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MODELING OF BANDPASS FILTERS WITH ATTENUATION POLES USING PARALLEL COUPLING CHANNELS

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Background. Microwave filters are critical components in modern communication systems, playing a fundamental role in signal processing by allowing specific frequency bands to pass while attenuating unwanted frequencies. Over the years, significant advancements have been made in the design and development of various types of microwave filters, including directional, microstrip, and multi-resonator filters. These filters are widely used in radar, satellite communications, and wireless networks, where high performance and precise frequency control are essential.

Objective. This paper is dedicated to reviewing various microwave filters that were constructed developed or analysed by the team, including directional filters, microstrip filters with attenuation poles, and multi-resonator filters. The studies focus on investigating their unique properties, such as the formation of attenuation poles, metamaterial characteristics, and the effects of resonator coupling on filter performance. New Python-based software realization for modelling different filters six resonators, four resonators, and two resonators were developed and frequently used.

Methods. Electrodynamics simulations using software tools like CST Studio Suite, AWR Microwave Office, and LabVIEW, modelling filters using equivalent circuit models and bridge circuits. Use of microstrip lines, circular resonators, and dielectric resonators to construct and analyse different filter configurations. Analysis of energy propagation paths, resonator coupling, and transmission characteristics to optimize filter design.

Results: Various structures were researched like Microwave Directional Filters, Microstrip Resonator Filters with 2, 4, 6 resonator, their structures and characteristics were analysed, New python-based software that allows modelling resonance curves using corresponding parameters for filters with 2, 4, 6 resonators. The parameters of the scattering matrix of a bridge quadrupole were expressed in an analytical form and were used for Python based program.

Conclusions: the research presented across these publications contributes significantly to the development and understanding of advanced microwave filter designs. The article reveals various resonator-based filters, including directional, microstrip, and multi-resonator filters, these studies have highlighted key performance enhancements achievable through resonator coupling, metamaterial properties, and the introduction of attenuation poles. The use of advanced simulation tools, such as CST Studio Suite, AWR Microwave Office, and LabVIEW, allowed for accurate modelling and validation of theoretical designs. The introduction of Fano resonances and trapped modes in filters demonstrated improvements in selectivity and attenuation characteristics, which are critical for modern communication systems. Trapped modes manifest as attenuation poles, resulting from the interference of even and odd oscillations. This is evidenced by the presence of two independent energy pathways, along which these interfering oscillations propagate. With appropriate design parameters (such as resonator coupling coefficients and resonance frequencies), a complete energy exchange between resonators can occur at a certain frequency, in a direction perpendicular to the primary energy flow from input to output. The design and properties of directional filters based on circular resonators and dielectric resonators were described. These filters have "metamaterial" properties and are widely used in modern microwave technology. The characteristics of bandpass and rejector filters, as well as the characteristics of the filters formed by two microstrip resonators and resonators connected to each other, are given. It is important to emphasize the phenomena of "Fano resonances" observed in these filters, which arise as the interference of oscillations from individual resonators.

Keywords: *microwave filters; resonators; attenuation poles; directional filters; microstrip filters; fano resonances; metamaterials; electrodynamics simulation; circuit modelling; Bandpass filters.*

INTRODUCTION

The bandpass filter is used most often and is designed to pass only a certain frequency band, cutting off all other components below and above this band. It is a mandatory component for all data transmission systems, since the separation of the frequencies used by them is often very insignificant, and this can lead to the occurrence of interference noise between them.

The bandpass filter is designed to isolate the working frequency band (receiving and transmitting) and delay adjacent frequencies with the suppression of their parasitic elements.

Bandpass filters continue to be extremely popular functional units of communication and telecommunications systems. For example, in analog-to-digital converters, input spectrum limiters are implemented on their basis. Leading microelectronic companies in the world today serially produce digital potentiometer microcircuits, which are used in the tasks of adjusting the parameters of active RC filters. With all the diversity, existing PFs need to improve the main parameters characterizing their properties when adjusting the pole frequency, pole attenuation and transmission coefficient in the passband.

To be an ideal bandpass filter, it must filter or attenuate certain frequencies that even lie within the band to eliminate noise.

Bandpass filters are also known as second-order filters because of the presence of two capacitors, reactive components in a single circuit. One capacitor is in the high-pass circuit and the other capacitor is in the low-pass circuit.

Different Types of Bandpass Filters These bandpass filters are mainly divided into two types of filters. They are wide-band filter, narrow-band filter, wide-band filter.

A bandpass filter with attenuation poles is a type of filter that allows signals within a specific frequency range (the passband) to pass through while attenuating signals outside this range (in the stopbands).

The attenuation poles are frequencies outside the passband where the signal is significantly attenuated, often to the point of near or complete suppression. These poles result in deep nulls or sharp drops in the transmission response of the filter, enhancing its ability to block unwanted frequencies.

ATTENUATION POLES IN BANDPASS FILTERS WITH EVEN-END ODD MODES

The experiment was started by analysing both the theoretical and experimental properties of a band-pass filter featuring attenuation poles created by a half-wave resonator, which is short-circuited at its midpoint. Simulations were performed using Microwave Office and LabVIEW software tools. The strong correlation between the theoretical predictions and experimental outcomes demonstrates the accuracy and efficiency of the chosen models [1].

Fig. 1 presents a photograph of a microstrip filter composed of an open-circuit line and two parallel resonators—one short ("half-wave") and the other long ("wave"). A similar filter design with adjustable bandwidth was explored in [2].

Fig. 1 Microstrip bandpass filter with two parallel resonators of different types. The long resonator was short-circuited with a 2 mm loop in the middle part.

As was noted in [3], when a short-circuit (SC) loop is placed at the center of a strip resonator, its behaviour mimics that of a two-resonator filter. In the design being analysed, a dielectric substrate with a permittivity of $\varepsilon = 9.8$ and a thickness of 2 mm was used. At the resonator's operating frequencies (around 1.5 GHz), the SC acts as an inductance, influencing the resonant frequencies of the even and odd oscillation modes differently [4].

Fig. 2 presents the experimental filter characteristics (Fig. 2a) alongside those calculated using the Microwave Office software (Fig. 2b) across the 0.5 to 6 GHz frequency range. Notably, attenuation poles (p1 and p2 in Fig. 2b), which are absent in the short-circuited middle resonator filter described in [3], can be observed.

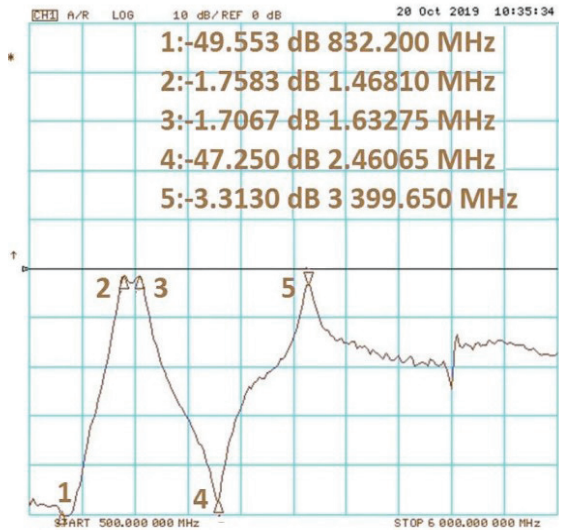


Fig. 2. Experimental characteristics of the Microstrip filter from Fig. 1.

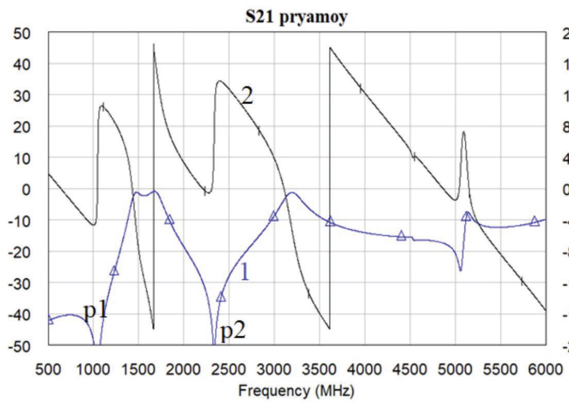
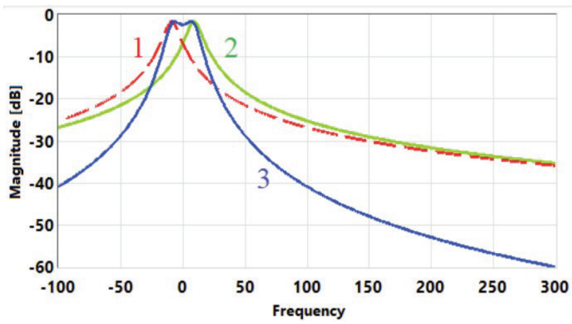


Fig. 3. Modelled characteristics of the strip filter from Fig. 1.

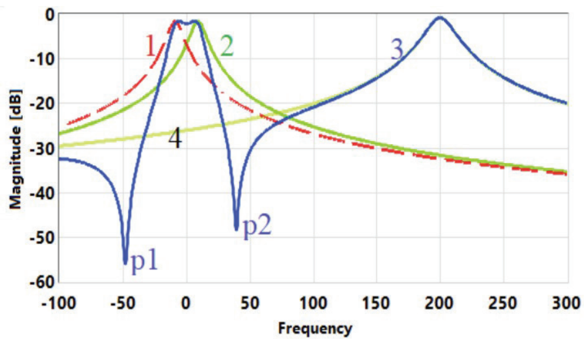
The presence of the attenuation poles is attributed to the short "half-wave" resonator, which has a resonant frequency of approximately 3.4 GHz. Since the resonators in this configuration are not coupled but connected in parallel, there are at least two independent energy transfer channels. Consequently, a bridge equivalent circuit can be applied to model the filter's S-parameters [5].

New algorithm was developed in LabVIEW to model bridge filters, enabling clear visualization of the amplitude and frequency characteristics of both individual branches and the overall quadrupole on a graph. In Fig. 4 (a), the frequency dependencies of S21 for even (curve 1) and odd (curve 2) modes are shown while curve 3 represents the total transfer coefficient characteristic of the quadrupole, which corresponds to the short-circuited "long" resonator. The frequencies in Fig. 4 are presented in relative units.

If another oscillation is introduced to simulate the short resonator from Fig. 1 (with its resonant frequency corresponding to $f_{rel} = 200$ in Fig. 3b), the attenuation poles appear at frequencies near regions p1 and p2, as shown in Fig. 4 (b). The reason for the formation of the poles is the different “signs” of the reactances of the “loops” of oscillations 1, 2, and 3. An abrupt change in phase (curve 2 in Fig. 3.) indicates a change in the sign of reactivity in the pole region (“antiresonance”).



a)



b)

Fig. 4. Simulated characteristic of filter in LabVIEW

Curves 1 and 2 in both (a) and (b) represent the characteristics of the in-phase and antiphase oscillations, respectively. Curve 3 illustrates the overall characteristic of the filter. Curve 4 highlights the low-frequency slope of the antiphase oscillation, centered at a frequency of $f_{rel} = 200$ If the frequency of the second resonator is tuned, as was done, for example, in [1], then the position of the attenuation poles can be controlled.

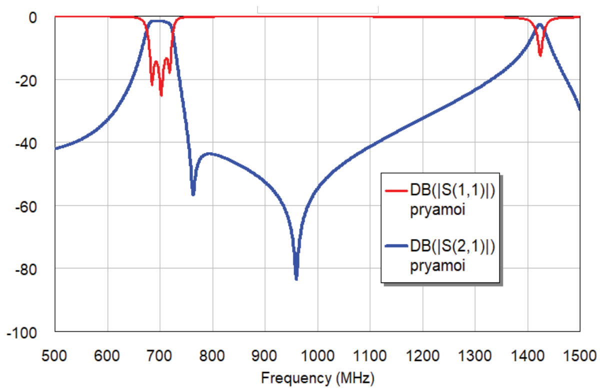
Such results correspond with experimental which proves new algorithm high level of uniformity. Further work on subject will create possibilities to achieve bandpass filter with better selectivity.

ATTENUATION POLES IN MICROWAVE THREE-RESONATOR BANDPASS FILTERS

As work continuous three-resonator microwave filters with attenuation poles were considered as the next step. Different mechanisms of formation of attenuation poles were investigated and models of such filters on the basis of bridge quadrupoles are proposed. [6] Analysis was carried out with the use of universal physical notions - natural, loaded and external quality factors of resonators and their mutual detuning

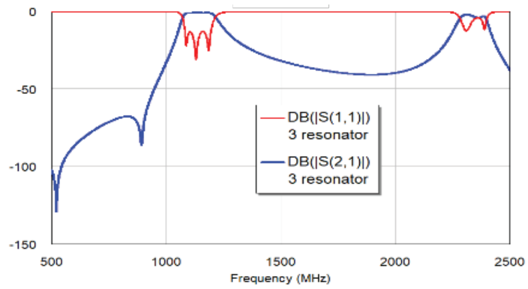
Information was found about the development of microwave filters with attenuation poles that is extensively documented in [7]. Among the most common designs are filters with elliptical characteristics, where attenuation poles arise from additional cross-couplings between resonators [8-10]. However, as demonstrated in [11], this is not the only method to generate attenuation poles. Another way is to use parallel communication channels with resonators of different quality factors. Previously, similar structures were used in 4-pole lattices with lumped-element resonators. As is known from [13], bridge filters are more versatile structures than ladder ones, they can be used for modelling an arbitrarily complex combination of resonators that form a particular filter.

In general, when inductive or capacitive couplings are used between resonators, the number of poles in an n-resonator filter can be as high as n-1 [10]. To illustrate this, Fig. 1a and 1b display the characteristics, while Fig. 5 (c) and 5 (d) show the topologies of the three-resonator filters discussed in [14].



a)

The attenuation poles in the three-resonator filters can also be located on opposite sides of the passband.



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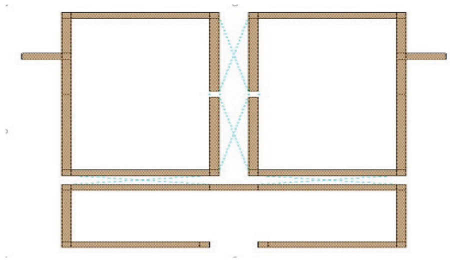
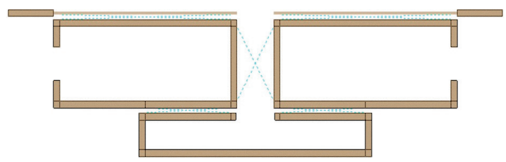
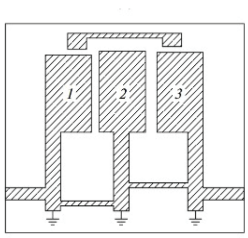


c)

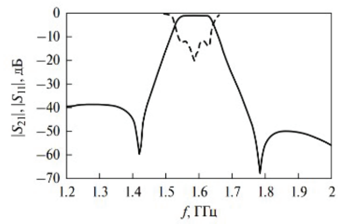


d)

Fig. 5. a), b) The characteristics of the three-resonator filters. c), d) topologies of the three-resonator filters.



a)



b

Fig. 6. a) Topology of a microstrip filter with additional coupling between the input and output resonators. Fig. 6 b) transmission coefficients S21 and reflection coefficients S11 of said filter [8].

As known from [11] two-resonator filters and three-resonator filters can also be considered in terms of own and loaded Q-factors, coupling coefficients and mutual detunings, which for series and parallel resonators are defined as [15] and shown as (1) (2) (3):

$$K_i = \frac{Q_{0i}}{Q_{ei}} \quad (1)$$

$$Q_{os} = \frac{\omega_0 \cdot L}{R_s} = \frac{1 \cdot R_s \cdot C}{\omega_0} \quad (2)$$

$$Q_{op} = \frac{R_p \cdot L}{\omega_0} = \omega_0 \cdot R_p \cdot C \quad (3)$$

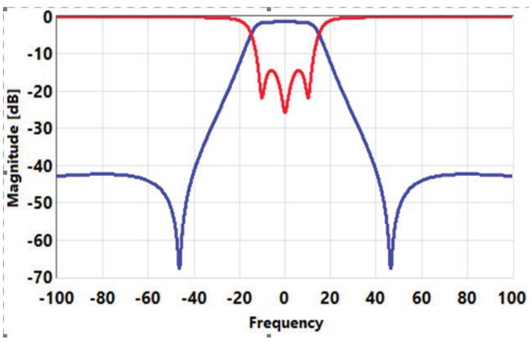
Where Q_{0i} unloaded Q-factor of “i” resonators, Q_{ei} – external Q-factor of “i” resonators, R_p и R_s – the loss resistance of the parallel and series resonators.

Fig. 3 a) shows the characteristics of a three-resonator filter that modelling the filter of Fig. 2 a) in terms of coupling coefficients and generalized detuning. Next modelling parameters were used (4) (5) (6).

$$K_1 = K_3 = 5, K_2 = 10 \quad (4)$$

$$b_1 = b_3 = 1.1 \quad (5)$$

$$a_1 = -a_3 = 14, a_2 = 0 \quad (6)$$



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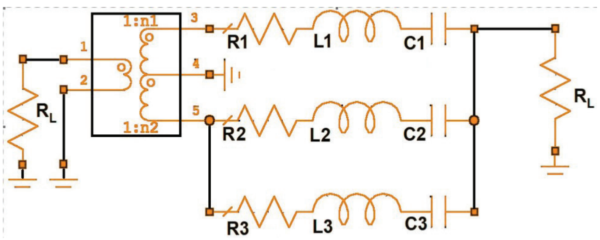


b)

Fig. 7. a) The characteristics of a three-resonator filter c) Schematic of a three-resonator filter.

b_i corresponds to relative quality factor and a_i to detuning - see formulas from [11]. As can be seen, the characteristics of Fig. 6 b) and 7 a) are quite coincide.

By knowing the coupling coefficients, relative Q-factors, and detuning values, the transition to the bridge circuit for the three-resonator filter in Fig. 3c, which exhibits similar characteristics to those in Fig. 3b, can be easily performed. The simulation was conducted using the AWR software package (academic licenses were obtained through the Cadence Academic Network of the university).

In this setup, an external load resistor was included. During the transition from an unbalanced bridge circuit to a circuit with a center-tapped transformer, as shown in Fig. 3c, accounting for the transformation of arm resistances [12], the following relationships must be satisfied (7) (8).

$$K_s = 2 \cdot R_L / R_S \quad (7)$$

$$K_P = R_P / 2 \cdot R_L \quad (8)$$

It`s important to add that small discrepancies in the characteristics of the filters in Fig. 4 and 5 are caused only by the fact that the main idea was, to demonstrate the possibilities of designing microwave filters with attenuation poles using a 4-pole lattice and not an exact approximation.

MICROSTRIP 4-RESONATOR FILTERS WITH ATTENUATION POLES

Modelling four-resonator filters using the electrodynamics method and bridge circuits [16] was analysed next. Resonators can be implemented using a variety of technologies, including microstrip lines, which are popular due to their planar structure and ease of integration with printed circuit boards [17] it help to lower cost by mass production.

These filters can also be reproduced on focused elements. The filter pictured below was modelled by CST Studio Suite software. It has the next parameters: dielectric permeability ε = 2.8, substrate thickness = 2 mm, strip thickness = 5.3 mm, tan δ = 0.001.

In Fig. 10 the gain of S21 where Fano resonance has formed, exhibiting anomalously high attenuation of about -45dB and -30dB at the peaks and a narrow resonant characteristic around f = 0.82 GHz.

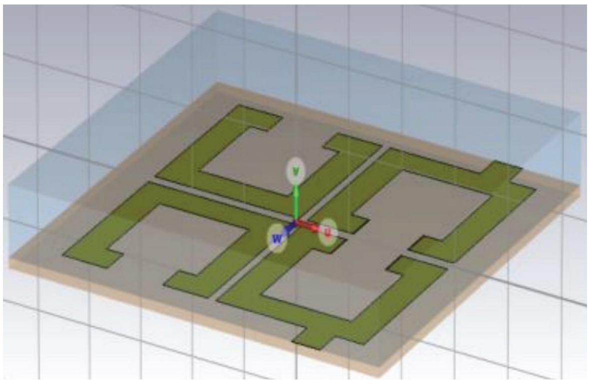


Fig. 8. Topology of the CST Studio Suite four-resonator filter.

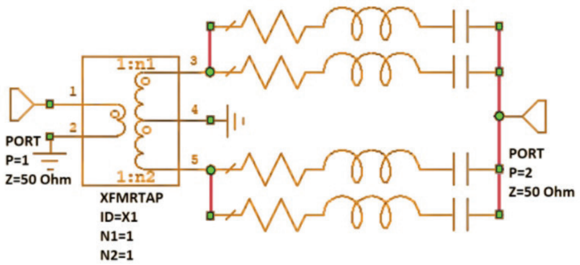


Fig. 9.AWR equivalent circuit.

Metamaterials are usually diagrams of equivalent chain models. Fig. 9 shows the equivalent circuit modelled in the AWR Microwave Office software. In this case, a series RLC circuit is connected to the two arms of the transformer [18]. The simulation helped to build a microstrip filter not only with microstrips, but also with a bridge filter circuit. Fig. 10 shows the result of the scheme. Bandwidth from 780 to 860 MHz. Attenuation is up to -40dB at peaks. The poles are formed because there are two paths of energy propagation that "intervene" in the region of zero transmission and create a "quasi-trapped" mode or "trapped" mode [19].

In standard 4-resonator filters, adding coupling between the 1st and 4th resonator leads to the formation of attenuation poles.

Once the data are analysed, it is evident that there is no significant fluctuation in the reflection coefficient in the vicinity of the poles. It is therefore only possible to ascribe the dramatic decrease in the transmission coefficient to the emergence of trapped modes at these frequencies within the structure.

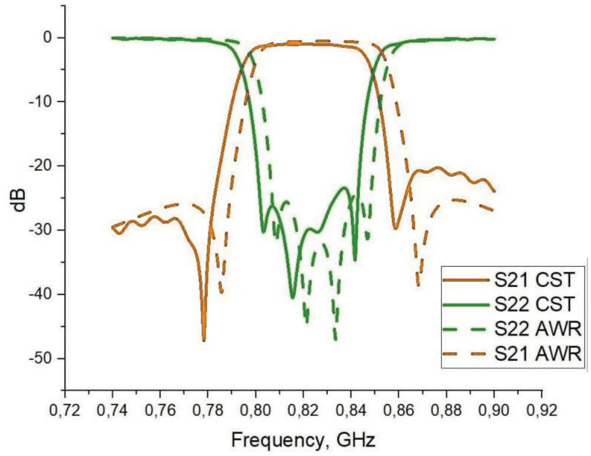


Fig. 10. Characteristic of the four-resonator filter in CST Studio Suite and AWR.

These modes' energy "circulates" along the closed channel 1-2-3-4-1 instead of radiating outward, as illustrated in Fig. 11. The formation and maintenance of the trapped modes are facilitated by adding connections between the resonators, which makes it possible to create conditions for the formation and maintenance of these trapped modes.

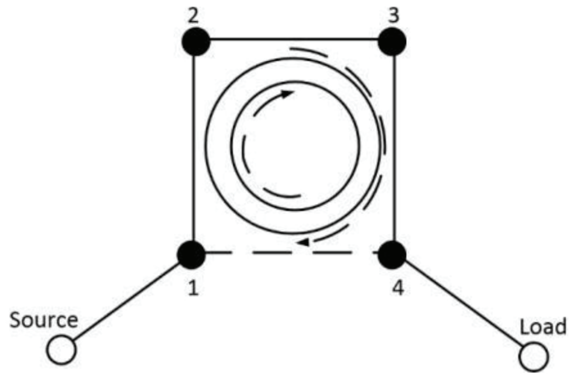


Fig. 11. Trajectory of propagation of trapped modes in a four-resonator filter.

The addition of extra connections between resonators allows the creation of trapped modes and also enables control over their properties. By adjusting the characteristics of these connections, the frequency behaviour of the trapped modes can be modified, offering significant flexibility in tuning the structure's properties. As a result, understanding the interaction between resonators and their impact on trapped mode formation is crucial for designing new devices with enhanced performance [20].

Next construction and properties of directional filters based on circular resonators and dielectric resonators and simulated metamaterial properties of directional filters in modern microwave technology were analysed [21].

In modern microwave technology, directional filters—also known as directional filters with specific propagation characteristics—are widely utilized, as discussed in [22]. Renewed interest in these devices has arisen due to their "metamaterial" properties.

Fig. 1a illustrates the waveguide structure of a directional filter from [23], which consisted of circular resonators excited by apertures placed within the circular polarization regions of rectangular waveguides. A modernized version of such directional filter based on dielectric resonators (DR) in the circular polarization regions of rectangular waveguides was patented in 1987 [24], and its characteristics as well as the characteristics of bandpass (BPF) and rejector filters (RF) were published in [25], the structure of the specified filter is shown in Fig.13.

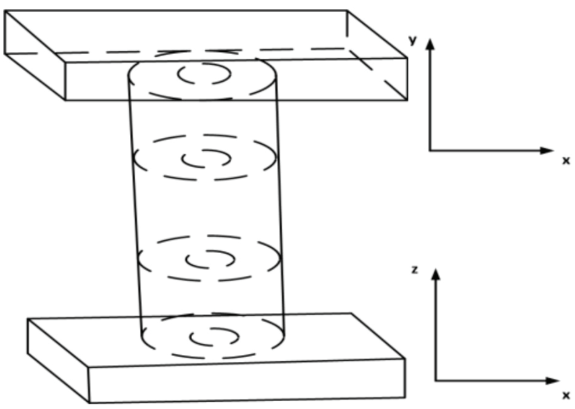


Fig. 12. The waveguide structure of a directional filter.

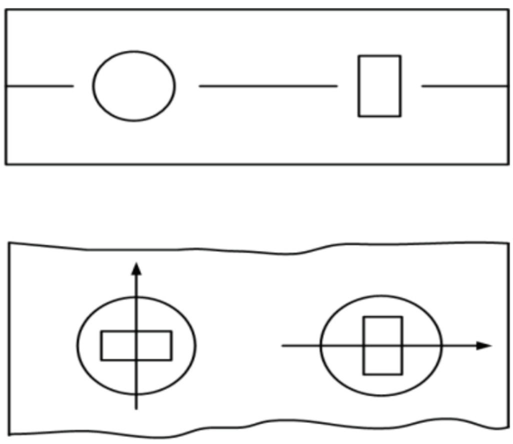
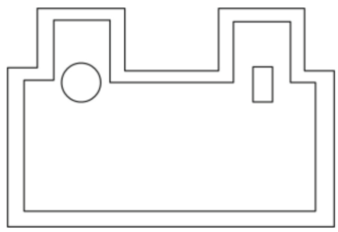


Fig. 13. Bandpass and rejector filters.

The RF, which consists of only one waveguide with two DRs in the circular polarization region Fig.14 (a) as described in [24], demonstrates a characteristic in the form of a "degenerate" oscillation, obtained as the interference of oscillations from individual resonators [25], which is commonly referenced as "Fano resonances" in modern literature [26].



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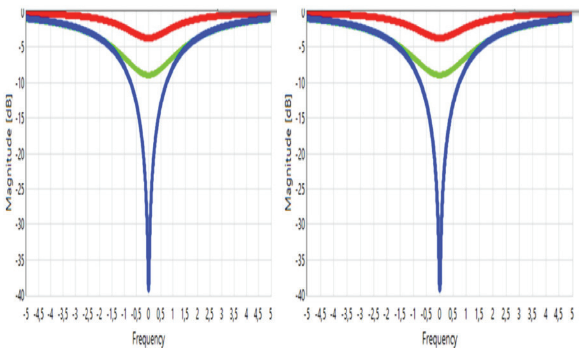
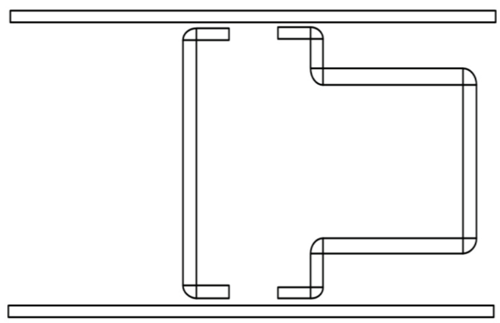


(b) (c)

Fig. 14. (a) The RF, which consists of only one waveguide with two DRs in the circular polarization region; (b), (c) Modelled filter characteristics.

The filter shown in Fig. 15 (a) is formed by two microstrip resonators - "halfwave" and "wave" and when choosing the distance between the resonators while at output 3 oscillations are in phase, and at output 4 - in antiphase, observation of its characteristics presented in Fig. 15 b).



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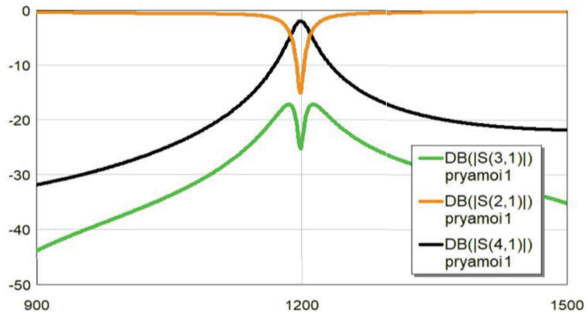

b)

Fig. 15. (a) Filter formed by two microstrip resonators - "halfwave" and "wave"; (b) Simulated filter characteristics.

The orange curve in Fig. 15 (b) similarly to the RF characteristic, demonstrates that at the resonance frequency the energy is "taken" from the line connecting outputs 1 and 2 to output 3.

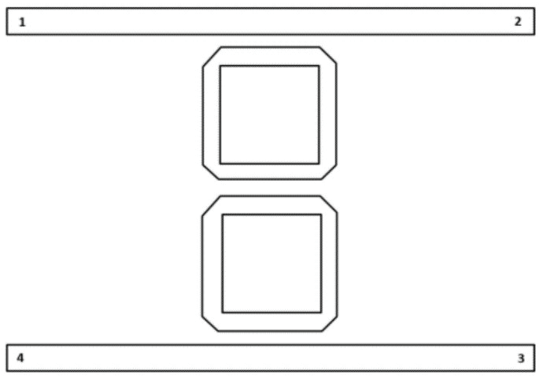

Fig. 16. Filter formed by interconnected resonators.

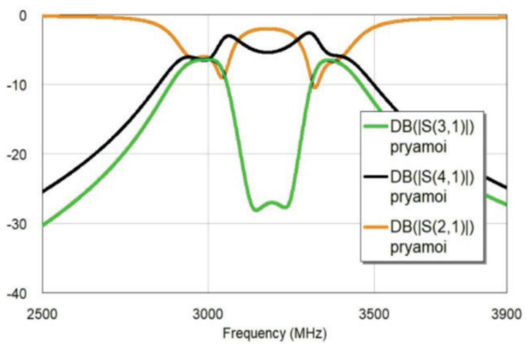

Fig.17. Simulated characteristics of the specified filter.

In a filter formed by interconnected resonators Fig. 16 (a), the energy in the region of the center frequency is distributed somewhat differently - it is divided between outputs 2 and 3 but is not supplied to output Fig. 16.

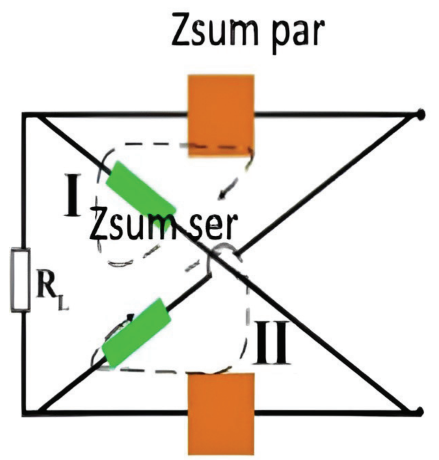

Fig. 18. Equivalent circuit of a multi-resonator filter with parallel and series oscillations

Canonical implementation of the model of crossed quadrupole arms (a) in the form of: n parallel connected series circuits.

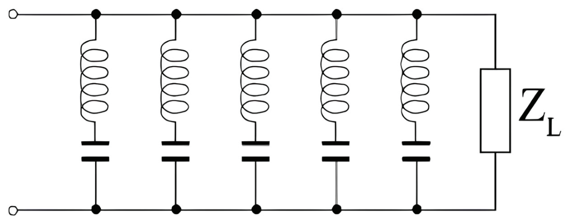

Fig. 19. Equivalent circuit of parallel circuits

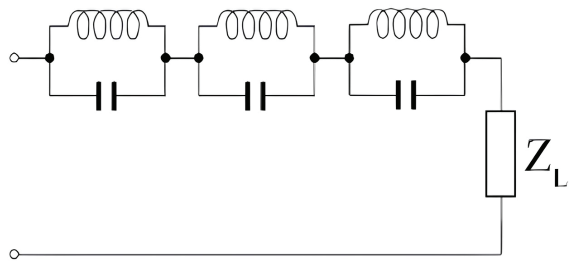

Fig. 20. Equivalent circuit of by-series oscillatory circuits

Fig. 18 shows the equivalent circuit of a multi-resonator filter with parallel and series oscillations. One branch is represented by series oscillatory circuits (Fig. 20), the other by parallel circuits (Fig. 19), and together they are represented as in Fig. 18.

The parameters of the scattering matrix of a bridge quadrupole with an arbitrary number of resonators can be expressed in an analytical form: (9) (10)

$$S_{12} = S_{21} = \frac{\sum_{i=1}^{n} K_e^i}{1+\sum_{i=1}^{n} K_e^i} - \frac{\sum_{j=1}^{n} K_o^j}{1+\sum_{j=1}^{n} K_o^j} \quad (9)$$

$$S_{11} = S_{22} = \frac{\sum_{i=1}^{n} K_e^i}{1+\sum_{i=1}^{n} K_e^i} - \frac{\sum_{j=1}^{n} K_o^j}{1+\sum_{j=1}^{n} K_o^j} \quad (10)$$

where K_e and K_o are coupling coefficients of the even and odd modes of shoulder resonators with the load. Expressions (9) and (10) can be used not only to analyse the properties of cells of metamaterials but also for designing bandpass and notch filters. Using the package developed using Python based on expressions (9) and (10), S-parameters of metamaterial cells for the case of Fano resonance, EIT, and notch filters were simulated and investigated. Calculations results are shown in Fig. 4 to Fig. 6. In the figures, red, green, light green, and light blue curves correspond to the individual resonators of metamaterial cells. In contrast, the dark blue curve represents two or more resonators' total transmission or reflection characteristics.

Python-based Software for 2-4-6 resonators filter modelling

We have created a new Python program that allows, in addition to the usual transmission and reflection coefficients, also constructing the characteristics of the phase and group delay time, as well as the energy stored in the system.

For correct operation, it is necessary to first set the frequency range of the study (F1, F2), then specify the values for the parallel and series circuits (F0_p1,p2,p3; F0_s1,s2,s3), the coupling coefficients for each resonator separately (K_p1,p2,p3; K_s1,s2,s3), as well as their quality factors (Q0_p1,p2,p3; Q0_s1,s2,s3). smoother graphs, the Num points parameter should be adjusted.

Fig. shows input parameters, while fig.22 shows S-parameters, fig.23 phase characteristic, fig.24 group delay, fig.25 stored energy.

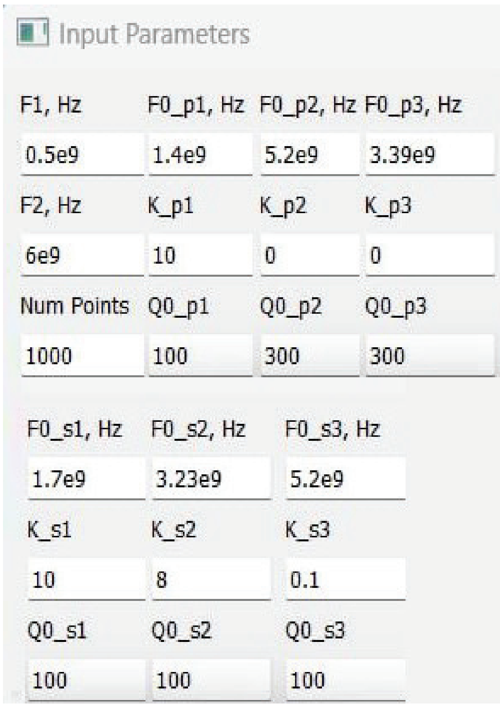

Fig. 21. Input parameters for Python program.

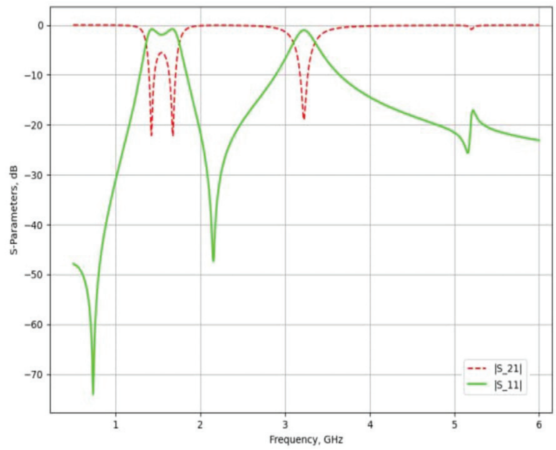

Fig. 22. Simulated S-parameters filter characteristics.

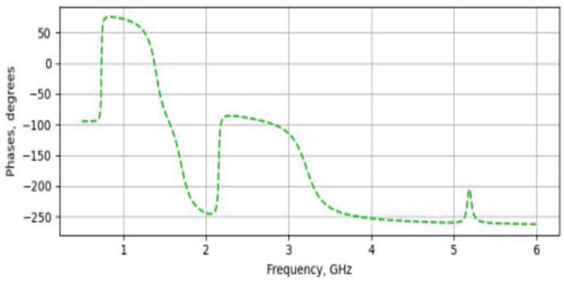

Fig. 23. Simulated phase filter characteristic.

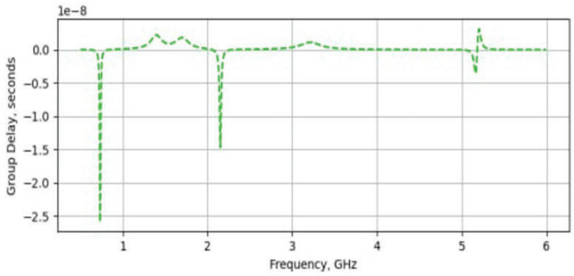

Fig. 24. Simulated group delay filter characteristic.

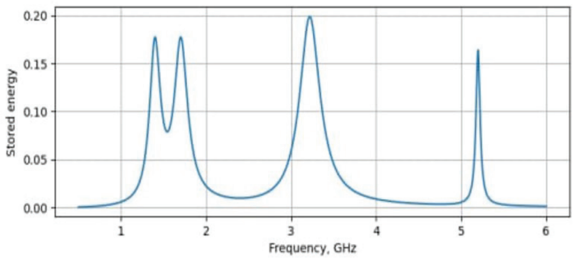

Fig. 25. Simulated stored energy filter characteristic.

The phase response is calculated during simulation, which allows achieving its linearity.

We can also assess the stored energy, allowing us to understand where the energy that doesn't reach the output is utilized (part of it passes through, part of it is reflected, and part of it is stored in the system).

The same program built for the calculation of the filter shown in the figure demonstrates how phase shifts in the passband affect group delay time as well as the phase.

Using this program, it is possible to assess not only the transmission efficiency of the signal within the passband but also the dynamic characteristics of the filter, such as phase changes depending on frequency and group delay time.

This allows for a better understanding of how the filter behaves during signal transmission and how its tuning affects energy transfer within a specific frequency range.

Along with the amplitude-frequency characteristic, the program displays the phase characteristic and group delay.

The program allows calculating the characteristics of two-, four-, and six-resonator filters. For example, to implement a two-resonator filter, it is necessary to set the following values Fig. 21. Input parameters for Python program.

In the figure above, four resonances are shown (red curve S21), where the two outer peaks reach nearly -25 dB, and the two middle peaks reach -40 dB. The coupling coefficients for the first and fourth resonators are 5, while for the second and third resonators, they are 18. The quality factor of all circuits is 500.

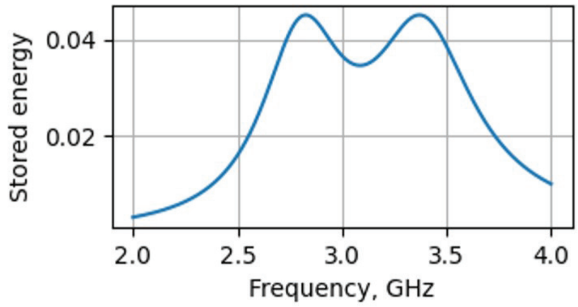

Fig. 26. Simulated stored energy 2 resonator filter characteristic.

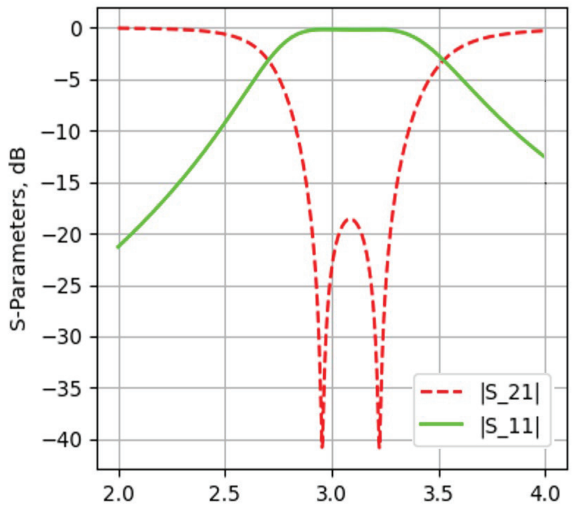

Fig. 27. Simulated S-parameters 2 resonator filter characteristics.

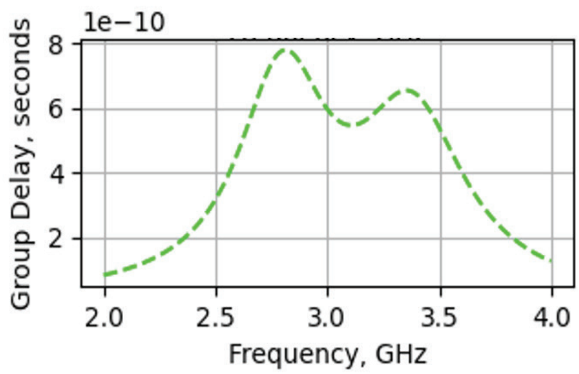

Fig. 28. Simulated group delay 2 resonator filter characteristic.

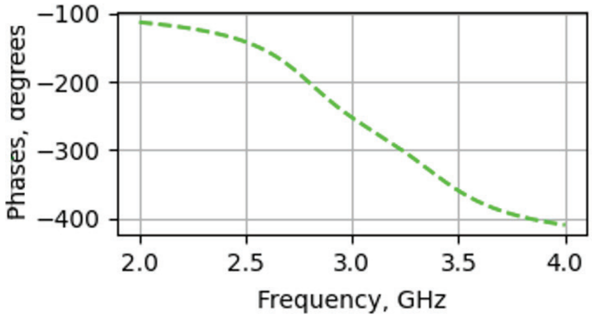

Fig. 29. Simulated phase 2 resonator filter characteristic.

If you narrow the frequency range as in the fragment above, you can more accurately estimate the phase characteristics (its linearity) and group delay time (the degree of nonlinearity).

The program's convenience is that it is easy to monitor the frequency range and simultaneously track the phase and group characteristics.

A four-resonator filter offers higher selectivity, better attenuation, and more precise control over the passband compared to a two-resonator filter, at the cost of increased complexity and size.

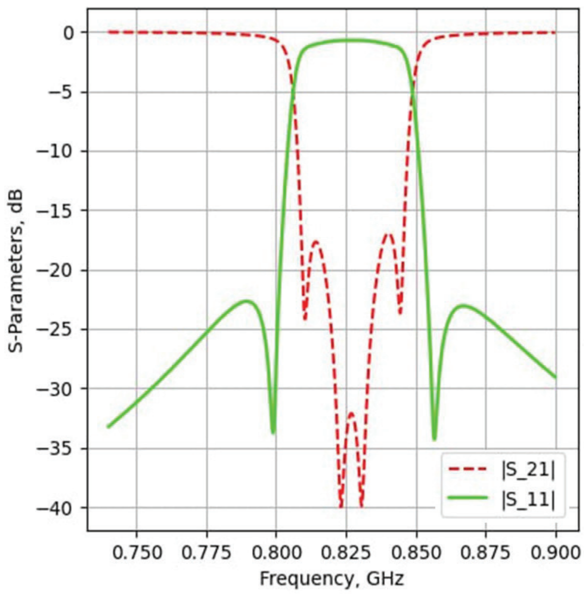

Fig. 30. Simulated S-parameters 4 resonator filter characteristics.

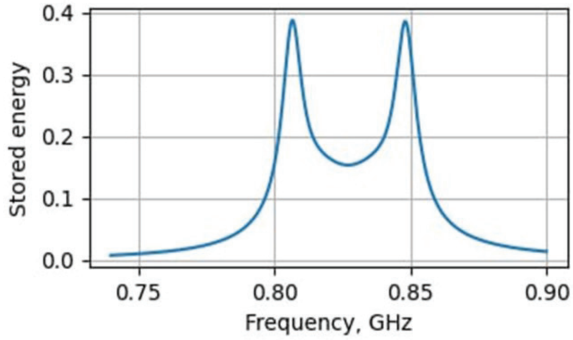

Fig. 31. Simulated stored energy 4 resonator filter characteristic.

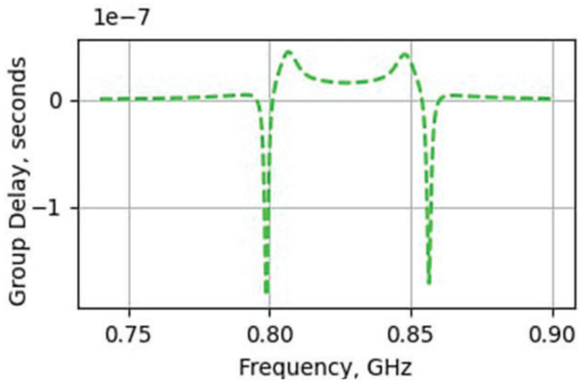

Fig. 32. Simulated group delay 4 resonator filter characteristic.

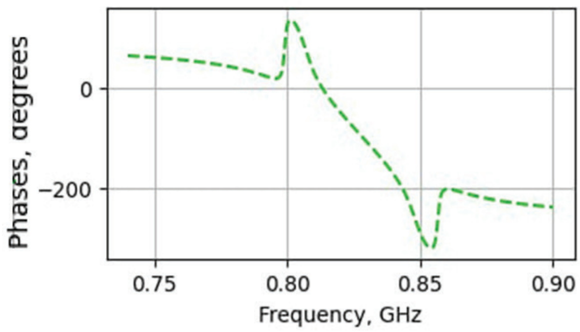

Fig. 33. Simulated phase 4 resonator filter characteristic.

The last one to be considered is the six-resonator filter and its characteristics. This filter consists of six resonators, each of which affects the overall properties of the filter, including the passband, reflection coefficients, and phase characteristics. Six-resonator filters typically have high selectivity and are capable of efficiently separating desired signals from interference. It is important to note that having more resonators allows the filter to achieve a narrower passband and create sharper transitions between the passband and the stopband, which is especially useful in complex radio frequency systems.

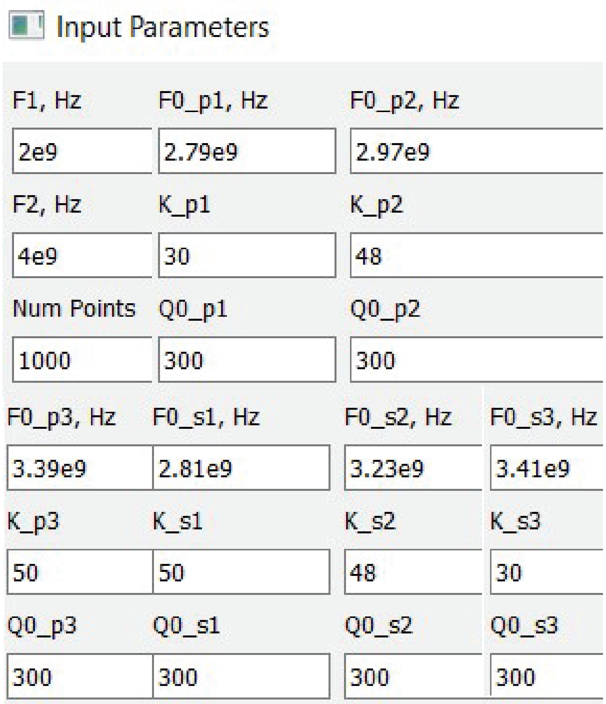

Fig. 34. Input parameters of 6 resonator filter.

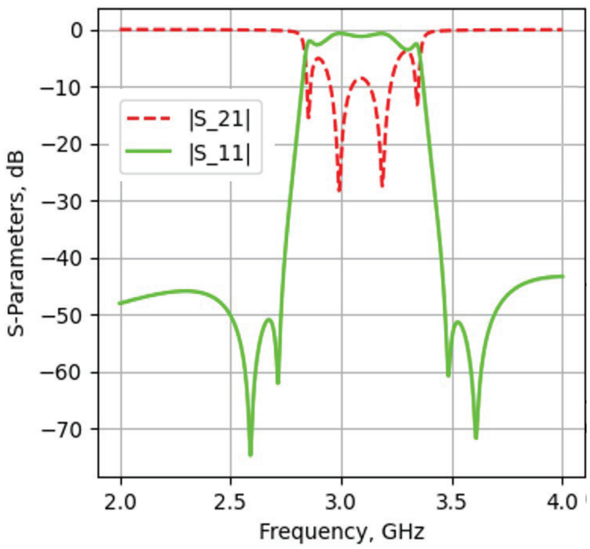

Fig. 35. S-parameters of 6 resonator filter.

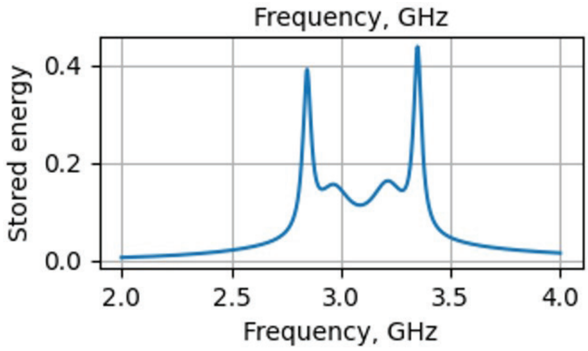

Fig. 36. Stored energy of 6 resonator filter.

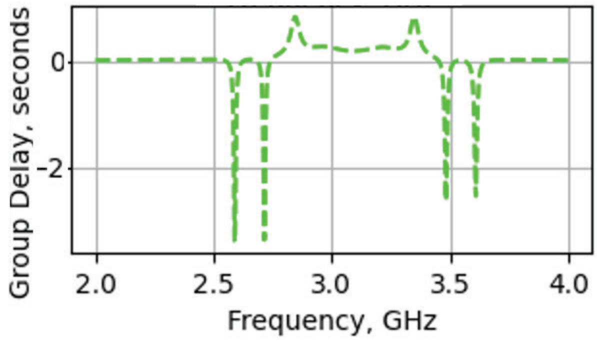

Fig. 37. Group delay of 6 resonator filter.

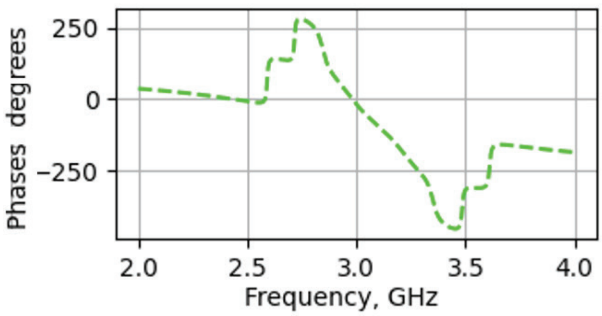

Fig. 38. Phase of 6 resonator filter.

Conclusions

Using simulation tools like CST Studio Suite, AWR Microwave Office, and LabVIEW, we were able to accurately model various designs and validate them against experimental data. The introduction of Fano resonances and trapped modes proved to be a game-changer, enhancing the selectivity and attenuation properties of the filters—essential features for modern communication systems.

Trapped modes manifest as attenuation poles, resulting from the interference of even and odd oscillations. This is evidenced by the presence of two independent energy pathways, along which these interfering oscillations propagate. With appropriate design parameters (such as resonator coupling coefficients and resonance frequencies), a complete energy exchange between resonators can occur at a certain frequency, in a direction perpendicular to the primary energy flow from input to output.

The design and properties of directional filters based on circular resonators and dielectric resonators were described. These filters have "metamaterial" properties and are widely used in modern microwave technology. The characteristics of bandpass and rejector filters, as well as the characteristics of the filters formed by two microstrip resonators and resonators connected to each other, are given. It is important to emphasize the phenomena of "Fano resonances" observed in these filters, which are arise as the interference of oscillations from individual resonators.

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Моделювання смугових фільтрів із полюсами затухання за допомогою паралельних каналів зв'язку

Проблематика. Мікрохвильові фільтри є критичними компонентами сучасних комунікаційних систем, вони відіграють основну роль у обробці сигналів, пропускаючи певні смуги частот і придушуючи небажані частоти. Протягом багатьох років досягнуто значних успіхів в розробці різних типів мікрохвильових фільтрів, включаючи напрямні, мікросмужкові та багаторезонаторні фільтри. Ці фільтри широко застосовуються в радарах, супутникових комунікаціях та бездротових мережах, де важлива висока продуктивність і точний контроль частот.

Мета досліджень. Ця стаття присвячена огляду різних мікрохвильових фільтрів, створених, розроблених або досліджених командою, включаючи напрямні фільтри, мікросмужкові фільтри з полюсами затухання та багаторезонаторні фільтри. Дослідження зосереджуються на вивченні їх унікальних властивостей, таких як формування полюсів затухання, характеристики метаматеріалів та вплив зв'язку резонаторів на продуктивність фільтра. Була розроблена нова програмна реалізація на основі Python для моделювання різних фільтрів із шістьма, чотирма та двома резонаторами, яка часто використовувалася.

Методика реалізації. Електродинамічні симуляції за допомогою таких програмних засобів, як CST Studio Suite, AWR Microwave Office та LabVIEW, моделювання фільтрів за допомогою еквівалентних схем та мостових схем. Використання мікросмужкових ліній, круглих резонаторів і діелектричних резонаторів для створення та аналізу різних конфігурацій фільтрів. Аналіз шляхів розповсюдження енергії, зв'язку резонаторів та характеристик передачі для оптимізації конструкції фільтра.

Результати досліджень. Було досліджено різні структури, такі як мікрохвильові напрямні фільтри, мікросмужкові резонаторні фільтри з 2, 4, 6 резонаторами, проаналізовано їх структури та характеристики. Розроблено нове програмне забезпечення на Python, яке дозволяє моделювати резонансні криві за допомогою відповідних параметрів для фільтрів із 2, 4, 6 резонаторами. Параметри матриці розсіювання мостового квадруполя були виражені в аналітичній формі та використані у програмі на Python.

Висновки. Дослідження, представлені в цих публікаціях, значно сприяють розвитку та розумінню сучасних конструкцій мікрохвильових фільтрів. У статті розглянуто різні фільтри на основі резонаторів, включаючи напрямні, мікросмужкові та багаторезонаторні фільтри. Дослідження показали ключові покращення продуктивності, яких можна досягти завдяки зв'язку резонаторів, властивостям метаматеріалів та введенню полюсів затухання. Використання передових інструментів моделювання, таких як CST Studio Suite, AWR Microwave Office та LabVIEW, дозволило точно моделювати та перевіряти теоретичні конструкції. Введення резонансів Фано та запірних модів у фільтри продемонструвало покращення вибірковості та характеристик затухання, що є критичним для сучасних комунікаційних систем. Запірні моди проявляються як полюси затухання, що виникають внаслідок інтерференції парних і непарних коливань. Це підтверджується наявністю двох незалежних шляхів енергії, якими поширюються ці коливання. За відповідних параметрів конструкції (таких як коефіцієнти зв'язку резонаторів і резонансні частоти) можливий повний обмін енергією між резонаторами на певній частоті, у напрямку, перпендикулярному основному потоку енергії від входу до виходу. Опис та властивості напрямних фільтрів на основі круглих резонаторів і діелектричних резонаторів були представлені. Ці фільтри мають властивості метаматеріалів і широко використовуються в сучасній мікрохвильовій техніці. Наведені характеристики смугових і загороджувальних фільтрів, а також характеристики фільтрів, утворених двома мікросмужковими резонаторами та зв'язаними між собою резонаторами. Важливо підкреслити явище резонансів Фано, що спостерігається в цих фільтрах, які виникають як результат інтерференції коливань від окремих резонаторів.

Ключові слова: *мікрохвильові фільтри; резонатори; полюси затухання; напрямні фільтри; мікросмужкові фільтри; резонанси Фано; метаматеріали; електродинамічне моделювання; моделювання схем; смугові фільтри.*