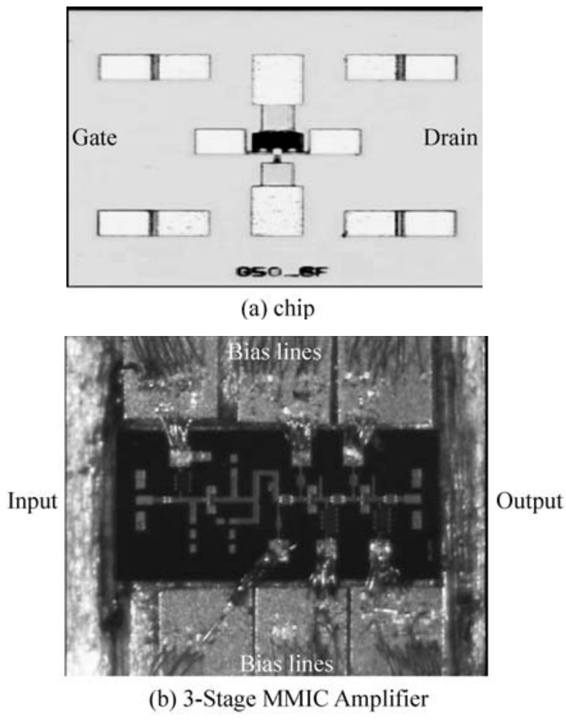
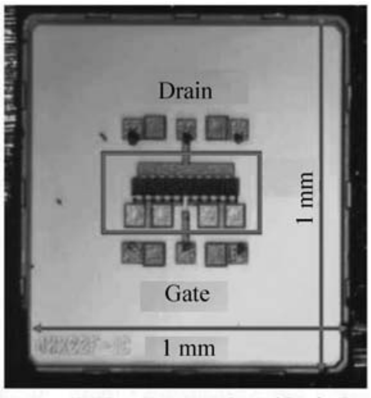
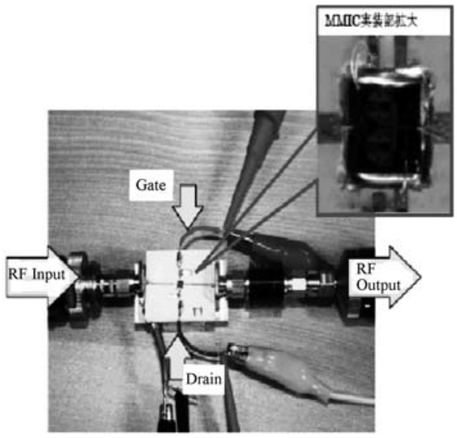


Fig. 6 Low Noise Amplifier



(a) Chip



(b) Single-Stage MMIC Amplifier

Fig. 7 High Power Amplifier

Components in a TR such as a low noise amplifier (LNA) and a high power amplifier (HPA) are first made on each chip, as shown in Figures 6 and 7, respectively. The LNA and HPA are currently in a world-wide race to achieve the best data [8]. So far, NF of 0.69 dB and gain of 10.9 dB have been achieved.

At the next stage, LAN and HPA may be integrated on a single chip. At the final stage, mixers and phase shifters are also put in a single package to realize a small space, low power and mass production. Packaging is an important but difficult task which requires much experience.

4.3 Phase Shifter

A phase shifter is a key device to realize PAA. At high microwave band, small insertion loss and high isolation are both difficult to achieve. Especially in K-band of 10 GHz to 30 GHz, a phase shifters of a loaded type and hybrid type with PIN diode or a HEMT tends to have a prohibitive loss [9]. Therefore, transmission lines should be switched to realize a digital phase shift with better performances so that a switching device is a key. Microwave delay lines are embedded in the LTCC (low temperature co-fired ceramics) substrate, as schematically illustrated in Figure 8, on which N-pairs of SPDT (single pole double throw) RF-MEMS switches are mounted. Phase-shift is controlled by appropriately choosing the N-set of binary-weighted delay lines. On the identical LTCC chip, an MMIC of LNA (low noise amplifier) is mounted.

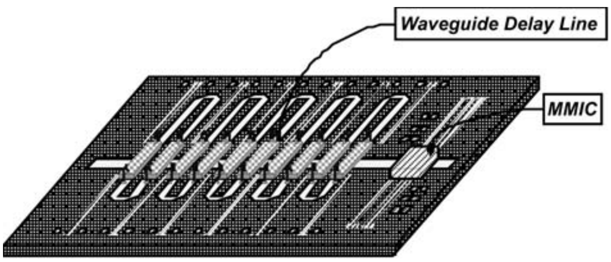


Fig. 8 Phase Shifter with Switched delay Lines

Nevertheless it was difficult for an RF-MEMS device to realize a secure ON state and to avoid adhesion with an excellent impedance matching. A new configuration to solve these difficulties has been proposed as shown in Figure 9. The signal path is composed of co-planar waveguides (CPW) with one input port and two output ports which are placed on the both sides of a movable arm.

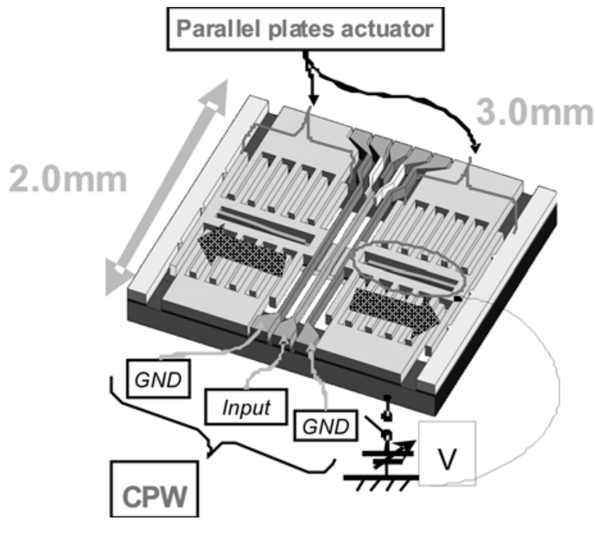


Fig. 9 Trial Design of a SPDT Switch by RF-MEMS Technology

Five pairs of electrostatic actuators with the fixed and movable electtrodes are constructed on the both sides of the CPW. Secure electrical contact with appropriate contact force is made by the arrayed electrostatic actuators. Permanent adhesion of the contact metal is avoided by designing the actuator's output force to be greater than the adhesion force. Simulation result suggests excellent performances.

5 SYSTEMS AND MISSIONS

The parameters relevant to a particular system are classified:

(1) concerning an antenna: the gain, beam scan coverage, side lobe levels, polar characteristics and input impedance,

(2) concerning amplifiers: the gain, output level and NF,

(3) concerning a switching device: the loss and reliability.

The values are determined as an optimal solution for a system. On the other hand, a system is studied on the bases of a particular mission or service. Therefore, the most important parameters are selected in relation to a service. Technology level for each technical field such as device fabrication or integration grade is decided to optimize system objectives, and may not always be the most advanced one.

The APAA can be conceived to be applied in mobile communications [10] for a car [11], a train, a ship [11], an airplane [13] or a spacecraft, as shown in Figure 10. Also the application will be expanded to traffic controls, radars, and microwave power transmission [14]. Taking account of surrounding conditions, the actual system or service will be decided in the third year of the program described in section 2. This phase of R&D should be led by business side or industries.

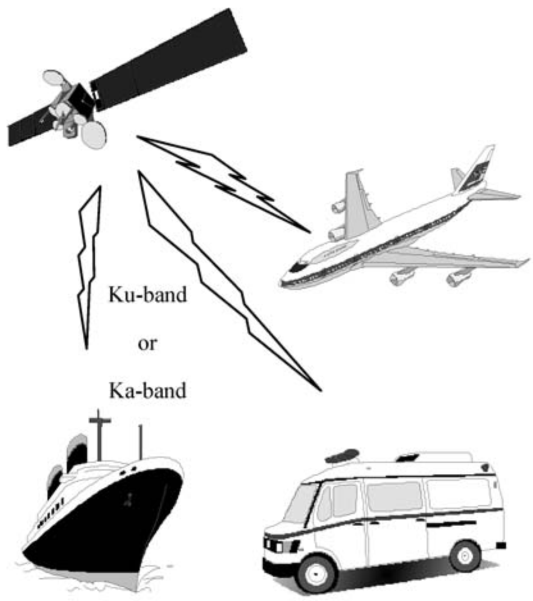


Fig. 10 Application Examples of APAA

If the requirement to the most important parameters is satisfied, the system development will be encouraged, as shown in Figure 11. The abscissa shows a technical factor such as cost, power consumption or reliability. The ordinate is the social attention or effort to be paid to the system. For example, at the worse stage of cost, most R&D resource is fed to the seeds. If the cost is improved (drastically reduced), needs gather more attention, and seeds may lose a principal role or turn their effort to the other technologies. We hope to have several innovation boundaries in the future of APAA.

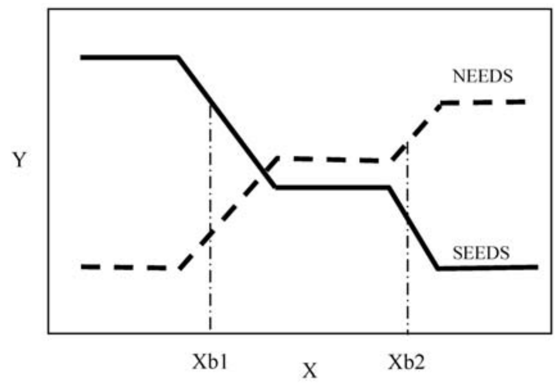


Fig. 11. Change of Seeds and Needs across Innovation Boundaries

6 CONCLUSION

In order to put an ideal antenna of APAA into practical use, the study from both sides of seeds and needs are necessary. Academic institutions are good at basic research or seeds study while industries at applications or needs study. Both communities are expected to have close and supplementary collaboration.

7 ACKNOWLEDGEMENTS

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Japanski projekt istraživanja i razvoja aktivnih faznih antenskih nizova za praktične primjene. U radu je prikazan japanski istraživački projekt razvoja aktivnih faznih antenskih nizova (APAA) za praktične primjene. Cilj projekta je realizacija APAA malog volumena, male težine i reducirane cijene u K-frekvencijskom području. Ključna tehnološka rješenja su parcijalna pobuda antenskog niza, monolitni mikrovalni integrirani krugovi (MMIC), fazni zakretači s mikro elektromehaničkim prekidačem u radiofrekvencijskom području (RF-MEMS) i pripadajući pobudni sklopovi, kao i integracija svih komponenata u sustav. U radu je objašnjena struktura i vremenski plan istraživanja i razvoja (R&D). Opisani su također do sada postignuti rezultati R&D.

Ključne riječi: japanski projekt, aktivni fazni antenski nizovi, redukcija troškova, zakretanje glavne latice, parcijalna pobuda antenskog niza, fazni zakretači s RF-MEMS

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