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A MICROSTRIP FOLDED HAIRPIN RESONATOR FILTER FOR THE 2.4 GHz BAND

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Abstract—A compact fourth-order folded hairpin resonator microstrip bandpass filter is designed, fabricated, and experimentally validated for the 2.4 GHz band on an FR4 substrate. Analytical synthesis, full-wave finite-element simulation, and numerical optimization of the filter structure are performed. It is shown that the degradation of the filter characteristics due to the use of an FR4 substrate is relatively small compared with the simulated results and can be attributed to manufacturing inaccuracies. The measured and simulated S-parameters show satisfactory agreement: the prototype's center frequency is shifted by about 50 MHz, which is consistent with the sensitivity analysis, while the measured $|S_{11}|$ level within the passband is approximately 10 dB higher than the simulated value. A numerical sensitivity analysis of $\pm 100 \mu\text{m}$ deviations shows that the coupling gaps affect the return loss (a variation of 17 – 22 dB) far more strongly than the resonator length does (a variation of 4 dB and a 70 MHz frequency shift). Compared with a conventional hairpin filter of the same specification, the folded topology reduces the transverse filter dimension by approximately 30%.

Keywords—Folded hairpin resonator, microstrip bandpass filter, microwave filter, finite-element method, FR4 substrate, sensitivity analysis, electromagnetic simulation, industrial, scientific, and medical band.

I. INTRODUCTION

The continuous growth of wireless communication technologies has stimulated the demand for compact, low-cost, and high-performance microwave components operating in the industrial, scientific, and medical (ISM) frequency bands. In particular, the 2.4 GHz frequency range remains one of the most extensively utilized spectrum bands due to its application in Wi-Fi, Bluetooth, Internet of Things (IoT) devices, wireless sensor networks, telemetry systems, and various industrial communication platforms. Reliable operation of these systems requires effective suppression of unwanted signals and electromagnetic interference, making the development of compact microwave bandpass filters an important research and engineering task [1], [2].

Microstrip filters are among the most widely used filtering structures because of their planar topology, compatibility with standard printed circuit board fabrication technologies, ease of integration with active circuitry, and relatively low manufacturing cost. In many practical applications, particularly in portable and embedded wireless devices, the reduction of filter dimensions is an important design objective. However, miniaturization of microwave filters is usually accompanied by increased sensitivity to manufacturing tolerances, stronger parasitic electromagnetic coupling, and higher conductor and dielectric losses, especially when low-cost substrate materials are employed [3].

Hairpin filters, which are based on folded half-wavelength resonators, represent a well-established solution for achieving compact dimensions while maintaining satisfactory electrical performance [4]. By folding conventional parallel-coupled resonators into U-shaped structures, the occupied circuit area can be significantly reduced. Further miniaturization can be achieved by introducing additional bends into the resonator geometry, resulting in so-called folded hairpin resonators. In such structures, the open ends of the resonator are bent inward, allowing a substantial reduction of the overall filter footprint compared to conventional hairpin configurations. This feature makes folded hairpin filters attractive for modern wireless systems where strict size constraints must be satisfied.

Despite their compactness, folded hairpin resonators introduce additional design challenges. The reduction of physical dimensions leads to smaller coupling gaps between resonators and increased electromagnetic interaction among different parts of the structure. Consequently, the electrical characteristics of the filter become highly sensitive to variations in resonator dimensions and coupling distances. Furthermore, when low-cost FR4 substrate material is used, the relatively high dielectric losses and uncertainties in substrate parameters may significantly affect insertion loss, return loss, and center frequency accuracy. Therefore, the practical applicability of compact folded hairpin filters implemented on FR4 substrates

requires careful investigation through a combination of analytical synthesis, full-wave electromagnetic simulation, optimization procedures, and experimental validation.

Several studies have demonstrated the effectiveness of folded resonator configurations for filter miniaturization. However, the trade-off between compact dimensions, manufacturing tolerances, and achievable electrical performance remains insufficiently investigated, particularly for low-cost implementations in the 2.4 GHz ISM band. In practical designs, the extremely small coupling gaps required by compact folded structures may approach the technological limits of standard printed circuit board fabrication processes, making tolerance analysis especially important.

In this work, a fourth-order microstrip bandpass filter based on folded hairpin resonators for the 2.4 GHz frequency band is designed, optimized, fabricated, and experimentally investigated. The filter is implemented on a low-cost FR4 substrate and analyzed using full-wave electromagnetic simulation based on the finite-element method. The simulated and measured frequency responses are compared in terms of insertion loss and return loss characteristics. In addition, a numerical sensitivity analysis is performed to evaluate the influence of variations in coupling gaps and resonator lengths on the filter performance. The obtained results provide an assessment of the feasibility of implementing highly compact folded hairpin filters using standard low-cost PCB technology and may be useful for the development of microwave filtering components for wireless communication systems.

II. REVIEW OF LATEST ARTICLES

Folded hairpin resonator filters are widely used and frequently investigated in the scientific literature. Owing to their compact geometry, these filters typically feature relatively small coupling gaps, which limits their practical implementation at higher frequencies. Consequently, most reported designs operate in the frequency range from approximately 0.9 to 2.5 GHz. In this frequency range, folded hairpin filters are often implemented on specialized low-loss microwave substrates in order to minimize dielectric losses and ensure predictable electrical performance.

In [5], the design and synthesis of a fifth-order folded hairpin resonator filter with a center frequency of 2.2 GHz are investigated in detail. The paper provides a comprehensive description of the filter synthesis procedure and employs a specialized high-frequency laminate as the substrate material. A prototype of the filter is fabricated, and the

calculated S_{11} and S_{21} characteristics are compared with the experimental results. Despite the use of a dedicated high-frequency substrate, the measured S_{21} characteristic exhibits deviations from the calculated response of up to 10 dB within the passband, demonstrating that the practical realization of a compact folded hairpin filter may involve significant discrepancies between simulated and measured characteristics even when a low-loss microwave laminate is employed.

A diplexer consisting of two third-order folded hairpin resonator filters with center frequencies of 0.9 GHz and 1.8 GHz is presented in [6]. A specialized high-frequency laminate is also used as the substrate, and the simulated and measured S-parameters are compared. The reported results also demonstrate noticeable discrepancies, with deviations in the return loss reaching approximately 10 dB. These results further indicate that the use of a high-quality microwave substrate does not by itself eliminate the differences between the simulated and experimentally measured characteristics of compact folded hairpin structures.

FR4 is also frequently used as a low-cost substrate for this type of filter. In [7] and [8], fourth- and third-order folded hairpin resonator filters, respectively, are investigated at approximately 2.5 GHz. Both designs are implemented on FR4 substrates; however, the main focus of these studies is the suppression of higher-order harmonics using additional structural elements. The comparison of simulated and measured S-parameters presented in [7] does not provide sufficient information for a quantitative assessment of the discrepancy between the two characteristics, whereas [8] reports only simulation results.

A fourth-order folded hairpin resonator filter with cross-coupling for operation at approximately 0.9 GHz is presented in [9]. The filter is implemented on an FR4 substrate; however, only experimental results are reported. Consequently, the available data do not allow the discrepancy between the measured and simulated characteristics to be evaluated.

The literature devoted to the synthesis and implementation of folded hairpin resonator filters provides relatively limited information on the sensitivity of their electrical characteristics to small variations in the key geometrical parameters. This issue is particularly important because the high degree of miniaturization achieved by folded hairpin structures is accompanied by small coupling gaps between adjacent resonators. These gaps can be comparable to the dimensional tolerances achievable with standard PCB manufacturing technologies. As a

result, even relatively small deviations in the fabricated geometry may lead to significant changes in the coupling coefficients and, consequently, to degradation of the filter frequency response.

For a compact folded hairpin filter implemented on an FR4 substrate at frequencies above 1 GHz, the deviation of the experimental characteristics from the simulated response may be caused not only by manufacturing inaccuracies but also by the electrical properties of the substrate material, which is not specifically intended for high-frequency microwave applications. From this perspective, it is important to determine whether the observed degradation of the fabricated filter characteristics can be explained primarily by the sensitivity of the structure to geometrical variations within typical manufacturing tolerances. This question is particularly relevant for assessing the feasibility of using inexpensive FR4 and conventional PCB manufacturing technologies for highly compact folded hairpin filters, but it has not been sufficiently addressed in the existing literature.

III. PROBLEM STATEMENT

The review of publications shows that, although folded hairpin resonators are well established as a means of reducing filter dimensions, their practical realization on low-cost FR4 substrates has not been investigated in combination with an experimentally validated tolerance sensitivity analysis. Because the folded topology requires coupling gaps considerably narrower than those of a conventional hairpin filter of the same electrical specification, its response can be expected to be more sensitive to the dimensional deviations inherent to standard low-cost PCB fabrication (typically ± 0.1 mm) and to the wide uncertainty of the FR4 dielectric constant ($\epsilon_r = 3.8 \dots 4.8$).

The problem addressed in this work consists of the following issues:

- to determine, for a fabricated folded hairpin filter prototype, the level of agreement that can be achieved in practice between the full-wave electromagnetic simulation and the measured S-parameters when a low-cost FR4 substrate is used;
- to quantitatively determine which geometrical parameters of the folded hairpin resonator – the coupling gaps or the resonator length – have the greatest influence on the filter response under dimensional tolerances typical of standard PCB manufacturing;
- to determine whether the observed degradation of the experimental S_{11} and S_{21}

characteristics relative to the simulated ones can be attributed to manufacturing inaccuracies.

The parameters of the filter 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 filter was designed, is 2400...2483 MHz. The pass band of the filter was taken 300 MHz, which is higher than the operation band.

The filter is realized on FR4 laminate with dielectric constant $\epsilon_r = 4.4$, substrate thickness $h = 1.5$ mm, and strip thickness $t = 2.54$ μm ; the dissipation is defined by $\tan \delta = 0.02$.

IV. PROPOSED METHOD

The following steps were defined to address the problem of the study.

- To design a folded hairpin microstrip bandpass filter according to the specification using analytical synthesis procedures, full-wave electromagnetic simulation, and numerical optimization techniques.
- To fabricate a physical prototype of the designed filter on an FR4 substrate using a photolithographic printed circuit board manufacturing process.
- To measure the frequency responses of the fabricated prototype 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 filter and the numerical model.
- 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 length (L_R parameter in Fig. 1), and coupling gaps (G_1 and G_2 parameters in Fig. 1) on the return loss (S_{11}) and insertion loss (S_{21}) characteristics are analyzed.

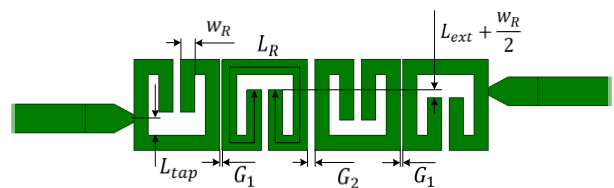


Fig. 1. Geometry parameters used in optimization and sensitivity analysis

- To compare the tolerance sensitivity of the filter 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.

V. RESULTS

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 [4]. 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.

2) *Initial Calculation of Resonator Dimensions.* The preliminary dimensions of the folded hairpin resonators are obtained from analytical microstrip transmission-line models.

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.

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 $Q(L_{\text{tap}})$ 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

$Q(L_{\text{tap}})$ 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 model for the simulation is shown in Fig. 2.

9) *Preliminary Sensitivity Analysis.* Prior to automated optimization, a manual investigation of the most critical geometrical parameters is performed. This stage allows to allocate the geometrical parameter values closer to the optimum, which decreases the number of iterations during the optimization.

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. The optimization of the filter was performed using the Nonlinear Programming by Quadratic Lagrangian (NLPQL) algorithm [11].

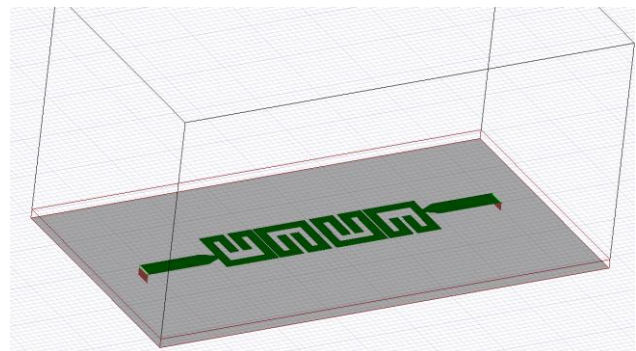


Fig. 2. Filter model for the full-wave electromagnetic simulation

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 following parameters, shown in Fig. 1, were included into the optimization process: gaps between

the resonators G_1 and G_2 , edge resonators extension L_{ext} , resonator length L_R and taper shift L_{tap} .

The design procedure described above allows to determine geometric 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:

- $|S_{11}| \leq -19$ dB in frequency range $f = 2.38 \dots 2.53$ GHz;
- $|S_{21}| \leq -15$ dB in frequency range $f = 2.8 \dots 3.27$ GHz;
- $|S_{21}| \leq -15$ dB in frequency range $f = 1.8 \dots 2.13$ GHz.

Using the 3D model, the prototype of the filter was fabricated as shown in Fig. 4. The dimensions of the filter are $62 \times 27 \text{ mm}^2$.

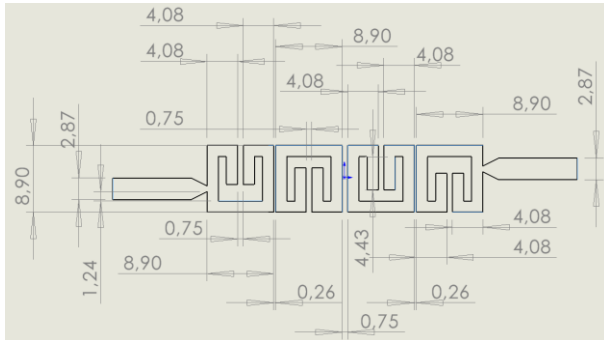


Fig. 3. Filter topology and its dimensions (all values are given in millimeters)

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



Fig. 4. Filter prototype

In Figure 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.

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.

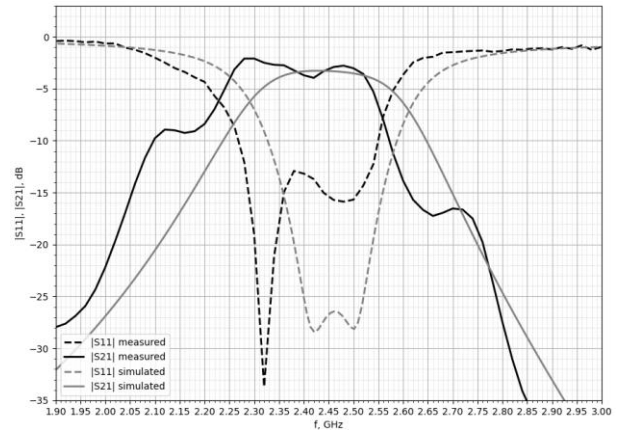


Fig. 5. Simulated and measured frequency responses of the filter

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 $\Delta L_R = L_R - L_{R0}$ from the nominal resonator length, where L_{R0} is the nominal value, extracted from the full-wave simulation; the graph is shown in Fig. 8.

All the values of the ΔG_1 , ΔG_2 , ΔL_R parameters were selected to be $\pm 100 \mu\text{m}$ around the nominal values shown in Fig. 1.

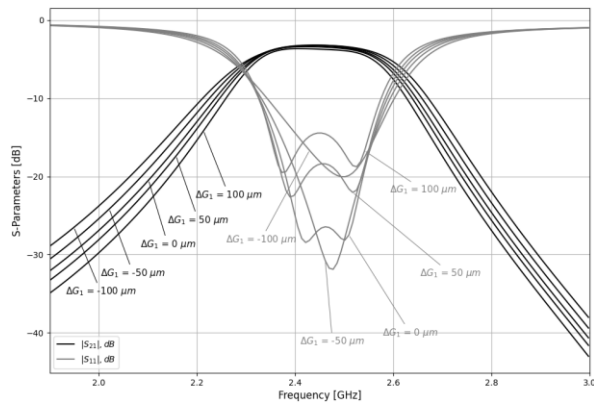


Fig. 6. Frequency responses of the filter for different values of gap width deviation ΔG_1

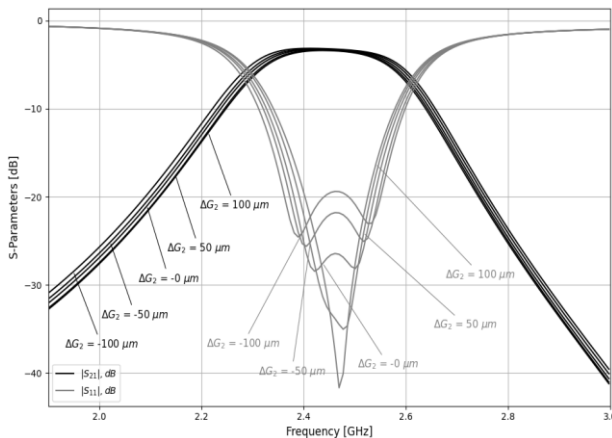


Fig. 7. Frequency responses of the filter for different values of gap width deviation ΔG_2

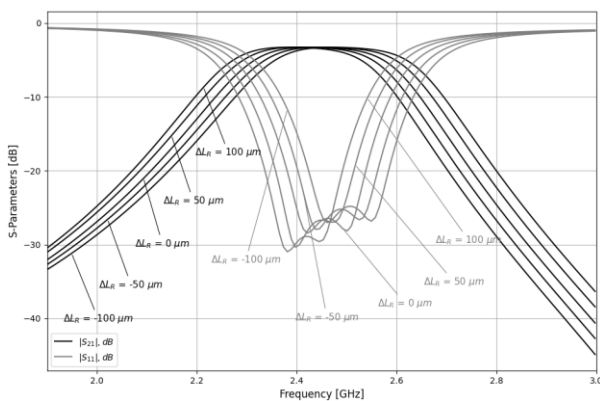


Fig. 8. Frequency responses of the filter for different values of resonator length deviation ΔL_R

As it can be seen from Fig. 6 – 8, 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 maximum return loss $|S_{11}|$ value within the passband changes in the range of approximately 22 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 4 dB for the ΔL_R parameter varying in the $\pm 100 \mu\text{m}$ range. The $\pm 100 \mu\text{m}$ variation of ΔL_R parameter also leads to the frequency variation in the range of 70 MHz.

VI. CONCLUSIONS

Experimental validation of a fabricated fourth-order folded hairpin microstrip bandpass filter for the 2.4 GHz ISM band confirms that the proposed design methodology, which combines analytical synthesis, full-wave electromagnetic simulation, and numerical optimization, provides an efficient approach to design compact wireless-band filters realized entirely with standard low-cost FR4 printed circuit board technology.

The comparison between simulated and measured frequency responses demonstrated satisfactory agreement, confirming the validity of the proposed design methodology. The center frequency of the fabricated prototype is shifted by approximately 50 MHz with respect to the simulated value; this shift lies within the range of frequency deviations attributable to manufacturing inaccuracies established by the sensitivity analysis (Fig. 8). Among the measured characteristics, the return loss (S_{11}) exhibits the most significant degradation relative to simulation, with the measured $|S_{11}|$ level within the pass band approximately 10 dB higher than predicted, which is consistent with the variations of this parameter due to inaccuracies in the realization of gaps G_1 and G_2 shown in Fig. 6 and Fig. 7.

Although the use of FR4 substrate inevitably introduces additional dielectric losses compared with low-loss microwave laminates, and the achievable return loss is correspondingly degraded relative to the simulated design, the obtained filter characteristics remain suitable for the majority of telecommunications equipment nodes, where compact size and low manufacturing cost are of primary importance.

The comparison of the proposed filter with the conventional hairpin filter investigated in [12] shows that folding the resonators reduces the transverse filter size by approximately 30% without introducing additional degradation of the measured electrical characteristics relative to the FEM predictions.

A numerical sensitivity analysis showed that the electrical performance of the folded hairpin filter is strongly influenced by variations in resonator

lengths and coupling gaps. Among the investigated parameters, the coupling gaps exhibited the greatest impact on the insertion loss, return loss, and center frequency, confirming that manufacturing tolerances represent one of the critical factors in the practical realization of highly compact microstrip filters. It can be concluded that the observed degradation of the experimental S11 and S21 characteristics relative to the simulated ones can be attributed to manufacturing inaccuracies.

The scientific novelty of the obtained results consists in establishing, for a folded hairpin resonator topology, a quantitative relationship between controlled geometrical deviations ($\pm 100 \mu\text{m}$) of the coupling gaps and the resonator length and the resulting changes in the return loss, insertion loss, and center frequency, with this relationship confirmed experimentally on a fabricated prototype rather than derived from simulation alone.

The practical significance of the results is that they provide a quantitative basis for allocating fabrication tolerances in compact folded hairpin filters realized on low-cost FR4 substrates: because the coupling gaps G_1 and G_2 impact the return loss more strongly than the resonator length L_R does, tighter dimensional control should be prioritized for the coupling gaps during photolithographic PCB fabrication, while comparable deviations in resonator length can be tolerated with a substantially smaller effect on the filter response.

The obtained results indicate that folded hairpin resonators provide an effective solution for achieving substantial size reduction while maintaining acceptable electrical performance on inexpensive FR4 substrates.

Future work may focus on further reduction of insertion loss through the use of low-loss substrate materials, investigation of higher-order filter topologies with improved selectivity, and the development of tolerance-aware optimization techniques capable of increasing the robustness of compact folded hairpin filters with respect to manufacturing variations.

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I. В. Трубаров. Мікросмушковий фільтр на основі U-подібних резонаторів зі складеними плечима для діапазону 2.4 ГГц

Розроблено, виготовлено та експериментально досліджено компактний мікросмушковий смугово-пропускний фільтр четвертого порядку на основі U-подібних резонаторів зі складеними плечима для діапазону 2,4 ГГц на підкладці FR4. Виконано аналітичний синтез, трьохвимірне моделювання методом скінченних елементів та чисельну оптимізацію конструкції фільтра. Показано, що погіршення характеристик фільтра внаслідок використання підкладки FR4 є відносно незначним у порівнянні з результатами моделювання та може бути пояснене варіаціями розмірів в межах технологічних допусків. Виміряні та змодельовані S-параметри демонструють прийнятну узгодженість: центральна частота прототипу зміщена приблизно на 50 МГц, що узгоджується з результатами аналізу чутливості, тоді як вимірний рівень ($|S_{11}|$) у смузі пропускання приблизно на 10 дБ вищий за отриманий в результаті моделювання. Чисельний аналіз чутливості для відхилень ± 100 мкм показав, що зазори між резонаторами значно сильніше впливають на зворотні втрати (розкид складає 17–22 дБ), ніж довжина резонатора (розкид 4 дБ і зміщення частоти на 70 МГц). Порівняно з фільтром на основі звичайних U-подібних резонаторів з аналогічною специфікацією запропонована топологія з U-подібними резонаторами зі складеними плечима забезпечує зменшення поперечного розміру фільтра приблизно на 30 %.

Ключові слова: U-подібний резонатор із складеними плечима, мікросмушковий смугово-пропускний фільтр, мікрохвильовий фільтр, метод скінченних елементів, підкладка FR4, аналіз чутливості, електромагнітне моделювання, ISM-діапазон.

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Напрямок наукової діяльності: мікрохвильові прилади, решітки діелектричних резонаторів, моделювання електромагнітних явищ.
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