MODELING AND DESIGN OF A VACUUM RESONATOR FILTER FOR LTE-A TRANSCEIVER WITH TWO CROSS COUPLINGS

NGHIÊN CỨU MÔ HÌNH HÓA VÀ THIẾT KẾ BỘ LỌC HỐC CỘNG HƯỞNG KHÔNG KHÍ CHO MÁY THU/PHÁT LTE-A VỚI HAI KHỚP NỐI CHÉO

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Abstract - In this paper, we present modeling and design of a bandpass filter for the use in Remote Radio Unit (RRU) transceivers (TRX) of Long Term Evolution Advantage (LTE-A) base stations. Generalized Chebyshev response is employed to synthesize the filter. An 11^{th} order vacuum cavity filter model with two quadrupt transmission zeroes turned by Group Delay Method is applied to achieve the filter's characteristics. A metal cylinder with rectangular cross section is used to connect two resonators with the aim of improving the mainline coupling. PC simulations are carried out and obtained results indicate that the designated filter meets all the requested specifications of a LTE-A TRX filter at Band 3, i.e., Return loss < -10dB@1805-188 MHz, Passband ripple< 0.2dB, Insertion Loss < 2dB, Isolation TX-RX ≥ 90 dB@ 1710-1785 Mhz.

Key words - Filter; Cavity filter; LTE-A base station; 11th order model

Tóm tắt - Bài báo nghiên cứu mô hình hóa và thiết kế bộ lọc thông dải sử dụng trong khối thu/phát vô tuyến từ xa (RRU-TRX) của các trạm phát sóng di động LTE-A. Đáp ứng Chebyshev tổng quát được sử dụng để tổng hợp bộ lọc. Mô hình bộ lọc hốc cộng hưởng siêu cao tần không khí mười một bậc với hai khớp nối chéo được tối ưu sử dụng Phương pháp trễ nhóm để đạt được yêu cầu kỹ thuật của bộ lọc. Việc sử dụng các thanh kim loại nối giữa hai hốc cộng hưởng được đề xuất nhằm tăng độ ghép nối, nhờ đó giảm chiều dài của ốc điều chỉnh cơ khí. Kết quả mô phỏng bộ lọc sau tối ưu đã đạt chỉ tiêu kỹ thuật của bộ lọc TRX LTE băng 3 bao gồm: Hệ số phản xạ < -10dB@1805-188 MHz, độ nhấp nhô trong băng tần < 0.2dB, Insertion Loss < 2dB, Isolation TX-RX ≥ 90 dB@ 1710-1785 Mhz.

Từ khóa - Bộ lọc; bộ lọc hốc cộng hưởng; trạm thu phát LTE; mô hình bộ lọc bậc 11

1. Introduction

Radio frequency (RF) filter is an important element within a variety of applications, enabling the wanted frequencies to be passed through the circuit, while rejecting those that are not needed. The ideal filter is a filter which has no loss in the pass band. In reality, it is impossible to have the perfect filter because there is always some loss in the pass band and the signal in the stop band cannot be rejected completely [1]. Based on the method to reject or to accept signal, there are four main categories of RF filters, i.e., low pass filter (LPF), high pass filter (HPF), band pass filter (BPF), band reject filter (BRF) [2]. A LPF only allows frequencies below the cut-off frequency through. This can also be thought of as a high reject filter as it rejects high frequencies. Similarly, a HPF only allows signals pass above the cut-off frequency and rejects those below. A BPF allows frequencies through within a given pass band. Finally, a BRF rejects signals within a certain band. It can be particularly useful for rejecting a specific undesired signal or set of signals falling within a given bandwidth. Based on the types of polynomial, there are some types of filter [3]. Butterworth Filter type provides the maximum in band flatness, although it provides a lower stop-band attenuation than a Chebyshev filter. However, it has better group delay performance, and hence lower overshoot. Bessel filter provides the optimum in-band phase response and therefore also provides the best step response. It is used to incorporate square waves as the shape is maintained best of all. Chebyshev filter provides fast roll-off after the cut-off frequency is reached. However, this is at the expense of in band ripple. The more in band ripple that can be tolerated, the faster the roll-off. Elliptic filter, also known as the Cauer filter has significant levels of in band and out of band ripple, and as expected the higher degree of ripple that can be tolerated, the steeper it reaches its ultimate roll-off [1].

Cavity filters are available in the frequency range of 30 MHz to 40 GHz bandwidth options from 0.5% to over 66% [4]. Cavity filters offer customers very high quality factor Q and low insertion loss, steep skirt selectivity, and narrower bandwidths than discrete component filters or microstrip filters. Cavity filters, Combline Cavity filters and Waveguide Cavity filters are widely used for bandpass filter, band reject filter or multiplexer applications. Cavity filters include cavity band pass filters, cavity band reject filters, cavity multiplexers, dual cavity duplexers, combline band pass filters, interdigital filters, waveguide bandpass filters and dielectric resonator loaded cavity filters [5].

In the LTE-A transceiver of mobile base station, the cavity resonator filter operates in the downlink section and is capable of handling high power while providing high rejection in adjacent LTE bands to reduce interferences. Some cavity filter models which are used in LTE system are manufactured recently. A triple-mode dielectric-loaded cylindrical cavity diplexer uses novel packaging technique for LTE base-station applications, In which, one diplexer has four metal cavities, loaded by a triple-mode dielectric resonator (DR), and designed to resonate at two different frequencies for the diplexer operation [6]. A new class of integrated rectangular Substrate Integrated Waveguide (SIW) filter and microstrip patch antenna for RF/microwave front-end subsystems is designed [7]. A novel transverse magnetic (TM) mode dielectric resonator and its filter realization are proposed for mobile communication system miniaturization applications [8].

This paper presents the modeling and design procedure of a vacuum resonator filter for LTE-A base station with two Quadrupt Cross couplings. Generalized Chebyshev (pseudo-elliptic) polynomials are used to synthesize the filter. Main strategies to optimize the coupling matrix and design filter are described. In particular, a newly metal cylinder which is used as conductors between two resonators is proposed to improve the mainline coupling. Furthermore, a bigger metal cylinder is also added on the top of resonator to improve Q-quality factor. The proposed resonator filter is designed to operate in LTE –A system at full Band 3. The simulated results prove that our design with two cross couplings totally meets all required specifications of a LTE-A filter, i.e., Return loss < -10dB@1805-1880 MHz, Passband ripple < 0.2dB, Insertion Loss < 2dB, Isolation TX-RX ≥ 90 dB@ 1710-1785 Mhz.

The rest of this paper is structured as follows: Section 2 presents the synthesis methodology of LTE filter. The filter properties are analyzed in Section 3. Numerical simulations and results are shown in Section 4 and Section 5, respectively. Our conclusion is given in Section 6.

2. Synthesis of LTE filter

The filter synthesis procedure commences with analyzing specification to reformulate the transfer and reflection parameters (S11, S21) which satisfy the rejection and in-band specifications [9], [10], [11]. Since the Generalized Chebyshev response may minimize the discrepancy between the idealized and the actual filter characteristics over the range of the filter, but with ripples in the passband, it is used to describe the behavior of the filter. The next step is for the configuration of the coupling matrix for realizing the filter response. Finally, the dimension of filter is defined, including the order of filter, number of TZs, topo of filter. There are a couple of tools being available for calculating coupling matrix, such as coupling matrix optimizer, dedale-HF, Coupling Matrix Synthesis (CMS) software, and so on.

The transfer and reflection function may be expressed as a ratio of polynomials [8]:

$$S_{11}(\omega) = \frac{F(\omega)/\epsilon_r}{E(\omega)} \tag{1}$$

$$S_{21}(\omega) = \frac{P(\omega)/\epsilon_r}{E(\omega)} \tag{2}$$

In which,

$$\varepsilon = \frac{1}{\sqrt{1-10^{-RL/10}}}\left|\frac{P(\omega)}{E(\omega)}\right| \tag{3}$$

The order of the filter based on Generalized Chebyshev response can be given by:

$$N \geq \frac{L_A+L_R+6}{20log_{10}\left[X+\sqrt{X^2-1}\right]} \tag{4}$$

Where L_A is the insertion loss in stopband, L_R is the return loss in passband, X is the ratio of stopband to passband frequency.

Transmission zeros component is used to provide a high close-to band rejection of RF noise and interference [12]. This component can be added in the filter model by several ways, e.g., a dumbbell element between non-adjacent resonators.

There are two stratetries to initialize the coupling matrix optimization, i.e., the mainline coupling factor decreases from 1 to 0 and the symmetrical matrix. In the triplet topology case, the tuning resonant cavity offset and the tune mainline coupling is optimized in order. In the quadrupt topology case, the order of optimization steps are reversed to the above case. After reaching the reflection and transfer specifications, the rejection loss is optimized. The result of synthesis LTE filter is shown in Figure 1 and Figure 2:

Coupling Matrix (CM)

	S	1	2	3	4	5	6	7	8	9	10	11	L
S	0	1.1145	0	0	0	0	0	0	0	0	0	0	0
1	1.1145	0	0.9352	0	0	0	0	0	0	0	0	0	0
2	0	0.9352	0	0.6268	0	0	0	0	0	0	0	0	0
3	0	0	0.6268	0	0.5603	0	-0.1000	0	0	0	0	0	0
4	0	0	0	0.5603	0	0.6477	0	0	0	0	0	0	0
5	0	0	0	0	0.6477	0	0.5316	0	0	0	0	0	0
6	0	0	0	-0.1000	0	0.5316	0	0.5423	0	0	0	0	0
7	0	0	0	0	0	0	0.5423	0	0.5406	0	-0.0800	0	0
8	0	0	0	0	0	0	0	0.5406	0	0.6416	0	0	0
9	0	0	0	0	0	0	0	0	0.6416	0	0.6248	0	0
10	0	0	0	0	0	0	0	-0.0800	0	0.6248	0	0.9352	0
11	0	0	0	0	0	0	0	0	0	0	0.9352	0	1.1145
L	0	0	0	0	0	0	0	0	0	0	0	1.1145	0

Figure 1. *Result of coupling matrix optimization*

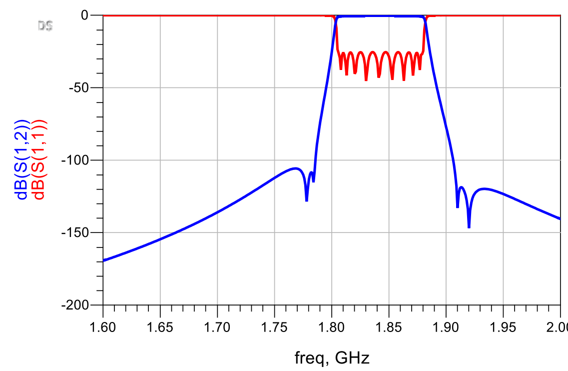


Figure 2. *S-parameter response*

The topology of filter according to the result of coupling matrix is presented in Figure 3.

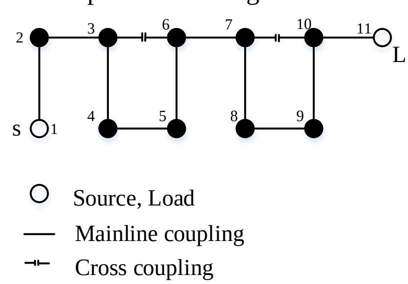


Figure 3. *Filter topology*

The result of synthesis is one quadrupt filter topology with 11 poles, two cross coupling, bandwidth of 75 MHz, the reflection S11 less than -20dB.

3. Analysis of filter's properties

After obtaining the coupling matrix from the filter specifications, the next step is to realize it with coupled resonator structure. This part of the process involves the selection of a certain resonator type, the use of coupling line to provide the desired coupling value between resonators and the implementation of a feed structure.

Firstly, a single cavity is calculated to optimize its consonance at the center value of the wanted frequency. Quarter-wave (λ/4-wave) coaxial resonators are constructed by shorting the center conductor of a coaxial cable to the shield at the far end of the circuit (in Figure 4), which acts like a parallel tuned L/C tank circuit [13]. Secondly, the diameter of resonator and cavity is calculated. The choice of combination of dielectric diameter D and conductor diameter d is a subject discussed in the following relations. If the unload quality factor is known for a cylindrical coaxial resonator, the following relation can be obtained from its derivative as follows:

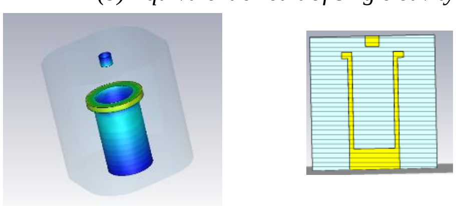
$$Q_u = \omega_0 \frac{L}{R} = \omega_0 \frac{\mu}{R_s} \frac{\ln(\frac{D}{d})}{(\frac{1}{d}+\frac{1}{D})} \quad (5)$$

with Q_u being maximum when D/d ~ 3.6 [14].

Because the electronic field focuses on the top of resonator, one cylindrical with bigger diameter is added to improve Q-unload as Figure 5. From the result of simulation, Q_u increases approximately 360° when the length of resonator is kept.

(a) (b)

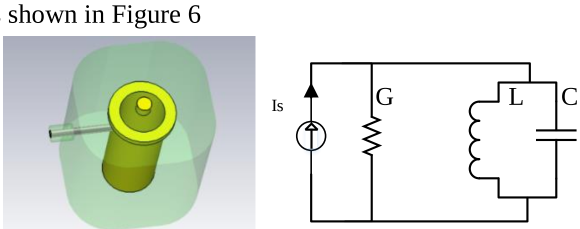
Figure 4. *(a) 3D model of single cavity (b) Equivalent circuit of single cavity*



(a) (b)

Figure 5. *Adding a cylindrical with bigger diameter (a) 3D model. (b) Elevational view*

Thirdly, the group delay method is applied to determine the location of feed line. The input coupling 3D model equivalent circuit of the input coupling and first resonator is shown in Figure 6



(a) (b)

Figure 6. *(a) The input coupling in 3D model; (b) The equivalent circuit of input coupling and the first resonator*

Resonant frequency $\omega_0 = \sqrt{LC}$. L,C are the conductor and capacitor of the equivalent circuit of the first resonator. External quality $Q_e = \frac{\omega_0 C}{G}$, in which, G is the admittance of the feed line. The group delay has its maximum value at resonance when $\omega = \omega_0$: $\tau_{max} = \tau(\omega 0) = (4Qe/\omega 0)$. The calculated results are Q_e of 19.26445, group delay T_d of 6.65625 ns at f_0 = 1.8425 GHz.

4. Simulation of LTE cavity filter

4.1. Workflow in design of one resonator filter

Before designing the filter by means of the software, bandwidth coupling or bandwidth cross coupling between two resonator is calculated. The designing workflow is composed of three steps as shown in Figure 8, which includes threes steps as follows:

(i) Creating some sub-projects (calculating parameters of resonators, cavity, mainline coupling, and probe location).

(ii) Assembling filter without TZs.

(iii) Turning filter with TZs.

In the first step, a single cavity is calculated to optimize its consonance at the center value of the wanted frequency. The inter-resonator coupling between the adjacent resonators, excluding the connection between the resonators 1st and 2nd, and the input/output of the resonator are also determined in this step. These calculations lead to the optimization of the external quality criterion Q_e which is energy coupled into the first or the last cavity. Then, the inter-coupling cavity between the first and last cavities is built up to determine coupling bandwidth between the 1st and 2nd cavities. The final sub-project needed to be designed is the cross-coupling in order to connect two resonator cavities by one cross-coupling and to adjust the length of two bells to reach the wanted bandwidth calculated above. In the second step, a filter without TZs is assembled including dimensions of resonator, cavities, coupling widows. The goal of this step is to correct the center value of wanted frequency. Finally, in the third step, cross-couplings are added to the filter. By optimizing the transfer parameters (S21, S12) with positions of TZs and turning S11 parameters, the center frequency is corrected again. An example of a filter comprised of 4 cavities is sketched in Figure 7.

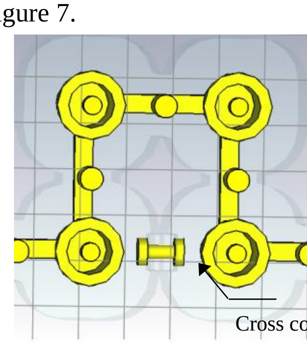


Figure 7. *Cross coupling in quadrupt topology*

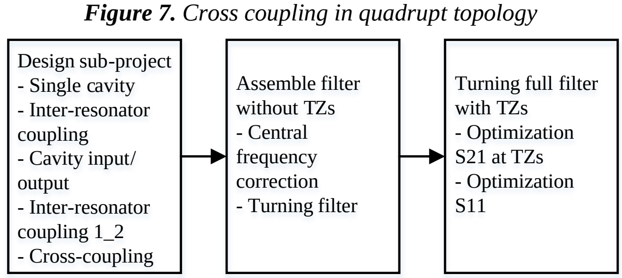


Figure 8. *The systematical workflow of resonant filter design*

4.2. Numerical simulations

In practice, we can estimate the unloaded quality factor Qu and the external quality factor Qe using EM-Simulator software as HFSS or CST [15,16]. The single cavity structure has been designed to obtain resonant frequency with desired unloaded-Q. In this model, a metal resonator ring is added at the top of resonator to increase unloaded-Q. The length of resonator equals 0.5 or 0.8 of a quarter wavelength. In this design (f_0 = 1.8425GHz), we choose 20 to 30 mm and then we change step by step to turn the length of resonator.

After determining the structure of the single cavity, an 2-pole structure has been built up to calculate main line coupling. Physically, main line coupling or main line bandwidth depends on the open aperture between each pair of resonators as well as the length of turning screw between them.

The filter needs to be connected to other system at the first/last resonator of the filter. The connectors are designed as connector N-type, the core of connector is made by silver, whereas the coat and envelope are made by a dielectric material such as Teflon. This core has been soldered directly into the first/last resonator. The external-Q is varied when the height of the connector compared with ground plane changes. The center frequency of group delay is changed when the height of the first resonator self-screw varies.

As shown in Figure 3, two negative couplings between two non-adjacent cavities (cavities number 3 and 6, 7 and 10) are required. Electrical-fields distribute strongly at the top of the resonators meanwhile magnetic fields dense concentrate at the bottom. To build a capacitive coupling, we can use a shield between two resonators with the gap in top. A metallic dumbbell could be added to increase the interaction of electric fields. Dumbbells are fixed on the filter by Teflon. The main parameters of the filter are listed in table [1].

The main line coupling can be improved by a metal cylinder with a rectangular cross section between two resonators. The thickness of line is chosen so easily for production and the length of main line coupling is 12mm.

Table 1. *Main parameters of the filter*

Main parameters of the filter	**Results**
The order of the filter	11
Dimensions of single cavity (Length* Width*Height)	30mm*30mm*32mm
Aperture open	From 11 to 17mm
The height of resonator	24.5mm
Inner diameter of resonator	6mm
Outer diameter of resonator	5mm
Gap between two adjacent resonator	2mm
The thickness of metal cylinder	3mm
Tap height	9.3mm

After calculating each part of the filter using CST software, each single component is connected to create a complete filter as Figure 9.

After that, the initial filter has been turned and optimized using CST functions to achieve desired results.

(a)

(b)

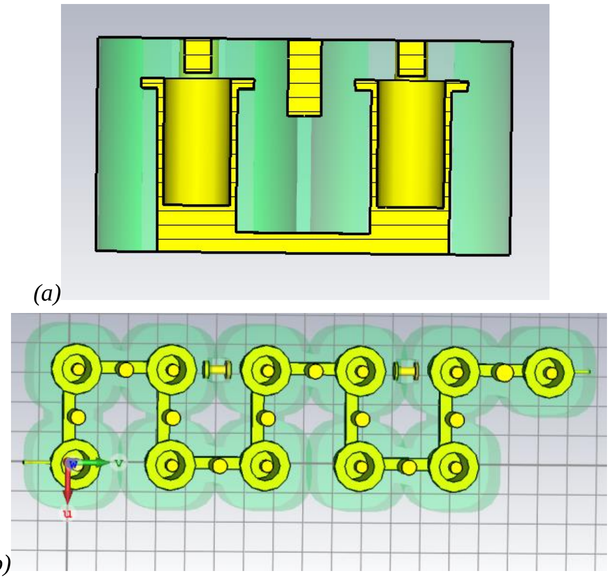


Figure 9. *(a) The cutting plane of two resonators (b) The Complete filter design*

5. Obtained results

The results of simulation of the whole filter without turning are shown in Figure 10. It can be seen that S11 > -10 dB, S21 > -1 dB in the passband.

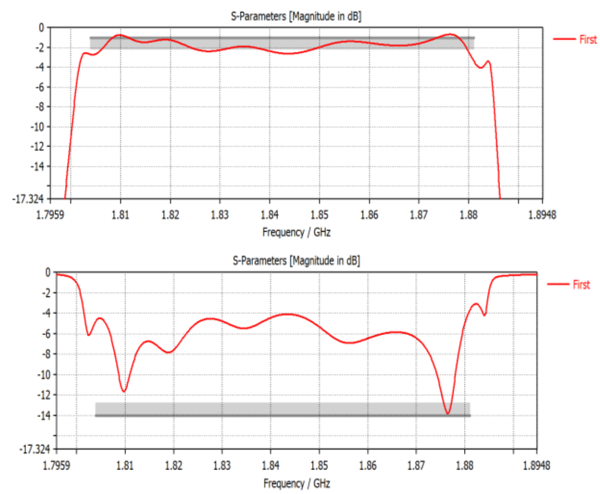


Figure 10. *Simulation results of S11 and S21 before turning*

The value of group delay time depends on the height of the feed line (H_f), in which, τ_d increases when H_f decreases. The center frequency depends on the length of self-screw of the input resonator.

We set each parameter range to be inversely proportional to how sensitive the S-parameter response of the filter is to variations in that parameter. In this case, the heights of the self-screw are allowed to vary by 10%. The algorithm is CMA Evolution Strategy. The goals of the optimization are as follows:

(i) To reduce S11 to below -14 dB across the range from 1803 MHz to 1882 MHz.

(ii) To reduce S21 to above -1 dB across the range from 1803 MHz to 1882 MHz.

(iii) To reduce S21 to below -91dB across the range from 1710 MHz to 1785 MHz.

The fast simulation time achieved with the frequency domain solver allows us to perform an optimization of 3000 iterations under 24 hours to get the improved results.

After optimizing, the responds of the filter are shown in Figure 11. The center frequency is 18425 MHz, bandwidth is 78 MHz, insertion loss is smaller than 1 dB and the band rejection is -85 dB at 1710-1788MHz. The reflection is less than -10dB. It can be seen that the results satisfy the design requirements.

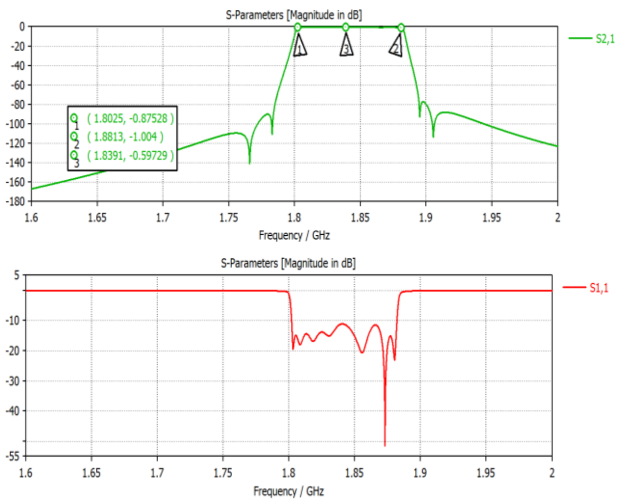


Figure 11. *Simulation results of S11 and S21 after turning*

6. Conclusion

In this work, a model based on the 11th order vacuum resonator filter with two transmission zeros is presented. The procedure of synthesis from requested specifications and the designing steps of the resonator cavity filter is given in detail. The simulation results demonstrate that the obtained characteristics are improved in comparison with the requested specifications, i.e., Return loss < -10dB@1805-188 MHz, Passband ripple < 0.2dB, Insertion Loss < 2dB, Isolation TX-RX ≥ 90 dB@ 1710-1785 Mhz. For our future work, this filter can be fabricated by dielectric materials to improve its operating characteristics such as size, quality factor. This proposed filter is suggested to be developed and applied in LTE system and other commercial products.

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