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Generative Model for Dual-Band Filters Based on Modified Complementary Split-Ring Resonators

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Abstract: This article presents a generative model for the inverse design of dual-band filters based on a type of modified complementary split-ring resonator (CSRR). It consists of a series of convolutional neural networks that incorporate the conditional deep convolutional generative adversarial network (GAN) technique. The filters are designed by etching the modified CSRRs on the surface of substrate-integrated waveguides. This design allows us to achieve two passbands with a compact size. In this GAN-based generative model, the CSRRs are represented as two-dimensional matrices. Each matrix corresponds to a training sample of the designed filter, and its S-parameters are extracted through an HFSS simulation. Both the matrices and the S-parameters are fed into the model as the training datasets. Different CSRRs with various sizes are employed for a wider applicable frequency band. Normalized matrices and normalized S-parameters are utilized to simplify the complex generative model resulting from the variations in CSRR sizes. The effectiveness of the generative model is validated through four design examples of dual-band filters, with their center frequencies located within 5 to 18 GHz. The inference time for each design is approximately 18.5 min. The measurement results of the fabricated filters are in good agreement with the simulation ones.

Keywords: generative model; dual-band filters; generative adversarial network (GAN); complementary split-ring resonator (CSRR)



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1. Introduction

Both the split-ring resonator (SRR), originally proposed by Pendry et al. [1], and the complementary split-ring resonator (CSRR), originally proposed by Falcone et al. [2], have attracted great interest among researchers. Various circuit prototypes of SRRs and CSRRs have been extensively elaborated and developed for applications such as multi-band microwave applications [3–5], sensing applications [6–8], and microwave filters [9–17]. With the increasing development of multi-functional and multi-standard communication systems, there is a growing demand for high-performance and miniaturized dual-band filters in microwave systems. Substrate-integrated waveguides (SIWs), originally proposed by Deslandes and Wu [18], have been widely utilized in the design of microwave filters [9–17,19] in recent years. Notably, the combination of substrate-integrated waveguides (SIWs) and SRRs/CSRRs has emerged as a significant approach in the design of band-pass filters, contributing to an enhanced performance and miniaturized size. The CSRRs can be viewed as electrical dipoles, and passbands below the waveguide cutoff can be obtained according to the theory of evanescent-mode propagation [20]. To achieve the goal of generating two passbands, various methods are utilized, including cascading different CSRRs [9], applying a defected ground structure [10], and placing the splits of the rings of a CSRR in the same direction [11]. In this paper, for the purpose of generating two passbands while minimizing the size of the filters, the CSRRs are simplified, folded, and modified by replacing the inner ring with complementary spiral resonators.

With the rapid advancements in artificial intelligence, the utilization of artificial neural networks (ANNs) has emerged as a powerful tool for facilitating filter designs. Researchers

have extensively explored various neural network architectures for parameterized electromagnetic (EM) modeling [21,22], as well as graphical modeling with fragment-type structures for planar microstrip circuits [23–25]. Benefiting from these advanced techniques, designers have achieved smaller filter sizes and optimized parameter indexes. The proposed modified CSRRs, with their curved and spiral planar circuit structure, are suitable for applications with a generative model using graphical modeling rather than parameter modeling. By representing the circuit prototypes with pixelated patterns and establishing the relationship between the two-dimensional patterns and the electromagnetic behaviors of these modified CSRRs, similar prototypes can be generated to meet the required EM specifications. In the generative model employed for inverse designs, the utilization of generative adversarial networks (GANs) has aroused significant attention in recent years [26–31]. The incorporation of convolutional neural networks (CNNs) within GAN-based architectures has demonstrated effectiveness in achieving successful inverse designs in various image-processing tasks. By employing a GAN-based generative model, the design process of the CSRR-based dual-band filters can be expedited, freeing designers from the tedious trial-and-error process. This approach achieves a rapid circuit prototype design and facilitates the development of CSRR-based filters.

The inverse design of microwave devices within a wide frequency range is a critical challenge that requires attention and a timely solution. One potential solution is to construct a generative model using multiple GANs, each built with varying minimum grid sizes of pixelated patterns. However, there are limitations in printed circuit board manufacturing precision, and reducing the grid size without careful consideration would result in significant manufacturing errors. To address this issue, multiple smaller patterns with the same pixel size are used to reduce the device size while ensuring the manufacturability of the circuit prototype. Additionally, the different pattern sizes are normalized to the same size, and the corresponding S-parameters are simulated and normalized within the same frequency range. Consequently, only one GAN is utilized to cover the inverse design of CSRR-based dual-band filters across the wide frequency band. The CNNs utilized in the generative model are trained to capture the correlation between the two-dimensional patterns and the electromagnetic characteristics of the CSRR-based filters. By leveraging the GAN, the generative model can generate filter prototypes with similar structures that satisfy specific S-parameters.

In this study, a generative model for the inverse design of dual-band filters based on a type of modified CSRR is presented. Firstly, the modified process of the CSRR structure adopted in this paper is explained, and the generation principle of two passbands is elucidated by an analysis of an equivalent circuit. Then, the generative model is built by representing the design area of the CSRR as a 32×32 matrix with a pixel cell size of 0.1 mm. The detailed construction process of the generative model is illustrated through the following three aspects: the preparation of the training datasets of normalized 32×32 matrices and normalized S-parameters within the frequency range of 1 to 20 GHz; the architecture of the generative model and its building process; and the inverse design process and results, which are illustrated by presenting four design examples of the CSRR-based dual-band filters. These inversely designed filters are fabricated and measured, and the measurement results of the fabricated filters are in good agreement with the simulation results.

2. Prototype and Principle of the Modified CSRRs

Figure 1 illustrates the prototypes of four different types of CSRRs, in which the golden area represents metallization and the white area represents a void. By etching the conventional CSRR in Figure 1a on an SIW, a passband below the waveguide cutoff frequency is obtained. The simplified CSRR in Figure 1b has a similar resonant circuit as that of the conventional CSRR, but the resonant frequency is slightly increased due to the reduction in equivalent capacitance and inductance. To enhance the compactness of the simplified CSRR, the CSRR ring is folded, as shown in Figure 1c, resulting in an increase in the equivalent inductance. Figure 1d extends Figure 1c by incorporating a complementary

spiral resonator (CSR) within the folded ring. This modification leads to an additional passband below the cutoff frequency. These four CSRR prototypes are arranged in parallel in opposite directions, and a slot is etched in the middle of the symmetrically mirrored units. This arrangement inhibits the TE₁₀ mode of the waveguide and increases the coupling of the two CSRRs, resulting in improved stopband rejection and wider passbands.

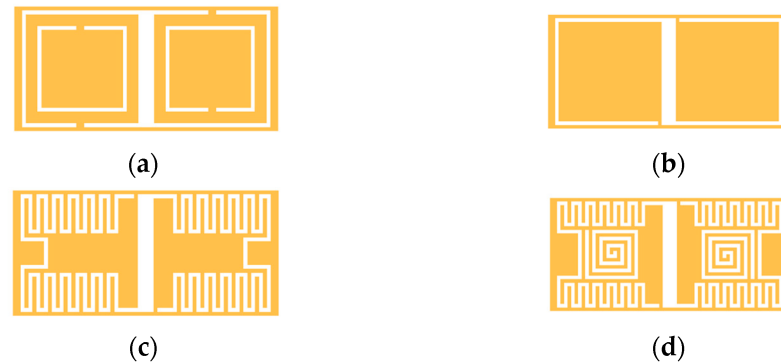


Figure 1. Prototype of the (a) conventional CSRR, (b) simplified CSRR, (c) simplified CSRR with a folded ring, and (d) modified CSRR with CSR etched inside the ring.

In order to demonstrate the improved effect of each modified step, circuit prototypes were designed based on the four CSRR structures shown in Figure 1. These CSRRs are arranged side-by-side, reversely oriented, and etched on a section of an SIW with an appropriate size. The input and output feeds are positioned at the center of both sides. The circuit prototypes are designed on a Taconic TLY-5 substrate with a thickness of 10 mil. The 3D simulation models of these designed circuit prototypes are depicted in Figure 2a,c,e,g, and their dimensions are listed in Table 1. The electromagnetic characteristics of these prototypes were investigated using full-wave simulation techniques, and the simulation results are presented in Figure 2b,d,f,h, respectively. From these results, it can be concluded that the circuit prototypes using the CSRRs in Figure 1a–c all exhibit one passband. The center frequencies of these passbands are 6.49 GHz, 6.57 GHz, and 5.43 GHz, respectively. This demonstrates that, under the same circuit size conditions, the simplified CSRR has a slightly higher resonant frequency compared to that of the traditional CSRR, while the simplified CSRR with a folded ring can make the most of the design space to achieve smaller resonant frequencies, thus offering the advantage of device miniaturization. Furthermore, the proposed modified CSRR is applied in the design of dual-band filters, as depicted in Figure 2g. By incorporating a folded outer ring and CSR inside the ring, the compactness of the SIW filters is further improved while achieving two passbands, as shown in Figure 2h. Three transmission zeros can be observed, with one located above the second passband and the remaining two located between the two passbands.

Table 1. Dimensions of the circuit prototypes in Figure 2.

Parameter	W_0	W	W_1	W_2	L	L_1	L_2	a	g
Dimension (mm)	0.74	4.00	2.20	3.00	7.00	5.60	6.40	0.10	0.20
Parameter	b	c	d	e	h	m	n	p	q
Dimension (mm)	0.40	0.10	1.00	0.80	0.70	0.70	0.70	1.50	1.40

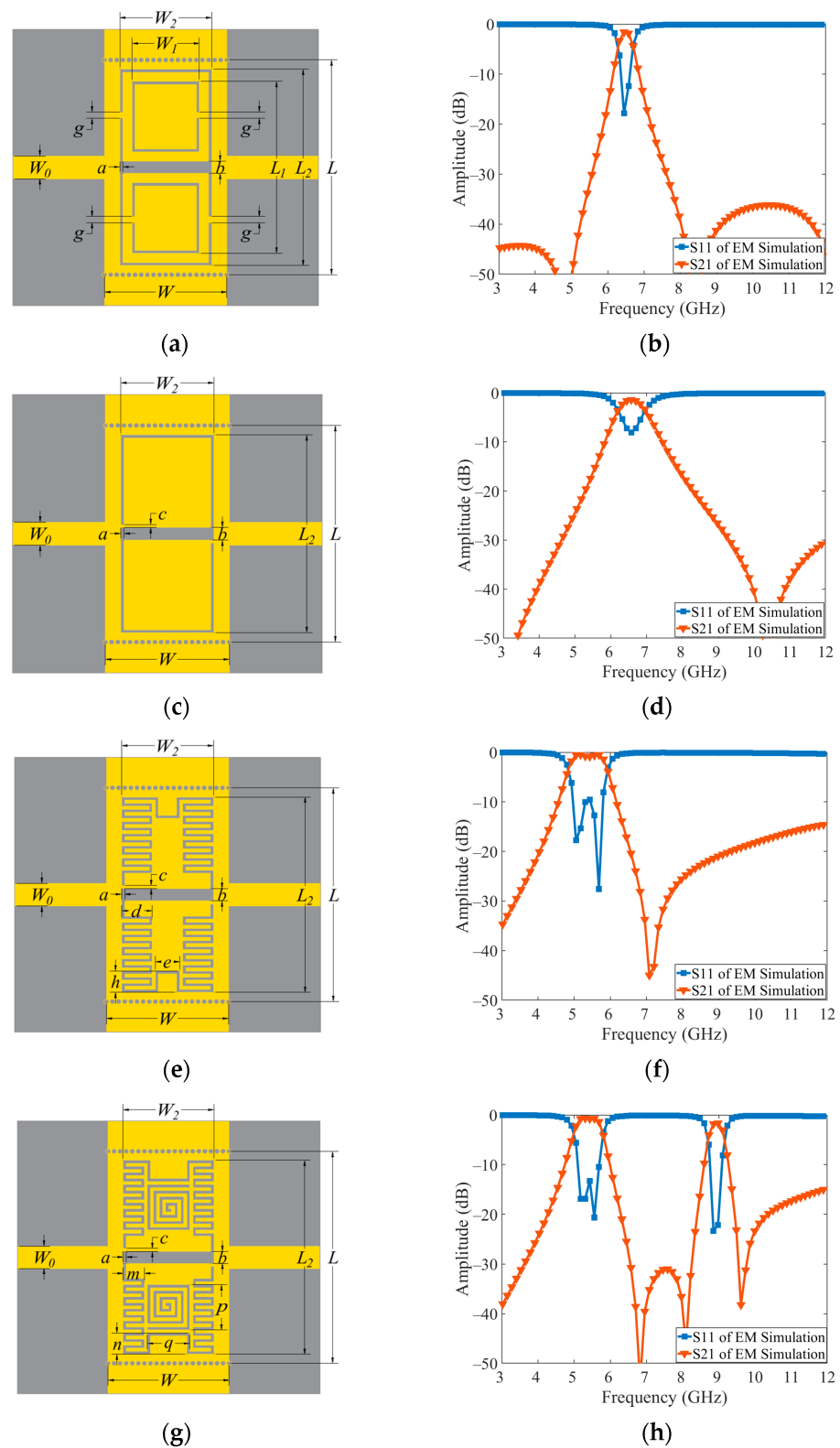


Figure 2. (a) Circuit prototype and (b) EM simulation of the bandpass filter based on the conventional CSRR in Figure 1a; (c) Circuit prototype and (d) EM simulation of the bandpass filter based on the simplified CSRR in Figure 1b; (e) Circuit prototype and (f) EM simulation of the bandpass filter based on the simplified CSRR with a folded ring in Figure 1c; (g) Circuit prototype and (h) EM simulation of the proposed CSRR-based dual-band filter based on the modified CSRR in Figure 1d.

Accordingly, the simplified equivalent circuit is derived in Figure 3 to provide a better understanding of the dual-bandpass behavior of the filter. The simplified equivalent circuit can be divided into five parts: two resonant circuits of CSRRs, two resonant circuits of CSRs, the mutual coupling of the two CSRRs and the two CSRs, the mutual coupling between the modified CSRRs and the waveguide transmission line, and the high-pass transmission characteristic contributed by the metallic vias of the SIW. For the four shunt-connected resonant units enclosed by yellow and blue boxes, the equivalent circuits of CSRRs and CSRs are all modeled with a parallel resonant consisting of a capacitor and an inductor. The capacitances of the CSRR and CSR are denoted by C_{CSRR} and C_{CSR} , respectively. The inductances of the CSRR and CSR are denoted by L_{CSRR} and L_{CSR} , respectively. Regarding the dominant mutual coupling, two coupling elements are considered in the equivalent circuit. The inductive and capacitive coupling between the CSRRs is described using a series unit consisting of an inductance and a capacitance, denoted by L_{s1} and C_{s1} , respectively. Similarly, the inductive and capacitive coupling between the CSRs is described using a series unit with the elements denoted by L_{s2} and C_{s2} . The mutual coupling between the modified CSRR and the waveguide transmission line is represented by a series unit denoted by L_c and C_c , respectively. The via walls are just represented by the inductance L_d at both feed ports. Three transmission zeros are produced by the three series units, which are contributed by the three mutual couplings. And the center frequencies f_1 and f_2 of the two passbands are located at the two resonance frequencies f_{CSRR} and f_{CSR} of the CSRR and CSR; they can be expressed as illustrated in [11]:

$$f_1 = f_{CSRR} = \frac{1}{2\pi\sqrt{L_{CSRR}C_{CSRR}}} \quad (1)$$

$$f_2 = f_{CSR} = \frac{1}{2\pi\sqrt{L_{CSR}C_{CSR}}} \quad (2)$$

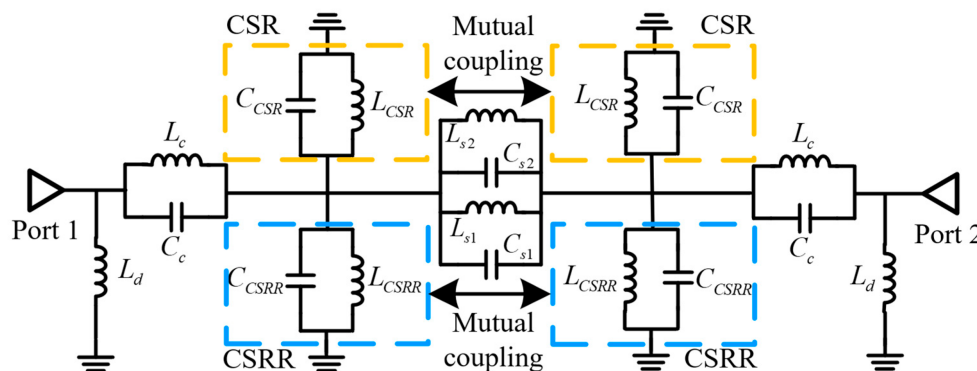


Figure 3. Simplified equivalent circuit of the dual-band filters based on the modified CSRR.

3. Generative Model for Dual-Band Filters

The proposed circuit prototype shown in Figure 1d consists of a folded outer ring and a spiral inner ring, which can be challenging to build using the traditional modeling method with multiple variable dimensions. To address this issue, a GAN-based generative model, known for its proficiency in pattern processing and generation, was developed based on the prototype of the proposed CSRRs. This generative model helps solve the quick design problems of dual-band filters across a wide frequency range. The circuit prototype of the CSRRs is represented using straight lines and square shapes, allowing it to be expressed as Boolean matrices, in which the value of 1 in the matrices denotes metallization and 0 denotes a void. Here, a 32×32 matrix with a cell pixel size of $0.1 \text{ mm} \times 0.1 \text{ mm}$ is used to represent the circuit prototype. By applying a series of deep learning networks to the patterns and corresponding electrical parameters, the generative model can be constructed for inverse designs of the dual-band filters. Through the extensive training of the networks,

an efficient generative model for the filters within the frequency range of 1 to 20 GHz is constructed. Figure 4 illustrates the building process of the generative model, which can be divided into two main parts: the preparation of the training dataset and the construction of the multiple interconnected CNNs. Additionally, four inverse design processes are presented to demonstrate the effectiveness of this method.

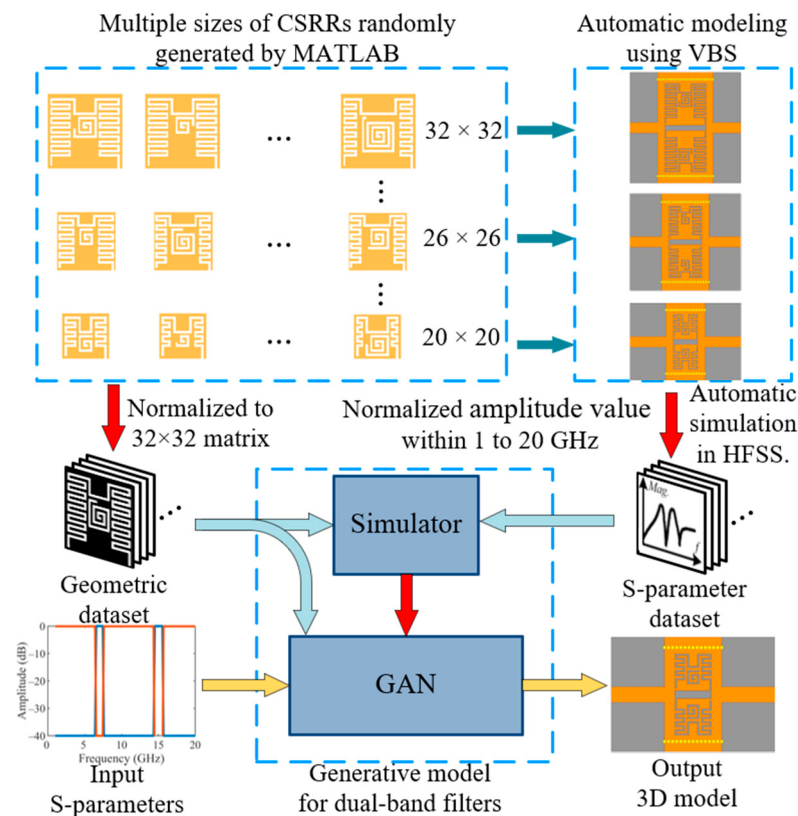


Figure 4. The building process of the generative model for CSRR-based dual-band filters.

3.1. Preparation of the Training Datasets

The top half of Figure 4 shows the two types of training datasets for the generative model: the geometric dataset constructed from CSRR patterns and the S-parameter dataset derived from the EM simulation results of the corresponding circuit prototypes. To extend the applicability of the generative model across a wider frequency range, the CSRR patterns are designed in a number of different sizes. However, this poses a challenge as it necessitates the use of multiple simulators to establish the relationships between the different-sized CSRR patterns and their respective simulation results in different frequency bands. To address the issue of increasing complexity in the generative model, a geometric dataset with standardized specifications and an S-parameter dataset with matching specifications are employed. This is accomplished by utilizing normalized Boolean matrices that are 32×32 and amplitude–frequency responses that are 128×1 , thereby streamlining the generative model and requiring only one simulator.

In this study, CSRR patterns of seven different sizes (ranging from 2 to 3.2 mm for the side length) with a uniform unit pixel size of 0.1 mm are employed to cover the center frequency range of the filters, spanning from 5 to 18 GHz. These patterns are automatically generated using MATLAB R2022b, incorporating the random fold depths of the outer ring and the random cycles and positions of the inner spiral ring. The filters constructed using the resulting normalized matrices are then modeled and simulated in HFSS using MATLAB-generated Visual Basic Script files. The construction processes of the two training datasets can be summarized in seven steps as follows:

1. Create an all-ones matrix in MATLAB to represent metal within the design area of the SIW surface.
2. Assign zero partially to the created all-ones matrix using MATLAB, forming the left and right sides of the outer ring. This represents etching two folded slots on the metal. It contains a random variable m_0 that is related to the fold depth m , as shown in Figure 2g.
3. Continue to assign 0 partially to this matrix using MATLAB to form the top side of the outer ring, completing the etching process of the outer ring on the metal. It contains a random variable n_0 that is related to the fold depth n , as shown in Figure 2g.
4. Calculate the space that can be utilized by the inner spiral ring based on the size of the outer ring. Then, assign zero partially to this matrix using MATLAB, forming the spiral inner ring and completing the etching process of the modified CSRR. The number of cycles in the spiral is determined by a random variable r_0 .
5. Extract the matrix based on the CSRR pattern designed in the previous four steps and output it to the geometric dataset.
6. After creating the etched CSRR pattern on the SIW surface, the remaining components of the 3D simulation model, such as the substrate, microstrip lines, ports, and air cavities, are constructed using HFSS scripts written in MATLAB. These simulation models are then automatically simulated, and the results are exported to the S-parameter dataset.
7. Repeat the above six steps using all-ones matrices with seven different sizes, with side lengths of 32, 30, 28, 26, 24, 22, and 20.

The matrices extracted in step 5 are normalized to the size of 32×32 . The amplitude–frequency responses obtained in step 6 are normalized within the frequency range of 1 to 20 GHz. The patterns of the modified CSRR are influenced by four factors, which are variable m_0 , variable n_0 , variable r_0 , and the size of the pattern. It is important to note that r_0 is a number with three decimal places, in which the integer part represents the cycle number and the decimal part represents the opening direction of the spiral ring. And all other variables are represented by integers. According to the mutual restriction of these variables, it is roughly estimated that the total number of such CSRR patterns is in the tens of thousands. During the training of the generative model, a moderate amount of randomness can help the network to better generalize and adapt to new data, but too much randomness may cause the network to overfit or underfit. Therefore, 15,000 pairs of data are sufficient to form these two datasets for training the generative model. It is worth noting that circuit prototypes of different sizes utilize different SIWs with varying cutoff frequencies while keeping other parameters such as the width of feed lines and thickness of the substrate constant. And the filters are all designed on the Taconic TLY-5 substrate with a thickness of 10 mil.

3.2. Generative Model Building Process

The bottom half of Figure 4 depicts the simplified architecture of the generative model and its building process. The generative model for CSRR-based dual-band filters is constructed with a conditional deep convolutional (CDC) GAN composed of a well-trained simulator and a generative adversarial network. The simulator, which is used for establishing the relationship between the CSRR pattern, which is composed of a 32×32 matrix, and its S-parameters, which are composed of a 128-point normalized transmission coefficient, is trained using a CNN with the two prepared training datasets in Section A. An effective simulator is capable of predicting the corresponding S-parameters based on the pattern of the CSRR. Validation loss is utilized to evaluate the training accuracy of the simulators, and the validation mean square error of the simulator gradually decreases to 5.2×10^{-5} after ten thousand iterations, which indicates that the simulator is well trained.

The generative adversarial network, which is constructed with two CNNs named the generator and discriminator, is utilized to implement the function of inversely designing filters with specific S-parameter requirements. The inverse design iterative process of the

generative model is illustrated in Figure 5. First, the normalized S-parameters, consisting of 128 points, are input into a well-constructed generator. The generator outputs a 32×32 Boolean matrix that represents the circuit prototype. Then, this output matrix is recognized by a well-constructed discriminator to determine if it exhibits similar features to the patterns in the geometric dataset. Once identified as similar, the S-parameters of the circuit prototype corresponding to this matrix are predicted by the pre-trained simulator and compared with the input S-parameters by calculating the Euclidean distances between the two S-parameter vectors. During the iterative process of inverse design, the independently created CNNs, the generator and the discriminator, continuously optimize their internal weights, resulting in the refinement of the generative model and the generation of increasingly accurate candidate matrices.

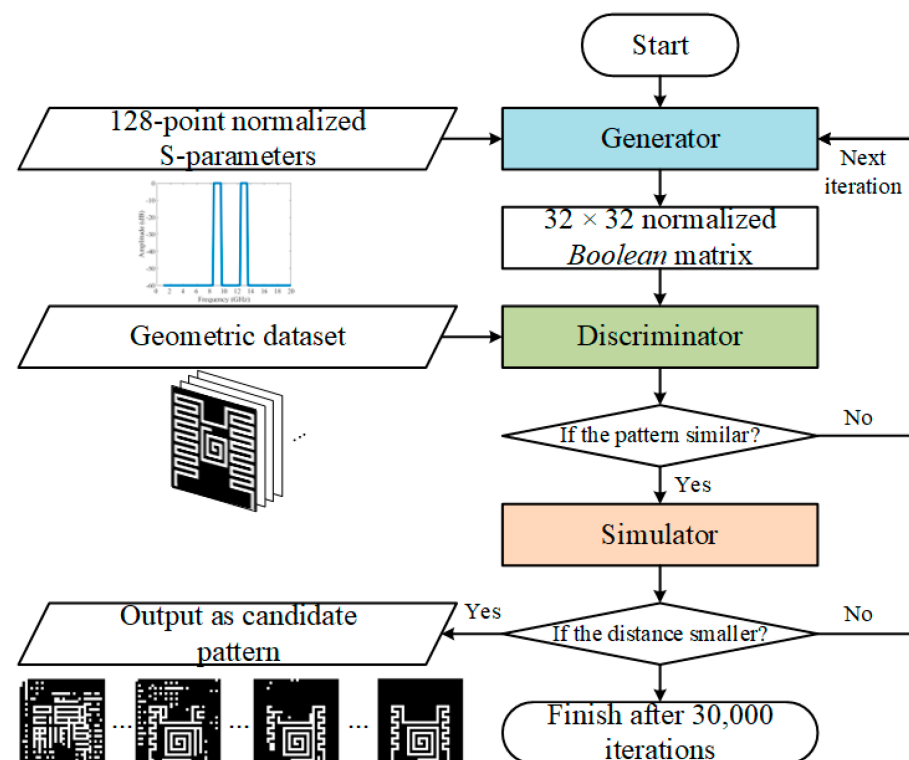


Figure 5. Inverse design iterative process of the generative model.

3.3. Inverse Design Process and Results

To validate the effectiveness of the constructed generative model, four inverse design examples are provided. Following the iterative process of the generative model shown in Figure 5, four dual-band filters were designed with center frequencies at 5 GHz and 7.5 GHz, 7.5 GHz and 11 GHz, 9 GHz and 13 GHz, and 10 GHz and 18 GHz, respectively. As shown in the top left corner of each subfigure in Figure 6, pixelated patterns generated by the generative model for different dual-band filters are presented. These patterns are processed as matrices in MATLAB to address any potential discontinuities. Using the processed pixelated patterns, the patterns within the design spaces are identified. Along with the fixed feed microstrip lines, simulation models can be constructed in HFSS. With the assistance of MATLAB, Visual Basic Script files specifically tailored to the size of the generated patterns are generated, enabling automated modeling and simulation in HFSS. The simulation models of the four inversely designed dual-band filters are given in the bottom left corner of each subfigure in Figure 6, while the simulation results are shown on the right side of each subfigure. The simulation results demonstrate that the desired S-parameters required for each filter have basically been fulfilled, indicating the feasibility of the proposed method. It is noted that all deep learning models are performed on a

workstation with a GTX 2080Ti GPU. On average, it takes about 18.5 min to complete a total of 30,000 iterations of training for one targeted inverse design.

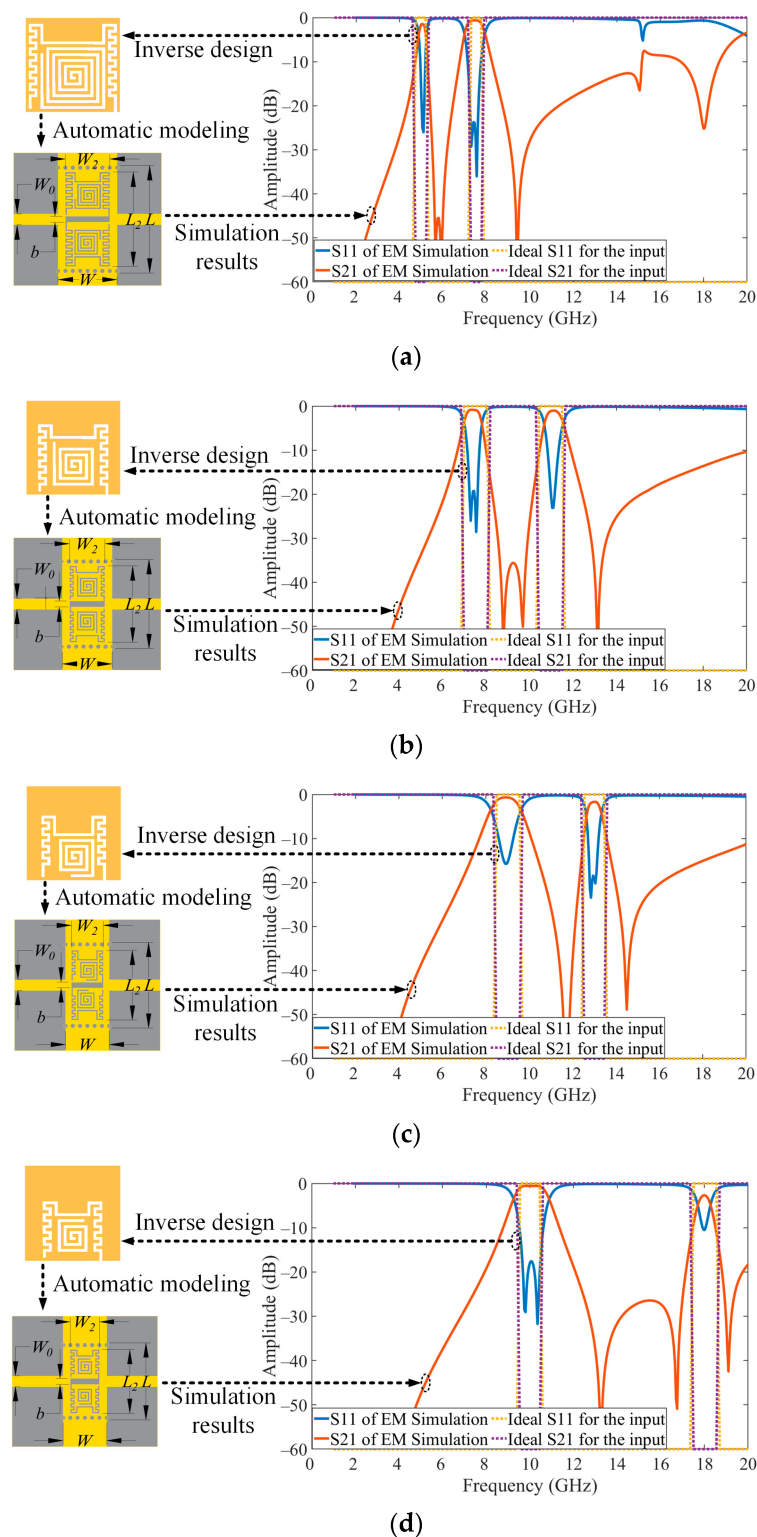


Figure 6. Generated pixelated patterns, simulation models, and simulation results of corresponding dual-band filters with customized center frequencies at (a) 5 GHz and 7.5 GHz, (b) 7.5 GHz and 11 GHz, (c) 9 GHz and 13 GHz, and (d) 10 GHz and 18 GHz (the dimensions of the circuit prototypes are listed in Table 2).

Table 2. Dimensions of the circuit prototypes in Figure 6.

Parameter	W_0 (mm)	W (mm)	L (mm)	W_2 (mm)	L_2 (mm)	b
Figure 6a	0.74	4.00	7.30	3.00	6.40	0.40
Figure 6b	0.74	3.40	6.10	2.40	5.20	0.40
Figure 6c	0.74	3.00	5.90	2.20	4.80	0.40
Figure 6d	0.74	3.00	5.30	2.00	4.40	0.40

The etched patterns of the CSRRs on the inversely designed dual-band filters are presented as images in the upper left corner of each subfigure in Figure 6. The side length of the unit square pixel in these images is 0.1 mm.

4. Fabrication and Measurement

To further demonstrate the feasibility of the proposed generative model for the CSRR-based dual-band filters, the inversely designed filters in Figure 6 are fabricated and measured using the Taconic TLY-5 substrate with a thickness of 10 mil, the relative permittivity (ϵ_r) is 2.2, and the dielectric loss tangent ($\tan \delta$) is 0.0009. Photographs of the fabricated dual-band filters, as well as their simulated and measured results are depicted in Figure 7. Based on the measured results, it can be observed that the center frequencies of the four dual-band filters exhibit a maximum deviation of 0.22 GHz compared to the preset ideal frequencies, covering the range from 4.92 GHz to 18.02 GHz. The corresponding 3 dB fractional bandwidth (FBW) for these center frequencies ranges from 4.1% to 15.7%. The measured minimum in-band insertion losses are less than 3.3 dB, and the measured pass-band return losses are above 10 dB. A maximum attenuation between the passbands is detected, ranging from 39 dB to 55 dB. The circuit prototypes have design areas ranging from approximately 0.017 to 0.039 λ_g^2 . The key technical properties are listed in Table 3 and compared with those of recently reported dual-band SIW filters in state-of-the-arts. The bandwidth performance of the designed filter is related to the input ideal S-parameters. By appropriately adjusting the passband bandwidths of the ideal S-parameters, the bandwidth of the designed filter can be expanded or reduced to a certain extent. In terms of the insertion loss performance, this is primarily attributed to radiation loss resulting from the partially closed structure. Additionally, there is a deviation in the insertion loss caused by the additional section of the microstrip line and the SMA connectors.

It can be concluded that the proposed CSRR-based dual-band filters effectively utilize the design area on the SIW, resulting in a compact size. The inclusion of the three transmission zeros through the modified CSRRs enhances the attenuation between the two passbands, ensuring both passbands exhibit excellent levels of side-band steepness and out-of-band rejection. Furthermore, the design of the four dual-band filters, covering center frequencies ranging from 5 to 18 GHz, was achieved using a time-efficient process with the assistance of a GAN-based generative model. This approach brings convenience to designs that need a large number of dual-band filters within the scope of application.

It can be observed in Figure 7 that the center frequencies of the dual-band filters have a slight deviation compared to the desired center frequencies. This mainly resulted due to two factors. Firstly, the generative model used for the inverse design of circuit patterns has inherent errors due to the limited dimensionality of the input S-parameters during prediction and inverse design processes. Secondly, the manufacturing process of the circuit boards introduces extra errors that can also contribute to frequency deviations. It can be seen in Figure 7a that the simulation and measurement results of the dual-band filter show a noticeable deviation at high frequencies. There are two possible reasons for this discrepancy. Firstly, the simulation model did not consider the impact of the added microstrip line and SMA connector on the external coupling parameters of the CSRR structure. Secondly, slight manufacturing errors in the PCB may have resulted in deviations in the center frequencies of the passbands, the coupling strength between the CSRR and CSR, and the coupling parameters of the modified CSRR to the microstrip line. These factors can potentially lead to significant deviations in the sensitive high-order transmission poles and zeros.

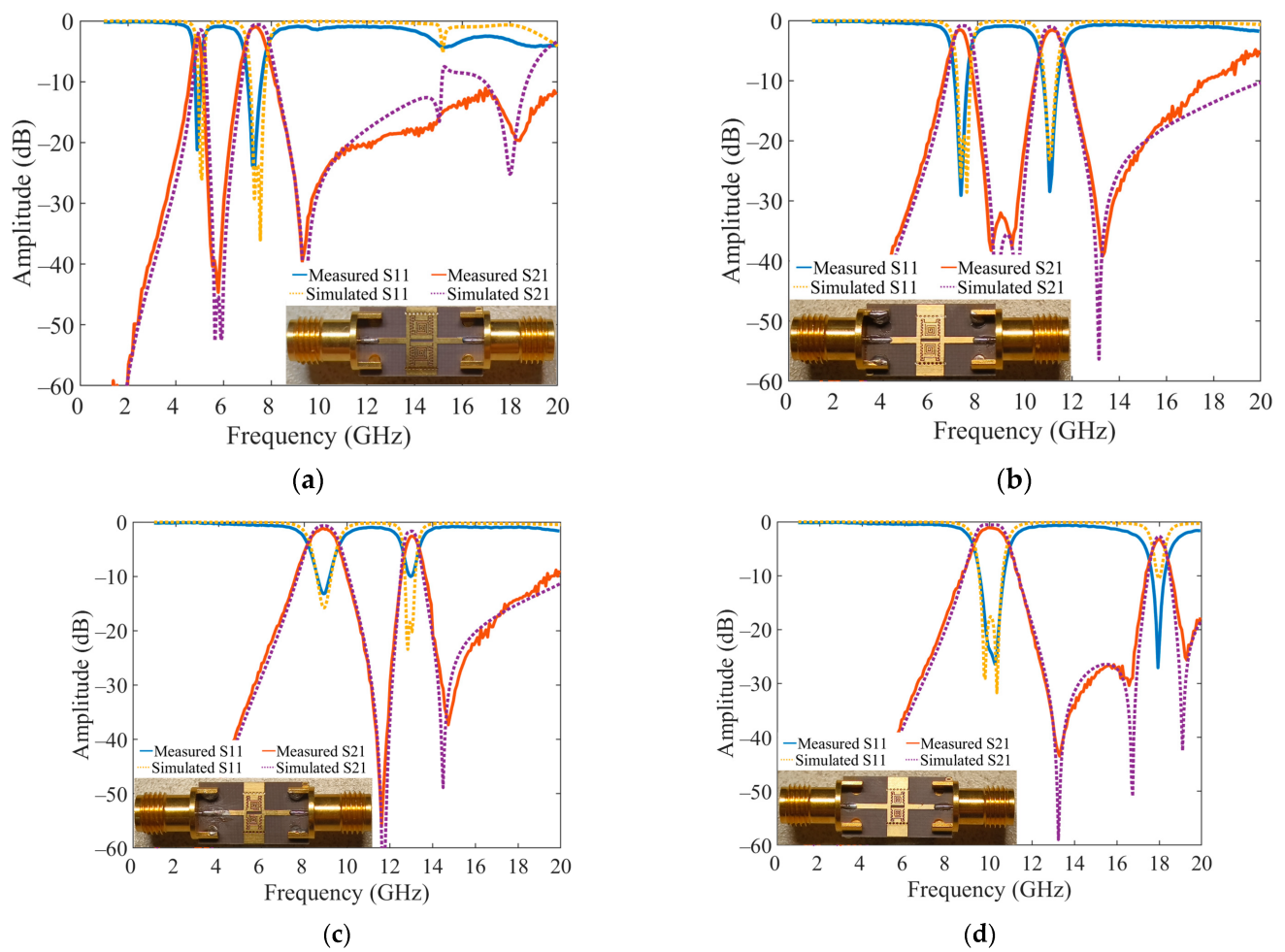


Figure 7. Photographs of the fabricated dual-band SIW filters; simulation and measurement results of the filters whose center frequencies located at (a) 4.92 GHz and 7.28 GHz, (b) 7.32 GHz and 11.08 GHz, (c) 8.93 GHz and 13.06 GHz, and (d) 10.06 GHz and 18.02 GHz.

Table 3. Comparison with other dual-band SIW filters in state-of-the-arts.

Refs.	Techniques	CF ₁ /CF ₂	3dB FBW ₁ /FBW ₂	IL ₁ /IL ₂	RL ₁ /RL ₂	Size ($\lambda_g \times \lambda_g$)	Max Attenuation between PBs (dB)
[10]	CSRR, DGS	2.40, 5.20	5.80, 6.45	3.60, 3.10	15, 15	0.152×0.156	34
[11]	CSRR, CSR	3.84, 4.96	6.69, 5.28	1.65, 3.33	21.11, 21.57	0.179×0.115	45
[12]	CSRR	7.89, 8.89	3.42, 3.39	1.5, 1.9	14, 12	0.87×0.85	37
[13]	CSRR	7.45, 10	6.0, 4.0	0.83, 0.95	20, 20	0.50×0.75	37
[14]	CSRR, multimode resonator	9.80, 13.50	11.20, 9.80	1.80, 1.50	9.8, 10.6	1.220×1.220	33
[15]	Folded CSRR	1.94, 4.84	14.43, 2.69	1.26, 2.69	15, 16	0.179×0.097	55
[16]	Strongly coupled CSRR	6, 12	18.33, 29.17	0.79, 1.39	16, 9	0.920×0.534	42
[17]	Open-loop ring resonator	1.5, 4.96	14, 7.3	0.85, 0.9	20, 23	0.16×0.08	48
[19]	E-shaped slot	3.6, 7.1	8.2, 6.7	1.3, 1.2	14, 15	0.29×0.29	57
Figure 7a	Folded CSRR, CSR, and CDCGAN	4.92, 7.28	7.3, 12.0	2.35, 1.00	23.3, 25.7	0.178×0.097	44
Figure 7b		7.32, 11.08	10.4, 8.5	1.66, 1.59	29.2, 30.0	0.221×0.123	39
Figure 7c		8.93, 13.06	14.3, 5.2	0.85, 2.60	13.1, 10.0	0.252×0.141	56
Figure 7d		10.06, 18.02	15.7, 4.1	1.10, 3.30	26.8, 27.0	0.264×0.149	44

CF: center frequency (GHz); FBW: fractional bandwidth (%); IL: insertion loss (dB); RL: return loss (dB); λ_g : the guided wavelength corresponding to the frequency of the first passband; PB: passband.

To improve the generative model's prediction errors, two improvements can be considered. Firstly, enhancing the architecture of the neural network within the generative model can make it more effective and accurate in the inverse design of such CSRR-based dual-band filters. Secondly, one could increase the data dimensionality of the S-parameter dataset used for training. This improves the model's frequency resolution but comes at the cost of increased training and inference time. Regarding existing manufacturing errors, these are currently unavoidable due to the precision limitations of printed circuit board fabrication. However, a feasible approach is to appropriately increase the size of individual pixels during the construction of CSRR patterns to reduce the percentage of fabrication errors. However, this also reduces the applicable frequency range of the circuit prototype. This compromise between fabrication errors and the frequency range necessitates careful consideration during the design process.

If the application scope and inverse design accuracy of this generative model are to be further expanded based on similar CSRR patterns, it would be necessary to incorporate a more diverse range of pattern sizes and increase the number of data points for the S-parameters used in the training dataset. In terms of the potential extension of the generative model for a more complex design, it would be necessary to specifically search for additional circuit prototypes that exhibit the desired electromagnetic characteristics. For example, if there is a need to incorporate tri-band passband filters, it would be necessary to construct plenty of filter patterns that satisfy these electromagnetic properties. These newly created patterns can then be combined with the existing data and input into the generative model, allowing for the generation of different types of circuit prototype patterns for both dual-band and tri-band filters.

5. Conclusions

A generative model based on a type of modified CSRR has been developed for inverse designs in this paper. By etching the proposed CSRR with a folded outer ring and a spiral inner ring on a section of the SIW, two passbands can be obtained in a compact size. Building on this basis and utilizing CDCGAN, the generative model has been constructed to facilitate the inverse design of dual-band filters based on a CSRR with a similar circuit prototype. With the proposed circuit prototype and the generative model, compared with the traditional design method, the design time is greatly reduced, and the applicable operation frequency range of the filters is further extended.

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