Progress In Electromagnetics Research M, Vol. 78, 135–143, 2019

A Novel Single PIN Diode Reconfigurable Impedance Matching Network with a Simplified Solution Method

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Abstract—In this paper, a reconfigurable impedance matching network (RIMN) based on PIN diode is presented. RIMN is an impedance matching circuit containing only one matching stub embedded with one PIN diode. It can match two different load impedances under different biasing of the PIN diode. The RIMN has a very simple structure, and the parameters in the structure are easy to be calculated with a simplified solution method. During the solving process, the parasitic parameters of PIN diode are taken into account. For verification, a RIMN working at 5.8 GHz is designed and fabricated. The measured insertion losses for different load impedances are less than 0.4 dB with reflection coefficients less than 30 dB at the targeted frequency. Simulation and measurement show that the proposed RIMN has good performance.

1. INTRODUCTION

Recently, much attention has been increasingly paid into the research of reconfigurable antennas and reconfigurable microwave circuit [1–3]. Reconfigurable antennas and microwave circuits often have different operating modes to accommodate different operating conditions. In those cases, input impedance is always changing with the modes. These different input impedances need to match the port impedance for better performance.

A switchable matching stub (SMS) is proposed by [4]. SMS is a single-stub matching structure. Whether the matching stub is connected to the circuit is controlled by a PIN diode. The SMS requires a lumped capacitance, and no DC bias circuit is designed. Therefore, the DC path and AC path are coupled to each other. A switched impedance matching circuit (SIMC) is proposed by [5]. The SIMC has a complex matching stub with an SPDT switch. The length of the matching stub changes among different states. Therefore, different input impedances can be matched. SIMC also requires some lumped capacitance in order to isolate the SPDT's AC from DC. A reconfigurable impedance transformer network (RITN) structure is proposed by [6]. The RITN contains two matching stubs and one PIN diode. The parasitic effects of the PIN diode are also considered. A biasing circuit of PIN diode is located at the end of a stub to isolate AC from DC. However, acquiring some of the parameters of the RITN is difficult and requires solving a complex equation because of the parasitic effects of the PIN diode. This equation usually has no analytical solution.

A novel reconfigurable impedance matching network (RIMN) is proposed in this paper. The RIMN can match real load impedance either Z_0 or Z_L to the port impedance Z_0 using only one PIN diode without extra lumped components. The parasitic effects of PIN diodes can increase computational complexity, because of which a simplification of the PIN diode equivalent circuit is introduced. By expanding the RIMN, complex load impedance matching can also be performed.

Received 24 November 2018, Accepted 24 January 2019, Scheduled 5 February 2019
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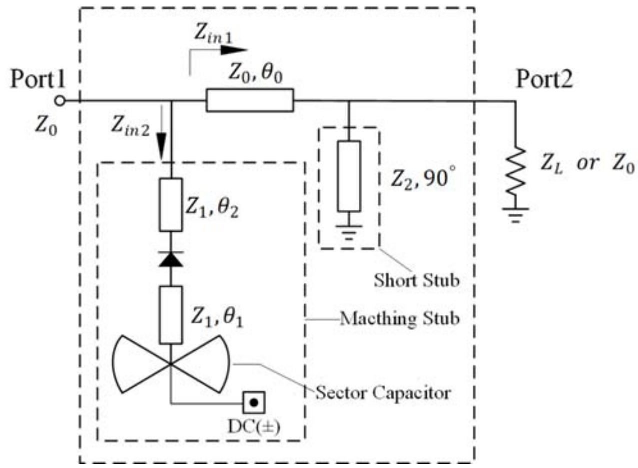


Figure 1. A block diagram of the reconfigurable impedance matching network.

2. THEORETICAL ANALYSIS

2.1. The Structure of Reconfigurable Impedance Matching Network

A simple block diagram of the RIMN is shown in Fig. 1, where Z_0 is port impedance. RIMN has a simple structure consisting of one matching stub, a shorted stub, and a microstrip line with length θ_0 and characteristic impedance Z_0. The matching stub is composed of a section of a microstrip line with a characteristic impedance of Z_1 embedded with a PIN diode and a sector capacitor at the terminal. Sector capacitor serves two purposes. One is to make the terminal of the microstrip line equivalent to the AC ground. The other is to reduce the effect of the DC circuit on the matching stub. DC circuit and sector capacitor are in parallel. Therefore, for any form the DC circuit takes, its effect on the AC circuits is ignorable. The short stub is a microstrip line grounding the cathode of the PIN diode with a characteristic impedance of Z_2 and a length of quarter-wavelength at targeted frequency. It does not contribute to impedance matching, so its position is flexible. In practical applications, if the rest part of the circuit connecting to the diode cathode is already grounded, the short stub can be removed.

As shown in Fig. 1, the input impedance of the load impedance transformed by the microstrip line of length θ_0 is Z_{in1}, and the input impedance of the matching stub is Z_{in2}. Under different DC bias conditions, the equivalent circuit of the PIN diode causes the variation of Z_{in2}. Meanwhile, since the load impedance is Z_0 or Z_L, the value of Z_{in1} is different. So according to the impedance matching conditions, the following equation needs to be satisfied for different DC bias.

$$\frac{1}{Z_0} = \frac{1}{Z_{in1}} + \frac{1}{Z_{in2}} \tag{1}$$

It is difficult to solve Eq. (1) directly because the expression of Z_{in2} in either bias is complicated. In the next subsection, the expression will be simplified to make Eq. (1) easier to solve.

2.2. Simplification of the Impedance Matching Equation

With the parasitic effects of the PIN diode taken into account, the equivalent circuit models of the PIN diode under forward bias and reverse bias are shown in Fig. 2(a) and Fig. 2(b), respectively, where L_0 is the parasitic inductance of PIN diodes; R_0 is the parasitic resistance of PIN diodes under the forward bias; C_0 and R_p are the parasitic capacitance and parasitic resistance of PIN diodes under the reverse bias. Accordingly the AC equivalent circuits of matching stub under different bias conditions are shown in Fig. 2(c) and Fig. 2(d). Under forward bias condition, the input impedance of the matching stub is Z_{in2_f}, while under reverse bias condition, the input impedance of the matching stub is Z_{in2_r}. In both cases, the PIN diode has the same parasitic inductance. Therefore, the input impedance Z_G at

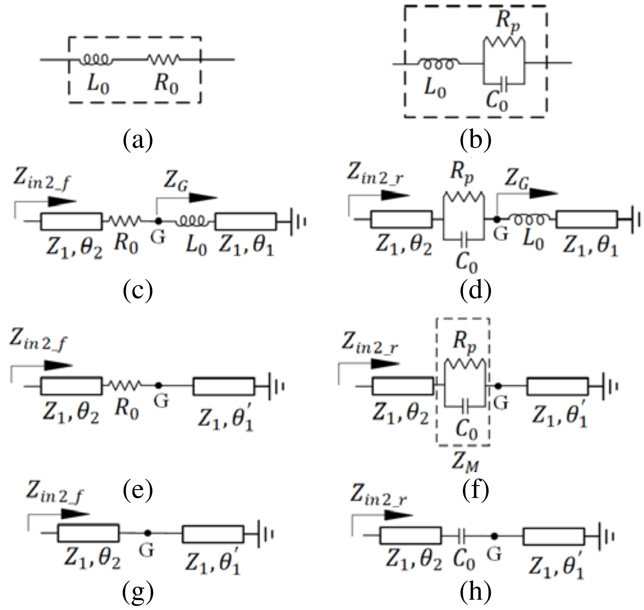


Figure 2. The simplification process of matching stub's input impedance. (a) PIN diode equivalent circuit model under forward bias condition. (b) PIN diode equivalent circuit model under reverse bias condition. (c) AC equivalent circuit of matching stub under forward bias condition. (d) AC equivalent circuit of matching stub under reverse bias condition. (e) AC equivalent circuit of matching stub under forward bias condition after converting parasitic inductance. (f) AC equivalent circuit of matching stub under reverse bias condition after converting parasitic inductance. (g) Simplified AC equivalent circuit of matching stub under forward bias condition. (h) Simplified AC equivalent circuit of matching stub under reverse bias condition.

the imaginary point G inside the PIN diode in Fig. 2(c) and Fig. 2(d) can be expressed as

$$Z_G = jZ_1 \tan\theta_1 + j\omega L_0 \tag{2}$$

ω is the central angular frequency. Z_G is a pure reactance, so its effect can be equivalent to a microstrip line with electrical length θ_1'. The relationship between the actual electrical length θ_1 and the equivalent electrical length θ_1' is as follows.

$$\theta_1 = \arctan\left(\tan\theta_1' - \frac{\omega L_0}{Z_1}\right) \tag{3}$$

As shown in Fig. 2(e), Z_{in2_f} can be expressed as Eq. (4).

$$Z_{in2\_f} = Z_1 \frac{j(\tan\theta_1' + \tan\theta_2) + R_0/Z_1}{1 - \tan\theta_1' \tan\theta_2 + j(R_0/Z_1)\tan\theta_2} \tag{4}$$

The PIN diode has a small resistance R_0 under forward bias condition which leads to Equation (5).

$$\frac{R_0}{Z_1} \simeq 0 \tag{5}$$

So, Z_{in2_f} can be simplified as

$$Z_{in2\_f} \simeq Z_1 \frac{j(\tan\theta_1' + \tan\theta_2)}{1 - \tan\theta_1' \tan\theta_2} = jZ_1 \tan(\theta_1' + \theta_2) \tag{6}$$

Then, the simplified circuit of the matching stub under the forward bias condition can be obtained as shown in Fig. 2(g).

Meanwhile in Fig. 2(f), apart from parasitic inductance, the impedance of the remaining parasitic effects of the reverse-bias PIN diode can be expressed as follows.

$$Z_M = \frac{R_p(1 - j\omega C_0 R_p)}{1 + \omega^2 C_0^2 R_p^2} \tag{7}$$

The PIN diode has a very large equivalent resistance R_p under reverse bias condition which leads to Equation (7).

$$\omega C_0 R_p \gg 1 \tag{8}$$

So Eq. (7) can be simplified to Eq. (9)

$$Z_M \simeq \frac{-j\omega C_0 R_p^2}{\omega^2 C_0^2 R_p^2} = \frac{1}{j\omega C_0} \tag{9}$$

Then, the simplified circuit of the matching stub under the reverse bias condition can be obtained as shown in Fig. 2(h). Under reverse bias conditions, the input impedance of the matching stub can be expressed as follows.

$$Z_{in2\_r} \simeq Z_1 \frac{Z_1 \tan\theta_1' - \dfrac{1}{\omega_0 C_0} + Z_1 \tan\theta_2}{Z_1 - \left(Z_1 \tan\theta_1' - \dfrac{1}{\omega_0 C_0}\right)\tan\theta_2} j \tag{10}$$

In the above simplification, the resistance in the PIN diode equivalent circuit is ignored based on the characteristics of the PIN diode under different biases. Therefore, Z_{in2} is pure reactance under both bias conditions which makes the matching equation easier to solve.

2.3. Solving the Impedance Matching Equation and Error Analysis

When the load impedance Z_L is arbitrary real impedance, it is easy to obtain the input impedance Z_{in1} as Eqs. (11) and (12) when the load impedance is Z_0 or Z_L.

$$Z_{in1\_0} = Z_0 \tag{11}$$

$$Z_{in1\_L} = Z_0 \frac{Z_L + jZ_0 \tan\theta_0}{Z_0 + jZ_L \tan\theta_0} \tag{12}$$

Therefore, RIMN has two potential ways of conducting impedance matching. One is matching the load impedance Z_0 under the forward bias while matching load Z_L under the reverse bias. The other is matching the load impedance Z_L under the forward bias while matching load Z_0 under the reverse bias. The former mode is selected because this mode is more conducive to solving Eq. (1). In this mode, Eq. (1) can be written as Eqs. (13) and (14) under either of the two bias conditions.

$$\frac{1}{Z_0} = \frac{1}{Z_{in1\_0}} + \frac{1}{Z_{in2\_f}} \tag{13}$$

$$\frac{1}{Z_0} = \frac{1}{Z_{in1\_L}} + \frac{1}{Z_{in2\_r}} \tag{14}$$

By solving Eqs. (13) and (14), the following solution can be acquired.

$$\theta_0 = \arctan\sqrt{\frac{Z_L}{Z_0}} \tag{15}$$

$$\theta_1' = \arctan\left(\frac{1 \pm \sqrt{1 - 4\omega^2 C_0^2 Z_1^2 + \dfrac{4\omega C_0 Z_0 \sqrt{Z_L/Z_0}}{Z_L/Z_0 - 1}}}{2\omega C_0 Z_1}\right) \tag{16}$$

$$\theta_2 = 90^\circ + N \times 180^\circ - \theta_1' \quad N \in 0, 1, 2... \tag{17}$$

By simplifying the equivalent circuit of the PIN diode and matching equation, each electrical length of microstrip lines in RIMN can be directly calculated. The above simplification brings convenience to calculation, but it will bring some errors too. Those errors are mainly attributed to the omission of the PIN diode's resistive effect. It is difficult to strictly analyze these errors from a mathematical point of view. Therefore, a comparative simulation is used to demonstrate the error.

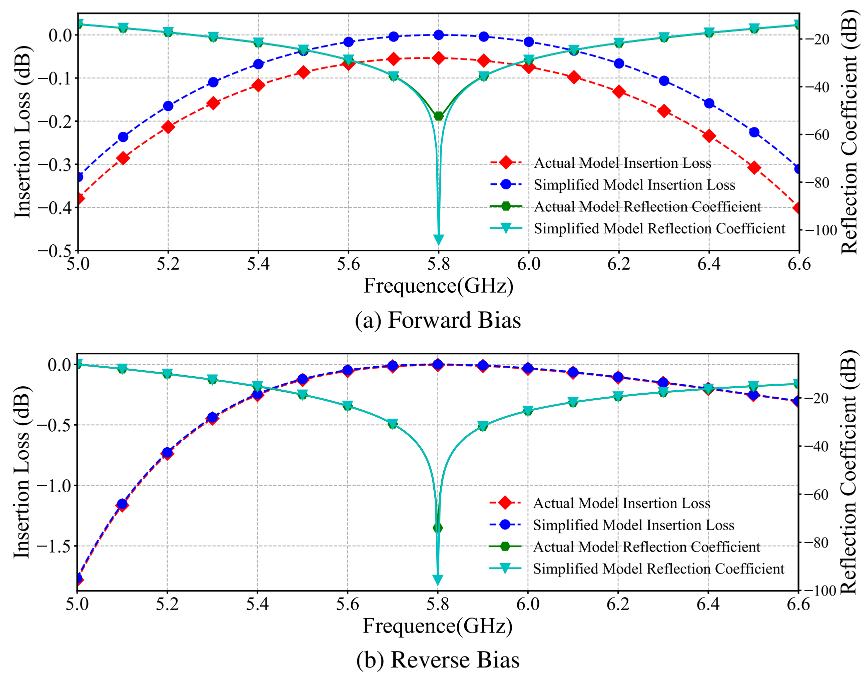


Figure 3. Frequency responses of reconfigurable impedance matching network with different PIN diode model

A RIMN working at 5.8 GHz is designed. The port impedance Z_0 and load impedance Z_L are chosen to be 50 Ω and 100 Ω. Parasitic parameters used in the design are typical values of MA4SPS502 from M/A-com. The values of each parameter are shown in Table 1. RIMNs with PIN diode's actual circuit and PIN diode's simplified circuit are simulated separately, and the result is shown in Fig. 3.

Table 1. Parameters of reconfigurable impedance matching network.

Parameter	L_0 (nH)	C_0 (pF)	R_0 (Ω)	R_p (Ω)
Value	0.35	0.09	2.4	100000
Parameter	Z_0 (Ω)	Z_1 (Ω)	Z_2 (Ω)	Z_L (Ω)
Value	50	100	100	100
Parameter	θ_0	θ_1	θ_2	
Value	54.74	154.90	108.83	

As can be seen from Fig. 3, the simplification process has little effect on reflection coefficient while it presents lower insertion loss. The reason is that the resistive effects of PIN diode are ignored, and only the parasitic inductance and parasitic capacitance are considered during the simplification process. In the actual case, the resistors R_0 and R_p consume part of the energy which contributes to insertion loss. The insertion loss increases by about 0.06 dB under forward bias conditions, and the insertion loss increases by about 0.007 dB under reverse bias conditions.

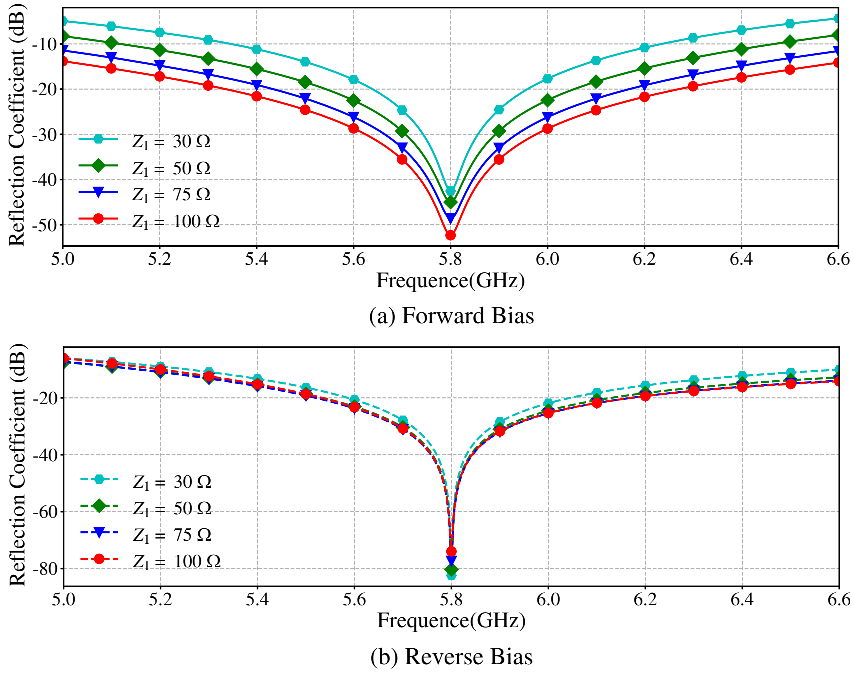


Figure 4. Reflection coefficient of reconfigurable impedance matching network with varied values of Z_1

2.4. Parameter Analysis

The selection of Z_1 will not affect the above solution process at the selected center frequency. However, in practical applications, the selection of Z_1 will impact the impedance bandwidth of RIMN. Fig. 4 shows the reflection coefficient for different Z_1 while other conditions are the same as those in Table 1. Under forward bias conditions, since the matching stub can be regarded as a high-impedance line according to the simplified circuit. Higher characteristic impedance of Z_1 results in wider impedance bandwidth. Under reverse bias, since the reactance of the parasitic capacitance is frequency dependent, the bandwidth is mainly limited by the value of the parasitic capacitance, so the selection of Z_1 makes no significant difference. According to the above analysis, the value of Z_1 should be as large as possible to enhance the impedance bandwidth of RIMN.

2.5. Expansion

The above solving process made a assumption that Z_L is a pure real impedance. RIMN can be applied to complex impedance matching through a extension as shown in Fig. 5. For the complex impedance $Z_L = A + jB$, the input impedance transformed by a microstrip line with a characteristic impedance of Z_0 and length of θ_0' is Z_L'.

$$Z_L' = \frac{AZ_0(1+\tan^2\theta_0')}{(Z_0 - B\tan\theta_0')^2 + (A\tan\theta_0')^2} Z_0 - \frac{BZ_0\tan^2\theta_0' - (Z_0^2 - A^2 - B^2)\tan\theta_0' - Z_0 B}{(Z_0 - B\tan\theta_0')^2 + (A\tan\theta_0')^2} Z_0 j \tag{18}$$

In the case of $A \neq 0$ and arbitrary value of B, Equations (19) and (20) always have a solution.

$$\text{imag}(Z_L') = 0 \tag{19}$$

$$\text{real}(Z_L') \neq 0 \tag{20}$$

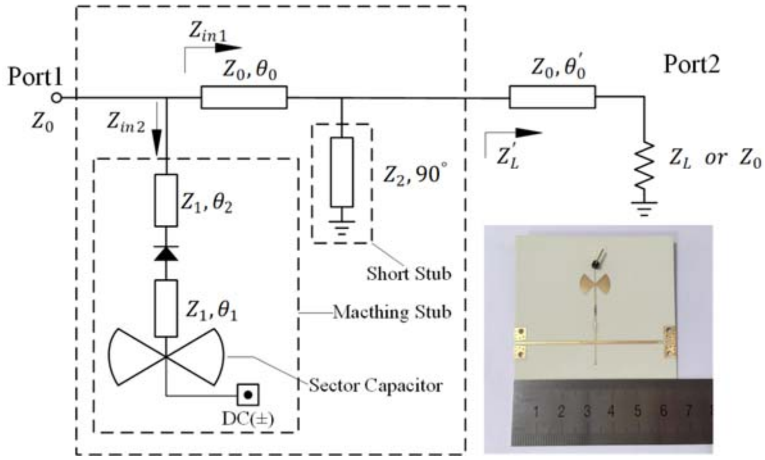


Figure 5. A block diagram and photograph of reconfigurable impedance matching network with a expansion.

The solution is Equation (21)

$$\theta_0' = \arctan\left(\frac{Z_0^2 - A^2 - B^2 \pm \sqrt{(Z_0^2 - A^2 - B^2)^2 - 4B^2 Z_0^2}}{BZ_0}\right) \tag{21}$$

So for any non-pure imaginary impedance Z_L, it can be transformed into an equivalent real load Z_L' by a microstrip line with θ_0' to adapt to RIMN. θ_0' has two possible values, both of which are feasible. Z_L' can be applied to previous analysis as a real load. There is no coupling between the parameters of the above two steps, which can be calculated separately. This amount of calculation is much smaller than that applying RIMN directly to complex impedance matching.

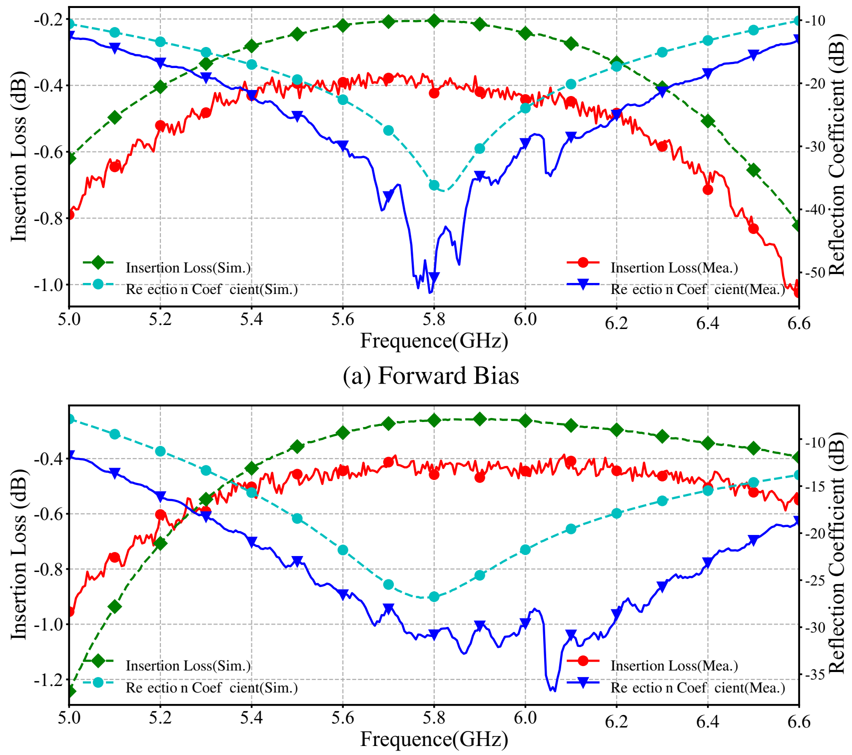
3. EXPERIMENTAL RESULT

For verification, a RIMN working at 5.8 GHz is designed and fabricated on a Rogers 4350 substrate with a thickness of 0.508 mm and relative dielectric constant of 3.66. As mentioned in Section 1, one of the main applications of RIMN is to match the input impedance of the reconfigurable antenna under different states. Therefore, two typical values of the input impedance of the reconfigurable antenna are selected for matching. The RIMN is designed to match impedances of $50\,\Omega$ and $50 + 20j\Omega$, respectively. The required PIN diode uses MA4SPS502 from M/A-Com. The forward bias current and reverse bias voltage of the diode are chosen to be 50 mA and -15 V, respectively. Its equivalent parasitic parameters are extracted by the method proposed by [7].

It is difficult to construct a load of $50 + 20j\Omega$ over a wide frequency range. So during the measurement process, RIMN will be treated as a dual-port device. Then the multi-line TRL de-embedding method [8] is used to measure its frequency response. Finally, the Advanced Design System (ADS) is used to obtain the S-parameter curve when matching different loads. ADS is a powerful simulation software which can get the frequency response of microwave networks with arbitrary load impedance.

Figure 6(a) shows the simulated and measured performances when load impedance is $50\,\Omega$. At the target frequency of 5.8 GHz, the reflection coefficients are less than 40 dB while the insertion losses are 0.4 dB. Fig. 6(b) shows the simulated and measured performances when load impedance is $50 + 20j\Omega$. At the targeted frequency of 5.8 GHz, the reflection coefficients are less than 30 dB while the insertion losses are 0.4 dB. The results of the simulation and measurement are basically consistent within the band of 5.0 GHz to 6.6 GHz.

However, there is a problem that for either reflection coefficients or insertion loss, the measurement result is a little larger than the simulation result. Based on the above theoretical analysis, the source of the loss is the resistance inside the diode. However, the effects of some external factors such as soldering



(a) Forward Bias

(b) Reverse Bias

Figure 6. Simulated and measured frequency responses of reconfigurable impedance matching network.

or packaging were not calculated. They also consume part of the energy causing the RIMN's reflection coefficients and insertion loss to increase.

Table 2 shows the comparison between RIMN and other circuits for impedance matching. The proposed RIMN employing a simple structure without lumped component has a good performance by compensating parasitic effect of PIN diode and reducing the effect of DC.

Table 2. Comparison between reconfigurable impedance matching network and other circuit.

Item	Amount of stub contributing in matching	Coupling between DC and AC	Compensation for parasitic parameters	Calculated amount	Whether require lumped components
SMS [4]	1	Yes	No	-	Require
SIMC [5]	1	No	-	Small	Require
RITN [6]	2	No	Yes	Large	Not Require
RIMN	1	No	Yes	Small	Not Require

4. CONCLUSION

In this paper, a RIMN has been proposed for impedance matching. It can match any non-pure imaginary impedance using only one stub with a PIN diode. The parameters in RIMN are solved and analyzed to satisfy matching conditions in the circuit. Through some mathematical simplification, it becomes easier to acquire the parameters. For verification, a RIMN working at 5.8 GHz is fabricated and measured. Good measured performances of this RIMN have been obtained.

ACKNOWLEDGMENT

This work was supported by the National Natural Science Foundation of China under Grants 61571289, 61571298, 61701303 and 61471240, Natural Science Foundation of Shanghai (17ZR1414300), and Shanghai Pujiang Program (17PJ1404100).

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