A method of reducing insertion loss for microstrip filters

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ABSTRACT

Based on the theory of multiple coupled-resonator filter, coupling matrix and microstrip square open loop resonator, this paper studies a method of designing bandpass microstrip filter in order to reduce insertion loss. The results of simulation on ADS software and measurement on vector network analysis machine of a sample of designed filter showed that the method can reduce insertion loss which compare to other common microstrip filters. The method can be completely used to design microstrip filters with low insertion loss and high selectivity, applying for wireless systems.

Keywords: Multiple coupled-resonator filter; Insertion loss; Transfer function of filter; Coupling matrix; Microstrip square open loop resonator.

1. INTRODUCTION

Researching, designing and optimizing the microwave filters with high selectivity, low insertion loss and wide stopband play a crucial role in meeting more stringent requirements for transceiver systems of Communications, Radar, Electronic warfare,... It's important for the effective using of electromagnetic spectrum resources.

The reducing insertion loss of microwave filters plays an important role in many practical applications, especially with high selectivity filters. Normally, microwave filters with low insertion loss and high selectivity are implemented on waveguide technology due to its numerous advantages such as high power handling capability and high Q-factor valuse revealed by waveguide cavities. However, waveguides are bulky and unsuitalbe for high density integration, require a complex, expensive and time-consuming fabrication process. While, microstrip technology is still widely used. The planar microstrip filters are compact, cheap in fabrication and easy to integrate with other components. Therefore, it allows to reduce the size and weight of electronic systems.

Based on the theory of multiple coupled-resonator filter, coupling matrix [3, 4] and microstrip square open loop resonator [2], this article studies a method of designing bandpass microstrip filter in order to reduce insertion loss. The calculation, design and simulation process is carried out on the Advanced Design System software (ADS). The article also presents a sample of narrow-band bandpass filter that was designed, simulated, fabricated, experimentally measured and compared to other common microstrip filters.

2. PROBLEM

2.1. Microstrip square open loop resonator

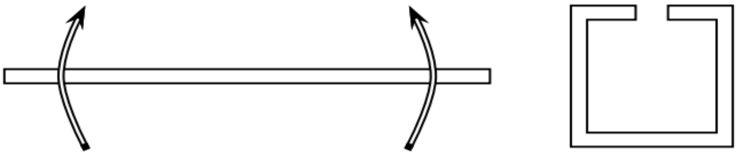


Figure 1. *The microstrip square open loop resonator.*

The microstrip square open loop resonator is obtained by folding the microstrip straight resonator, its electric length is $\lambda / 2$. Thus, the size of the microstrip square open loop resonator is approximated $(\lambda / 8)\,\mathrm{x}(\lambda / 8)$.

To obtain the desired filters, we must combine individual resonators together. The coupling is characterized by coupling coefficients. The coupling coefficient of coupled RF/microwave resonators, which can be different in structure and can have different self-resonant frequencies, may be defined on the basis of the ratio of coupled energy to stored energy [2]:

$$k_{12} = \frac{\iiint \varepsilon \vec{\mathbf{E}}_1 \cdot \vec{\mathbf{E}}_2 dv}{\sqrt{\iiint \varepsilon \left|\vec{\mathbf{E}}_1\right|^2 dv \times \iiint \varepsilon \left|\vec{\mathbf{E}}_2\right|^2 dv}} + \frac{\iiint \mu \vec{\mathbf{H}}_1 \cdot \vec{\mathbf{H}}_2 dv}{\sqrt{\iiint \mu \left|\vec{\mathbf{H}}_1\right|^2 dv \times \iiint \mu \left|\vec{\mathbf{H}}_2\right|^2 dv}} \qquad (1)$$

where $\vec{\mathbf{E}}$, $\vec{\mathbf{H}}$ represent the electric and magnetic field vectors of resonators. The first element in the right side of equation (1) represents electric coupling and the second element represents magnetic coupling. The total coupling coefficient may be electric, magnetic or mixed which depends on their relatioship. Besides, depending on direction of two adjacent resonators, we can obtain different types of coupling (figure 2).

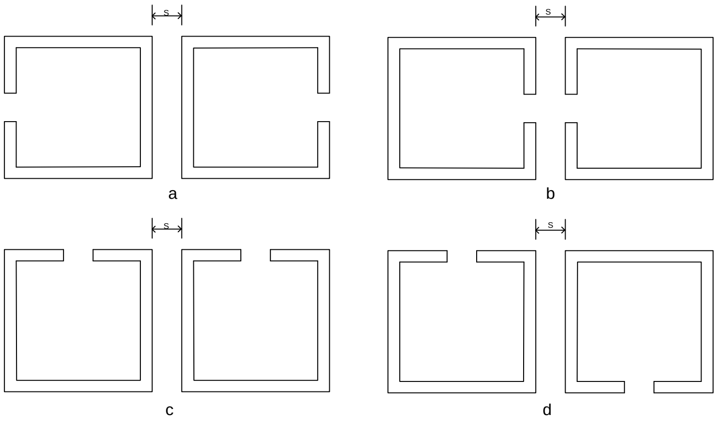


Figure 2. *Different types of coupling two-resonators:*

(a) Magnetic coupling; (b) Electric coupling; (c) and (d) Mixed coupling.

The *k* value given in equation (1) is impractical for computational purposes, because it requires knowing every values of electric and magnetic field. Another expression can be calculated based on physical conditions: when two resonators are coupled together, they will resonate at two frequencies as f_1 and f_2, different from self-resonant frequency f_0 of each ones. Therefore, coupling coefficient can be calculated from the following equation:

$$k = \frac{f_2^2 - f_1^2}{f_2^2 + f_1^2} \qquad (2)$$

This expression allows to realize coupling coefficients according to selected physical structures, that determine physical dimensions of the elements to achive the coupling coefficient. The dimensions are determined based on frequency responses and results of simulation on ADS software.

2.2. Design multiple coupled-resonator bandpass filtes based on microstrip square open loop resonators

The multiple coupled-resonator filters based on microstrip square open loop resonators play a important role in design of bandpass filters, especially for bandpass filters with high selectivity.

Because to obtain high selectivity, we need use many resonators, then the distance from the input to the output of filter will be increased, lead to increase attenuation of filter.

In the previous section, we presented the microstrip square open loop resonators as well as the coupling coefficient of two resonators. In fact, to create a filter with the desired frequency response, we must combine many resonators together. The multiple coupled-resonator bandpass circuit, originally introduced by Atia and Williams [3], features a model consisting of N resonators interconnected by transformers, as depicted in figure 3(a). In this model, each resonator is composed of a 1 F capacitor in series with a 1 H self-inductance, resulting in a resonant frequency of 1 rad/s for all resonators. However, this circuit is limited to filters with symmetric frequency responses. Cameron [4] later refined this model, as shown in figure 3(b), by adding frequency-independent reactance elements in series within each loop. This modification allows the circuit to account for resonant frequency shifts in individual resonators, enabling it to represent asymmetric characteristics.

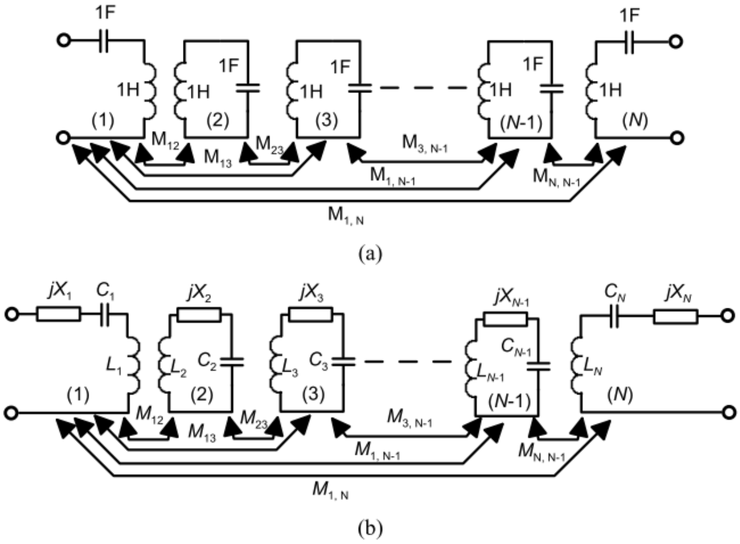


Figure 3. *Models of the general coupled-resonator filter:*
(a) Atia-Williams; (b) Cameron.

Let us consider the circuit presented in figure 3(b), which operates between a voltage *E(V)* with an internal impedance of R_S and a load R_L. Using the loop currents method (applying Kirchhoff's equations for each loop), the circuit can be described by the following equation:

$$E\cdot[1,0,\ldots,0]^t = [R + sI + jM]\cdot\left[i_1, i_2, \ldots, i_N\right]^t \tag{3}$$

Here, *R* is an *N* × *N* matrix with the source and load impedance values located in the top left and bottom right corners, while all other entries are zero. *I* represents the identity matrix, *s* is the complex frequency variable (*s*= *jω*), and *M* is the coupling matrix that contains the mutual coupling values between all the resonators:

$$M = \begin{bmatrix} X_1 & M_{12} & M_{13} & \cdots & M_{1N} \\ M_{12} & X_2 & & & \\ M_{13} & & \ddots & & \\ \vdots & & & \ddots & M_{N-1,N} \\ M_{1N} & & & M_{N-1,N} & X_N \end{bmatrix} \tag{4}$$

In this context, the entries on the main diagonal represent the values of the frequency-independent reactance elements X_i, also known as self-couplings.

Thus, the typical multiple coupled-resonator filter is represented in equation (4). The challenge in filter design is to derive the coupling matrix M, which produces a transfer function that meets the specified filter requirements, including desired bandwidth, insertion loss, return loss, ripple constants, and more. The transfer function is explicitly defined using characteristic polynomials, such as Butterworth, Chebyshev, Generalized Chebyshev, Elliptic, and is represented as follows:

$$S_{11}(s)=\frac{F(s)}{E(s)},\ S_{21}(s)=\frac{P(s)}{\varepsilon\cdot E(s)} \tag{5}$$

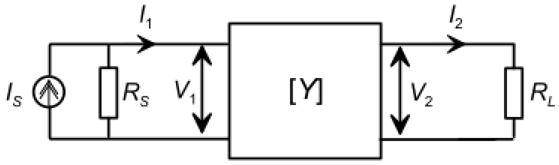


Figure 4. *Representation of the N-order coupled-resonator filter as two-port network.*

There are many diffirent ways to synthesize coupling matrix [4, 5]. In the direct synthesis approach for the coupling matrix, the prototype network depicted in figure 4 is regarded as a two-port block, functioning between a current source I_S with an internal impedance R_S and a load resistance R_L. The network can be characterized using the standard two-port admittance Y, as expressed in the following equation:

$$\begin{bmatrix} i_1 \\ i_2 \end{bmatrix}=\begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{21} \end{bmatrix}\times\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \tag{6}$$

The Y-matrix entries can be obtained from the characteristic polynomials *P(s), F(s)* and *E(s)* by utilizing the ABCD-matrix representation, which leads to an expression for the input impedance/admittance. Alternatively, these Y-matrix elements can be expressed in terms of the $N\times N$ coupling matrix M, with the frequency variable $s = j\omega$, as shown below:

$$Y_{11}(s)=j[-M-\omega I]_{11}^{-1}\ . \tag{7}$$

$$Y_{22}(s)=j[-M-\omega I]_{NN}^{-1}. \tag{8}$$

$$Y_{12}(s)=Y_{21}(s)=j[-M-\omega I]_{N1}^{-1}. \tag{9}$$

The matrix M, which is real and symmetric about its main diagonal, can be factored based on its eigenvalues. Simultaneously, by applying the Gram-Schmidt orthonormalization process, we can extract the elements of the coupling matrix from the characteristic polynomials of the filter.

The $N\times N$ coupling matrix obtained through the direct synthesis process typically contains nonzero entries across all elements. This implies that every resonator is coupled to every other resonator, which is either impractical or extremely challenging to implement in a real circuit. To address this issue, similarity transformations (or rotations) are applied to the M-matrix to eliminate the unwanted couplings until a more feasible configuration is achieved. This method preserves the eigenmodes and eigenvectors of the coupling matrix, ensuring that the filter's transfer characteristics remain unchanged compared to the original matrix.

The coupling matrix M can be generated using optimization. This technique aims to synthesize the coupling matrix M that produces a filter frequency response, minimizing a cost function to compensate for the difference between the coupling matrix's generated response and the ideal response.

3. DESIGN, SIMULATION AND DISCUSSION

3.1. Design a sample of bandpass filter by using microstrip square open loop resonators

To demonstrate and verify the method of designing bandpass microstrip filter based on microstrip square open loop resonators , we designed a sample of narrow-band bandpass filter to satisfy the following specifications:

- Centre frequency: 1085 MHz;
- Bandwidth of 3 dB: 25 MHz;
- Bandwidth of 40 dB: 70 MHz;
- Insertion loss in passband: ≤ -10 dB;
- Return loss in passband: ≤ -14 dB.

To achive the desired narrow-band, the designed filter includes 8-order corresponding to 8 microstrip square open loop resonators coupled together. To optimize the distance from the input to the ouput of designed filter in order to minimize insertion loss, the authors selected a structure of the filter with the coupling sheme described in figure 5(a). After synthesizing the coupling matrix and expanding the coupling coefficients, we can obtain the PCB layout as shown in 5(b).

The selected high frequency circuit materials is Roger RO3010 with the specifications as follow: Thickness h=1.27 mm, dielectric constant $\varepsilon = 10.2$, copper cladding $t = 17\mu m$, dissipation factor $tg\delta = 0.0022$.

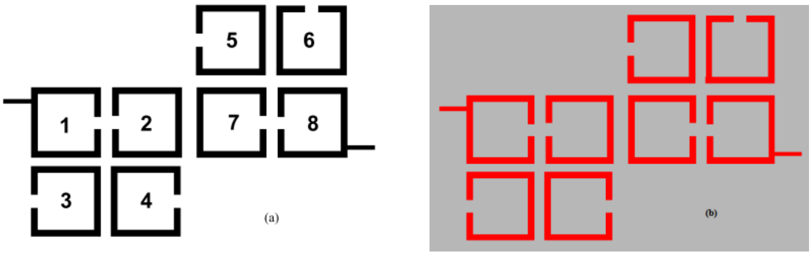


Figure 5. *Coupling scheme and PCB layout of the designed filter:*
(a) Coupling scheme; (b) PCB layout.

Using the momentum simulation tool of ADS software, we obtained the simulated results of the scattering parameters S of the filter in figure 6.

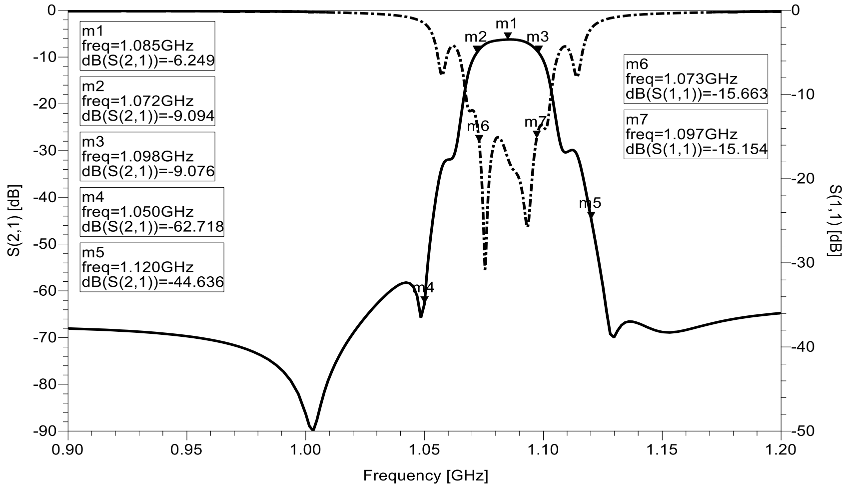


Figure 6. *Momentum simulation frequency response of the designed filter.*

The actual filter is obtained after fabrication as shown in figure 7. Figure 8 represents measured results of the actual filter (shown by dashed line) compared to simulated results (shown by solid line).

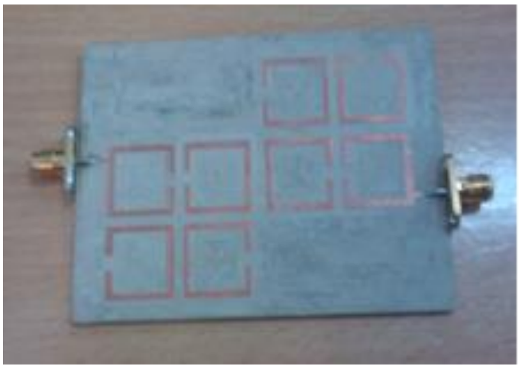
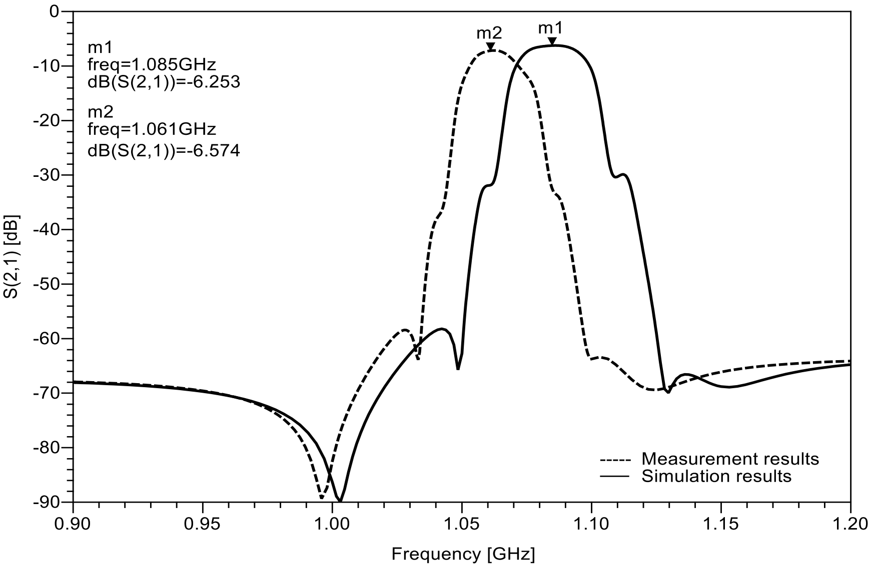


Figure 7. *Image of the actual filter after fabrication.*



Hình 8. *Measurement results of the actual filter compared to simulation results.*

From simulation results and measurement results in figure 6 and 8, it’s observed that:

- The designed filter with high selectivity, satisfy the desired specifications as passband, stopband, insertion loss and return loss in the passband.
- The frequency response of the actual filter is similar to the momentum simulation frequency response on ADS software. The insertion loss of simulated result and measured result are approximated. However, the center frequency of measured result is less than around 25 MHz compared to simulated result. This can be explained by accuracy when fabricating PCB, this problem can be overcome by compensating (when designing, we consider to increase the center frequency compared to the required frequency).

3.2. Compare to other common microstrip filters

In the other common microstrip filters as Parallel-Coupled Line, End-Coupled Line, Harpin,... We can observe that the Harpin filter is a variation of the Parallel-Coupled Line filter by folding two side branches so it has relatively minimal size and better insertion loss than other types. Therefore, the authors chose to design and simulate a Harpin filter with the above specifications to compare with the sample of designed filter. The results of design implementation on ADS software are shown in figure 9 and the results of momentum simulation as in figure 10.

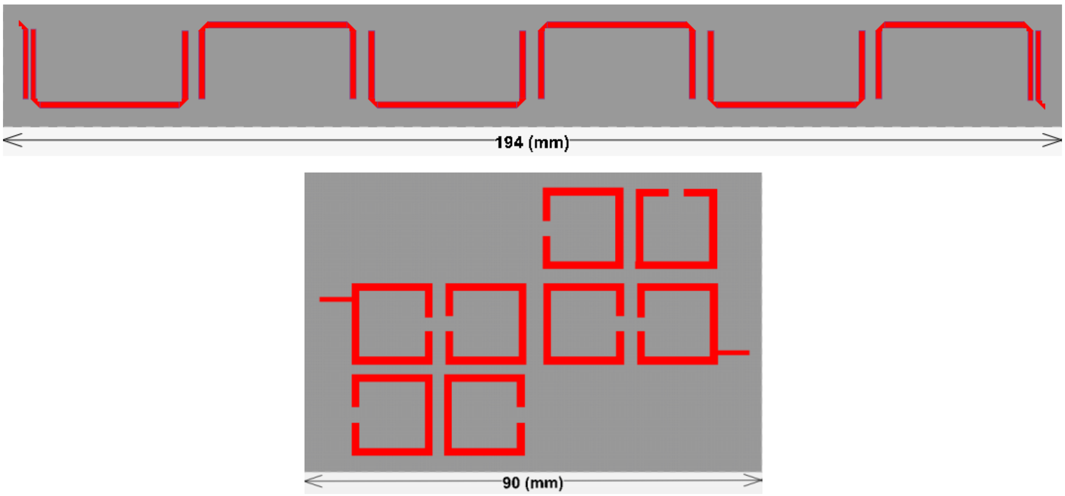


Figure 9. *PCB layout of the Harpin filter compared to the designed filter.*

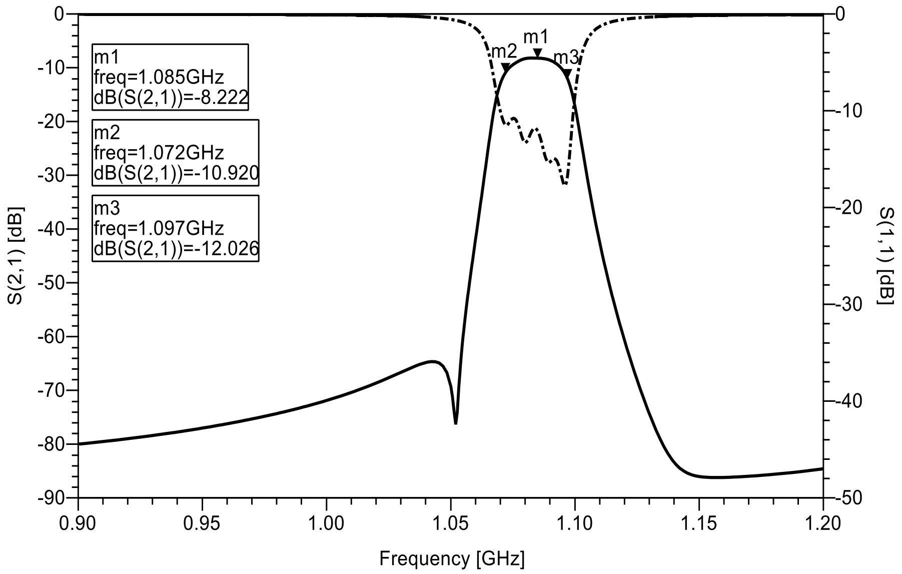


Figure 10. *Momentum simulation frequency response of the Harpin filter.*

From above comparation of simulated results and PCB layout, it’s observed that:

The insertion loss of the multiple coupled-resonator filter based on microstrip square open loop resonators is better than the Harpin filter’s one (more than 1÷2 dB). This can be explained by the fact that the designed filter has an almost optimal size in terms of length from the input to the output of filter. Besides, its size is also reduced compared to the Harpin filter.

4. CONCLUSIONS

The article studied a method of designing bandpass microstrip filter with high selectivity based on microstrip square open loop resonators. The clarification of this proposal design is confirmed by the results of simulation on ADS software and measurement of a fabricated sample filter.

The results of the article can be applied to design microstrip filters with high selectivity and low insertion loss for transceiver systems of Communications, Radar, Electronic warfare,... Due to the limitation of accuracy when fabricating printed circuit boards, this proposal method should be applied to design filters with frequency range from L-band (1÷2 GHz) to X-band (8÷12 GHz).

Besides, we can further improve the selectivity of filter by increasing its order to meet more stringent requirements in wireless systems.

This work is also a reference to expand investigation, optimize filters and develop new structures of microstrip filters.

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TÓM TẮT

Nghiên cứu phương pháp giảm nhỏ tổn hao chèn cho bộ lọc siêu cao tần có độ chọn lọc cao trên mạch dải

Dựa trên lý thuyết về bộ lọc cộng hưởng ghép, ma trận ghép và khung cộng hưởng hở mạch hình vuông, bài báo tiến hành nghiên cứu một phương pháp thiết kế bộ lọc thông dải siêu cao tần có độ chọn lọc cao trên công nghệ mạch dải nhằm mục đích giảm nhỏ tổn hao chèn. Kết quả mô phỏng trên phần mềm ADS và đo đạc thực nghiệm trên máy phân tích mạng véc tơ của mẫu bộ lọc thiết kế cho thấy phương pháp đã giảm nhỏ tổn hao chèn so với các loại bộ lọc có cấu trúc thông dụng khác trên mạch dải. Phương pháp này hoàn toàn có thể được áp dụng để chế tạo bộ lọc có độ chọn lọc cao, tổn hao chèn nhỏ trên mạch dải ứng dụng cho các thiết bị vô tuyến điện tử.

Từ khoá: Bộ lọc cộng hưởng ghép; Tổn hao chèn; Hàm truyền bộ lọc; Ma trận ghép; Khung cộng hưởng mạch dải hở mạch hình vuông.