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Research Article

COMPACT WIDE-STOPBAND LOWPASS FILTER USING STEPPED IMPEDANCE HAIRPIN RESONATOR WITH RADIAL STUBS

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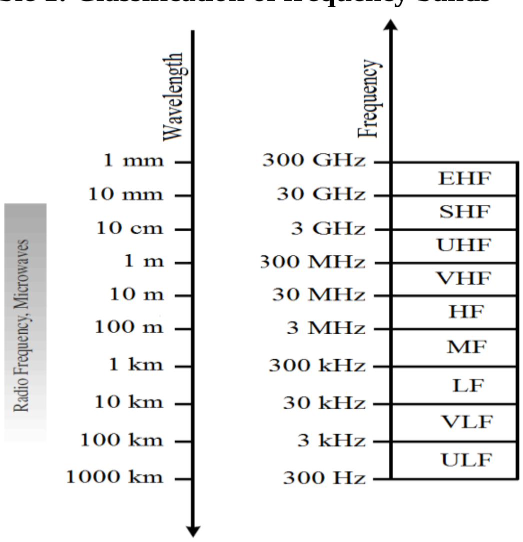
ABSTRACT
This study aims to define importance of use of low-pass filters in modern technologies, and then methods to design microstrip low-pass filters are examined. In following, an overview on related works in this context has been considered, and then a microstrip low-pass filter with a favorable function is designed that the way this filter is designed is as follow: 1- modify basic resonator and design a new resonator, 2- design a low-pass filter with a proper function using designed resonator. Finally, the designed filter is made, that the response by the given sample properly adapts with the response by the sample undergone analysis. Further, to define the proposed structure in a better way, the results from designed filter are compared with the results of previous works.

Keywords*: Microwave Circuits, Low-pass Filter, Microstrip Components, Hairpin Resonator*

INTRODUCTION
With increasing advancement of communication technologies, the need to higher frequency bands is increasingly felt. Indeed, by arrival of modern equipment and due to various reasons such as avoidance from spectral interference and so forth, we oblige to use more frequency bands. But this is not the only advantage of using high frequencies. By increasing frequencies, rate of communication exchanges increase, and high load of information can be exchanged at a certain time interval. Further, by increasing frequency bands, the possibility to transmit waves to remote areas and coping with atmospheric factors such as clouds and fog will be possible, and dimensions of required antennas will reduce for exchange of information in a large extent. Table 1 represents various frequency bands, including frequency of 300 Hz to frequencies near 300 GHz.

Table 1: Classification of frequency bands



The term "microwaves" refers to a series of waves with wavelength of 1m to 1mm, representing frequency band of 300 Hz to frequencies near 300 GHz. According to this definition regarding table 1, frequency bands including UHF, SHF and EHF can be considered as series of microwave frequency band. A series of microwave frequency band is divided into smaller standard bands, that the table relating to frequency allocation of these various bands can be observed in table 2.

Table 2: Microwave frequency band

Frequency Range	**Band designation**
140-220 GHz	G-band
110-170 GHz	D- band
75-110 GHz	W- band
60-90 GHz	E- band
50-70 GHz	V- band
40-60 GHz	U- band
33-50 GHz	Q- band
26.5-40 GHz	Ka- band
18-26.5 GHz	K- band
12.4-18 GHz	Ku- band
8-12.4 GHz	X- band
4-8 GHz	C- band
2-4 GHz	S- band
1-2 GHz	L- band
300-3000 MHz	UHF- band
30-300 MHz	VHF- band

Microwave Frequency Band

Filters are one of the most useful microwave equipment that separation or picking up different frequencies can be known of their important usage. Since, limitation exists in electromagnetic spectrum, this spectrum must be shared for various equipment and applications, and thereby these filters are used for separation of various frequencies. Low-pass filters are the most important frequency filters by themselves. These filters as their names indicate pass the frequencies less than their cut frequency and do not allow higher frequencies to pass. According to figure 1, image of output curve for an ideal low-pass filter can be observed.

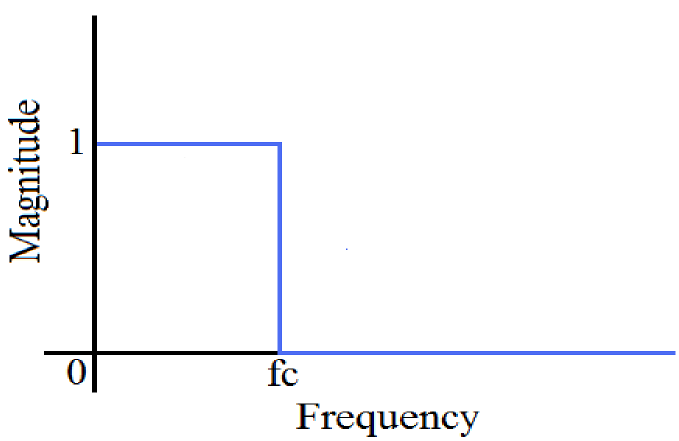


Figure 1: Output curve for an ideal low-pass filter

According to figure 1, it can observe output curve for an ideal low-pass filter, where there will not be an immediate passing from passing area to cutoff area, and the curve at this stage has a little slope.

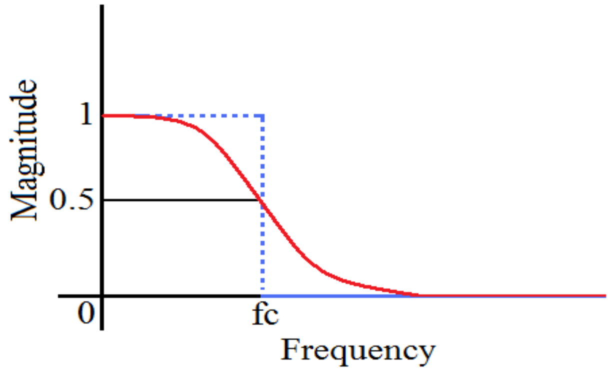


Figure 2: Response curve for a practical low-pass filter

According to definition, cutoff frequency at a low-pass filter is a frequency in which use of output signal reaches to half, reported with -3dB.

Important Parameters in Designing Filter Bipolar Networks

To define the systems with one input port and output port, bipolar networks theories are used, where ports represent pair of terminal lines. In this technique, it is looked into the system as a black box, for which the relationships between input and output are written down. The advantage of this technique lies on a fact that it can define and predict external behavior of a system regardless of what is inside a black box. Figure 3 represents an image of bipolar network.

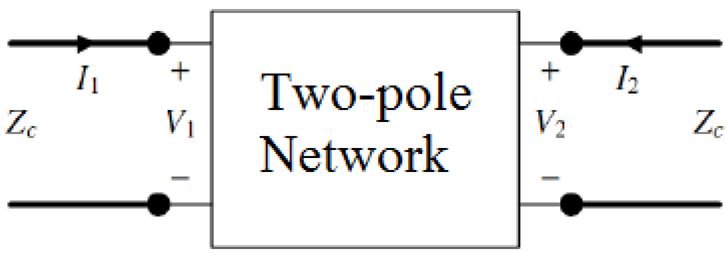


Figure 3: Bipolar network

In this network, inputs and outputs represent the values of voltage and flow, respectively. To define bipolar networks, there are various parameters of which it can refer to parameters of Z,Y and ABCD and parameters of scattering, that parameters of Z,Y and ABCD among these four parameters deal with values of voltage and flow. The weakness in use of these three parameters at microwave frequencies lays on a fact that measurement of values of flow and voltage is problematic in these frequencies. But, scattering parameters which are displayed with word “S” define the waves radiated to input and output ports in network, that measurement of these waves at high frequencies is almost easier and more practical.

In designing microwaves circuits, each of four introduced methods adapted with conditions is used, but scattering parameters among these parameters due to a direct referral to conditions of waves in input and output ports can be highly used; in following, scattering parameters are clearly defined.

Scattering Parameters

As defined earlier, scattering parameters among various parameters which define bipolar networks define waves radiated to each of two ports at network. Firstly, it should be noted that all the waves radiated to a port at microwave frequencies is not entered into network and another port, and an amount of this wave is reflected at the early port. The reason for this can be searched in lack of impedance balance and existence of nonlinear feature of transmission line. Figure 4 represents an image of a bipolar network together with waves reflected from its ports.

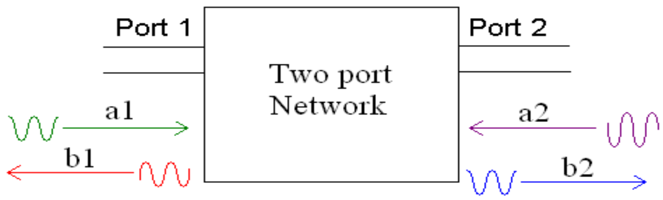


Figure 4: Bipolar network and waves radiated to it

In this sense, it can define scattering parameters as equations in matrix form as follows:

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \cdot \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \qquad (1)$$

Where, there will be as follows in the equations:

$$S_{11} = \left. \frac{b_1}{a_1} \right|_{a_2=0} \qquad S_{12} = \left. \frac{b_1}{a_2} \right|_{a_1=0} \qquad (2)$$

$$S_{21} = \left. \frac{b_2}{a_1} \right|_{a_2=0} \qquad S_{22} = \left. \frac{b_2}{a_2} \right|_{a_1=0}$$

According to equations above, it can perceive that parameter S_{11} is the ratio of wave radiated from port 1; for this, parameter S_{21} is a ratio between the output waves of port 2 to input wave of port 1. If port 1 is considered as input of signal and port 2 is considered as output port in a defined bipolar network, then only parameters S_{11} and S_{21} of four scattering parameters will be important. On definition and analysis of microwave filters, scattering parameters are the most important instruments for which further explanations are represented in next section.

The Extent of Efficiency of a Low-pass Filter

In this section, analysis of efficiency of a low-pass filter is considered, for which some of important and standard indicators are introduced. It is well known that function of filters implies passing a signal through a spectrum of frequencies and lack of passing signal in other spectra. Using the responded curve in figure 1, the parameters which specify function of a low-pass filter are considered.

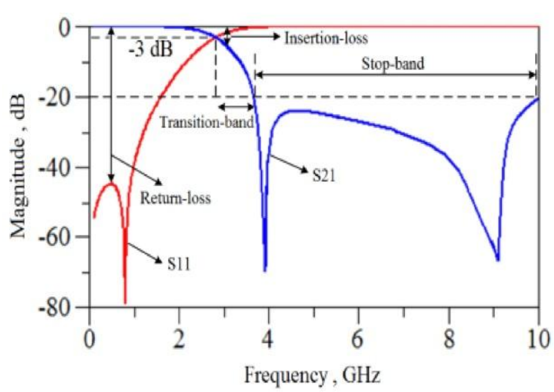


Figure 1: Curve of scattering parameters for a practical low-pass filter

Cutoff Band

In a low-pass filter, if value of S21 goes under a certain limit, it can announce that a signal no longer passes through filter, so that it can say filter is in cutoff band. The certain limit for the filters in the past was considered about -10dB, but today with advancement of designs and improvement of function of filters, -20db is considered as the limit to enter to the cutoff band

Sharpness of Response

As observed in figure 1, in a low-pass filter with practical conditions from the moment reaching to a cutoff frequency to the moment when no signal passes through filter, a spectrum of frequencies still pass through filter so that this filter encompasses the frequencies in which value of S21 reaches to -20Db. The width of this frequency spectrum which is called transition band is defined as parameter of sharpness of response of a low-pass filter. It is natural that the more width of this band is lowers; filter's response to its ideal model is closer, whereby the filter will have a better function.

Pass Loss

According to the response curve of an ideal low-pass filter, it is expected that signals in pass band pass through filter, i.e. the curve relating to parameter S21 equals to zero; but as shown in figure 1, some wastes exist in pass band which are called pass wastes. It is obvious that the more pass wastes be less for a filter, that filter will be closer to an ideal response.

Return Loss

At an ideal state in transition band, it is expected that infinite negative limit exists in the curve relating to parameter S21 which represents radiated signal to input port; but with regard to figure 1, this does not practically come true, and signal return in input port is witnessed in transition band. It is obvious that the more curve S11 in transition band tends to infinite negative side; filter will have less return loss and tends to its ideal model.

Dimensions of Filter

With increasing tendency of modern technologies to smaller size of equipment and arrival of portable equipment, the need to design various circuits in intensive form is increasingly felt. This goes true for the filters which are one of the most useful communication equipment. Indeed, having small dimensions is one of the most important requirements for a microwave filter. To compare dimensions of filters, they are generally defined as the area preoccupied by the filter. This preoccupied area can be shown with mm^2 unit, but this area is generally defined as a coefficient of the parameter(λg) for a better comparison, where there will be as follow for λg:

$\lambda\, g=\lambda 0/\sqrt{\varepsilon_{re}}=300/f(GHz).\sqrt{\varepsilon}$ mm (1)

The Principles for Design of Low-pass Filters

Design of Low-pass Filters using Transfer Functions

Transfer functions of bipolar filters are mathematical definition for network's response, that they can be called mathematical definition of parameter S_{21}. Generally, domain of a square is defined rather than defining S21. There will be formula as follow for a low-pass filter:

$$|S_{21}(j\Omega)|^2 = \frac{1}{1+\varepsilon^2 F_n^2(\Omega)} \tag{3}$$

Where ε represents ripple constant, and $Fn^2(\Omega)$is called filtering function. Ω is the frequency variable. According to the proposed definition, now several approximate functions are examined, and then low-pass filters are designed using them.

Butterworth Approximation

A mathematical definition for Butterworth approximation for the filters with wastes at passing which equal to LAR=3.01 dB at frequency is as follow:

$$|S_{21}(j\Omega)|^2 = \frac{1}{1+\Omega^{2n}} \tag{4}$$

Here, n represents degree of filter. Indeed, n represents the number of reactive elements which have been used in structure of filter. Butterworth approximation is called Maximally flat filter or filter with highest rate of smoothness, because as shown in figure 5 square of domain for its transfer function has greatest zero derivatives at zero frequency, and thus this approximation has the highest closeness in terms of smoothness of response at frequencies near to zero to ideal low-pass filter model. The more getting near to cutoff frequency(Ωc), this smoothness of response removes. Figure 5 represents response of Butterworth approximation based on its transfer wastes.

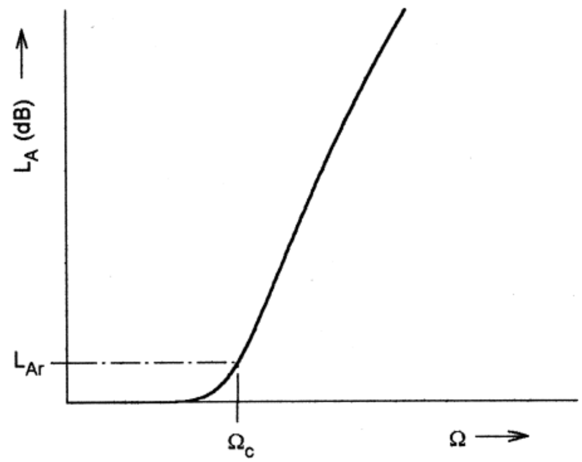


Figure 5: Curve of wastes at transfer of Butterworth approximation

According to this figure, it is obvious that filter has few wastes at transfer in frequencies near to Ω=0, where the wastes immediately increase by passing through cutoff frequency(Ωc). Relative transfer function of Butterworth approximation is as follow:
According to formula 5, all the poles are on a unique circle and angle between the poles equals with each other. Figure 6 represents an image of response by a five-order Butterworth filter, in which where the poles of this filter are placed has been represented.

$$p_i = j \exp\left[\frac{(2i-1)\pi}{2n}\right] \tag{5}$$

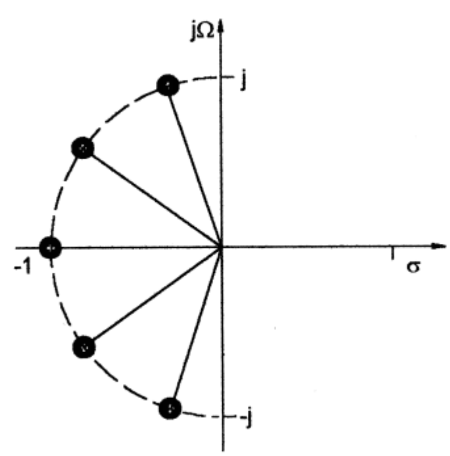


Figure 7: The place in which poles are placed in the five-order Butterworth filter

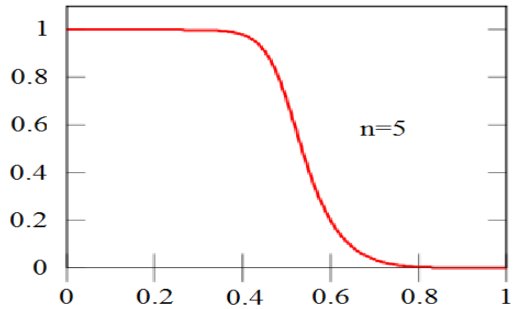


Figure 6: Curve of response by a five-order Butterworth filter

Chebyshev Approximation

There will be formula 6 for this approximation:

$$|S_{21}(j\Omega)|^2 = \frac{1}{1+\varepsilon^2 T_n^2(\Omega)} \tag{6}$$

There will be formula 7 for ripple constant(ε).

$$\varepsilon = \sqrt{10^{\frac{L_{Ar}}{10}} - 1} \tag{7}$$

Where, LAr represents extent of ripple in passing band in terms of Db. There will be as follow for Tn function:

$$T_n(\Omega) = \begin{cases} \cos(n \cos^{-1}\Omega) & |\Omega| \le 1 \\ \cosh(n \cosh^{-1}\Omega) & |\Omega| \ge 1 \end{cases} \tag{8}$$

Where, n represents order of filter. In this sense, curve of wastes at transfer for a Chebyshev function can be observed in figure 8.

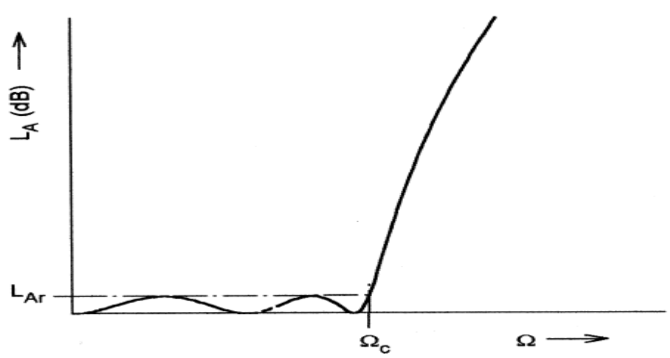


Figure 8: Curve of wastes at transfer for a Chebyshev function

$$S_{21}(p) = \frac{\prod_{i=1}^{n}[\eta^2 + \sin^2(i\pi/n)]^{1/2}}{\prod_{i=1}^{n}(p+p_i)} \tag{9}$$

According to figure above, it is obvious that Chebyshev approximation enjoys a passing band with constant ripple and definite band as maximally flat. The equation relating to square of S_{21} domain in Chebyshev approximation, the equation relating to transfer function of S_{11} can be defined as follow:
Where, there will be as follows:

$$p_i = j\cos\left[\sin^{-1} j\eta + \frac{(2i-1)\pi}{2n}\right]$$

$$\eta = \sinh\left(\frac{1}{n}\sinh^{-1}\frac{1}{\varepsilon}\right) \qquad (10)$$

According to figure 9, response by a five-order Chebyshev approximation can be observed.

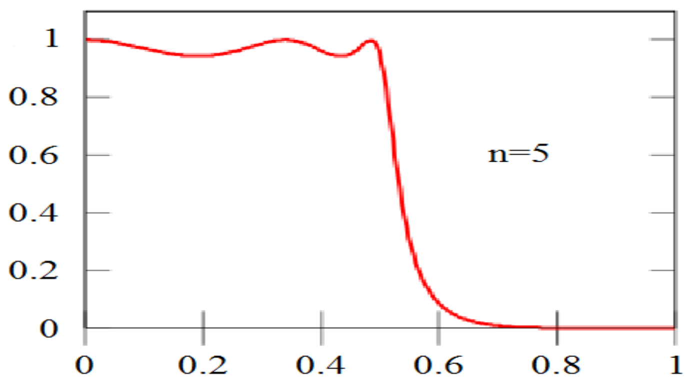


Figure 9: Response by a five-order Chebyshev approximation

Likewise state of maximally flat, all zeros of transfer at this approximation undergo infinite. Butterworth and Chebyshev filter are generally called all -pole filters. Yet, it is obvious that where poles are placed in Chebyshev approximation differs from where they are placed in Butterworth filter. Poles of Chebyshev filter are on an oval in left half plane, such as large diagonal of oval is placed on axis jΩ and its small diagonal is placed on axis σ. Where poles are placed in a five-order Chebyshev filter can be observed in figure 10.

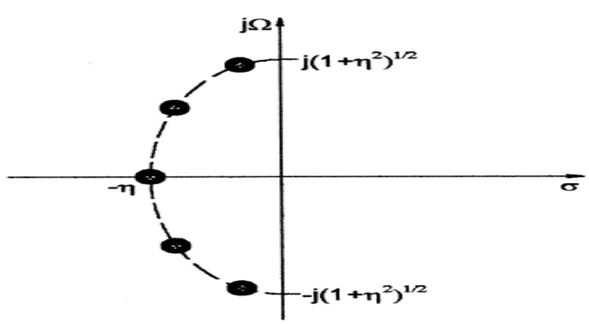


Figure 10: Where poles are placed in five-order Chebyshev filter

Implementation of Chebyshev Filter

The circuit required for implementation of Chebyshev filter is similar to a circuit which is used for Implementation of Butterworth filter. To estimate values of elements regarding value of ripple, LAr and cutoff frequency (Ωc= 1), there will be:

$$g_0 = 1.0$$

$$g_1 = \frac{2}{\gamma}\sin\left(\frac{\pi}{2n}\right)$$

$$g_i = \frac{1}{g_{i-1}} \frac{4\sin\left[\frac{(2i-1)\pi}{2n}\right]\cdot\sin\left[\frac{(2i-3)\pi}{2n}\right]}{\gamma^2 + \sin^2\left[\frac{(i-1)\pi}{n}\right]} \qquad \text{for } i = 2, 3, \cdots n \tag{11}$$

$$g_{n+1} = \begin{cases} 1.0 & \text{for } n \text{ odd} \\ \coth^2\left(\frac{\beta}{4}\right) & \text{for } n \text{ even} \end{cases}$$

According to the above equations, there will be:

$$\beta = \ln\left[\coth\left(\frac{L_{Ar}}{17.37}\right)\right] \tag{12}$$

$$\gamma = \sinh\left(\frac{\beta}{2n}\right)$$

To determine the required order for design of a Chebyshev filter, it can use the equation as follow:
Where, there will be as follow regarding ripple value at frequency Ω=Ωs.

$$n \geq \frac{\cosh^{-1}\sqrt{\frac{10^{0.1L_{As}}-1}{10^{0.1L_{Ar}}-1}}}{\cosh^{-1}\Omega_s} \tag{13}$$

Implementation of Oval Filter

Figure 11 represents two proposed circuits for implementation of oval filter. These circuits regarding their status can be used.

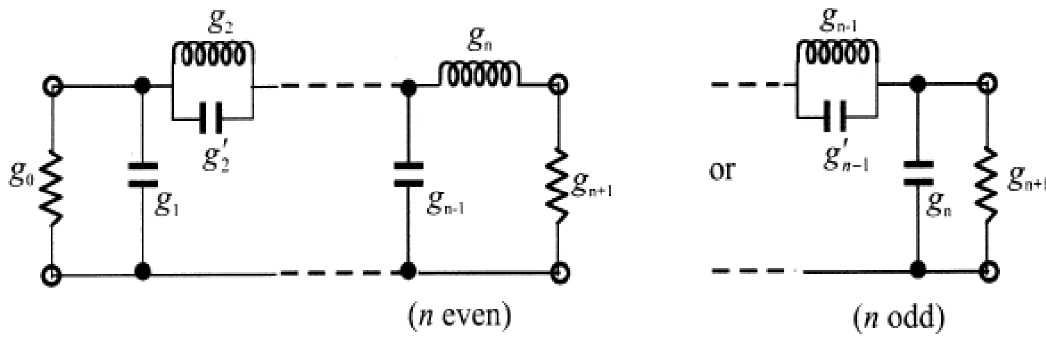
Despite Butterworth and Chebyshev filters, any simple formula does not exist for determining values of elements at circuit. In following, the designed filters must be implemented and produced using Microstrip technology.

In next section, a third-order Butterworth filter is implemented.

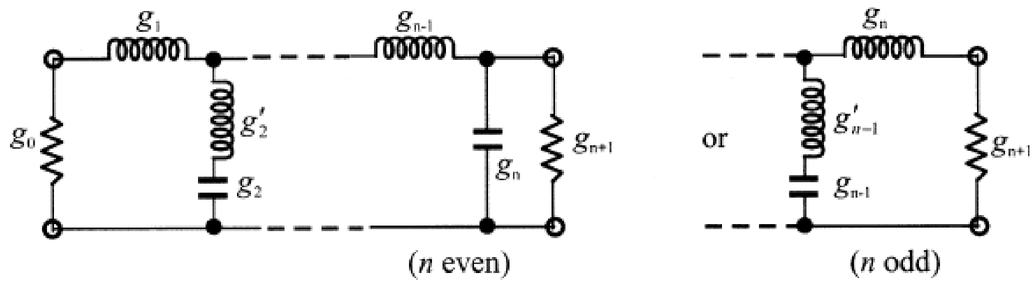
Transition functions of bipolar filters are a mathematical definition for attribute of response by network, called mathematical definition of parameter S21. Generally, in most of cases, definition of square of domain rather than definition of S21 is considered.

The advantages for use of analyzable approximation function are with high accuracy, because the design is based on mathematical functions.

Most of filter parameters such as dimensions, extent of ripples and losses at circuit can be predicted, but response by filters is not close to ideal from, and the process for converting circuit LC to Layout is not always easy, and it will be much more difficult by increasing order of filter.



(a)



(b)

Figure 11: Proposed circuits for oval filter

Design of A Low-Pass Filter using Basic Resonators

Another method to design microstrip filters is use of basic resonators which are considered in this section. Resonators are the most important part of a filter. Indeed, microstrip filters have been generally developed from one or several resonators that are set in a structure by a number of extra components as anti-harmonic components. Basic resonators generally are as the result of deep study and effort in the context of microstrip filters, and as their name indicate, they are used as a basis for design of many filters. To date, we get familiar with most of these resonators, and we consider representing examples of design for low-pass filters.

Step Impedance Resonator

This resonator which has taken its name from its appearance is a mix of rectangular-form components with various widths and lengths, for which a sample can be observed in figure 12

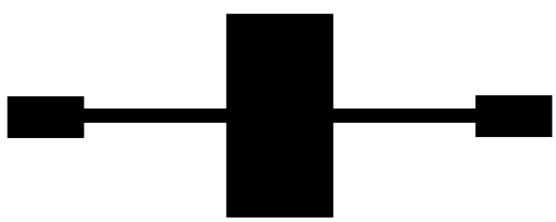
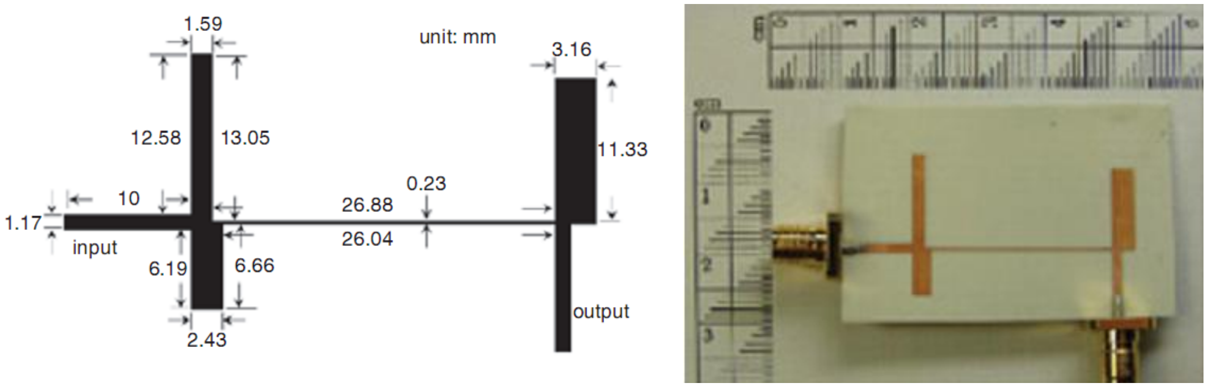


Figure 12: Step impedance resonator

Step impedance resonator is one of the most useful resonators in the context of design of microstrip filters, on which numerous studies have been conducted, and as a result efficient mathematical models to define its components have been represented; for this, this resonator is superior to other resonators in terms of mathematical explanation. Simple structure of resonator is another advantage of using it in microwave designs. According to figure 13, a sample of designed filter using step impedance resonator can be observed.



(a) **(b)**

Figure 13: Proposed filter ((Tang and Chen, 2010)

The response of this filter can be observed in figure 14.

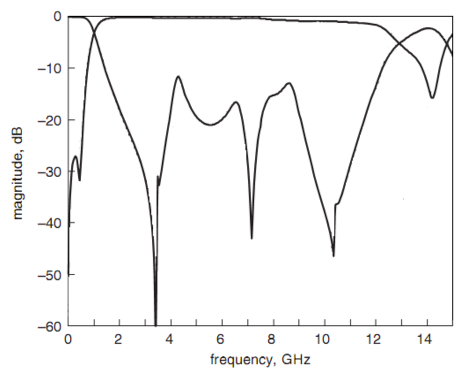


Figure 14: Response of proposed filter (Tang and Chen, 2010)

However, as said, step impedance resonator enjoys proper equations and a simple structure, but as specified, the response of filters has a large difference with ideal state, especially it has transfer band which has caused use of this resonator reduces in recent years.

Hairpin Resonator

This resonator has an appearance similar to hairpin, for this it is called a hairpin resonator. The structure of this resonator has been developed from a transfer line which has been equipped with a pair of parallel coupled line. These parallel coupled lines in structure of resonator have raised capacitive properties, which improve performance of this resonator compared to step impedance resonator. According to figure 15, general structure of hairpin resonator can be observed.

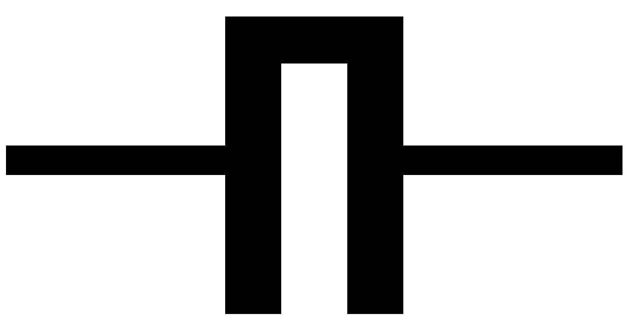


Figure 15: Hairpin resonator

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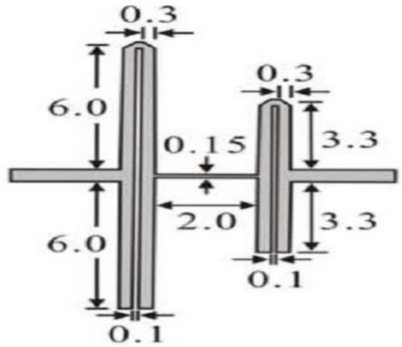
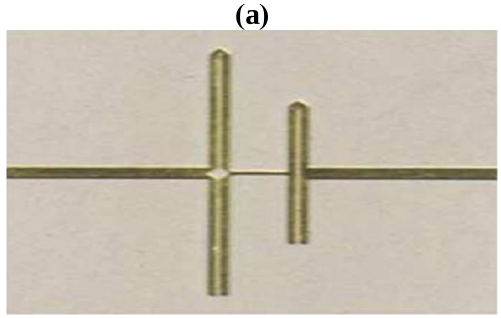
Figure 16 represents a sample from designed filter with this resonator together with an image and its response.



(a)



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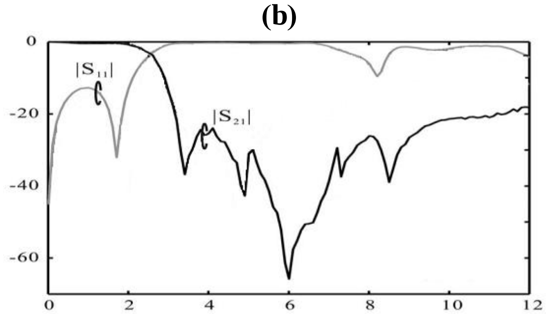


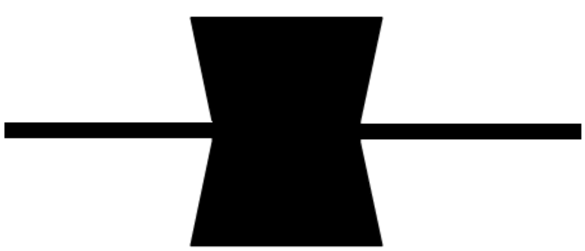
(c)

Figure 16: Proposed filter in (Sha *et al.*, 2008), a-structure of filter, b-made sample, c-curve of response

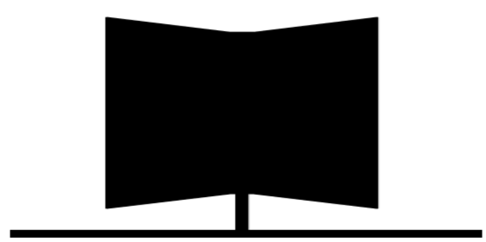
Hairpin resonator compared to step impedance resonator enjoys a better response, and enjoys an advantage of simple structure likewise impedance resonator, and it has been largely used in recent years.

Cone Resonator

This resonator has cone structure which has been represented in one of two forms as follows in figure 17.



(a)



(b)

Figure 17: Structure of cone resonator (a-first type, b-second type)

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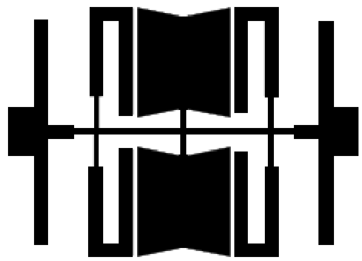
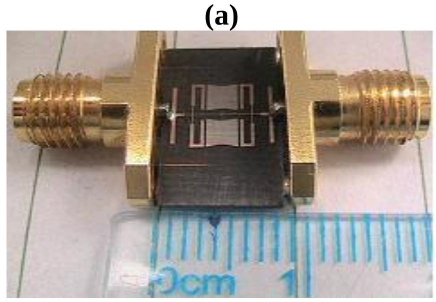
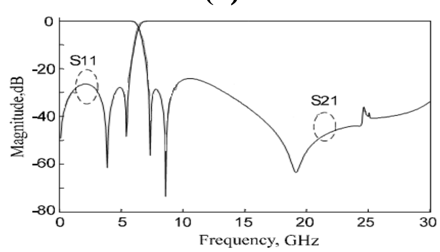
Use of this resonator in various forms has been drawn into attention. It has a relatively simple structure and designer is free to change it. According to figure 18, an example of low-pass filter with this resonator together with an image of its sample and response can be observed.



(a)



(b)



(c)

Figure 18: Proposed filter in (Sha *et al.*, 2008), a-structure of filter, b-made sample, c-curve of response

As shown in figure, filter above is obtained by using two cone resonators as a mirror together with extra components for rise of capacitive properties to remove some harmonics and improve performance of filter.

Spiral Resonator

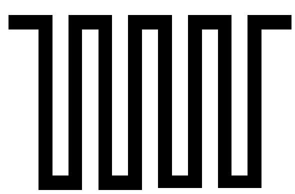


Figure 19: Structure of spiral resonator

This resonator has a spiral form; thereby significant values create coupling capacitor.

Other advantages of this resonator can be maximum use of space and low preoccupied area. On the other hand, various branches can be considered for creation of coupling with parallel components and improvement of filter's function.

Radial Resonator

This resonator has a structure relatively similar to cone resonator. Image of structure of this resonator can be observed in figure 20.

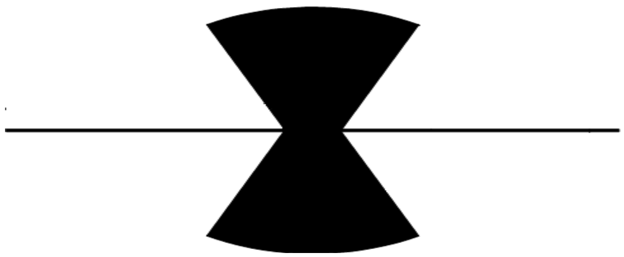


Figure 20: ???????

Resonators with defective earth layer structure

General structure of a microstrip circuit has three different layers of earth, dielectric and microstrip, in which dielectric layer obliges to separate two other layers. Earth layer is a metal layer. If some areas are removed from earth layer, this will directly affect filter's response, and this can be used for improvement of filter's response. One of the important advantages of use of defective earth layer structure lies on a fact that the need to magnifying dimensions is removed due to strengthening the effects of certain areas under structure, and thereby it can achieve better results by smaller dimensions.

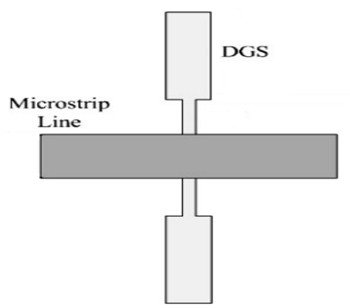


Figure 21: ??????

Circle Resonator

The structure of this resonator is the same as circle that can be observed in figure 20.

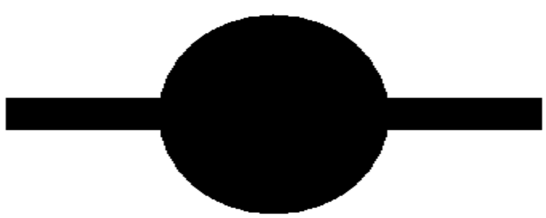


Figure 20: Structure of Circle resonator

Designers have brought about some changes in form of circle resonator and have cut pieces of it and/or have added some pieces to it. Advantages of this resonator can lie on a fact that the response is influenced of some changes in form of it, that this can be used for improvement of its function. Yet, this resonator general suffers from gradual transition band, and its curved edges influence the edges under other pieces, whereby the analysis will be much more difficult.

Research Article

Represent a New Form of Low-Pass Filter and Design a Low-Pass Filter by Using

The third method in design of low-pass filters is design of a new resonator that designer is required having sufficient knowledge and vision in the context of microstrip technology to implement this method so as to represent a suitable structure for design of a resonator after studying various designs. As said, basic resonators are resulted after several years study and research, so that the designer generally can achieve suitable responses in case of using them at shorter duration. Yet, the procedure to design filters by using a new resonator is a time consuming process, and also representing mathematical models to define that resonator is problematic. Yet, design of a new resonator is followed by several advantages of which more freedom of action by designer in selection of structure of resonator has been regarded as one of the most important advantages. In this method, designer can represent a suitable structure regarding existing physical constraints and conditions, such that the presented model can span existing limitations and represent a suitable response.

Another negative point in design of a new resonator lies on a fact that a new resonator generally includes more complicated structures than the structures in basic resonators, whereby the process of creating these circuits, in addition to impossible representation of mathematical circuits, faces problems. One of important problems in design of filters is the capability to use them at various cutoff frequencies, i.e. the filter enjoys a feature through which it can change the value of cutoff frequency without a change in structure.

Design a New Low-Pass Filter

In this section, given previous information, we intend to design a microstrip low-pass to meet needs of modern technology.

To sum up, after designing filter at two stages, the results are examined.

1-design and simulate filter via software

2-build filter and measure it via measurement devices

To simulate given filter, the software is used, that the used software is defined in summary in next section.

ADS Software

Advanced Design System software or ADS is one of the microwave analysis software. As its name indicates, it implies design of advanced systems that can be used as a strong design means by RF/microwave engineers and DSP designers and signal designers. This software has been used in communication lines, wireless communications and analysis of electronic circuits. This software has been created by Agilent EEs of EDA Company since 1983. This plan includes a library from common components that they can be used for simulation of a circuit or system. In this software, it can design and then simulate structure of microstrip in layout section, and observe the obtained results regarding the need in various parameters. The results of outputs like parameters of S, frequency spectrum, diagram of time interval and input-output power are in numerical and graphical forms. Further, various optimization techniques to achieve the given performance of circuit can be used via this software.

Design of resonator

Designed resonator is based on hairpin resonator, which was introduced for the first time in 1972, which a simple structure with small dimensions is of its important features. According to figure 21, image of structure hairpin resonator is represented. In this figure, LC circuit in this resonator has been represented.

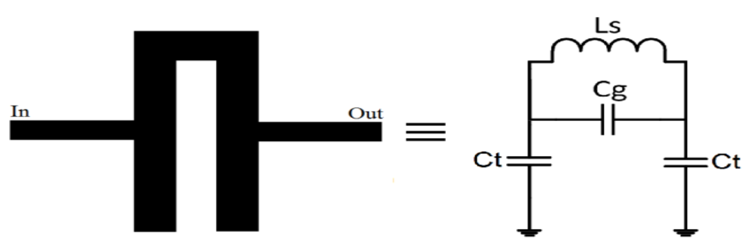


Figure 21: Structure of basic hairpin resonator

According to the filter represented in (Wei *et al.*, 2011), hairpin resonator has been used. In this filter, parallel resonance antenna in general hairpin has been replaced with two radial segments. An image of structure of this resonator can be observed in figure 22.

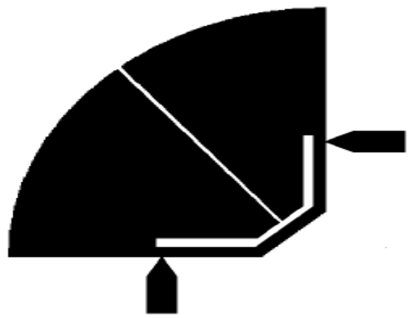


Figure 22: Proposed resonator in (Wei *et al.*, 2011)

The results from simulation of this filter indicate that cutoff frequency of filter is 1.67 GHz, and stop band is in the range of 2.3 to 10 GHz. Image of output wave has been represented in figure 23.

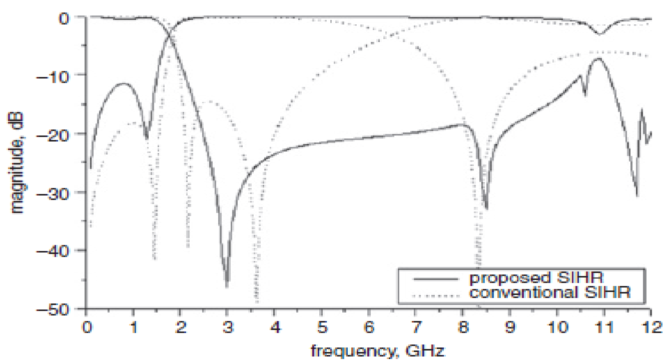
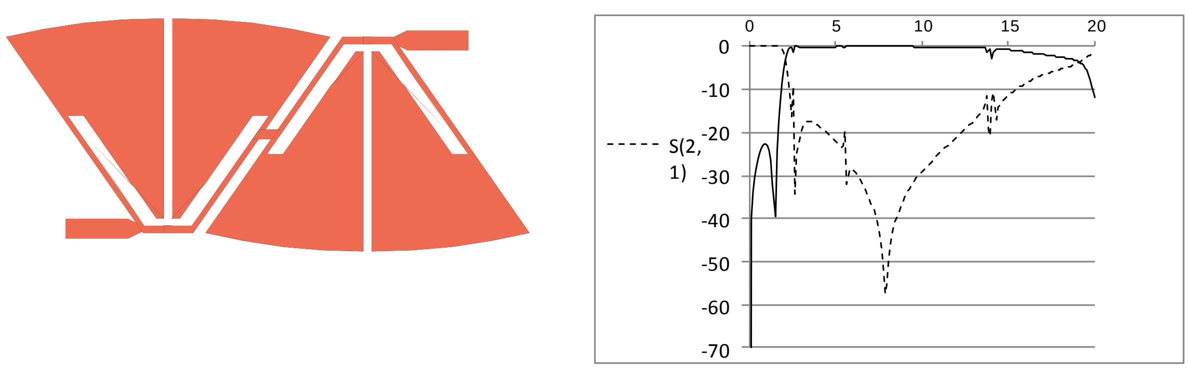


Figure 23: Image of simulated wave in resonator

Design of Proposed Filter

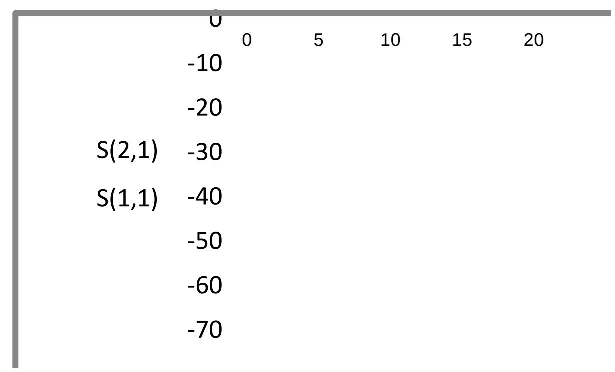
According to the resonator defined above, low-pass filter is designed; the response reaches to 0.5 GHz by arranging a series of another resonator and putting its ports. At this stage, stop band reaches to 2.6 to 12.6 GHz and return wastes appear in -22.7 dB. Further, width of band has been considered less than -20 dB. Figure 24 represents a series filter together with its frequency response.



(a) **(b)**

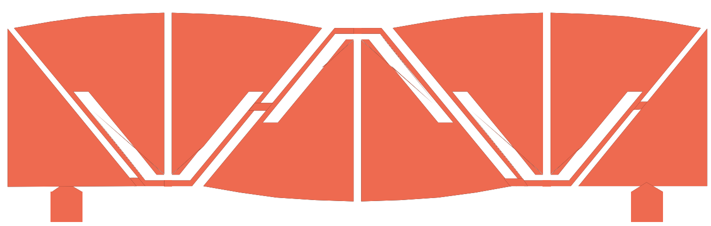
Figure 24: Structure of designed resonator, a-structure of filter, b- curve of response

It is observed that the new structure represents a better response, and its dimensions are about 12.5×9.5 mm, that is very suitable. The strength of this filter is increasing stop band, increasing sharpness of response till the width of sharpness reaches to 0.5 Ghz, reduction of return wastes to -22.7 dB that gives a favorable result compared to -12 dB. According to the filter defined in (Wei *et al.*, 2011), stop band is in range of less than -15 dB, yet this filter likewise new simulation in recent years has been designed in a way that gives better result than -20 dB. To improve performance of filter and reach to better results, two resonators in one side and one resonator in an inverse side are used. The designed filter has been represented in figure 25.

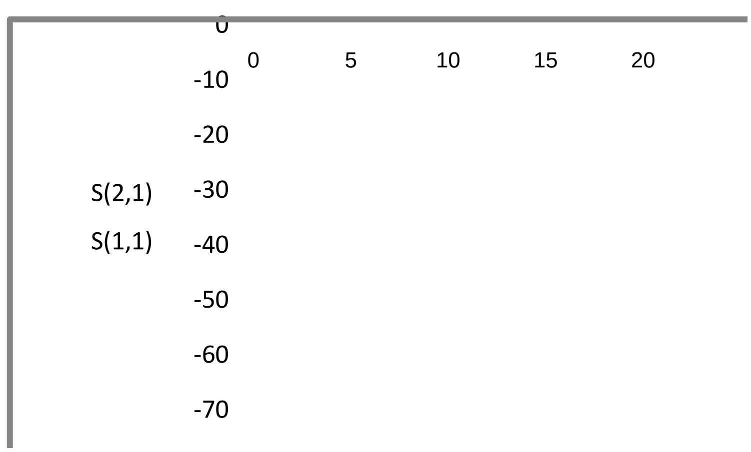


(a) **(b)**

Figure 25: Designed filter with three resonators, a-structure of filter, b- curve of response



(a)



(b)

Figure 26: Designed filter with three resonators, a-structure of filter, b- curve of response

As observed, what can be obtained from design is a low-pass filter with favorable features. Cutoff frequency of designed filter is about 2.3 Ghz. Return wastes are about -50 dB, that is an acceptable value.

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Research Article

Transfer band is in range of 2.3 to 2.6 GHz, representing sharpness of response. Cutoff band of system is better than -20 dB, which is in range of 2.6 to 22.6 GHz, including width of band (20 GHz) and its width goes beyond 8.5 cutoff frequency of system, representing a wide width of band. After simulations via software and reaching to favorable results, the considered filter was built and practical measurements were fulfilled. Figure 27 represents results of practical measurement and frequency responses compared to results of simulation.

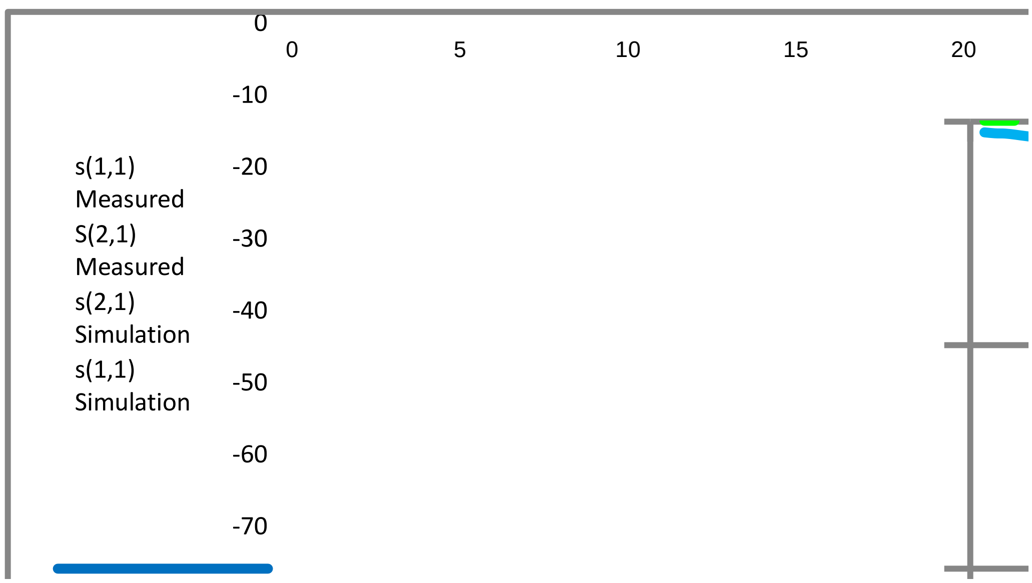

Figure 27: Comparison of results of simulation and practical measurement

As shown in figure, practical results represent better responses at stop band, where these results indicate practicability of filter in communication equipment.
Filter made with size is evident in Figure 28.

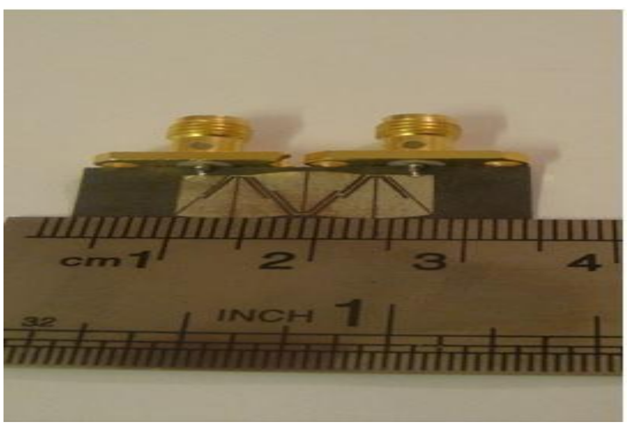

Figure 28: Filter

Quantitative Analysis of Designed Filter
In following, to judge on efficiency of designed low-pass filter, the obtained quantitative results are compared with the results from some of low-pass filters, that recently the results from comparisons have been published in the most authentic scientific journals. Table 1 represents the comparison between designed filter and other proposed filters.

Table 1: Comparison of features of designed filter with other filters

λg²	Stop band	Return wastes	Sharpness of response	Cutoff frequency	Filter
0/0220	3/44	14	24/2	2/5	6
0/0372	5/25	11/5	42/5	2/4	14
0/6241	1/01	8	21/25	1/18	16
0/0156	1/13	10/1	170	1/5	17
0/0085	5/3	12/5	21/25	1/3	18
0/0063	4/86	15/2	85	0/75	19
0/0542	0/1	5	34	2/4	22
0/0119	4/1	20	48/5	1/0	23
0/0064	2/63	12	24/28	1/67	24
0/0222	7/6	16/3	56/6	0/5	25
0/0111	20	50	50	2/3	New filter

CONCLUSION

In this project, a low-pass filter using a resonator with a new structure has been designed. According to the obtained results, the proposed filter in this project as compared to other proposed filters in international articles has favorable features. For instance, this filter among all filters has the highest rate of return wastes, and has the highest width at stop band. Another problem which must be considered is that the proposed filters generally have not a proper response in all parameters. For instance, the proposed filter in (Wang *et al.*, 2010) which has the best response in terms of sharpness has very poor response in other aspects including input wastes, return wastes and width of cutoff band. Yet, the filter which was proposed in this project has proper response at all the areas, through which it can meet to need of modern equipment in today's world.

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