Dual-Band Singly-Fed Proximity-Coupled Tip-Truncated Triangular Patch Array for Land Vehicle Mobile System

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Abstract

This paper proposes a dual-band left-handed circularly polarized triangular-patch array that is developed for land vehicle mobile system aimed at mobile satellite communications. The array consists of six tip-truncated triangular patches, which the first three patches are used for reception and the second three patches are used for transmission purpose. Each of three-patches has a beam pattern that can be switched in three different 120°-coverage beam in azimuth-cut plane at a minimum targeted gain at a desired elevation angle. The targeted minimum gain of the array is 5 dBic, in order for data communications with a large geostationary satellite can be achieved. The array is able to operate in two different frequency bands i.e. 2.50 GHz band for reception (down-link) and 2.65 GHz band for transmission (up-link). The array is simulated using the Method of Moments-based software (Ansoft Maxwell), fabricated and measured to confirm the simulated results. The measurement results show that the 5dBic-gain and the 3dB-axial ratio of the reception elements cover all of 360° azimuth direction. In the case of transmission elements, 4.3dBic-gain and the 3dB-axial ratio can be obtained.

1. Introduction

The Japan Aerospace Exploration Agency (JAXA) has developed satellite mission technologies from the first Engineering Test Satellite-I (ETS-I) up to the ETS-VII. The latest version in its series is called ETS-VIII (Kiku-8), which is one of the largest geostationary S-band satellites in the world aimed to meet the future mobile satellite communications.

The ETS-VIII conducted an orbital experiment 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].

Hence, an antenna onboard on land vehicle mobile system aiming at ETS-VIII applications is required. The targeted minimum gain of the antenna is 5 dBi at a specified elevation angle (especially at $El = 48^\circ$) for data transfer up to few hundreds kbps. The antenna should be designed as thin, compact, small and simple as possible, because it will be mounted on bullet trains, ships or cars [2].

Various antennas onboard vehicle have been developed aimed at ETS-VIII [3]–[7]. One of those antennas [7] has been tested in outdoor environment 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) based Electromagnetic (EM) simulator (Zeland IE3D). However, the complicated feeding line of such printed antenna is considered to be difficult in terms of design and fabrication.

In this paper, a new simple feeding technique of the antenna is proposed in order to simplify the feeding network and possibly miniaturize the antenna. The antenna is composed of an equilateral-triangular microstrip patch, which the tip area of the patch is truncated to achieve circular polarization radiation. In published paper [8], the circular polarization can be achieved simply by cutting a correct sized section from the tip of an equilateral-triangular patch. Unlike [8], in our proposed feeding technique, a proximity-coupled feed is chosen rather than a coaxial probe excitation. Unlike coaxial probe feeding, in the case of microstrip antennas, proximity-coupled feeding technique provides the advantages of flexible impedance matching design, reduce the undesired radiation from discontinuities of the feed network, and allow an easy integration with circuit devices, in comparison to the coaxial probe feed [9–10].

In this paper, an equilateral-triangular array that is fed by proximity-coupled feeding is proposed to be used for land vehicle mobile systems, aimed at mobile satellite communication applications. The array is designed for dual band operation and numerically simulated by the MoM-based software (Ansoft Maxwell). To validate its performance, the array is then experimentally confirmed by the measurement in Anechoic chamber and compared with the simulated results.

2. Methods

**Specification and target.** Table 1 shows the specifications and targets required for an antenna onboard vehicle to be used for mobile satellite communication, especially in ETS-VIII applications. A gain more than 5 dBi (for a hundred kbps data rate) and an axial ratio less than 3 dB with a left-handed circular polarization (LHCP) should be considered in designing the antenna. The antenna’s operating frequencies are set to 2.5025 GHz and 2.6575 GHz for the reception and transmission element, respectively, as shown in Table 1. The direction of the ETS-VIII satellite seen from Japan territory has a certain elevation angle depending on the place. The beam of the designed antenna must provide the area from the northern to the southern part of Japan ($EI = 38^\circ$ to $EI = 58^\circ$) as shown in Figure 1.

**Array structure.** At the beginning of design, the authors design a single patch (element) at the reception operating frequency. Figure 2 shows the structure of a single patch

![Figure 1. Japan Map: Elevation Angle of Beam Direction](image-url)

**Table 1. Specifications and Objectives on the Antenna for Mobile Satellite Communications (ETS-VIII)**

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency bands</td>
<td>Elevation angle ($El$)</td>
</tr>
<tr>
<td>Transmission (Tx)</td>
<td>$48^\circ \pm 10^\circ$</td>
</tr>
<tr>
<td>Reception (Rx)</td>
<td>Azimuth angle ($Az$)</td>
</tr>
<tr>
<td></td>
<td>$0^\circ$ to $360^\circ$</td>
</tr>
<tr>
<td>Polarization</td>
<td>Minimum gain</td>
</tr>
<tr>
<td>Left-handed circular polarization</td>
<td>$5$ dBi</td>
</tr>
<tr>
<td></td>
<td>Maximum axial ratio</td>
</tr>
<tr>
<td></td>
<td>$3$ dB</td>
</tr>
<tr>
<td></td>
<td>Minimum isolation between elements</td>
</tr>
</tbody>
</table>

With a left-handed circular polarization (LHCP) should be considered in designing the antenna. The antenna’s operating frequencies are set to 2.5025 GHz and 2.6575 GHz for the reception and transmission element, respectively, as shown in Table 1. The direction of the ETS-VIII satellite seen from Japan territory has a certain elevation angle depending on the place. The beam of the designed antenna must provide the area from the northern to the southern part of Japan ($EI = 38^\circ$ to $EI = 58^\circ$) as shown in Figure 1.
The patch antenna is proximity-coupled fed with a microstrip line whose width, $w$ is 1.34 mm.

The microstrip feeding line is a 50Ω transmission line with additional step-width $\Delta w = 0.2$ mm at the end of line. 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, $\varepsilon_r = 2.17$ and a loss tangent, $\tan \delta = 0.0009$. The length of the stub, $l_e$ is 14 mm and the feed length between patch edge and step-width, $l_s$ is 5 mm. In addition, the feeding is attached to the transmission line by the length $l_f$.

A small triangular tip of surface area $\Delta S$ 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 Figure 2), which gives the $y$-directed resonant mode, a resonant frequency slightly larger than that of the $x$-directed resonant mode. Precisely, 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 about $l_f$ 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 triangular patch edges, $a = 47.48$ mm and $b = 52.48$ mm can be obtained.

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

Figure 5(a) and (b) depicts the relationship between gain ($G$) and axial ratio ($Ar$) at an azimuth angle (Az) 0° and 90°, respectively. The main beam is in the boresight direction with the gain of 6.1 dBi and the axial ratio of 0.2 dB. The gain beamwidth is more than 5 dBi, almost 30% (or 51°) both for the $xz$- and $yz$-plane direction. Moreover, the axial ratio less than 3 dB can cover 65% (or 117°) and 61% (or 109°) in the $xz$- and $yz$-plane, respectively.

By considering the previous results, the design of antenna is then configured in array structure in order to meet the specification and target of vehicle antenna aiming at ETS-VIII applications The array structure is discussed in the following paragraphs.
Figure 6 describes the structure of the array for dual-band operation. The array is composed of three triangular elements for reception and other three elements for transmission. Because each operating frequency is different for reception and transmission, so thus they have different sizes. In addition, in order to meet the specification and the target gain more than 5 dBic and the axial ratio less than 3 dB in the whole azimuth angles at elevation angle \( El = 48 \)°, the size of reception and transmission elements for array structure is slightly change compared with the single antenna as previously discussed.

As shown in Figure 6, the triangular patch element size is \( a = 47.64 \) mm and \( b = 52.64 \) mm for reception unit and \( a = 44.54 \) mm and \( b = 49.54 \) mm for transmission unit. The length of the inserted-feed into the dielectric, \( l_s \) is 14 mm and 13 mm for reception and transmission, respectively. In order to obtain good axial ratio performance in the azimuth angles, the length between the center of the array and the truncated tip of an element is set by \( c = 21 \) mm and \( c = 16 \) mm for reception and transmission, respectively.

Moreover, to get the gain more than 5 dBic and the axial ratio less than 3 dB in the azimuth angles, the feed line of the reception elements is set by \( l_s = 6 \) mm and 9 mm for the transmission one. The fabricated array is shown in Figure 7. An aluminum plate, whose thickness is 2 mm, is used to support the array gets robust structure, especially when it installed on vehicle’s roof.

3. Results and Discussion

S parameters. Figure 8 shows the scattering (\( S \)) parameters obtained from the simulated array design and the measurement for element no. #1 of the Rx and Tx (in Figure 6 notated as Rx1 and Tx1). The figure
shows that the measured results (both Rx and Tx) are shifted by about 1% to higher frequency, with respect to the target frequency, compared to the simulated results. It is considered that the measurement systems (i.e. cable, connectors, plastic screws, etc.) affect the characteristics of the array. However, the measured patterns are quite similar to the simulated ones. The isolation of the nearest elements (e.g. Rx1 to Tx1 and Rx1 to Tx3 in Figure 6), is higher than 20 dB although the frequency is shifted to the higher frequency. Indeed, these results are better than the previous developed array [7].

**Input impedance characteristics.** Figure 9 shows the input impedance characteristics of element no. #1 (notated as Rx1 and Tx1 in Figure 6). This graph also shows the measured input impedance is shifted to higher frequency from the target frequency by about 1%. However, the pattern tends to meet the simulated characteristics. The receiving element is inductive with a resistance about 46.63 $\Omega$ at the minimum $|S_{11}|$ frequency (2.54 GHz). On the other hand, the transmitting element is capacitive with a resistance about 45.27 $\Omega$ at the minimum $|S_{11}|$ frequency (2.6975 GHz).

**Frequency characteristics.** The antenna is numerically optimized by minimizing the axial ratio at elevation angle $\theta_{\text{el}} = 48^\circ$ based on the simulation at the targeted receive and transmit frequency as shown in Figure 10, in the case element no. #1 is off state. The figure depicts the frequency characteristics in case of $\theta_{\text{el}} = 48^\circ$ both for reception and transmission elements at the desired beam directions, i.e azimuth angle $\theta_\text{az} = 0^\circ$ and $\theta_\text{az} = 60^\circ$ for reception and transmission, respectively. The minimum measured axial ratio occurs at 2.5150 GHz with 1.5 dB for reception and 2.6675 GHz with 0.4 dB for transmission. As for the simulated one, the minimum axial ratio occurs at 2.4950 GHz with 1.1 dB for reception and at 2.6575 GHz with 0.3 dB for transmission. However, the pattern tendency between measured and simulated results is similar.

**Radiation pattern in the elevation plane.** Figure 11 (a) and (b) show the radiation pattern of the antenna in the elevation-cut plane when element no. #1 is off state, for reception and transmission mode. According to Figure 11 (a), it can be stated that the axial ratio of the reception element satisfies less than 3 dB (1.6 dB) in the
target elevation angle \( E_l = 48^\circ \), and yet at the lower elevation angle as well. The gain is 4.2 dBic rather than 5.4 dBic at \( E_l = 48^\circ \). Moreover, the gain characteristics tend to shift to higher elevation angle, on the other hand the axial ratio shifts to the lower elevation due to the finite ground plane effect in fabrication.

In addition, the measured peak gain is about 0.6 dB lower than the simulation at \( E_l = 68^\circ \) for reception. The measured axial ratio and the gain meet the targets less than 3 dB (i.e. 0.4 dB) and more than 5 dBic (5.5 dBic) at elevation angle \( E_l = 48^\circ \) for transmission unit, as shown in Figure 11 (b). The measured peak gain is about 0.12 dB lower than the simulation at \( E_l = 66^\circ \) for transmission.

**Beam switching mechanism. Beam generation.** The beam of the array is generated by a mechanism on switching OFF one of the radiating elements. By considering the mutual coupling among elements, their phase and distance, the beam direction can be varied.

![Image of radiation characteristics in the elevation-cut plane](image1.png)

*Figure 11. Radiation Characteristics in the Elevation-cut Plane: (a) (\( A_z = 0^\circ \) to \( A_z = 180^\circ \)) for Rx; (b) (\( A_z = 60^\circ \) to \( A_z = 240^\circ \)) for Tx*

Theoretically, the generated beam is shifted of \(-90^\circ\) in the azimuth-cut direction from the element that is switched OFF, in the case of a LHCp array. For example, when Rx element #1 (referring to Figure 6) placed at \( A_z = 90^\circ \) is switched OFF, the beam is theoretically directed toward the azimuth angle \( A_z = 0^\circ \) (see Figure 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 Figure 6 and each beam shown with symbol #2 and #3 in Figure 12, respectively).

**Verification of beam switching mechanism by measurement.** Figure 12 (a) and (b) describe the measured gain and the axial ratio characteristics compared with the simulated results, which is conducted at elevation angle \( E_l = 48^\circ \) in the azimuth-cut direction for reception and transmission antenna, respectively. The measured gain is above 4.3 dBic over 120° of azimuth angle. Additionally, the 3-dB axial ratio satisfies the target in the whole azimuth space. Hence, the difference of feed line distance from the center of the patch \( l_f = 6 \text{ mm} \) (in Figure 6) for reception array, rather than 9 mm of the
most effective distance for a single element, should be investigated further and optimized. Figure 12 (b) shows the azimuth-cut direction performances for the transmission array. The transmission array can cover more than 120° for the measured 5-dBi gain and the measured 3-dB axial ratio. Moreover, a minimum gain by 5.0 dBi and a maximum axial ratio by 2.8 dB in the azimuth direction are confirmed. The measured results tend to meet the simulated results.

4. Conclusions

The Japan Aerospace Exploration Agency (JAXA) has launched ETS-VIII to conduct orbital experiments on mobile satellite communications in the S-band operation. 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. However, the complicated feeding line of the antenna is a drawback in terms of design and fabrication. This paper has proposed a modified model of antenna in order to simplify the feeding network and possibly miniaturize the antenna. The MoM-based software is used for designing the array and measurement of the fabricated array is conducted to confirm the simulated results. The developed array is simple feed, thin, small, and compact in design.

The design of the array also allows a simple beam switching mechanism, able to generate beams that can cover the desired azimuth coverage both for reception and transmission elements. The measured results show that the frequency characteristics and the 3-dB axial ratio coverage in the azimuth-cut direction meet the specification of the antenna onboard vehicle at an elevation angle $E_l = 48°$ for ETS-VIII applications.

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References