Synthesis of Microstrip Filters Using Triangular Open-Loop Resonators

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Abstract: **This paper presents a design of microstrip triangular open loop resonator filter. Because of their structure, the triangular open loop coupled resonator offers wide variety of coupling schemes and different in value and sign coupling coefficient. The coupling schemes are electrical, magnetic and mixed. The paper presents three designs of Chebyshev filter with tapped input/output lines based on triangular open loop resonators.. There is a good agreement between the theoretical and EM simulation results.**

Keywords: coupling coefficient, triangular open loop resonator, cross coupled filters.

I. Introduction

The fast development of the mobile communication systems stimulates the research of microwave filters with specific symmetrical response. Microstrip filters are preferred for these systems, because of their compact size, low weight, easy integration in integrated circuits, fine adjustment.

Most of the microwave filters are of Chebyshev type. They are equiripple in the passband and maximally flat in the stopband. Such filters can be realized by cascading resonators in series. High filter selectivity requires higher filter order and more resonators. Because of the low unloaded Q factor of the microstrip resonators, the passband loss increases. Alternative way is to use cross-coupled filters with coupling between non-adjacent resonators. Non-adjacent couplings cause transmission zeroes in the stopband or equalization in the group delay.

Among the variety of filter topologies, the classic half-wavelength and hairpin resonator filters are commonly used. Miniaturization is an important requirement for the used resonators. In order to reduce the size of the half wavelength it is possible to fold back the ends of the resonator into a “U” shape. The further miniaturization of half wavelength is achieved by the square open loop filters [1]. The resonator is bent in square form.

The authors of [2] propose to use triangular open loop resonators in order to achieve compact cascaded quadruplet filter with two symmetrical transmission zeros. The geometrical form of triangular resonators allows coupling in different coupling schemes, which exhibits various coupling types. It is possible to form the resonator as an isosceles right-angled, isosceles or equilateral triangle, according to the desired topology. The form of the resonator used in simulations is isosceles right-angled triangle.

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The synthesis of cross coupled filters is based on the works from Atia and Williams [3], Cameron and Rhodes [4,5] considering waveguide cavity filter design. It is based on the deriving the coupling matrix from the transfer function and its reduction to the corresponding topology form. This technique is found to be useful in the design of microstrip cross-coupled filters. Hong and Lancaster proposed in several papers [6,7] numerical method for cross coupled filter design based on approximation of the low pass filter prototype elements.

This paper presents a design procedure of all pole Chebyshev type and cross-coupled filters based on isosceles right angled triangular resonators. A full wave EM simulator is used for obtaining the coupling coefficients between the resonators. Numerical results for the values of the coupling coefficients are presented. Three design examples are carried out. The frequency responses from full wave EM simulator are presented in order to validate the procedure.

II. Triangular open loop resonator coupling structures

The triangular open loop resonator is half wavelength long for the central frequency of the filter.

The coupling mechanism is based on the fringe fields of closely situated resonators. The nature of coupling depends on the resonator configuration. It is clear that half wavelength triangular resonator is symmetrical along the center of the hypotenuse. The coupling coefficient for synchronously tuned resonators can be calculated easily by the resonance frequencies of even and odd mode [1]:

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

A full wave EM simulator based on the Method of the Moments (MoM) is used to identify the resonance frequencies. Most of the coupling structures are simulated using the symmetry in their topology for electrical and magnetic wall introducing in-between. When symmetry does not present, the whole structure is simulated. This does not constrain in any way the obtained results. The simulation are carried out for standard FR-4 substrate with $\varepsilon_r = 4.4$, $h = 1.5mm$, $tg\delta = 0.02$.

The coupling structures are formed by different orientation in the plane of identical resonators. They should be closely situated and separated by distance ***d.***
Both resonators in the coupling structure may have or not an offset in the direction of the coupled lines- denotes as ***delta*** (Fig.1b). This offset is made for two major reasons- to achieve loose coupling or to make possible connection of another resonator.

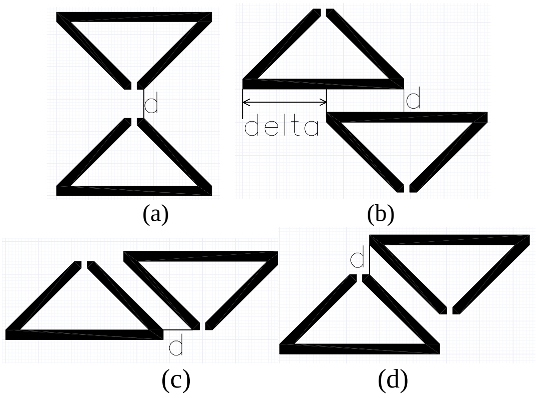

Fig.1 Topologies of triangular open loop resonators (a) electrical coupling, (b) magnetic coupling, (c), (d) and (e) mixed coupling

Figure 2 shows the topology of the microstrip triangular open loop resonator with the following dimensions: strip width $w = 2.77mm$, corresponding to 50Ω line on FR-4, hypotenuse length $c = 45mm$, cathetus length $a = 29mm$, gap between the cathetuses $s = 2mm$.

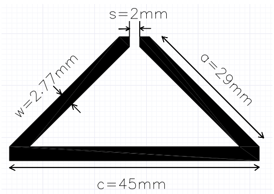

Fig.2 Triangular open loop resonator used in the simulations tuned on 811MHz

The first resonance frequency of the resonator is 811MHz. A number of full wave EM simulations are carried out in order to obtain the resonance frequencies in the frequency response. Following the above mentioned considerations, an electrical coupling presents in the structure shown on Fig.1a. Both resonators are close each other with their open ends. The coupling coefficient is calculated according to Eq.(1).

The numerical results for the coupling coefficient are presented on Fig.3. The coupling between the non-adjacent resonators should be out-of-phase the other couplings. In the case of triangular coupled resonators, the coupling is not strong enough. This leads to transmission zeros in the frequency response away from the passband.

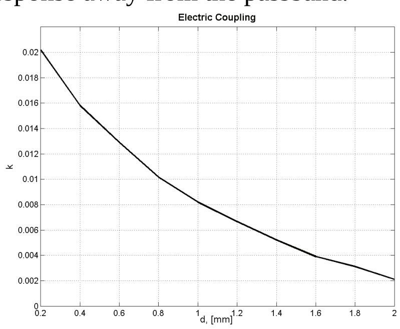

Fig.3 Coupling coefficient for electrically coupled resonators

Magnetic nature of coupling presents in the coupling structure shown on Fig.1b, when the offset distance ***delta*** is zero. Both resonators are coupled through their hypotenuses, where short circuit is present for the resonance frequency.

The magnetic field at this point is predominant over the electric. The results for the coupling coefficient for different offsets ***delta*** are shown on Fig.4.

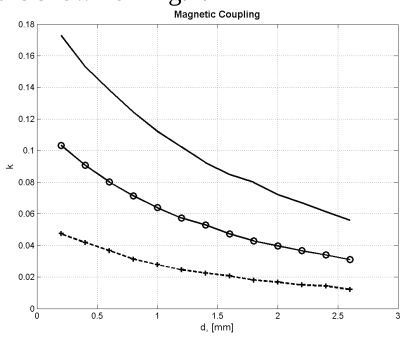

Fig.4. Coupling coefficient for magnetic coupling. Solid line- $delta = 0$ (no offset), circles- $delta = 0.5c = 22.5mm$, dashed- $delta = 0.25c = 11.25mm$.

More flexible form of predominant magnetic coupling is when an offset is presented in the structure (Fig.1b). The coupling is not purely magnetic in nature because of the offset. When *delta* is one half of the hypotenuses, the one more side (the other side of the hypotenuses) is present for additional coupling. In this way the coupling coefficient lowers its values, but remains the monotonically decreasing behavior (Fig.4 circles). When the offset *delta* is a quarter of the hypotenuses, the coupling becomes weaker (Fig.4 dashed). The character of the coupling is not longer magnetic, but mixed.

Mixed coupling presents, when both triangular resonators are close with their cathetuses (Fig.1c,d).

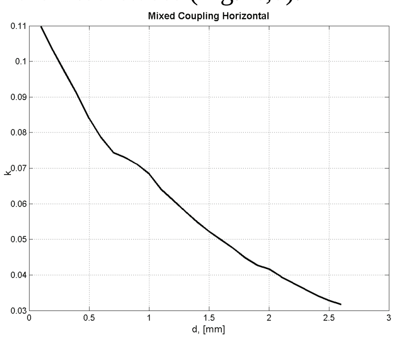

Fig.5 Mixed coupling with spacing in horizontal direction

The coupling resonators are opposite situated in the plane. The currents in the coupled lines are equal in amplitude and in-phase. The value of the coupling coefficient is with positive sign. The approach chosen in this paper for obtaining the coupling coefficient is to fix one of the resonators and to move the other one either in horizontal (Fig.1c), or in vertical (Fig.1d) direction. When horizontal spacing is introduced, the graphical results are presented on Fig.5. The graphical results for vertical spacing between the resonators (Fig.1d) are presented on Fig.6. The coupling coefficient has the same behavior as the coupling coefficient for horizontal spacing.

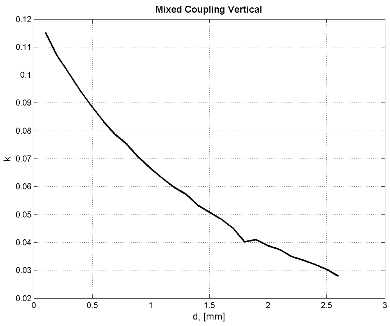

Fig.6 Mixed coupling with spacing in vertical direction

In order to determine the exact tapping position of the input/output lines, it is necessary to derive the external quality factor Q_e. The mathematical expression for it is [1]:

$$Q_e = \frac{f_0}{\Delta f_{\pm\frac{\pi}{2}}} \quad (2),$$

where f_0 is the resonance frequency of the resonator, and $\Delta f_{\pm\frac{\pi}{2}}$ is the bandwidth at which the phase of the s_{11} shifts to $\pm\frac{\pi}{2}, rad$ with respect to the phase at the resonance frequency. Using Ansoft Designer SV, it is extracted the external quality factor. The results are shown on Fig.7.

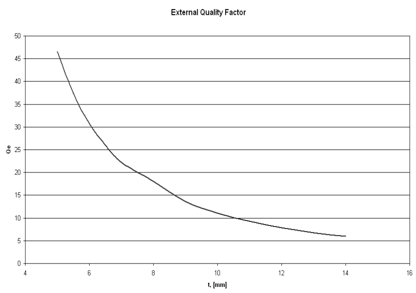

Fig.7 Coupling coefficient versus the distance between the resonators.

The external quality factor decreases with the distance from the center of the resonator. For narrow bandwidth filters Q_e is bigger and he tapping position is closer to the center of the resonator. This leads to bigger sensitivity of the filter's response against the tapping position. Consequently the passband reflection coefficient will degrade.

III. DESIGN EXAMPLES

Three microstrip filters are synthesized and simulated in order to prove the design procedure. The design procedure starts with computation of the elements of the coupling matrix corresponding to the filter topology. The next step is to define the coupling structures for realizing the coupling coefficients. From the presented figures (3-6), the distance between the resonators is found. For magnetic coupling the offset should be previously known. The tapping position can be found by Fig.7.

III.A. Third order Chebyshev microstrip filter

The filter specification is as follows:

Order: *3*; **Approximation:** *Chebyshev type*; **Center frequency:** $f_0 = 810MHz$ **;** **Bandwidth:** $\Delta f = 70MHz$ **;** **Ripple:** $0.1dB$

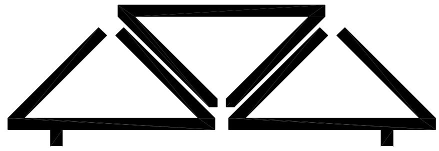

Fig.7 Third order Chebyshev filter topology

The coupling matrix elements are derived from the Chebyshev approximation. They are as follows: $M_{12} = M_{23} = 0.089$ and theexternal quality factor is $Q_e = 12.53$. The coupling is realized by mixed coupling with vertical spacing. The spacing between the resonators is found by means of Fig.6 $s = 0.32mm$. The tap position is $t = 9.2mm$ from the center of the resonator. The simulated frequency response is shown on Fig.8.

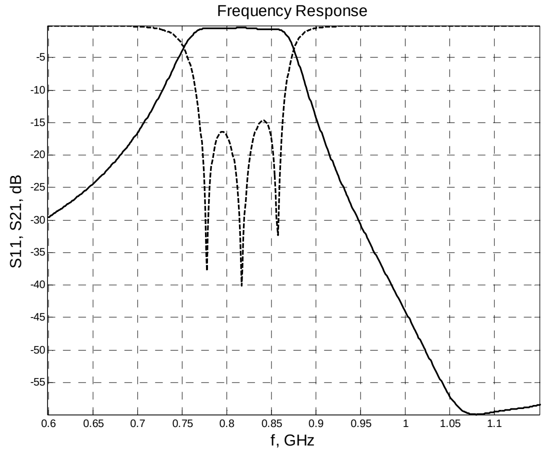

Fig.8. Frequency response of third order microstrip filter. S_{21} - solid line, S_{11} - dashed line

As it is clearly seen the transmission coefficient follows exactly the equiripple response of the Chebyshev approximation. In the transmission coefficient is seen a transmission zero on $1070MHz$ because of the parasitic coupling between the first and the third resonator. It is positive in sign and the transmission zero is above the passband. The realized bandwidth is 80MHz and the maximum level of the reflection coefficient is 15dB. The passband loss is less than 2dB, mainly due to the high dielectric loss of the FR-4 substrate.

III.B. Forth order Chebyshev microstrip filter

The filter specification is as follows:

Center frequency: $f_0 = 810MHz$ **;** **Bandwidth:** $\Delta f = 80MHz$ **; Ripple:** $0.1dB$

The topology of the filter is shown on Fig. 9.

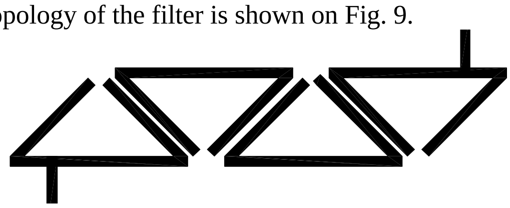

Fig.9. Forth order mictrostrip triangular filter

The coupling coefficients are found to be $M_{12} = M_{34} = 0.091$, $M_{23} = 0.0691$. The external quality factor is $Q_e = 10.48$. The couplings are realized with mixed coupled structure with horizontal spacing. The spacing is found by means of Fig.5. The spacing between the resonators realizing the M_{12} and M_{34} is $s_{12} = s_{34} = 0.41mm$ and the spacing for M_{23} is $s_{23} = 0.8mm$. The tap position is $t = 10.4mm$. The results of the full wave EM simulation are shown on Fig.10.

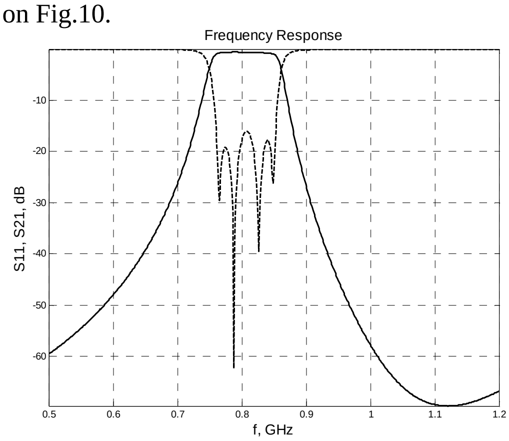

Fig.10. Frequency response of forth order microstrip filter. S_{21} - solid line, S_{11} - dashed line

The realized passband is 90MHz, due to the higher strength of the couplings. The insertion loss is less than 1.5dB, due to the high dielectric loss of the FR-4 substrate and the conductor loss. In the S_{11}, it is seen the Chebyshev type response with four easily distinguished resonances. The maximum reflection coefficient is 16dB.

III.C. Forth order cross-coupled Chebyshev microstrip filter

The filter specification is as follows:

Center frequency: $f_0 = 810MHz$**; Bandwidth:** $\Delta f = 80MHz$**; Ripple:** $0.1dB$ **Frequencies of symmetric transmission zeros:** $f_0 = 670MHz$ **and** $f_0 = 950MHz$**.**

The topology of the simulated filter is shown on Fig.11.

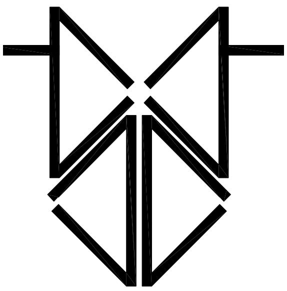

Fig.11. Forth ordercross coupled mictrostrip triangular filter

The coupling coefficients from the approximation are: $M_{12} = M_{34} = 0.089$, $M_{23} = 0.0707$, $M_{14} = -0.004$. The couplings M_{12} and M_{34} are realized with horizontal spaced coupled resonators and the spacing is $s_{12} = s_{34} = 0.38mm$ (Fig.5). The coupling M_{23} is realized by magnetic coupling with no offset. The spacing is found by Fig.4 $s_{23} = 2mm$. The negative coupling coefficient M_{41} is realized by electrically coupled resonators. The distance between the electrically coupled resonators is $s_{14} = 1.6mm$. The frequency response is shown on Fig.12.

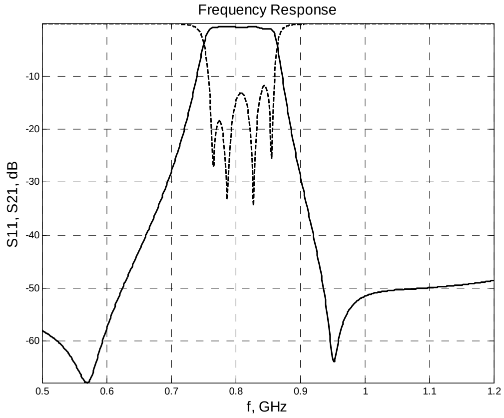

Fig.11 Frequency response of forth order cross coupled microstrip filter. S_{21} -solid line, S_{11} - dashed line

The realized passband is 90MHz and the insertion loss is lower than 1.5dB. The transmission zeros are not symmetrical, the upper one is placed at 950MHz, but the lower one is at 580MHz. This is because of the frequency dependence of the electrical coupling. The maximum value of the reflection coefficient in the passband is better than 13dB.

V. CONCLUSION

This paper presents a research of the microstrip filters based on triangular open loop coupled resonators. The form of the resonator used is isosceles right-angled triangle. There are described the four basic coupling topologies with electric, magnetic and mixed coupling. In order to characterize the coupling coefficient, a full wave EM simulator is used for obtaining the resonance frequencies when introducing electrical and magnetic walls. Three design examples are synthesized and simulated in order to verify the procedure. The frequency responses from full wave EM simulator are presented in order to validate the procedure.

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