3-6-2 Feed Array Element

MATSUMOTO Yasushi and TANAKA Masato

A new design of microstrip antenna (MSA) is studied for satellite-borne phased array antennas. Noble characteristics, low mass, simple construction, high efficiency, low mutual coupling, are achieved by a honeycomb-based structure with a surrounding metal cylinder (cup MSA). S-band cup MSAs are successfully developed for phased array-fed antennas on Engineering Test Satellite VIII (ETS-VIII).

Keywords
Phased array antenna, Satellite antenna, Feed array, Element antenna, Microstrip antenna

1 Introduction

Satellite-borne phased-array antennas are regarded as vital elements of next-generation satellite communications systems, and have been subject to extensive research and development [1]-[4]. A satellite-borne phased-array antenna consists of numerous antenna elements. Thus, the structure of the element antenna significantly influences the electrical performance and mechanical design (including size and weight) of the phased-array antenna as a whole. The structures of the element antenna therefore need to provide both the required electrical characteristics (in terms of gain and mutual coupling, for example) and the required mechanical characteristics (e.g., compact size, light weight, and resistance to vibration).

Microstrip antennas (MSA) are lightweight, thin, and can radiate circularly polarized waves. Due to these characteristics, they have often been used as the antenna elements in satellite-borne phased arrays or feed arrays [5][6]. However, these elements are exposed to space in orbit, limiting the choice of constituent materials to those that can endure the space environment. Further, the material and thickness of the substrate determine most of the critical characteristics of the basic MSA structure, including gain and frequency bandwidth. These restrictions in turn limit the flexibility in the design of MSA arrays.

To solve this problem, methods have been proposed in which the structure of the MSA is configured to improve the electrical characteristics. For example, parasitic elements on the front face of the element can improve the gain and frequency characteristics [5][7]. However, this structure tends to increase the mutual coupling between adjacent elements when incorporated into an array [8].

It is also known that constructing the MSA within a cylindrical cavity made of a conductor with an open end (a “cavity-backed MSA”) can improve some characteristics [9]-[11]. However, the structure uses a metal sheet for the feed elements and the parasitic elements to provide rigidity, attached via metal supports to the metal cavity. This significantly increases weight, defeating the purpose of MSA design. Further, feed pins are used to excite the element, which is also disadvantageous in that this method tends to generate PIM (passive intermodulation) at the metal joints of the feed point.

On the other hand, a cup structure—consisting of the MSA printed on a circular substrate and enclosed in a metal cylinder—enables the construction of an antenna element (referred to hereinafter as a “cup MSA”) that is electrically equivalent to a cavity-backed MSA while at the same time remaining mechanically simple and light, rendering this structure suitable for installation on a satellite [12][13].

This paper discusses the development of the cup MSA elements used in the phased-array antennas for mobile satellite communications [14] to be equipped on the Engineering Test Satellite VIII (ETS-VIII). This antenna element is small, light, and offers the required resistance to vibration due to its honeycomb structure. The element is excited through coupling apertures, which decreases the number of metal joints that can cause PIM. The weight of the developed element is approximately half of the loading weight of elements featuring equivalent electrical performance.

2 Honeycomb structure of the cup MSA

Fig.1 shows the basic honeycomb structure of the cup micro-strip antenna element (the “cup MSA element”).

The cup MSA consists of a substrate (the base of the cup) and a metal cylinder enclosing the substrate. On the honeycomb substrate, a circular print patch is formed. On the back of the honeycomb substrate (the opposite side of the radiating surface), a dielectric substrate is attached; this substrate in turn holds a hybrid coupler to generate circularly polarized waves. The dielectric substrate and the honeycomb substrate share a common ground plane. Coupling slots are provided on this ground plane. The circularly polarized waves are generated via electromagnetic coupling through these two slots. The weight of the substrates (including the MSA, the hybrid couplers, and the connectors) is negligible relative to the weight of the metal cup. The axial ratio of the MSA tends to degenerate more easily on thick honeycomb substrates than on thin substrates, because unnecessary modes are easily excited on the thick substrate, causing coupling between the feeding points. To avoid this problem, parasitic slots are placed at the symmetrical positions relative to the feed slots [15].

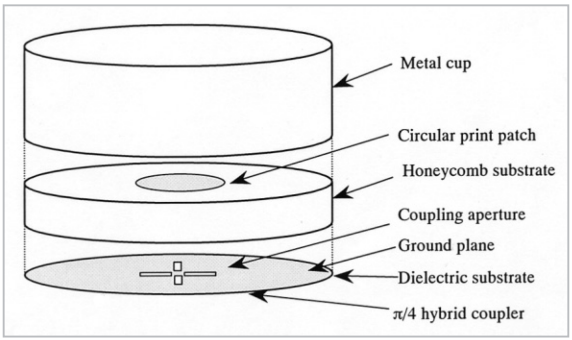

Fig.1 Structure of a honeycomb-based cup MSA.

The metal cylinder has the effect of suppressing the side-lobe and back-lobe levels of the MSA. It has also been confirmed that the cylinder decreases mutual coupling between adjacent elements and increases the aperture efficiency of each element [12]. Suppression of the mutual coupling is necessary to reduce excitation error in the feed array. The reduction of the back-lobe level effectively suppresses electromagnetic interference among the antennas on the satellite.

The metal cylinder itself is integrally molded and offers high mechanical rigidity. This cylinder adds strength to the honeycomb substrate, helping to form an element with high mechanical rigidity that can endure the harsh launch environment.

3 Development of antenna elements for the ETS-VIII

Cup MSA elements were developed as phased-array feed elements for the S-band large deployable antennas to be installed on the ETS-VIII. The satellite employs two separate S-band antennas; one for transmitting and the other for receiving. Thus, the feed-array elements were also designed separately. In a phased-array feed reflector antenna, the position of the feed array, the element spacing, and the number of elements have a significant effect on electrical performance, total weight, and size of the antenna system. These parameters were optimized within the limitations of shape and size imposed by satellite deployment [14] to satisfy the required antenna performance. Table 1 shows the characteristics of the developed cup MSA antenna.

Table 1 Required characteristics for the feed array of large deployable antennas on the ETS-VIII

	Transmit	Receive
Frequency	2.50 GHz	2.66 GHz
Polarization	RHCP	RHCP
Bandwidth	> 40 MHz	> 5 MHz
Gain	> 8.9 dBi	> 8.9 dBi
Mutual Coupling (1λ spacing)	< -40 dB	< -40 dB
Axial ratio	< 1.5 dB	< 1.5 dB
Maximum Input	> 20 W	-
Diameter	< 1 λ	< 1 λ
Weight	< 200 g	< 200 g
Number of element	31	31

The radiation pattern of a cup MSA can be controlled to some extent by the size of the cup. For example, Figs.2 and 3 show the changes in gain when the height and the diameter of the cup are varied, respectively, for an MSA with a PTFE substrate (ε = 2.17) [12]. The gain is at maximum when the height of the cup is approximately 50 mm. It is known that the cup height resulting in maximum gain does not depend on the diameter of the cup

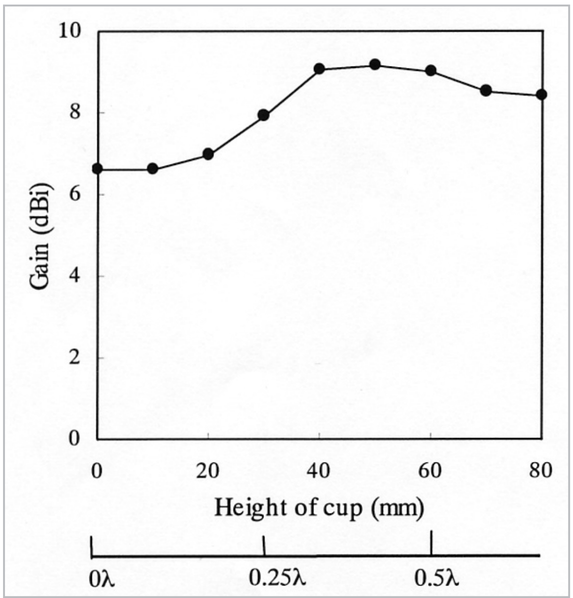

Fig.2 Element gain vs. cup height. (cup diameter =1 λ)

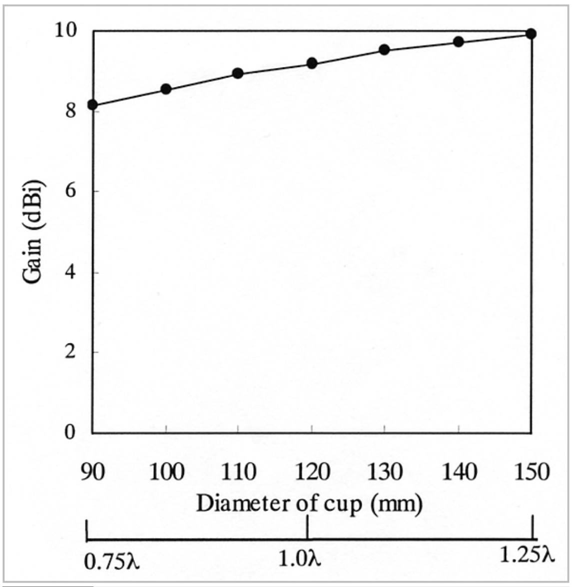

Fig.3 Element gain vs. cup diameter. (cup height = 50 mm)

(3/4λ to 5/4λ). When the height of the cup is maintained (at the height of maximum gain), the element gain increases in a linear manner with cup diameter. This tendency is also seen in the honeycomb-based cup MSA. Taking these facts into consideration, cup diameter was adjusted to the maximum value permitting the required element spacing (1 wavelength), and the cup height was adjusted to produce maximum gain (50 mm). A 5-mm thickness honeycomb substrate is used as the MSA substrate, taking the required bandwidth into consideration. The size of the feed slots was determined after several different prototypes were built, in order to obtain the desired axial ratio.

Table 2 shows the characteristics of the

Table 2 Measured characteristics of the receiving cup MSA.

Center frequency	2.6575 GHz
Polarization	LHCP
Bandwidth	> 5 MHz
Gain	10.9 dBi* / 9.9 dBi**
Beam width	57.0 deg* /54.5 deg**
Axial ratio	1.5 dB
Mutual coupling	< -40 dB (1λspacing)
Cup Diameter	114 mm (1λ)
Cup Height:	50 mm (0.44λ)
Weight	160 g

*lone element / **in array (1λspacing)

developed receiving element. Fig.4 shows the element pattern of the cup MSA in comparison with that of an element without a metal cup. The attachment of the cup decreases the beam width and increases the gain of the element by 1.2 dB. Here, the increase in gain provided by the cup is less than seen in the results of Fig.2 (showing difference in gain between cup heights of 0 mm and 50 mm). This is because the MSA diameters differ in these two cases due to a difference in the dielectric constants of the substrates used (PTFE substrate shown in Fig.2; honeycomb substrate in Fig.4). The MSA on the honeycomb substrate is larger than that on the PTFE substrate, resulting in higher element gain.

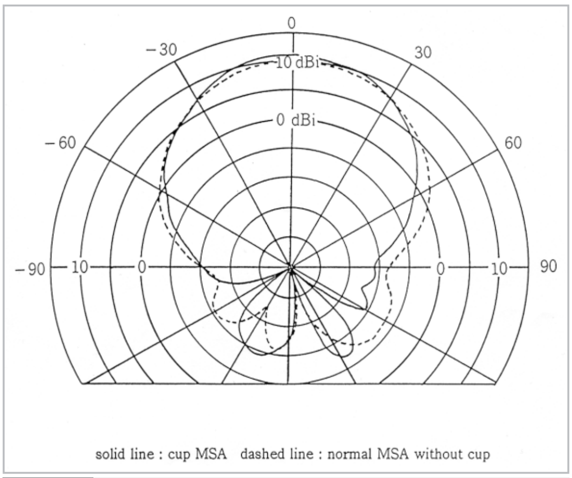

Fig.4 *Element pattern of a cup MSA compared with that of a normal MSA.*

Next, the performance of the elements was tested in the arrayed condition. An array was constructed with seven elements and the element pattern was measured. Only the element in the center was excited, and the other elements were terminated. Fig.5 shows the results.

Table 2 compares the element gains and the beam widths for an individual element and an element within the array. The beam width in the array is 54.5 degrees, which is narrower than the beam width of the element on its own. However, the forward gain decreases at the same time. This is probably due to the scattering by the metal cylinders of the adjacent elements. The coupling between the

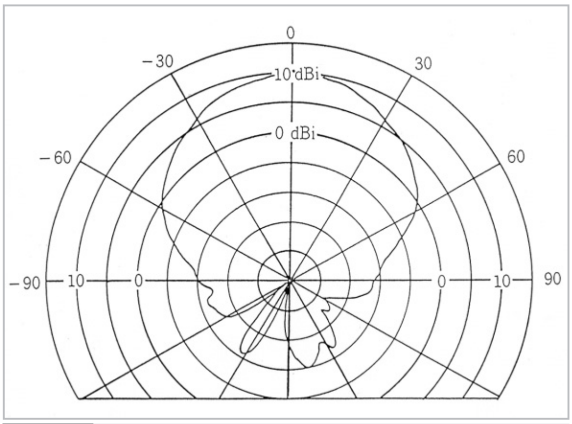

Fig.5 *Element pattern of a cup MSA in an array. (element spacing = 1 λ)*

adjacent elements is −40 dB or less, which is sufficiently low. As shown in Table 2, the remaining characteristics also satisfy the required performance for a feed-array element.

Table 3 compares the cup MSA with other elements. The elements chosen for comparison are those that can operate with the S-band circularly polarized waves and have a diameter within one wavelength. The values in the table for the cup helical, cup dipole, and cup MSA elements are those measured using prototype elements. The values for other elements are values regarded as typical. The honeycomb-based cup MSA element discussed here offers characteristics equivalent to the cup helical and cup dipole elements, at approximately half the weight.

Table 3 *Comparison of the cup MSA and typical array elements in the S-band.*

Element	Horn	Cup Helical	Cup dipole	Normal MSA*	Cup MSA
Bandwidth (%)	~50*	~40	~10	~5*	~5
Gain (dBi)	8~9*	8.9	8.2	7~9*	~11
Coupling (dB) (1λ spacing)	<-40*	-23	-36	<-35*	-40
Max.Input(W)	~100*	180	100	40*	40
Height (mm)	>500*	200	130	~20*	<60
Diameter (mm)	120	120	120	120	120
Weight (g)	-	~350	~300	<100*	160

*Typical Value

Environmental tests based on the mechanical and thermal conditions on the ETS-VIII (i.e., vibration test and thermal vacuum test) had shown that the element satisfied the required performances.

4 Summary

A lightweight, highly efficient cup MSA element has been developed as a phased-array feed element. This element features a light and highly rigid structure, a result of the honeycomb structure of the substrate. The electromagnetically coupled feed decreases the number of metal joints that can cause PIM. This has all resulted in the successful development of an S-band feed-array element for the ETS-VIII that provides the required electrical and environmental performance at approximately half the weight of conventional array elements.

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***MATSUMOTO Yasushi**, Dr. Eng.*

Associate Professor, Research Institute of Electrical Communication, Tohoku University (present Leader, Communication System EMC Group, Wireless Communications Division)

Wireless Communications

***TANAKA Masato**, Dr. Eng.*

Chief Researcher, General Affairs Division (present Senior Researcher, Research Planning Office, Strategic Planning Division)

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