

Research Article

Characterization and Performance Evaluation of PIN Diodes and Scope of Flexible Polymer Composites for Wearable Electronics

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Different semiconductor materials have been used for the fabrication of PIN diodes such as Si, Ge, GaAs, SiC-3C, SiC-4H, and InAs. These different semiconductor materials show different characteristics and advantages such as SiC-4H is ultrafast switch. But, when flexible polymers composites like Si-nanomembranes, polyethylene terephthalate (PET), and biodegradable polymer composite like carbon nanotubes (CNT) are used for fabrication, the device has the capability to switch from rigid electronic devices to flexible and wearable electronic devices. These polymer composites' outstanding characteristics like conductivity, charge selectivity, flexibility, and lightweight make them eligible for their selection in fabrication process for wearable electronics devices. In this article, the performance of PIN diodes (BAR64-02) as an RF switch is investigated from 1 to 10 GHz. PIN diodes can control large amounts of RF power at very low DC voltage, implying their suitability for RF applications. In this paper, the benefit of using plastic polymer composites for the fabrication of PIN diodes, capacitors, and antennas is thoroughly described. Along with this, individual characterization, fabrication, and testing of all biasing components are also done to analyze the individual effect of each biasing component on the performance of PIN diodes. The complete biasing circuitry for the PIN diode is modeled in the HFSS software. When a PIN diode is inserted in between 50 Ω microstrip line, it introduces 1 dB insertion loss and 20 dB isolation loss from 1 to 7 GHz. Finally, a PIN diode is integrated in a reconfigurable antenna to study the actual effect. The transmission loss in the RF signal is nearly 1 dB from 1 to 7 GHz in the presence of biasing components.

1. Introduction

The exclusive properties and features of flexible electronics like high elasticity, durability, stability, being extremely lightweight, and the ability to be fabricated on rough surfaces make them a splendid aspirant for extensive applications. The areas of flexible electronics have been continuously advancing every single day, from new research in compatible materials to new procedures for fabricating such devices in alternative shapes, in a quicker, economical, and more handy manner [1–2]. Flexible electronics interact with surroundings in ways that were not possible earlier. Many consumer applications, including folding phones, rollable large-area displays,

electronic textiles, biomedical sensors, and flexible integrated circuits, are only possible due to the advancement in fabrication techniques. These advanced fabrication processes introduce the ultra-downscaling capability of silicon [1–4], which convert rigid wafers into single-crystal Si-nanomembranes (SiNMs). Therefore, silicon attracts researchers' interest for its incorporation into flexible electronics area. The ultrathin and transferrable single-crystal Si can be easily released from SOI and easily integrated on plastic polymer substrate using an elastomer stamp [5–6]. A large number of semiconductor materials such as amorphous silicon, polycrystalline silicon, organics, and polymers have been used for low-frequency flexible electronics because they suffer low crystalline quality

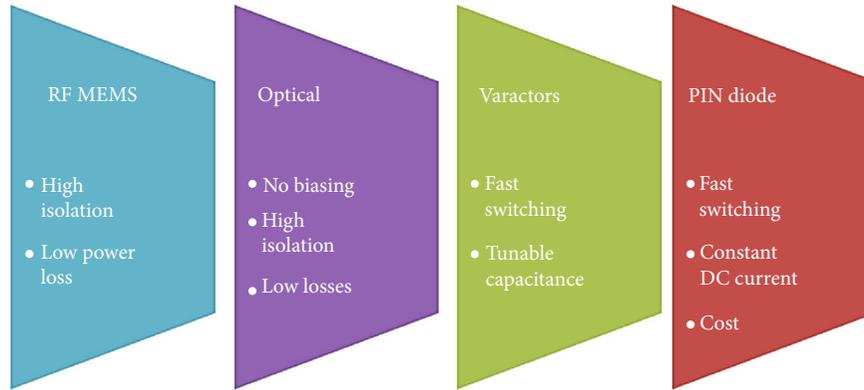


FIGURE 1: Performance comparison of various switches.

and low carrier mobilities. On the other hand, flexible low-cost polyethylene terephthalate (PET) substrates and single-crystal Si-nanomembranes (SiNMs) offer high carrier mobilities so these materials are well suited for microwave applications [5–8]. In the literature, a lot of flexible plastic substrates are available to realize flexible electronics like PET, polyethylene naphthalate (PEN), polycarbonate (PC), polyethersulfone (PES), and polyimide (PI). Nowadays, many compound semiconductors could also be released into thin membrane forms to attain mechanical flexibility while maintaining their outstanding electronic properties. Hence, semiconductor properties like high electron mobility (GaAs, InGaAs, InAs, GaN), wide band-gap (GaN), and high breakdown electric field (GaN) are maintained along with additional mechanical flexibility [9–12]. Many printing technologies have been already advanced like roll-to-roll, inkjet, screen-printing, vacuum-based deposition, and polydimethylsiloxane (PDMS)-assisted transfer printing techniques, which can transfer semiconductor properties on a plastic polymer substrate [10–17].

RF switches are key component for controlling the linking between different circuits in a reconfigurable device [18] at RF frequencies. A perfect RF switch provides negligible resistance in the ON state and very high resistance in the OFF state to the signal flow. However, practical RF switch provides definite values of impedance in the ON and OFF state. Several types of RF switches like MEMS, optical, and semiconductor are reported in the literature for altering the performance of a reconfigurable system [19–21]. All of these switches have certain advantages and drawbacks. The MEMS switching devices have the advantage of very high isolation with minimum power loss, but certain disadvantages such as high operating voltage (20–100 V), very low switching speed (1–200 seconds), high cost, and lower reliability restrict the use of MEMS switches [22–25]. The optical switches provide very high isolation and require no DC bias for their activation. They can be simply incorporated into a device without any DC bias lines hence eliminate redundant interference and radiation pattern alteration [26–28]. However, optical switches have lossy performance and very complex activation procedure. Various semiconductor switches like varactor [29–32], PIN are usually used in the reconfigurable system because they are a faster and more compact substitute to RF-MEMS [33–37]. The advan-

tages of semiconductor switches include fast switching, high isolation, low power consumption, and low operating voltage (0–10 V). Different switches are selected depending on the suitable application. For example, a fast and discrete switching response requires PIN diode [34], while a continuous tuning response requires a varactor diode [31]. The PIN diode offers high switching speed (1–100 ns) and high isolation compared to other semiconductor switches. Reconfigurable antennas using PIN diodes [38–41] have more degrees of freedom in choosing different reconfiguration states. Researchers can choose the appropriate switch for specific application by keeping the individual performance of switch in their mind. Figure 1 depicts an illustration that compares the different properties of the different switching mechanism for operation. PIN diode is best option among semiconductor switches if cost, switching speed, and isolation are concerned. If a microwave PIN diode is fabricated using a flexible material like SiNM and PET polymers, then high semiconductor performance can be achieved along with attractive mechanical features. In this paper, working operation and characterization of microwave PIN diode as an RF switch and different techniques and materials used to fabricate flexible PIN diode are presented.

2. PIN Diode: Preface

PIN diodes can be fabricated using different combinations of semiconductor materials like Ge and Si. If a wide-band-gap material is used for fabrication, then the PIN diode can handle high operating voltage as well as extreme temperature surroundings. SiC PIN diodes can handle high voltage and offer very high speed, whereas InGaAs on InP substrates give lower turn-on voltage for PIN diode. If a PIN diode is fabricated using an SOI substrate, then it gives high-voltage-handling capability and high reverse breakdown voltage. Also compound semiconductors have played crucial roles in high-frequency electronics because of their extraordinary material properties like high electron mobility (GaAs, InGaAs, InAs, GaN), wide bandgap (GaN), high breakdown electric field (GaN), and high thermal stability (GaN). These compound semiconductors can also be released into thin membrane forms to achieve mechanical elasticity while maintaining their electronic properties.

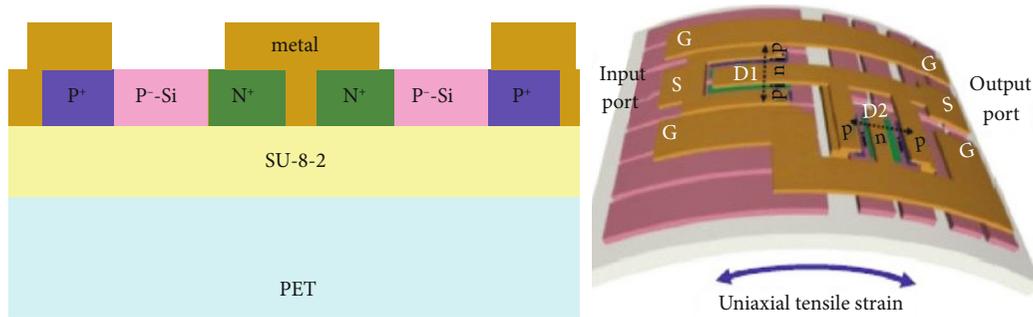


FIGURE 2: Schematic cross section of Si nanomembrane PIN diodes on a flexible PET substrate [12].

PIN diode can be fabricated using flexible single-crystal SiNM, which can be easily integrated on a low-cost plastic substrate for high performance [16–17]. The fabrication process of the flexible PIN diodes on a plastic substrate by using the SiNM transfer technique is entirely well matched with that used to fabricate flexible thin film transistors. The fabrication process starts with a lightly doped p-type Si (0 0 1) UNIBOND SOI substrate with a 200 nm Si top layer and a 200 nm buried oxide (BOX) layer. Optical photolithography is used to define the heavily doped n- and p-type regions in the top Si layer. The flexible single-crystal Si PIN diodes that are monolithically integrated on a low-cost, low-temperature, PET substrate [12] as shown in Figure 2. Flexible and stretchable passive components like inductors and capacitors are essential elements for RF filters, bias networks, power dividers, and impedance matching networks. Flexible inductors and capacitors can also be fabricated not only on plastic substrate but also on biodegradable carbon nanofiber (CNF) (polymer composite) substrates for environmental-friendly applications [10, 13]. The polymer composite CNFs gives excellent mechanical properties along with high electrical conductivity.

The semiconductor device PIN diode is used as an RF switch and its performance mainly depends on the layout, dimensions, and the temperament of the semiconductor material used in fabricated prototype. The sketch of a PIN diode is depicted in Figure 3. It is fabricated by inserting a wide region of intrinsic semiconductors among p-type and n-type semiconductors. In this, heavy doping of p- and n-type regions is done to get good ohmic contacts. On the other hand, the central I layer is lightly doped and wider in nature compared to p and n layers. Therefore, due to the wide I layer, PIN diodes have low junction capacitance, very high carrier lifetime and very high breakdown voltage. PIN diodes perform as switches due to the high-level injection. When the diode is in the OFF state, it is non-conductive. But when the PIN diode is in the ON state, high-level injection takes place and it behaves as a variable resistor. When it is forward-biased, the concentration of charge carrier in the p and n regions is higher than the intrinsic concentration in the I region. Therefore, E field expands on the whole length of the I region because of high-level injection. This extended E field increases the speed of transportation for charge carriers from p to n layers. As a consequence of this, the diode has faster operation and hence best suitable for high-speed RF applications.

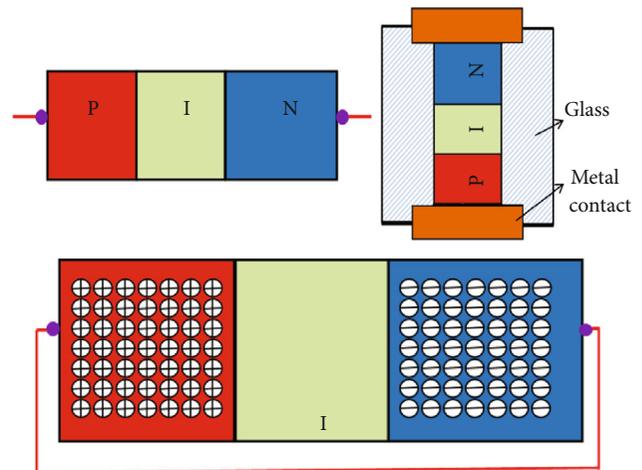


FIGURE 3: Layout of a basic PIN diode.

At low frequency, the PIN diode tracks the ordinary PN diode equation. Its I - V characteristic (Figure 4(a)) determines the forward voltage (V_F) and reverse voltage (V_R). At RF frequencies, during forward bias, the diode is ON for both positive and negative cycles. As in negative half cycle, the charge carriers in the I layer are not entirely cleared by the input signal, as there is not adequate time. Therefore, diode is continuously ON in the negative as well as positive RF cycle. When the diode is reverse-biased, very high impedance and low capacitance oppose the flow of RF signal. PIN diode acts as a current controlled resistor under forward bias conditions. Under this condition, equivalent model comprises of series combination of resistance (R_S) and a very low inductance (L) as shown in Figure 4(b). Under reverse bias, equivalent circuit of a PIN diode is shown in Figure 4(c), which comprises parallel connection of resistance (R_P) and capacitance (C_T).

3. Characterization of PIN as Switch

The low-cost silicon PIN diode is a powerful RF switch because it provides good return loss, high linearity, and high switching speed. The operating parameters that define PIN diode's switch characteristics are mainly insertion loss and isolation loss. The insertion loss is the amount of signal loss through the physical layout in the ON state, whereas

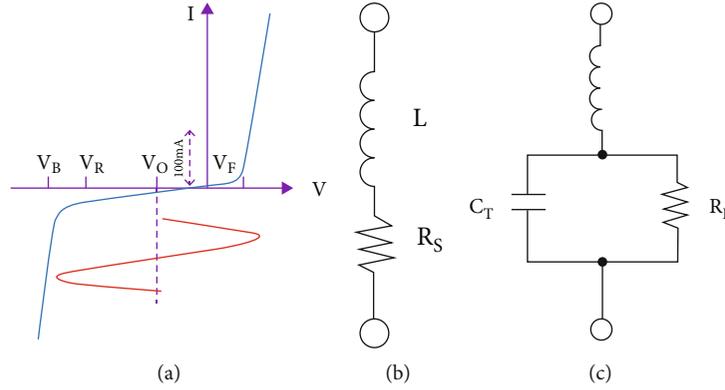


FIGURE 4: (a) V-I characteristic of PIN diode. (b, c) Equivalent model under forward and reverse bias.

isolation loss is the measure of how efficiently a switch is in OFF state. The biasing of PIN diode must be done precisely to get a good separation between DC power supply and RF signal. If proper biasing is not done RF current can flow in the DC biased signal, which degrades the effective operation of DC power supply. The DC signal can be easily separated from the RF signal by putting a series RF inductor and a shunt capacitor in the DC bias line. The equivalent model of Infineon diode is done in ADS software to study the actual effect of practical diode as shown in Figure 5. The insertion loss and isolation are calculated from equations (1) and (2). Under forward bias, the PIN diode is modeled as a series combination of resistance (2.1Ω) and inductance ($0.6 \mu\text{H}$) as shown in Figure 5(b), and in reverse bias, it is modeled as a parallel combination of resistance ($3 \text{ k}\Omega$) and capacitance (0.17 pF) as shown in Figure 5(c).

$$\text{Insertion loss} = 20 \log_{10} \left(1 + \frac{R_S}{2Z_0} \right). \quad (1)$$

$$\text{Isolation loss} = 10 \log_{10} (1 + (4\pi f C Z_0)^{-2}). \quad (2)$$

From the simulated parameter, it is found that insertion loss is 0.1 dB from $1\text{--}8 \text{ GHz}$ under switch in ON condition as shown in Figure 5(d). Also, it is observed that when diode is in switch OFF condition; insertion loss is better than 19 dB . Therefore, it shows very high impedance and there will be no transmission of signal from source to load. These are only simulated parameters, but when PIN diode is actually placed in a fabricated prototype, it encounters microstrip line, bias voltage, and bias lines. In this paper, PIN diode is used for closing or opening a connection between a microstrip lines. The PIN diode is properly biased using an SMD capacitor and an inductor. So first, the performance of a microstrip line is evaluated. Then characterization of RF inductor and RF capacitor is also done to study the amount of insertion loss introduced by them. To find out the response of these components, some prototype has been fabricated and tested successfully.

4. Performance Evaluation of Biasing Component

Fabrication of all prototypes is done on a $20 \times 20 \text{ mm}^2$ sized FR4 substrate using the MITS PCB prototyping machine. The relative dielectric constant of FR4 $\epsilon_r = 4.4$, and the height is 1.57 mm . Here, Infineon BAR64-02 PIN diodes, Coil Craft Inductors, and Murata SMD Ceramic Capacitors are used during fabrication. The measurement of S parameters is done using an Agilent N5222A Vector Network Analyzer.

4.1. Microstrip Line (50Ω) Structure. A 50Ω transmission line is designed and tested here. The schematic for microstrip line, measurement setup, and the fabricated structure are revealed in Figure 6(a) and 6(b). The measured parameter of the microstrip line and E field distribution are shown in Figure 6(c) and 6(d). Ideally, the 50Ω microstrip structure has 0 dB insertion loss, but actually insertion loss is not negligible. The simulated value of insertion loss is 0.5 dB over $1\text{--}10 \text{ GHz}$, whereas measured value of insertion loss is 0.1 dB from 1 to 6 GHz and 0.4 dB from 6 to 9 GHz .

4.2. RF Bypass Element: SMD Capacitor. A DC block capacitor plays a major role when the biasing components of PIN diode are designed. It is used to provide isolation between RF signal and DC signal. DC block capacitor also helps to isolate two or more different DC regions distinctly to bias more than two diodes independently. The value of RF bypass/DC Block capacitor is chosen to provide minimum impedance for RF signal and maximum impedance for DC signal. Ideally, DC blocking capacitor should behave as a short circuit at operating frequency. Usually $X_C = 1/\omega C = 1/2\pi f C$ should be less than 2 ohms at operating frequency. So, when a capacitor is positioned in between the 50-ohm line, the signal should bypass with least insertion loss. To find out the insertion loss of a 30 pF SMD multilayer capacitor; it is placed in 0.5 mm wide gap of 50-ohm transmission line as depicted in Figure 7. During HFSS simulation, a capacitor is modeled as 30 pF using lumped boundary condition. The proposed structure, measurement setup, and the fabricated prototype are shown in Figure 7(a) and 7(b). Simulated and measured S parameters and electric field distribution are shown in

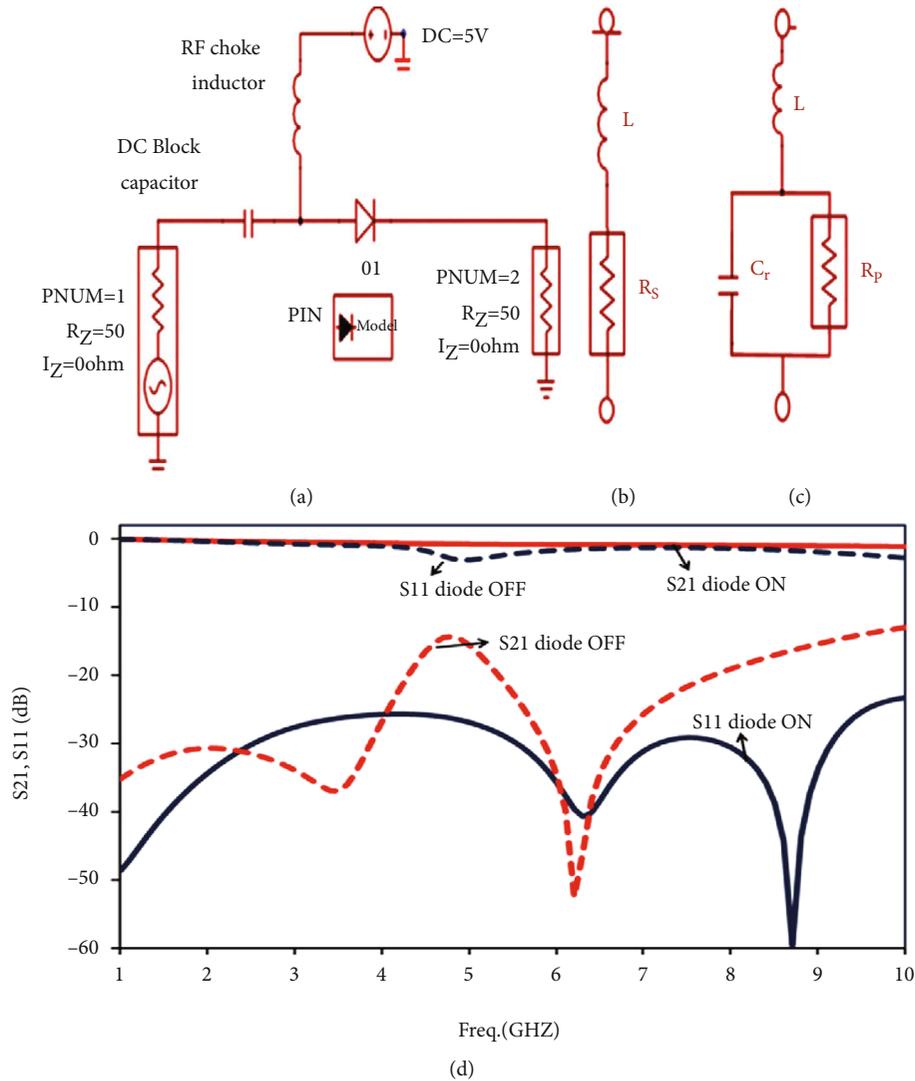


FIGURE 5: (a) The biasing circuit; (b, c) equivalent model in ON and OFF states; (d) S parameter vs. frequency.

Figure 7(c) and 7(d). Simulated value of S_{21} is 0.5 dB from 1–7 GHz whereas measured value is 0.2 dB from 1–7 GHz.

4.3. Testing of RF Choke Element: RF Inductor. The RF choke coil is designed for blocking or decoupling higher frequencies. RF choke coil provides large impedance to RF signal while minimum impedance to DC. Generally, the choke coil reactance $X_L = \omega L$ should be greater than 5 kΩ at operating frequency, where ω =angular frequency in Hz, L is the inductance measured in Henry. As choking and blocking means providing high impedance to that signal. It is clear that we want to isolate the DC signal and the RF signal to reduce the interference. In this regards capacitor and inductor plays an important role. The values of both components are chosen so that they have least influence of RF and DC signals. Here inclusion of capacitors and inductor in a circuit are checked in the presence of DC power supply. For this, a prototype is designed and fabricated as shown in Figure 8(a) and 8(b). The layout consists of SMD capacitor of value 0.3 nF and inductor of value 0.3 uH. When DC signal is

applied, the capacitor should bypass the RF signal and should offer very high impedance to the DC signal. The measured results shown in Figure 8(c) indicate that S_{21} is better than 2 dB and S_{11} is better than 13 dB from 1 to 7 GHz. The E filed distribution is given in Figure 8(d).

5. Performance of PIN Diode: An RF Switch

For the characterization PIN diode, a prototype has been fabricated and tested as depicted in Figure 9. For proper biasing, an Infineon BAR64-02 PIN diode, 2 RF inductors, and 2 SMD capacitors are used. When we apply +1.1 V on the DC pad, the diode is forward-biased. At this time, diode should offer very low impedance to the flow of RF signal, and hence S_{21} should be minimum. The results shown in Figure 10(a) indicate that S_{21} is better than 2.5 dB for 1–6.5 GHz. At the time of reverse bias, the diode should block RF by giving maximum impedance. The results shown in Figure 10(b) indicate that isolation loss is better than

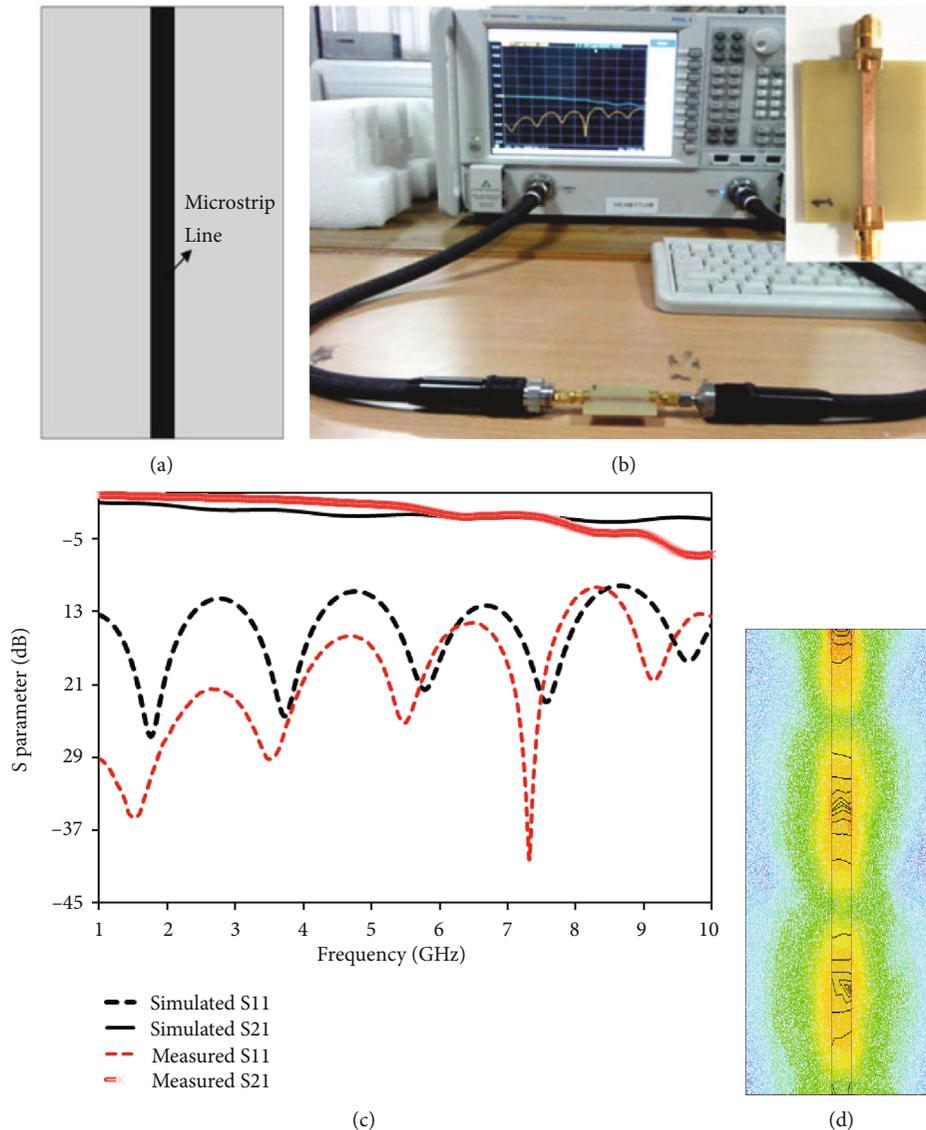


FIGURE 6: (a) Microstrip line; (b) measurement setup; (c) S parameter vs. frequency; (d) E field distribution.

18 dB. As S_{11} parameter gets distorted after 7 GHz, its operating bandwidth should not exceed after 7 GHz.

6. Implantation of PIN Diode in a Reconfigurable Antenna

Flexible antennas are fabricated on substrates such as Kapton, PET, and liquid crystal polymer (LCP) substrates. Dielectric constant and loss tangent are important material parameters to design low cost and compact flexible antenna for wearable devices. A reconfigurable antenna was designed and tested as shown in Figure 11. In the proposed antenna [38], a reconfigurable feeding structure is used to switch its operating bands among multiple narrow bands. Here, five PIN diodes are implanted in the feed structure to control different stub positions autonomously. The implantation of PIN diode into antenna structure offer very low insertion loss of 1 dB up to frequency 7 GHz. These unique features

are beneficial for space and aviation applications compared with the current bulky and surface mounting antenna modules since they can minimize weight and drag-force during high-speed motion.

7. Conclusion

PIN diodes have been used as a microwave switch in a lot of microwave circuits. With the advancement in fabrication technology, we are shifting to flexible and wearable electronics. The flexible devices can be fabricated on such polymers, which not only have excellent electrical properties like high carrier mobilities, dielectric constant, and low loss tangent but also have excellent mechanical features like high elasticity, durability, stability, and being extremely lightweight. The flexible PIN diode can be fabricated not only on polymer substrate like PET, polyethylene naphthalate (PEN), polycarbonate (PC), polyethersulfone (PES), and polyimide

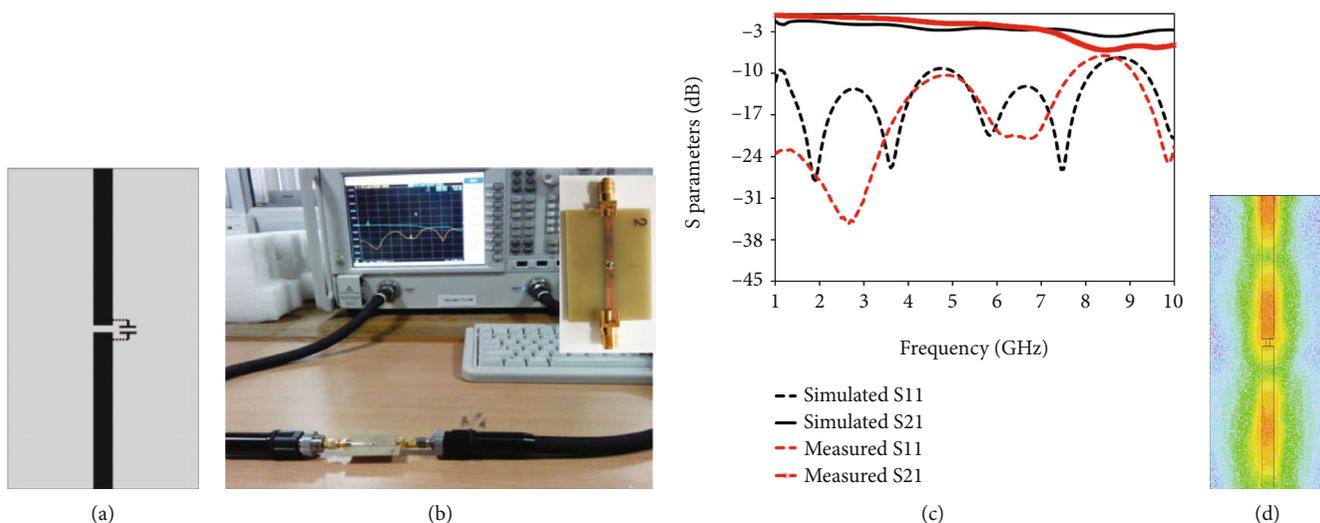


FIGURE 7: (a) Layout for RF bypass capacitor; (b) measurement setup; (c) S parameter vs. frequency; (d) field distribution.

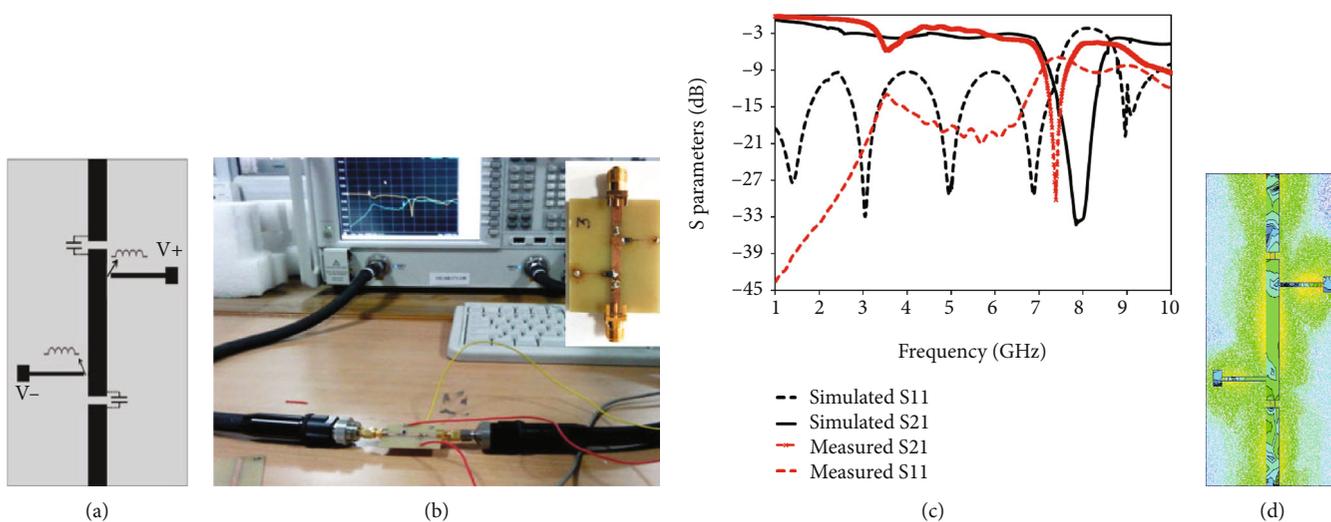


FIGURE 8: (a) RF choke under test; (b) measurement setup; (c) S parameter vs. frequency; (d) E field distribution.

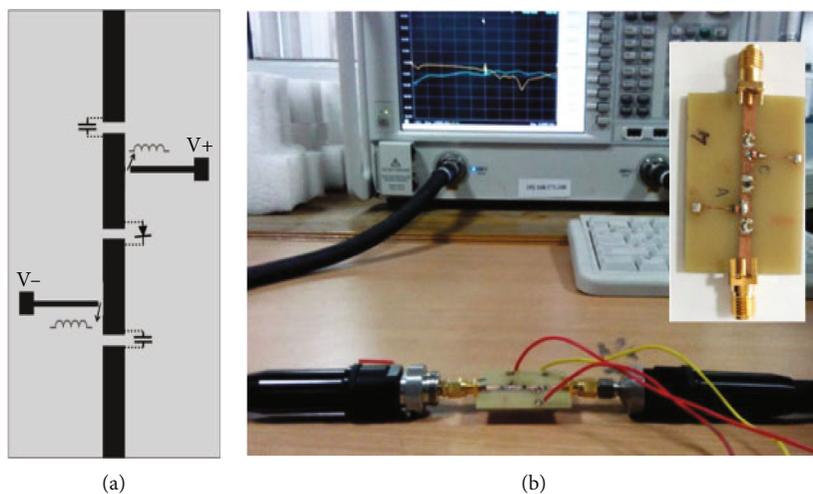


FIGURE 9: (a) Characterization of PIN diode; (b) experimental setup.

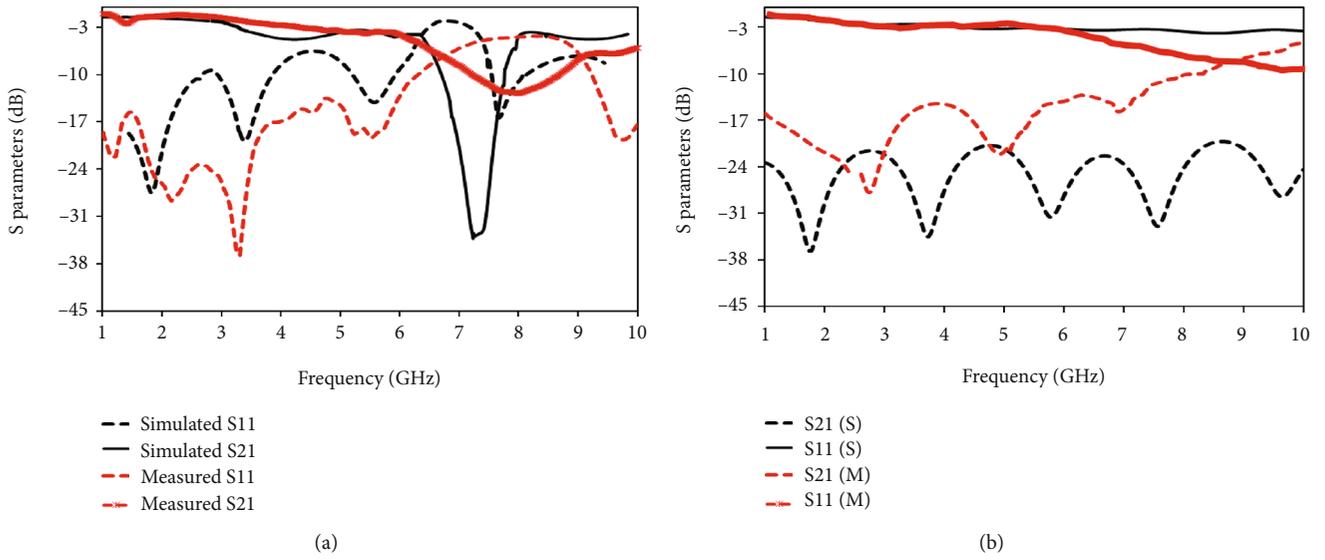


FIGURE 10: S parameter vs. frequency of PIN diode in (a) ON state and (b) OFF state.

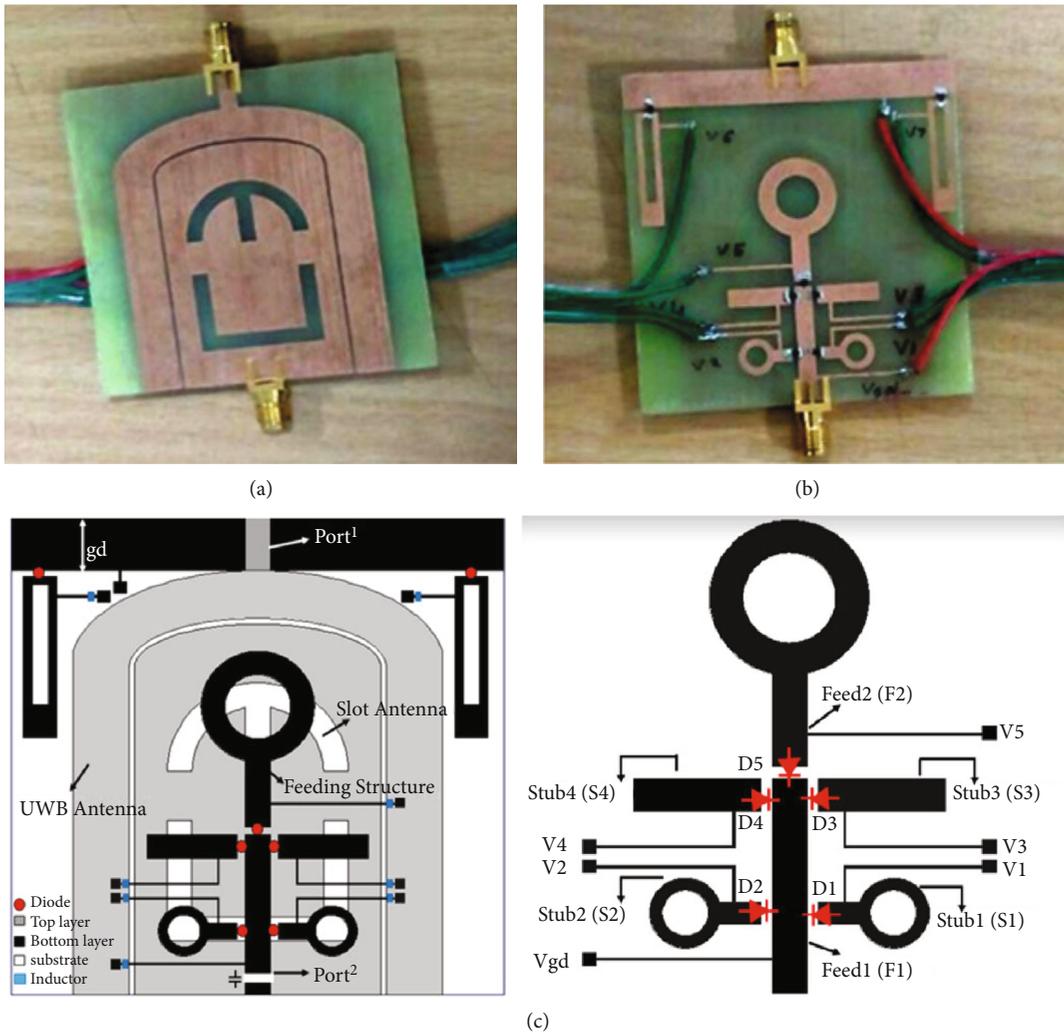


FIGURE 11: Fabricated layout of reconfigurable antenna using PIN diode: (a) top view; (b) bottom view; (c) measurement setup.

(PI), but also on biodegradable polymer composite carbon nanofiber CNF substrates for environmental-friendly small footprint applications. Some points need to be addressed during fabrication. The fabricated device should give low series resistance and capacitance in order to be able to achieve high-frequency operation. The polymer substrate material is chosen so that device should maintain its performance over repeated bending operations. The performance of PIN diode has been successfully investigated by testing a reconfigurable antenna. Each biasing component, i.e., SMD inductor, SMD capacitor, and PIN diode is implanted individually in the microstrip line structure to study the insertion and isolation loss. After fabrication of prototypes, measurement for transmission parameters was successfully done. It is concluded that the PIN diode is an ideal choice for high RF power applications because of high switching speed and low power dissipation. From the observed performance parameters of PIN diode, it is concluded that the transmission loss of RF signal is nearly 1 dB, and the isolation loss is better than 20 dB from 1 to 7 GHz in the presence of biasing components.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

S.S. and R.R.: Conceptualization and writing—original draft preparation; C.P. and D.B: methodology; K.K.S. and N.U.S: writing—review and editing.

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