Synthesis of microstrip filters based on miniaturized hexagonal resonators

Marin V. Nedelchev, Ilia G. Iliev

The paper proposes the application of the miniaturized hexagonal resonators in the microstrip filter design and their applicability in mobile communication systems. The main coupling topologies are researched and the coupling mechanism is explained. Using full-wave electromagnetic simulator, the coupling topologies are analyzed, in order to find the coupling coefficients in value and in sign. It is researched the coupling coefficient dependence by the coupling resonators position. The graphical results for the coupling coefficient in dependence of the resonator spacing are presented, when different coupling topologies are examined. Two triplet filters with asymmetric responses are synthesized. The results of the simulation show very good match of the theory and the simulation results.

Keywords: *miniaturized resonators, coupled resonators, microstrip filters*

Проектиране на микролентови филтри на базата на миниатюризирани шестоъгълни резонатори (Марин В. Неделчев, Илия Г. Илиев). *В работата е предложено и изследвано приложението на миниатюризирани шестоъгълни резонатори в микролентови лентопропускащи филтри за мобилни комуникационни системи. Изследвани са основни топологии на свързани резонатори използвани при проектирането на филтри. С помощта на електромагнитен симулатор са анализирани свързаните структури, за да се определят коефициентите на връзка, както по стойност, така и по знак. Изследван е характерът на връзката в зависимост от разположението на свързаните резонатори. Показани са в графичен вид коефициентите на връзка в зависимост от разстоянието между резонаторите при различни характери на връзката. Проектирани са два трирезонаторни филтъра с асиметрични характеристики. Резултатите от симулационното изследване показват много добро съвпадение на теоретичните и получените резултати.*

Ключови думи: *миниатюризирани резонатори, свързани резонатори, коефициент на връзка, микролентови филтри*

Introduction

The rapid development of the mobile communication systems stimulates the research of microwave filters with specific asymmetric characteristics [1]. In order to achieve the high slope of the characteristics of filters and linear group delay the proper filters are cross-coupled, which have couplings between non-adjacent resonators. This kind of filters have improved characteristics compared to conventional filters in which compromise is between slope and linear group time. The filters with asymmetric frequency response are composed of coupled resonators tuned to different frequencies. On the other hand due to its easy production and tuning, the microstrip filters are subject to continuous research in recent years. The main objective of implementing microstrip filters is their miniaturization. This can be achieved by use of miniaturized resonators. The methods for the synthesis microstrip filters are limited to the preparation of the coupling coefficients matrix from the approximation [2]. The individual coupling coefficients are realized by coupled resonators. For this reason, as the task is the issue of the analysis of different topologies connected microstrip resonators. In the references, the use of electromagnetic simulator connection between the physical structure of microstrip resonators and related coupling coefficient [3]-[6]. This approach to solving the problem is related to the solution of Maxwell's equations for the specific topology numerical method used in computational software. This paper analyzes coupling coefficient between asynchronously tuned hexagonal microstrip resonators with magnetic and hybrid connection. Using a microwave simulator are analyzed different topologies of coupled resonators and their coupling coefficient. The represented graphics can be used in the design of microstrip filters with asymmetric characteristics for mobile communication systems. There are designed two triplet filters with asymmetrical response. The results of the simulation study indicate excellent coincidence between the theoretical and simulation results.

Analysis of the coupling coefficient for miniaturized hexagonal microstrip resonators

The mechanism of the coupling between closely spaced resonators is based on common field between them. The nature of the coupling depends on the spatial orientation of both resonators. The coupling coefficients for synchronously tuned resonators are calculated by the resonant frequencies of the even and odd mode excitation of the structure [1]:

$$k = \frac{f_e^2 - f_o^2}{f_e^2 + f_o^2} \quad (1)$$

where f_e is the frequency of even mode, and f_o is the frequency of odd mode. The necessary condition for the observation of these resonant peaks in the characteristics of the coupled resonators is to be overcritical loaded. In this case, the couplling coefficient is greater than a critical value $1/Q$, where Q is the quality factor of the resonators. In the paper, it is used an electromagnetic simulator based on the method of moments in order to determine the resonance frequency of even and odd mode.

Magnetic coupling

When two resonators are arranged in the manner shown in Fig.1, the coupling has magnetic manner. Due to the symmetry of the resonator, point A is assumed to have zero potential. At this point, the fundamental resonance frequency of the electric field has a minimum and a maximum of magnetic field. The mutual inductance of two lines defines the magnetic nature of the relationship as mutual capacitance between the lines is negligible. The mutual capacity is negligible because of the minimum of the electric field.

The coefficient of magnetic coupling is with a positive sign, as the frequency of even mode is greater than the frequency of odd mode.

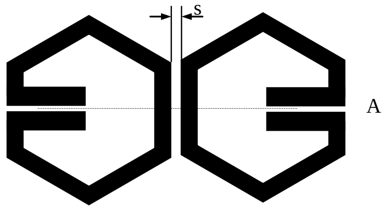


Fig.1. Magnetic coupling.

In Figure 2 are shown the results of the simulation study of the dependence of the coefficient of magnetic coupling from the distance between the resonators. The simulations are performed for dielectric substrate FR-4 with thickness 1,5mm.

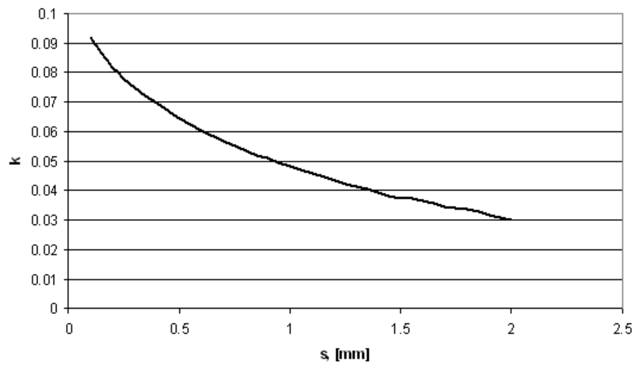


Fig.2. Magnetic coupling coefficient in dependence of the gap between the resonators.

The geometric parameters of the resonator are respectively arm length $l = 13mm$, width of the main transmission line $w = 2.8mm$, width of the coupled lines $w_1 = 3.1mm$ and distance between the coupled lines of the resonator $0.3mm$. In the simulations, the coupled resonators are loaded overcritical and the frequency response observed two characteristic resonance of even and odd mode. Those frequencies are recorded and according to formula (1) is calculated the magnetic coupling coefficient. The topology of magnetically coupled resonators is used for realization of positive coupling coefficients in cross coupled filters.

Electrical coupling

The topology of the electrically coupled resonators is shown on Fig.3.

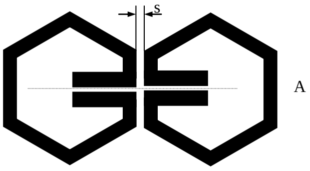


Fig.3. Topology of electrically coupled microstrip resonators.

The coupling is considered to be electric, as the maximum of the electric field is in point A in Figure 3. At this point, the resonant frequency of the electrical component of the field dominates over the magnetic. Therefore, the strength of the coupling is determined by the mutual capacitance of the coupled lines. The mutual inductance is negligible because of the small amplitude of the magnetic field. Figure 4 shows the dependence of the coefficient of the electrical coupling from the distance between the resonators.

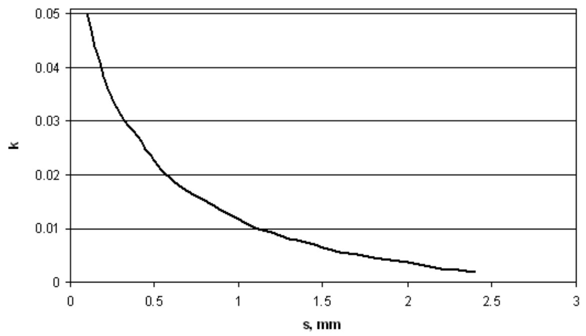


Fig.4. Electric coupling coefficient in dependence of the gap between the resonators.

The electrical coupling coefficient has a negative value. Due to the short length of the coupled lines (5mm), the total coupling coefficient takes smaller values than other topologies coupled resonators. The application topology shown in Figure 4 is limited in realization of negative factors in connection with cross-coupled filters. Negative coefficients are thus necessary to be able to realize the zeros of the transfer function for finite frequencies.

Hybrid coupling of I and II type

The hybrid coupling type I is observed in the disposal of the resonators coupled as shown in Fig. 5a. One of the resonators is connected with the side that is closer to the open end. This type of connection is used for the design of cascaded triplet filters cross-linked (Cascaded Triplet) with zero of the transfer function located in upper the stopband. Using the topology in this type of filter is desirable, because it allows for the realization of magnetic connection of the second resonator with third resonator (cross-coupling) and hybrid connection of the first resonator with the third.

The hybrid coupling type II is observed in the disposal of the resonators connected as shown in Fig.5b. One of the resonators is connected with the side, which is close to its middle. For small deviations of the resonant frequency, the magnetic component of the field is dominant in the coupling. This topology is used in the design of CT filters with zero of the transfer function in lower bandstop. The specific location of the coupled resonators realized electrical coupling of the first resonator with a third resonator (cross-coupling), while the coupling between the second and the third remains of a hybrid type II.

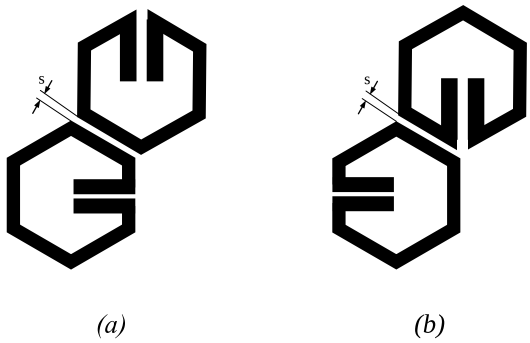
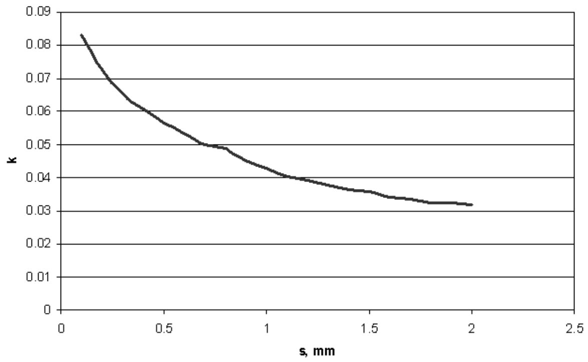
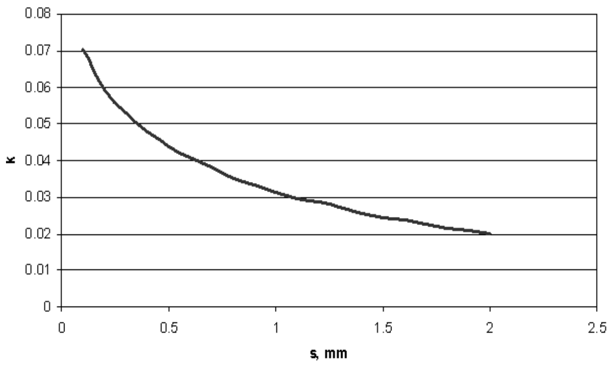


Fig.5. Topology of hybrid coupled resonators of (a) I type and (b) II type.

In an environment of Ansoft Designer is researched the topology of coupled hexagonal resonator. Both resonators are of the same length of transmission line, but with a different shape. The topology is researched for overcritical loaded resonators, which are reported in the frequencies of the two resonant peaks in the frequency response. The coupling coefficient is calculated by Eq. (1). The dependence of the coupling coefficient from the distance between the resonators is given in Fig. 5. From the presented results, it can be seen that the coefficient of relationship is monotonically decreasing with distance s. When the hybrid coupling cannot be determined which of the two components of the electromagnetic field dominates over the other. The coupling coefficient decreases with increasing the distance between the coupled lines due to the weakening of the total electromagnetic field between both resonators. This decay becomes an exponential law.



(a)



(b)

Fig.5 Coupling coefficient in dependence for hybrid coupling (a) I type andu (b) II type.

The range of the investigated distances between the coupled resonators is limited from below by the technological limit for the production of a gap of less than 0,2mm. The top limit is consistent with the radiation losses of coupled lines. The change of the coupling coefficient in the relation of the gap width of 1.5 mm to 2 mm is less than 5%, which means that the influence of the two coupled lines carrying the coupling decreases. The topology of the hybrid coupling I type is used for the realization of positive coupling coefficients in connection with cross coupled filters. The location of the resonators is suitable to be connected to the third resonator by magnetic coupling.

Experimental results from the synthesis of microstrip resonator filters

It is proposed a methodology for the synthesis of microstrip filters, used in the design of two example filters. The designed filters are simulated in full EM simulator in order to obtain their frequency characteristics. For the simulation of the microstrip filters is used dielectric substrate of FR-4 glass fiber with the following parameters:

- Relative dielectric permittivity $\varepsilon_r = 4.5$;
- Height of the substrate: $h = 1.5mm$
- Thickness of the copper foil: $t = 17.5\mu m$;
- Loss tangent: $tg\delta = 0.011$.

Example 1

To design a microstrip three resonator band-pass filter with a zero in the transfer function with the following parameters: center frequency $f_0 = 825MHz$; bandwidth at -3dB level: $\Delta f = 50MHz$; frequencies to zero of the transfer function $f_1 = 925MHz$, and return losses in the pass band $RL = -20dB$ .For realization of the transfer function is chosen topology of a triplet microstrip filter with a zero above the pass band, shown schematically in Figure 6. The calculated the matrix of the coupling coefficients for the selected topology and Chebyshev approximation. The coupling coefficients are $M_{S1} = M_{3L} = 0.0644$, $M_{11} = M_{33} = 0.0043$, $M_{22} = -0.0165$, $M_{12} = M_{23} = 0.0596$, $M_{31} = -0.017$.

As it can be seen from the calculated coupling matrix, the elements on the main diagonal are non-zero. It follows that the resonators are tuned to different frequencies of the center frequency of the filter. Positive factors of connection between the resonators are realized by hybrid connection type I, and the negative of the electrical connection.

The geometrical parameters of the resonator are as follows: length of the arm: $l = 13mm$, width of the main transmission line $w = 2.8mm$, width of the coupled lines: $w_1 = 3.1mm$.

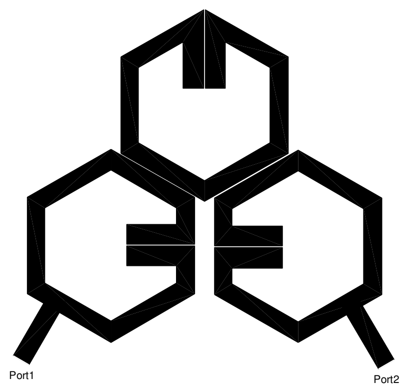


Fig.6. Topology of miniaturized filter with a zero of the transfer function above the passband.

The results of the studies for the electrical connection in Fig4. are obtained for the distance between the electrically coupled resonators $d_{el} = 3.14mm$ and hybrid connection of I type $d_{hyb1} = 0.28mm$ from Fig.5a.

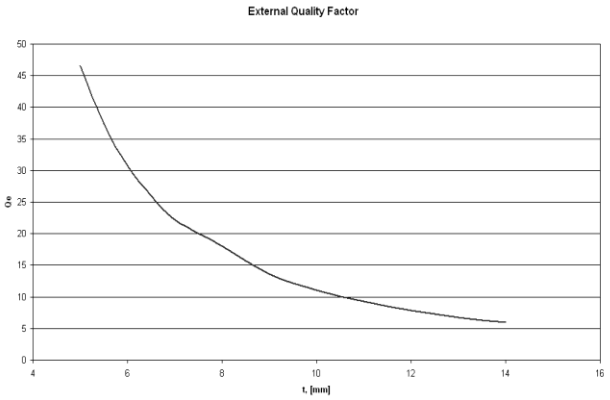
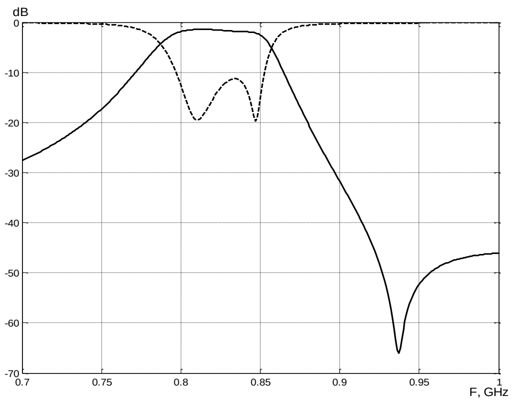


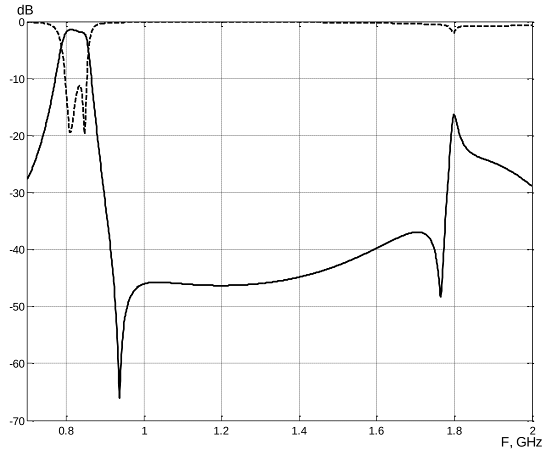
Fig.7. External quality factor in dependence of the tap position of the input/output line.

A simulation of external quality factor depending on tap position of input/output line is performed. The simulation results are presented on Fig. 7. The tap position is found to be $t = 8.5cm$ from Fig.7. It is performed an electromagnetic analysis of the designed filter using the dimensions of the filter of studies for the coupling coefficient. The results of the electromagnetic simulation are shown in Fig.8.

The losses in the pass band are less than -3dB mainly due to losses in the dielectric losses of the finite conductivity of the copper. From the simulated results it is seen that the frequency of the zero of the transfer function is 937MHz and it is 12 MHz higher than the theoretical value. This is due to the sensitivity of the electrical coupling to the change of distance between the resonators. Of reflectance in the pass band is clearly visible the equiripple character indicative of the Chebyshev approximation.



(a)



(b)

Fig.8. Frequency responses of miniaturized triplet filter with transmission zero above the passband in (a) narrow band and (b) broad band.

Fig. 8b shows a frequency filter in broad bandwidth. It can be seen that the spurious bandwidth is at frequency 1,8GHz, which is not a multiple of the basic frequency. This can ensure the insulation of the devices from the signals the harmonic frequencies. The second harmonic is suppressed to -37dB to main located in the pass band. The dimensions of the filter are 63x67mm.

Example 2

To design a microstrip three resonator band-pass filter with a zero in the transfer function with the following parameters: center frequency $f_0 = 825MHz$; bandwidth at -3dB level: $\Delta f = 50MHz$; frequencies to zero of the transfer function $f_1 = 750MHz$, and return losses in the pass band $RL = -20dB$.

For the realization is chosen a topology of triplet microstrip filter with transfer function zero below the passband shown in Figure 9. There are used hexagonal miniaturized microstrip resonators whose shape allows convenient implementation of topologies coupled resonators. Following the proposed methodology for synthesis of microstrip resonator filters is calculated the coupling coefficient matrix according to the Chebyshev approximation. The calculated coupling coefficients are: $M_{S1} = M_{3L} = 0.067$, $M_{11} = M_{33} = -0.0131$, $M_{22} = 0.0447$, $M_{12} = M_{23} = 0.0562$, $M_{31} = 0.0727$.

Fig.9 shows the topology of the synthesized filter.

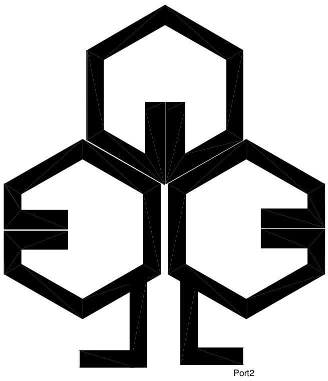
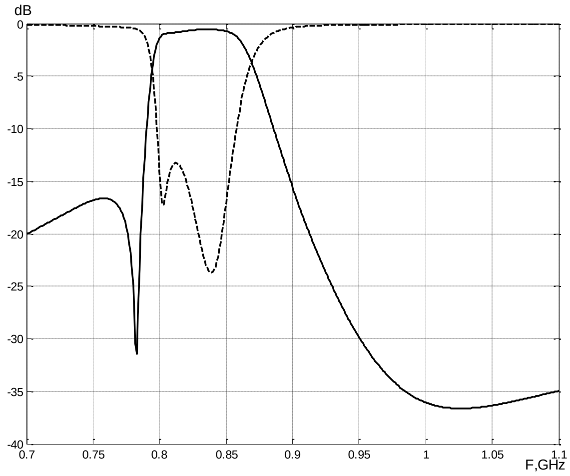


Fig.9. Triplet filter with cross coupling.

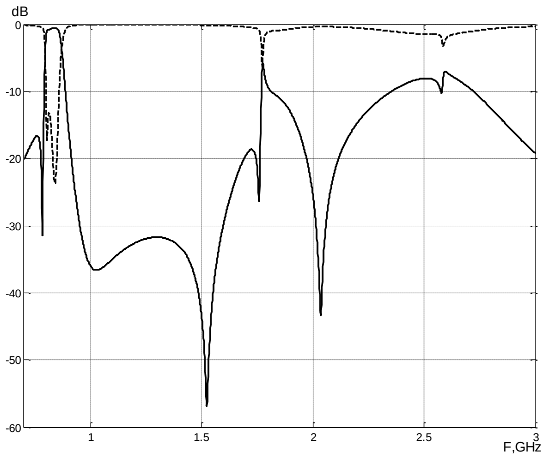
The results of studies magnetic coupling in Fig.2 is obtained for the distance between the coupled magnetic resonators $d_{mag} = 1.29mm$ and hybrid connection type II from Fig.5b $d_{hyb2} = 0.32mm$. The tap position is found to be $t = 9.45cm$ from Fig.7 and the external quality factor is $Q_e = 14.92$. The results of the electromagnetic simulation are presented on Fig 10.

From the presented results it can be seen that the filter has a -3dB frequencies of 800MHz to 865MHz. The increase in the pass band is mainly due to variations in the coefficient of hybrid coupling II type. The losses in the pass band is smaller than -2dB. The return loss, however, is below -13dB and ensures better matching of the filter with the devices coupled to it.

The frequency of the zero of the transfer function is 781MHz. This deviation is due to the deviation of the value of the coefficient of magnetic coupling of the distance between the coupled resonators. The attenuation of the filter for the frequency of the zero of the transfer function is greater than 36dB. Fig. 10a shows that at the frequency of 1GHz appears one more zero of the transfer function, which is not predicted in the approximation. It is due to the parasitic coupling between adjacent input and output lines. On the one hand this connection increases the steepness of the filter from the upper part of the pass band, but on the other hand, it is undesirable connection. The spurious bandwidth is at the frequency of 1785MHz and it is not an accurate harmonic of the fundamental frequency. This result can be expected because the resonator length is not a multiple of half of wavelength. The dimensions of the filter are 63x57mm.



(a)



(b)

Fig.10. Frequency responses of miniaturized triplet filter with transmission zero lower the passband in (a) narrow band and (b) broad band.

Conclusion

The paper analyzes the coupling coefficient in asynchronously tuned hexagonal microstrip resonators with electrical, magnetic and hybrid couplings. Using a microwave simulator there are analyzed the topologies of coupled resonators. There are represented graphics that can be used in the design of microstrip filters with asymmetrical characteristics for mobile communication systems. There are designed two triplet filter with asymmetrical responses. Simulation and theoretical results have a very good coincidence, proving the feasibility of the proposed graphical relationships. The dimensions of the designed filters are 32% smaller than the half-wave resonator filters are tuned to the same frequency.

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***Associate Professor Ilia Georgiev Iliev PhD**, Department Radio communications and Video technologies, Faculty of Telecommunications, Technical University Sofia His research interests are in digital, mobile communication systems, microwave device synthesis, software defined and cognitive radio.*

tel: +359 2 965 2276 e-mail: igiliev@tu-sofia.bg

***Associate Professor Marin Veselinov Nedelchev PhD**, Department Radio communications and Video technologies, Faculty of Telecommunications, Technical University Sofia His research interests are in digital, mobile communication systems, microwave device synthesis, software defined and cognitive radio.*

tel: +359 2 965 2676 e-mail:mnedelchev@tu-sofia.bg

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