Parasitic Compensation and Hence Isolation Improvement of PIN Diode-Based Switches

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***Abstract*—This brief presents a transmission line based resonant technique to nullify the parasitic effect of a PIN diode used to design a narrowband high frequency switch. Resonant condition is obtained by using a section of transmission line in series with a single PIN diode in a shunt branch. The method guarantees isolation improvement at any design frequency lower than the series resonant frequency of a diode. It does not use any lumped component other than those required for biasing. Thus, the method greatly improves the high frequency performance of a PIN diode as a switch. A transmission line based analysis is carried out to obtain the design equations. The theoretical prediction is verified by fabrication and measurement. A single-pole-single-throw (SPST) switch using just one single PIN diode provides measured isolation of 40 dB and insertion loss of 1.5 dB at 10.55 GHz. The return loss is more than 20 dB over 10.2-10.8 GHz. A low cost NXP semiconductors BAP64-02 PIN diode with high parasitic and the manufacturer specified highest frequency as 6 GHz is used to show the competency of the proposed method. A second SPST switch using two diodes provides isolation of 72 dB, insertion loss of 1.8 dB and return loss of 35 dB at 10.55 GHz. An SP4T switch is also fabricated and tested. Measured 1 dB compression point for all the switches is higher than 23 dBm.**

***Index Terms*—PIN diode, RF switch, SPST switch, transmission line.**

I. INTRODUCTION

ELECTRONIC switches play an important role in the microwave and millimeter-wave circuits. They are frequently used in phased array RADARs, high speed wireless systems, automotive radar systems, etc. A single-pole single-throw (SPST) switch is an elementary switch, which can be used to design switches with any number of pole and throw positions. An electronic switch can be implemented by using RF MEMS [1] or an active device like transistors [2] or PIN diodes [3]. MEMS switches have the advantage of high isolation and low insertion loss over active device based switches. However, they are usually expensive and require high driving voltages. At microwave and millimeter-wave frequencies, discrete PIN diodes are usually preferred over other active devices for moderate to high power applications [3]. PIN has a high power handling capability and lower time constant. In general, it is difficult to achieve high isolation using a single PIN diode either in series or shunt configuration. At higher frequencies, the performance of PIN based switches further deteriorates due to parasitic reactance of the diode package. However, only a few techniques are available in the open literature those deal with the parasitic reactance for isolation improvement. A differential switch with mode blocker to block differential mode signal is reported in [4]. High isolation is shown over a narrow bandwidth. Still, the circuit complexity can be a problem at higher frequencies as a crossover is required to implement the switch. Another low loss PIN diode switch using an impedance transforming network is reported in [5]. The switch uses two shunt PIN with two $\lambda/4$ lines and impedance transforming network thereby increasing the size of the switch for maximum isolation of 30 dB at 4.7 GHz. A cascaded series-shunt configuration can improve the high frequency performance of an SPST switch [6]. However, series-shunt configuration using multiple PIN diodes increases the insertion loss and implementation area and cost of an SPST switch.

The parasitic inductor of the PIN diode in forward bias state and capacitance in the reverse bias state are the primary factors those limit the isolation performance of the shunt switch. External capacitance or open circuited stub less than $\lambda_g/4$ is used to tune out the parasitic inductor. These conventional approaches of tuning out parasitic inductance have been used to design reconfigurable power divider [7], and LNA protection switch [8]. In [7], an impedance matching network composed of PIN loaded with open stub in parallel with short circuited stub is used. Open stub tunes out parasitic inductance but capacitance is not compensated. In [8], open stubs are attached to the PIN diodes to compensate for the parasitic inductance. In [9], high impedance lines along with the open stub are used to improve the isolation of the PIN diode based shunt switch. Although parasitic inductance has been compensated to improve the isolation of the switch, none of [7]–[9] tried to compensate all parasitic associated with a PIN diode.

In this brief, a new design approach is presented to nullify the parasitic effect of a PIN diode and hence to improve the isolation characteristics of a PIN based shunt switch. In contrary to conventional approaches using multiple diodes or lumped inductors, the properties of a transmission line is used for the improvement. The highest frequency of operation of a conventional switch is usually limited by the diode parasitic reactance. Thus, the method extends the highest frequency of operation of a PIN diode based switch. The proposed procedure does not deteriorate insertion loss, time constant or power handling capability of the switch. A transmission line based model is used to derive the design equations. Finally, three switches are fabricated and tested, which closely matches the theoretical predictions.

II. DESIGN AND ANALYSIS OF THE SWITCH

Fig. 1(a) shows the conventional SPST switch with a PIN diode in series and shunt configurations. The figure also

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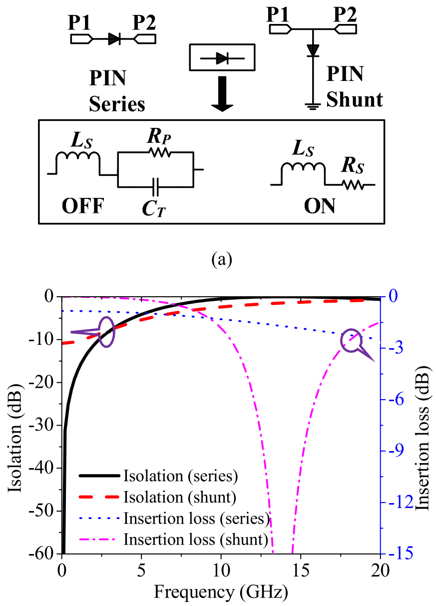


(b)

Fig. 1. (a) Conventional SPST switch with PIN diode in series and shunt configurations and equivalent circuits of the PIN diode. (b) Simulated isolation and insertion loss of conventional series and shunt type switches.

displays equivalent circuits of the diode in ON and OFF conditions. These three parasitic components of a PIN diode mostly affect the switch performance and are enough to model the diode. Other parasitic reactance of the diode and package do influence the switch performance but they are small enough to be neglected even at lower millimeter-wave frequencies for most of the commercially available diodes. The calculated isolation and insertion loss variations for the two conditions are shown in Fig. 1(b). An NXP semiconductors BAP64-02 PIN diode is considered. The frequency at which the diode is being used is beyond the highest specified frequency by the manufacturer, which is 6 GHz. Therefore, the required parameters for the design are not provided by the manufacturer. Here, the diode parameters are extracted from the measured S-parameters of the diode. A PIN diode connected in series is used to extract the design parameters. Accuracy of the extraction method does influence the switch performance. For example, if there is an error of ±10% in extracted C_T for the BAP64-02 PIN diode, the operating frequency shifts by approximately ±4 % and isolation may decrease by 20 dB at the design frequency. However, a vector network analyzer with through-reflect-line calibration provides accurate model of the diode. Following relations are used to derive diode parameters at any frequency f_0 from its measured complex S-parameters after through-reflect-line calibration.

In forward bias condition, the series resistance is

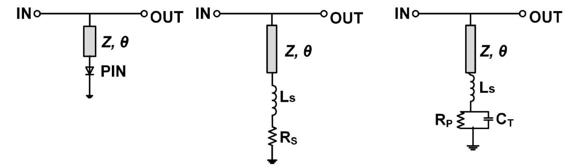
$$R_s = Z_o\left[\frac{1-|S_{11}|^2-|S_{21}|^2}{|S_{21}|^2}\right], \tag{1}$$

and the lead inductance is

$$L_s = \pm\frac{Z_o}{\omega}\left[4\frac{|S_{11}|^2}{|S_{21}|^2}-\left\{\frac{1-|S_{11}|^2-|S_{21}|^2}{|S_{21}|^2}\right\}\right]. \tag{2}$$

Similarly, in the reverse bias condition, the parallel resistance is

$$R_p = 2Z_o \times \left(\frac{(S_{11\mathrm{OFFr}}S_{21\mathrm{OFFr}}+S_{11\mathrm{OFFi}}S_{21\mathrm{OFFi}})\times(1+X^2)}{S^2_{21\mathrm{OFFr}}+S^2_{21\mathrm{OFFi}}}\right), \tag{3}$$



(a) (b) (c)

Fig. 2. (a) Proposed switch and equivalent circuits for (b) ON and (c) OFF states of the diode.

junction and parasitic capacitance are

$$C_T = \frac{X}{\omega_o \times R_p}, \tag{4}$$

where

$$X = \left(\frac{\omega L_s}{2Z_o} - \frac{S_{11\mathrm{OFFi}}S_{21\mathrm{OFFr}}-S_{11\mathrm{OFFr}}S_{21\mathrm{OFFi}}}{S^2_{21\mathrm{OFFr}}+S^2_{21\mathrm{OFFi}}}\right) \times \left(\frac{S^2_{21\mathrm{OFFr}}+S^2_{21\mathrm{OFFi}}}{S_{11\mathrm{OFFr}}S_{21\mathrm{OFFr}}+S_{11\mathrm{OFFi}}S_{21\mathrm{OFFi}}}\right), \tag{5}$$

Z_o is the characteristic impedance of the system used to measure S-parameters of the diode and $\omega_o = 2\pi f_o$.

The subscript ON and OFF denotes the complex S-parameters in ON and OFF states of the diode, respectively, and r and i are the real and imaginary part of the S-parameters. The method can be used below the series resonant frequency of the diode. The extracted diode parameters by measurement at 10.5 GHz for a forward bias current of 10 mA are $R_S = 10\Omega$, $L_S = 0.6$ nH, junction and parasitic capacitance $C_T = 0.22$ pF and $R_P = 20$ MΩ. The time constant of the diode is 2.2 ps.

The series type conventional switch using a single PIN provides isolation of 10 dB till 2.3 GHz. For shunt type, isolation is 10 dB till 1.2 GHz. However, the shunt switch provides less insertion loss compared to the series switch. Furthermore, insertion loss shows a dip at 13.85 GHz, at the series resonant frequency of the diode. Isolation and insertion loss performance degrade faster than expected because of the diode parasitic. It is observed that the switching characteristic is lost. Therefore, conventional methods cannot be used to obtain an acceptable performance of the switch using the PIN diode at a higher frequency. The following section shows that the isolation characteristics of the switch can be greatly improved by using a section of transmission line at any design frequency f_0 below the series resonant frequency of the diode. Fig. 2(a) shows the schematic of the proposed shunt type switch. A PIN diode is connected in shunt configuration through a section of transmission line of characteristic impedance Z and electrical length θ at f_0. A shunt connection is chosen since it can provide lower insertion loss. Further, a series connected impedance transformer can only match the real part to 50 Ω. One must use an additional shunt transmission line section to cancel the reactive parts. Thus, compensation network for a series connected diode becomes bigger than a shunt connected diode.

Fig. 2 (b) and (c) show the equivalent circuit of the SPST switch when the diode is ON and OFF, respectively. Input impedance looking into the shunt arm in ON and OFF states of the diode are

$$Z_{in(\mathrm{ON,OFF})} = Z\frac{Z_{L(\mathrm{ON,OFF})}+jZ\tan\theta}{Z+jZ_{L(ON,OFF)}\tan\theta}, \tag{6}$$

where $Z_{L(\mathrm{ON,OFF})}$ is the impedance of the PIN diode in ON/OFF condition and are

$$Z_{L(\mathrm{ON})} = R_S + j\omega L_S,$$

and

$$Z_{L(\mathrm{OFF})} = \frac{R_P + j\left(\omega L_S - \omega R_P^2 C_T + \omega^3 L_S R_P^2 C_T^2\right)}{1 + \omega^2 R_P^2 C_T^2}.$$

Next, for a given diode, values of Z and θ are obtained for the best isolation and insertion loss conditions. Now two possibilities exist. Case I: input impedance $Z_{in(ON)}$ is high when the diode is ON and the switch is also ON. Then, $Z_{in(OFF)}$ is low and isolation of the switch depends on it. Case II: $Z_{in(ON)}$ is low when the diode is ON and the switch is OFF. Then, $Z_{in(OFF)}$ determines the insertion loss. Furthermore, minimum or maximum impedance conditions are obtained at the resonant frequencies of the shunt arm. The analytical expressions for Z and θ for the case I and case II are obtained using the resonant condition. Assume that Z_L is the diode impedance given by

$$Z_{L(\mathrm{ON,OFF})} = R_{(\mathrm{ON,OFF})} + jX_{(\mathrm{ON,OFF})}, \tag{7}$$

where $R_{(\mathrm{ON,OFF})}$ and $X_{(\mathrm{ON,OFF})}$ are the real and imaginary parts of $Z_{L(\mathrm{ON,OFF})}$.

Then from (6),

$$\begin{aligned} Z_{in(\mathrm{ON,OFF})} = {} & \frac{Z^2 R_{(\mathrm{ON,OFF})} \sec^2\theta_{(\mathrm{ON,OFF})}}{\left(Z - X_{(\mathrm{ON,OFF})}\tan\theta_{(\mathrm{ON,OFF})}\right)^2 + R^2_{(\mathrm{ON,OFF})}\tan^2\theta_{(\mathrm{ON,OFF})}} \\ & - \frac{j\left(ZR^2_{(\mathrm{ON,OFF})}\tan\theta_{(\mathrm{ON,OFF})} - X_{(\mathrm{ON,OFF})}Z^2\right)}{\left(Z - X_{(\mathrm{ON,OFF})}\tan\theta_{(\mathrm{ON,OFF})}\right)^2 + R^2_{(\mathrm{ON,OFF})}\tan^2\theta_{(\mathrm{ON,OFF})}} \\ & + \frac{j\left(X^2_{(\mathrm{ON,OFF})}Z\tan\theta_{(\mathrm{ON,OFF})} - Z^3\tan\theta_{(\mathrm{ON,OFF})} + X_{(\mathrm{ON,OFF})}Z^2\tan^2\theta_{(\mathrm{ON,OFF})}\right)}{\left(Z - X_{(ON,OFF)}\tan\theta_{(\mathrm{ON,OFF})}\right)^2 + R^2_{(\mathrm{ON,OFF})}\tan^2\theta_{(\mathrm{ON,OFF})}}. \end{aligned} \tag{8}$$

At resonance,

$$\begin{aligned} & ZR^2_{(\mathrm{ON,OFF})}\tan\theta_{(\mathrm{ON,OFF})} - X_{(\mathrm{ON,OFF})}Z^2 + X^2_{(\mathrm{ON,OFF})}Z\tan\theta_{(\mathrm{ON,OFF})} \\ & \quad - Z^3\tan\theta_{(\mathrm{ON,OFF})} + X_{(\mathrm{ON,OFF})}Z^2\tan^2\theta_{(\mathrm{ON,OFF})} = 0, \end{aligned}$$

which simplifies to $\tan^2\theta_{(\mathrm{ON,OFF})} + A_{(\mathrm{ON,OFF})}\tan\theta_{(\mathrm{ON,OFF})} - 1 = 0$, where

$$A_{(\mathrm{ON,OFF})} = \frac{R^2_{(ON,OFF)} + X^2_{(\mathrm{ON,OFF})} - Z^2}{X_{(\mathrm{ON,OFF})}Z}. \tag{9}$$

Therefore,

$$\tan\theta_{(\mathrm{ON,OFF})} = \frac{-A_{(\mathrm{ON,OFF})} \pm \sqrt{A^2_{(\mathrm{ON,OFF})} + 4}}{2}. \tag{10}$$

The value of θ should be the same in ON and OFF states to be realizable. The value of Z for which $\tan\theta_{(\mathrm{ON})} = \tan\theta_{(\mathrm{OFF})}$ is

$$Z = \sqrt{\frac{|Z_{\mathrm{OFF}}|^2 X_{\mathrm{ON}} - |Z_{\mathrm{ON}}|^2 X_{\mathrm{OFF}}}{X_{\mathrm{ON}} - X_{\mathrm{OFF}}}}, \tag{11}$$

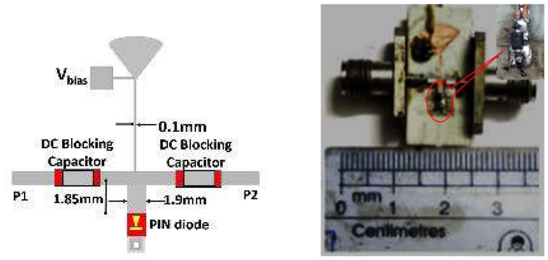
where

$$\left|Z_{(\mathrm{ON,OFF})}\right|^2 = R^2_{(\mathrm{ON,OFF})} + X^2_{(\mathrm{ON,OFF})}.$$

Equations (10) and (11) provide solutions that depend on the diode parameters and can be used to design switches even at millimeter-wave frequencies. Equation (10) provides two solutions those correspond to solutions for the case I and case II discussed before.

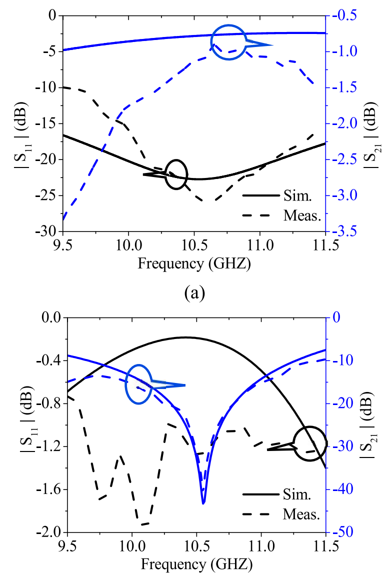
III. Fabrication and Measurement

To verify the proposed technique, an SPST switch is designed first at 10.55 GHz and fabricated using a 0.508 mm thick RO4003C substrate of dielectric constant $\varepsilon_r = 3.38$, and $\tan\delta = 0.0027$. Using (10) and (11), the solutions for case I for the same BAP64-02 PIN diode are Z = 34.45Ω and $\theta = 39.9°$. The solutions for case II are $Z = 34.45\Omega$ and $\theta = 129.9°$. Solution for the case I is chosen for compact size.



(a) (b)

Fig. 3. (a) Layout and (b) a photograph of the fabricated switch (unit: mm).



(a)

(b)

Fig. 4. Simulated and measured responses in (a) ON and (b) OFF conditions of the switch.

Fig. 3 shows the prototype and layout of the fabricated switch. The bias tee shown in the figure provides an RF isolation of a least 35 dB over 9.85 - 10.76 GHz. Two 4.3 pF capacitors at the input and output are used for DC blocking. Fig. 4 shows the measured and simulated results of the fabricated switch. Measured insertion loss is less than 2 dB over 9.9 - 11.5 GHz. Over the band, the return loss is more than 17.8 dB. In the OFF condition, the isolation is more than 20 dB over 10.2 - 10.8 GHz with a dip of 40.8 dB at 10.55 GHz. Fig. 5 shows the measured loss with input power for both the ON and OFF states of the switch. Because of our limitation of measurement, the input power is shown till 23 dBm. Loss is calculated as the difference of output power and input power. It is clear from the figure that loss is less than 1 dB till 23 dBm of input power at 10.55 GHz confirming linearity of the switch over the range.

The methods using two or multiple diodes also provide isolation improvement for the present case. The conventional series-shunt technique of isolation improvement cannot be directly applied here. However, the basic concept of rejection improvement by adding up rejection from individual diodes can be applied for the present case. For example, an SPST switch is fabricated using two blocks of the previous circuits. The resultant circuit is shown in Fig. 6. A 50 Ω transmission line 270° at the design frequency is used as the connecting lines. The 270^o line instead of 90° is used to accommodate the bias tee. The full wave simulated and the measured responses

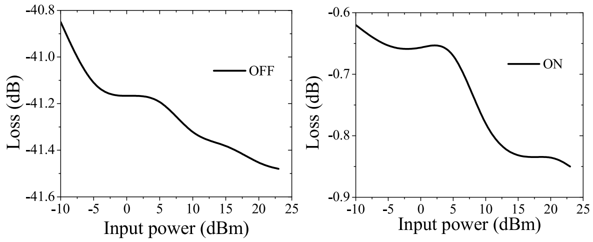
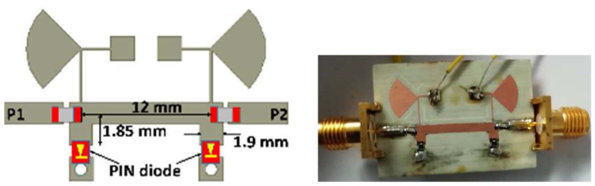
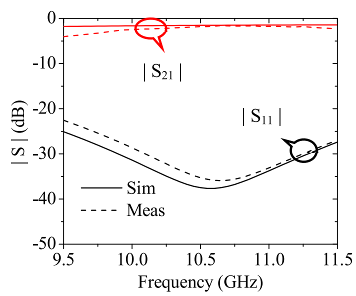


Fig. 5. Linearity test of the switch at10.55 GHz.

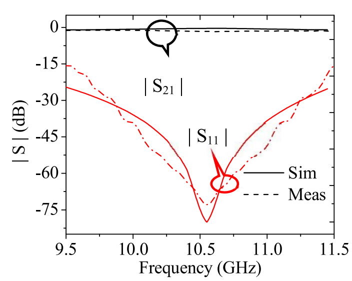


(a) (b)

Fig. 6. (a) Layout and (b) a photograph of the fabricated two diode SPST switch.



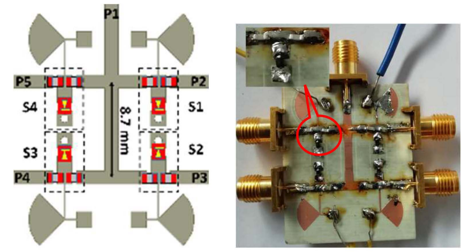
(a)



(b)

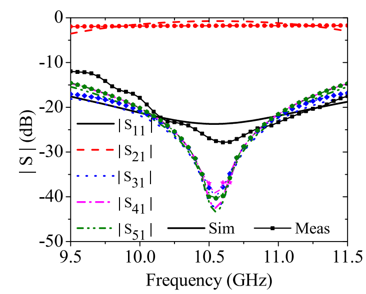
Fig. 7. Simulated and measured responses in (a) ON and (b) OFF conditions of the two diode SPST switch.

of two diode SPST switch are shown in Fig. 7. As expected, measured isolation is improved to 72 dB at 10.55 GHz with 40 dB isolation over 10 - 11.1 GHz. Measured insertion loss at the design frequency is 1.8 dB. It can be further improved by using multiple of them at the cost of increased implementation area and high insertion loss. Further, since the SPST switch is the basic switch, it can be extended to other higher order switches. One such example is shown in Fig. 8, where an SP4T switch is designed using the proposed SPST switch. All the dimensions of the basic block remain the same as before. The full wave simulated and measured response of the SP4T switch are shown in Fig. 9. The measured insertion loss is always less than 1.7 dB at the design frequency with at least 39 dB of the isolation. Fig. 10 shows the measured loss with input power variation for both the two diode SPST switch and SP4T switch. The variation of measured loss is less than

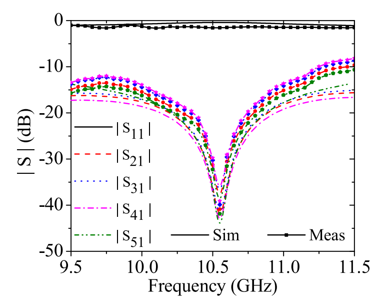


(a) (b)

Fig. 8. (a) Layout and (b) a photograph of the fabricated SP4T switch.

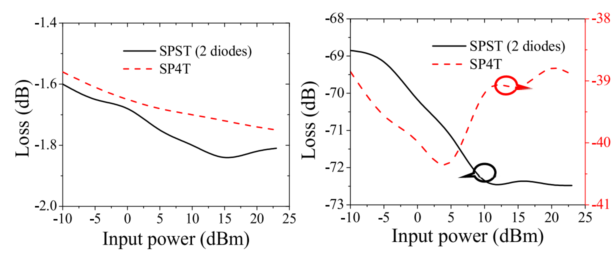


(a)



(b)

Fig. 9. Simulated and measured responses of the SP4T switch (a) when switch S1 is ON and (b) when all switches are in OFF conditions.



(a) (b)

Fig. 10. Linearity test of the switch at 10.55 GHz. (a) ON state (b) OFF state.

1 dB till 23 dBm of input power. The procedure can be followed for any arbitrary frequency below the series resonance frequency of the diode. Another SPST switch using MACOM's MA4AGFCP910 PIN diode is fabricated to illustrate the usefulness of the proposed technique. The diode parameters at 24 GHz have been extracted from the measured response of the diode using (1) to (5). The response of the diode as a switch in series and shunt configuration using the extracted parameters is shown in Fig. 11.

It is clear from the figure that the diode as a switch in series configuration provides isolation of 12 dB while in shunt configuration isolation of 13 dB is achieved at the design

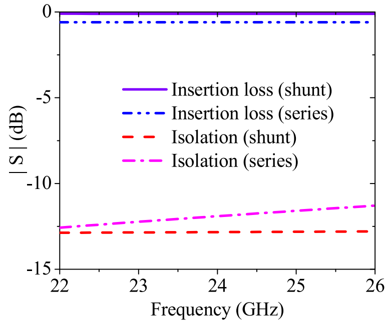


Fig. 11. The response of the MA4AGFCP910 PIN diode as switch in series configuration and shunt configuration.

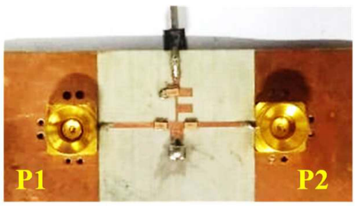


Fig. 12. Photograph of the fabricated prototype.

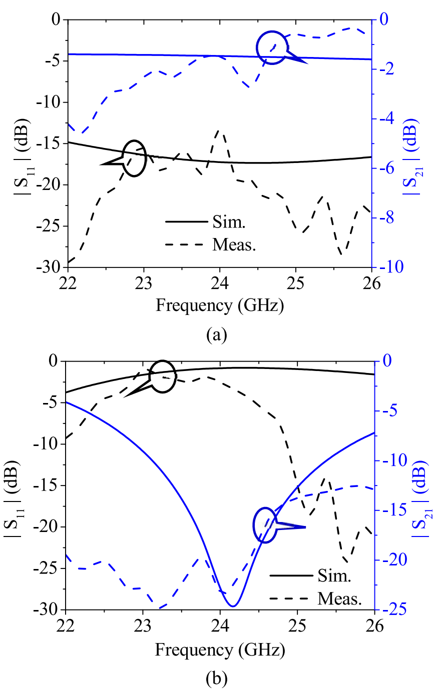


Fig. 13. Simulated and measured S-parameters response of the SPST switch designed at 24 GHz. (a) ON state (b) OFF state.

frequency. An SPST switch using the proposed technique is designed at 24 GHz using the same diode on a 0.254 mm thick RO4003C substrate of the dielectric constant of 3.38. The photograph of the fabricated switch is shown in Fig. 12 and the simulated and measured response of the switch in ON state and OFF state are shown in Fig. 13. It is clear that the switch using the proposed technique provides isolation of 25 dB which was only 13 dB for the conventional case.

IV. Conclusion

This brief presents a novel technique that greatly extends the highest frequency of operation of an SPST switch using a PIN diode. The effect of parasitic reactance is nullified using a resonant circuit. resonant circuit uses a single PIN diode and a section of a transmission line. No lumped component like inductor is used. Thus, the method also improves the insertion loss performance of the switch. To validate the proposed method, an SPST switch is fabricated using a low cost BAP64-02 PIN diode with a series resonant frequency of 13.85 GHz. Even though the manufacturer specification for the highest frequency of operation is 6 GHz, the switch provides measured isolation of 40.9 dB at 10.55 GHz. It is worthwhile to mention that a conventional SPST switch using the same diode does not provide any switching response at this frequency. It is also shown that the unit section can be used in cascade to improve the isolation further. The basic SPST switch can be used to design higher order switches. As an example, an SP4T switch is designed and fabricated. The same design equations can also be used for any other PIN diode. The proposed method relaxes the stringent parasitic reactance condition of a diode required for millimeter-wave applications. A comparison with other PIN diode based switches is given in Table I. It shows that the present switch performance is comparable to [8] at design frequency and is better than other reported works, thus making it a better alternative.

TABLE I
PERFORMANCE COMPARISON WITH OTHER PIN DIODE BASED SWITCHES

Ref.	Freq. (GHz)	No. of PIN diodes	$\|S_{21}\|_{OFF}$ (dB)	$\|S_{21}\|_{ON}$ (dB)	RL (dB)	P1 (dBm)	Size (λ_g^2)
[4]	0-4	2	20	1.3	10	NR	NR
[5]	4.6-4.8	2	20	0.5	18	NR	1.04
[7]	4.83-5.2	1	28	1.13	22	NR	NR
[8]	9.3-9.5	3	48.9	1.83	15	NR	NR
[9]	82-100	1	32	2	10	NR	NR
This work	10.55	1	40.9	1.11	20	> 23	0.083

NR: Not reported

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