Effect of PIN Diode Integration on Patch Antennas for Frequency Reconfigurable Antenna Applications

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Abstract

PIN diodes are commonly used to design reconfigurable antennas owing to their sufficient isolation, lower cost, and ease of fabrication. This study aims to explore the effect of biasing conditions of a PIN diode radio frequency (RF) switch on a frequency-reconfigurable antenna. This approach investigates the contribution of the forward diode current and the reversed biased voltage on the shift in the operating band, the impedance matching, and the radiation efficiency of a reconfigurable antenna. The benefits and drawbacks of different approaches to modeling PIN diode RF switches are demonstrated on Ansys electromagnetic switch. The result shows a significant match between simulated and measured operating bands, impedance matching, and radiation efficiency. The proposed RF switch model can be used as a practical simulation model for implementing various reconfigurable microwave components.

Keywords: biasing circuit, microstrip antenna, PIN diode switch, reconfigurable antenna, RF switch

1. Introduction

Microstrip antennas are one of the most popular printed antennas which play a significant role in today's wireless communication systems. Extensive developments including bandwidth enhancement, surface wave reduction, gain enhancement, and radiation efficiency improvement are aimed at fulfilling the requirements of existing and future communication systems, which have made the microstrip antenna an important element in the field of radio frequency (RF) and microwave engineering. In recent years, research interests have been focused on increasing the features of microstrip antennas as multi-band [1-3], wideband [4], multi-polarization [5], switched parasitic Multiple-input-multiple-output antennas [6], and frequency, polarization, and pattern diversity.

Reconfigurability can be achieved through two methods, (i) modifying the length of the current path or (ii) placing the slotted filters into the antenna structure using RF switches [7]. Naturally, changing the state of the RF switches modifies the impedance levels which in turn modulates the frequency response of the antenna. The application of numerous reconfigurable antennas has been reported in the literature, and novelty is observed in terms of the type of reconfigurability (frequency, pattern, or polarization), design simplification, or improvement in the antenna parameters. The RF switch is a key component of reconfigurable antenna modeling and biasing conditions have a significant effect on its performance, durability, and robustness. An electronic RF switch draws a significant amount of current; thus, it is essential to estimate the requirement of the power supply for reconfigurable operations.

Previous research has proposed the different models use, including an ideal open and short circuit and a diode equivalent circuit without direct current (DC) blocking capacitors of the RF PIN diode switch for reconfigurable antennas. The DC blocking capacitors and RF blocking inductors are necessary components to protect the RF signal and diode biasing source,

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respectively. Investigation into the isolation and insertion loss of these switches after integrating them into a microwave system is required to ensure the desired switching operations. However, the switching operation of a PIN diode RF is greatly dependent on the biasing elements and conditions.

Moreover, due to the rapid development of computer-added, it is convenient and common practice to use a software package to design and analyze a new system. Although the accuracy of the simulation results is completely dependent on the accuracy of the component models, defined in the software package. Nevertheless, the reconfigurable antenna is a well-established field, neither modeling nor biasing conditions of the RF switches for reconfigurable antenna application are discussed in the literature.

This paper aims to demonstrate the (i) effect of the different RF switch models and (ii) biasing conditions on the radiation performance of a reconfigurable antenna. The use of different RF switches in optical [8-9], MEMS [10], FETs [11], PIN diodes [12], and micro-fluids [13] reconfigurable antennas have been proposed. Optically controlled reconfigurable antennas are extremely delicate, thus, making them difficult to implement for practical applications [8-9]. MEMS RF switches require higher operating voltage and are relatively higher in cost [10].

On the contrary, FET-based switches require low operating power and are cheaper, but suffer from higher loss and poor linearity. PIN diode-based switches offer a low-cost and low-loss solution [12]. Hence, most of the reconfigurable antennas, frequency [14-18], polarization [19-21], and pattern [22-23] proposed in the literature are developed using a PIN diode RF switch. Vian and Popovicet.al. [8], achieved frequency, pattern, and polarization reconfigurability by incorporating eight PIN diodes in a single antenna structure. The compound reconfigurability of the antenna is remarkable but the integration of numerous PIN diodes makes the overall structure too complicated for fabrication and installation. However, considerable results have been obtained so far due to ease of integration and moderate isolation. Thus, in this work, the PIN diode RF switch was chosen to identify the effect of the RF switch modeling and biasing the conditions on the accuracy, durability, and performance of reconfigurable antennas.

Numerous studies of reconfigurable antennas using different switching elements have been proposed for decades. The novelty of most of these antennas lies in their structure or switching mechanism. However, a detailed investigation of the antenna characteristics concerning the biasing conditions is unavailable in the previous studies. The investigation is imperative to establish the trade-off between antenna performance and DC power consumption.

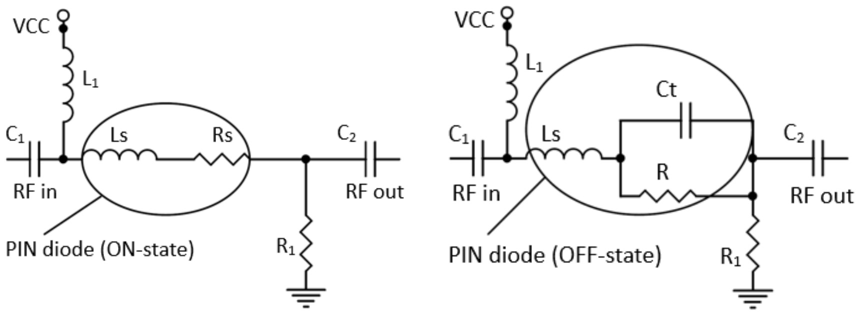
The present study emphasizes the antenna characteristics against the supplied forward current and reverses bias voltage. The effects of bias conditions on the performance of a PIN diode-integrated reconfigurable antenna are reported using a simple slotted rectangular patch antenna. A trade-off between the antenna radiation performance and the diode current was established. A detailed analysis of a frequency reconfigurable antenna against the RF switch model and the biasing condition of the switch has been presented. A PIN diode RF switch integrated rectangular slot has been incorporated into the patch of a conventional rectangular patch antenna to obtain dual-band frequency reconfigurability.

In the simulation, the performance of the antenna has been analyzed using an ideal switch model and an actual switch model. Thereafter the forward diode current and the reverse diode capacitance were varied to observe the effect of the biasing conditions on the performance of the antenna. The prototype of the frequency reconfigurable antenna was developed, and its scattering parameter and radiation efficiency were experimentally analyzed for different biasing conditions. During simulation, it was found that the other antenna parameters, such as radiation pattern, half-power beam width, etc., were not significantly affected by the biasing conditions, thus, experimental results have not been presented. The ideal model of the switch has been shown to exhibit an unacceptable frequency shift after fabrication, making it unacceptable for simulation. This study proposed the switch model has a good agreement amongst simulation and measured performance of the antenna.

2. Configurations and Modeling of RF Switch

Series and shunt are commonly used configurations of PIN diode RF switch [24] as shown in Fig. 1. The isolation and insertion loss of a series configuration switch depends on the OFF-state diode capacitance (Ct) and the ON-state diode resistance (Rs), respectively. On the other hand, the isolation and insertion loss of a shunt configuration depends on the ON-state diode resistance (Rs) and the OFF-state diode capacitance (Ct), respectively. However, in a shunt configuration switch, the switching element is not directly connected to the RF transmission line; thus, providing lower insertion loss than the series configuration switch. Moreover, the series configuration of the PIN diode RF switch (shown in Fig. 1.) is easy to integrate with reconfigurable antenna applications as has been widely reported in the previous literature. In Fig. 1, capacitors C_1 and C_2 are the DC blocking capacitors, R_1 is a current limiting resistor, L_1 is used to protect the DC power supply from RF signals, and LS is the diode inductance.

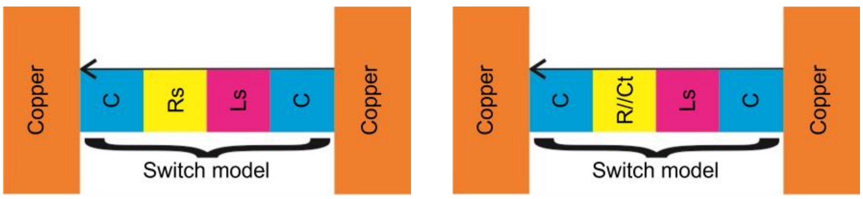
Using Ansys Electromagnetics Suite, a high-frequency-structural-simulator (HFSS), an equivalent circuit was designed by assigning the lumped R-L-C boundary to the multiple 2D or 3D interconnected structures. A single structure can be modeled as a single component or a parallel combination of R-L, R-C, L-C, or R-L-C circuits. However, it is necessary to define the direction of the current flow while assigning the lumped R-L-C boundary.



(a) ON-state (b) OFF-state

Fig. 1 Series configuration of an RF switch

In this work, a 2D sheet was chosen to model a PIN diode RF switch in the ON-state and the OFF-state, as shown in Fig. 1. Excluding biasing elements, four interconnected structures are required to model a PIN diode RF switch in the ON-state or the OFF-state, as shown in Fig. 2. For the ON-state, the parallel combination of R and Ct is replaced by Rs as shown in Fig. 2(b). Moreover, the dimensions of sheets are chosen based on the dimensions of the practical surface-mount capacitors and diodes. The values of Ls, Ct, and Rs can be found in the technical datasheet of the respective diode [25].



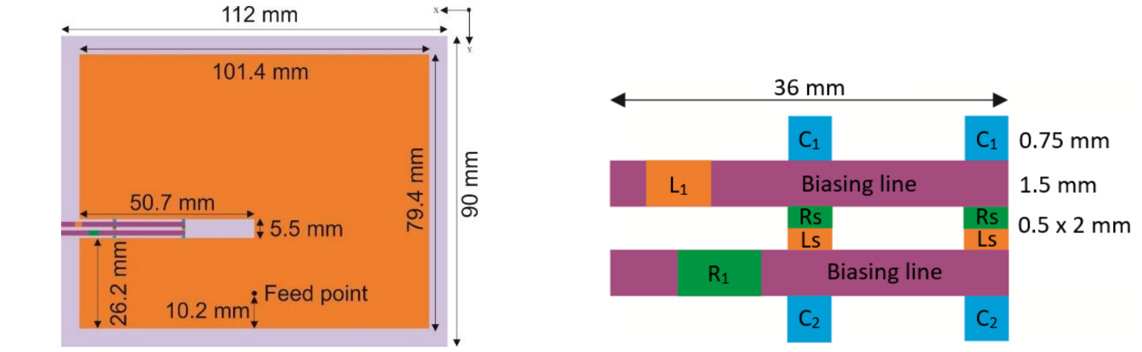
(a) ON-state (b) OFF-state

Fig. 2 Model of PIN diode RF switch in the Ansys Electromagnetics Suite, HFSS

3. Performance Analysis of the Frequency Reconfigurable Antenna

In this section, a conventional rectangular patch antenna was designed, and a rectangular slot integrated with two PIN diode RF switches introduced frequency reconfigurability. The antenna was designed on an FR4 substrate of thickness 1.6 mm and fed through a 50 Ω co-axial sub-miniature version-A (SMA) connector. The FR4 substrates are commonly used for printed circuit board (PCB) development and are much cheaper compared to other low-loss substrates such as Rogers RT Duroid.

Also, a low-frequency patch antenna exhibits acceptable performance for the FR4 substrate of loss tangent 0.02. The configuration of the antenna and magnified view of the switch model is shown in Fig. 3. The proposed antenna configuration and the magnified view of the biasing arrangement are shown in Fig. 3.



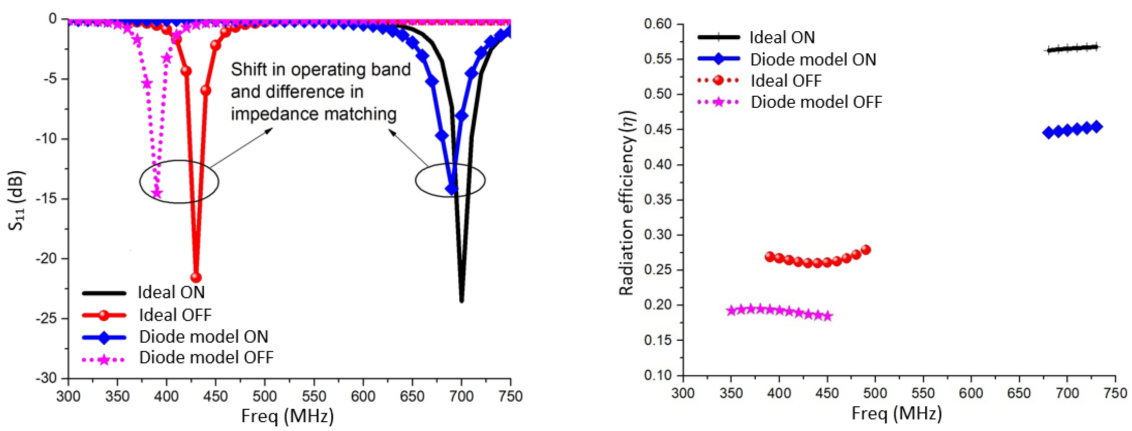
(a) Test antenna layout (b) Switch model

Fig. 3 Configuration of the frequency reconfigurable antenna (L_1 = 1 mH, R_1 = 100 Ω, C_1 = C_2 = 1 uF, Rs, and Ls are taken from datasheet)

3.1. Simulation analysis

This section presents the performance of the frequency reconfigurable antenna against different switch models and biasing conditions. In the ideal condition, for the OFF-state, all the circuit elements and biasing line have been removed and for the ON-state, two copper sheets were used to establish the connection. The switch model discussed in Section 2 was used as a practical switch. The biasing conditions were controlled by changing the ON-state resistance, and the OFF-state capacitance, as presented in the technical datasheet of the PIN diode NXP BAP65-02 [25].

The proposed antenna is intended to operate in 400 MHz wireless medical telemetry service (WMTS) and 700 MHz global system for mobile (GSM) bands. Thus, the PIN diode NXP BAP65-02 is chosen, which is known to support the intended frequency range. If another diode is used, the series inductance, ON-state resistance, and OFF-state capacitance will change accordingly. The PIN diode NXP BAP65-02 has sufficiently good isolation in the OFF-state and low insertion loss in the ON-state, as presented in its technical datasheet [25]. The antenna response was obtained for the ideal switch and the practical switch model, as shown in Fig. 4. In an ideal case, the switch positions are open and short in the OFF-state and the ON-state, respectively. In practice, for the ON-state, a diode resistance of 0.35 Ω is set, corresponding to 100 mA forward diode current. Similarly, in the OFF-state, the capacitance was set to 0.375 pF, corresponding to 20 V reverse voltage. The variation in NXP BAP65-02 ON-state diode forward resistance and OFF-state junction capacitance against the forward current and the reverse voltage, respectively listed in Table 1, is reproduced from the technical datasheet [25].



(a) Scattering parameter (S_{11}) of the antenna for different diode models (b) Radiation efficiency of the antenna for different diode models

Fig. 4 Performance of the antenna for the ideal condition of the switch and PIN diode RF switch model

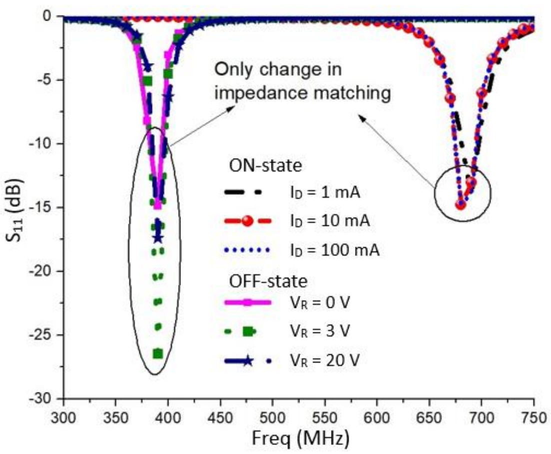
Table 1 NXP BAP65-02 characteristics [25]

Forward characteristics		Reverse characteristics	
Forward current (mA)	Forward resistance Rs (Ω)	Reverse voltage (V_R)	Junction capacitance C_d (pF)
1	1	0	0.65
5	0.65	1	0.55
10	0.56	3	0.5
100	0.35	20	0.375

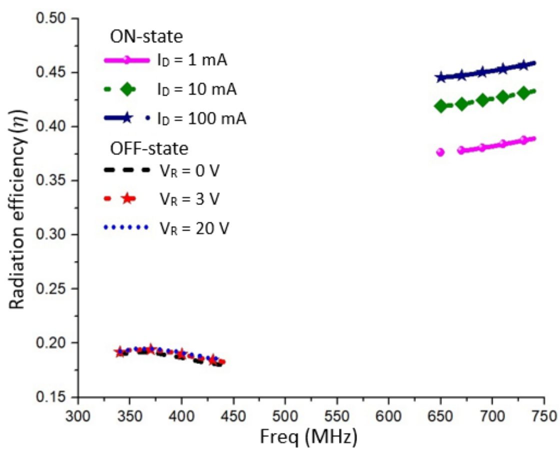
The scattering parameters and the radiation efficiency of the antenna are shown in Fig. 4. It is evident in Fig. 4(a) that there is a considerable difference between impedance matching as well as operating bands for both conditions. Moreover, in the OFF-state, the operating bands are completely different, confirming the incapacity of the ideal diode model. To develop an electronically reconfigurable antenna, practical diode(s) are integrated into the antenna structure. When these active elements are added to the antenna structure, the distributed reactance sufficiently changes, leading to the shift in series or parallel resonance center frequency. Thus, the shift in the operating band should be accounted for to develop a practical electronically reconfigurable antenna.

In Fig. 4(b), it can be observed that the ideal model of the diode exhibits much better radiation performance than a practical model, which confirms the significant losses due to the integration of PIN diode RF switches. Although, it should be noted that the antenna has poor radiation efficiency in the OFF-state than the ON-state. The performance of the reconfigurable antenna was further analyzed to consider the different biasing conditions. In the ON-state, the forward diode current was increased stepwise to observe its effect on the shift in the operating band, the impedance matching, and the radiation efficiency. In the OFF-state, the reversed biased voltage is varied to analyze the antenna performances.

The forward current and reverse bias voltage change did not shift the operating bands, as shown in Fig. 5(a). However, a remarkable change in the impedance matching can be observed in the OFF-state. A higher forward diode current yields better radiation efficiency, whereas the reverse bias voltage did not affect the radiation performance, as shown in Fig. 5(b). The simulated radiation patterns against different biasing conditions are shown in Fig. 6. It has been observed that there is a negligible effect of the biasing conditions on the radiation pattern in both the OFF and ON conditions. However, in the ON-state, the back radiation pattern of the antenna is slightly affected, as shown in Fig. 6(b). It has been noticed in Fig. 5(b) that higher forward current yields more radiation from the antenna structure, which holds for the front as well as back radiations. Therefore, as the forward current increases, the back radiation of the antenna also increases due to improvement in the radiation efficiency.

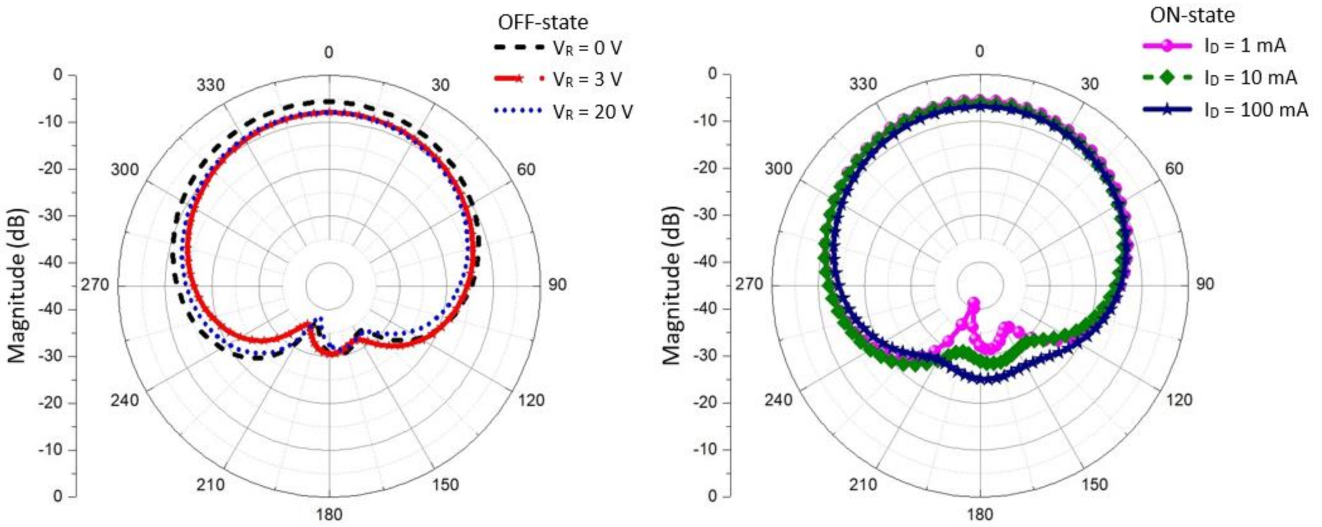


(a) Scattering parameter (S_{11}) of the antenna in ON-state and OFF-state against different forward current and reverse voltages, respectively



(b) Radiation efficiency of the antenna in ON-state and OFF-state against different forward current and reverse voltages, respectively

Fig. 5 Simulated performance against different biasing conditions



(a) OFF-state E-plane radiation pattern at 400 MHz (b) ON-state radiation pattern at 700 MHz

Fig. 6 E-plane radiation pattern of the antenna in ON-state and OFF-state against different forward current and reverse voltages, respectively

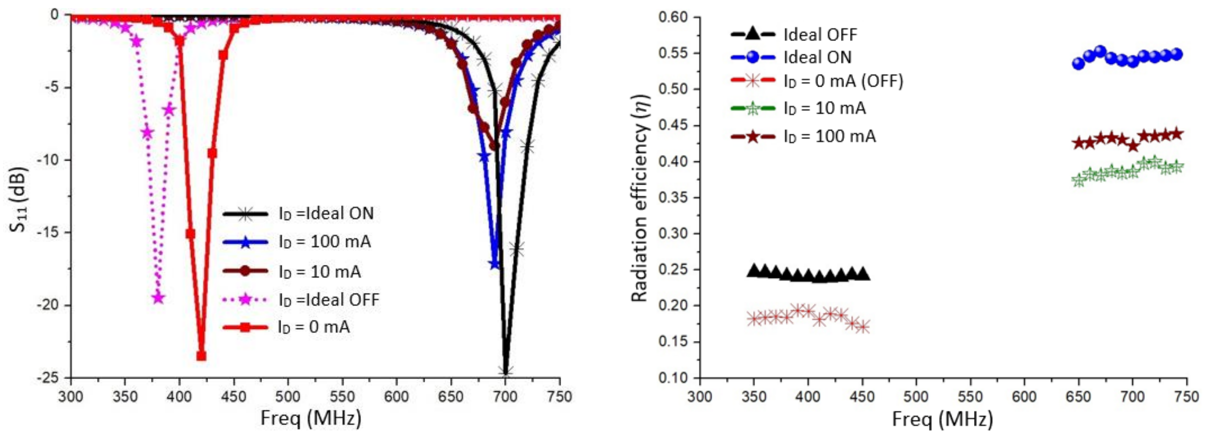
3.2. *Experimental analysis*

A physical prototype of the antenna was developed and experimentally analyzed to validate the simulated observations. The prototype of the antenna with the S_{11} parameter measurement setup is shown in Fig. 7. The PCB of this design can be developed using a traditional chemical etching process or a PCB milling machine. A PCB milling machine is a non-chemical computer-aided machine that creates a high-quality PCB by milling the metals from a PCB laminate. The computer guides the milling bits as per the layout provided. To realize a prototype with an ideal diode model, the switch positions were open and short for the OFF-state and the ON-state, respectively.

(a) Scattering parameter measurement setup (b) Top view of the prototype (c) Top view of the prototype

Fig. 7 S_{11} measurement setup and prototype of the antenna

For a practical realization, two surface-mount capacitors were soldered at the anode and cathode of a PIN diode NXP BAP65-02. The RF switches were biased using a DC power supply. The S_{11} parameters were measured using a two-port network analyzer. The radiation efficiency (η = G / D) is measured using the gain (G) / directivity(D) method, as suggested by Huang [26] and Kumar et al. [27]. The gain of the antenna was measured using the two-antenna method and divided by the simulated directivity to estimate the radiation efficiency. The discussion on radiation efficiency presented is derived from the measured gain. However, the measured gain curve is not presented in this paper. The measured S_{11} parameters and the radiation efficiency of the antenna against forward diode current are shown in Fig. 8. Since the reverse bias voltage does not significantly affect the antenna performance, the corresponding experimental analysis was not conducted. An unacceptable shift in the operating band for the OFF-state and a slight shift in the ON-state can be observed in Fig. 8(a) for the ideal and the practical diode models, as observed during simulation analysis.

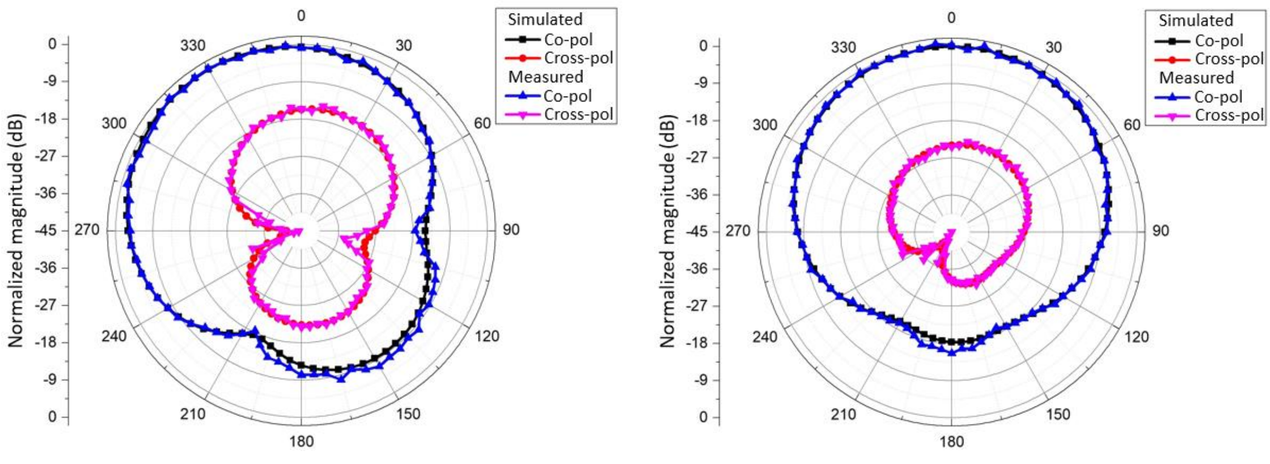


(a) Measured scattering parameter (S_{11}) against the forward current

(b) Measured radiation efficiency against the forward current

Fig. 8 Measured performance against different biasing current

However, for a forward current of 10 mA, the antenna has extremely poor impedance matching. In the ON-state, the measured radiation efficiency for the ideal diode model is nearly 11% better than the practical model with a diode forward current of 100 mA. As observed in the simulation, the measured radiation efficiency of the antenna is extremely poor in the ON-state. The simulated and measured radiation patterns of the fabricated prototype have been presented in Fig. 9. The antenna radiation pattern is measured using a radiation pattern measurement setup that consists of an RF source, a spectrum analyzer, a turntable with an automated data logger and 360° rotatable antenna stand to hold the antenna under test (AUT), and another 360° rotatable antenna stand to hold the source antenna. This setup is placed in an electromagnetically shielded chamber. In the ON-state, the antenna has perfect broadside radiation, and the co and cross-polarization isolation is more than 18 dB. In the OFF-state, the antenna has a slightly tilted main lobe, and the isolation between co and cross-polarization is more than 16 dB. A good agreement has been demonstrated between simulation and measured results which validates the proposed work.



(a) Simulated and measured E-plane radiation at 690 MHz in ON-state

(b) Simulated and measured E-plane radiation at 420 MHz in OFF-state

Fig. 9 Simulated and measured E-plane radiation pattern of the fabricated prototype

4. Conclusions

An investigation on reconfigurable antenna characteristics against different diode models and biasing condition of the diode has been carried out. During the simulation, the reactance of a diode should be considered to develop a practical antenna to avoid a mismatch between simulated and measured results. Increasing the diode forward current can improve the impedance matching and the radiation efficiency of an antenna. The reverse bias voltage has an insignificant effect on the radiation performance. However, the OFF-state radiation efficiency is poor when the diode is not active. The result shows that the proposed RF switch model has good impedance matching, radiation efficiency, and co and cross-polarization isolation. The proposed method also be performed for other active switching elements such as a varactor diode, field-effect transistor, and bipolar junction transistors.

Conflicts of Interest

The authors declare no conflict of interest.

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