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MANUFACTURING TOLERANCE INVESTIGATION OF MICROSTRIP HAIRPIN FILTERS USING FULL-WAVE ELECTROMAGNETIC SIMULATION

Abstract. Two fourth-order hairpin filters with identical electrical specifications but different resonator widths (1 mm and 2 mm) were designed for operation in the 2.4 GHz frequency band. The design procedure combined analytical synthesis, full-wave electromagnetic simulation based on the finite-element method, preliminary sensitivity analysis, and numerical optimization using the Nonlinear Programming by Quadratic Lagrangian (NLPQL) algorithm. Physical prototypes were fabricated using a laboratory photolithographic process and experimentally characterized using a vector network analyzer. The measured scattering parameters were compared with simulation results to evaluate the influence of practical manufacturing limitations.

To assess the impact of fabrication accuracy, a detailed sensitivity analysis was performed by introducing controlled deviations of resonator width, resonator length, and coupling gaps from their nominal values. The considered deviations corresponded to the achievable manufacturing accuracy of approximately $\pm 100 \mu\text{m}$. The results demonstrated that coupling gaps represent the most critical geometrical parameters, producing the largest variations in return loss and passband characteristics. Deviations in resonator width and resonator length had a smaller but still noticeable influence on filter performance. Comparison of the measured and simulated responses showed generally acceptable agreement. The observed discrepancies can be explained by dimensional inaccuracies introduced during fabrication and by variations in the dielectric properties of the FR4 substrate.

The comparative analysis of the two filter configurations revealed that increasing the resonator width from 1 mm to 2 mm does not significantly improve tolerance robustness. Both filters exhibited approximately the same sensitivity to variations of the investigated geometrical parameters. The obtained results indicate that compact and inexpensive hairpin filters for the 2.4 GHz band can be successfully implemented on FR4 substrates using low-cost fabrication technologies. Since wider resonators did not provide a substantial tolerance advantage, the use of narrower resonators appears preferable due to reduced filter dimensions and larger achievable coupling gaps.

Keywords: hairpin filter, microstrip filter, manufacturing tolerance, full-wave electromagnetic simulation, finite-element method, FR4 substrate, sensitivity analysis, microwave filter design.

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ДОСЛІДЖЕННЯ ВИРОБНИЧИХ ДОПУСКІВ МІКРОСМУЖКОВИХ ФІЛЬТРІВ НА U-ПОДІБНИХ РЕЗОНАТОРАХ ІЗ ВИКОРИСТАННЯМ ТРИВИМІРНОГО ЕЛЕКТРОМАГНІТНОГО МОДЕЛЮВАННЯ

Анотація. Для роботи в діапазоні частот 2,4 ГГц було спроектовано два фільтри на четвертого порядку U-подібних резонаторах з однаковими електричними характеристиками, але різною шириною смужок резонаторів (1 мм та 2 мм). Процедура проектування поєднувала аналітичний синтез, повнохвильове електромагнітне моделювання методом скінченних елементів, попередній аналіз чутливості та чисельну оптимізацію із застосуванням алгоритму нелінійного програмування на основі квадратичного лагранжіана. Фізичні прототипи були виготовлені за допомогою лабораторного фотолітографічного процесу та експериментально досліджені з використанням векторного аналізатора кіл. Виміряні S-параметри було порівняно з результатами моделювання для оцінювання впливу практичних обмежень технології виготовлення.

Для оцінювання впливу точності виготовлення було проведено детальний аналіз чутливості шляхом введення контрольованих відхилень ширини резонаторів, довжини резонаторів та зв'язних зазорів від їхніх номінальних значень. Розглянуті відхилення відповідали досяжній точності виготовлення приблизно $\pm 100 \mu\text{м}$. Отримані результати показали, що зв'язні зазори є найбільш критичними геометричними параметрами та спричиняють найбільші зміни коефіцієнта відбиття і характеристики смуги пропускання. Відхилення ширини та довжини резонаторів мали менший, проте все ж помітний вплив на характеристики фільтра. Порівняння виміряних і змодельованих частотних характеристик продемонструвало загалом задовільну відповідність. Виявлені розбіжності можуть бути пояснені похибками геометричних розмірів, що виникають під час виготовлення, а також варіаціями діелектричних властивостей підкладки FR4.

Порівняльний аналіз двох конфігурацій фільтра показав, що збільшення ширини резонатора з 1 мм до 2 мм не забезпечує суттєвого підвищення стійкості до виробничих допусків. Обидві конструкції продемонстрували приблизно однакову чутливість до змін досліджуваних геометричних параметрів. Отримані результати свідчать про те, що компактні та недорогі hairpin-фільтри для діапазону 2,4 ГГц можуть бути успішно реалізовані на підкладках FR4 із використанням низьковартісних технологій виготовлення. Оскільки ширші резонатори не продемонстрували істотних

переваг з точки зору стійкості до допусків, доцільним є використання вузьких резонаторів, що забезпечують менші габарити фільтра та більші допустимі зазори між резонаторами.

Ключові слова: *фільтр на U-подібних резонаторах, мікросмужковий фільтр, виробничі допуски, повнохвильове електромагнітне моделювання, метод скінченних елементів, підкладка FR4, аналіз чутливості, проектування мікрохвильових фільтрів.*

1. Introduction

The continuous growth of wireless communication technologies has led to an increasing demand for compact, low-cost, and reliable microwave components operating in the industrial, scientific, and medical (ISM) frequency bands. Among them, the 2.4 GHz band remains one of the most widely utilized frequency ranges due to its application in Wi-Fi, Bluetooth, Internet of Things (IoT) devices, wireless sensor networks, and various telemetry systems. To ensure proper operation of such equipment, microwave bandpass filters are commonly employed to suppress unwanted signals and improve electromagnetic compatibility. Owing to their planar configuration, ease of fabrication, and compatibility with printed circuit board technologies, microstrip filters have become one of the most popular solutions for these applications [1], [2].

Despite their structural simplicity, microstrip bandpass filters require careful design, since their electrical behavior is highly sensitive to both geometrical dimensions and material properties. Variations in resonator geometry, coupling distances, substrate parameters, or fabrication accuracy may noticeably affect the filter characteristics. This sensitivity becomes increasingly important at higher frequencies, where small manufacturing errors can result in passband displacement and deterioration of insertion and return loss performance. For this reason, practical filter development generally combines theoretical synthesis with electromagnetic modeling and optimization procedures [3].

Among various microstrip filter topologies, hairpin bandpass filters have attracted considerable attention because they provide a favorable compromise between electrical performance and physical size. By folding conventional half-wavelength resonators into U-shaped structures, the occupied area can be significantly reduced while maintaining the required frequency response characteristics.

Despite their advantages, the practical implementation of hairpin filters remains strongly dependent on manufacturing accuracy. The electrical performance of such structures is determined by several geometrical parameters, including resonator dimensions and coupling gaps. Deviations introduced during printed circuit board fabrication may alter the resonant frequencies and coupling coefficients, resulting in shifts of the passband, degradation of return loss, and increased insertion loss. These effects are particularly important for low-cost fabrication processes, where dimensional tolerances are often comparable to critical geometrical features of the filter.

The present work investigates the influence of resonator width on the manufacturing tolerance sensitivity of compact 2.4 GHz hairpin microstrip filters fabricated on an FR4 substrate. Two filter configurations with identical electrical specifications but different resonator widths were designed, simulated, and experimentally manufactured using a photolithographic process. The sensitivity of the filters to dimensional deviations in resonator width, resonator length, and coupling gaps was analyzed using full-wave electromagnetic simulation and verified experimentally. The obtained results provide additional insight into the relationship between resonator geometry and fabrication tolerance in low-cost microstrip filter designs.

2. Statement of the problem

The practical implementation of microstrip bandpass filters often requires a compromise between electrical performance, physical dimensions, manufacturing complexity, and production cost. For many wireless communication applications, particularly in the 2.4 GHz ISM band, the use of expensive low-loss microwave substrates may not be economically justified. Consequently, low-cost materials such as FR4 laminate remain attractive for the development of compact microwave filters intended for prototyping, educational purposes, low-volume production, and cost-sensitive applications.

However, the use of FR4 laminate introduces additional challenges. In comparison with specialized microwave laminates, FR4 is characterized by relatively high dielectric losses and significant variations of dielectric properties between manufacturing batches. Furthermore, low-cost printed circuit board fabrication processes, especially those based on photolithographic techniques, do not always provide the dimensional accuracy required for microwave structures. As a result, deviations in conductor width, resonator length, and coupling gaps may lead to discrepancies between the designed and the realized filter characteristics.

Since the electromagnetic behavior of hairpin filters is strongly determined by the geometry of their resonators and coupling structures, the influence of manufacturing tolerances becomes an important factor in practical filter design. At the same time, different geometrical configurations may exhibit different levels of sensitivity to fabrication inaccuracies. In particular, it can be reasonably assumed that the width of the resonator conductors may affect the stability of the filter characteristics with respect to dimensional deviations introduced during manufacturing. Wider conductors may be expected to reduce the relative influence of fabrication errors, while narrower conductors may provide more compact structures at the cost of increased sensitivity. Nevertheless, the actual impact of resonator width on the tolerance sensitivity of hairpin filters is not obvious and cannot be reliably estimated without detailed electromagnetic analysis.

Therefore, there is a need for a comparative investigation of hairpin filter structures with different resonator widths in order to assess the extent to which this parameter influences the susceptibility of the filter characteristics to typical manufacturing inaccuracies encountered in low-cost fabrication processes.

3. Analysis of recent studies and publications

Hairpin microstrip filters remain one of the most widely investigated filter topologies due to their compact size, relatively simple design procedure, and suitability for implementation using standard printed circuit board technologies. The folded structure of half-wavelength resonators enables a significant reduction in occupied area compared to conventional parallel-coupled microstrip filters while maintaining acceptable frequency-selective characteristics. Owing to these advantages, hairpin filters have been successfully applied in a wide range of wireless communication systems operating from the UHF band [4] to microwave frequencies [5], [6] and even millimeter-wave applications [7], [8].

However, comparatively less attention has been paid to the influence of resonator geometry on the sensitivity of filter characteristics to manufacturing inaccuracies. In particular, the effect of resonator conductor width on tolerance sensitivity remains insufficiently investigated, despite its potential importance for practical filter fabrication.

4. Research objectives and tasks

The objective of this work is to investigate the influence of resonator conductor width on the manufacturing tolerance sensitivity of compact 2.4 GHz hairpin microstrip filters fabricated on an FR4 substrate using a low-cost photolithographic process.

To achieve this objective, the following tasks were defined:

- To design two hairpin microstrip bandpass filters with identical electrical specifications but different resonator conductor widths using analytical synthesis procedures, full-wave electromagnetic simulation, and numerical optimization techniques.
- To fabricate physical prototypes of the designed filters on an FR4 substrate using a photolithographic printed circuit board manufacturing process.
- To measure the frequency responses of the fabricated prototypes and compare the obtained S-parameters (S_{11} and S_{21}) with the results of full-wave electromagnetic simulations in order to evaluate the degree of agreement between the manufactured filters and the corresponding idealized numerical models.
- To investigate the influence of manufacturing inaccuracies on the filter performance by introducing controlled variations of selected geometrical parameters in the electromagnetic model. Considering the fabrication accuracy of approximately ± 0.1 mm, the effects of deviations in resonator width, resonator length, and coupling gaps on the S_{11} and S_{21} characteristics are analyzed.
- To compare the tolerance sensitivity of the two filter configurations and assess whether variations in resonator conductor width affect the robustness of the filter characteristics with respect to typical dimensional deviations encountered during low-cost fabrication.

The parameters of the filters are as follows: pass band frequency: 2443 MHz, pass band width: 300 MHz, stop band width: 1000 MHz, stop band attenuation: 40 dB, response approximation type: Chebyshev type 1, pass band ripple: 0.05 dB, input and output impedance: 50 Ω .

The main operation frequency band, for which the filters were designed, is 2400...2483 MHz. The pass band of the filter was taken 300 MHz, which is higher than the operation band.

For the realization of the filters, the FR4 laminate was used. The parameters of the material are as follows: dielectric constant $\epsilon_r = 4.4$; thickness $h = 1.5$ mm; thickness of strip $t = 2.54$ μm ; dissipation is defined by loss tangent value $\tan \delta = 0.02$.

5. Research results

5.1. Filter Design and Simulation

In the further discussion, two independent filter models are considered:

- *Filter 1* with the resonator strip width $w_r = 1\text{mm}$;
- *Filter 2* with the resonator strip width $w_r = 2\text{mm}$.

General view of a hairpin filter topology and basic geometry parameters that are relevant for the further optimization procedure and sensitivity analysis are shown in Fig. 1.

Based on the parameters of the synthesized low-pass prototype, the dimensions and coupling parameters of the hairpin microstrip filter can be determined using the design procedure described in [9]. The main stages of the design process are summarized below.

- 1) *Low-Pass Prototype Synthesis*. A normalized low-pass prototype is synthesized using classical network synthesis techniques. The prototype coefficients are determined according to the required passband

characteristics, and the minimum filter order satisfying the specification is selected. For the considered design, a fourth-order filter topology is required.

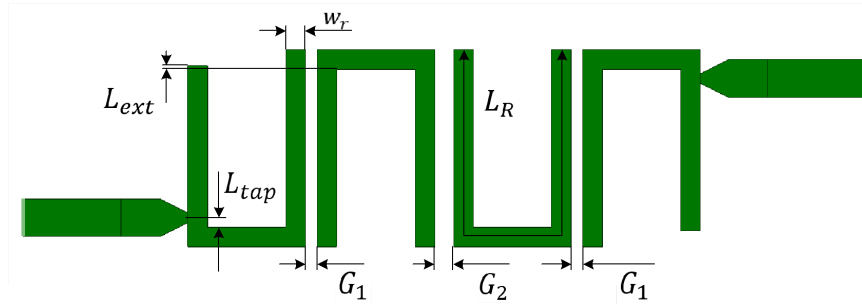


Fig. 1. Geometrical parameters for optimization and sensitivity analysis

- 2) *Initial Calculation of Resonator Dimensions.* The preliminary dimensions of the U-shaped resonators are obtained from analytical microstrip transmission-line models. The calculations include the estimation of the effective dielectric constant and the determination of resonator length and conductor width corresponding to the desired center frequency.
- 3) *Calculation of Coupling Coefficients and External Quality Factors.* The required coupling coefficients between adjacent resonators and the external quality factors are calculated from the low-pass prototype parameters and the specified fractional bandwidth.
- 4) *Design of the Tapered Feed Transition.* A tapered section is introduced between the feed line and the resonator in order to improve impedance matching, reduce reflection losses, and provide smoother coupling between the external circuitry and the filter.
- 5) *Extraction of Coupling and External-Q Dependencies.* Full-wave electromagnetic simulations are performed for pairs of coupled resonators and for the input/output resonator structures. The finite-element method (FEM) is employed to establish the relationships between geometrical dimensions and electrical parameters. As a result, the dependencies of the coupling coefficient on the resonator gap $k(g)$, where g is the gap value, represented by the G_1 and G_2 values in the final filter model shown in Fig. 1, and the external quality factor on the tap position $Q(L_{tap})$ are obtained.
- 6) *Selection of Resonator Spacing.* The spacing between adjacent resonators is determined using the extracted $k(g)$ relationship. The gap values are selected to provide the coupling coefficients required by the filter synthesis procedure.
- 7) *Design of Input and Output Feeding Structures.* The feeding lines are designed as 50-ohm microstrip transmission lines compatible with standard microwave measurement equipment. Since the filter employs tapped-line excitation, the tap position is selected using the previously obtained $Q(L_{tap})$ dependence to achieve the required external quality factor.
- 8) *Full-Wave Electromagnetic Modeling of the Filter.* A complete three-dimensional model of the filter is developed and analyzed using FEM-based electromagnetic simulation. This stage provides accurate predictions of the scattering parameters and electromagnetic field distribution within the structure. A detailed discussion of numerical techniques applicable to microstrip filter design can be found in [10]. The simulations presented in this work were performed using the commercial HFSS software package. The filter models for the simulation are shown in Fig. 2.
- 9) *Preliminary Sensitivity Analysis.* Prior to automated optimization, a manual investigation of the most critical geometrical parameters is performed. Particular attention is paid to the coupling gaps between adjacent resonators, since small variations of these dimensions may produce significant changes in the filter response. Several alternative gap values are analyzed using full-wave simulation in order to identify a geometrical configuration that provides improved initial characteristics. This preliminary study allows the design to start from a more favorable solution and reduces the number of iterations required during the subsequent optimization stage.
- 10) *Geometrical Optimization.* The final dimensions of the resonators and coupling gaps are refined through an iterative optimization process. At each iteration, full-wave electromagnetic analysis is performed and the geometrical parameters are adjusted until the required frequency response is achieved.

5.2. Geometry Optimization of the Filters

The most filter characteristics, such as central frequency, bandwidth, insertion loss S_{21} curve fulfil or are very close to the desired ones due to the detailed filter synthesis procedure. However, the most sensitive characteristic of the filtering structure is return loss S_{11} . Therefore, the geometrical parameters optimization aims primarily at improving the S_{11} curve of the filter, and to a lesser extent at tuning other characteristics.

The optimization of the filter was performed using the Nonlinear Programming by Quadratic Lagrangian (NLPQL) algorithm [11]. NLPQL is a gradient-based local optimization method intended for constrained nonlinear problems. The algorithm iteratively approximates the original optimization problem by a sequence of quadratic subproblems formed from local gradient information and a quasi-Newton approximation of the Hessian matrix of the Lagrangian function. At each iteration, the design variables are updated in the direction providing the greatest improvement of the objective function while satisfying the imposed constraints.

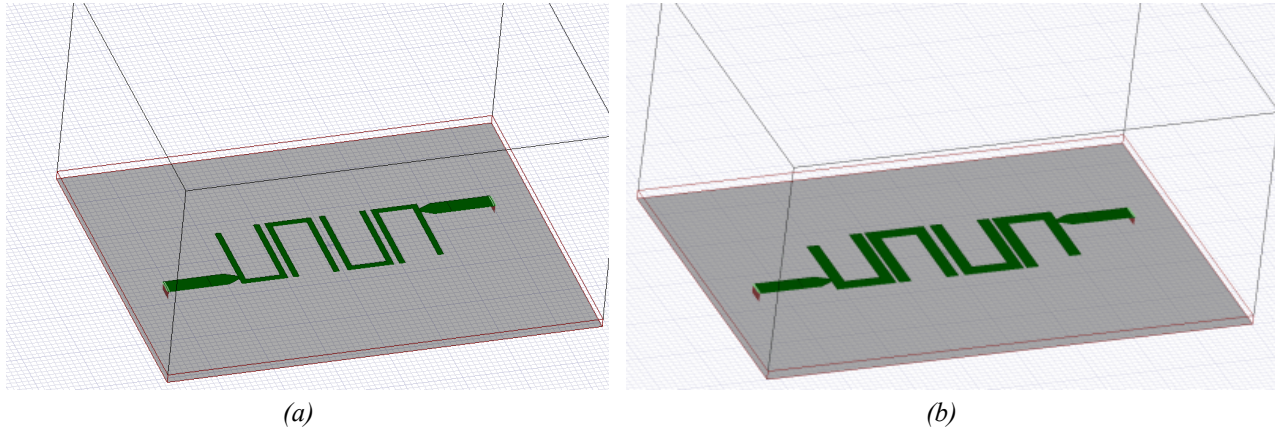


Fig. 2. Filter model for FEM simulation: a – model for Filter 1 ($w_r = 1\text{mm}$); b – model for Filter 2 ($w_r = 2\text{mm}$)

Compared with global optimization approaches such as genetic algorithms, NLPQL generally requires significantly fewer full-wave electromagnetic simulations, which substantially reduces the overall computational cost. This is particularly important for full-wave optimization of microwave structures, where each simulation may require considerable computational resources and time. Consequently, NLPQL provides an effective trade-off between optimization accuracy and computational efficiency for the fine tuning of analytically synthesized hairpin filters.

The following parameters, shown in Fig. 2, were included into the optimization process: gaps between the resonators G_1 and G_2 , edge resonators extension L_{ext} , resonator length L_R , taper shift L_{tap} .

The design procedure described above allows to determine geometrical parameters of the filter with relatively high accuracy that makes the values being located close to the optimal values. It allows to decrease the number of optimization algorithm iterations and dramatically decrease the probability of finding spurious local optima. As a result of the optimization, the final values of geometrical parameters of the filter were determined. The final dimensions and topology of the filter are shown in Fig. 3.

The cost function for the optimization task consisted of the following criteria:

- $|S_{11}| \leq -19\text{ dB}$ in frequency range $f=2.38\dots 2.53\text{ GHz}$;
- $|S_{21}| \leq -20\text{ dB}$ in frequency range $f=2.8\dots 3.27\text{ GHz}$;
- $|S_{21}| \leq -20\text{ dB}$ in frequency range $f=1.83\dots 2.13\text{ GHz}$.

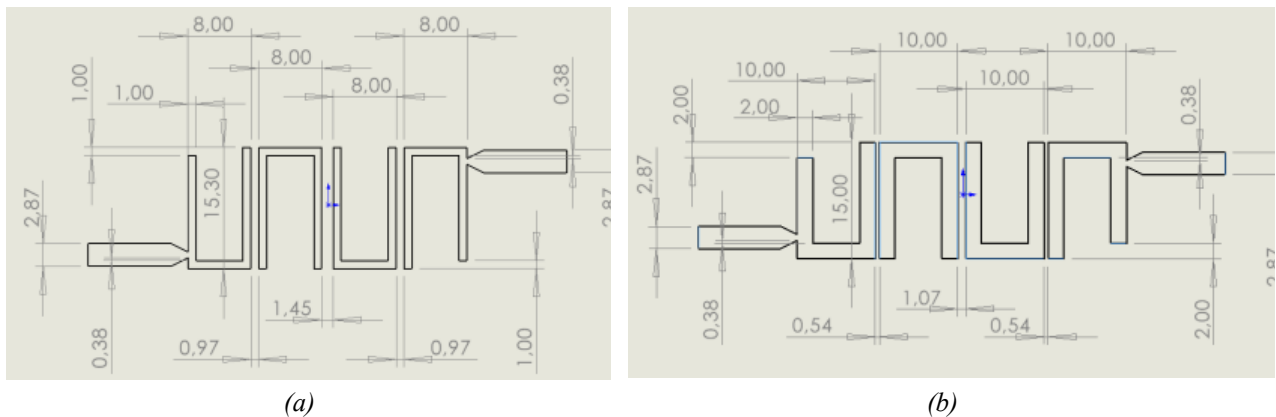


Fig. 3. Topology of the filters and their dimensions (the values are given in millimeters): a – Filter 1 ($w_r = 1\text{mm}$); b – Filter 2 ($w_r = 2\text{mm}$)

5.3. Fabrication of the Filter Prototypes and Analysis of Measurement Results

Using 3D model, the prototypes of the filters were fabricated as shown in Fig. 4. The dimensions of the filters are $60 \times 40 \text{ mm}^2$ for Filter 1 and $68 \times 40 \text{ mm}^2$ for Filter 2.

The prototypes were fabricated using a laboratory photolithographic process, which may introduce dimensional deviations of approximately $\pm 0.1 \text{ mm}$. Such deviations are especially critical for the coupling gaps of the hairpin filter and can noticeably affect the bandwidth and center frequency.

In Fig. 5, the simulated and measured results for the insertion loss $|S_{21}|$ and return loss $|S_{11}|$ frequency responses of the filter are shown. The measured results were taken using a vector network analyzer and the fabricated filter prototype. It can be seen that there is some mismatch between the simulation results and measured values.

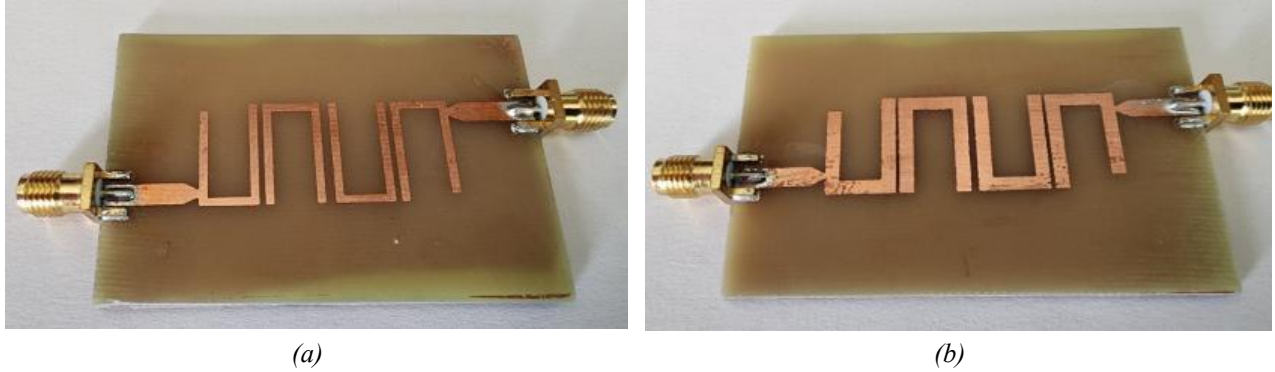


Fig. 4. Fabricated filter prototypes: a – Filter 1 ($w_r = 1 \text{ mm}$); b – Filter 2 ($w_r = 2 \text{ mm}$)

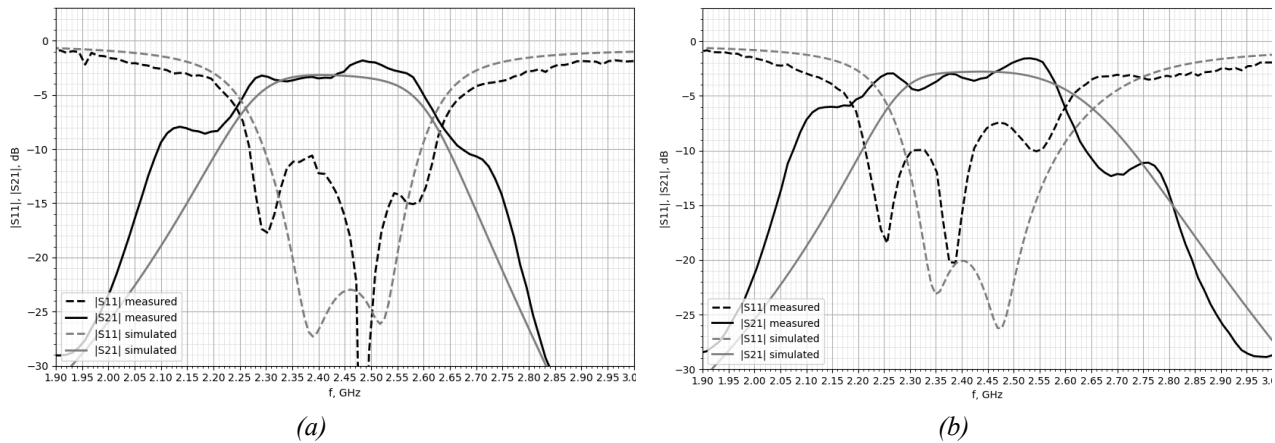


Fig. 5. Frequency responses of the filter: a – Filter 1 ($w_r = 1 \text{ mm}$); b – Filter 2 ($w_r = 2 \text{ mm}$)

5.4. Sensitivity Analysis of the Filter Characteristics

The possible reasons for the mismatch between the calculated and measured characteristics may include the following factors:

- inaccuracy of distances due to the precision of the fabrication process, especially the gaps between resonators.
- roughness of the microstrip edges, which is caused by the etching process.
- the fact that the actual values of loss tangent and dielectric constant of FR4 laminate may not correspond to the values used in the simulation.

FR4 laminate, which was used for the device, is not suited for microstrip structures, since its dielectric constant is not specified with high accuracy and may vary in considerably wide range (3.8...4.8).

To evaluate the impact of key geometrical parameters at the filter parameters, the model was simulated for a set of deviations from their calculated values. The modeling was done for the following parameters:

- the deviations $\Delta G_1 = G_1 - G_{10}$, $\Delta G_2 = G_2 - G_{20}$ from resonator gap nominal values, where G_{10} , G_{20} are the nominal values of gaps, obtained from the design procedure and shown in Fig. 3; the graphs are shown in Fig. 6 and Fig. 7;
- the deviation $\Delta w_r = w_r - w_{r0}$ from resonator strip width nominal values, where w_{r0} is the nominal value strip width, obtained from the design procedure and shown in Fig. 3; the graphs are shown in Fig. 8;

- the deviation $\Delta L_R = L_R - L_{R0}$ from the nominal resonator length, where L_{R0} is the nominal value, extracted from the full-wave simulation; the graph is shown in Fig. 9.

All the values of the ΔG_1 , ΔG_2 , Δw_r , ΔL_R parameters were selected to be $\pm 100 \mu\text{m}$ around the nominal values shown in Fig. 3.

As it can be seen from Fig. 6 – 9, the sensitivity of the frequency responses functions for G_1 and G_2 gap widths is considerably higher relative to the sensitivity for ΔL_R value. The impact of the strip width deviation Δw_r is higher than ΔL_R , but smaller than ΔG_1 , ΔG_2 .

For both filters, the maximum return loss $|S_{11}|$ value within the passband changes in the range of approximately 19 dB for the change of G_1 value in the $\pm 100 \mu\text{m}$ range, and in the range of approximately 17 dB for the G_2 varying in the $\pm 100 \mu\text{m}$ range. At the same time, it changes in the range of only 2 dB for the ΔL_R parameter varying in the $\pm 100 \mu\text{m}$ range, and in the range of approximately 5 dB for the Δw_r parameter varying in the $\pm 100 \mu\text{m}$ range.

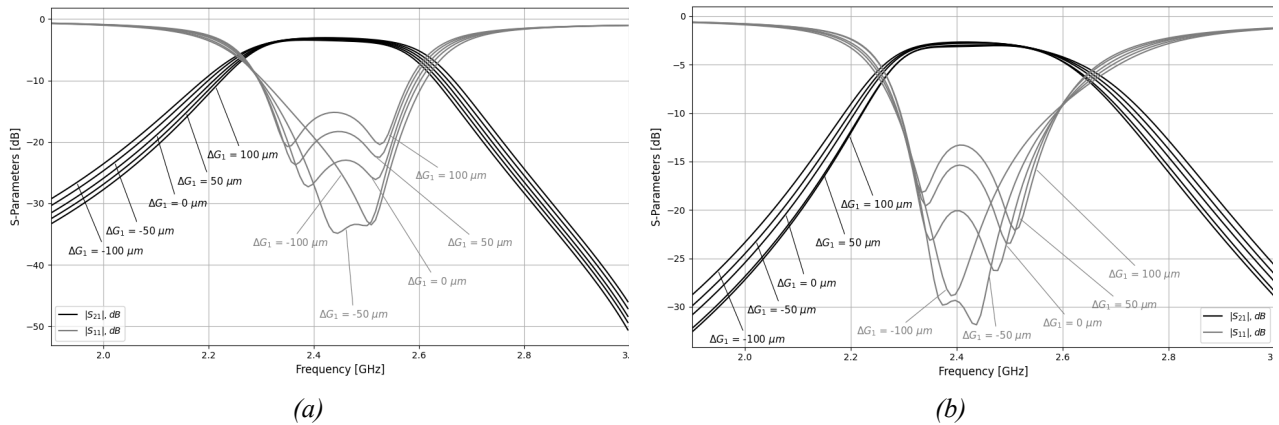


Fig. 6. Frequency responses of the filter for different values of gap width deviation ΔG_1 : a – Filter 1 ($w_r = 1\text{mm}$); b – Filter 2 ($w_r = 2\text{mm}$)

The $\pm 100 \mu\text{m}$ variation of ΔL_R parameter also leads to the frequency variation in the range of 30 MHz, whereas the variation of Δw_r parameter leads to the frequency variation in the range of 60 MHz.

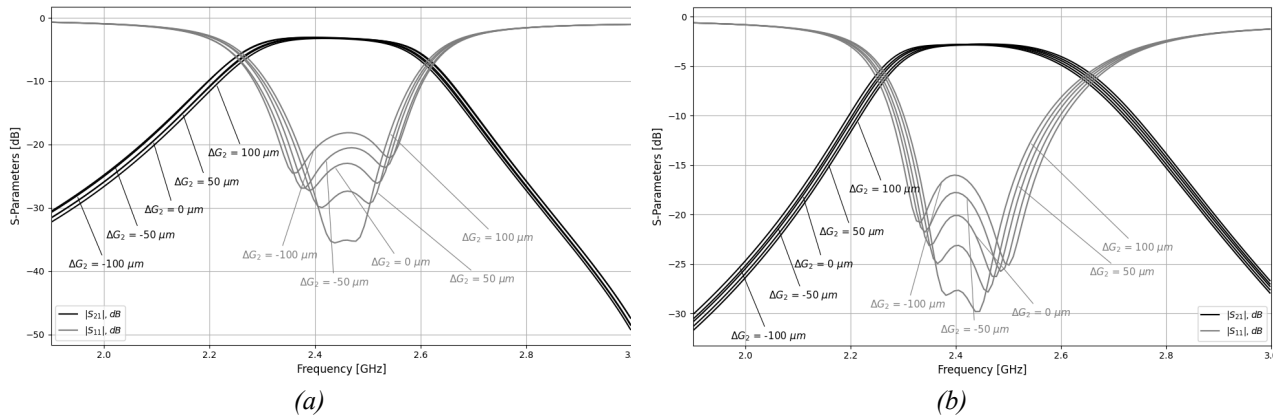


Fig. 7. Frequency responses of the filter for different values of gap width deviation ΔG_2 : a – Filter 1 ($w_r = 1\text{mm}$); b – Filter 2 ($w_r = 2\text{mm}$)

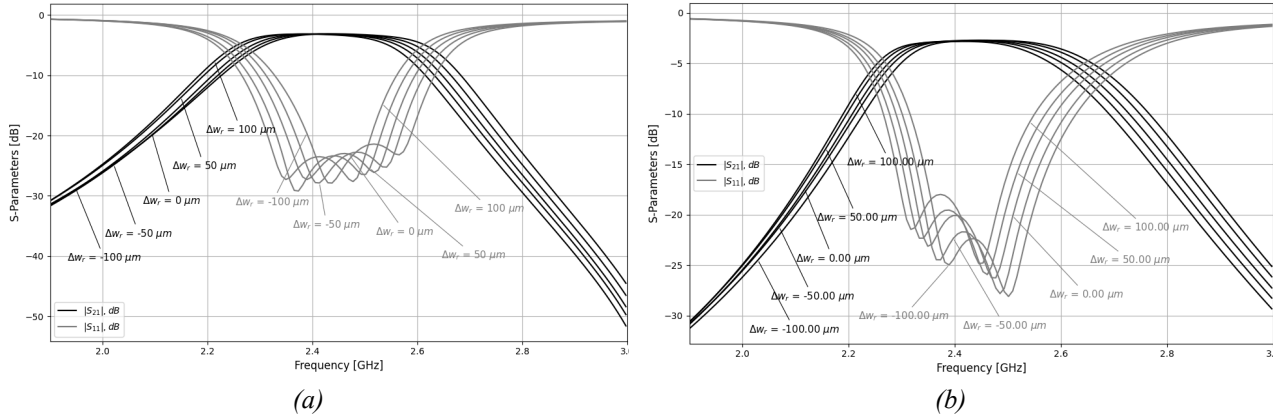


Fig. 8. Frequency responses of the filter for different values of resonator strip width deviation Δw_r : a – Filter 1 ($w_r = 1\text{ mm}$); b – Filter 2 ($w_r = 2\text{ mm}$)

6. Conclusions and prospects for further research

In this work, two compact fourth-order hairpin microstrip bandpass filters operating in the 2.4 GHz ISM band were designed, optimized, fabricated, and experimentally investigated. The considered filter structures were implemented on an FR4 substrate using a low-cost photolithographic manufacturing process and differed only in the width of the resonator conductors.

The comparison between the measured and simulated frequency responses demonstrated generally acceptable agreement between experimental results and full-wave electromagnetic modeling. The observed discrepancies can be largely attributed to manufacturing inaccuracies, including deviations of critical geometrical dimensions, as well as to the inherent variability of the dielectric properties of the FR4 substrate. These factors are difficult to represent accurately in an idealized numerical model and inevitably affect the electrical characteristics of the fabricated prototypes.

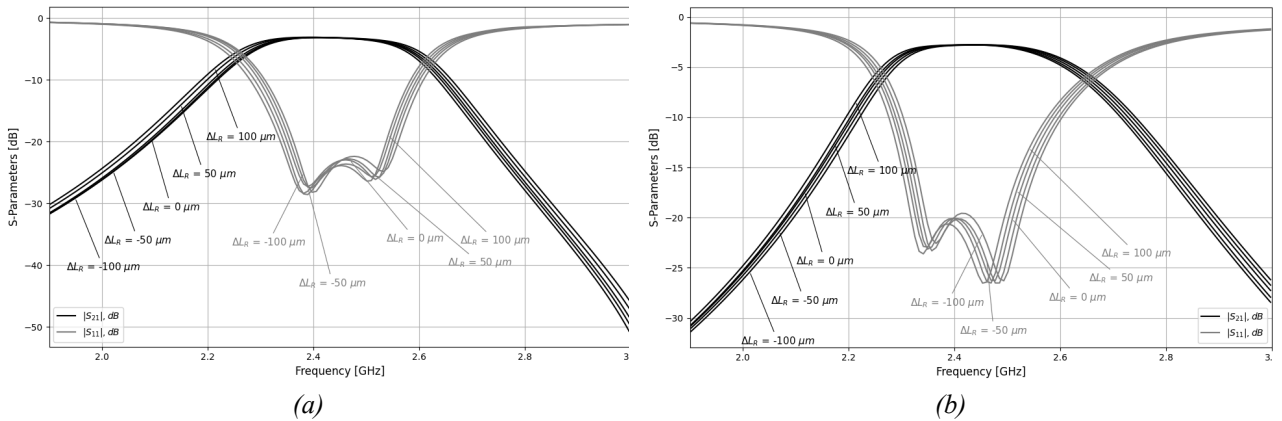


Fig. 9. Frequency responses of the filter for different values of resonator length deviation ΔL_r : a – Filter 1 ($w_r = 1\text{ mm}$); b – Filter 2 ($w_r = 2\text{ mm}$)

The performed sensitivity analysis confirmed that the frequency response of hairpin filters is strongly influenced by variations of key geometrical parameters. In particular, deviations in resonator length and coupling gaps may produce noticeable changes in the S_{11} and S_{21} characteristics, including passband displacement and degradation of matching performance. This result highlights the importance of considering manufacturing tolerances during the design stage, especially when low-cost fabrication technologies are employed.

At the same time, the comparative analysis of the two filter configurations showed that the change in resonator conductor width from 1 mm to 2 mm did not lead to a substantial difference in tolerance sensitivity. The investigated structures demonstrated approximately the same susceptibility to dimensional deviations of the most critical geometrical parameters. Therefore, within the considered range of resonator widths, conductor width cannot be regarded as a dominant factor affecting the robustness of the filter characteristics against manufacturing inaccuracies.

The obtained results also demonstrate that the considered design and fabrication approach can be successfully applied to the development of compact and inexpensive microwave filters operating at frequencies as high as 2.4 GHz. Despite the limitations associated with FR4 substrates and low-cost manufacturing processes, acceptable electrical performance can be achieved through careful electromagnetic modeling and optimization.

Since no significant increase in tolerance robustness was observed for wider resonators, the use of narrower resonator conductors appears to be a reasonable design choice. Narrower resonators allow larger coupling gaps to be employed while simultaneously reducing the overall dimensions of the filter, which is advantageous for compact microwave systems.

Further research may focus on a more comprehensive statistical evaluation of manufacturing tolerances using Monte Carlo analysis. Such an approach would allow the combined influence of multiple simultaneous dimensional deviations to be investigated and would provide a more realistic assessment of manufacturing yield. Another promising direction is the study of the influence of variations in substrate dielectric properties, including the spread of dielectric constant and substrate thickness, on filter performance. In addition, similar investigations may be extended to other planar filter topologies in order to determine whether the observed tolerance behavior is specific to hairpin structures or represents a more general characteristic of compact microstrip filters.

Declaration on artificial intelligence

Artificial intelligence was used for grammar checking and stylistic editing of the text. All scientific ideas, methodology, measurements, data analysis, and conclusions were developed by the author personally.

Conflict of interest

The author declares that there is no conflict of interest and confirms that during the preparation of this work there were no commercial, financial, or other relationships that could be construed as influencing the results of the study or their interpretation. The work was performed in accordance with the principles of academic integrity, ethical standards for conducting scientific research, and editorial policy requirements for preventing conflicts of interest.

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