(Received 13 October 2023, Accepted 26 December 2023, Scheduled 18 January 2024)

A Novel Microwave Equalizer Based on SIR Loading with Internal Coupled-Lines

Xiaolei Yang[1], Honglin Zhang[1,*], Wencheng Ren[1],
Chunlei Yuan[1], Lijie Xu[2], and Dong Chen[2]

[1]54th Research Institute of CETC, No. 589, West Zhongshan Road, Shijiazhuang 050081, China
[2]College of Electronic and Optical Engineering & College of Flexible Electronics
Nanjing University of Posts and Telecommunications, No. 9, Wenyuan Road, Nanjing 210023, China

ABSTRACT: This paper proposes the design of a microwave equalizer based on stepped impedance resonator (SIR) loading with an internal coupled-line. By loading a ring-type stepped impedance resonator (SIR) with internal coupled-lines, a microwave equalizer with positive slope transmission characteristics is presented. The frequency response is synthesized using a second-order SIR, and a detailed theoretical derivation of the equalizer is presented. A prototype of the equalizer is fabricated and measured to validate its expected performance, with the measurements showing good agreement with the predictions. The microwave amplitude equalizer demonstrates the necessary gain slope across its entire operational frequency range. Finally, a potential design scheme for a microwave amplitude equalizer is proposed.

1. INTRODUCTION

Amplitude equalizer is first used in low-frequency audio, post and telecommunications, CATV, and other equipment [1]. Because radar, microwave communication, satellite, mobile communication, and other equipment require the flatness of amplitude-frequency response of microwave broadband signal transmission, the operating frequency of amplitude equalizer has been extended to microwave frequency band or even millimeter wave frequency band [2].

Microwave amplitude equalizers can be divided into two types: active and passive. Since a passive structure has better advantages in terms of system burden, response time, and power capacity, it has been widely studied [3–9]. Since integrated transmission line equalizer has the advantages of small size, light weight, and convenient integration with solid state circuit, it is widely used [10]. With the increase in frequency and the application of ultra-wideband circuits, various new integrated transmission line equalizer structures have emerged. In [11], a microstrip equalizer is designed by $\lambda/4$ length shunt short-circuit stubs around an R-C parallel resonating circuit. In [12], by employing open SIRs to adjust the equalization slope parameters, a microstrip equalizer is achieved.

In this paper, a novel microwave equalizer that utilizes a ring-type SIR with internal coupled-lines loading is presented. By theoretical and simulation analysis of the microwave equalizer, a positive slope transmission characteristic is designed. Subsequently, a proposed microwave equalizer sample was fabricated and measured. The measurement results were in high agreement with the expected results, demonstrating that the intended design was achieved.

* Corresponding author: Honglin Zhang (zhlandhsl@163.com).

2. ANTENNA AND ITS EQUIVALENT CIRCUIT

Figure 1 illustrates the schematic diagram of the proposed microwave equalizer. As shown in Fig. 1, the entire structure is symmetrical relative to the vertical centerline and connected to $50\,\Omega$ SMA. The proposed equalizer is processed on a Rogers RO4003C substrate, with a thickness 0.508 mm, relative permittivity $\varepsilon_r = 3.38$, and loss tangent $\tan\delta = 0.0027$. In our design, a microstrip line is loaded between the main transmission lines with an input/output characteristic impedance of $50\,\Omega$. At the same time, at the connection point with the main transmission line, a ring-type SIR with internal coupled-lines and a resistor R in parallel are also added.

The proposed equalizer consists of two sets of notch structures, each consisting of a ring-type SIR with internal coupled-lines and a resistor R, which are placed on a segment of microstrip for power transmission. The characteristic impedance of this microstrip is denoted as Z_1, and the input impedance as seen from the SIR with internal coupled-lines terminals is denoted as Z_i. The input and output are microstrip lines with a characteristic impedance of $50\,\Omega$, denoted by Z_0. The notch structure is composed of the SIR with internal coupled-lines and resistor, which completes the required attenuation while also participating in mutual matching to achieve low standing waves throughout the entire operating frequency band. Fig. 2 depicts the equivalent structure and two-port network model of the proposed microwave equalizer. Fig. 2(a) illustrates the equivalent structure of the proposed microwave equalizer, while Fig. 2(b) shows the two-port network model of the proposed microwave equalizer.

In our design, the ring-type SIR with internal coupled-lines is first analyzed equivalently. Fig. 3 depicts the evolutionary process and corresponding circuit analysis of the ring-type SIR with internal coupled-lines. Fig. 3(a) shows the split-ring

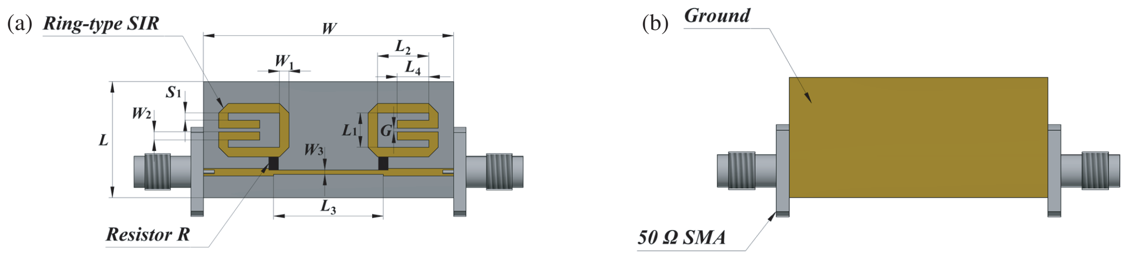

FIGURE 1. Configuration of the proposed microwave equalizer: (a) Top layer; (b) Bottom layer.

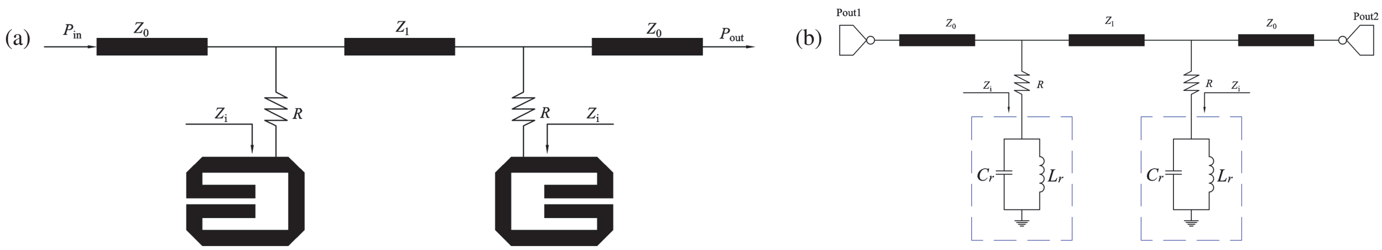

FIGURE 2. Equivalent structure and two-port network model of the proposed microwave equalizer: (a) Equivalent structure; (b) Two-port network model.

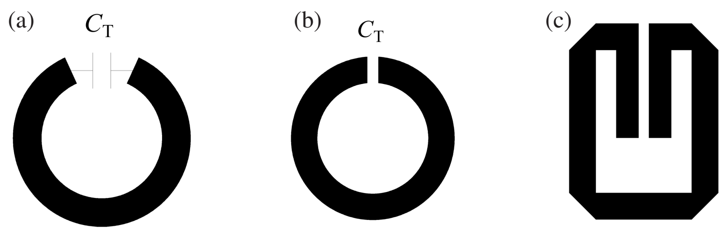

FIGURE 3. Structural variations of type SIRs: (a) Conventional split-ring resonator; (b) Edge-coupled split-ring resonator; (c) SIR with internal coupled-lines.

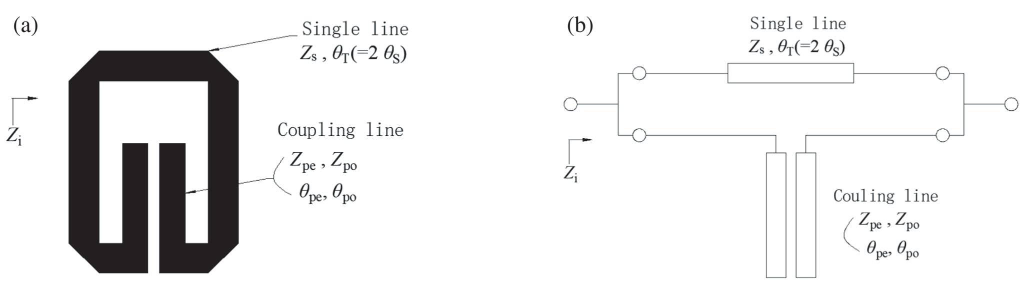

FIGURE 4. Electrical parameters and equivalent circuit of the SIR with internal coupled-lines: (a) Electrical parameters; (b) Equivalent circuit.

resonator with a lumped-element capacitor. However, due to the disadvantages of large capacitance loss and significant resonance frequency variation, the split-ring resonator with an edge coupling structure shown in Fig. 3(b) has been adopted. Nevertheless, this structure has the drawback of a low capacitance value, making it unsuitable for designing compact split-ring resonators. Therefore, the SIR with internal coupled-lines shown in Fig. 3(c) is more suitable for practical applications.

Figure 4 depicts the electrical parameters of the proposed SIR with internal coupled-lines, as well as its equivalent circuit. This circuit can be analyzed as a single transmission line and two open-end parallel coupling lines.

According to the microwave network theory [13], as shown in Fig. 4(b), the coupled line matrix F_1 and single transmission line matrix F_2 are respectively

$$F_1 = \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} = \begin{bmatrix} Z_{pe}\cos\theta_{pe} + Z_{po}\cot\theta_{po} & -j\frac{2Z_{pe}Z_{po}\cot\theta_{pe}\cot\theta_{po}}{Z_{pe}\cot\theta_{pe} - Z_{po}\cot\theta_{po}} \\ j\frac{2}{Z_{pe}\cot\theta_{pe} - Z_{po}\cot\theta_{po}} & \frac{Z_{pe}\cot\theta_{pe} + Z_{po}\cot\theta_{po}}{Z_{pe}\cot\theta_{pe} - Z_{po}\cot\theta_{po}} \end{bmatrix} \quad (1)$$

$$F_2 = \begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix} = \begin{bmatrix} \cos\theta_S & jZ_S\sin\theta_S \\ j\frac{\sin\theta_S}{Z_S} & \cos\theta_S \end{bmatrix} \tag{2}$$

where Z_{pe} and Z_{po} denote the even- and odd-mode impedances, respectively, while the even- and odd-mode electrical lengths of the parallel coupling line are denoted by θ_{pe} and θ_{po}, respectively. Furthermore, Z_S represents the characteristic impedance of the single line, while θ_s represents its electrical length.

According to the $ABCD$ transfer matrix, the overall matrix F_T is

$$F_T = \begin{bmatrix} A_T & B_T \\ C_T & D_T \end{bmatrix} = F_1 \times F_2 \tag{3}$$

where,

$$A_T = \frac{A_1B_2 + A_2B_1}{B_1 + B_2} \tag{4}$$

$$B_T = \frac{B_1B_2}{B_1 + B_2} \tag{5}$$

$$C_T = \frac{-(A_1-A_2)(D_1-D_2)-(B_1+B_2)(C_1+C_2)}{B_1+B_2} \tag{6}$$

$$D_T = \frac{B_1D_2 + B_2D_1}{B_1 + B_2} = A_T \tag{7}$$

Assuming that the circuit impedance as shown in Fig. 4(b) is Z_L, then the impedance Z_i can be calculated using Eq. (3):

$$Z_i = \frac{A_TZ_L + B_T}{C_TZ_L + D_T} = \frac{A_T + B_T/Z_L}{C_T + D_T/Z_L} \tag{8}$$

In the SIR with internal coupled-lines, when Z_L is an open circuit and assumed to be infinite, Eq. (8) yields that Z_i equals:

$$\begin{aligned} Z_i &= \frac{A_T}{C_T} \\ &= \frac{A_1B_2 + A_2B_1}{-(A_1 - A_2)(D_1 - D_2) - (B_1 + B_2)(C_1 + C_2)} \end{aligned} \tag{9}$$

Substitute each matrix element with Eq. (1) and Eq. (2), Z_i can be obtained.

Next, the derivation of the proposed microwave equalizer equivalent circuit is presented. As shown in Fig. 2(b), the $ABCD$-matrices of the two-port network with A, A' as reference planes are respectively

$$F_1' = \begin{bmatrix} 1 & 0 \\ \frac{Z_0}{R+Z_1} & 1 \end{bmatrix} \tag{10}$$

$$F_2' = \begin{bmatrix} \cos\theta_1 & j\frac{Z_1}{Z_0}\sin\theta_1 \\ j\frac{Z_0}{Z_1}\sin\theta_1 & \cos\theta_1 \end{bmatrix} \tag{11}$$

$$F_3' = \begin{bmatrix} 1 & 0 \\ \frac{Z_0}{R+Z_1} & 1 \end{bmatrix} \tag{12}$$

where Z_0, Z_1, and θ_1 are the characteristic impedances and electrical lengths of microstrip, respectively.

The overall transfer A-matrix after cascading is:

$$a = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} = F_1 \times F_2 \times F_3 \tag{13}$$

The relationship between S-matrix and A-matrix:

$$S = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} = \frac{1}{a_{11} + a_{12} + a_{21} + a_{22}} \times \begin{bmatrix} a_{11}+a_{12}-a_{21}-a_{22} & 2*det\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \\ 2 & -a_{11}+a_{12}-a_{21}+a_{22} \end{bmatrix} \tag{14}$$

In order to achieve matching at the frequency point where attenuation is minimized, the S-parameter should satisfy:

$$S_{11} = 0, \quad S_{12} = IL \tag{15}$$

where IL is the minimum attenuation of the equalizer.

From Eq. (10) to Eq. (15), the equalization network resistor R and impedance Z_i of the SIR with internal coupled-lines can be obtained for the desired operating frequency range and attenuation, respectively.

Up to this point, the equivalent circuit has been deduced, and a comprehensive simulation using full-wave analysis will be employed for evaluating our design. The schematic diagram of the structural is illustrated in Fig. 1, and the dimensions of the structural parameters are shown in Table 1.

TABLE 1. Geometric parametes of the proposed microwave amplitude equalizer.

Parameter	Value (mm)	Parameter	Value (mm)
W	34.2	L_2	7.0
L	15.9	L_3	15.0
W_1	1.3	L_4	4.3
W_2	1.1	S_1	1.0
W_3	0.6	G	0.5
L_1	4.7	R	80 (ohm)

According to the preceding analysis, it is evident that the performance of the proposed equalizer is determined by the resistor R and the impedance Z_i of the SIR with internal coupled-lines. In our design, we make the assumption that the resistance value of resistor R remains constant. The impact of varying impedance Z_i on the equalizer's performance is then simulated. Based on Eqs. (1) to (9) and Fig. 1, the S-parameter varies with W_1, W_2, L_1, and G, as shown in Figs. 5–6.

Figures 5(a) and (b) show the variation of S_{21} with W_1 and W_2. From Fig. 5, it can be seen that as the microstrip width of SIR changes, the resonant frequency of the equalizer will shift towards higher or lower frequencies. Fig. 5(a) shows that as W_1 increases, the resonant frequency shifts towards the high

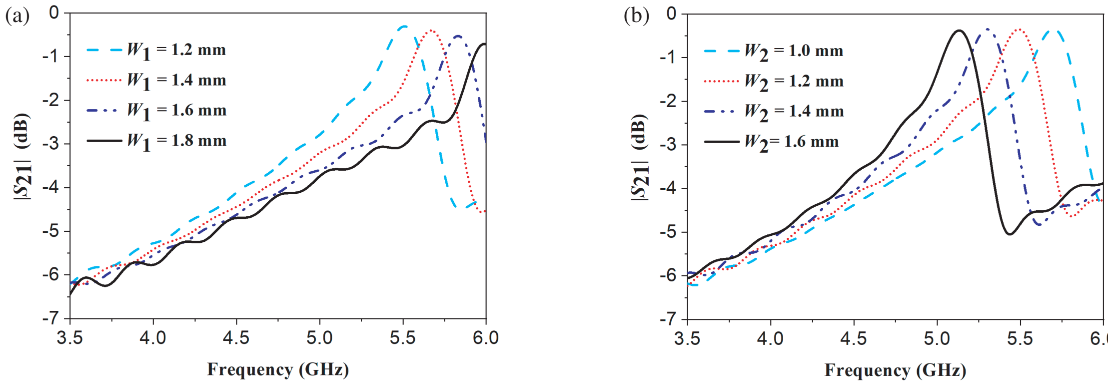

FIGURE 5. The simulation S_{21}: (a) The simulation S_{21} varies with W_1; (b) The simulation S_{21} varies with W_2.

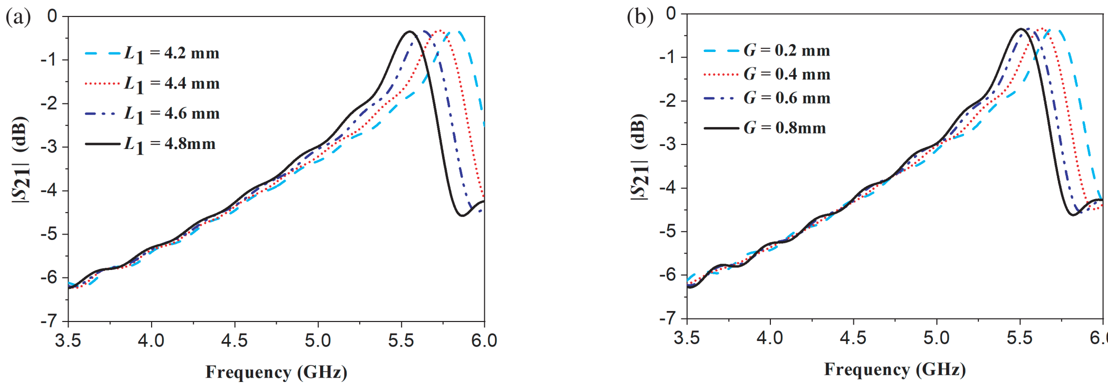

FIGURE 6. The simulation S_{21}: (a) The simulation S_{21} varies with L_1; (b) The simulation S_{21} varies with G.

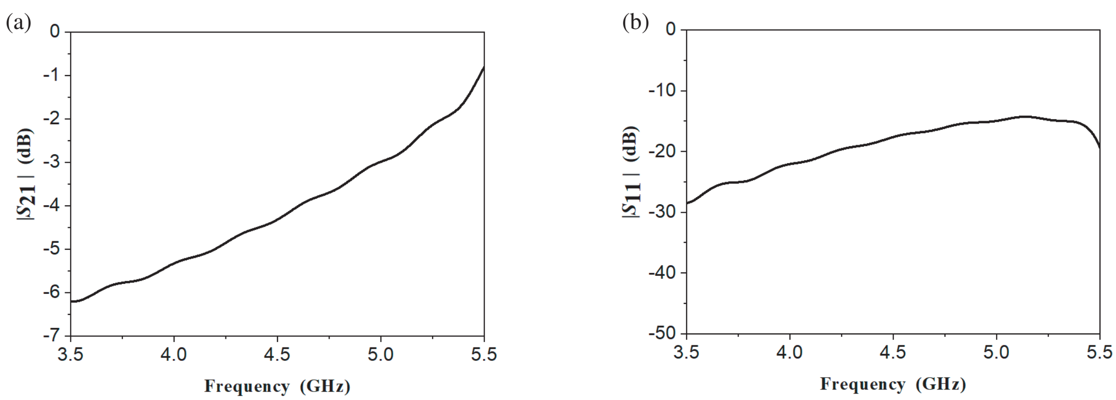

FIGURE 7. The S-parameter simulation results of the proposed equalizer: (a) The simulate S_{21}; (b) The simulate S_{11}.

frequency range. As shown in Fig. 5(b), as W_2 increases, the resonant frequency shifts towards the lower frequency range.

In a similar fashion, Figs. 6(a) and (b) show the variation of S_{21} in relation to L_1 and G. Fig. 6(a) reveals that as the length L_1 of the SIR increases, the resonant frequency moves towards the lower frequency range. Similarly, Fig. 6(b) demonstrates that as the internal coupling gap G of the SIR increases, the resonant frequency also shifts towards the lower frequency range. Generally, it can be observed from Figs. 5 and 6 that changes in the size of the SIR affect the resonant frequency of the equalizer. Additionally, it is evident that as the size of the SIR changes, the positive slope transmission characteristics of the equalizer remain consistent within the effective frequency range and will shift towards higher or lower frequency ranges.

Figure 7 depicts the simulation results of the S-parameters for the proposed microwave equalizer.

From Fig. 7, it can be observed that within the bandwidth of 3.5 GHz to 5.5 GHz, the maximum attenuation of the equalizer is 6.2 dB at 3.5 GHz, and the minimum attenuation is 0.8 dB at 5.5 GHz, with positive slope transmission characteristics. The return loss is less than -14 dB within the bandwidth of 2.5 GHz $\sim$ 5.5 GHz, indicating good low standing wave characteristics.

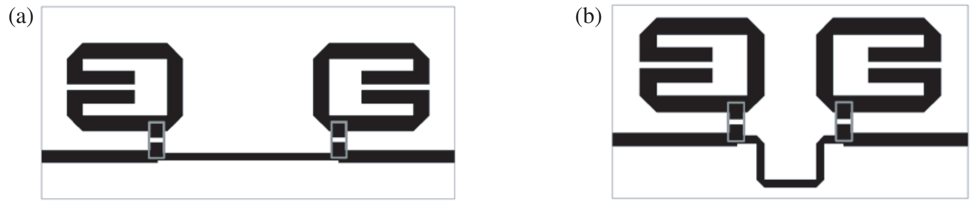

FIGURE 8. Miniaturization of the proposed equalizer: (a) The proposed equalizer; (b) The evolution process.

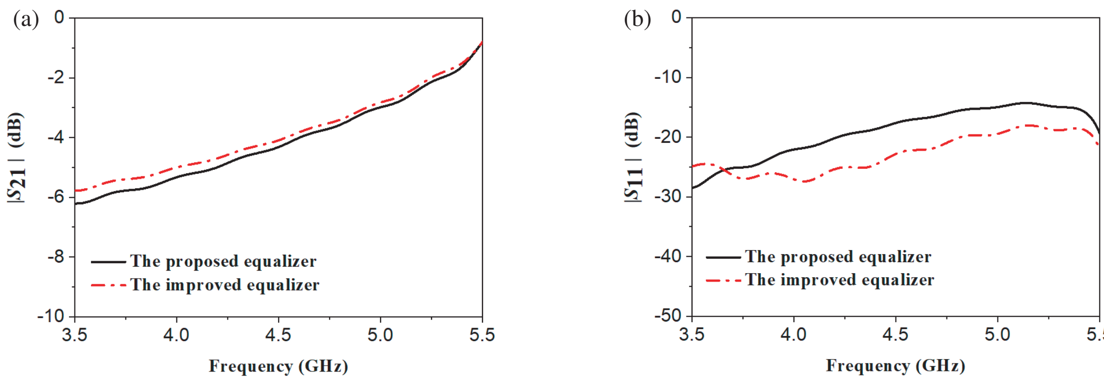

FIGURE 9. Simulation S-parameters before and after miniaturization of the proposed equalizer: (a) The simulate S_{21}; (b) The simulate S_{11}.

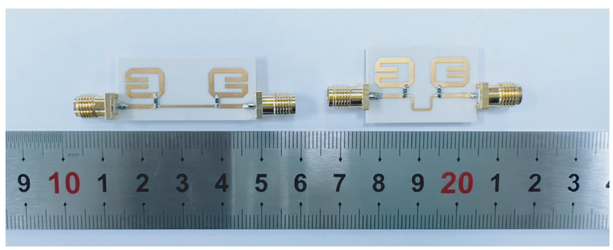

FIGURE 10. Photograph of the proposed microwave equalizer.

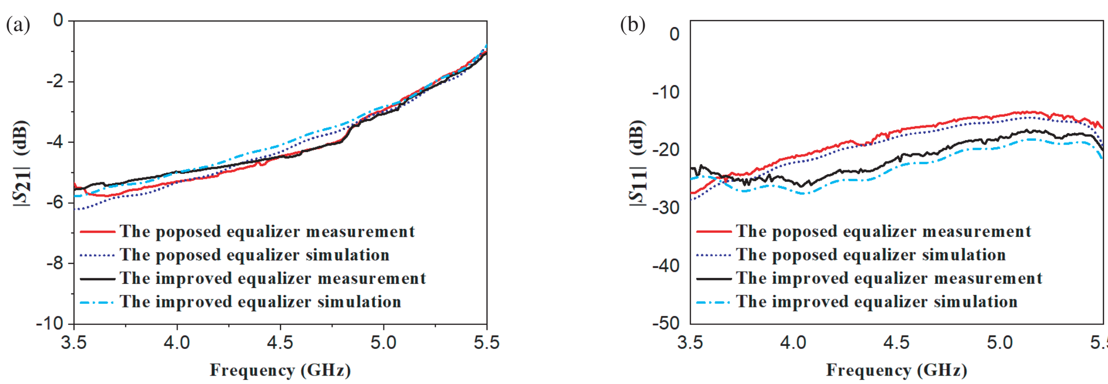

FIGURE 11. Simulated and measured S-parameter of the proposed equalizer: (a) The simulation and measurement S_{21}; (b) The simulation and measurement S_{11}.

In our design, the proposed equalizer has been miniaturized, as shown in Fig. 8.

From Fig. 8, it can be observed that the miniaturization development of the proposed equalizer is achieved by employing a microstrip transmission line with a bending impedance of Z_1. As a result of miniaturization, the proposed equalizer has a reduced size of $W = 27.4$ mm and $L = 14.9$ mm. Fig. 9 shows a comparison of the electrical characteristics before and after miniaturization evolution.

The electrical performance of the proposed equalizer always maintains good consistency before and after miniaturization, as shown in Fig. 9.

3. MEASURED RESULTS

In order to verify the design of the proposed equalizer, a sample equalizer was manufactured and measured. The size parameters have been optimized using CST electromagnetic simulation software, and the structural dimensions are as mentioned above. Simultaneously, a physical photo of the proposed equalizer is shown in Fig. 10. The S-parameter of the proposed equalizer was measured using Keysight E5071C vector network analyzer. The comparison between the simulated and measured S-parameters is shown in Fig. 11.

As shown in Fig. 11, the minimum attenuation of the proposed equalizer was measured to be 1.0 dB at 5.5 GHz. The maximum attenuation was measured to be 5.5 dB at 3.5 GHz. The return loss is less than -16.6 dB over the entire operating frequency range. It exhibits excellent positive slope transmission characteristics.

The discrepancies between the minimum attenuation measured and simulated values are mainly attributable to the transmission losses between SMA connectors and microstrip lines. On the other hand, the discrepancies between the maximum attenuation measured and simulated values are primarily due to inaccuracies in the discrete resistor values and their parasitic parameters.

4. CONCLUSION

This paper presents a novel ring-type SIR with internal coupled-lines loading a microwave equalizer. By combining the SIR with an energy absorbing resistor R, a notch filter with a positive slope amplitude-frequency characteristic is formed. The transmission mechanism of the proposed equalizer is described in detail. At the same time, the proposed equalizer is compactly designed. The simulated and measured results are in good agreement, which provides valuable verification for our proposed design method.

REFERENCES

[1] Gmitrovic, M. V., B. D. Milovanovic, and Z. D. Milosavljevic, "Fixed and variable slope CATV amplitude equalizers," *Applied Microwave and Wireless*, Vol. 10, 76–85, 1998.

[2] Kampa, J. and K. Petrus, "Microwave amplitude equalizer," in *13th International Conference on Microwaves, Radar and Wireless Communications. MIKON-2000. Conference Proceedings (IEEE Cat. No. 00ex428)*, Vol. 1, 37–40, 2000.

[3] Wang, Y., D. Zhou, Y. Zhang, and C. Chang, "Using multilayered substrate integrated waveguide to design microwave gain equalizer," *Advances in Materials Science and Engineering*, Vol. 30, 1341–1344, 2014.

[4] Tang, S., Y. Zhang, and J. Zhang, "A novel compact size microstrip equalizer based on spiral resonators," in *2010 International Conference on Microwave and Millimeter Wave Technology*, 730–733, 2010.

[5] Wang, Z. and B. Jia, "Research on microwave equalizer of aperture-backed technique," in *2008 8th International Symposium on Antennas, Propagation and EM Theory*, 1375–1378, 2008.

[6] Mellor, D. J., "On the design of matched equalizers of prescribed gain versus frequency profiles," in *1977 IEEE MTT-S International Microwave Symposium Digest*, 308–311, 1977.

[7] Ying, Z., D.-F. Zhou, Z.-X. Niu, and B. Zhao, "A improved branch resonator and it's application in microstrip equalizer designing," in *2007 International Conference on Microwave and Millimeter Wave Technology*, 1–4, 2007.

[8] Ying, Z., D.-F. Zhou, Z.-X. Niu, and D.-W. Zhang, "Study of the influence of resistors for microstrip equalizer," in *2005 Asia-Pacific Microwave Conference Proceedings*, Vol. 5, 4, 2005.

[9] Zhang, Y., M. Yu, B. Yan, and R. Xu, "Research on the millimeter wave power equalizer," in *2007 International Symposium on Microwave, Antenna, Propagation and EMC Technologies For Wireless Communications*, 446–449, 2007.

[10] Zhou, T.-F., Y. Zhang, and R.-M. Xu, "Research on the millimeter wave gain equalizer," in *2011 IEEE International Conference on Microwave Technology & Computational Electromagnetics*, 180–182, 2011.

[11] Gourav, C. and G. Anand, "Non-reflective broadband microwave gain equalizer for EW applications," *2019 IEEE MTT-S International Microwave and RF Conference (IMARC)*, 1–4, 2019.

[12] Jiang, S., J. Xu, and D. Ding, "A 5–19 GHz amplitude-shaped power amplifier using microstrip sirs loaded with film resistors," in *2016 IEEE International Conference on Microwave and Millimeter Wave Technology (ICMMT)*, Vol. 1, 138–140, 2016.

[13] Pozar, D. M., *Microwave Engineering*, John Wiley & Sons, 2011.