

**ELECTROMAGNETIC DESIGN AND ACTUAL
FABRICATION OF A BANDPASS CROSS-COUPLED FILTER
APPLIED FOR MOBILE COMMUNICATION**

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Abstract

This paper outlines the design and development of a cross-coupled band-pass filter with operational frequency at 1.2 GHz, intended for mobile communication applications. To enhance computational efficiency, the filter is decomposed into individual components and each part is simulated separately using HFSS simulator and AWR software, which facilitates the extraction of critical parameters in accordance with a general coupling matrix (CM). A Rogers RO4003C substrate with a thickness of 0.813 mm and dielectric properties of $\varepsilon_r = 2.2$ and $\tan \varphi = 0.0027$ was used in the simulation. The dimensions of the fabricated cross-coupled filter are as follows $25 \times 52 \times 0.847 \text{ mm}^3$, where the filter shows a desirable frequency response with two transmission-limiting zeros as expected. The simulated cross-coupled filter has an excellent electromagnetic performance, it exhibits an insertion loss of 1.1 dB and a return loss of -25 dB within a frequency range of 1.13 GHz to 1.28 GHz. The results show that the analysis, simulation and measurements agree well with each other, proving the accuracy and efficiency of the filter design.

Key words: cross-coupled, communication, electromagnetic, substrate, filter

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Introduction. In the field of radio frequency and microwave filter design, the cross-coupled bandpass filter represents a recent innovation developed to meet the growing demands of advanced communications and processing systems. This type of filter offers a sophisticated solution that reduces noise and distortion while maintaining signal quality across multiple frequency ranges, making it ideal for complex applications that require simultaneous processing of different frequencies [1]. The cross-coupled bandpass filter focuses on passing signals within three specific frequency ranges, while filtering out other unwanted frequencies. Analytically, the $N \times N$ coupling matrix is a mathematical tool used in many fields of physics and engineering, particularly in the analysis of communications and electronics systems [2], which represents an advanced model for studying the interactions between an array of connected resonators. This matrix enables us to understand how energy interacts between the various components of a system, and thus to estimate the overall performance of the system under the influence of a range of different parameters, such as frequencies and mutual interactions [3].

In this paper, a cross-coupled filter design was proposed. The design parameters were optimized using a High Frequency Structure Simulator (HFSS) to achieve performance consistent with specified requirements, such as frequency response, selectivity characteristics, and insertion loss. The coupling matrix for the proposed filter was presented and interpreted as described in [4]. The design was divided into sub-modules to simulate each component separately to ensure modelling accuracy and verify partial performance before assembling the entire system. Simulation results were presented using both AWR and HFSS software. The comparison showed good agreement between the results obtained from the two simulators, demonstrating congruence in performance and calculation accuracy. The manufacturing process and settings associated with the measurement phase were also addressed to verify the design's validity and stability.

Design of equivalent circuit. Figure 1a represents a circuit consisting of n coupled resonators. The circuit consists of several fundamental components, including inductance (L_i), capacitance (C_i), and conductance (G_i), which are interconnected together to form electrical networks. In a coupled resonator circuit, we can consider each resonator to be an element containing inductance, capacitance, and resistance. If we consider i to be the current in the loop and v to be the voltage source, by applying Kirchhoff's voltage law, we can derive an equation for any closed loop within the circuit, given by [5]:

$$\begin{aligned}
(1) \quad & \left(G_1 + j\omega C_1 + \frac{1}{j\omega L_1} \right) v_1 - j\omega C_{12} v_2 \dots - j\omega C_{1n} v_n = i_s \\
& -j\omega C_{21} v_1 + \left(j\omega C_2 + \frac{1}{j\omega L_2} \right) v_2 \dots - j\omega C_{2n} v_n = 0 \\
& \vdots \\
& -j\omega C_{n1} v_1 - j\omega C_{n2} v_2 \dots + \left(G_n + j\omega C_n + \frac{1}{j\omega L_n} \right) v_n = 0.
\end{aligned}$$

Using these equations, we can study the natural frequencies of the system, the different couplings, and the interaction between the resonators in the circuit, which helps in developing better designs for resonant circuits [6]. These mathematical analyses provide a framework for understanding how different factors such as inductance, capacitance, and resistance affect the behaviour of a coupled resonant system, and how to control these effects to achieve the best system performance.

$$(2) \quad \begin{bmatrix} G_1 + j\omega C_1 + \frac{1}{j\omega L_1} & -j\omega C_{12} & \dots & -j\omega C_{1n} \\ -j\omega C_{21} & j\omega C_2 + \frac{1}{j\omega L_2} & \dots & -j\omega C_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ -j\omega C_{n1} & -j\omega C_{n2} & \dots & G_n + j\omega C_n + \frac{1}{j\omega L_n} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_n \end{bmatrix} = \begin{bmatrix} i_s \\ 0 \\ \vdots \\ 0 \end{bmatrix}$$

$$(3) \quad S_{11} = \pm \left(1 - \frac{2}{\sqrt{q_{e1}}} [A]_{11}^{-1} \right) \quad \text{and} \quad S_{21} = \pm \left(\frac{2}{\sqrt{q_{e1}q_{en}}} [A]_{n1}^{-1} \right).$$

Coefficients S_{11} and S_{22} can be used to measure reflections at various inputs, while coefficients S_{12} and S_{21} are used to measure signal transmittance through the system. These coefficients are used at microwave frequencies and provide valuable information about the system's efficiency in transmitting or reflecting electromagnetic energy. By using the formulas described in [7], the filter coupling matrix and the external quality factors can be calculated. These calculations help to ensure that the filter operates efficiently while minimizing losses and achieving the desired performance in practical applications.

$$(4) \quad Q_{es} = \frac{g_0 g_1}{FBW}, \quad Q_{eL} = \frac{g_n g_{n+1}}{FBW}$$

$$(5) \quad M_{i,i+1} = \frac{FBW}{\sqrt{g_i g_{i+1}}}, \quad i = 1 \text{ to } (n-1)$$

$$(6) \quad m_{i,i+1} = \frac{M_{i,i+1}}{FBW}, \quad i = 1 \text{ to } (n-1).$$

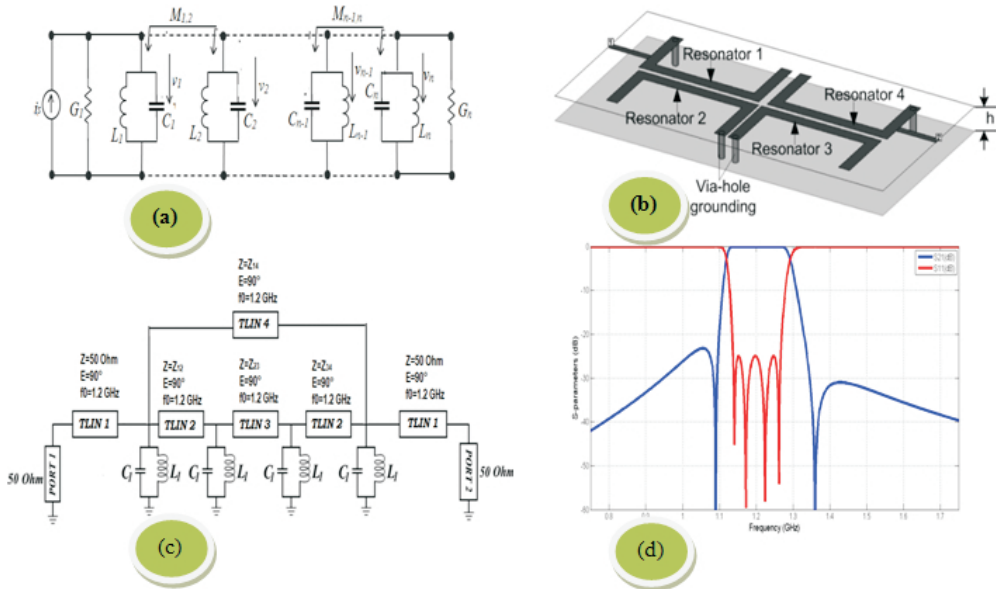


Fig. 1. a) Typical series-resonator bandpass network; b) 3D Structure of four-pole filter; c) Lumped elements of 4th order; d) Ideal response

The filter specifications presented represent, order $n = 4$, centre frequency ($f_0 = 1.2$ GHz), bandwidth at -3 dB ($BW = 150$ MHz), and return loss $R_L = 25$ dB, (Fig. 1b). This matrix contains elements representing the coupling effects between different resonators [8]. Here we will show a general form of this matrix.

$$(7) \quad [m] = \begin{bmatrix} 0 & 0.8559 & 0 & -0.2196 \\ 0.8559 & 0 & 0.9571 & 0 \\ -0.2196 & 0 & 0.8559 & 0 \\ 0 & 0.9571 & 0 & 0 \end{bmatrix}$$

$$(8) \quad \omega_0 = 2\pi f_0 = 7.5398 \text{ with } FBW = \frac{BW}{f_0} = 0.1284 = 12.84\%$$

$$(9) \quad Q_e = \frac{g_0 g_1}{FBW} = \frac{1 * 0.9314}{0.128416} = 7.2538.$$

As shown in Fig. 1c, the capacitance C_1 , inductance L_1 and the series impedances Z_{12} , Z_{23} , Z_{34} are also calculated using the following equations [9]:

$$(10) \quad C_1 = \frac{Q_{eS}}{\omega_0 \times Z} = 0.0423 \text{ pF}$$

$$(11) \quad L_1 = \frac{Z}{\omega_0 \times Q_{eS}} = 176.24 \text{ nH}$$

$$(12) \quad Z_{i,i+1} = \frac{Z}{M_{i,i+1} \times Q_e}.$$

Analysis of Fig. 1d, using AWR reveals that the designed bandpass filter has a centre frequency of 1.20 GHz and a bandwidth of 150 MHz. Within this range, the reflection loss is -25 dB, demonstrating that the filter operates efficiently at passing the signal while significantly reducing reflection [10].

Design and analysis of a micro strip filter into different parts using electromagnetic simulation. Cross-coupled filter design may include multiple components, it is best to break it down into smaller, individual parts so that each part is simulated independently [11]. After dividing the design into separate parts, an HFSS electromagnetic simulator is used to analyze each part individually. After simulating each part individually, parameters related to each part are extracted, such as losses, frequencies passed or blocked, reflections, and wavelength. These parameters determine the final performance of the strip filter. Various structures can be combined to obtain a final, integrated design that achieves the desired performance [12]. The proposed structure is designed using Rogers RO4003C, a material with a dielectric constant of 3.38, which is ideal for microwave applications due to its superior electrical properties in the high-frequency range. The top and bottom layers of the structure are made of perfect electrical conductors (copper). Dielectric constant ($\epsilon_r = 3.38$), thickness of height ($h = 0.813$ mm) and loss tangent of 0.0027. Based on the dimensions and design developed using Rogers RO4003C material, the coupling coefficient between the resonators (k) is calculated based on the two characteristic resonator frequencies (f_1 and f_2) using the following equation [13]:

$$(13) \quad K = \frac{f_2^2 - f_1^2}{f_2^2 + f_1^2}.$$

When f_1 and f_2 are close together, the coupling coefficient k will be larger, meaning the resonators interact more strongly with each other. If the differences between the frequencies are large (i.e., f_1 and f_2 are far apart), k will be small, meaning that the coupling between the resonators is weak.

Figure 2a shows the input/output resonator used to extract the external quality factor in the context of microstrip filter design. In Fig 2b, a design curve for (Q_e) versus t is shown [14]. This curve is an important tool in microstrip filter design, as it shows the relationship between the external quality factor (Q_e) and the thickness of the dielectric material (t) in the system – the (Q_e) versus t curve. This relationship helps to determine how the distance (t) affects the performance of the microstrip filter, especially with regard to the efficiency in filtering frequencies. As the distance (t) increases, the external quality factor (Q_e) increases. To extract the coupling between resonators 1 and 2 in a microstrip filter, EM simulation is used in the order shown in Fig. 2c. This involves determining the geometric positions of the resonators, setting up the simulation to analyze the electromagnetic field interaction between the resonators, and then extracting the coupling coefficients from the simulation results [15]. The coupling between the resonators

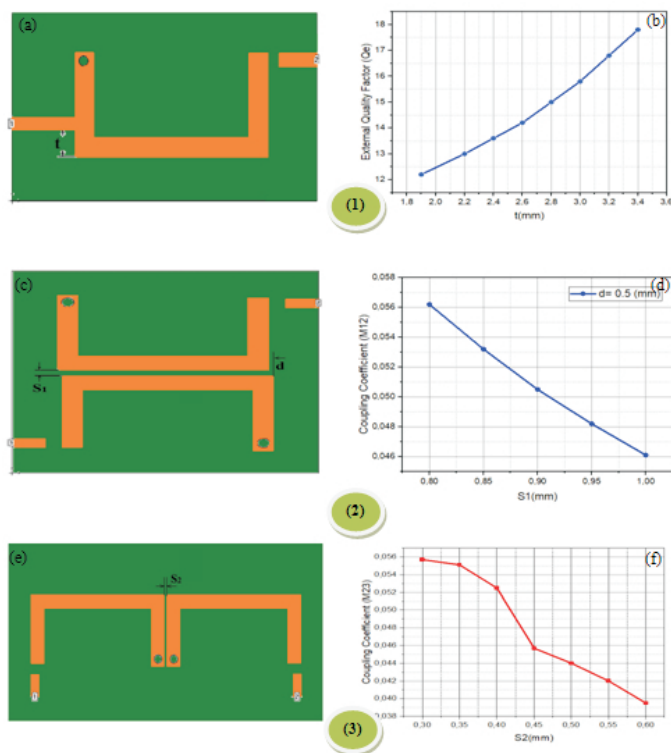


Fig. 2. The order in which external quality factor and coupling coefficients are derived in the design of cross-coupled filter.
1) Design curve for Q_e ; 2) Design curve for M_{12} ; 3) Design curve for M_{23}

in a microstrip filter is mainly controlled by the spacing (s_1) in Fig. 2d. Offset (d) may be necessary when additional couplings need to be implemented to improve the filter performance and ensure adequate filtering of frequencies. Fig. 2e shows the EM simulation setup to determine the coupling between resonators 2 and 3 in a microstrip filter. EM simulation is a powerful tool for understanding these interactions and achieving the ideal balance between coupling strength and frequency response of the filter. S -coefficients (such as S_{23} or S_{32}) that represent the transmission and reflection between resonators 2 and 3 are calculated. These coefficients help in understanding how energy is transferred between the resonators. Using the same approach described for extracting the coupling between the resonators, a design curve for M_{23} is produced that shows the relationship between the coupling coefficient and the geometric properties of the filter [16]. This curve is plotted in Fig. 2f and is an important tool in analyzing the effect of filter design on the coupling between the resonators. By analyzing the design curves extracted from EM simulation, the physical dimensions such as $t = 2.9$ mm, $s_1 = 0.9$ mm, $s_2 = 0.5$ mm, and $s_3 = 1.5$ mm are determined. These dimensions are consis-

tent with the design requirements and help in achieving the optimum frequency response of the filter.

Fabrication of the proposed filter and experimental validation. The proposed filter was fabricated using a PCB process on a 0.813 mm thick Rogers RO4003C substrate with precise electrical properties such as a relative transmittance of 3.38 and a low loss tangent ($\tan(\delta)$) of 0.0027 [17].

The filter fabrication involved copper plating and drilling holes through the substrate to form the cross-coupled circuit. Using an Anritsu-MS2037C harmonic analyzer (Fig. 3a) to measure the S_{11} and S_{21} bands of the fabricated filter enabled experimental validation of the filter’s performance. The fabricated filter has simple structure, compact size and low insertion loss so that these performances are very attractive in the practical applications in modern communication systems [18]. These offsets suggest practical effects related to the manufacturing process or the material properties of the prototype, but overall, the filter’s performance remains consistent with expectations. Figure 3b (bottom view) and Fig. 3c (top view) show a photograph of the fabricated filter measuring 25×52 mm, while Fig. 3d shows the simulation and electromagnetic (EM) measurements of the filter. The insertion loss at the centre frequency was measured and found to be less than 1.13 dB, indicating high signal transmission efficiency through the filter. As shown in Fig. 3e two transmission zeros were observed at 1.06 and 1.34 GHz [19], indicating signal blocking at these frequencies, which is required in filter design to pass the specified frequency range and block other frequencies. Figure 3f illustrates the electric field distribution in the bandpass filter at 1.2 GHz, as simulated using HFSS.

T a b l e 1

Comparison of the designed filter to other reported filter designs

Ref. No.	f_0 [GHz]	FBW [%]	Insertion loss [dB]	Return loss (RL) [dB]	Circuit size
[13]	4.26	66.9	1.98	09	$40 \times 50 \times 1.52$
[14]	1.8	2.7	3.35	15	$20 \times 25 \times 0.8$
[15]	1	20	0.6	18	$15 \times 42 \times 1.27$
This work (HFSS)	1.2	15	1.14	25	$25 \times 50 \times 0.813$

(f_0 – centre frequency, FBW – fractional bandwidth, IL – insertion loss, RL – return loss)

Table 1 summarizes the comparison with other filters and demonstrates that the proposed filter offers superior size reduction and excellent frequency performance [20].

Conclusion. This research paper first presents analytical Chebyshev equations for calculating various synthesis parameters of a bandpass microstrip cross-coupled filter. The design incorporates the coupling matrix, quality coefficients, and the initial geometric dimensions. Second, the ideal frequency response of the

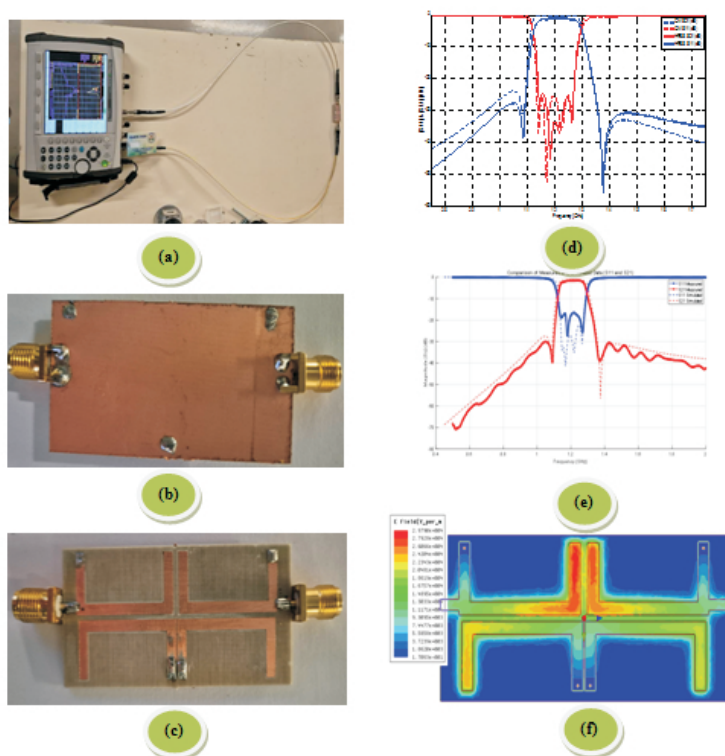


Fig. 3. Fabrication and response of the cross-coupled filter; (a) Experimental measurement; (b) Bottom view; (c) Top view; (d) Compared with the ideal response; (e) Compared with the measurement; (f) Electric field

developed filter is achieved using lumped equivalent circuit elements modelled in AWR Office. Finally, EM simulations performed with HFSS software provide the response results of the proposed cross-coupled filter, spanning a frequency range from 1.13 GHz to 1.28 GHz, with a central frequency of 1.2 GHz. Accordingly, a strong consistency between HFSS simulation curves and AWR realization results demonstrates the design of a high-performance filter structure tailored for mobile communication applications. The filter achieves an insertion loss of 1.1 dB and a return loss of -25 dB across the entire bandwidth, with a fractional bandwidth of 15.84%. When the analytical and measurement results are compared, the fractional bandwidth (FBW) is 15%, and the centre frequency is 1.20 GHz. It is effectively observed that the analytical, simulation, and measurement results are in a very good agreement.

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