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A Novel Capacitive Cross - Coupling for Enhancement of Microwave Cavity Filter

***Tran Thi Thu Huong*[1,2], *Vu Van Yem*[1,*]**
[1]*Hanoi University of Science and Technology, Hanoi, Vietnam*
[2]*University of Economics - Technology for Industries, Hanoi, Vietnam*
[*]*Email: yem.vuvan@hust.edu.vn*

Abstract

Normally, the microwave cavity filter is cast and gilded, which causes a fixed transmission zero point. Thus, the specifications of the filter cannot be turned during its operation. A novel enhancement capacitive cross-coupling structure is proposed to fabricate a microwave cavity filter with a turnable transmission zero point. This structure is implemented by adding a new tap screw to the center of the supporting Teflon piece of cross-coupling dumbbell resulted in an adjustable capacitor. The capacitive cross-coupling factor is achieved a greater value leading to an improved slope of the cavity filter. The simulation results show that cross-coupling bandwidth can be varied in the range from 35.4 MHz to 40 MHz by changing the screw length from 0 mm to 7 mm, respectively. To verify the efficiency of the novel design, this structure is used to fabricate a microwave cavity filter in eNodeB for Band 3 - Long Term Evolution (LTE) application. The filter is built up of 10 coaxial resonator cavities with two new capacitive cross-couplings. The simulation results of the filter fully meet specification requirements including a band of 1805 to 1880 MHz, return loss below -12.7 dB, passband ripple of 0.1 dB, and insertion loss below 0.2dB. For a bandwidth below 20 MHz, the signal rejection reduces 1 dB by changing the screw length from 0 mm to 6 mm. In addition to Band 3, this structure can be developed for different frequency bands.

Keywords: Cavity filter, resonator, cross-coupling, band-pass filter, screw.

1. Introduction

The unwanted signal is isolated by the band-pass filters in the base station system in an advanced mobile network. Although, the microwave cavity filters have been used since 1940s but now they are still widely used because of their advantages. Their characteristics are low insertion loss, high power handing and easy integrating with other units in the transceiver systems. Moreover, the frequency resources are limited and the selectivity of band-pass filter is usual in the wireless systems. The concept of transmission-zero (TZ0) or null is the critical frequencies where signal transmission between input and output is stopped. In the cavity filter, two nonadjacent cavities can be connected by a capacitive or inductive cross coupling. This line makes one or two transmission-zero. An approximate model of cross coupling wall is relevant lumped element components [1]. By analyzing the phase of signal that transmits in the filter, a null above the band-pass is made by a inductive cross – coupling with cascade triplet whereas a null under the band-pass is created by capacitive cross – coupling. Moreover, a cascaded quadruplet with capacitive cross – coupling produces two transmission-zeros (TZ0s) zeros on the lower and upper skirt. In simulation, inductance and capacitive properties of a cross coupling line are distinguished by phase of transmission signal [2].

For design solutions of cross – coupling, there are several types of different physical models. In planar technology, TZ0s is made by the coupling strip [3]. In ceramic-filled cavity filter, capacitive coupling is generated by the surface of the silver-plated ceramic [4]. In waveguide cavity, the structure of cross-coupling is variety, several coupling structures of coaxial cavities are studied to evaluate the selectivity of the filter in [5], in which, the cross coupling with a metallic dumbbell is also analyzed. A new internal bypass metallic loop structure is proposed to introduce transmission-zeros below or above pass band by adjusting the length of this wire [6]. One mixed Cross-Coupling that is carried out in [7] allows to control the number of transmission-zeros. However, all these solutions are restricted with strength of cross coupling or coupling bandwidth between two cavities. TZ0 point position fine-tuning step is difficult, often have to cast some dumbbells for backup. To overcome this limitation, a novel cross coupling structure is proposed to get stronger coupling strength. The position of TZ0 can be tunable without backup the dumbbell. This novel structure consists of a metallic tap screw adding to the center of PTFE piece of the old cross coupling structure in [5]. Thus, a new capacitor is made by the tuning screw, the cross bar of dumbbell and PTFE dielectric. Therefore, the electromagnetic coupling can be impacted.

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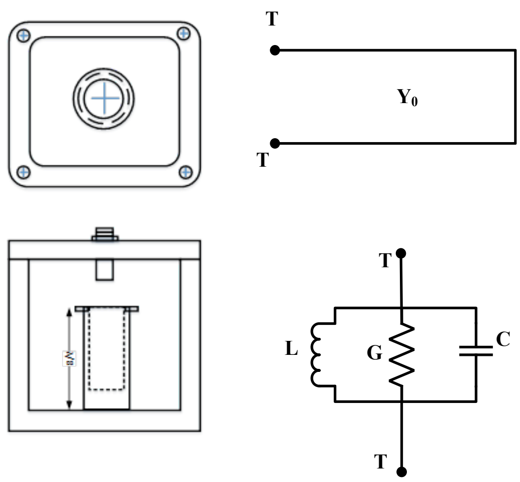
The rest of paper is organized as the following. In Section 2, the review of modelling and designing method of cavity filter is described, in which tuning methods is used flexibly in designing steps. A novel cross coupling structure is proposed and decomposed in Section 3. A cavity band-pass filter in LTE transceiver system using the proposed cross coupling is designed and simulated and the results are presented in Section 4. Finally, a brief conclusion is given in Section 5.

2. Modelling and Designing Method of Iris-Coupled Cavity

2.1. Method for Designing a Cavity Band Pass Filter from Low Pass Prototype Filter

There are three basic steps in a designing one cavity filter: Analysis and synthesis of the cavity filter for finding the topology of filter (arrangement of resonance cavities, the number of transmission-zeros); model designing of the cavity filter (including a single resonator cavity, the mainline coupling, cross coupling, external coupling, and full cavity filter model); tuning and optimizing the cavity filter manual and automatic.



(a) (b)

Fig. 1. a) Cross sections of a cavity resonance. b) Equivalent LC circuit of one coaxial cavity.

The cavity filter can be assumed as a network of lumped elements connected in series or parallel in which the real impedance part is extreme at a certain frequency. The serial network is related to the minimum of input impedance, while the parallel network is related to the maximum input impedance value at resonant frequency. The coaxial cavity filter with quansi-$\lambda/4$ resonator has an equivalent circuit model in Fig. 1. The inner inductor is implemented by one cylindrical tube with silver – plated surface. It is coaxial with the cavity and it has a hole in the middle to reduce the weight without affecting the inductance value. Moreover, bottom of resonator is integrated with the housing. So, the inner inductor is connected to ground plane. The capacitor element is made by a metal screw and resonator with air dielectric. Additionally, one part of screw is integrated the cover of cavity filter. From that, one LC parallel circuit is made up. The conductivity element is the characteristic quantity for losses of a resonator cavity. So, a cavity resonator has an equivalent diagram as GLC parallel circuit as in Fig. 1b.

The insertion loss of a single cavity resonator can be expressed as the following equation:

$$L(f) = -10\log\left[\frac{1+\left(2Q\dfrac{f-f_0}{f_0}\right)^2}{\left(1-\dfrac{Q}{Q_u}\right)^2}\right] \quad (1)$$

in which, Q is the loaded quality coefficient, Q_u is the unloaded quality coefficient. At $f = f_0$,

$$L(f) = -10\log\left[\frac{1}{\left(1-\dfrac{Q}{Q_u}\right)^2}\right] \quad (2)$$

or

$$Q_u = \frac{Q}{1+10^{\frac{L(f_0)}{20}}} \quad (3)$$

The exact value Q_u can be found from the insertion loss value at resonance frequency and -3 dB bandwidth of a cavity filter. A coupling probe of cavity must be balanced and minimum to avoid the source impedance and load impedance affecting on resonator; SWR of load must be the lowest value; input SWR at f_0 is minimized to avoid loss based on the non-matching.

$$G = Y_0\alpha_t l = \frac{2n-1}{4}Y_0\alpha_t\lambda_{g0} \quad (4)$$

$$b = \omega_0 C = \frac{1}{\omega_0 L} = \frac{2n-1}{4}\pi Y_0\left(\frac{\lambda_{g0}}{\lambda_0}\right)^2 \quad (5)$$

$$Y_{in} = G + jb\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right) \quad (6)$$

$$Q = \frac{b}{G} = \frac{\pi\lambda_{g0}}{\alpha_t\lambda_0^2} \quad (7)$$

In which, n = 1, 2, 3…; G is the real-valued conductance; Y_0 is the admittance of the transmission line connecting the resonators; α_t is the attenuation factor of cavity; λ_{g0} is the propagation wavelength of prototype filter; b is the susceptance of the resonator; Y_{in} is the input characteristic admittance of the resonator; Q is the quality factor of cavity resonator; ω_0 is midband corner frequency; λ_0 is the propagation wavelength at the midband frequency.

The link between the two resonant cavities can be the most significant factor affecting on a filter performance. To simplify the production and tuning, a common coupling method is shown by Matthaei [8] by using an impedance inverter [K-] and admittance inverter [J-]. Two cavities are coupled the electromagnetic energy by a coupling wall. Coupling coefficient is [8]:

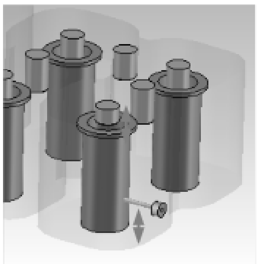
$$k_{j,j+1}\Big|_{j=1\to n-1} = \frac{J_{j,j+1}}{\sqrt{b_j, b_{j+1}}} = \frac{\omega}{\omega_1^{'} \sqrt{g_j g_{j+1}}} \quad (8)$$

The field distribution of one cavity resonator and coupling structure will be shown in the Section 3.

2.2. Tuning Methods

There are several tuning methods such as Group Delay, Field Strengths, Pin-Probes and Eigen Modes, Port-Tuning, Slope Susceptance, Sensitivity Data. These tuning methods can be used in conjunction with each other in the designing steps. In this paper, Group Delay method is used to tune the location of the probe so that the value of the first resonator group delay is satisfied with requirement. The second method is Slope Susceptance to tune coupling bandwidth.

In the designing and tuning the input and probe in Fig. 2, there are following notes: Except the first and second cavity resonators, the rest resonator circuittions are shorted by turning shelf coupling screws to the bottom; the height of the probe and the length of self - coupling screw at input or output resonator are varied. When the value of the group delay reaches the maximum at the center frequency and is equal to the calculated value in synthesis step, a true design probe location is obtained.



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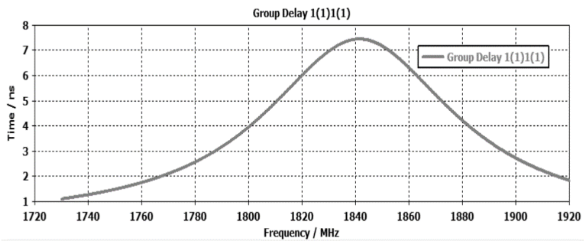


(b)

Fig. 2. a) Input/out probe designing. b) Group delay simulation result.

To design the coupling line between two cavities as the wanted CBW_{ij}/K_{ij} above, the slope susceptance method is applied. Firstly, the discrete ports are added to all cavity resonator with impedance of 50 ohm. [S] scatter parameters and [Y] admittances are calculated in Spara task of CST microwave schematic. The results show the images of *Y* and *k* parameters in task Post processing base on (9) [9].

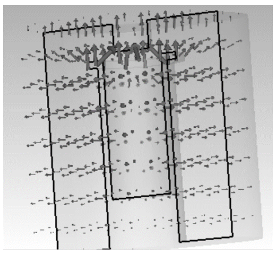
$$k_{ij} = \frac{2.B_{ij}}{\sqrt{\frac{dB_{ij}}{df}\frac{dB_{ij}}{df}}} = 2.\frac{im(Y_{ij})}{sqr(im(Y_{iideriv}))}.(im(Y_{jjderiv})) \quad (9)$$

Parameters *(imY, Y_{deriv}, k_{ij})* can be calculated by *mix template results* feature of CST studio suite. In the next section, a novel cross coupling structure with a new iris is proposed to help to improve slope of transferred feature of cavity filter.

3. Novel Cross-Coupling Structure of Cavity Filter

3.1. Cross Coupling Structure and Its Principle

The electromagnetic field of a cavity resonator is simulated in Eigen mode and shown in Fig. 3. As the result, the electrical field concentrates within the gap of screw and resonator and the magnetic field is largest at the bottom of resonator.



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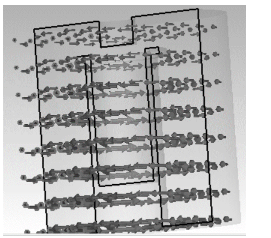

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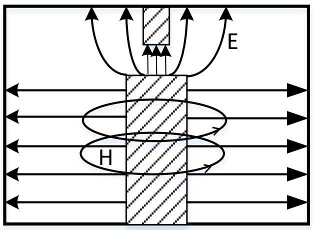

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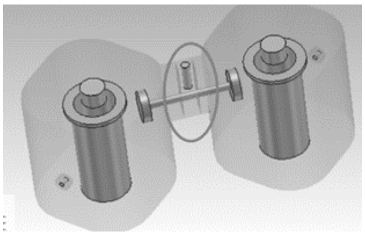
Fig. 3. The EM field distribution in the resonant cavity. a) The electrical field strength. b) The magnetic field strength. c) The electromagnetic field diagram.



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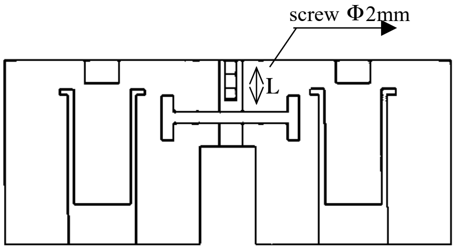


(b)

Fig. 4. a) 3D model of cross coupling between two non-adjacent cavities. b) Vertical cut of cross coupling.

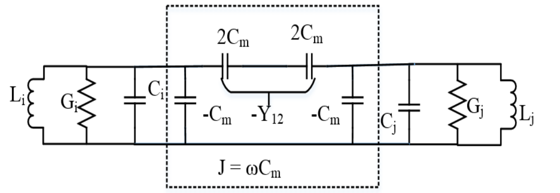
In cavity filter, the triplet cross coupling is used to create a transmission-zero at bellow of the pass band [1]. In this structure, the cross coupling consists of two dumbbells, one cross bar, one piece of PTFE dielectric and a tuning screw. The cross bar is used to connect two dumbbells. A new metal screw is added to the center of cross bar dumbbell structure. The PTFE piece is used to support this bar, it is spiral tapping to help to tune screw. Moreover, one end of this screw is attached to the filter cover, the other end is exposed to the air in the center of PTFE. Thus, the new capacitor is created in which the screw and cross bar are the polarities of the capacitor with PTFE and air dielectric. L_c (mm) is the length of cross coupling screw, height of PTFE is h_{ij} (mm), radius of a dumbbell is r_cross (mm), cross bar length is L_{cross} (mm) (Fig. 4).

3.2. Analysis of coupling characteristics of the proposed structure

The cross – coupling structure links both capacitive and inductive parts of two nonadjacent cavities. In the old capacitive cross coupling structure (without cross screw), two dumbbells and resonators create an equivalent model in Fig. 5a [11]. The equivalent model of proposed cross coupling is considered as presented in Fig. 5b. Because of added new screw, a new capacitor C_s is created the screw connects. Dielectric of C_s is made by air and PTFE and it is a variable capacitor. Because the surfaces of screw and resonator are kept at constants, so the value of C_s dependents on the length of cross coupling screw.

The capacitor cross coupling has the larger value:

$$C_m' = C_m + C_s \tag{10}$$



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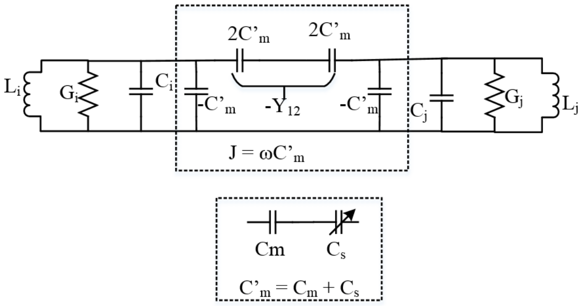


(b)

Fig. 5. a) Equivalent model of old cross coupling structure. b) Equivalent model of the proposed cross coupling structure.

where C_m is the capacitor of old cross coupling and the admittance inverters

$$J'_m = \omega C'_m \tag{11}$$

The frequency of odd and even modes are:

$$f_{odd} = \frac{1}{2\pi\sqrt{L\left(C + C_m^{'}\right)}} = \frac{1}{2\pi\sqrt{L\left(C + C_m + C_s\right)}} \tag{12}$$

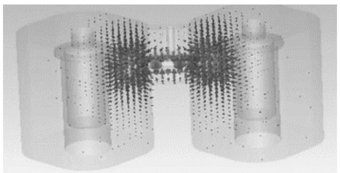
$$f_{even} = \frac{1}{2\pi\sqrt{L\left(C - C_m^{'}\right)}} = \frac{1}{2\pi\sqrt{L\left(C - C_m - C_s\right)}} \tag{13}$$

The capacitive coupling coefficient is:

$$k_E = \frac{C_m^{'}}{C} = \frac{f_{odd}^2 - f_{even}^2}{f_{odd}^2 + f_{even}^2} \tag{14}$$

From that, f_{odd} is decreased and f_{even} is increased. So the capacitive coupling coefficient is also become larger. In other words, the coupling bandwidth of the proposed structure is also increased.

To evaluate its coupling bandwidth, an Eigen mode simulation of a cross coupling is shown in Fig. 6a. Two wave guide ports link weakly with cavity resonator. PTFE is tapped by a spiral with depth of 7 mm. We can see that electrical energy is focused on the middle contact surface cross bar and new screw. So electrical energy coupling between two cavity resonators are increased at a new post. When changing the srew length L_c (mm), the coupling bandwidth of two cavity resonators is changed. The simulation results about amplitude and phase are presented in Fig. 6b.



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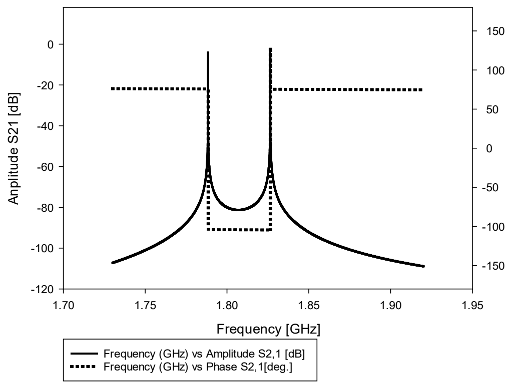

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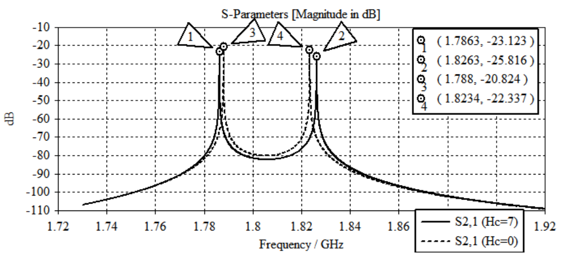
Fig. 6. a) Electrical energy density in Eigenmode simulation of a cross coupling. b) Amplitude and phase of S21 in a cross-coupling line



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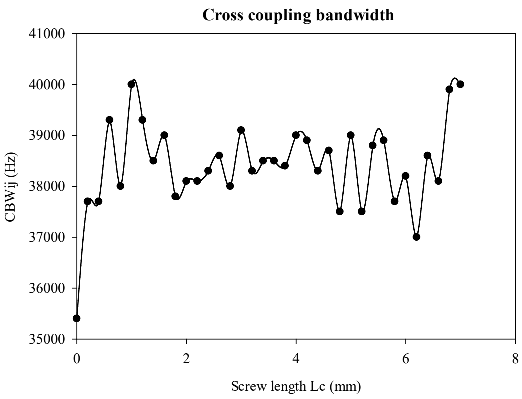


(b)

Fig. 7. a) Cross CBW results. b) Relation between the Cross CBW and screw length.

It can be seen from Fig. 7 that if one new screw is added, the cross-coupling bandwidth (CBW) increases rapidly (~2.7 MHz). If L_c is changed from 0 mm to 0.2 mm, CBW raises the value of 2.3 MHz. And if L_c changes in range 0⇗7 mm, CBW varies the value of 4.6 MHz (from 35.4 MHz to 40 MHz). This show that CBW reaches the larger value. The rejection slope in the cutoff band is steeper. Moreover, the capacitor C_s can be variable by tuning screw, so using this screw to help to optimal position of TZ0 point in post-production step. Thus, the out of band rejection slope of the filter can be optimized by turning this cross coupling screw without changing dumbbell. Moreover, the diameter of the cross coupling screw is small (Ø = 2 mm), so C_s also has a small value. The post-production tuning step is more flexible.

4. Filter Design Example

4.1. Filter Design

One cavity filter with the proposed structure is designed as following. This cavity filter is used in eNodeB Band 3 with frequency range of 1805-1880 MHz, pass-band ripple of 1 dB, insertion loss maximum of 1.2dB, return loss in pass band of -10dB, out - of - band rejection of 100 dB.

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

$$N \geq \frac{L_A + L_R + 6}{20\log_{10}[X + \sqrt{X^2 - 1}]} \qquad (15)$$

where L_A is the insertion loss in stopband, L_R is the return loss in passband, X is the ratio of stopband to the passband frequency [10]. The 10th order triplet topology of this filter has been shown in Fig. 8a. It is also added two transmission-zeros between resonators 3 and 5, 5 and 7 to increase the sharp roll-off of filter at stopband attenuation. Equivalent schematic model of the filter with proposed cross coupling is presented in Fig. 8b.

Simulation results in Genesys software is shown in Table 1. These simulation results will be used in optimization step. With the coaxial cavity, the value of unloaded-Q has last mostly from 1000 to 6000 [12]. It should be noted that a higher value of Q_u leads to a higher selectivity, a sharper behavior of filter, and to a smaller ripple level in pass band. Q_u is calculated based on the mid-band insertion loss value IL(f_0) as follows:

$$Q_u = \frac{4.343\sum_{i=1}^{N} g_i f_0}{\Delta f . IL(f_0)}, \qquad (16)$$

The external quality factor of cavity i+1 is computed as:

$$Q_{ex,i+1} = \frac{g_i g_{i+1}}{BW} \text{ for i =1 to (N-1)} \qquad (17)$$

The group delay is related to Q_e as

$$\Gamma_{d1}(\omega_0) = \frac{4Q_e}{\omega_0} \qquad (18)$$

Table 1. CBW_{ij} of two adjacent and non-adjacent cavities.

CBW_{ij}	Values (MHz)	CBW_{ij}	Values (MHz)
$CBW_{S,1}$	91.967	$CBW_{5,7}$	-15.88
$CBW_{1,2}$	70.759	$CBW_{6,7}$	39.810
$CBW_{2,3}$	48.164	$CBW_{7,8}$	44.111
$CBW_{3,4}$	39.244	$CBW_{8,9}$	48.164
$CBW_{3,5}$	-20.141	$CBW_{9,10}$	70.759
$CBW_{4,5}$	37.673	$CBW_{10,L}$	91.967
$CBW_{5,6}$	39.310		

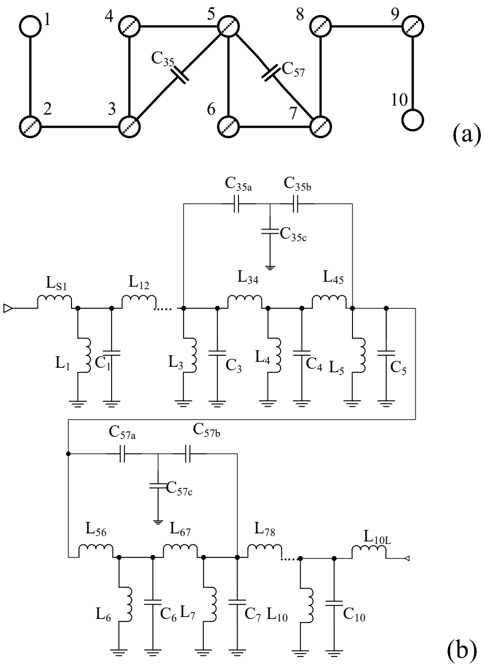


Fig. 8. a) The topology of cavity filter. b) Equivalent schematic model.

Practically, the unloaded quality factor Q_u and the external quality factor Q_{ex} can be estimated by using EM-Simulator software as HFSS or CST. The single cavity structure has been designed to obtain resonant frequency with desired unloaded Q. In this model, metal resonator ring is added at the top of resonator to increase unloaded Q.

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

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 enveloped are made by a dielectric material such as Teflon. This core has been soldered directly into first/last resonator. The external-Q factor is varied by changing the height of the connector compared with ground plane.

Table 2. Main parameters of the filter.

Main parameters of the filter	Results
The order of the filter	10
Dimensions of single cavity (Length*Width*Height)	30mm*30mm*32mm
Aperture open (W_{ij})	$W_{12,67}$ = 10mm W_{78} = 15mm W_{89} = 17mm W_{910} = 20mm
The height of resonator	26.3mm
Inner diameter of resonator	6mm
Outer diameter of resonator	5mm
Gap between two adjacent resonator	2.2mm
Tap height	8.1mm
Diameter of self-coupling screw	4mm
Diameter of main-coupling screw	4mm

Table 3. Parameters of cross coupling.

Main parameters of the filter	Results
Diameter of dumbbell 3 5	15.4mm
Diameter of dumbbell 5 7	16.2mm
Length of dumbbell	2mm
Diameter of cross-coupling screw	4mm

The main parameters of the filter are calculated step by step [13]. The dimensions of resonator and cavity depend on resonant frequency, quality factor of filter; Aperture opens depend on coupling bandwidth, the bandpass ripple and slope parameters; The tap height is calculated from the external quality factor. After that, these parameters are optimized by EM simulation tools. The parameters of cross coupling are designed by calculating the approximately value. After that, the cross coupling structure is optimized so that the coupling bandwidth is approximately 20MHz. The main parameters of the filter are listed in Table 2. As shown in Table 1, we need the negative coupling factor between two non-adjacent cavities (cavities: 3rd and 5th, 5th and 7th) with the bandwidth of 20.14 MHz and 15.88 MHz. The dimensions of capacitive cross coupling structure are optimized to achieve the desired coupling bandwidth. These parameters are listed in Table 3.

After calculating each part of the filter using EM-simulation software, they are connected to create a complete filter as shown in the Fig. 8. This initial filter has been tuned and optimized by using CMA (Covariance Matrix Adaptive) evolution strategy algorithm in order to achieve desired results.

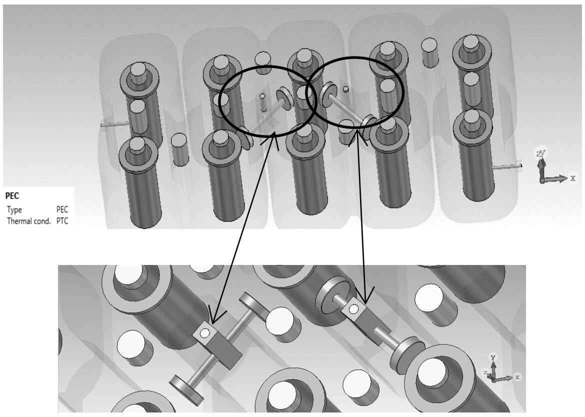
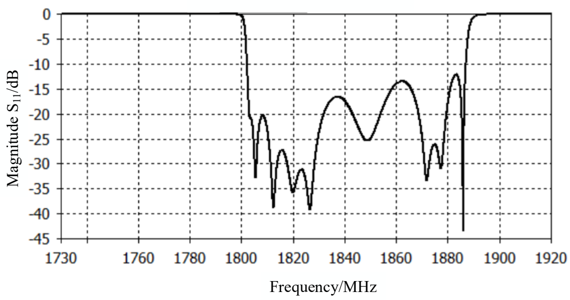


Fig. 9. Physical model of the complete filter



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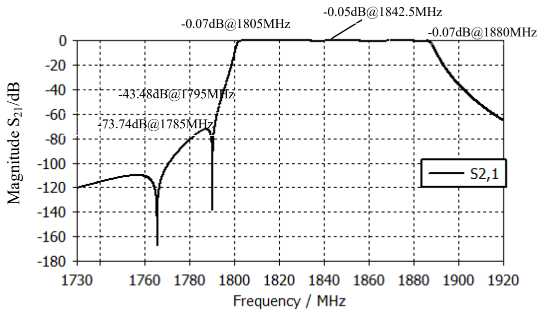

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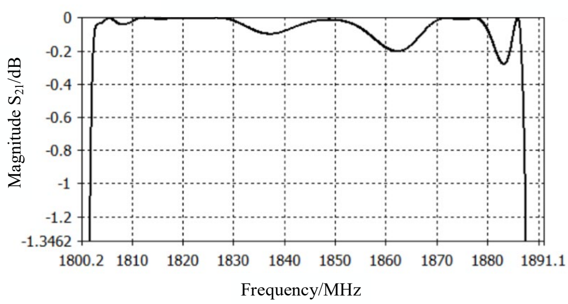


(c)

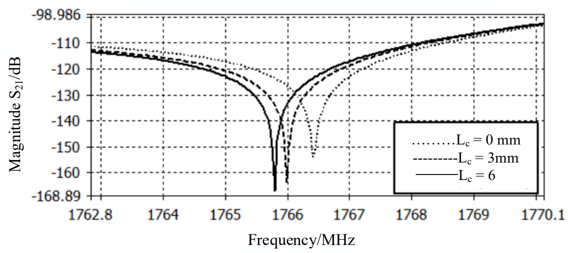
Fig. 10. Simulated S-parameters response. a) S_{11}/dB. b) S_{21}/dB. c) Ripple of S_{21}/dB

4.2. Simulation Results and Evaluation

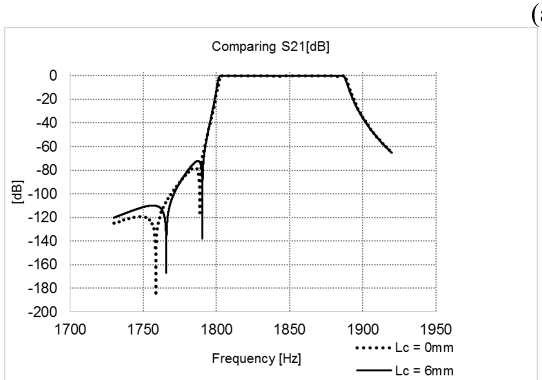
The responses of the filter are shown in Fig. 10. The center frequency is 1842.5 MHz, bandwidth is 75 MHz, insertion loss is smaller than 0.2 dB and the band rejection is -103 dB at 1770 MHz. The return loss is about 12.7 dB, pass band ripple is 0.1 dB. It can be seen that the results satisfy the design requirements, even some features are better than required objects.

Simulation results with two different values of cross coupling screw length are presented in Fig. 11, in which, L_c = 0 mm and L_c = 6 mm. In Fig. 11a, the position of transmission zero drops with the cross-coupling bandwidth of L_c of 6 mm is larger compared to L_c of 0 mm. The second transmission-zero in case L_c of 6 mm is lower than that in case L_c of 0 mm of 14 dB as in Fig. 11b.

In comparing out of band slope characteristic S_{21}[dB], the two following cases have been considered: 43.33dB@1795 MHz (L_c = 0 mm), 43.48dB@ 1795 MHz (L_c = 6 mm); S_{21} = -72.6dB@1785MHz (L_c = 0 mm), -73.75dB@ 1785MHz (L_c = 6 mm). At 1785MHz, is the edge frequency band RX filter in Band 3 transceiver system), S_{21} is improved ~1 dB. Moreover, positions of TZ0 points are changed when changing L_c. The position of TZ0 when L_c = 6 mm is closer than with L_c = 0 mm. This is an important, useful feature that makes fine-tuning easier.



(a)



(b)

Fig. 11. a) Transmission-zeros with different lengths of cross coupling screw. b) Comparing S_{21} with two cases

Table 4. The comparison of state-of-the-art cavity filters with cross-coupling

Parameters	[14]	This work
Cross-coupling	Rotated Rod	Dumbbell+screw
Order	4	10
f_0 (GHz)	2.02	1.8425
Bandwidth (MHz)	30	75
Insertion loss (dB)	0.72	0.2
Return loss (dB)	23	12.7
Stopband Rejection	32@BW-10MHz	43.48@BW-10MHz

It is difficult to compare the specifications of the new proposed structure with similar research results because the works related to improving the structure of the coaxial resonant cavity filter, Duplexer's, etc. with the same frequency range is not or very little published. A comparison between the capacitive cross-coupling for cavity filters with the state-of-the-arts is shown in Table 4. It reveals that this filter has the merits of higher selectively, wide bandwidth.

5. Conclusion

In this paper, the dumbbell cross-coupling structure with a new tap screw is proposed to improve the out-of-band rejection slope of microwave cavity filter. By the proposed structure, one new distributed variable capacitor is created. The cross-coupling bandwidth is changed by changing the length of this tap screw. Based on low pass prototype filter theory, its equivalent schematic is built and optimized. Thanks to using the proposed structure, the TZ0 of filter can be closer to the pass band and the slope is better. If the screw is tuned, the added capacitor will be variable. From that, the position of TZ0 can be tunned to reach the best rejection slope without replacing the dumbbell. So, the post – production tuning step also becomes more flexible. However, fine-tuning will be more complicated due to the addition of a screw element. This is really helpful in practice. In order to verify the performance of the proposed structure, a Band 3 cavity filter for LTE application is developed with the new cross coupling. The simulation results illustrate that the designated filter characteristics are better than the requested specifications, the rejection slope is improved significantly.

This proposed filter is suggested to be used in other frequency bands as well as in other system that use resonator cavity filter type. The cross-coupling structure can be designed for a different dumbbell shape to improve the rejection slope of cavity filter. Dielectric materials can be used in fabricating to improve mobile transmission characteristics.

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References

[1] J. Brian Thomas, Cross-Coupling in coaxial cavity filters - a tutorial overview, IEEE Transactions on Microwave Theory and Techniques, Vol.51, No.4, April 2003 https://doi.org/10.1109/TMTT.2003.809180

[2] Jia-Sheng Hong, Microstrip Filters for RF/Microwave Applications, Wiley Series in Microwave and Optical Engineering, Hoboken, New Jersey, John Wiley & Sons, Inc, 2011 https://doi.org/10.1002/9780470937297

[3] B. Mohajer-Iravani and M. A. EL Sabbagh, High-selective wideband combline filters based on miniaturized-engineered resonators, interresonator tapped-in coupling, and probe coupling, 2012 IEEE Radio and Wireless Symposium, Santa Clara, CA, 2012 https://doi.org/10.1109/RWS.2012.6175330

[4] Zhengjun Du, Jin Pan, Ma Boyuan, Xinyang Ji, Deqiang Yang, A novel capacitive cross-coupling structure for ceramic-filled cavity filters, IEEE Access, vol. 9, pp: 27201 – 27209, 09 February 2021. https://doi.org/10.1109/ACCESS.2021.3058194

[5] Sai Li, Xuedao Wang, Yi Li, and Jianpeng Wang, Design of compact coaxial cavity bandpass filter with high selectivity, 2019 IEEE MTT-S International Microwave Biomedical Conference (IMBioC), Nanjing, China, 6-8 May 2019 https://doi.org/10.1109/IMBIOC.2019.8777891

[6] Muhamad Latif, Giuseppe Macchiarella and Farooq Mukhtar, A novel coupling structure for inline realization of cross-coupled rectangular waveguide filters, IEEE Access, vol.8, pp. 107527 – 107538, 2020 https://doi.org/10.1109/ACCESS.2020.3000847

[7] Alexander Zakharov, Sergii Rozenko, and Michael Ilchenko, Two types of trisection bandpass filters with mixed cross-coupling, IEEE Microwave and Wireless Components Letter, Volume 28, Issue 7, July 2018 https://doi.org/10.1109/LMWC.2018.2837905

[8] G. L. Matthaei, L. Young, and E. M. T. Jones, Microwave Filters, Impedance-Matching Networks and Coupling Structures. New York, McGraw-Hill, 1964. https://doi.org/10.21236/AD0402930

[9] Larry D. Paarmann, Design and Analysis of Analog Filters: A Signal Processing Perspective, Springer US, 2003

[10] I.C. Hunter, Theory and design of microwave filters. stevenage, U.K. IEEE IET Electromagnetic Waves Series 48, 2001, p.60. https://doi.org/10.1049/PBEW048E

[11] J.-S. Hong, M. J. Lancaster, Couplings of microstrip square open-loop resonators for cross-coupled planar microwave filters, IEEE Trans. Microw. Theory Techn., vol. 44, no. 11, pp. 2099–2109, Nov. 1996. https://doi.org/10.1109/22.543968

[12] R. J. Vidmar. (August 1992). On the use of atmospheric plasmas as electromagnetic reflectors. IEEE Trans. Plasma Sci. [Online]. 21(3). pp. 876-880. Available: http://www.halcyon.com/pub/journals/21ps03-vidmar.

[13] Dhanasekharan Natarajan (2013), A Practical Design of Lumped, Semi-Lumped and Microwave Cavity Filters: Lecture Notes in Electrical Engineering, Springer. https://doi.org/10.1007/978-3-642-32861-9

[14] Hoft, Michael, Tunable capacitive coupling for cavity resonator filters, 2009 German Microwave Conference, Munich. https://doi.org/10.1109/GEMIC.2009.4815881