Polarization-Diversity Cross-Shaped Patch Antenna for Satellite-DMB Systems

Jong-Hyuk Lim, Gyu-Tae Back, and Tae-Yeoul Yun

A small reconfigurable patch antenna is proposed to achieve polarization diversity for digital multimedia broadcasting systems at 2.6 GHz. To obtain polarization diversity, a pair of on-slit PIN diodes is inserted in each diagonal of a cross-shaped patch. Thus, four PIN-diodes on these slits are utilized to change the connection of the slits and thus achieve polarization. Bias circuits for the diodes are allocated in the cutting corner of the cross-shaped patch to minimize the antenna size. The antenna produces left-hand circular polarization, right-hand circular polarization, or linear polarization, depending on the PIN-diode status. Analysis of circular polarization operation is explicated. Measurements show a gain of about 1.5 dB, a cross polarization of about −20 dB, and an axial ratio of about 2.5 dB.

Keywords: Axial ratio, circular polarization, DMB, patch antenna, polarization diversity, reconfigurable antenna.

I. Introduction

In wireless mobile and satellite communication applications, the reconfigurable antenna for polarization diversity has become popular in antenna engineering, due to its ability to maintain communication quality with a single antenna. Polarization-diversity systems enable a single handset to access a number of services and realize frequency reuse because users are allowed to roam any existing networks [1], [2]. Moreover, polarization diversity reduces the detrimental fading loss caused by multipath effects in wireless communication systems such as wireless local area networks (WLANs) [3]. In active read/write microwave tagging systems, polarization diversity provides a powerful modulation scheme [4].

In a Korean satellite digital multimedia broadcasting (DMB) system operating near 2.6 GHz, mobile terminals need polarization diversity in order to choose either the right-hand circular polarization (RHCP) signal from the satellite or the linear polarization (LP) signal from the gap-filler in the shadow region. To achieve polarization diversity, the microstrip patch antenna was selected in this study because it has attractive advantages, such as a low profile, light weight, easy fabrication, and conformability with RF circuitry [5].

Various studies using microstrip antennas to achieve polarization diversity have been reported [1]-[9]. The polarization diversity antenna proposed in [3] is attained by a multiple-feed method. It makes use of a dual radiator with vertical and horizontal LP characteristics, which is oriented orthogonally for polarization diversity. On the other hand, a single-feed method with a single patch uses an electrical switch such as a PIN diode or a micro-electro-mechanical system (MEMS). The polarization-diversity antennas presented in [1] and [4] operate with RHCP or left-hand circular polarization

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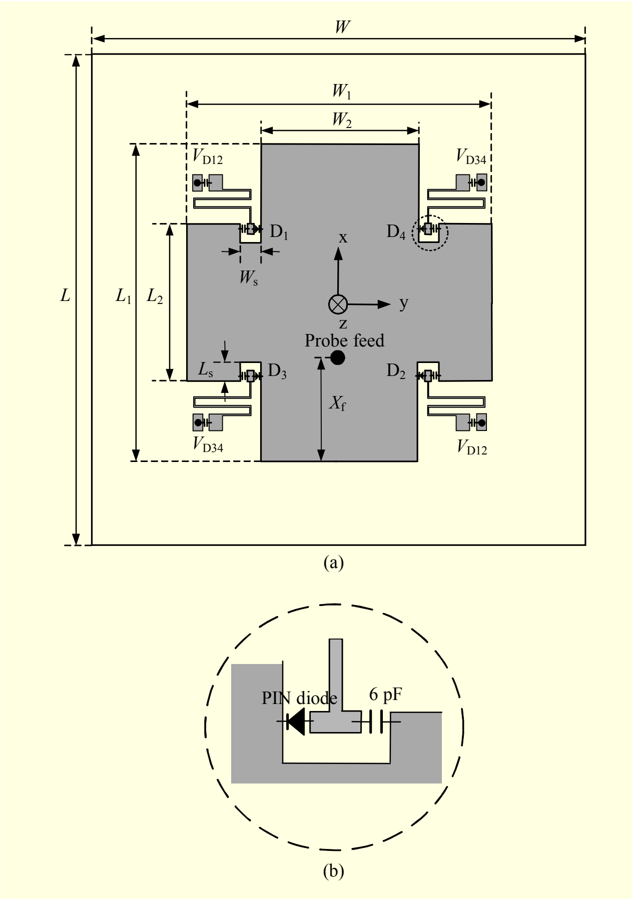

Fig. 1. (a) Geometry of the proposed reconfigurable antenna and (b) enlarged layout of the switch biasing network.

(LHCP). Other reconfigurable antennas proposed in [2], [5]-[7] operate with RHCP, LHCP, or LP. In addition, a reconfigurable antenna with frequency and polarization switching was studied in [8], [9]. Although these methods have the advantage of using a single element, they require increased antenna size due to the bias circuit for switching devices.

In this paper, a small reconfigurable antenna is proposed which obtains polarization diversity of LHCP, RHCP, and LP by electrically controlled switching PIN diodes. The antenna structure is simply configured with a corner-truncated and cross-shaped patch that includes bias circuits without increasing the size. This paper presents the reconfigurable antenna structure and modeling of the PIN-diode in section II. Measurement results and discussion are given in section III, and conclusions are given in section IV.

II. Antenna Design

The proposed reconfigurable antenna is shown in Fig. 1. It consists of a cross-shaped patch, two pairs of switching diodes (D_1 and D_2, D_3 and D_4) on slits, meandered quarter-wavelength ($\lambda/4$) bias-lines at 2.6 GHz, and a probe feed. A single-feed cross-shaped patch antenna with W_1 = 29.8 mm, L_1 = 30 mm, X_f = 10 mm, W_2 = L_2 =15 mm, W_s = 2 mm, and L_s = 1.8 mm was fabricated on a substrate with a thickness of 1.6 mm and a dielectric constant (ε_r) of 4.3. The overall size of the substrate including the ground was kept at 40 mm × 40 mm.

Surface current distributions at the corners of a rectangular patch are very small; therefore, the difference between the operation of a rectangular patch and that of a corner-truncated cross-shaped patch is very small. To achieve polarization diversity, four PIN-diodes are located in the slits, and bias circuits are added in the cut corners. Thus, a cross-shaped patch was adopted in this study for size reduction.

The following steps explain the method used to design the polarization diversity antenna. First, the proposed reconfigurable antenna was simulated using Ansoft's High Frequency Structure Simulator (HFSS) with an ideal conductor instead of a switching device. Second, a PIN-diode of a real switch was modeled with the measured data using the through-reflect-line (TRL) calibration. Finally, reconfigurability was validated by replacing the ideal switch with the real PIN-diode.

A reconfigurable antenna using MEMS usually has low loss but it has the drawbacks of longer response time, higher cost, and higher DC voltage when compared with the PIN diode. Therefore, we adopted the PIN-diode on the microstrip patch to overcome the disadvantages of MEMS.

1. Ideal Reconfigurable Antenna

An ideal reconfigurable antenna was simulated by using HFSS. The on-state diode is considered a short circuit, while the off-state diode is represented by an open circuit. The cross-shaped patch operates with LP with the fundamental TM_{10} mode, as shown in Fig. 2(a), in which the arrows indicate the surface current distribution magnitude and direction. It operates at 2.66 GHz. As shown in Fig. 2(b), the four slits are added to perturb the normal operation of the patch. Then, the antenna operates with LP due to the TM_{10} mode, and the resonant frequency slightly decreases to 2.6 GHz because the current path is somewhat lengthened by the perturbing slits. In general, a single-feed circular-polarization (CP) patch antenna is designed by perturbing the mode of the patch and is analyzed by using the variation resonant method [10]. Based on a similar concept, a pair of slits is inserted at the diagonal corner of the cross-shaped patch to perturb the normal operation mode of TM_{10}. As shown in Figs. 2(c) and (d), when the phase of the input signal is changed from 0° to 90°, the surface current rotates counter-clockwise, which means that the two perturbing slits cause the antenna to operate with RHCP. On the other hand, if the two slits are located on the opposite diagonal, an

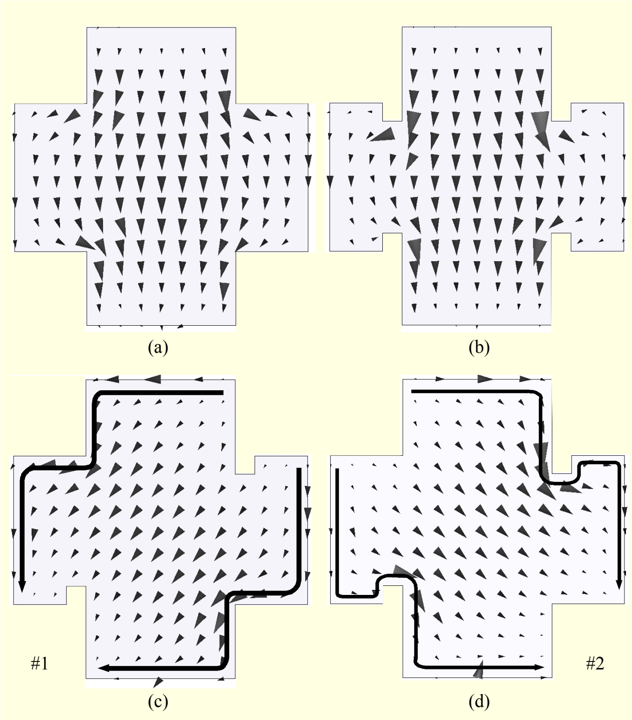

Fig. 2. Surface current distributions: (a) TM_{10} mode of a cross-shaped patch without perturbation, (b) TM_{10} mode of a cross-shaped patch with four slit perturbation, (c) RHCP with two slit perturbation and an input signal of 0°, and (d) RHCP with two slit perturbation and an input signal of 90°.

LHCP pattern can be obtained because of the symmetrical structure. The resonant frequency for a mode of path 1 is higher than that for a mode of path 2. Two orthogonal modes should have the same magnitude, but there should be a 90° phase difference of the electric field at the center frequency between the two resonant frequencies in order to achieve an optimized CP. Therefore, a parametric analysis was performed by varying the length (L_s) and width (W_s) of the slit.

Figure 3 shows simulated return losses and axial ratios (ARs) to find the L_s and W_s of the slit which perturb the antenna and cause it to be circularly polarized. In Figs. 3(a) and (b), L_s is varied, and W_s is fixed at 2 mm. In Figs. 3(c) and (d), W_s is varied, and L_s is fixed at 1.8 mm. The closest two resonant frequencies for the return loss and a minimum AR were obtained when the slit was 1.8 mm long and 2 mm wide, resulting in the best CP. When the length and width differed from the optimized values, the two resonant frequencies for the return loss were distant from each other and the ARs increased.

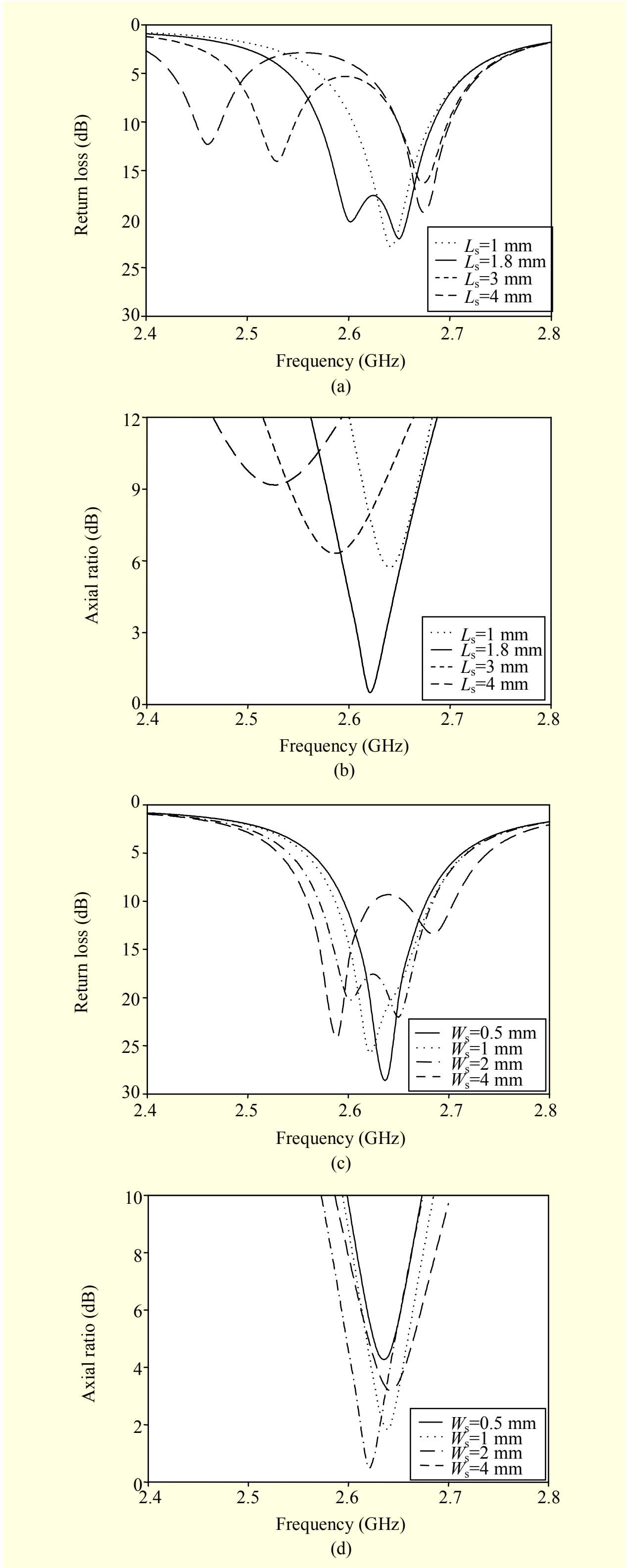

Fig. 3. Parametric analysis for the CP operation with perturbing length (L_s) and width (W_s) of the slit: (a) return loss and (b) axial ratio with varying L_s and fixed W_s =2 mm, and (c) return loss and (d) axial ratio with varying W_s and fixed L_s of 1.8 mm.

2. Equivalent Circuit Modeling of PIN-Diode

As previously mentioned, we propose a reconfigurable antenna with an ideal switch which ignores practical

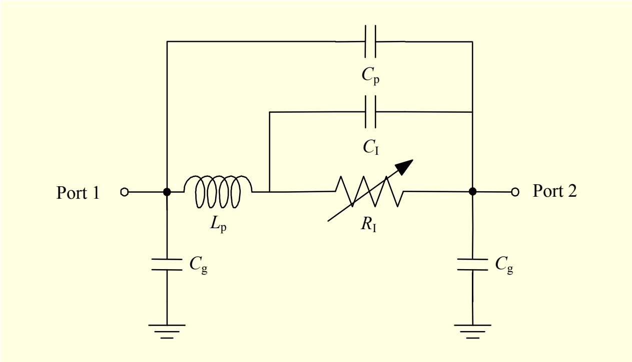

Fig. 4. Equivalent circuit for the PIN-diode.

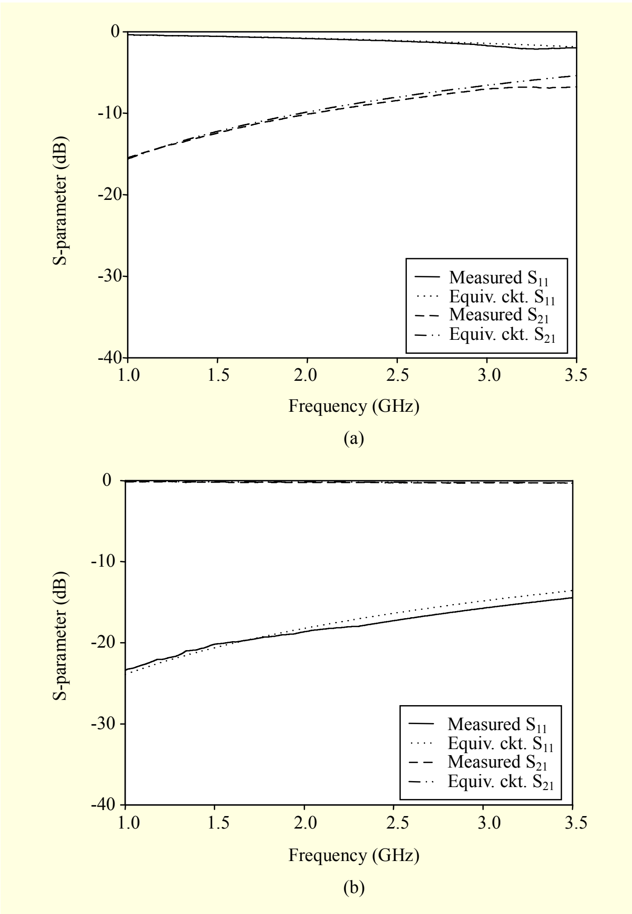

Fig. 5. S-parameter comparison between the measurement and equivalent circuit for a PIN-diode with (a) diode off and (b) diode on.

characteristics such as the parasitic effect and finite isolation when the ideal conductor is replaced with a real PIN-diode switch. Therefore, modeling the PIN diode in the on and off states must be performed to obtain a good prediction of the reconfigurability results.

Figure 4 shows the adopted equivalent circuit for the PIN-diode, including the surface mounting effect. The intrinsic capacitance is denoted by C_I, the resistance by R_I, and the packaging effects by C_p and L_p. Also, C_g represents the mounting parasitic effects between the PIN-diode and the ground of the substrate with $\varepsilon_r = 4.3$ and a thickness of 1.6 mm.

Table 1. Model parameters for the equivalent circuit.

Diode states	L_p (nH)	R_I (Ω)	C_I (pF)	C_P (pF)	C_g (pF)
On	1.03	1.5	-	0.0078	0.0035
Off		3k	0.19		

Figures 5(a) and (b) validate the equivalent-circuit model for the SDP510Q PIN-diode with the measured data for the frequency range from 1 GHz to 3.5 GHz which was obtained using TRL calibration. Near 2.6 GHz, the PIN diode has an insertion loss of 0.27 dB for the diode 'on' state and an isolation of 8.1 dB for the diode 'off' state due to the low resistance (1.5 Ω) and total capacitance (0.268 pF), respectively. Finally, model parameters for the equivalent circuit were extracted from 1 GHz to 3.5 GHz and are summarized in Table 1.

3. Real Reconfigurable Antenna Design with PIN Diodes

A real reconfigurable antenna was obtained by replacing an ideal conductor with a real PIN diode, which was simulated by Ansoft Designer using S-parameters of an equivalent circuit of the diode. As shown in Fig. 1(b), to control the connectivity of the slits, four PIN diodes are mounted on the slits, which are biased with λ/4 meandered and 0.1 mm wide microstrip lines to minimize the size and loading effects of the bias lines. Eight capacitors (6 pF) isolate the RF signal from DC. PIN diodes consume a bias current of 10 mA and a voltage of 0.8 V.

When all diodes are in the on state or off state, the antenna has the LP characteristic with the fundamental TM_{10} mode, which is similar to that previously shown in Figs. 2(a) and (b). When D_1 and D_2 turn on with D_3 and D_4 off, the antenna operates with RHCP. When D_3 and D_4 turn on with D_1 and D_2 off, the antenna operates with LHCP at the same frequency as the RHCP case due to the symmetrical structure. Thus, polarization diversity can be obtained by changing the status of the ideal switch of the conductance on the slits.

III. Results and Discussion

1. Experimental Results

To confirm the polarization diversity, the proposed antenna was simulated and measured with four different diode switching modes of diodes. The input return loss for each

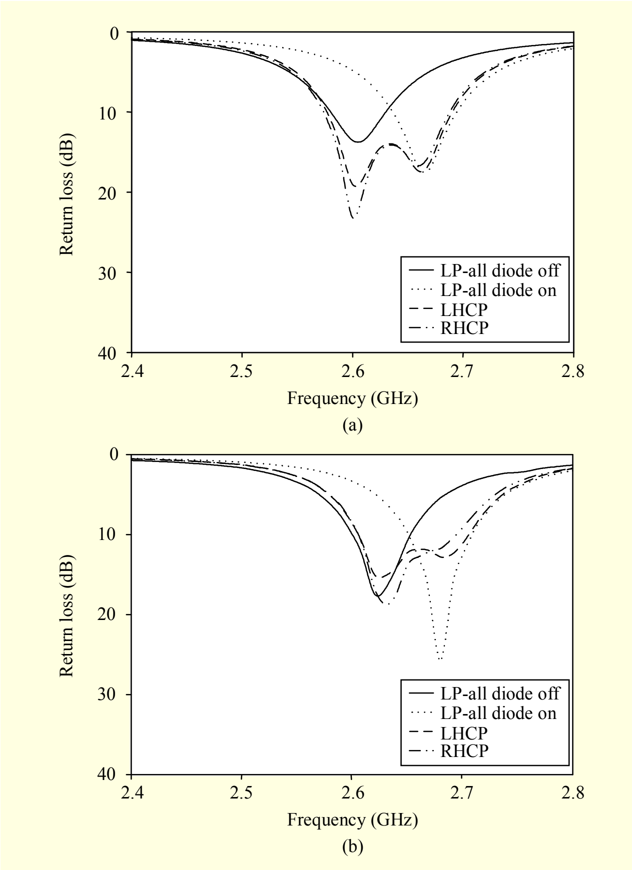

Fig. 6. Input return loss for LP, LHCP, and RHCP: (a) simulation and (b) measurement.

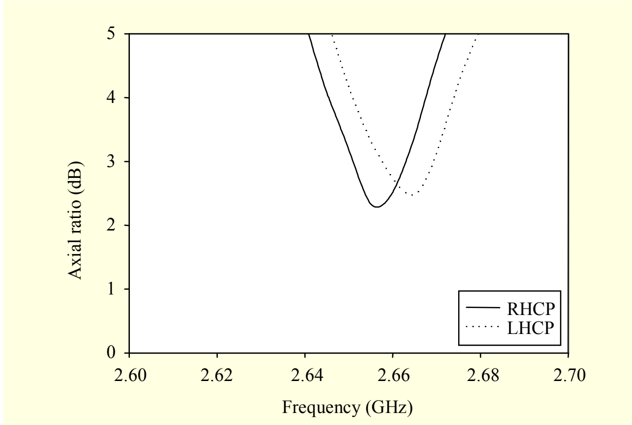

Fig. 7. Measured AR for CP.

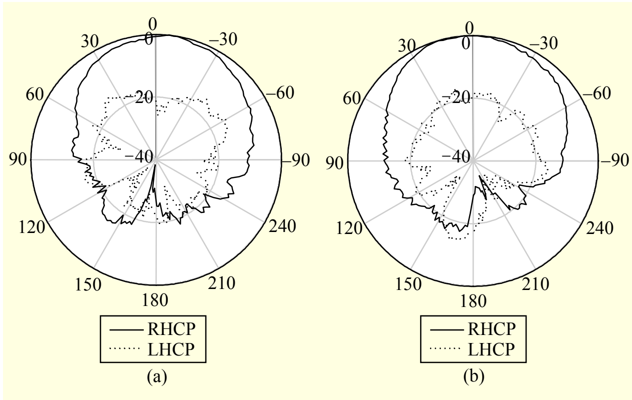

Fig. 8. Measured RHCP radiation patterns at 2.66 GHz in the (a) x-z plane and (b) y-z plane.

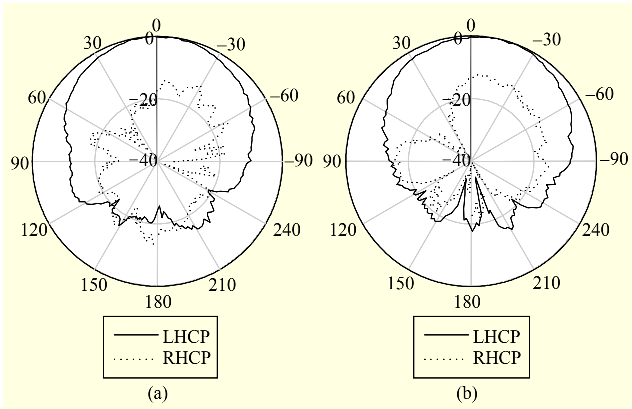

Fig. 9. Measured LHCP radiation patterns at 2.66 GHz in the (a) x-z plane and (b) y-z plane.

polarization is plotted in Figs. 6(a) and (b) for simulation and measurement, respectively. When all diodes are in the on or off state, for example, with LP, the input impedance bandwidth of −10 dB is 60 MHz and 2.62% from 2.65 GHz to 2.71 GHz and is 60 MHz and 2.3% from 2.58 GHz to 2.64 GHz. When the antenna operates with CP, the input impedance bandwidth is 85 MHz and 3.2% from 2.605 GHz to 2.69 GHz with RHCP and is 95 MHz and 3.58% from 2.605 GHz to 2.7 GHz for LHCP. The measured input return loss results with real PIN-diodes agree very well with the simulated results.

Figure 7 shows the measured AR for CP. The obtained 3 dB AR bandwidth reaches about 15 MHz or 0.56% from 2.65 GHz to 2.665 GHz. As shown in Figs. 6 and 7, the resonant frequency of the fundamental TM_{10} mode is 2.68 GHz, and that of the perturbed TM_{01} mode is 2.62 GHz, which is lower than the fundamental TM_{10}. Thus, the minimum ARs are obtained at 2.66 GHz between the resonant frequencies of TM_{10} and TM_{01} modes and have 2.47 dB and 2.3 dB for RHCP and LHCP, respectively. Therefore, the realized antenna has excellent polarization diversities in the DMB band.

Figure 8 shows the measured radiation patterns of the *x-z* and *y-z* planes for RHCP at 2.66 GHz when D_1 and D_2 are on and D_3 and D_4 are off. Figure 9 shows the radiation patterns for LHCP at 2.66 GHz when D_1 and D_2 are off and D_3 and D_4 are on. The peak antenna gains were obtained at 1.58 dBi and 1.67 dBi for RHCP and LHCP, respectively. Figure 10 exhibits

Table 2. Summary of simulation and measurement results.

Items / Polarization	Diode state (on/off)	−10 dB impedance bandwidth (GHz)		BW (%)	AR (dB)	Gain (dBi)
		Simulation	Measurement	Measurement		
LP	All off	2.58 - 2.64	2.6 - 2.66	2.28	-	1.87
LP	All on	2.64 - 2.7	2.65 - 2.71	2.23	-	0.82
RHCP	D1, D2 on D3, D4 off	2.58 - 2.69	2.605 - 2.69	3-dB AR 0.56	2.47	1.58
LHCP	D1, D2 off D3, D4 on	2.58 - 2.69	2.605 - 2.7	3-dB AR 0.56	2.3	1.67

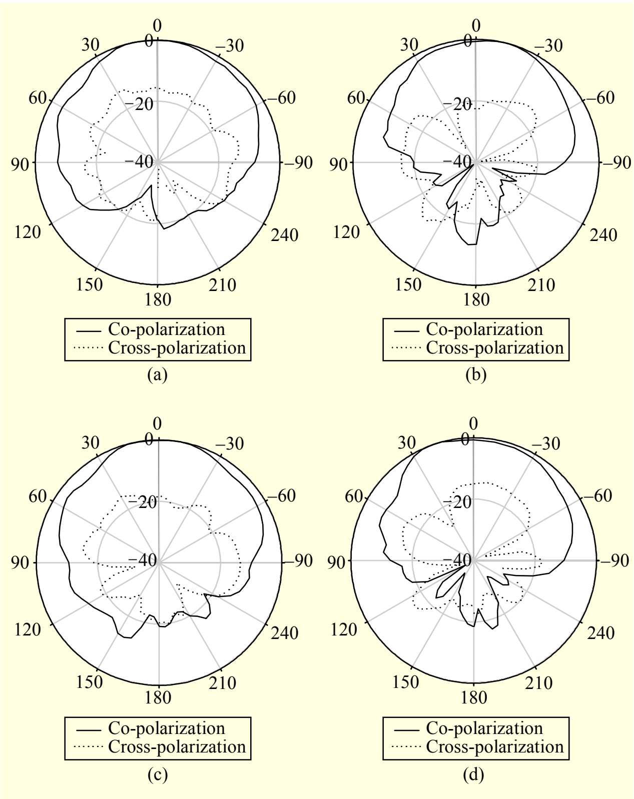

Fig. 10. Measured LP radiation patterns in the (a) x-z plane and (b) y-z plane for all diodes off at 2.62 GHz, (c) x-z plane and (d) y-z plane for all diodes on at 2.66 GHz.

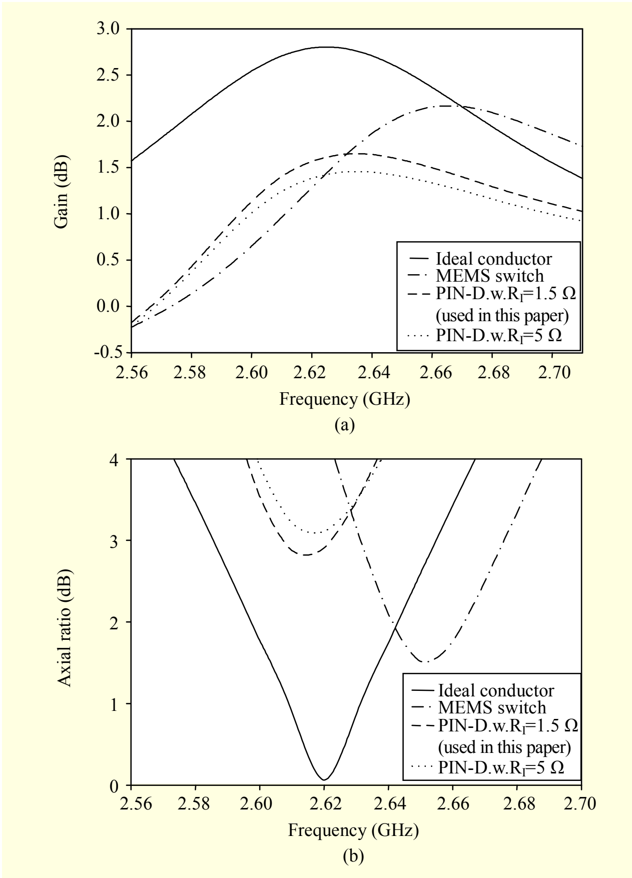

Fig. 11. Simulated results for the RHCP with four types of switch: (a) gain and (b) axial ratio.

the measured radiation patterns for LP when all diodes are off or on. The peak antenna gains were obtained at 1.87 dBi and 0.82 dBi, respectively. The cross polarization is below −20 dB. All simulated and measured data are summarized in Table 2. The measured bandwidth agrees very well with the calculation. In addition, the polarization diversity behavior is completely dependent on the PIN-diode status. The somewhat low gains and ARs are caused by non-ideal characteristics of the PIN-diode, the effects of which will be discussed in the following section.

2. Discussion of Switch Effect

To analyze the parasitic effects of switching devices on the antenna, the proposed antenna was simulated by Ansoft Designer with an ideal conductor, an MEMS switch ($R_I = 0.9\ \Omega$, $C_I = 0.04$ pF, and $L = 0.3$ nH), SDP510Q of the real PIN-diode ($R_I = 1.5\ \Omega$, $C_I = 0.26$ pF, and $L_p = 1.03$ nH) used in this paper, and an equivalent circuit model of the PIN-diode for a large resistance ($R_I = 5\ \Omega$, $C_I = 0.26$ pF, and $L_p = 1.03$ nH). Return loss, antenna gain, radiation pattern, and AR were analyzed for various sets of R_I and C_I from the equivalent circuit model.

Figure 11 shows the simulated gain and axial ratio for the RHCP with four types of switches. As the intrinsic resistance R_I increases, the antenna gain and axial ratio decrease without a frequency shift. On the other hand, when the intrinsic capacitance C_I increases, not only does the resonant frequency move down, but the gain and axial ratio decrease because of the higher cross polarization caused by the worse isolation of the diode. Therefore, the non-ideal RF characteristics of the PIN-diode used in this paper resulted in the low gains of around 1.5 dBi and the 3 dB AR bandwidth of 0.56%. This degraded performance compared to that of the ideal conductor should improve with a better RF switch, for example, MEMS. However, this switch is more expensive and has a slower response.

IV. Conclusion

A novel reconfigurable antenna for polarization diversity was demonstrated through simulation and measurement. A PIN-diode was modeled and used for a switching device. The proposed antenna for LHCP, RHCP, and LP was controlled by switching PIN-diodes. In addition, proper bandwidths and axial ratios were obtained. The new reconfigurable antenna should be useful for Korean satellite DMB systems requiring polarization diversities.

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