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MULTI-BAND ORTHOGONAL LINEAR POLARIZATION DISCRIMINATION PLANAR ARRAY ANTENNA

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Abstract—In this paper, a novel planar array antenna for multi-band linear polarization discrimination is proposed. The proposed array antenna consists of 12 patch elements and a double-balanced multiplier. A slot-ring and four diodes used in the multiplier also act as an antenna and amplitude detector, respectively. Furthermore, slot lines which are parts of feeding circuits also act as slot antennas. The Both-sided MIC technology is effectively employed to realize the feeding circuit which eliminates the extra impedance matching circuit. The array antenna is realized in a very simple and compact structure as all the antenna elements, feeding circuit and the multiplier/amplitude detector are arranged on both sides of a substrate. The proposed array antenna can discriminate $\pm 45^\circ$ linear polarization in three frequency bands. The ability of the proposed array antenna to discriminate orthogonal linear polarization is successfully confirmed in C and X band by the experimental investigation.

1. INTRODUCTION

The planar antenna technology has many attractive features such as low cost, low profile and easy to be integrated with active components and ICs [1, 2]. This emerging planar array antenna technology covers a wide range of applications such as point to point and point to multi point wireless communication systems, radar systems, remote sensing, GPS, ITS etc. [3–8]. The polarization detection of the received signal is becoming important in recent years for many applications such as polarimetric sensors, MIMO, satellite remote sensing, ITS, radars etc.. In a word, if the polarization characteristics

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and propagation conditions of the received signals can be detected, the modules and systems for the applications 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 [5]. To meet this requirement, the authors have reported an orthogonally polarized microstrip array antenna for circular polarization discrimination [9], where RHCP/LHCP (Right Hand Circular Polarization/Left Hand Circular Polarization) of the received signal can be discriminated at the design frequency.

In this paper, a novel multi-band linear polarization discriminator is proposed. The proposed discriminator integrates a patch array antenna with a double-balanced multiplier [10] and is able to discriminate orthogonal linear polarization. A slot-ring and four diodes used in the multiplier also act as a slot-ring antenna and an amplitude detector, respectively. Furthermore, through the experimental investigation, it is discovered that the four slot lines used in the feed circuit also acts as antennas. Therefore, the array antenna receives $\pm 45^\circ$ polarized RF signals and discriminate the polarization in three bands. The array antenna is realized by arranging all the patch elements, feed circuits and the double-balanced multiplier upon both sides of a Teflon glass fiber substrate. Therefore, the fabrication is very easy compared with other polarization discriminators [11, 12]. The Both-sided MIC technology [13] is successfully employed to realize the proposed array antenna. Consequently, the array antenna needs no impedance matching circuits and has a very simple circuit configuration mainly due to the excellent combination of both the microstrip-slot parallel branch circuit and the slot-microstrip series branch circuit [13–15]. As the single array antenna can discriminate linear polarization in three different bands, it is suitable for compact and low cost applications, such as, short range wireless data transmission implemented in small device, polarization diversity applications, polarimetric radars etc.. So far from the knowledge of the authors, this is the first time to propose and realize a multi-band polarization detection array antenna using the planar antenna technology.

The structure, basic behavior and design of the array antenna are described in Sections 2 and 3. Basic behaviors of the double-balanced multiplier and amplitude detector are described in Subsections 2.1 and 2.2, respectively. Finally, the simulation and experiment data are presented in Section 4.

2. DISCRIMINATION MECHANISM

Figure 1 shows the proposed 12-element array antenna integrated with the double-balanced multiplier/amplitude detector. The slot-ring circuit shown in Fig. 1(b) operates as both a double-balance multiplier, slot-ring antenna and amplitude detector. Slot lines used in the feeding circuit also act as slot-line antennas. Therefore, from the output of the multiplier/detector, the polarization of the received signal can be detected. The diodes D1 and D3 are directed outward on the slot-ring and the other diodes D2 and D4 are directed inward on the slot-ring. Four microstrip feed lines are arranged on the slot-ring.

The proposed discriminator works in following operation modes; patch array antenna, slot-ring antenna and slot-line antenna modes as shown in Fig. 2.

2.1. Patch Array Antenna Mode

Figure 2(a) shows the basic concept of the patch array antenna mode. The signal received by the patch array antenna is split into two orthogonal components. These two components are input to the multiplier in a balanced mode. Then the received RF signal is converted into DC voltage by the multiplier. The array antenna including the feed circuits has a mirror symmetric structure to be realized in a very simple way [15]. The slot-ring is located at the

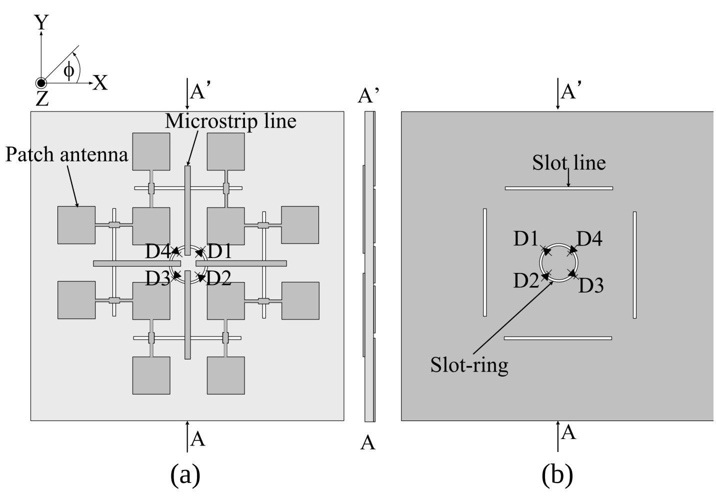


Figure 1. Concept for realizing linear polarization detection antenna. (a) Obverse side. (b) Reserve side.

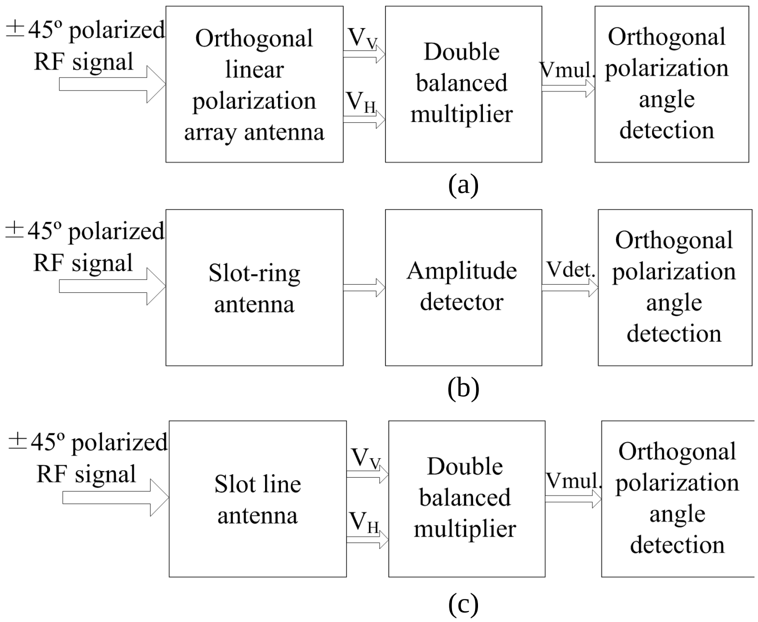


Figure 2. Basic concept of the polarization discriminator. (a) Patch array antenna mode. (b) Slot-ring antenna mode. (c) Slot-line antenna mode.

center of the array antenna and four microstrip lines are coupled with the slot-ring. For the patch antenna elements, the vertical (V_V) and horizontal (V_H) components of the received RF signal are collected and input to the multiplier. (In this paper, the vector component parallel to the Y axis is called the vertical component (V_V) and the vector component parallel to the X axis is called the horizontal component (V_H)).

Figure 3 shows the vertical (V_V) and horizontal (V_H) components of the received signal for $\phi = +45°$ polarized RF signal. The vertical (V_V) and horizontal (V_H) components of the array antenna can be expressed by the following equations,

$$V_H = V \sin(\omega t + \theta_H) \quad (1)$$

$$V_V = V \sin(\omega t + \theta_V) \quad (2)$$

The output voltage (V_{mul}) of the double balanced multiplier shown in Fig. 2(a) is as follows:

$$V_{mul} \propto V \times V \cos(\theta_H - \theta_V) \quad (3)$$

When the phase difference $(\theta_H - \theta_V)$ is 0°, the output voltage of the multiplier is positive value which indicates the received signal polarization tilt angle is +45°. When the phase difference is 180°, the output voltage of the multiplier is negative value which means the received signal polarization tilt angle is −45°. Therefore, from the polarity of the output voltage (V_{mul}) of the multiplier, it is very easy to determine whether the received signal has +45° or −45° linear polarization. Needless to say, the output voltage of the multiplier depends on the diode polarity loaded on the slot-ring.

The basic behavior of the double balanced multiplier is shown in Table 1. For $\phi = \pm 45°$, the vertical and horizontal components ($+V_V$, $-V_V$, $+V_H$, $-V_H$) are multiplied by the multiplier. The multiplier output V_{mul} is obtained at the center conductor of the slot-ring. In addition, the output voltage depends on the polarity of the four diodes which are loaded on the slot-ring at every $\lambda_g/2$ interval at the array antenna designed frequency. 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 $\phi = +45°$. In the same way, they are $(-V_V + V_H)$, $(+V_V + V_H)$, $(+V_V - V_H)$ and $(-V_V - V_H)$ for −45°. Therefore, the output voltage (V_{mul}) of the multiplier is

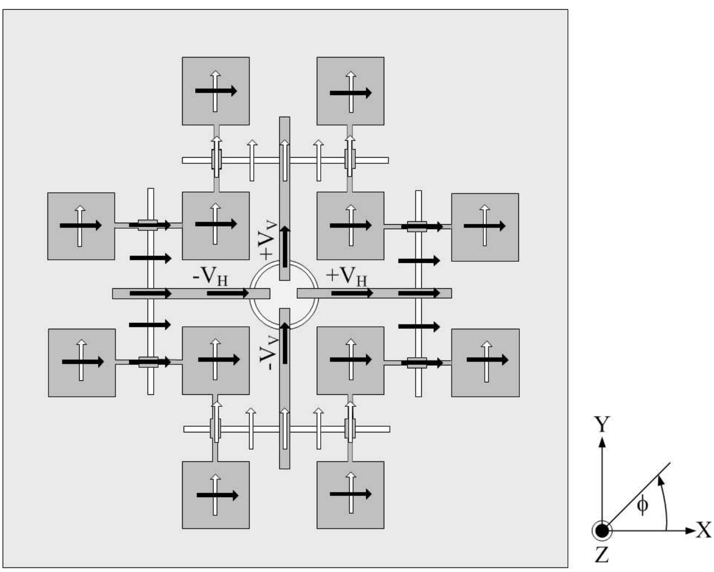
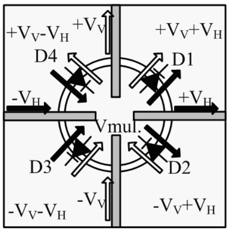
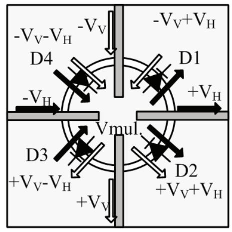
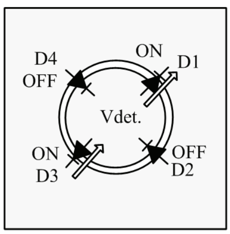
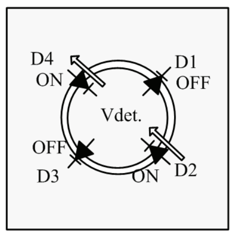


Figure 3. Basic behavior of the array antenna for +45° polarization discrimination.

Table 1. Basic behavior of the double balanced multiplier and the amplitu

	$\phi = +45°$	$\phi = -45°$
Double balanced multiplier for patch array antenna and slot-line antenna	 Vmul. > 0	 Vmul. < 0
Amplitude detector for slot-ring antenna	 Vdet. > 0	 Vdet. < 0

positive or negative for $+45°$ or $-45°$ polarization, respectively. The basic behavior of the 4-element sub-array antenna is explained in [15] where the design of the feed circuit is also described.

2.2. Slot-ring Antenna Mode

At the resonant frequency of the slot-ring, it acts as both a slot-ring antenna and the amplitude detector as shown in Fig. 2(b). Since the diodes are loaded on the slot-ring at every $\lambda_g/4$ interval at the slot-ring antenna design frequency, the output voltage of the slot-ring antenna depends on the polarity of the four diodes. The basic behavior of the amplitude detector is also summarized in Table 1. When $+45°$ polarized signal is received, the diodes D1 and D3 detect the received RF signal and the output voltage V_{det} is positive value according to the diode polarity. When $-45°$ polarized signal is received, the diodes D2 and D4 detect the received RF signal and the output voltage V_{det} is negative value.

2.3. Slot-line Antenna Mode

The concept of the slot-line antenna mode is shown in Fig. 2(c). The same basic behavior of the patch array antenna is applicable for the slot-line antennas. As the slot lines are also mirror symmetric structure, a balanced multiplication of the vertical and horizontal components of the signal received by slot lines is possible. These components are input to the multiplier, and from the output voltage of the multiplier, the polarization discrimination can be realized.

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 ring. On the other hand, the slot-ring output V_{mul} and V_{det} are low frequency signals, and can be easily obtained from the center conductor of the slot-ring without interference with RF signals.

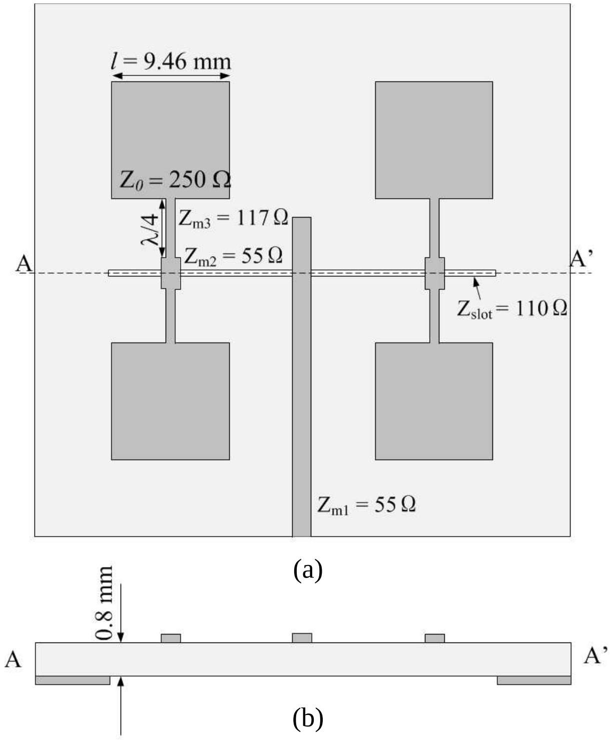


Figure 4. Structure of the 4-element sub-array antenna. (a) Top view. (b) Cross section view.

3. DESIGN OF THE LINEAR POLARIZATION DETECTION ARRAY ANTENNA

A 4-element sub-array antenna shown in Fig. 4 is designed and the characteristics are investigated to the prior of the full array antenna design. As the sub-array antenna is the main building block of the array antenna, design of the sub-array antenna plays an important role for the performance of the full array antenna. All the patch elements and the microstrip 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 is 0.8 mm with the relative dielectric constant ε_r of 2.15. The size of each patch element is $9.46 \times 9.46\,\mathrm{mm}^2$ for 10.2 GHz. A microstrip line having characteristic impedance of $55\,\Omega$ (Z_{m1} in Fig. 4) is connected in parallel with a slot line having impedance of $110\,\Omega$. In this case, width of the microstrip line and slot line are 2.4 mm and 0.2 mm respectively. The slot line connects with microstrip line of $55\,\Omega$ (Z_{m2} in Fig. 4) in series.

Simulation of the 4-element sub-array is performed by the Advanced Design System (ADS) momentum by Agilent Technologies. The simulated and experimental data of the S_{11} characteristics of the sub-array element is shown in Fig. 5.

The $|S_{11}|$ characteristics confirm that the sub-array impedance is matched at 10.2 GHz which is shown in Fig. 5.

Figure 6 shows a photograph of the proposed array antenna using the dimensions of the sub-array antenna. The size of the array antenna is $110 \times 110\,\mathrm{mm}^2$ and the design frequency is 10.2 GHz. Twelve square patch elements and the feed circuits are arranged in a mirror symmetric structure [15]. All the patch elements and the microstrip lines are

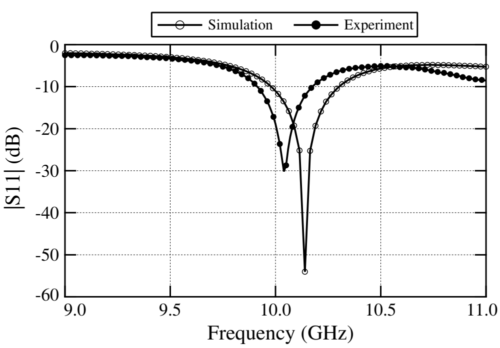


Figure 5. $|S_{11}|$ characteristics of the sub-array element.

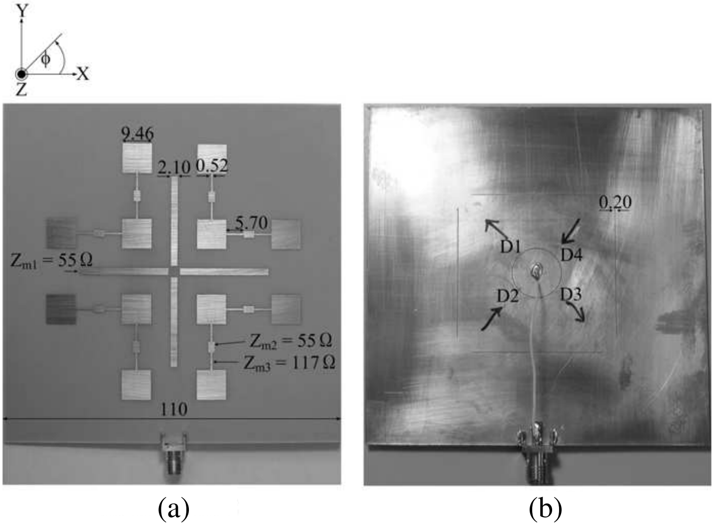


Figure 6. Prototype of the 12-element array antenna (unit: mm). (a) Obverse side. (b) Reverse side.

arranged on the obverse side of the Teflon glass fiber substrate. The slot lines and the slot ring including four diodes are arranged on the reverse side. The dimensions for the slot lines and the microstrip lines are same as the sub-array antenna shown in Fig. 4. The circumference of the slot-ring is adjusted to be $2\lambda_g$ (43.98 mm) at 10.2 GHz with the width of 0.2 mm. In addition, the slot-ring circumference $1\lambda_g$ at 5.5 GHz where it acts as an amplitude detector. Four zero bias diodes (MSS20 146 B-10D: Aeroflex) are loaded on the slot-ring to realize the star-coupled double balanced multiplier. Furthermore, the four slot lines also act as slot antennas at 9.6 GHz.

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

The experiment of the proposed array antenna was performed in an anechoic chamber as shown in Fig. 7. A standard horn antenna (11966 double ridged waveguide horn antenna by Agilent) is used as the transmission antenna and the proposed 12-element array antenna is put at 1.5 m distant from the horn antenna. The input power to the standard horn antenna is maintained around +15 dBm. A 100 kΩ resistor is connected with the output of the array antenna in order to measure the output voltage. The output voltage is measured by using a digital multi meter (Agilent 34401A multimeter) from 3 GHz to 12 GHz. Fig. 8 shows the output voltage V_{mul} and V_{det}. From the Fig. 8, it is found that the output voltage is peak at 5.5 GHz, 9.6 GHz and 10.2 GHz for ±45° polarizations. And for 0° and 90° polarizations, the output voltage is almost zero due to the multiplier and amplitude detector principle. As mentioned above, at 5.5 GHz, the slot-ring performs as both the antenna and the direct amplitude detector of the ±45° polarized signal. Therefore, the output voltage $|V_{det}|$ is maximum at that frequency. As the design frequency of the

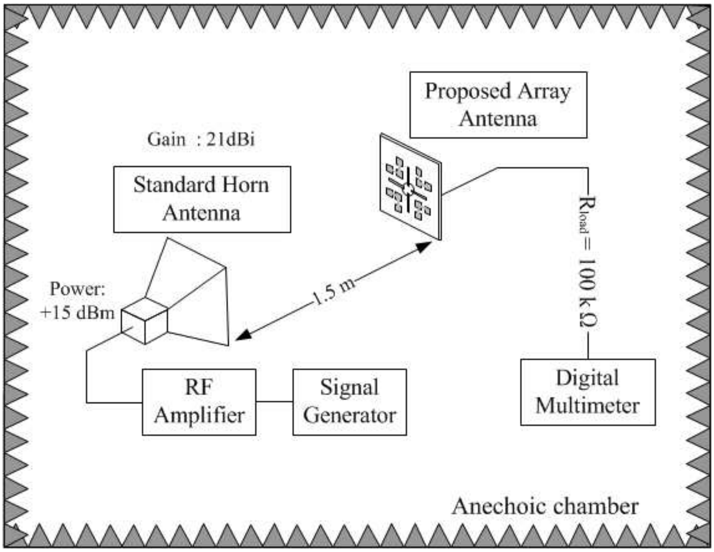


Figure 7. Experimental setup.

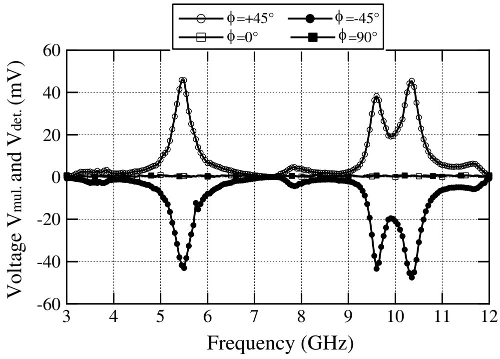


Figure 8. Frequency characteristics of the output voltage $V_{mul.}$, $V_{det.}$ of the array antenna.

array antenna is 10.2 GHz, the output voltage V_{mul} is maximum at that frequency (+45.25 mV and −45.39 mV for +45° and −45° polarized signals, respectively). The output voltage V_{mul} of the discriminator are +38.36 mV and −35.67 mV for +45° and −45° polarized signal, respectively for the slot-line mode at 9.6 GHz. For the design of the sub-array, it was considered that the feed mode is same for the transmission and reception antenna. Therefore, the simulation and the experiment for the sub-array is performed considering it as a transmission antenna. As a result, from the $|S_{11}|$ characteristics of Fig. 5, it is found that the sub-array antenna impedance is matched only at 10.2 GHz for both simulation and experiment. If the slot line is enhanced as a receiving antenna, there will be a balanced mode on the slot line. Therefore, a revised simulation is done

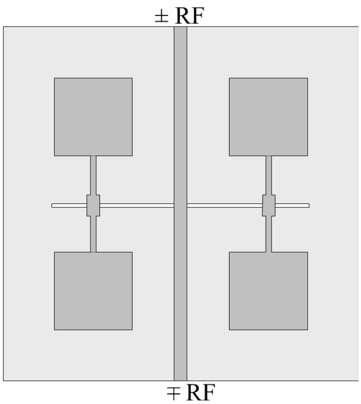


Figure 9. Structure of the balanced feed sub-array antenna.

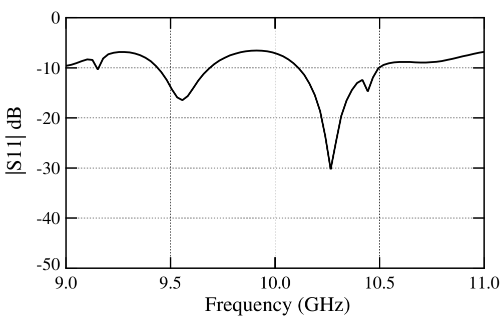
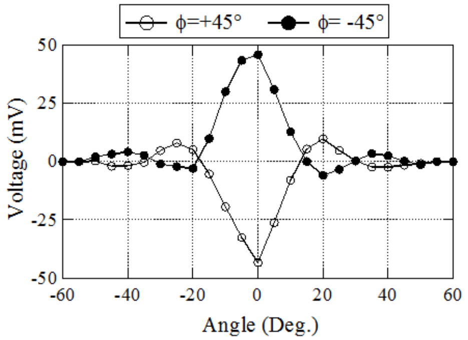
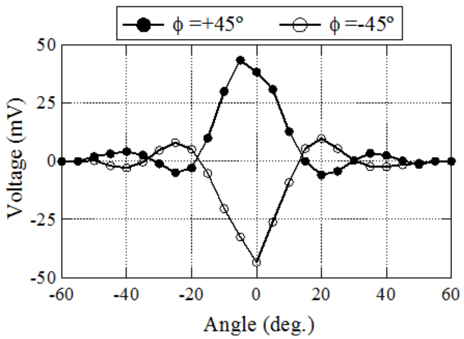


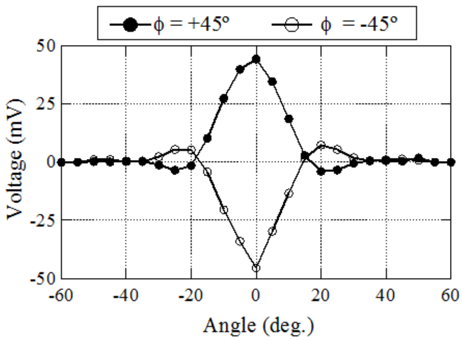
Figure 10. Simulated $|S_{11}|$ characteristics of the balanced fed sub-array antenna.



(a)



(b)



(c)

Figure 11. Polarization discrimination performance of the array antenna in X-Z plane. (a) At 5.5 GHz. (b) At 9.6 GHz. (c) At 10.2 GHz.

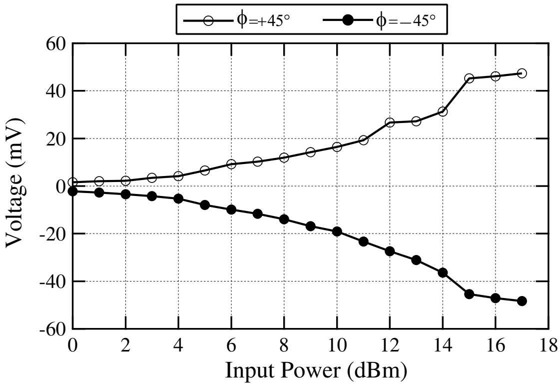


Figure 12. Polarization discrimination performance of the array antenna according to input power at 10.2 GHz.

considering the sub-array antenna as a reception antenna using a balanced mode feed circuit as shown in Fig. 9. In this case, the simulated $|S_{11}|$ characteristics is found as shown in Fig. 10. From this $|S_{11}|$ characteristics, it is found that, the impedance is matched at both 9.6 GHz and 10.2 GHz. Judging from the $|S_{11}|$ characteristics of Fig. 10, it can be estimated that the slot lines accompanied with the boundary condition of the patch antennas and the feeders are radiators. In this case, 9.6 GHz is the slot line antenna resonant frequency. Besides, the middle portion of the slot line acts as the receiving slot antenna, because the low $|S_{11}|$ of 9.6 GHz is obtained only by the balanced fed simulation. The same basic behavior is applicable for the four slot lines for the $\pm 45°$ linear polarization discrimination at 9.6 GHz.

Therefore, from the output voltage of the multiplier according to Equation (3), it is evident that, the array antenna detects the $\pm 45°$ signals in three frequency bands. Figs. 11 (a), (b) and (c) show the polarization discrimination ability of the array antenna when the antenna is rotated at in X-Z plane at 5.5 GHz, 9.6 GHz and 10.2 GHz respectively. From Fig. 11, it is evident that the array antenna can discriminate the polarization angle from $-15°$ to $+15°$. Since the array antenna contains nonlinear devices, its performance is clearly sensitive to the signal level. Therefore, the polarization discrimination performance of the array antenna is observed by varying the signal level as shown in Fig. 12. The graph indicates that the output voltage of the array antenna increases along with the increment of the input power.

5. CONCLUSION

In this paper, multi-band orthogonal linear 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 slot-ring RF multiplier/detector are arranged on both sides of a substrate. As the array antenna is mirror symmetric and orthogonally polarized, a balanced RF multiplication/detection is very simply possible. The basic behavior of the orthogonal polarization discrimination for three frequency bands are clarified by the simulation and experiment. The slot ring acts as an antenna/detector at 5.5 GHz, and as RF multiplier at the patch antenna design frequency of 10.2 GHz. In addition, each slot line also acts as antenna and able to discriminate the linear polarization at 9.6 GHz. The experimental results agree with the simulation results. The experiment results of the proposed array antenna confirm the orthogonal linear polarization detection ability. Excellent design flexibility and performance of the proposed array antenna makes it a very attractive candidate for various wireless applications, especially for RF sensors and advanced wireless communication systems.

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