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DESIGN OF RECONFIGURABLE PATCH ANTENNA WITH A SWITCHABLE V-SLOT

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Abstract—In this paper we present the design of a novel Patch Antenna with Switchable V-Slot (PASVS) that resonates at two different frequencies. The antenna operates at the lower frequency when the switch is OFF and at the higher frequency when the switch is ON. This antenna is designed for special applications which need small frequency ratio. The different effects of the feeding position, slot location, and slot length are investigated in this paper. This investigation has been used to optimize the design of the PASVS antenna in terms of the return loss (RL), bandwidth, gain, and required frequency ratio.

1. INTRODUCTION

Many of the wireless communications today require antennas that operate at more than just one frequency while maintaining a small size [1]. Although patch antennas suffer from narrow bandwidths, different approaches have been used to increase bandwidths of patch antenna [2, 3]. In [4], E-shaped patch antenna using two slots is introduced to design an antenna resonating at two resonant frequencies.

In [5, 6], the design of patch antennas with switchable slots has been presented for different wireless communication applications, e.g., dual band, circular polarized antennas for the UHF band. Another design for a wideband, multiple frequency microstrip patch antenna based on multi-slots hole-coupled in a substrate has been presented in [3].

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PIN diodes have been used in different designs to develop reconfigurable antennas. It is explained in [6] how the antenna can be reconfigured at different frequency bands depending on the state of an embedded switch, which was implemented using a PIN diode. In [7], PIN diodes were used to shorten an annular slot antenna, which produce a reconfigurable antenna with a controlled radiation pattern. Pattern and frequency reconfigurable slot antenna has been obtained using matching stubs and PIN diodes [8]. The PIN diodes are used to connect or disconnect the stubs creating a reconfigurable matching network. Wu and Ma [9] developed an antenna that has the ability to switch its radiation pattern between three states by using three PIN diodes with a DC biased network. Another application using PIN diodes in reconfiguring the antenna is to achieve circular polarization diversity. This kind of reconfiguration has been presented in [10] by switching four diodes between ON and OFF, then the antenna can operate between two cases: right-hand circular polarization (RHCP) or left-hand circular polarization (LHCP) mode.

In this paper we propose a patch antenna with switchable V-slot (PASVS) to achieve the antenna reconfigurability. A switching diode is inserted between the two arms of a V-slot cut on the patch to control the antenna operation status using DC bias so that the antenna operates at two resonant frequencies corresponding to the ON and OFF modes of the switch. The shape of the V slot is expected to give an advantage in the frequency ratio than the one used in [5], because the V-shape has the ability to be longer (depends also on the angle of the V-shape) than using a slot parallel to the patch edge.

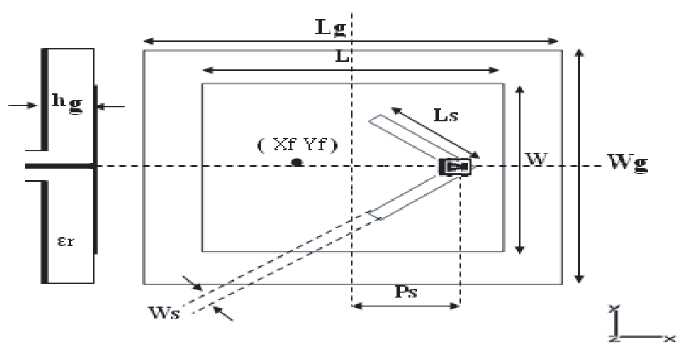


Figure 1. The geometry of a patch antenna with a switchable V-slot (PASVS).

2. OPERATIONAL MECHANISM OF PASVS

A basic PASVS structure is shown in Fig. 1. The antenna dimensions are $Lg \times Wg$. The antenna was designed and fabricated on a dielectric substrate with permittivity ε_r and thickness h_g. The material of the ground plane and patch is copper. A $50\,\Omega$ coaxial line is used to feed the antenna with an inner conductor connected at the feeding position (X_f, Y_f), where the dimensions are measured from the center of the patch. A V-slot with two arms, each with length L_s and width W_s, and a vertex at the position P_s was incorporated into the patch. A switch (which can be P-I-N diode or MEMS switch) was inserted between the two arms to change the resonant frequency.

We will study the behavior of the antenna in three modes: without the slot, with the slot when the switch is OFF, and with the slot when the switch is ON. We use it for the simulation of the Finite Integration Technique (FIT) based on the commercial software CST.

The ON and OFF modes are designed as explained in Section 8 of this paper, so that the effective length of the radiating patch is shorter in the case of the ON mode than in OFF mode, which leads to a resonant frequency in the ON case higher than the OFF mode.

In the OFF mode, the switch is removed from the simulation and the patch should be simulated with a complete V-slot. When the switch is ON, it is modeled as a metal tape. The configuration of the three modes are shown in Fig. 2.

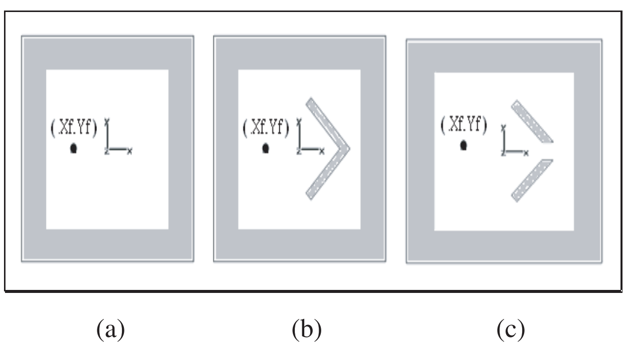
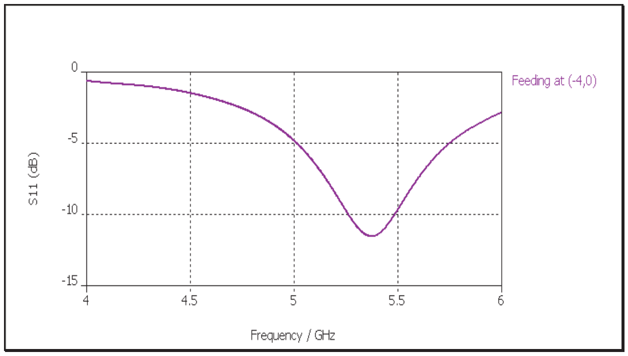


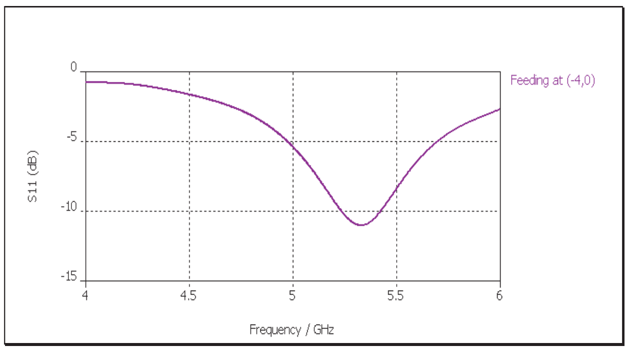
Figure 2. (a) The patch antenna without slot, (b) OFF mode, (c) ON mode.

As an initial design, we used a $25\,\text{mm} \times 25\,\text{mm}$ FR-4 substrate ($\varepsilon_r = 4.9$ and Loss tangent of 0.019) with thickness $h_g = 1.575\,\text{mm}$. The other patch parameters are listed below (in mm) according to Fig. 1:

$$L = W = 12,\ (X_f, Y_f) = (-4, 0),\ L_s = 6,\ W_s = 1,\ P_s = 4.25 \quad (1)$$



(a)



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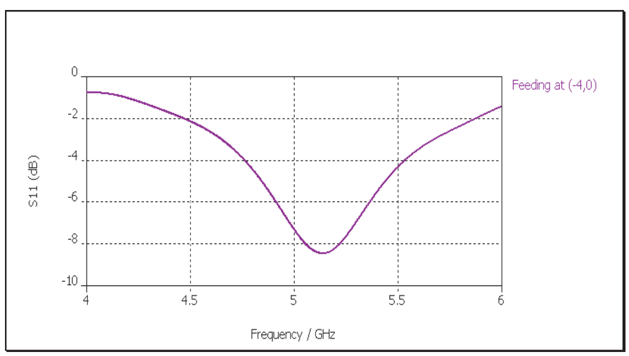


(c)

Figure 3. (a) Return loss for the patch antenna without slot. (b) Return loss for a patch antenna with the slot when the switch is ON. (c) Return loss for a patch antenna with the slot when the switch is OFF.

It is shown from Fig. 3(c) that the antenna in the OFF mode suffers from high return loss (-8.436 dB).

In order to optimize the design of the PASVS antenna, the effects of the feeding position, the slot position, and the slot length were investigated to improve the return losses in the two modes as well as the frequency ratio.

3. EFFECT OF DIFFERENT FEEDING POSITIONS

In this analysis, the antenna parameters remained the same as in Eq. (1), except that the feeding position X_f was changed from -4 to -1.5. Fig. 4 shows how the return losses for the ON and OFF modes changed with changing the probe position.

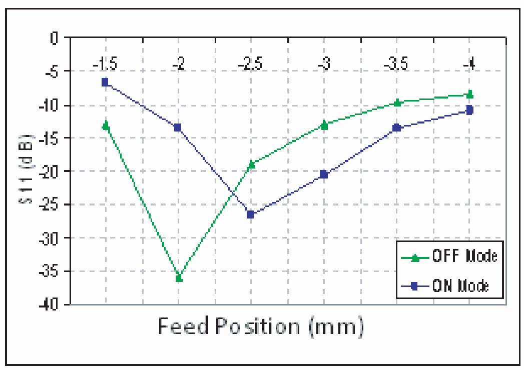


Figure 4. The effect of the different feeding positions on the return loss of the PASVS antenna.

In the ON mode, a good return loss could be obtained when the probe was located between -2 mm and -3.5 mm. In the OFF mode, a good return loss could be obtained when the probe was located between -1.5 mm and -3 mm. We can see from the figure an overlapping region between -2 mm and -3 mm, where the antenna could get good return losses for both of the modes. Since the point $X_f = -2.5$ mm was a satisfactory position where the antenna could match well for both the OFF and ON modes and since the gain obtained was acceptable in both of the OFF and ON modes, thus we chose the feeding point to be at $X_f = -2.5$ mm.

4. EFFECT OF THE SLOT LENGTH

The frequency ratio is defined as the ratio between the resonant frequency of the ON mode and the resonant frequency of the OFF mode. It can be controled by changing the slot length or position. The effect of the slot length is displayed in Fig. 5.

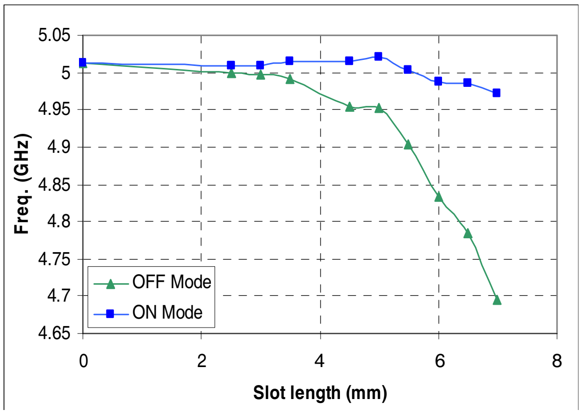


Figure 5. The simulated resonant frequency of the PASVS versus the slot length.

The patch antenna parameters were the same as in Eq. (1) except that we put the probe at $X_f = -2.5\,\text{mm}$. The slot length L_s was tested from 7 mm to 0 mm. It is noted that as the slot length increases, the resonant frequencies of the antenna decrease for both of the ON and OFF modes. Using the above results, we can choose an appropriate slot length to get a suitable frequency ratio. In all of the above cases, the antennas had return loss lower than $-10\,\text{dB}$ as shown in Fig. 6.

Another parameter which should be considered in the design is the bandwidth. Based on the results of Figures 5, 7, and 8 we can choose an appropriate slot length to get a suitable frequency ratio and bandwidth. We have chosen the slot length L_s to be 6.5 mm.

5. THE NEW ANTENNA SPECIFICATIONS AND RESULTS

Based on the above analysis steps, we have chosen our final design for the patch antenna with the following dimensions (see Fig. 1):

$$\begin{aligned} L &= W = 12\,\text{mm},\ (X_f, Y_f) = (-2.5\,\text{mm}, 0), \\ L_s &= 6.5\,\text{mm},\ W_s = 1\,\text{mm},\ P_s = 4.25\,\text{mm} \end{aligned} \tag{2}$$

The proposed patch without slot worked at 5.012 GHz, as shown in Fig. 10. When the slot was incorporated into the patch and the switch was turned ON, the antenna resonated at 4.986 GHz. Once the switch was turned OFF, the antenna frequency shifted to 4.784 GHz.

6. RADIATION EFFICIENCY AND GAIN

The 3D-radiation patterns for the two modes in this design were very similar to each other, which is an advantage for this design. Fig. 10 shows the radiation efficiency and gain for OFF and ON modes at their resonant frequencies. Figs. 11, 12, and 13 show comparisons between the copolarization and the crosspolarization at 4.784 GHz for the ON

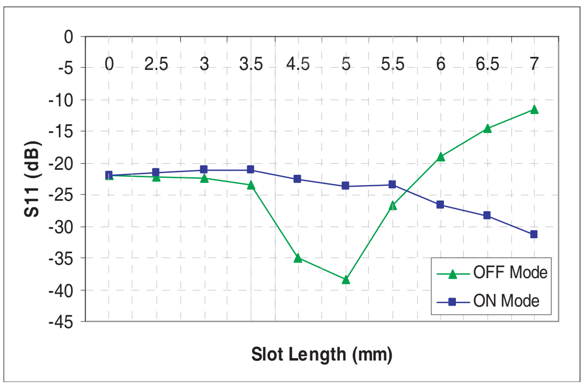


Figure 6. S_{11} versus the slot length.

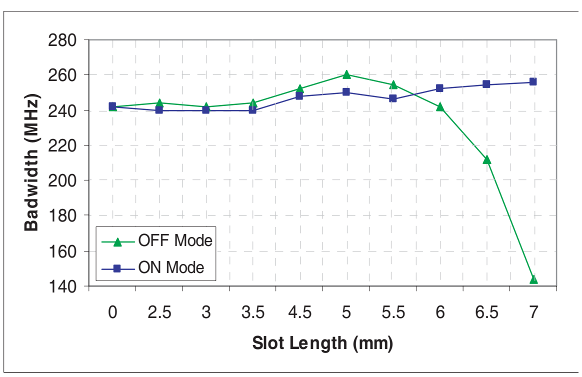


Figure 7. Bandwidth versus the slot length.

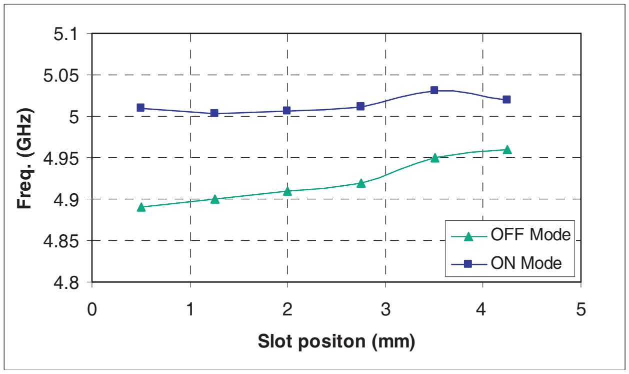


Figure 8. The resonant frequency of the PASVS (CST simulation) the slot position.

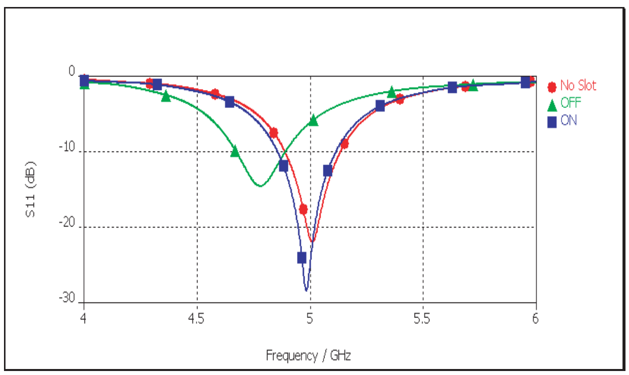


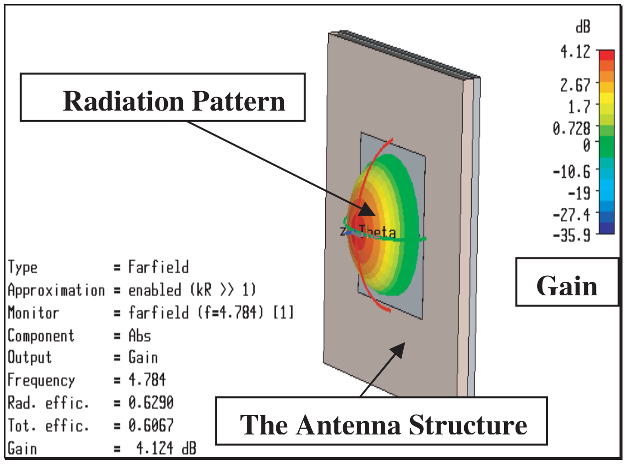
Figure 9. The CST-simulated S_{11} results of a PASVS for the ON/OFF modes of the switch, compared to a patch antenna without a slot. The frequency ratio of the two modes was 1.05.

and OFF modes in XZ and YZ planes.

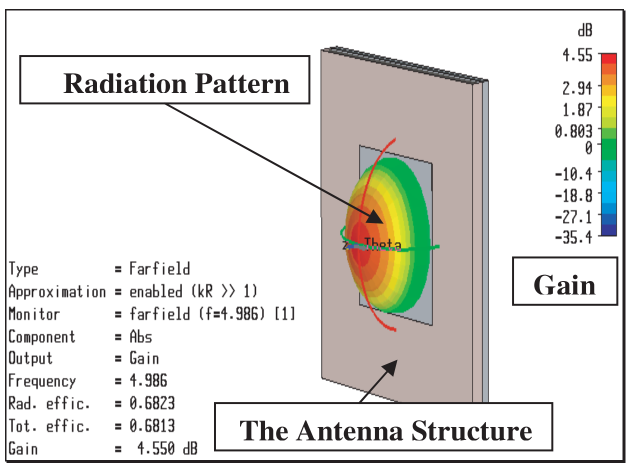
It can be seen from the figures that the crosspolar levels are very small compared to the copolar.

7. MEASURED RESULTS

The antennas were fabricated using FR-4 as a substrate ($\varepsilon_r = 4.9$ and loss tangent of 0.019 with 1.575 mm thickness). An SMA connector is used with a $50\,\Omega$ coaxial line to feed the patch. The dimensions of the patch antennas are the same as Eq. (2). The measured return loss of the fabricated antenna for both of the ON and OFF modes are shown in Fig. 13. The fabricated antenna has a return loss of −12.143 dB with bandwidth of 120 MHz and resonates at 4.89 GHz in the OFF mode and the frequency ratio is 1.078 while the frequency ratio for the

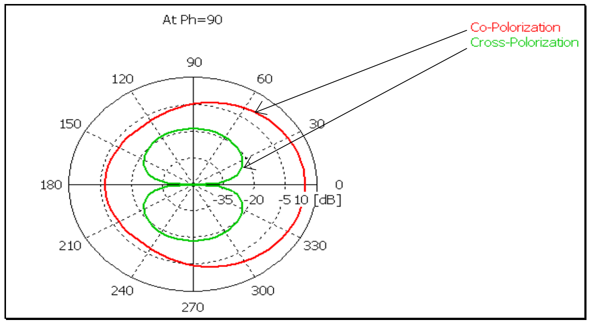


(a)

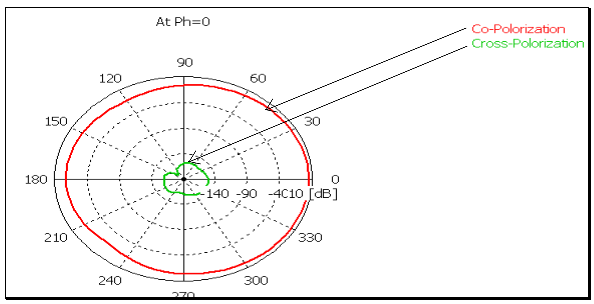


(b)

Figure 10. (a) The 3D radiation pattern for the antenna in the OFF mode having 63% efficiency and maximum gain of 4.12 dB. (b) The 3D radiation pattern for the antenna in the ON mode having 68% efficiency and maximum gain of 4.55 dB.



(a)



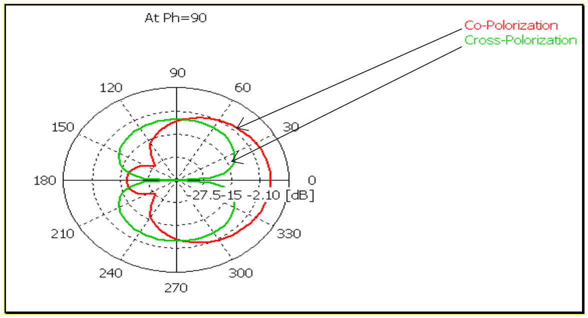
(b)

Figure 11. (a) Copolar and Crosspolar components at $\phi = 90$ for the OFF mode. (b) Copolar and Crosspolar components at $\phi = 0$ for the OFF mode.

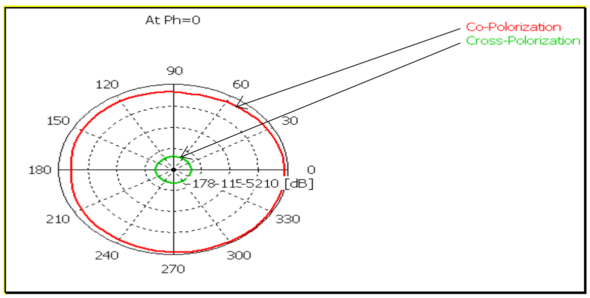
simulated antenna is 1.05. The radiation pattern and the gain were also measured. The gain versus frequency for both of the ON and OFF modes are shown in Fig. 14. It is found that the gain at the resonant frequencies are 4 dB for the ON mode and 2.8 dB for the OFF mode.

8. CURRENT DISTRIBUTION

Figure 15 shows the current distribution on the patch (with the dimensions of Eq.(2)), for the two cases of the switch (ON and OFF). In the two cases the current travels between two radiating apertures at the edges. It is shown in the figure that when the antenna is ON, part of this current flows through the metal of the switch, while when the switch is OFF the current flow around the slot to travel in a longer path. Therefore, the effective length of the patch is shorter in the case of the ON mode which corresponds to higher resonance frequency than in OFF mode.



(a)



(b)

Figure 12. (a) Copolar and Crosspolar components at $\phi = 90$ for the ON mode. (b) Copolar and Crosspolar components at $\phi = 0$ for the ON mode.

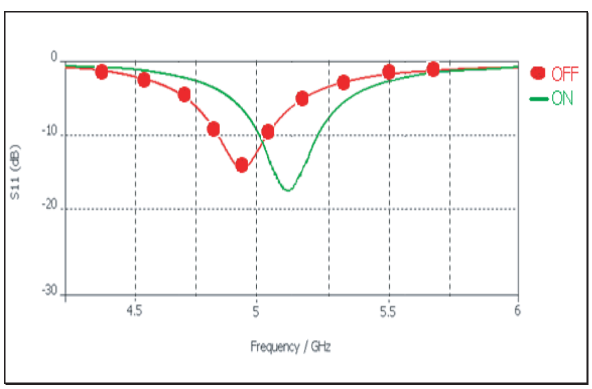


Figure 13. The measured S_{11} comparison for both of the OFF and ON switch modes for the fabricated antenna. The frequency ratio was 1.078.

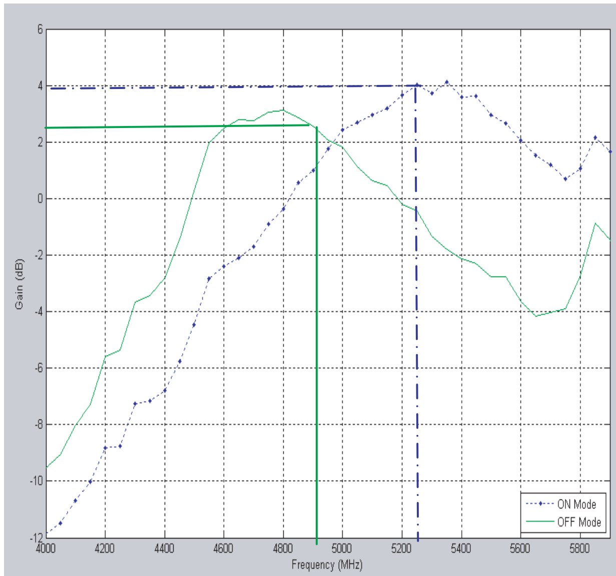


Figure 14. The measured total gain radiation pattern for both of the OFF and ON switch modes for the fabricated antenna.

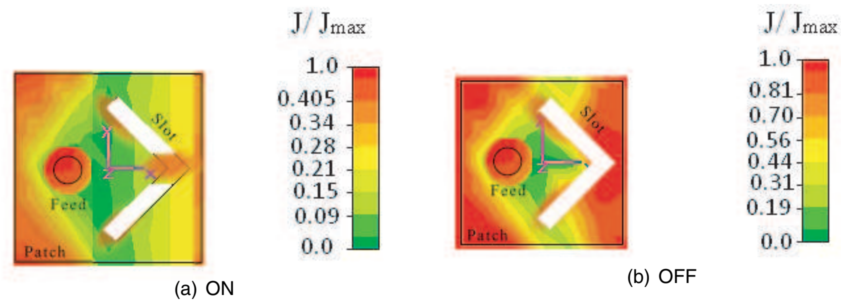


Figure 15. The normalized electric current densities (normalized to the maximum current $J_{\max}$ in the patch) on the patch at the resonant frequency for each of the two cases: (a) ON mode, (b) OFF mode.

9. CONCLUSION

A novel reconfigurable microstrip patch antenna with switchable V-slot has been designed, fabricated, and measured. The antenna has been designed to work at two operating frequencies with small frequency ratio. The effects of the feeding position, slot lengths, and slot position on the return loss, bandwidth, and frequency ratio have been investigated. Both the simulated and the measured results are acceptable in terms of the return loss, bandwidth, gain and required frequency ratio.

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