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ORTHOGONAL CIRCULAR POLARIZATION DETECTION PATCH ARRAY ANTENNA USING DOUBLE-BALANCED RF MULTIPLIER

M. A. Hossain*, Y. Ushijima, E. Nishiyama, I. Toyoda, and M. Aikawa

Department of Electrical and Electronic Engineering, Saga University,
1 Honjo-machi, Saga-shi, Saga 840-8502, Japan

Abstract—In this paper, a technical concept and design of circular polarization detection patch array antenna using a double-balanced RF multiplier is proposed. The microwave integration technology is effectively employed to realize the proposed array antenna. The double-balanced RF multiplier is integrated with an orthogonal planar array antenna. The array antenna which consists of 12 patch elements and the RF multiplier is realized by embedding four zero bias Schottky barrier diodes on a slot-ring. The Both-sided MIC technology is successfully employed to realize the array antenna. The array antenna is realized in a very simple and compact structure as all the antenna elements, feeding circuit and the RF multiplier are integrated on both sides of a dielectric substrate. The ability of the proposed array antenna to detect the orthogonal circular polarization (LHCP and RHCP) is successfully confirmed by the experimental investigation.

1. INTRODUCTION

Along with the rapid progressing of the ubiquitous society, the planar antenna technology is emerging and being widely used in various sectors of wireless communications systems due to their low profile, light weight, low cost and easy to be integrated with semiconductor devices and ICs [1, 2]. In the past decades, the planar antenna technologies had an enormous development in reconfigurable antenna, compact and broadband antennas, high gain antenna and so on to meet the up-growing requirements of the wireless applications. Moreover,

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* Corresponding author: Md. Azad Hossain (azad@ceng.ec.saga-u.ac.jp).

the evolution of the planar antenna technology keeps emerging. In addition, the integrated antennas receive a great deal of attention because they can reduce the size, weight and cost of many transmitting and receiving modules [3].

The circular polarization planar antenna has been widely used in modern wireless communication systems and sensor systems such as radar, navigation, satellite and mobile systems etc. [4]. The distinct advantages of the circular polarization antenna over the linear polarization antennas are the flexibility of the transmitter and the receiver orientations [5–7]. Numerous researches have been done in microstrip planar antennas with circular polarizations and switchable circular polarizations by integrating active components [8]. Furthermore, new concepts and technologies keep emerging in the wireless communications systems. The polarization detection of the received signal for many applications such as polarimetric sensors, MIMO, satellite remote sensing, ITS, radars etc. is becoming important in recent years. In a word, if the detection of the propagation characteristics and the wireless environment of the received points are possible, the above application modules and systems will be advanced and expanded much more effectively. For instance, polarization detection antenna can be a vital element for the realization of the anti-jamming technology of radar systems [9]. Moreover, the proposed array antenna can be used as a very simple receiver for the short range wireless data transmission co-operating with a circular polarization switchable array antenna. The authors have reported an orthogonally polarized microstrip array antenna for linear polarization discrimination [10], where ±45° linear polarizations of the received signal can be detected by the receiving array antenna. So far from the knowledge of the authors, there have been no reports regarding the circular polarization detection planar array antenna yet.

In this paper, a novel circular polarization detection patch array antenna is proposed. The Both-sided MIC [11–13] technology is effectively employed to realize the circular polarization detection planar antenna. The proposed antenna is an orthogonally polarized array antenna which is realized in mirror symmetrically fed structure [13]. The mirror symmetric structure allows the array antenna to receive the RF signals in a balanced form. Therefore, a double-balanced star multiplier circuit proposed by Robert B. Mouw [14] is effectively integrated at the center of the proposed array antenna.

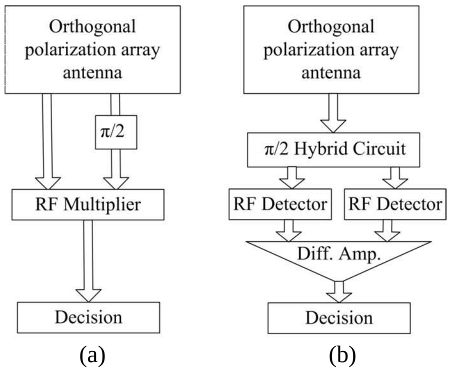


Figure 1. Concept of orthogonal circular polarization detection.

2. THE CONCEPT OF CIRCULAR POLARIZATION DETECTION ARRAY ANTENNA

There are two kinds of orthogonal polarizations, that is, linear (vertical, horizontal) and circular (LHCP, RHCP) polarizations. To realize the orthogonal polarization detection, the receiving antenna should be the orthogonally polarized antenna. The block diagram of Figures 1(a) and (b) are the basic concepts to realize the circular polarization detection. For the concept of Figure 1(a), a RF multiplier circuit is integrated with the orthogonally polarized planar array antenna. The received RF signals from the array antenna are processed i.e., multiplied at the RF multiplier. From the polarity of the multiplier output voltage, the polarization of the received signal can be detected. In the other option of Figure 1(b), a $\pi/2$ hybrid circuit is integrated with the orthogonal polarization array antenna. The output of the hybrid circuit is connected with the RF amplitude detectors followed by a differential amplifier. In this case, from the polarity of the output voltage of the differential amplifier, the amplitude of the received signal can be detected. Comparing to the concepts of Figures 1(a) and (b), the concept (a) is simpler and compact as it can be realized by using only the passive elements in a single layer systems. On the other hand, concept (b) needs to be in multilayer systems or air bridges to make crossovers. The authors have reported a dual polarized array antenna [15] using the $\pi/2$ hybrid circuit which can be used to realize the concept (b) in single layer system. In that case, air bridges should be used to realize the array antenna. In addition, absence of differential amplifier eliminates the power consumption for concept (a). Therefore, in this paper, the concept of Figure 1(a) is used to realize the circular polarization detection array antenna.

It is well known that the circular polarized RF signal consist of both the vertical (V_V) and the horizontal (V_H) linear polarized RF signals with $\pm\pi/2$ phase difference. The orthogonal linear RF signal voltage can be written as follows:

$$V_V = a\sin\omega t \tag{1}$$

$$V_H = a\sin(\omega t \pm \pi/2) \tag{2}$$

where, a is the amplitude of the signal, ω the angular velocity, and the $\pm$ stands for the advanced/delayed signal i.e., RHCP/LHCP. If these signals are input into the RF multiplier, the output will be zero in principle, because they are orthogonal to each other. If $\pm\pi/4$ phase shift can be done for these signals, circular polarization detection is possible. Then the RF signals will be as follows:

$$V_V = a\sin(\omega t - \pi/4) \tag{3}$$

$$V_H = a\sin(\omega t \pm \pi/2 + \pi/4) \tag{4}$$

The output voltage V_{mul} of RF multiplier is as follows

$$\begin{aligned} V_{mul} \propto V_H \times V_V &= a\sin(\omega t - \pi/4) \times a\sin(\omega t \pm \pi/2 + \pi/4) \\ &= -a^2/2\cos(\pi/2 \pm \pi/2) + a^2/2\cos(2\omega t \pm \pi/2) \end{aligned} \tag{5}$$

For the low frequency signal, the output voltage V_{mul} can be simply expressed as follows for considering $\pm\pi/2$ as $+\pi/2$ and $-\pi/2$ respectively:

$$\begin{aligned} = \ & -a^2/2 \quad \text{[for LHCP]}, \\ & +a^2/2 \quad \text{[for RHCP]} \end{aligned} \tag{6}$$

Therefore, the output of the RF multiplier is either positive or negative which corresponds to LHCP or RHCP. Needless to say, as for formula (5), $V_{mul.} \propto -(V_H) \times (V_V)$ is also possible, which depends on the diode arrangement of the RF multiplier. Figure 2 shows the possible array antenna structures for realizing the circular polarization detection array antenna. The RF multiplier is located at the center of the array antenna and the received RF signals from the patch elements are input to the RF multiplier via the feed circuit. As the array antenna is a mirror symmetric structure, the RF signals from the four microstrip lines are input to the RF multiplier in a balanced form. In order to realize a circular polarization detection array antenna, $\pi/2$ phase difference is done between the microstrip lines parallel to the Y axis and the X axis. For more precise explanation, $\pi/4$ advance and delay is made for the RF signals in the feed circuit. As shown in Figure 2, the microstrip line parallel to Y axis is increased by $\lambda_g/8$

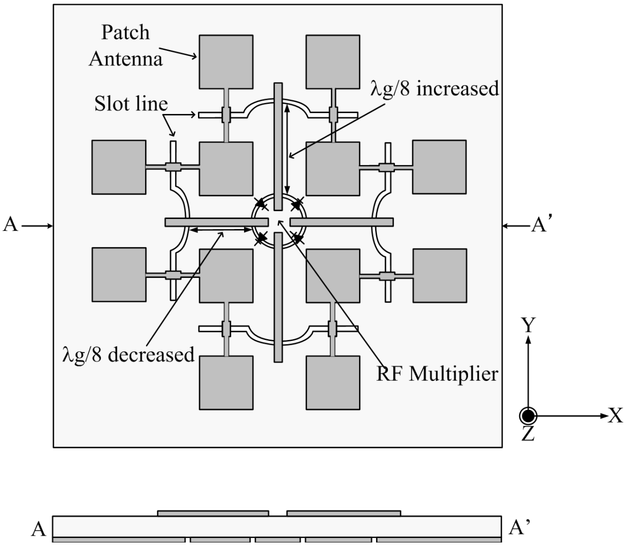
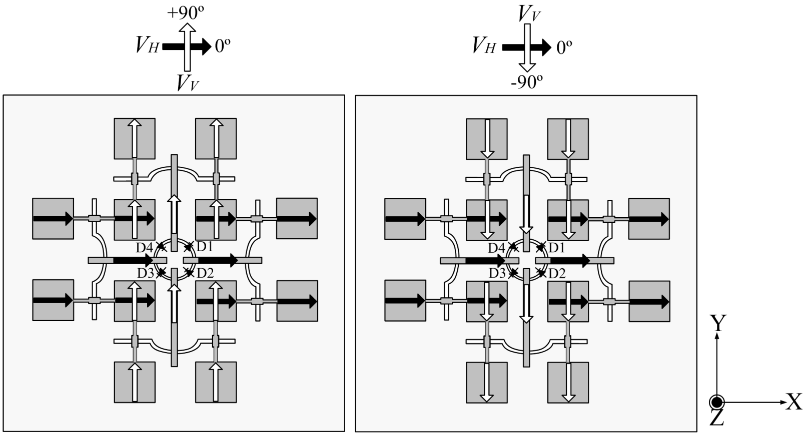


Figure 2. Circular polarization detection array antenna.

by bending the slotline outward, and the microstrip line parallel to X axis is decreased by $\lambda_g/8$ by bending the slotline inward to the center of the array antenna.

3. THE BASIC BEHAVIOR OF THE CIRCULAR POLARIZATION DETECTION ARRAY ANTENNA

Figures 3 (a) and (b) show the basic behavior of the array antenna for the detection of LHCP and RHCP. The white arrows represent the vertical component (V_V) and the black arrows represent the horizontal component (V_H). As the proposed array antenna is mirror symmetric, the vertical component (V_V) and the horizontal component (V_H) of the received signals are fed to the RF multiplier in a balanced form. When the array antenna receives LHCP, the vertical (V_V) and horizontal (V_H) components are as of Figure 3(a), where the vertical (V_V) component is $\pi/2$ advanced from the horizontal (V_H) component. The longer microstrip lines parallel to Y axis delays the vertical (V_V) component by $\pi/4$, and the shorter microstrip lines advances the horizontal (V_H) component by $\pi/4$. Therefore, the vertical (V_V) and horizontal (V_H) components input to the RF multiplier are in phase. For RHCP, the vertical (V_V) component is $\pi/2$ delayed from the horizontal (V_H) component. As of the same principle for LHCP, the longer microstrip lines parallel to Y axis delays the vertical (V_V) component by $\pi/4$, and



(a) (b)

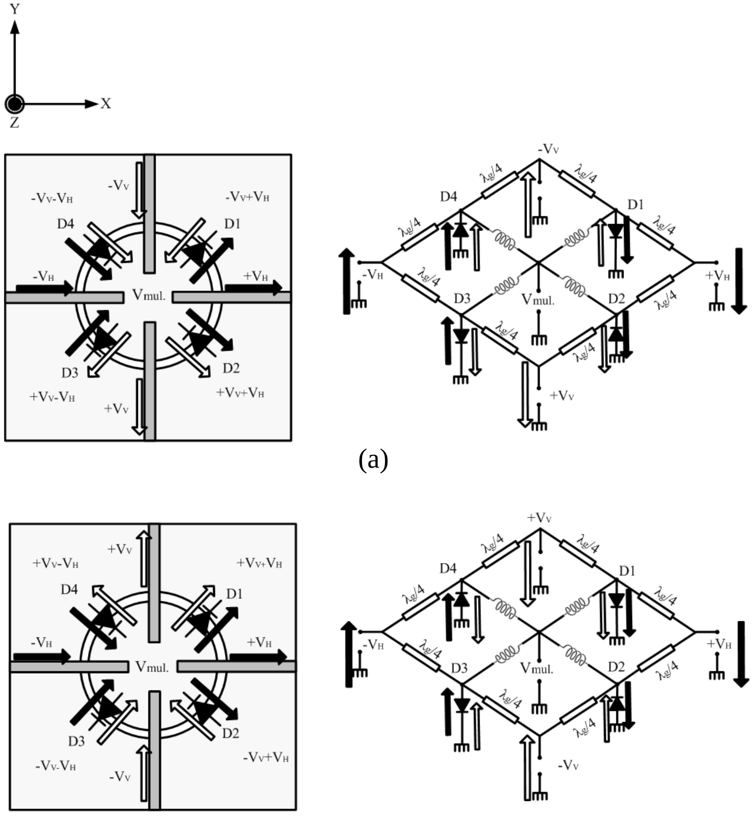
Figure 3. Basic behavior of the array antenna. (a) LHCP. (b) RHCP.

the shorter microstrip lines advances the horizontal (V_H) component by $\pi/4$. Therefore, for RHCP, the vertical (V_V) and horizontal (V_H) components input to the RF multiplier are out of phase. Therefore, using the proposed array antenna and RF multiplier described in the following section, the circular polarization detection can be achieved very easily.

4. THE RF MULTIPLIER

The structure and the equivalent circuit of the RF multiplier which is a kind of double-balanced modulators are shown in Figure 4. This RF multiplier is realized by the use of the Both-sided MIC technology using a slot-ring and four diodes. The circumference of the slot-ring is taken to be two wavelength i.e., $2\lambda_g$ at the design frequency of the array antenna. Four diodes are loaded on the slot-ring at every $\lambda_g/2$ interval. The diodes D1 and D3 are directed outward on the slot-ring and the D2 and D4 are directed inward on the slot-ring. Four microstrip lines are arranged on the slot-ring multiplier from the array antenna elements. As the array antenna is orthogonally polarized and mirror symmetric, the vertical and horizontal components ($\pm V_V$, $\pm V_H$) of the received RF signals are input to the slot-ring multiplier as shown in Figure 4.

The basic principle of the RF multiplier is explained here using Figures 4(a) and (b). For LHCP and RHCP, the vertical and horizontal components ($+V_V$, $-V_V$, $+V_H$, $-V_H$) are multiplied by the RF



(a)

(b)

Figure 4. Basic behavior of the slot-ring multiplier. (a) LHCP. (b) RHCP.

multiplier. The polarity and algebraic sum of the corresponding RF components at each diode are also shown in Figures 4(a) and (b). For LHCP, both V_V and V_H are of same polarity and are fed to D1 and D3. In addition, for D2 and D4, the polarity of V_V and V_H are out of phase. Therefore, the RF voltages at diodes D1, D2, D3 and D4 are $(-V_V+V_H)$, $(+V_V+V_H)$, $(+V_V-V_H)$ and $(-V_V-V_H)$, respectively, for LHCP. In the same way, they are $(+V_V+V_H)$, $(-V_V+V_H)$, $(-V_V-V_H)$ and $(-V_V+V_H)$ for RHCP. The multiplier output is obtained at the center conductor of the slot-ring. The RF voltages at each diode and the 2nd order nonlinear output are summarized in the Table 1. As shown in the Table, for LHCP, the output voltage $V_{mul.}$ is negative value, and for RHCP, the output voltage $V_{mul.}$ is positive value.

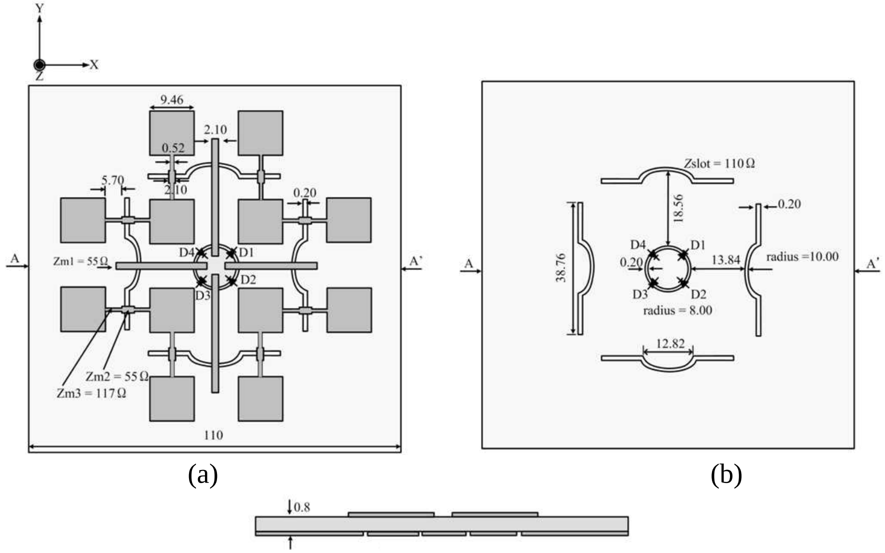
Table 1. RF Voltage fed to each diode and the output voltage $V_{mul.}$ of the RF Multiplier.

Diode	LHCP	RHCP
	RF voltage $\rightarrow$ The 2nd order nonlinear output	RF voltage $\rightarrow$ The 2nd order nonlinear output
D1	$+(-V_V+V_H)$ $\rightarrow +V_V^2-2V_VV_H+V_H^2$	$+(+V_V+V_H)$ $\rightarrow +V_V^2+2V_VV_H+V_H^2$
D2	$-(+V_V+V_H)$ $\rightarrow -V_V^2-2V_VV_H-V_H^2$	$-(-V_V+V_H)$ $\rightarrow -V_V^2+2V_VV_H-V_H^2$
D3	$+(+V_V-V_H)$ $\rightarrow +V_V^2-2V_VV_H+V_H^2$	$+(-V_V-V_H)$ $\rightarrow +V_V^2+2V_VV_H+V_H^2$
D4	$-(-V_V-V_H)$ $\rightarrow -V_V^2-2V_VV_H-V_H^2$	$-(-V_V+V_H)$ $\rightarrow -V_V^2+2V_VV_H-V_H^2$
Output voltage $V_{mul.}$	$-$ (Negative)	$+$ (Positive)

The vertical (V_V) and horizontal (V_H) components of the received RF signals are in a high frequency band and then concentrate on the slot line. On the other hand, the multiplier output $V_{mul.}$ is a low frequency signal, and then the $V_{mul.}$ can be easily obtained from the center conductor of the RF multiplier without interference with RF signals.

5. DESIGN OF THE CIRCULAR POLARIZATION DETECTION ARRAY ANTENNA

Figure 5 shows the analytical model of the proposed array antenna. The size of the substrate is $110 \times 110\,\mathrm{mm}^2$ and the design frequency is 10.2 GHz. The Both-sided MIC technology is effectively employed in forming this array antenna. This type of array antenna needs no impedance matching circuits in principle and has a very simple configuration, which are mainly due to the combination effect of both the microstrip-slot parallel branch circuit and the slot-microstrip series branch circuit [?]. Twelve square patch elements and the feed circuit are arranged in mirror symmetric structure. All the patch elements and the microstrip feed lines are arranged on the obverse side of a Teflon glass fiber substrate. The slot lines and the slot ring including four diodes are arranged on the reverse side. The thickness of the substrate



(a) (b)

(c)

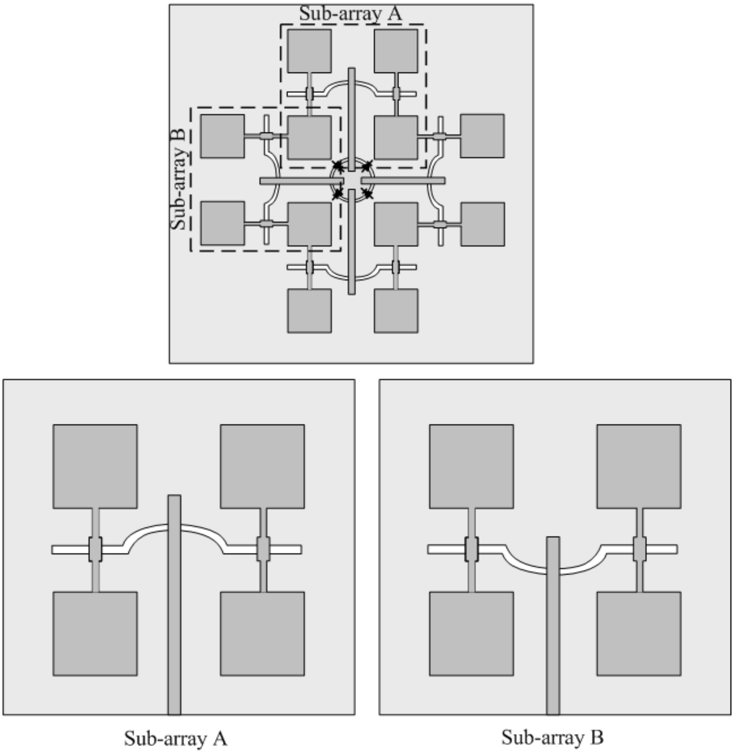
Figure 5. Structure of the proposed array antenna (unit in mm). (a) Obverse side. (b) Reverse side. (c) Cross section (A–A′).

is 0.8 mm with the relative dielectric constant ϵ_r of 2.15. The length of the sides of each patch element is 9.46 mm. A microstrip line (Z_{m1}) of the characteristic impedance of 55 Ω is connected in parallel with a slot line of 110 Ω. The slot line is connected with microstrip line (Z_{m2}) of 55 Ω in series. A quarter wavelength impedance transformer microstrip line (Z_{m3}) of 117 Ω is arranged between the microstrip line (Z_{m2}) and the patch elements. The circumference of the slot-ring is adjusted to be $2\lambda_g$ (43.98 mm) with the slot width of 0.2 mm at the design frequency of 10.2 GHz. Four zero bias Schottky diodes (MSS20 146 B-10D: Aeroflex) are loaded on the slot-ring to realize the double-balanced RF multiplier.

6. ANALYTICAL AND EXPERIMENTAL RESULTS AND DISCUSSIONS

In this section, the simulation results, experimental procedure and the results are described. The ADS Momentum (Advanced Design System) is used for the analysis of the proposed array antenna. The simulation and experimental characteristics of the two Sub-arrays named here as Sub-array A″ and Sub-array B″, are shown in Figure 6.

The Sub-arrays are the parts of the proposed 12 element array



Sub-array A

Sub-array B

Figure 6. The sub-arrays of the proposed array antenna.

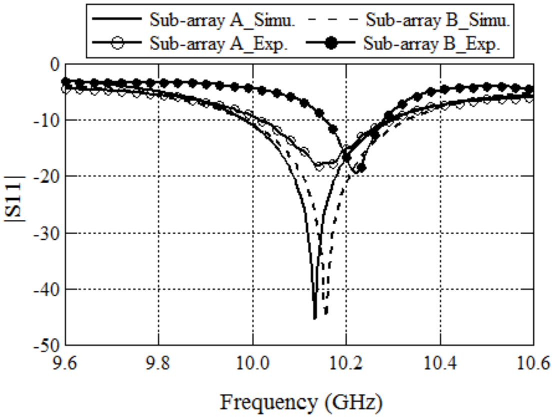


Figure 7. Return loss of the sub-array elements.

antenna, where the Sub-arrays are shown inside the dotted line in Figure 6. As the array antenna is symmetric with respect to both the vertical and horizontal axis, the simulation and the experimental investigations for these two Sub-arrays is used to design the whole 12 elements array antenna. The simulation and experimental results for the return loss characteristics of the Sub-arrays A and B are shown in Figure 7. The return loss better than 10 dB is achieved from 10.0 GHz to 10.3 GHz in simulation. Return loss better than −10 dB is also confirmed from 10.10 GHz to 10.30 GHz experimentally. The simulated gain for the both Sub-arrays is 10.04 dBi which yields, the gain of the whole 12 element array circular polarization detection array antenna is estimated to be 13 dBic.

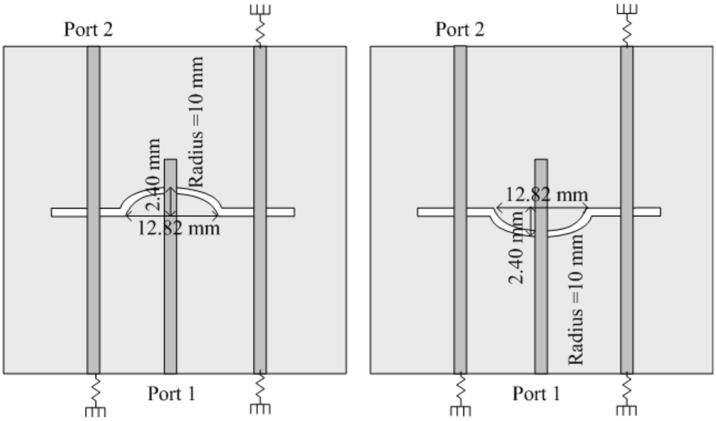


Figure 8. Feed circuit for adjusting the 90° phase difference.

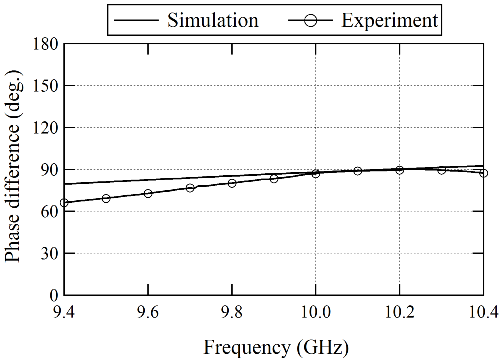
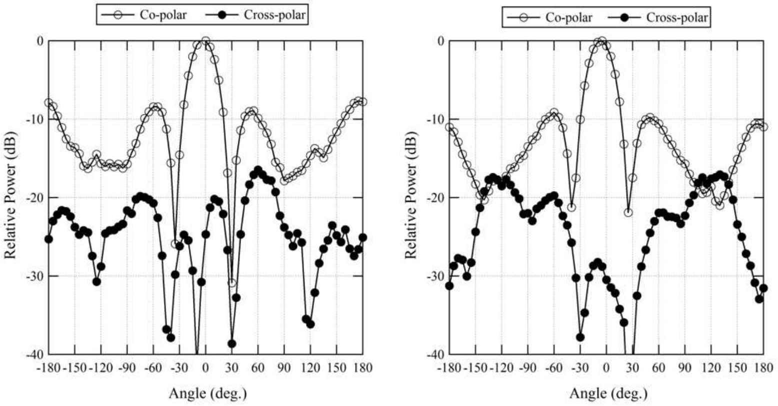


Figure 9. Phase difference of the feed circuits.

In order to realize the circular polarization detection, there must be a $\pi/2$ phase difference between the Sub-array A and Sub-array B. As explained in Section 2, this $\pi/2$ phase difference is achieved by bending the slot lines inward and outward. As a result, the length of the microstrip lines of Sub-arrays can be adjusted to achieve the $\pi/2$ phase difference. Figure 8 shows the feed circuits of the Sub-array A and B, respectively. For Sub-array A, the slot line is bended outward to use a quarter circle of the radius of 10 mm which yields 2.4 mm ($\lambda_g/8$) increment of the microstrip line. For Sub-array B, the slot line is bended inward to use a quarter circle of the radius of 10 mm which yields 2.4 mm ($\lambda_g/8$) decrease of the microstrip line. Hence, the combination of these circuits, $\pi/2$ phase difference is achieved. In order to design the $\pi/2$ phase difference of two Sub-arrays, the phase of S_{21} are simulated and measured. The simulated and experimental results for the phase difference of the fed circuits are shown in Figure 9. For simulation and experiment, the phase difference is found exactly to be $\pi/2$ at 10.20 GHz. Therefore by both the simulation and the experimental results, Sub-array A and B are designed to achieve $\pi/2$ phase difference.

Figures 10(a) and (b) show the experimental results for the radiation pattern of the Sub-arrays A and B at 10.2 GHz, respectively. The photograph of the fabricated array antenna is shown in Figure 11. The experiment of the proposed array antenna was performed in an



(a) (b)

Figure 10. Radiation patterns of the sub-arrays at 10.2 GHz. (a) Radiation pattern of sub-array A. (b) Radiation pattern of sub-array B.

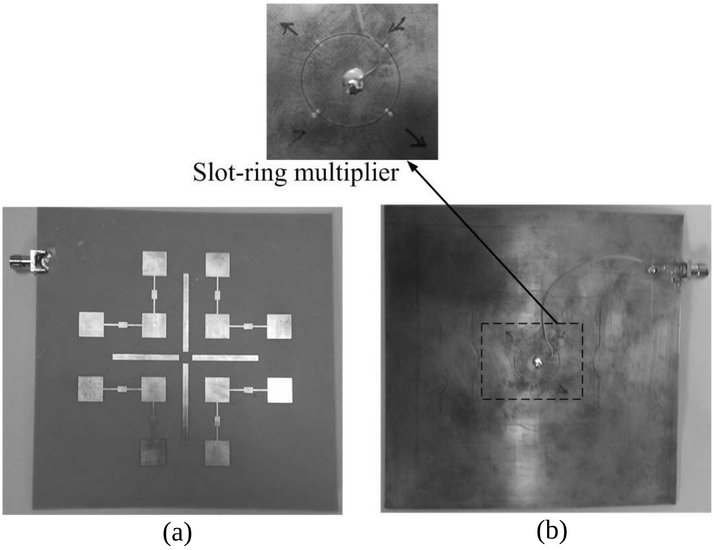


Figure 11. Photograph of the array antenna. (a) Obverse. (b) Reverse.

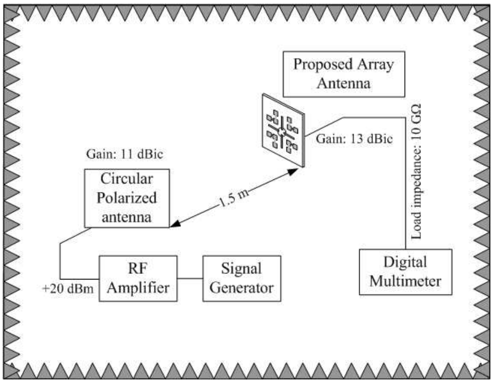


Figure 12. Orientation of the experiment.

anechoic chamber as shown in Figure 12. A dual-circular polarization patch array antenna whose gain is 11 dBic [15] is used as a transmitting antenna. The proposed array antenna is set at 1.5 m distant from the transmitting antenna. The input power for the transmitting antenna is +20 dBm. The frequency of the dual-circular polarized antenna is varied from 9 GHz to 11 GHz and the detection output voltage $V_{mul.}$ of the RF multiplier is measured by using digital multi meter

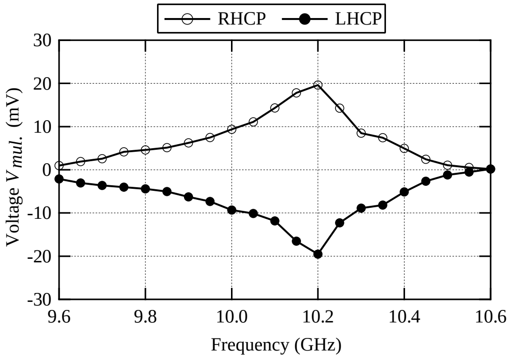


Figure 13. Frequency characteristics of the circular polarization detection.

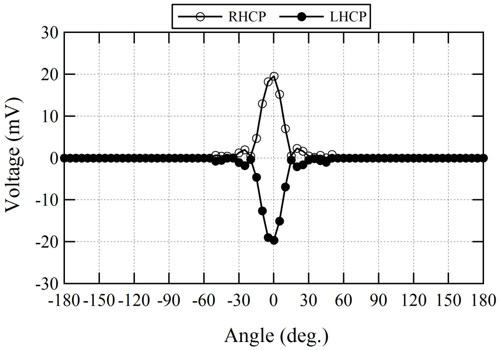


Figure 14. Output voltage $V_{mul.}$ vs. rotation angle with respect to Y axis at 10.2 GHz.

(Agilent 34401A multimeter). Figure 13 shows the measured output voltage $V_{mul.}$ of the fabricated array antenna. The maximum peak voltage of +19.63 mV and −19.52 mV are obtained at 10.2 GHz for RHCP and LHCP, respectively. The positive voltage indicates that the received signal is RHCP and the negative voltage indicates that the received signal is LHCP. Figure 14 shows the experimental result for the output voltage $V_{mul.}$ vs. the rotation angle with respect to the Y axis at 10.2 GHz. This result indicates that the array antenna can detect the polarization from −15 deg. to +15 deg. Therefore by the experimental results of the array antenna, it is successfully confirmed that the proposed array antenna has the good ability to discriminate the LHCP and RHCP from the received RF signal.

7. CONCLUSION

In this paper, the orthogonal circular polarization detection array antenna is proposed. The Both-sided MIC technology is effectively employed to realize the array antenna. The structure of the array antenna is very simple and compact as the feed circuit, antenna elements and the double-balanced RF multiplier is integrated on both sides of a dielectric substrate. As the array antenna is a mirror symmetric structure and orthogonally polarized, the received RF signals fed to the RF multiplier is in a balanced form. As a result, orthogonal circular polarization detection is very simply possible. The experimental results for the design of the array antenna agree well with the simulation results. The experimental results show the ability to detect the orthogonal circular polarization. Simple structure and good performance of the proposed array antenna makes it very attractive for various wireless applications such as wireless sensing systems including polarimetric sensors, MIMO and short range wireless data transmission etc.

REFERENCES

1. Nishiyama, E., M. Aikawa, and S. Egashira, "FDTD analysis of stacked microstrip antenna with high gain," *Progress In Electromagnetic Research*, Vol. 33, 29–43, 2001.
2. Yang, F. and Y. Rahmat-sami, "Patch Antennas with Switchable Slots (PASS) in wireless communications: Concepts, design and application," *IEEE Trans. on Antennas and Propagation*, Vol. 47, No. 2, 13–29, 2005.
3. Qian, Y. and T. Itoh, "Progress in active integrated antennas and their applications," *IEEE Trans. Micro. Theory Tech.*, Vol. 46, No. 11, 1891–1900, 1998.
4. Chen, L., F.-S. Zhang, Y.-C. Jiao, F. Zhang, and X. Xue, "A three-fed microstrip antenna for wideband circular polarizations," *IEEE Antennas and Wireless Prop. Letters*, Vol. 9, 359–362, 2010.
5. Sung, Y. J., T. U. Jang, and Y. S. Kim, "A reconfigurable microstrip antenna for switchable polarization," *IEEE Microwave and Wireless Component Letters*, Vol. 14, No. 11, 534–536, 2004.
6. Hsu, S.-H. and K. Chang, "A novel reconfigurable microstrip antenna with switchable circular polarization," *IEEE Antennas and Wireless Prop. Letters*, Vol. 6, 160–162, 2007.
7. Nasimuddin, K. P. Esselle, and A. K. Verma, "Wideband circularly polarized stacked microstrip antennas with single

microstrip feeds and short horns," *IEEE International Symposium on Antenna and Propagation*, Vol. 6, 21–24, 2007.

8. Flynt, R. A. and F. Lu, "Low cost and compact active integrated antenna transceiver for system applications," *IEEE Trans. on Microwave Theory and Technique*, Vol. 44, No. 10, 1642–1649, 1996.
9. Shi, L., X. Wang, and S. Xiao, "Polarization discrimination between repeater false target and radar target," *Science in China, series F: Information Science*, Vol. 52, No. 1, 149–158, 2009.
10. Yoshimura, S., Y. Ushijima, E. Nishiyama, and M. Aikawa, "Linear polarization discrimination array antenna," *International Symposium on Antenna and Propagation ISAP*, 2011.
11. Kodama, K., E. Nishiyama, and M. Aikawa, "Slot array antenna using both-sided MIC technology," *IEEE International Symposium on Antenna and Propagation*, Vol. 03, 2715–2718, 2004.
12. Aikawa, M. and H. Ogawa, "Double-sided MIC's and their applications," *IEEE Trans. on Microwave Theory and Technique*, Vol. 37, No. 2, 406–413, 1989.
13. Egashira, K., E. Nishiyama, and M. Aikawa, "Microstrip array antenna using both-sided MIC feed circuits," *Asia-Pacific Microwave conference, APMC*, 2002.
14. Mouw, R. B., "A broad-band hybrid junction and application to star modulator," *IEEE Trans. on Microwave Theory and Technique*, Vol. 16, No. 11, 911–918, 1968.
15. Ushijima, Y., E. Nishiyama, and M. Aikawa, "Circular polarization switchable microstrip array antenna with SPDT switch circuit," *IEEE International Symposium on Antenna and Propagation*, 2010.