Circularly Polarized Triangular Microstrip Array Antenna Using Single-Fed Proximity-Coupled for Mobile Satellite Communications Applications

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Abstract—**The Japan Aerospace Exploration Agency (JAXA) will launch the Engineering Test Satellite VIII (ETS-VIII) to support the next generation of mobile satellite communications covering the area of Japan (beam coverage *El* = 38º to 58º). In this paper, a dual-band left-handed circularly polarized triangular-patch array antenna is developed for ground applications. The targeted minimum gain of the antenna is set to 5 dBic at the central elevation angle (*El* = 48º), in Tokyo area, for applications using data transfer of around a hundred kbps. The antenna consists of three equilateral triangular patches with truncated-tip for both reception and transmission units operating at 2.50 and 2.65 GHz frequency bands, respectively. The antenna was simulated using the Method of Moments (MoM) analysis, fabricated and measured to confirm the simulation results. The measurement results show that the frequency characteristics and the 3-dB axial ratio coverage in the conical-cut direction of the fabricated antenna satisfy the specifications for ETS-VIII.**

Keywords—**Mobile satellite communications, ETS-VIII, dual-band, circular polarization, triangular-patch array antenna, Method of Moments (MoM)**

I. INTRODUCTION

The Japan Aerospace Exploration Agency (JAXA) has been developing satellite mission technologies from the first Engineering Test Satellite-I (ETS-I) through ETS-VII. The latest version in the series, ETS-VIII, is one of the largest geostationary S-band satellites in the world and is now under development to meet future requirements of mobile communications.

The ETS-VIII will conduct various orbital experiments in Japan and surrounding areas to verify mobile satellite communications functions, making use of a small satellite handset similar to a mobile phone. The mobile communication technologies adopted by ETS-VIII are expected to benefit our daily life in the field of communications, broadcasting, and global positioning. Quick and accurate directions for example, can be given to an emergency vehicle by means of traffic control information via satellite in the event of a disaster [1].

Therefore, an antenna for land mobile systems aiming at ETS-VIII is needed. The targeted minimum gain of the antenna is set to 5 dBic at an elevation of 48° in Tokyo area for applications of a few hundred kbps. The antenna should be designed as thin, compact, small and simple as possible, for it to be mounted on a bullet train, ship and car [2].

Up to now, various antennae have been developed aimed at ETS-VIII [3]-[7]. The performances of the antenna [7] have been experimented outdoor by using a pseudo-satellite station. The measurement results agree well with the simulation results, where the simulation results were calculated using the Method of Moment (MoM). However, the complicated feeding line of the antenna is considered to be difficult in terms of design and fabrication.

In this paper, a novel model of antenna is proposed in order to simplify the feeding network and possibly miniaturize the antenna. The antenna is composed of an equilateral-triangular microstrip antenna with a truncated tip in order to achieve circular polarization radiation. From [8], the circular polarization can be achieved simply by cutting a correct sized section from the tip of an equilateral-triangular patch. This time, a proximity-coupled feed is proposed rather than a probe excitation feed. For microstrip antennas, using a proximity-coupled feed can provide the advantages of flexible impedance matching design, reduce the radiation from discontinuities in the feed network, and allow an easy integration with circuit devices, in comparison to the coaxial probe feed [9]-[10].

In this research, the possibility for the equilateral-triangular antenna fed by proximity-coupled feed in order to be used in mobile satellite applications is investigated. Moreover, the proposed antenna, usable in ETS-VIII applications, is numerically analyzed by the MoM (Ensemble v.8 Ansoft software) and experimentally confirmed.

II. SPECIFICATIONS AND TARGETS

Table I shows the specifications and targets required for an antenna to be used with mobile satellite communication, in particular aimed at ETS-VIII applications, which are used in this paper. A gain more than 5 dBic (for a hundred kbps data rate) and an axial ratio less than 3 dB with a left-handed circular polarization (LHCP) should be considered to design the antenna. The antenna frequencies are set to 2.5025 GHz and 2.6575 GHz for the reception and transmission antenna, respectively, as shown in Table I. The direction of ETS-VIII seen from Japan has a certain elevation angle depending on the place. The beam of the antenna should cover the area from the northern to the southern part of Japan (*El* = 38° to *El* = 58°) as shown in Fig. 1.

TABLE I
SPECIFICATIONS AND OBJECTIVES ON THE ANTENNA FOR MOBILE SATELLITE COMMUNICATIONS (ETS-VIII)

SPECIFICATIONS		
Frequency bands	Transmission (Tx)	2655.5 to 2658.0 MHz
	Reception (Rx)	2500.5 to 2503.0 MHz
Polarization	Left-handed circular polarization for both transmission and reception	
TARGETS		
Elevation angle (*El*)		48° (Tokyo) ± 10°
Azimuth angle (*Az*)		0° to 360°
Minimum gain		5 dBic
Maximum axial ratio		3 dB
Minimum isolation		20 dB

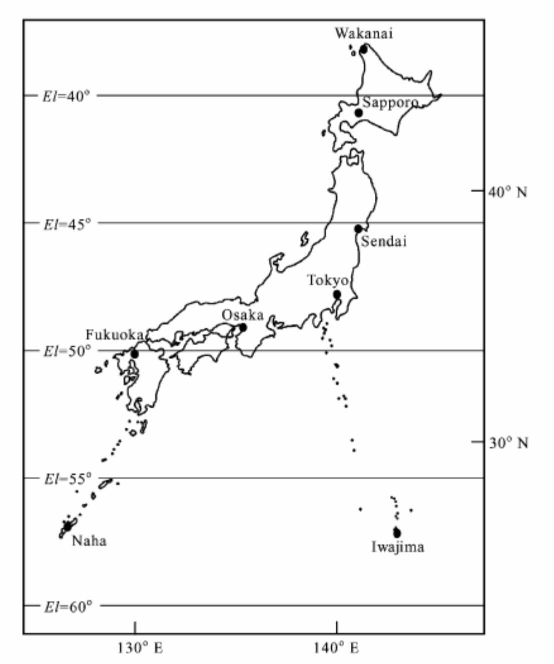


Fig. 1. Japan map: elevation angle of beam direction

III. ANTENNA CONFIGURATION

Fig. 2 shows the configuration of a single patch antenna. At the beginning, the author designed a single patch at the reception operating frequency. The patch antenna is proximity-coupled fed with a microstrip line whose width w is 1.34 mm.

The feed is attached to a 50 Ω transmission line by a step-width Δw = 0.2 mm. The step-width is set to 30° cut-angle for reactance compensation. The substrate thickness for the microstrip line and the triangular patch layers are $h_a = h_b$ = 0.8 mm with a relative permittivity ε_r = 2.17 and a loss tangent tan δ = 0.0009. The length of the stub l_e is 14 mm. In addition, the feed length between patch edge and step-width l_s is 5 mm. Then, the feed is attached to the transmission line by the length l_t.

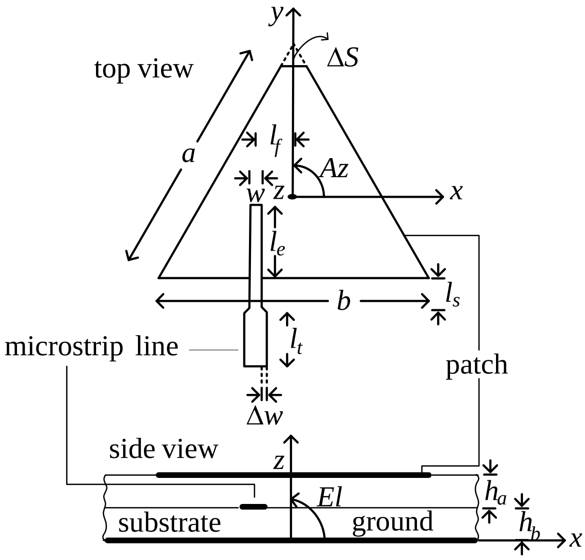


Fig. 2. Configuration of single patch antenna

A small triangular tip of surface area ΔS is cut in the triangular patch to ensure an effective excited patch surface current path in the y-direction is slightly shorter than that in the x-direction (as shown in Fig. 2), which gives the y-directed resonant mode a resonant frequency slightly larger than that of the x-directed resonant mode. That is, the dominant mode of the triangular patch can be divided into two orthogonal resonant modes of equal amplitudes and 90° phase difference for circular polarization operation.

Moreover, by shifting the microstrip line by l_f at an effective position away from the center of the patch, LHCP operation can be obtained at the target frequency 2.5025 GHz. Finally, the patch lengths a = 47.48 mm and b = 52.48 mm can be obtained.

In this paper, the Method of Moment (MoM) was employed to simulate the model with an infinite ground plane. Fig. 3 shows the relationship between the reflection coefficient (S_{11}) and frequency for the simulation model of Rx antenna. The S_{11} is below -10 dB at the target frequency. The character of the Tx antenna can be simulated in the same manner and is therefore neglected in this discussion. Fig 4 defines the impedance characteristics of a single element. The antenna has an inductive impedance with resistance 47.63 Ω at the center frequency 2.5025 GHz caused by an inductive effect due to the narrow feed line rather than a conductive effect due to the dielectric thickness.

Fig. 5(a) and (b) depicts the relationship between gain (G) and axial ratio (Ar) at an azimuth angle 0° and 90°, respectively. The main beam in the boresight direction has a gain of 6.1 dBic and an axial ratio of 0.2 dB. The gain beamwidth is more than 5 dBic almost on 30% (51°) both for the x-z and y-z plane direction. Moreover, the axial ratio less than 3 dB can cover 65% (117°) and 61% (109°) in the x-z and y-z planes, respectively.

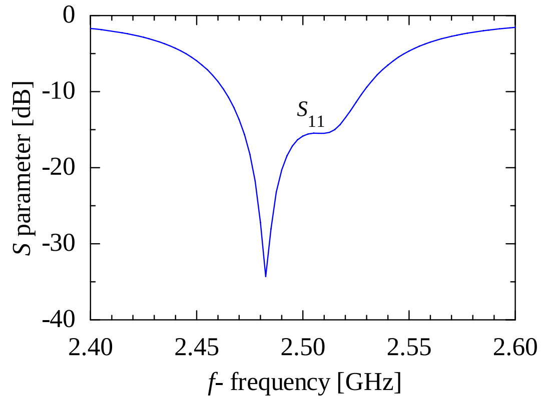


Fig. 3. Reflection coefficient versus frequency of single triangular patch antenna (reception)

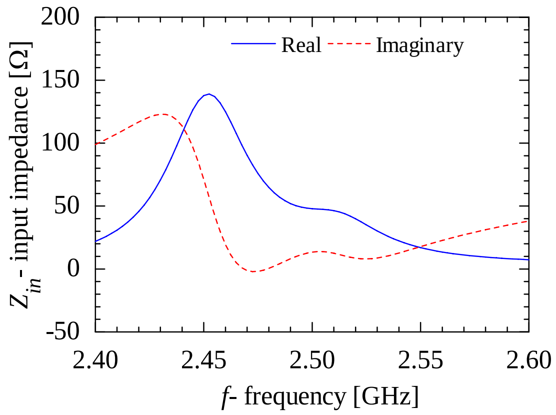
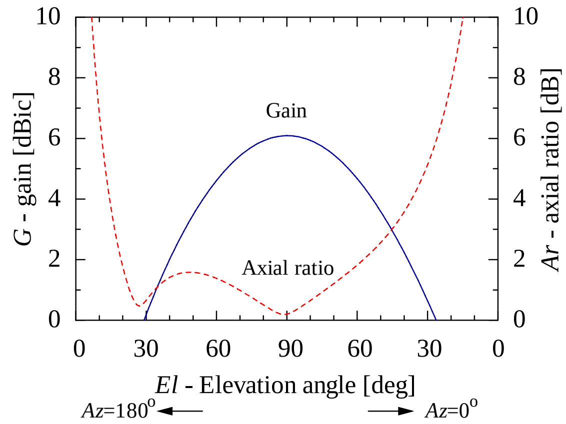
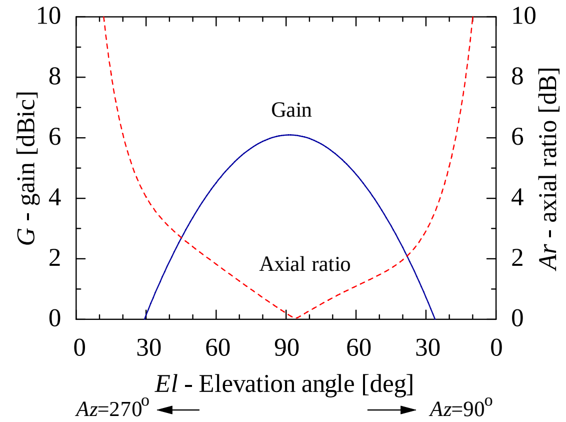


Fig. 4. Impedance characteristics of single triangular patch antenna (reception)



(a) Az = 0° (x-z plane)

Fig. 5. Radiation pattern (reception)



(b) Az = 90° (y-z plane)

Fig. 5. Radiation pattern (reception) (cont`d)

Considering these results, the antenna can be proposed as a candidate aimed at ETS-VIII applications when employed in array configuration. The array antenna will be discussed below.

Fig 6 describes the configuration of the triangular patch array antenna for dual-band operation. The antenna is composed of three triangular patches for each reception and transmission unit. As the operating frequency between reception and transmission antenna is different, each of them should also have different dimensions.

Besides, in order to meet the specifications and the targets the gain more than 5 dBic and the axial ratio less than 3 dB in the whole azimuth angles at elevation angle El = 48°, some dimensions parameters of reception and transmission antenna in array configuration have different length or distance.

It is shown in Fig. 6 that the patch lengths are a = 47.64 mm and b = 52.64 mm for reception and a = 44.54 mm and b = 49.54 mm for transmission, respectively. The length of the inserted-feed into the dielectric l_e is 14 mm and 13 mm for reception and transmission, respectively. In order to get a good axial ratio performance in azimuth, this time, the length between the center of the array and the truncated tip of one element c = 21 mm and c = 16 mm for reception and transmission units are obtained, respectively.

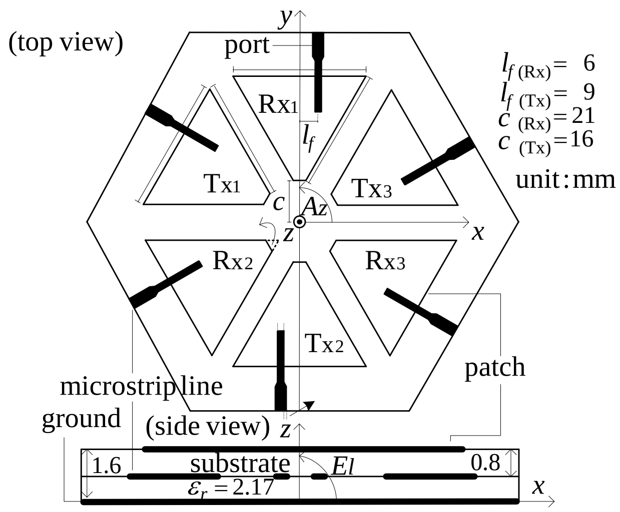


Fig. 6. Dual-band triangular-patch array antenna with truncated tip

Moreover, aiming at a gain more than 5 dBic and an axial ratio less than 3 dB in azimuth, the feed line for the reception antenna is shifted by l_f = 6 mm rather than 9 mm for the transmission antenna. The top and side views of the fabricated triangular-patch array antenna are shown in Fig. 6. An aluminum plate, whose thickness is 2 mm, is used to support the substrate.

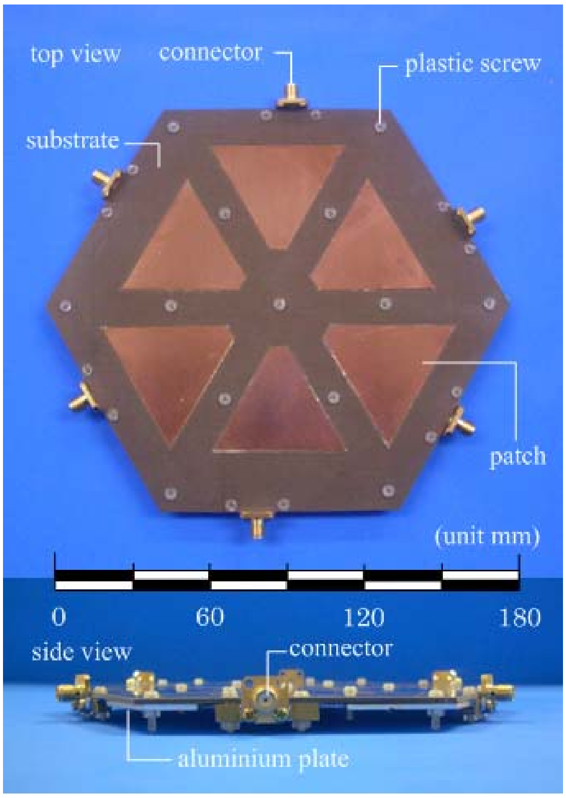


Fig. 7. Fabricated antenna

IV. Performance of the Antenna

A. S parameters

Fig. 8 shows the *S* parameters obtained from the simulation model and the measurement for element no. 1 of the Rx and Tx, shown in Fig. 6 as Rx1 and Tx1. This figure shows that the measurement results for both Rx and Tx are shifted of 1% (with respect to the target frequency), respectively, to higher frequencies from the simulation result. It is considered that the measurement systems (i.e. cable, connectors, plastic screws, etc.) affect the characteristics of the antenna. However, the results patterns are similar to the simulation ones. The isolation of the closest patches (e.g., Rx1 to Tx1 and Rx1 to Tx3 in Fig. 6), is higher than 20 dB although the frequency is shifted to the upper frequency. This result improves the performances of the previous antenna [7].

B. Impedance characteristics

Fig. 9 shows the input impedance characteristics of patch Rx1 and Tx1. This figure also shows the measurement impedance characteristics are shifted to the upper frequency from the target frequency by 1%. However, the shape of the results tends to be similar to the simulation ones. The receiving antenna is inductive with a resistance about 46.63 Ω at the minimum S_{11} frequency (2.54 GHz). On the other hand, the transmitting antenna is capacitive with a resistance about 45.27 Ω at the minimum S_{11} frequency (2.6975 GHz).

C. Frequency characteristics

The antenna was numerically optimized by minimizing the axial ratio at elevation angle *El* = 48° based on simulations for the targeted receive and transmit frequency as shown in Fig. 10, in the case patch 1 off. This figure depicts the frequency characteristics in case of *El* = 48° both for reception and transmission units in the theoretical beam directions, i.e azimuth angle *Az* = 0° and *Az* = 60° at each reception and transmission, respectively. The minimum axial ratio occurs at 2.515 GHz with 1.5 dB and 2.6675 GHz with 0.4 dB by measurement for reception and transmission, respectively. On the other hand, it occurs at 2.495 GHz with 1.1 dB and 2.655 GHz with 0.3 dB by simulation for reception and transmission, respectively. However, the shape of the measurement result tends to meet the analysis performance.

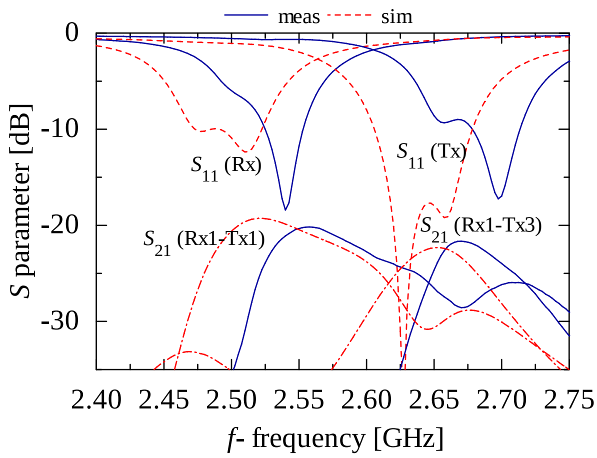


Fig. 8. Reflection coefficient versus frequency of dual-band triangular patch antenna with truncated tip

D. Radiation pattern in the elevation plane

Fig. 11 (a) and (b) shows the radiation pattern of the antenna in the elevation-cut plane when element #1 is switched OFF, each for reception and transmission unit. According to Fig. 11 (a), it can be stated that the axial ratio of the reception antenna satisfies less than 3 dB (1.6 dB) in the target elevation angle *El* = 48°, even at the lower elevation angle as well. The gain is 4.2 dBic rather than 5.4 dBic at *El* = 48°. The gain performance tends to shift to the upper elevation angle, on the other hand the axial ratio shifts that lower because of the finite ground plane effect.

In addition, the peak gain is about 0.6 dB lower than that of the simulation at *El* = 68°. Furthermore, the axial ratio and the gain of transmission antenna meet the targets less than 3 dB (i.e. 0.4 dB) and more than 5 dBic (5.5 dBic) at elevation angle *El* = 48° shown in Fig. 11 (b) for the measurement result. Moreover, the peak gain is about 0.12 dB lower than that of the simulation at *El* = 66°.

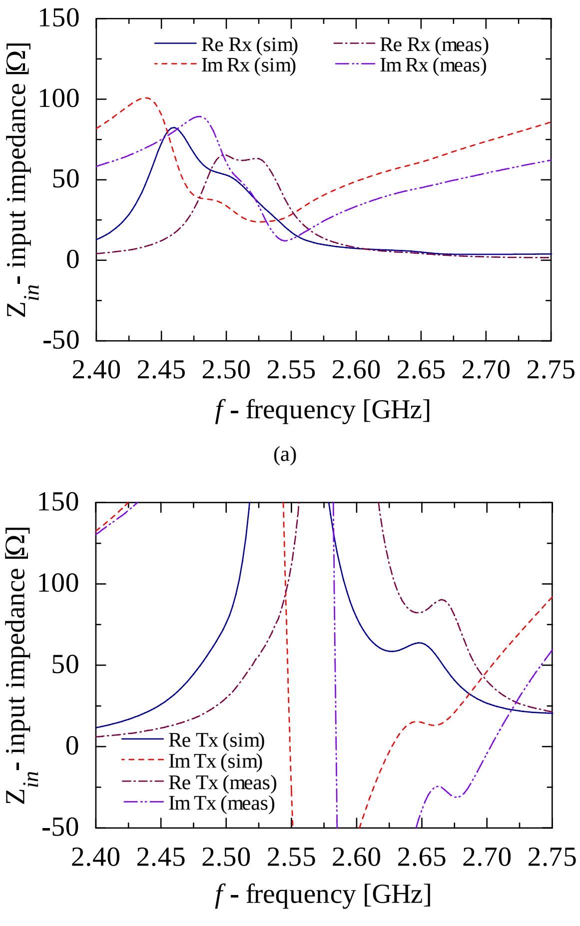


Fig. 9. Impedance characteristics of dual-band triangular patch antenna with truncated tip (a) Rx (b) Tx

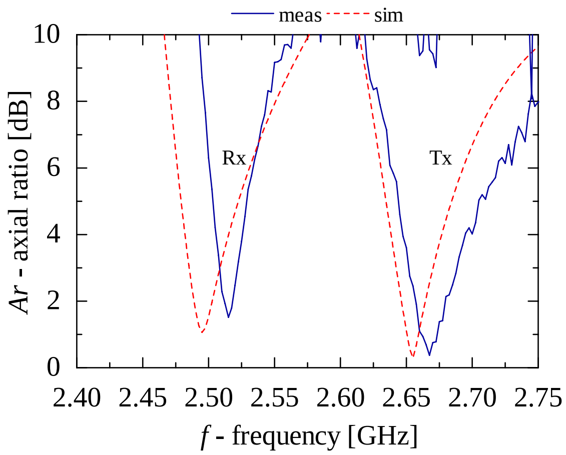


Fig. 10. Frequency characteristics of dual-band triangular patch antenna with truncated tip (Rx and Tx)

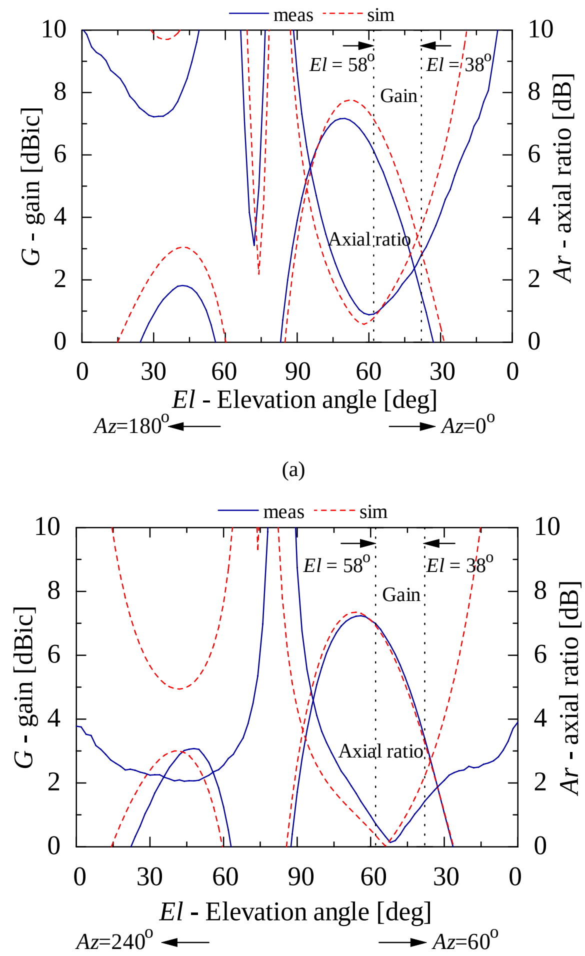


Fig. 11. Radiation characteristics in the elevation-cut plane
(a) (*Az* = 0° to *Az* = 180°) for Rx
(b) (*Az* = 60° to *Az* = 240°) for Tx

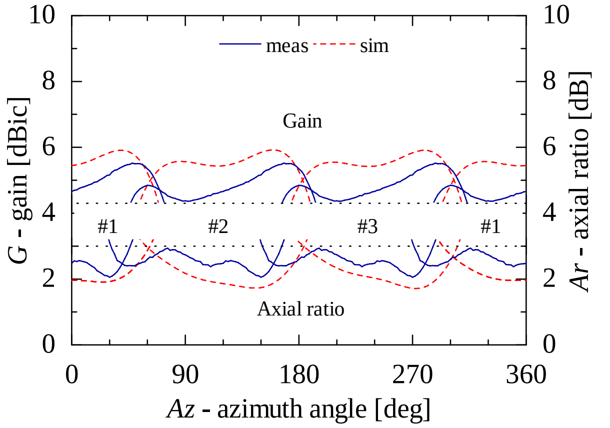
E. Beam switching technique

E.1 Beam generation

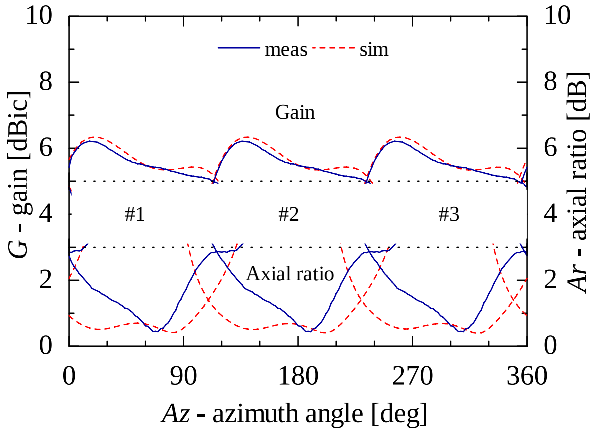
The beam of the antenna is generated by a mechanism that consists in switching OFF one of the radiating elements. By considering the mutual coupling between elements, their phase and distance, the beam direction can be varied. Theoretically, the generated beam is shifted of -90° in the conical-cut direction from the element that is switched OFF, in the case of a LHCP antenna. For example, when Rx element 1 (refers to Fig. 6) placed at *Az* = 90° is switched OFF, the beam is theoretically directed toward the azimuth angle *Az* = 0° (see Fig. 12, beam no. 1 shown with symbol #1 in the graph). The other two beams for reception can be generated in the same manner, switching each element OFF successively (Rx2 and Rx3 in Fig. 6 and each beam shown with symbol #2 and #3 in Fig. 12, respectively).

E.2 Verification of Beam Switching

Fig. 12 (a) and (b) describes the gain and the axial ratio for the measurement results compared to the simulation ones which were performed at an elevation angle *El* = 48° in the conical-cut direction for reception and transmission antenna, respectively. The gain is above 4.3 dBic over 120° of azimuth angle. Additionally, the 3-dB axial ratio satisfies the target in the whole azimuth



(a) Rx



(b) Tx

Fig. 12. Radiation characteristics in the conical-cut direction (*El* = 48°)

space. The difference of feed line distance from the center of the patch l_f = 6 mm (see Fig. 6) for reception antenna, rather than 9 mm of the most effective distance for a single element, should be investigated further and optimized. Fig. 12 (b) shows the conical-cut direction performances for the transmission antenna. The transmission antenna has a coverage more than 120° for the 5-dBic gain and the 3-dB axial ratio. In addition, a minimum gain that is 5.0 dBic and a maximum axial ratio 2.8 dB in the azimuth direction are obtained. Moreover, the measurement results tend to meet the simulation ones.

VI. Conclusion and Future Work

The Japan Aerospace Exploration Agency (JAXA) will launch ETS-VIII in 2006 to conduct orbital experiments on mobile satellite communications in the S-band. Up to now, a circularly polarized satellite-tracking dual-band equilateral triangular-patch array antenna for mobile satellite communications aimed at ETS-VIII applications has been developed. But, the complicated feeding line of the antenna is a drawback in terms of design and fabrication. In this paper, a novel model of antenna is proposed in order to simplify the feeding network and possibly miniaturize the antenna. The MoM was employed in the design of the antenna and measurement of the fabricated antenna was performed to confirm the simulation results. The antenna developed is simple feed, thin, small, and compact in design.

The design of the antenna allows a simple beam switching, able to generate beams that can cover the azimuth angles desired for such an antenna in both reception and transmission units. The measurement results show that the frequency characteristics and the 3-dB axial ratio coverage in the conical-cut direction of the fabricated antenna satisfy the specifications of ETS-VIII at an elevation angle *El* = 48°

In order to electronically control the generated beam of the antenna aimed at ETS-VIII satellite, a switching network is needed for the antenna to track the satellite in the whole azimuth space. Therefore, in the next step the design of switching circuit will be investigated and the possibility to integrate it with the antenna will be analyzed.

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