

Radiation Properties of Multiband Circular MSA with Half-Ring Slots

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SUMMARY Novel multiband circular microstrip antennas (C-MSAs) with multiple half-ring slots are presented in this paper. Two antenna-feeding systems, i.e. an embedded L-probe beneath the patch and a coplanar circular arc-shaped probe (T-probe), are used to feed the C-MSA with multiple half-ring slots. The embedded L-probe is used to excite the C-MSA with a double-layer dielectric substrate due to its tremendous performance to provide a wideband impedance matching. The coplanar T-probe is proposed to realize an excellent multiband C-MSA in a single-layer structure. The C-MSA with four half-ring slots fed by the embedded L-probe exhibits satisfactory radiation characteristics. Five frequencies with broadside radiation patterns and gains of at least 5.0 dBi are obtained. It is also confirmed by simulation that resonant frequency and gain can be easily controlled to meet the desired frequency requirements. Moreover, the C-MSA with three half-ring slots fed by the coplanar T-probe presents satisfactory performance over the four observed frequencies with good return losses (-10 dB reference). Broadside radiation patterns with acceptable cross-polarization level and gains in the range of 3.0–7.0 dBi are obtained. Couplings between the C-MSA and the coplanar T-probe have an important contribution to obtain good return losses. It can be controlled by adjusting the distance between them and the arc angle of the coplanar T-probe appropriately. Experiments of both types of antenna were conducted to verify the simulation results and good agreements are confirmed. Due to the performances, these two C-MSAs are considered to be an effective model as a multiband planar antenna.

key words: circular, coplanar, microstrip, multiband, L-probe, slot

1. Introduction

There has been a remarkable growth in demand for wireless communication systems to cover multiple applications using a single antenna. The development of multiband terminals or multimode multiband terminals covering various combinations of the second-generation terminals may expand the mass-market [1], [2]. Indeed, the extensive researches on multiband antenna have been scrutinized to satisfy such requirement. To author's knowledge, the investigation of fractal structure as multiband antenna was firstly reported by Puente et al. [3], [4]. It was reported on the experimental and numerical results of a planar antenna with Sierpinski gasket geometry. It was demonstrated that self-similarity properties of the fractal structures could be used to perform as a multiband antenna. On the other hand, Song et al. [2] investigated on the utilization of a circular ring monopole antenna, which was a non-fractal structure, to obtain multiband properties as reported in [3], [4]. However, the radiation patterns of those

reported structures seem to be deteriorated as the frequency increases.

The modified Sierpinski gasket microstrip antenna (SG-MSA) fed by the embedded L-probe with a double-layer dielectric substrate was reported by Tada et al. as a multiband planar antenna [5]. Three operating frequencies with excellent radiation properties were achieved. If one would design the antenna to operate at more than three frequencies, however, it was difficult for this model to realize good radiation patterns. This is due to the complexity of Sierpinski gasket structure. There are some methods to overcome this complicated structure have been reported [6], [7]. The first method is creating multiple current paths on the microstrip antenna by inserting multiple slots. Inverted V-shaped slots were employed on the rhombic microstrip antenna fed by the embedded L-probe [6]. It was revealed that the mixture of the inverted V-shaped slots and the embedded L-shaped probe makes a good impedance matching over a wideband frequency range. The other method is removing some portion of Sierpinski gasket structure without sacrificing the multiband performances [7]. An equilateral triangular MSA (ET-MSA) with folded slots reported in [7] was proposed to improve the degraded antenna gain appeared in [6]. However, gains of the ET-MSA with folded slots seem to vary among the observed frequencies.

On the other hand, a circular microstrip antenna fed by a coaxial probe with one or two open-ring slots was proposed as a dual or broadband frequency antenna [8]. Two adjacent resonant modes with very similar radiation characteristics are excited at near the dominant modes and then enhance the impedance bandwidth. A compact circular microstrip antenna with an offset circular slot fed by a coaxial probe printed on a single-layer substrate was reported for a dual-frequency operation [9]. The other reports on single-layer dual frequency operation were a slot-loaded rectangular patch [10], a slot-loaded bow-tie MSA [11], and a rectangular MSA with a pair of bent slots [12]. However, it seems that it is difficult for the single-layer microstrip antennas to obtain more than three operating frequencies due to the use of a coaxial probe (direct feed). A rhombic MSA with inverted V-shaped slots fed by a coplanar L-probe with a V-shaped stub was reported [13]. Multiband performance of four operating frequencies in a single-layer structure with 2.4 mm thickness was obtained. However, the 3rd and 4th modes of this antenna seem to have a problem in cross-polarization level.

For these reasons, a circular microstrip antenna (C-

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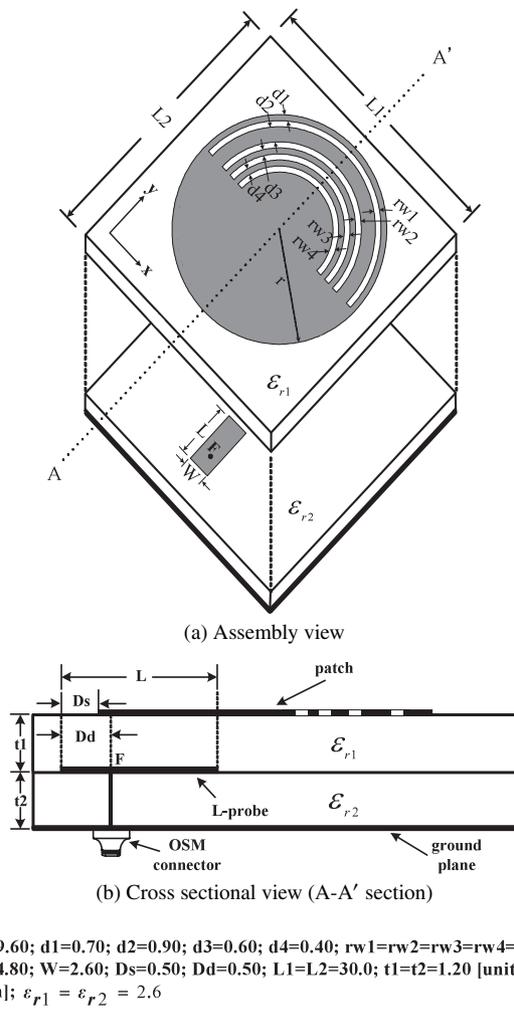


Fig. 1 Assembly and sectional view of C-MSA with four half-ring slots fed by an embedded L-probe.

MSA) with multiple half-ring slots is proposed in this paper. Two types of feeding system, i.e. an embedded L-probe beneath the patch and a coplanar T-probe, are used for the C-MSA. The embedded L-probe constructed in a double-layer substrate is well known as a wideband impedance matching scheme to MSAs [14]–[17] while the coplanar T-probe is introduced to feed the C-MSA in a single-layer structure. The basic configurations of these antenna systems are described in detail in Fig. 1 and Fig. 8, respectively. Geometry shown in Fig. 1 is composed of a double-layer PTFE substrate; circular patch is printed on the top substrate and the L-probe is printed on the bottom one while that of in Fig. 8 is composed of a single-layer substrate.

The main contributions of this paper are described as follows. First, the C-MSA with four half-ring slots fed by the embedded L-probe is proposed to realize a multiband microstrip antenna with stable gain characteristics and is confirmed to obtain higher gains compared with those of the ET-MSAs with folded slots, as reported in the previous study [7]. Second, the C-MSA with three half-ring slots fed

by the coplanar T-probe is proposed to realize a single-layer multiband planar antenna. Excellent radiation properties of more than three operating frequencies are confirmed. Structure of this paper is as follows. The working mechanism of the C-MSA with four half-ring slots fed by the embedded L-probe is discussed with observation of the surface current distributions obtained by IE3D™ [18] in Sect. 2. Section 3 discusses upon important parametric studies for design of the C-MSA with half-ring slots fed by the embedded L-probe i.e. effects of width of slot (rw) and distance between slots (d). Design method of the embedded L-probe is also discussed in this section. In order to verify the simulated results, experiments were conducted and the results are presented in Sect. 4. Section 5 describes the C-MSA with three half-ring slots fed by the coplanar T-probe and an excellent multiband performance is presented. Section 6 concludes the paper.

2. Working Mechanism of Circular MSA (C-MSA) with Four Half-Ring Slots Fed by an Embedded L-Probe

A working mechanism of the proposed C-MSA with four half-ring slots fed by the embedded L-probe is described in this section by the observation of current distributions. The current distributions are obtained by IE3D based on method of moment [18]. The parameters used in the simulation are $r = 9.6$ mm, $d1 = 0.7$ mm, $d2 = 0.9$ mm, $d3 = 0.6$ mm, $d4 = 0.4$ mm, $rw1 = rw2 = rw3 = rw4 = 0.4$ mm, $L = 4.8$ mm, $W = 2.6$ mm, $Ds = 0.5$ mm, and $Dd = 0.5$ mm, as shown in Fig. 1. The multiple half-ring slots are installed in the C-MSA in order to create multiple current paths on the patch. Thus, the number of operating frequency can be controlled as expected by this method. In case of one half-ring slot, a new mode (2nd mode) is excited in addition to the 1st mode (dominant mode). Correspondingly, in case of two, three, and four half-ring slots, the numbers of new modes are increased to be two, three, and four, respectively. Consequently, the number of operating frequency is equivalent to the number of slot + 1.

Figure 2 shows current distributions of the C-MSA with four half-ring slots. The magnitude of surface current density for the test antenna is shown in the figure as light and shade colors. As shown in Fig. 2, the current of the 1st mode starts to flow from the bottom portion of the circular patch, due to the existence of the embedded L-probe, and it terminates at the center of upper portion of the circular patch. Moreover, the currents of the other modes terminate at the center of each half-ring slot. It is also interesting to note that the length of current path is corresponding to the resonant frequency. Thus, the frequency of each mode is controlled by the position of the corresponding slot on the patch. As the current path length becomes longer, the resonant frequency can be shifted toward lower frequency region.

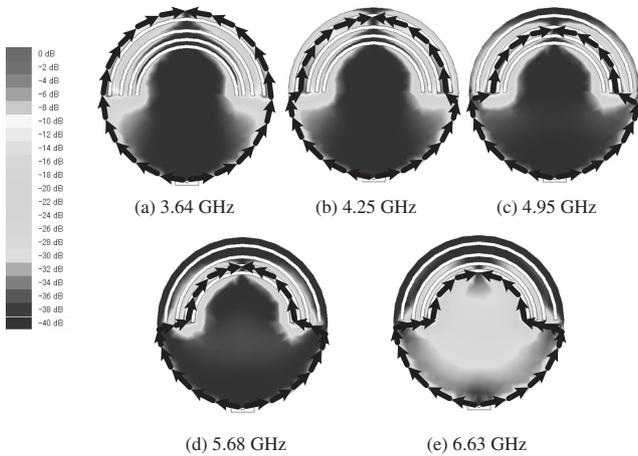


Fig. 2 Current distributions of the proposed antenna obtained by IE3D (a) 1st mode, (b) 2nd mode, (c) 3rd mode, (d) 4th mode, and (e) 5th mode, respectively.

3. Design Consideration of Circular MSA (C-MSA) with Four Half-Ring Slots Fed by an Embedded L-Probe

One of the most important points of view of design of a multiband antenna is tuning the resonant frequency at the desired one. For some applications, it is important for the antenna design to have the feature of miniaturization. However, in case of miniaturizing the antenna electrically, it leads to degradation of the gain. For these reasons, this section focuses upon designing the C-MSA with multiple half-ring slots fed by the embedded L-probe. The effects of some parameters including the slot width (rw) and distance between slots (d) on the resonant frequency and gain of the C-MSA are investigated by IE3D simulator [18]. The term of resonant frequency is defined as the frequency where the return loss becomes minimum. In addition, design method of the embedded L-probe is also presented in this section.

3.1 Effect of Slot Width (rw)

Figure 3 shows the effect of slot width of the half-ring slot ($rw1$) on the resonant frequency and gain of the C-MSA, where only one half-ring slot is assumed on the C-MSA and $d1$ is set to remain constant at 0.5 mm. The dimensions in the figure caption are used in the simulation. It is observed by simulation that the resonant frequency of the 2nd mode is much dependent on the parameter $rw1$ rather than that of the 1st mode, as shown in Fig. 3. This is because the current of the 1st mode flows along the edge of the circular patch while the current path length of the 2nd mode becomes shorter as the $rw1$ is increased. Gain of the 1st mode shows an increasing trend while that of the 2nd mode shows a constant tendency as the increment of $rw1$, as shown in Fig. 3. Thus, one could control the resonant frequency of the 2nd mode without significantly affecting the antenna gain in the range of $rw1$ between 0.5 and 3.0 mm. The increasing tendency of

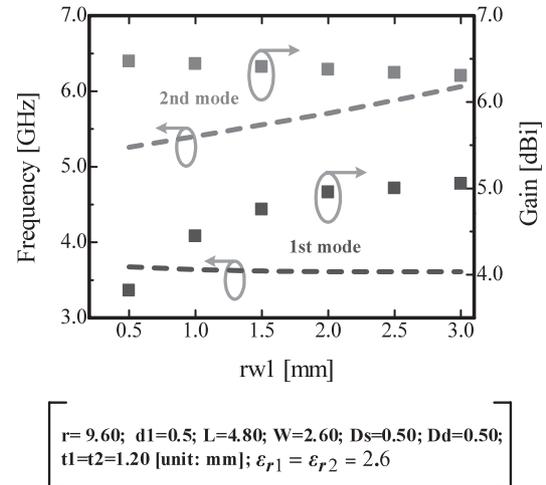


Fig. 3 Resonant frequency and gain against slot width of C-MSA in case of one half-ring slot ($rw1$) fed by an embedded L-probe (sim.).

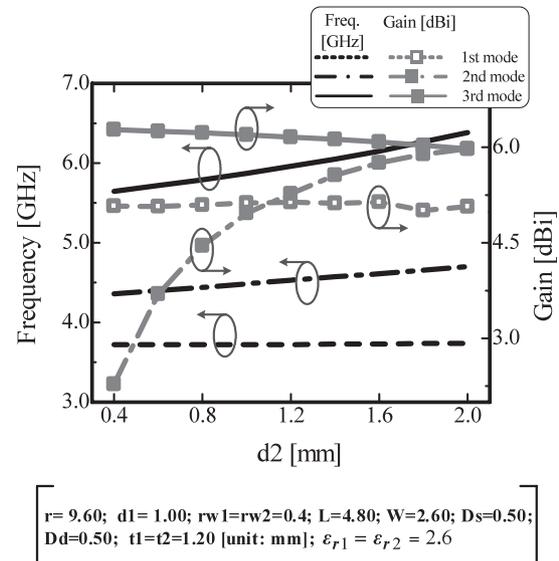


Fig. 4 Resonant frequency and gain against distance between the 1st and 2nd slots of C-MSA in case of two half-ring slots ($d2$) fed by an embedded L-probe (sim.).

the 1st mode gain in the range between 0.5 mm and 2.0 mm is due to the Q-factor of the antenna, which means that one could obtain stable gain by selecting a substrate with low loss $\tan \delta$ of the dielectric material and/or high conductivity of the surface conductor.

3.2 Effect of Distance between Slots (d)

Figure 4 describes the resonant frequency and gain of the C-MSA as a function of $d2$, where two half-ring slots are assumed and width of the half-ring slot (rw) is remained at 0.4 mm. The dimensions in the figure caption are used in the simulation. As shown in Fig. 4, tweaking the slot position, i.e. varying the value of $d2$, is one of the methods to control the resonant frequency. In other words, changing

the distance of $d2$ also varies the length of the current path. The resonant frequency of the 1st and 2nd modes show a constant tendency while that of the 3rd mode is increased as the distance of $d2$ becomes larger, as shown in Fig. 4. The reason why the 3rd mode behaves as shown in Fig. 4 is due to alteration of the current path length. Gain of the C-MSA can also be observed in Fig. 4. Gain of the 1st and 3rd modes show a constant tendency while that of the 2nd mode shows an increasing trend, which is due to the Q-factor of the antenna, as the increment of $d2$ in the range between 0.4 and 2.0 mm.

3.3 Design Method of an Embedded L-Probe for the Test Antenna

This sub-section presents a design method of the embedded L-probe, where four half-ring slots are assumed on the circular patch. Frequency dependences of two parameters, i.e. L and W , on the return losses in designing the embedded L-probe are presented in Fig. A·1. The return losses are improved for all the five modes as the length L of the embedded L-probe becomes longer in the range between 1.2 mm and 4.8 mm. Moreover, similar tendency is also observed when width of the embedded L-probe W is increased in the range between 0.6 mm and 2.6 mm. It is also confirmed that the return loss of less than -10 dB can be obtained for all the five modes by widening the width W in the observation range. Thus, the dimension of the embedded L-probe for the test antenna are then determined as $L = 4.8$ mm and $W = 2.6$ mm, as shown in Fig. A·1.

4. Experimental Results of Circular MSA (C-MSA) with Four Half-Ring Slots Fed by an Embedded L-Probe

A prototype antenna with optimum parameters to realize stable high gain over the observed frequencies was manufactured and measured in our laboratory. The structure of the antenna is shown in Fig. 1, where the dimensions presented in the figure caption are used in both simulation and experiment. Those parameters are $r = 9.6$ mm, $d1 = 0.7$ mm, $d2 = 0.9$ mm, $d3 = 0.6$ mm, $d4 = 0.4$ mm, $rw1 = rw2 = rw3 = rw4 = 0.4$ mm, $L = 4.8$ mm, $W = 2.6$ mm, $Ds = 0.5$ mm, and $Dd = 0.5$ mm. The antenna is composed of a double-layer PTFE substrate with relative permittivity $\epsilon_r = 2.6$, $\tan \delta = 0.0018$, and 1.2 mm thickness. The circular patch with four half-ring slots is printed on the top layer while the L-probe is printed on the bottom one. The ground plane ($L1$ and $L2$) with size of 30×30 mm is used in both simulation and experiment, which makes the antenna compact and easy to be installed in the small-required area. Five resonant frequencies, in which four of them are regarded as the new modes, are examined at 3.64, 4.25, 4.95, 5.68, and 6.63 GHz, respectively, as shown in Fig. 5. The measured results agree well with the results obtained by IE3D. The return loss performance of a typical circular MSA without slot is also presented in Fig. 5 for comparison.

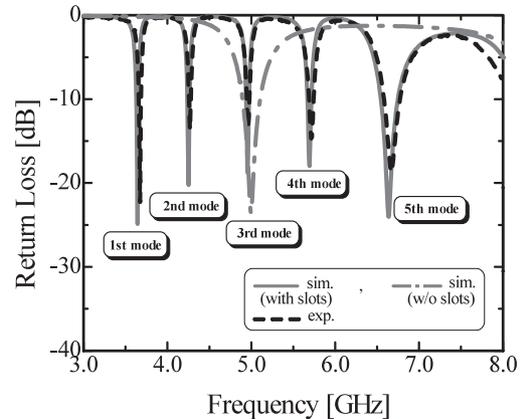


Fig. 5 Return loss characteristics of C-MSA with four half-ring slots and C-MSA without half-ring slots fed by an embedded L-probe.

As shown in Fig. 5, satisfactory matching is obtained at the five observed frequencies. This is due to the utilization of the embedded L-probe. Furthermore, the existence of the half-ring slot succeeds in shifting the frequency of the 1st mode to lower region, while the circular patch without the half-ring slots is designed to operate at 5.0 GHz. Hence, miniaturization of the antenna is obtained by the use of half-ring slots. Figure 6 presents the measured and simulated radiation patterns of the antenna for the five observed modes. It is revealed that good agreements between simulated and measured results are obtained in the co-polarization of both E- and H-planes. Cross-polarization levels are around -20 dB for the 1st, 2nd, 3rd, and 4th modes, respectively, while it is slightly increased for the 5th mode due to the effect of higher modes. In addition, gains of 5.0–6.0 dBi with 0.5 dBi deviations between measured and simulated data are observed, as shown in Fig. 7. These gains are relatively higher than those of reported in the previous study [7]. The deviation is due to the error in the fabrication such as the misalignment of coaxial connector and very small air gap between the top and bottom layers. The mixture of such errors could lead to the deviation of gain at higher frequencies.

5. Circular Microstrip Antenna (C-MSA) with Three Half-Ring Slots Fed by a Coplanar T-Probe

Excellent radiation characteristics of the circular microstrip antenna (C-MSA) with four half-ring slots fed by the embedded L-probe has been presented. The gain of such C-MSA exceeds 5.0 dBi over the entire observed frequencies, which satisfies the requirement of constant gain for multi-band and electrically miniaturized antennas. However, the previous C-MSA with four half-ring slots is composed of a double-layer substrate. In order to make a compact C-MSA, which can be installed in a single-layer substrate, a coplanar T-probe is proposed as an alternative feed method for the C-MSA. It is confirmed by simulation that gap distance between the C-MSA and the coplanar T-probe (G_s) as well as arc angle of the coplanar T-probe (θ) play an important role

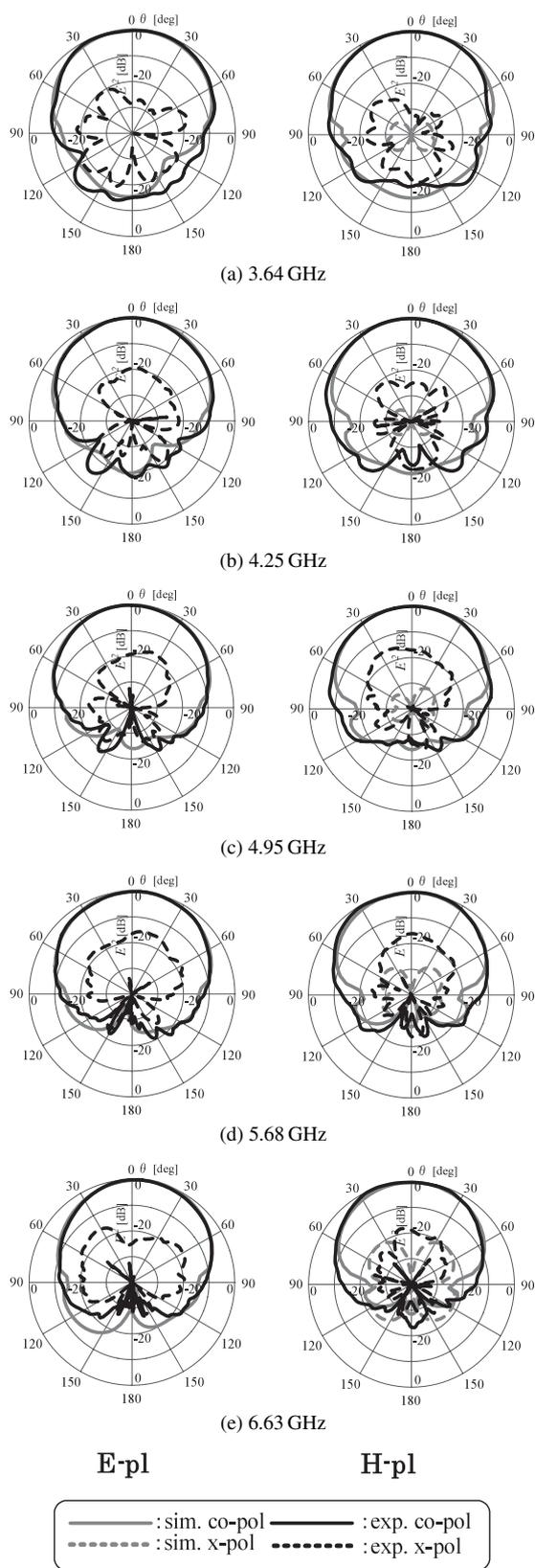


Fig. 6 Radiation patterns of C-MSA with four half-ring slots fed by an embedded L-probe.

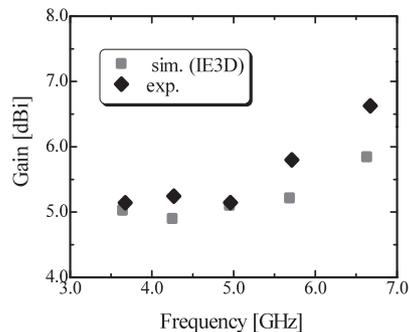


Fig. 7 Gains of C-MSA with four half-ring slots fed by an embedded L-probe.

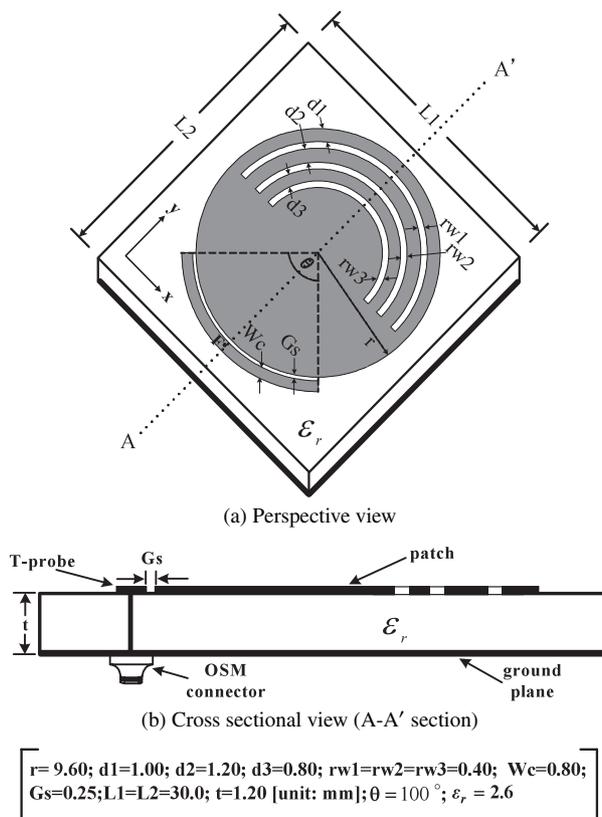


Fig. 8 Structure of C-MSA with three half-ring slots fed by a coplanar T-probe and its dimension.

in controlling the coupling. Thus, the number of excited frequencies with good return losses (reference of -10 dB) also depends on these parameters. It is expected that excellent multiband performance of more than three operating frequencies can be obtained by this scheme.

Structure of the proposed antenna is depicted in Fig. 8. Three half-ring slots are installed in the C-MSA to obtain four operating frequencies. The number of slots used in the test antenna with a single-layer substrate is different from the previous test antenna with a double-layer substrate. The reason is to attain a high gain for each resonant frequency in the range of 3.0 to 7.0 GHz. As already explained in Sect. 3, adjusting the appropriate slot distance (d) can be used to

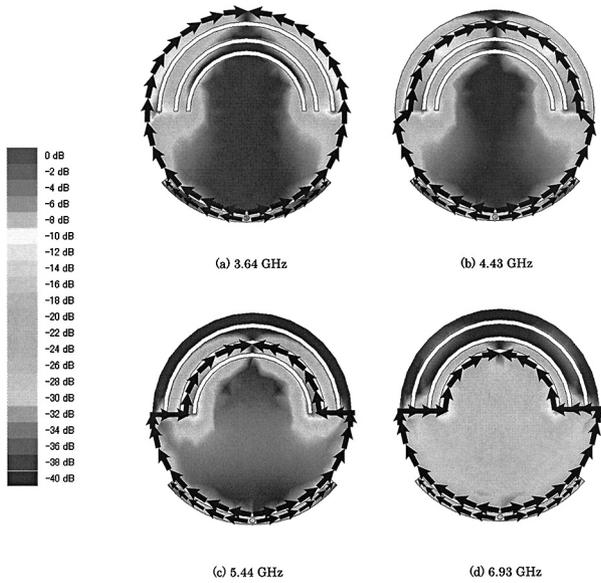


Fig. 9 Current distributions of C-MSA with three half-ring slots fed by a coplanar T-probe, (a) 1st mode, (b) 2nd mode, (c) 3rd mode, (d) 4th mode, respectively.

control the antenna gain as well as the resonant frequency. By considering the parameter d , the C-MSA with three half-ring slots can obtain the purpose. The gap distance is set as narrow as possible at 0.25 mm, which makes the four operating frequencies with good return losses.

Figure 9 shows current distributions of the proposed antenna. Currents on the C-MSA itself are found to have the same characteristics as that of the C-MSA fed by the embedded L-probe i.e. currents are terminated at the center of C-MSA for the dominant mode and the center of each slot for the new-excited modes, respectively, as shown in Fig. 9. Furthermore, the gap G_s and arc angle of the coplanar T-probe θ are the important parameters in this design. In this paper, four operating frequencies are obtained with return loss of less than -10 dB. Figure 10 shows the variation of minimum return loss of the modes as a parameter of the gap G_s . The other parameters listed in the figure caption are used in the simulation. It is found that the impedance matching of the entire observed frequencies is degraded as the gap G_s becomes wider. The value of G_s in the range between 0.1 mm and 0.25 mm are suitable to obtain the return loss of less than -10 dB, as shown in Fig. 10. $G_s = 0.25$ mm is selected as the optimum value in this design for easiness in fabrication.

Another important parameter in this design is the arc angle of the coplanar T-probe. Figure 11 illustrates the effect of θ on the minimum return loss of C-MSA with three half-ring slots. It is shown in the figure that $\theta = 100^\circ$ is the most appropriate value to obtain return losses of less than -10 dB. Figure 12 describes return loss characteristics of the proposed antenna, where the dimensions listed in the caption of Fig. 8 are used in both simulation and experiment. Four resonant frequencies are observed at 3.64, 4.43, 5.44, and 6.93 GHz, respectively. It is confirmed that experimen-

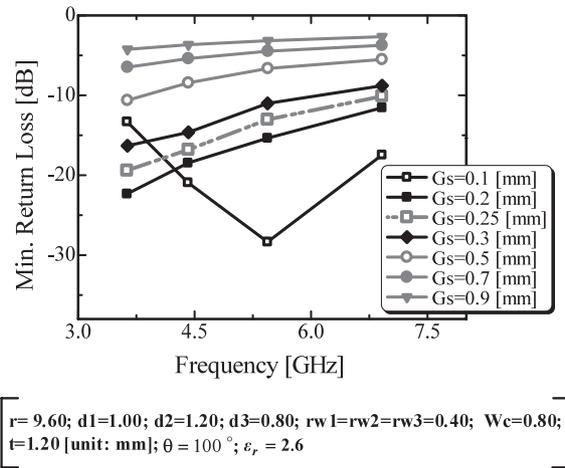


Fig. 10 Minimum return loss value of C-MSA with three half-ring slots fed by a coplanar T-probe as a function of small gap G_s (sim.).

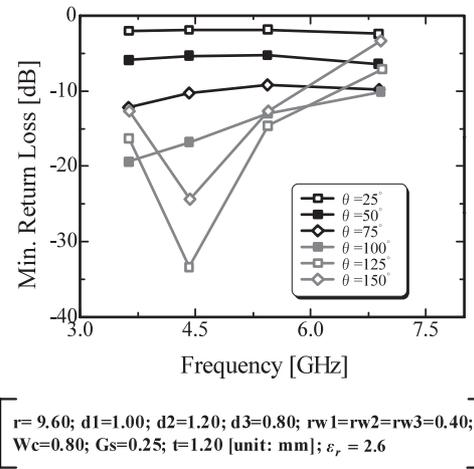


Fig. 11 Minimum return loss value of C-MSA with three half-ring slots fed by a coplanar T-probe as a function of θ (sim.).

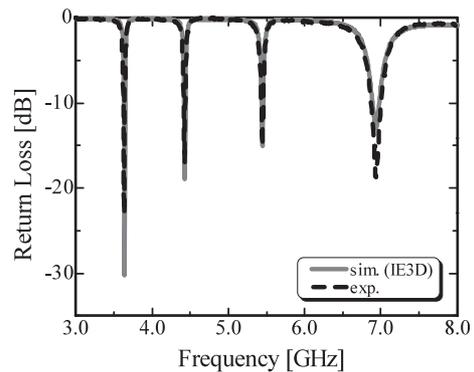


Fig. 12 Return loss characteristics of C-MSA with three half-ring slots fed by a coplanar T-probe.

tal results agree well to those obtained by IE3D simulator. It is also verified by experiment that all the observed modes have minimum return loss of less than -10 dB. Figure 13 presents radiation patterns of the proposed antenna. Broad-

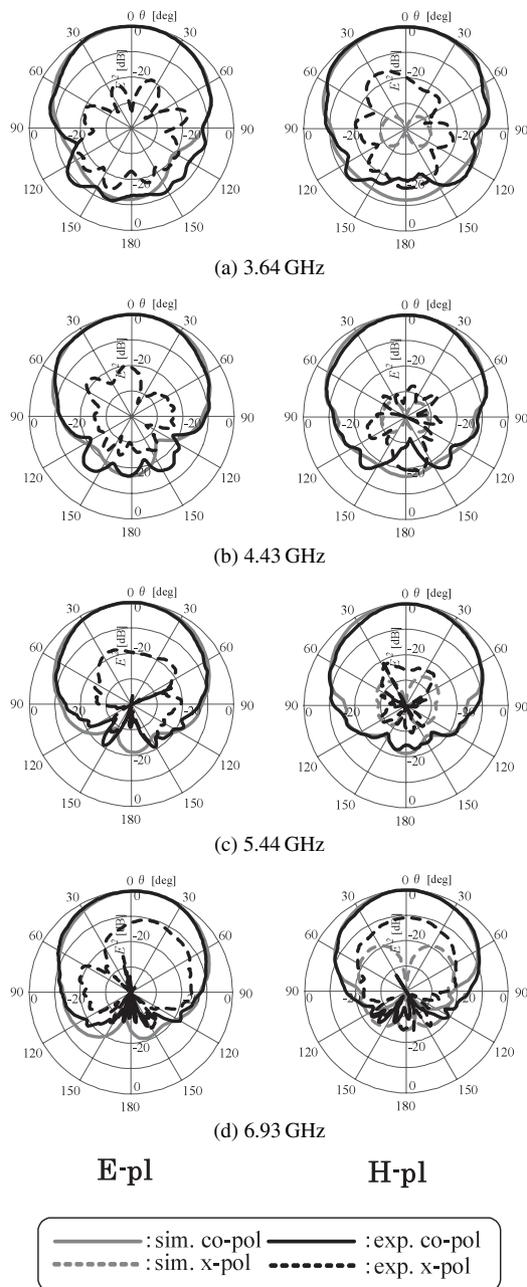


Fig. 13 Radiation patterns of C-MSA with three half-ring slots fed by a coplanar T-probe.

side radiation patterns are obtained at each of the four observed frequencies for both E- and H- planes. The cross polarization level is observed to have the value of around -20 dB for the 1st, 2nd, and 3rd modes while it is slightly increased for the 4th mode. Good agreements between the simulated and measured results are verified for the co-polarization in both the E- and H-planes, respectively. Gains of 2.97 dBi, 4.22 dBi, 5.33 dBi, and 7.25 dBi are also measured for the 1st, 2nd, 3rd and 4th mode, respectively, with at most 0.3 dBi deviations in comparison to the simulation.

6. Conclusions

Novel circular microstrip antennas (C-MSAs) with multiple half-ring slots have been demonstrated to operate as a multi-band antenna. Two antenna-feeding techniques are used to feed the C-MSA with multiple half-ring slots i.e. an embedded L-probe and a coplanar T-probe. The C-MSA with four half-ring slots fed by the embedded L-probe exhibits satisfactory performance over the five operating frequencies with broadside radiation patterns and stable high gain of more than 5.0 dBi. It is found by the simulation that the resonant frequency and gain of this antenna can be easily controlled to meet some specific applications by tuning the slot width and distance between the slots. Moreover, the C-MSA with three half-ring slots fed by the coplanar T-probe demonstrates satisfactory performance of four operating frequencies, broadside radiation patterns with low cross-polarization, and gain in the range of 3.0 to 7.0 dBi. The gap between the C-MSA and the coplanar T-probe and the arc angle of the coplanar T-probe play an important role in controlling impedance matching between the feeder and the C-MSA. Due to the outstanding performances, these two proposed antennas are suitable for multiband planar antennas.

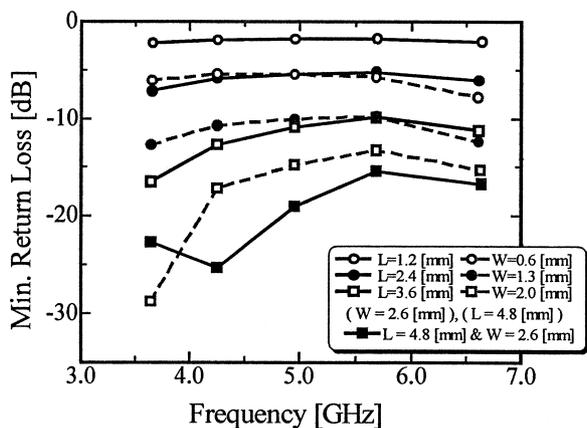
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Appendix: Determination of Dimensions of the L-Probe for the Test Antenna

Figure A-1 presents the return losses of the C-MSA with four half-ring slots fed by the embedded L-probe as a function of parameters L and W , where dimensions listed in the caption are used in the simulation. IE3D was used to optimize the antenna performance. The return loss values of less than -10 dB for the five resonant frequencies can be obtained as the length of the embedded L-probe L becomes longer in the range of 1.2 mm to 4.8 mm and width W is remained at 2.6 mm. In addition, width of the embedded L-probe W can be adjusted to meet the values of less than -10 dB. The return losses are improved by increasing W in the range of 0.6 mm to 2.6 mm with the L is remained at 4.8 mm, as shown in Fig. A-1. For this reason, $L = 4.8$ mm and $W = 2.6$ mm are used in the both simulation and experiment.



$$\left[\begin{array}{l} r=9.60; d1=0.70; d2=0.90; d3=0.60; d4=0.40; rw1=rw2=rw3=rw4=0.40; \\ Ds=0.50; Dd=0.50; t1=t2=1.20 \text{ (unit: mm)}; \epsilon_{r1} = \epsilon_{r2} = 2.6 \end{array} \right]$$

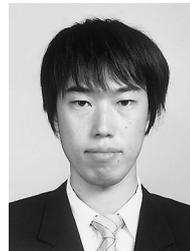
Fig. A-1 Return loss characteristics of the test C-MSA with four half-ring slots fed by an embedded L-probe as parameters of L and W (sim.).



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