A Phased Array Antenna Using Bi-Layered MSA with Slots Having Conical Radiation Pattern

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Abstract

A new type of bi-layered microstrip antenna (MSA) with conical radiation pattern for mobile satellite communications is proposed as an element antenna in this paper. The MSA consists of three patches with slots on bi-layered substrate and the feed is passing through the ground of the substrate. Firstly, the element antenna is designed as transmitting antennas for mobile station of satellite communications. The performance of the antenna is investigated by electromagnetic simulator. The designed element antenna has the conical radiation pattern in two orthogonal planes and the gain of main beam direction, ±40°, with 4 dBi. Using the element antenna, beam scanning characteristics of 16-element linear array antenna are investigated. The simulated results showed that the proposed bi-layered MSA would be promising for the mobile satellite communications antennas.

Keywords: *Microstrip antenna (MSA); Conical radiation pattern; Phased array antennas; Mobile satellite communications; Beam scanning characteristics*

1. Introduction

A phased array antenna (PAA) is very attractive for radar/communications applications. Nowadays, an active phased array antenna is considered to apply for mobile satellite communications or digital satellite TV receiving systems [1] - [5]. In these cases, an element antenna with hemispherical radiation pattern, such as dipole antenna with a ground plane [6], [7] or usual microstrip antenna (MSA) [8] is used for mobile antennas. However, the hemispherical radiation pattern of the element antenna is insufficient for satellite communications mobile station antenna. For example in Tokyo (Japan), the satellite is located in the direction of about 45° in elevation to a car. Similarly, in Europe, the satellite is located in the 30° in elevation. Thus the main beam direction of the element antenna should be pointed toward the satellite.

The authors have proposed a PAA composed of crossed dipole antenna with conical radiation pattern as an element antenna [6], [7]. The antenna consists of two half-wavelength dipole antennas and a reflector. The reflector is located at nearly half-wavelength above the antenna element. The PAA using the element antenna can scan the beam in all directions successfully. The height of the antenna, however, is inimical to install on a car roof as mobile station antennas.

To obtain the conical radiation pattern by low profile antennas, usually higher order mode MSA [9] is applied. However, the use of higher order mode brings almost twice-size in width as compared with the fundamental mode antenna. Commonly, to array element antennas for PAA, the array distance between each element is taken in approximately quarter wavelength [10]. Considering this, the higher mode MSA is not adequate to array antenna.

For this purpose, a phased array antenna of which the element antenna has a conic-like beam and is composed of MSA, has been also proposed in reference [8], [11]. However, this array antenna can scan beams in only H-plane, because the radiation pattern, which looks like a wing of a butterfly, can be obtained in H-plane only, and is not conical. In addition, the mutual coupling between the feeds is too high to scan beams widely, because the proposed antenna element has two feed points to the one antenna element. Thus the gain characteristics are poor.

To overcome this difficulty, in this paper we propose a new type of element antenna, consisting of MSA with three patches. Firstly, the element antenna is examined analytically by an electromagnetic field simulator, HFSS [12]. And then, based on the results, a 16-element linear array is examined, and the beam scanning characteristics are investigated to aim at the fundamental research of the radiation characteristics of PAA with a lot of number of elements.

The purpose of this paper is to provide one approach to mobile station antennas for satellite communication such as Ku-band VSAT (very small aperture terminal) system in Japan [13]. This system employs linear polarization antenna, which radiates vertically polarized wave for transmitting and horizontally polarized wave for receiving. The operational frequency range is from 12.5 GHz to 12.75 GHz for receiving band and from 14.1 GHz to 14.4 GHz for transmitting band. In this paper, we choose operational frequency band as same as VSAT transmitting band. Then, the centre frequency is 14.25 GHz.

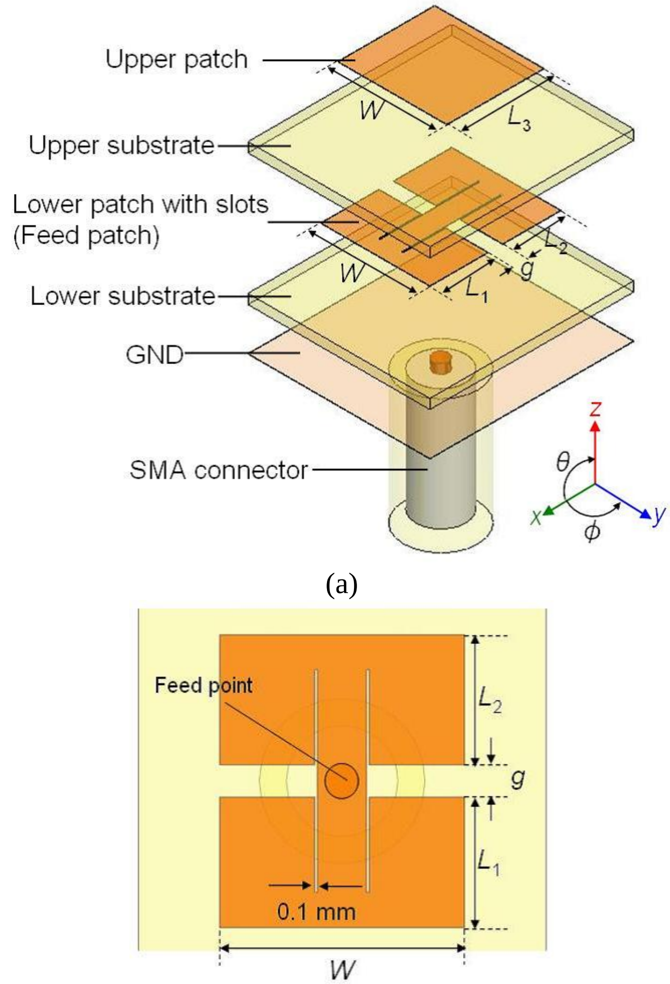
2. Bi-layered MSA

2.1. Structure

Figure 1(a) shows analysis model of 3-D structure of the proposed element antenna. The antenna consists of three microstrip square patches. One is a parasitic element on upper substrate, other two patches are radiation elements on lower substrate. The top view of the lower patch is shown in Figure 1(b). The two radiation patches are connected by a thick microstrip line, and the centre of the line is also connected to a coaxial cable to feed the radiation patches. Each radiation patch has two slot lines with the width of 0.1 mm along the thick microstrip line for improving the impedance matching. In this case, W is the width of three patches, L_1, L_2 are the length of the radiation element. A length, L_3, is of the parasitic element and g is the gap between the radiation patches. Then, the total length, L_1+L_2+g, is not equal to L_3. These element antennas are constructed on PPE substrates with ε_r=3.5 and thickness of 0.8 mm.

2.2. Characteristics

Under the condition of the operational frequency at 14.25 GHz, the parameters are decided as $L_1=L_2$=4.8 mm (0.228 λ), L_3=8.0 mm (0.38 λ), W=9.0 mm (0.4275 λ) and g=1.2 mm (0.057 λ). Those dimensions are optimized in the desired frequency band so as to realize the good return loss characteristics and also to realize the conical radiation pattern.



(b)

Figure 1. Structure of Proposed Antenna Element (a) 3-D Structure and (b) Top View of the Lower Patch

Figure 2 shows the 3-D radiation pattern of the element antenna. It is found that conically shaped radiation pattern is obtained in two orthogonal planes, that is X-Z and Y-Z planes. Figure 3(a) and (b) illustrate the radiation patterns in H- and E-planes of the element antenna, where H-plane is the plane of ϕ=0° and E-plane also ϕ=90° plane. It is found that we can realize the conical radiation pattern in each plane and no radiation for zenith direction. In this case, the antenna gain is almost 4 dBi at = ± 40°, and the cross polarization level is less than -36 dB.

As you may know, the gain of usual microstrip antenna, which has the peak radiation into zenith direction and has a uniform radiation pattern, is 7 dBi or more. As compared with the gain of this usual microstrip antenna, the gain of the proposed antenna seems to be low. However, once the proposed antenna is applied to PAA for satellite communication systems, the beam scanning gain characteristics of the proposed antenna are superior to that of usual one as in the reference [14].The antenna gain around ϕ plane at θ =40° is shown in Figure 4. From this figure, it can be observed that the blindness angle, which means the gain less than -3dB against the peak gain, appears. In

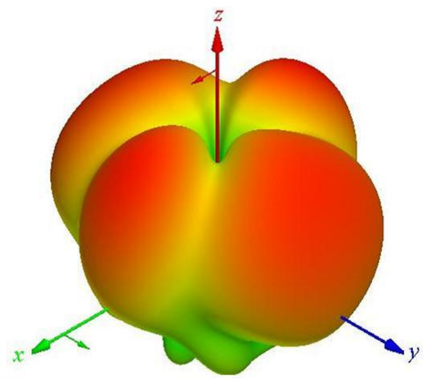


Figure 2. 3-D Radiation Pattern

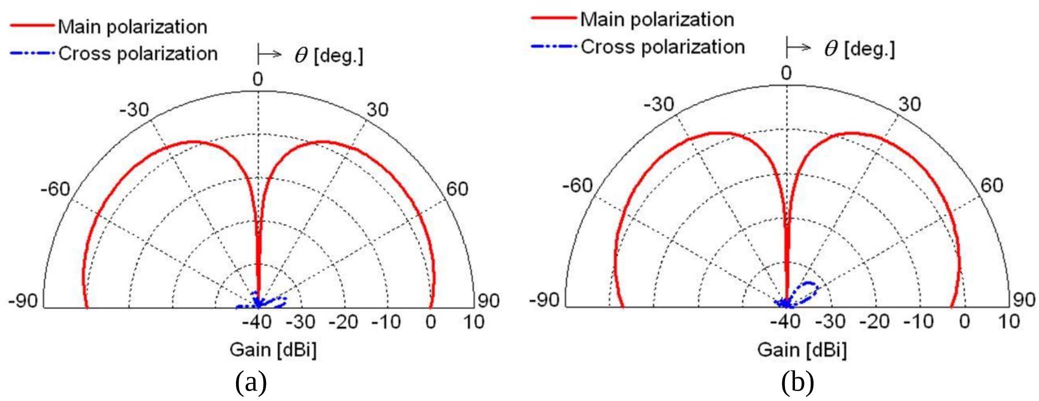


Fig. 3 Radiation Patterns of Element Antenna (a) H-plane, and (b) E-plane

PAA, when the main antenna beam points the blindness angle, it causes not only communication down but high grating lobes. One approach to avoid these problems is to arrange the antenna elements alternately with an inclination angle of 45°. To do so, the antenna gain fluctuation can be suppressed. Thus, it is expected antenna main beam can fully be scanned hemi-spherically, if the approach is applied.

Figure 5 shows the simulated result of the frequency response of the return loss characteristics of the antenna. In this figure, the first resonance frequency occurs at 14.1 GHz and the return loss is nearly -17 dB. Also, over the wide frequency range from 13.9 GHz to 15.7 GHz, that is over 12 % frequency range, the return loss less than -14 dB can be observed.

In VSAT system, for example, that is Ku-band satellite communications system, the both transmitting and receiving frequency band-width are only 2%. Moreover, total frequency band-width, including frequency gap between transmitting and receiving bands, is 14%. Considering this, the simulated results are well for the satellite communications systems.

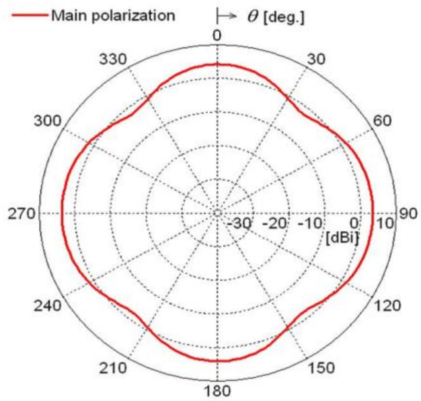


Figure 4. Radiation Patterns of Element Antenna (θ=45 deg.)

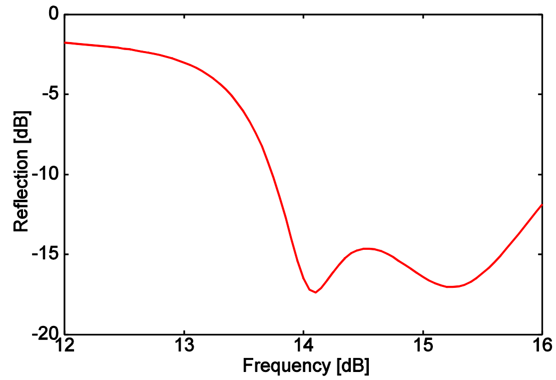


Figure 5. Reflection Characteristic of Element Antenna

2.3. Principle of Operation

Considering the proposed antenna structure as shown in Figure 1, one can imagine that the current flows in opposite direction on each patch. Therefore, it is expected that this structure brings us no radiation occurs to zenith direction theoretically, and that conical radiation patterns may be obtained.

Figure 6 shows current distributions at each time step on the upper parasitic and lower radiation patches in the operational frequency of 14.25 GHz. In this figure, (a) is the figures of a time of reference. The current flows X-axis strongly. The current distribution at each time step is depicted in the figure from (b) to (g).

From Figure 6(a), it can be seen that the current flows at the edge of each patch and that the current flows in the opposite direction with almost same amplitude each other. In addition, the current is induced on the surface of the parasitic element, particular at edge, so as to enhance the antenna gain. Thus, the radiated power from two patches is canceled in the zenith direction, and conical radiation pattern can be obtained in H-plane.

On the other hand, in Figure 6(b), current flows on the surface of the radiation patches, and its direction is opposite into Y-axis each other. In this case, the induced current on the parasitic element strongly flows at the edge. Therefore, also conical radiation pattern is achieved in E-plane. As a result, the antenna has conical radiation patterns in two orthogonal planes.

3. Beam Scanning Characteristics of 16-element Linear Array Antenna

Using the proposed element antenna, beam scanning characteristics of linear phased array antenna is examined. Figure 7 illustrates analysis model of the phased array antenna. In this case, Fig.7 (a) shows E-plane (X-axis plane) linear array, and (b) H-plane (Y-axis plane) linear array. The antenna is composed of 16-element linear array with the array distance of 0.65 λ. The parameters of the element antennas are the same as shown in Fig.1. The size of the antenna is 228 mm (10.8 λ) in length$\times$ 21.0 (1.0 λ) mm in width. The element antennas which has 0.51 $\lambda\times$0.42 λin size, is arranged with the array distance of 0.65 λ, therefore, the proposed antenna can completely be arranged as shown in Fig. 7.

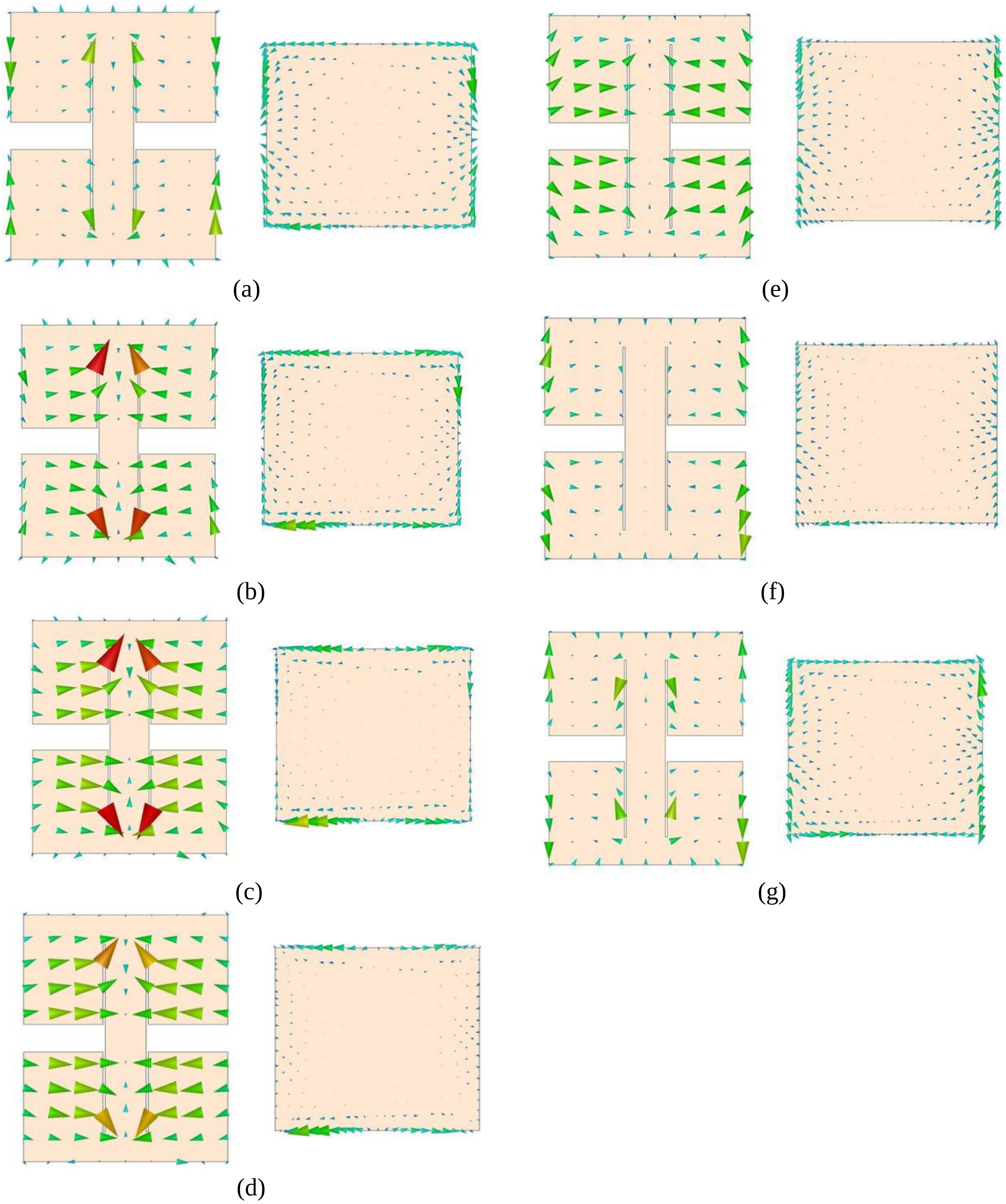
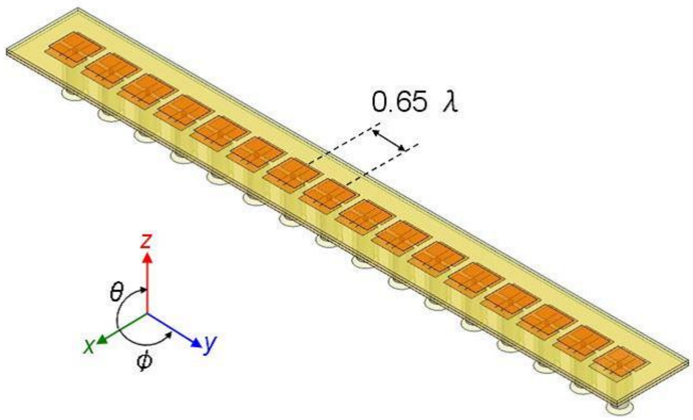
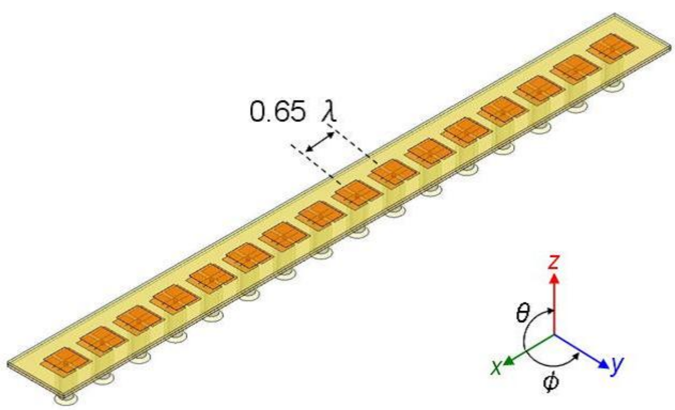


Fig. 6 Current Distribution on each Patch with Different Times

The purpose of the array is an examination for mobile station antennas of satellite communications. The antennas require the radiated power in side direction instead of in zenith direction. The proposed antenna element has a conical radiation pattern. Hence, the characteristics of the element antenna are desirable to scan the antenna beam to satellite directions, not zenith direction, for instance from 30° to 60 ° in elevation in Japan. Therefore, the characteristics are preferable to the antenna for satellite communications.

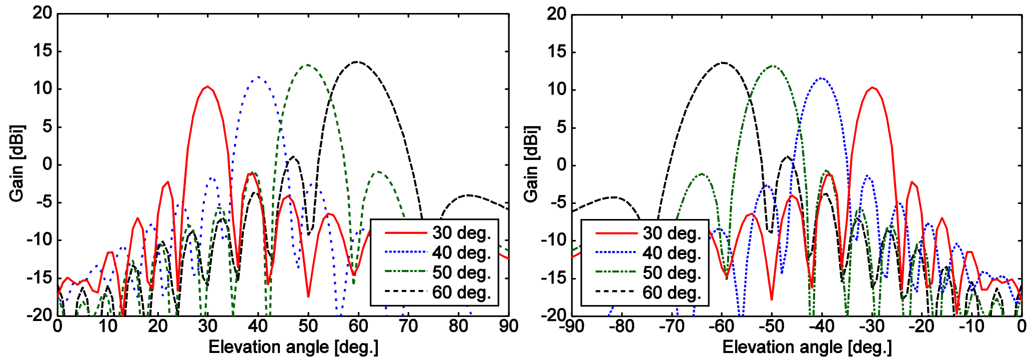


(a)



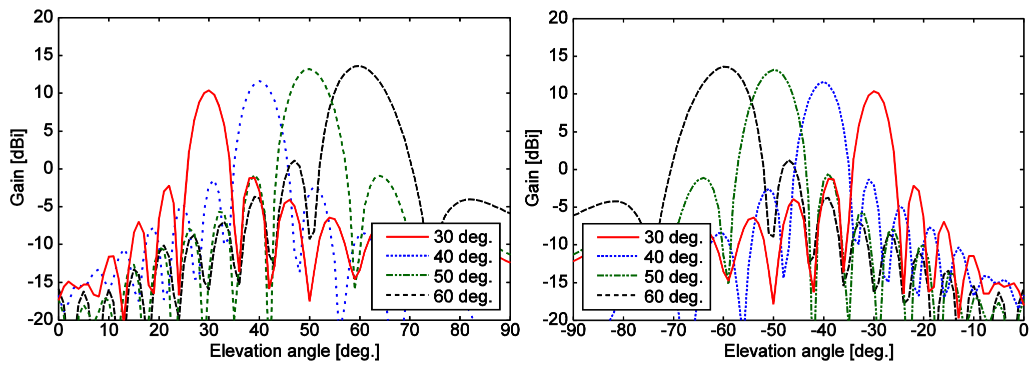
(b)

Figure 7. Analysis Model of 16-element Linear Array Antenna (a) E-plane and (b) H-plane.



(a) (b)

Figure 8 Beam Scanning Radiation Patterns in E-plane (a) Positive Scanning Angle (b) Negative Scanning Angle.



(a) (b)

Fig. 9 Beam Scanning Radiation Patterns in H-plane.(a) Positive Scanning Angle (b) Negative Scanning Angle

Figure 8 illustrates the beam scanning radiation patterns of the E-plane array antenna, and Figure 9 shows that of H-plane array antenna. In these cases, (a) is the radiation patterns when the beams scan toward positive elevation angle, that is +X or +Y direction, and (b) is toward negative angle. In all the cases, the antennas steer the beam from 20° to 50° in elevation. On scanning the beam, the maximum antenna gain of the main beam is over 14 dBi, and the minimum gain is 10 dBi, that is to say, the directivity is 14 dBi /10 dBi.

Figure 10 shows one example of the beam scanning radiation pattern (±180° elevation angle), when the main beam is directed toward +40°. From this figure, it is realized that even if the radiation pattern of the element antenna is conical, the main beam becomes only one lobe, when the beam is scanned. Thus, even if the proposed element antenna is applied to an array antenna with great number of element, the side lobe level and grating lobes can be expected to be suppressed greatly [13].

Figure 11 shows the computed results of the return loss characteristics on each input port of the array elements. Figure 10 (a) is in the case of E-plane linear array, and (b) H-plane. From these figures, the return loss characteristics are almost same as that of

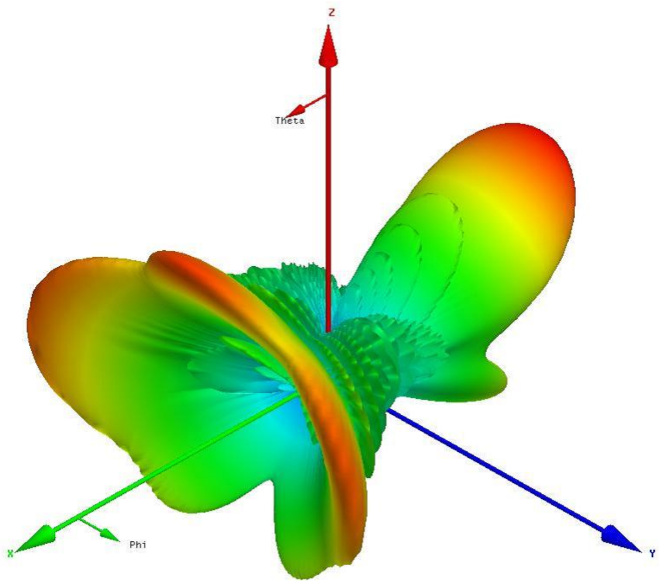


Figure 10. Beam Scanning Radiation Pattern

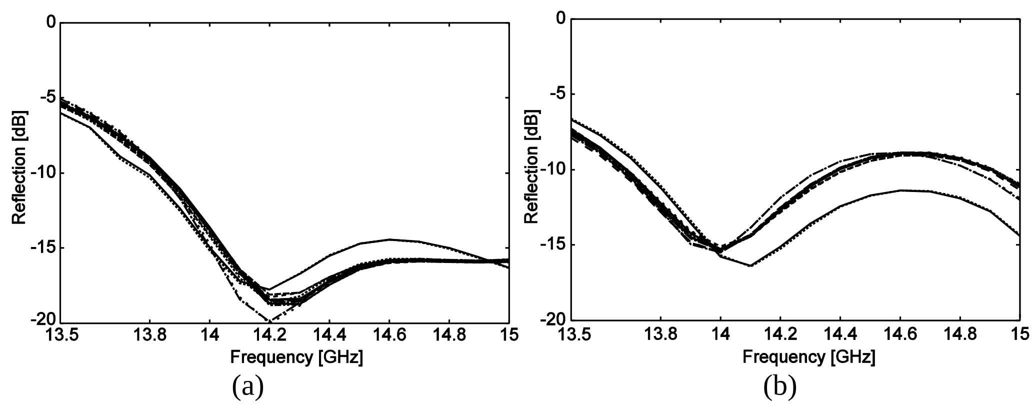


Figure 11. Return Loss Characteristics of Linear Array Antenna. (a) E-plane (b) H-plane

element antenna shown in Fig.5, and the return loss less than -14 dB is obtained over 12 % of the frequency range.

The directivity of 16-element linear array of isotropic elements is 12 dBi. Considering this, the proposed antenna gain of maximum 14 dBi seems to be lower than a usual array antenna. This may be caused by mutual coupling between the element antennas.

4. Conclusion

So far, various type PAA are proposed and considered. The element antennas having hemispherical radiation pattern are commonly used for the PAA. However, for mobile station antennas of mobile satellite communications, such a radiation pattern of element antenna is insufficient because the desired satellite for a car is out of zenith direction. As a countermeasure of this problem, PAA with element antenna having conical radiation pattern have proposed by using crossed dipole antenna. Further, with a view to being low profile, PAA consisting of MSA as an element antenna also has been proposed. However, the PAA is defective in beam scanning range.

To overcome these difficulties, a low profile bi-layered MSA is proposed and analytically examined as an element antenna for PAA of mobile stations for satellite communications. It is confirmed that the element antenna has conical shaped radiation pattern, which is suitable for the satellite communications antennas because no satellite is located in zenith direction. Then 16-element linear array consisting of the proposed element antenna is investigated, analytically aiming at fundamental research of radiation characteristics of PAA with a lot of number of antenna elements. It is found that this antenna is promising for the mobile satellite communications antennas.

References

[1] R. Baggen, S. Voccaro, and D. L. del Rio, "Design considerations for compact mobile Ku-Band satellite terminals," in *Proc. of 2nd European Conf. on Antennnas Propag*., **(2007)** November, pp.1-5.

[2] L. Zaid, G. Kossiavas, J. Y. Dauviganac, J. Cazajous, and A. Papiernik, "Dual-frequency and broad-band antennas with stacked quarter wavelength elements," *IEEE Trans. Antennas Propag*., vol. 47, no. 4, **(1999)** April, pp.654-660.

[3] Y. Kazama, A. Sugawara, T. Takano, and D. Redenamad, "Novel phased array antenna with elements of conical beam patterns," in *Proc. of IEEE Antennas Propag. Soc. Int. Symp*., **(2008)** July, pp.1-4.

[4] T. Takano, T. Imura, M. Okumura, and Y. Kazama, "A partially driven array antenna with parasitic elements of 60% in number," in *Proc. of 1st European Conf. on Antennas Propag*., **(2006)**, November, pp.1-6.

[5] A. Derneryd, "A theoritical investigation of the rectangular microstrip antenna element," *IEEE Trans. Antennas Propag.*, vol. 26, no. 4, **(1978)** July, pp.532-535.

[6] S. Hasegawa, T. Yasuzumi, O. Hashimoto, and Y. Kazama, "Polarization tracking phased array antenna with cross dipole antenna –Measured results-," in *Proc. of IEEE Antennas Propag. Soc. Int. Symp*., **(2010)** July, pp.1-4.

[7] S. Hasegawa, T. Yasuzumi, O. Hashimoto, and Y. Kazama, "A phased array antenna using cross dipole antenna for mobile satellite communications," in *Proc. of International Conf. on Electromagnetics in Advanced Applications*, **(2010)** September, pp.465-468.

[8] T. Yasuzumi, M. Kojima, O. Hashimoto, and Y. Kazama, "A study on phased array antenna using bi-layered MSA," in *Proc. of 3rd European Conf. on Antennas Propag*., **(2009)** March, pp.1285-1288.

[9] Y. Kazama, N. Morita, and S. Tokumaru, "Mobile communications higher-order-mode microstrip antennas for road vehicle communications," IEICE Trans. Commun., vol.J82-B, no.10, **(1999)** October, pp.1898-1904.

[10] C. A. Balanis, "ANTENNA THEORY," 3rd. Ed., Jon Wiley & Sons, Inc., New Jersey, **(2005)**.

[11] T. Yasuzumi, M. Nakayama, Y. Kazama, and O. Hashimoto, "A study on phased array antenna using MSA composed by 3-patches," in *Proc. of Loughborough Antennas Propag. Conf.*, **(2009)** November, pp.281-284.

[12] High Frequency Structure Simulator (HFSS) ver.11.1, Ansoft Corporation.

[13] Ordinance Regulating Radio Equipment, issued by Ministry of Internal Affairs and Communications in Japan.

[14] T.Suda, A. Sugawara, Y. Kazama, and T. Takano,"A phased array antenna with radiation pattern of element antenna being conical," IEICE Trans. on Commun., vol J93-B, no.9, **(2010)** September, pp. 1229-1238, (in Japanese).

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