International Journal of Modern Engineering Research (IJMER)
www.ijmer.com Vol.3, Issue.2, March-April. 2013 pp-1105-1114 ISSN: 2249-6645

Analysis and Design of an UWB Band pass Filter with Improved Upper Stop band Performances

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Abstract: *In this work, we are interesting in the analysis and the design of an ultra wideband (UWB) band pass filter with improved upper stop band performances, using microstrip lines.*

The design of the UWB band pass filter is based on the use of stepped-impedance low pass filter and high pass filter; whereas the simulation of its frequency response ([S]) is done using MATPAR software and it is based on the electromagnetic (EM) parameters for each section of line forming the band pass structure.

Our filter with bandwidth between 2.9-10.8 GHz, measures just 12.6×1.524×31.58 mm and was fabricated using RT/D 5880 substrate by means of stepped-impedance 5-pole microstrip low pass filter and high pass filter constructed from quasilumped elements. The simulated results of stop band performances are better than 15 dB for a frequency range up to 25 GHz.

Keywords: *Analysis design and simulation, EM-parameters, UWB band pass filter, stepped-impedance low pass filter, high pass filter with quasilumped elements, MATPAR software, S-parameters.*

I. INTRODUCTION

FILTERS play important roles in many RF/microwave applications. They are used to separate or combine different frequencies. The electromagnetic (EM) spectrum is limited and has to be shared; filters are used to select or confine the RF/microwave signals within assigned spectral limits. Emerging applications such as wireless communications continue to challenge RF/microwave filters with ever more stringent requirements-higher performance, smaller size, lighter weight, and lower cost. Depending on the requirements and specifications, RF/microwave filters may be designed as lumped element or distributed element circuits; they may be realized in various transmission line structures, such as waveguide, coaxial line [1-2], and microstrip [3-4].

The recent advance of novel materials and fabrication technologies, including monolithic microwave integrated circuit (MMIC), microelectromechanic system (MEMS), micromachining, high-temperature superconductor (HTS), and low-temperature cofired ceramics (LTCC), has stimulated the rapid development of new microstrip and other filters [5]. In the meantime, advances in computer-aided-engineering (CAE) tools such as full-wave electromagnetic (EM) simulators have revolutionized filter design. Many novel microstrip filters with advanced filtering characteristics have been demonstrated [5].

With the ready availability of accurate CAE tools, it is possible to apply some basic formulas for calculating the dimensions of these filters and simulating their frequency responses [5].

In this work, we are interesting in the analysis and the design of an ultra wideband (UWB) band pass filter with improved upper stop band performances, using microstrip lines. The design of the UWB band pass filter is based on the use of stepped-impedance low pass filter and high pass filter constructed from quasilumped elements. The cutoff frequencies of 3.1 and 10.6 GHz were selected respectively for each type of filter. Our filter has not only compact size but also a wider upper stop band resulting from low pass characteristics. The simulated results of stop band performances are better than 15 dB for a frequency range up to 25 GHz.

What follows are the analysis, the design and the simulation of this UWB band pass filter.

II. BASIC CONCEPTS

This section describes the basic concepts and theories necessary for the overall design of RF/microwave filters including microstrip lines structures.

The transfer function of a two-port filter network is a mathematical description of network response characteristics, namely, a mathematical expression of S_{21}. On many occasions, an amplitude-squared transfer function for a lossless passive filter network is defined as:

$$\left|S_{21}(j\omega)\right|^2 = \frac{1}{1+\varepsilon^2 F_n^2(\omega)} \qquad (1)$$

Where ε is a ripple constant, $F_n(\omega)$ represents a filtering or characteristic function, and ω is a frequency variable. For our discussion here, it is convenient to let ω represent a radian frequency variable of a low pass prototype filter that has a cutoff frequency at $\omega = \omega_c$ (rad/s).

For a given transfer function of equation (1), the insertion loss response of the filter can be computed by:

$$L_A(\omega) = 10 \log \frac{1}{\left|S_{21}(j\omega)\right|^2} \quad (dB) \qquad (2)$$

Since $|S_{11}|^2+|S_{21}|^2=1$ for a lossless, passive two-port network, the return loss response of the filter can be expressed by:

$$L_R(\omega) = 10 \log \left(1 - \left|S_{21}(j\omega)\right|^2\right) \quad (dB) \qquad (3)$$

The transfer function is an essential feature of the filter. It is given by different mathematical laws called filtering function. The most ones used are: Butterworth and Chebyshev laws.

II.1 Butterworth (Maximally Flat) response

The amplitude-squared transfer function for Butterworth filters that have an insertion loss L_{Ar}=3.01 dB at the cutoff frequency ω_c is given by:

$$\left|S_{21}(j\omega)\right|^2 = \frac{1}{1+\left(\frac{\omega}{\omega_c}\right)^{2.n}} \qquad (4)$$

Where n is the degree or the order of filter, which corresponds to the number of reactive elements, required in the low pass prototype filter. This type of response is also referred to as maximally flat because its amplitude-squared transfer function defined in equation (4) has the maximum number of (2n-1) zero derivatives at $\omega=0$. Figure 1 shows a typical maximally flat response.

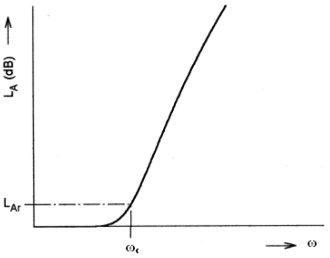


Fig. 1. Butterworth (maximally flat) low pass response.

II.2 Chebyshev response

The Chebyshev response that exhibits the equal-ripple pass band and maximally flat stop band is depicted in figure 2. The amplitude-squared transfer function that describes this type of response is:

$$\left|S_{21}(j\omega)\right|^2 = \frac{1}{1+\varepsilon^2 T_n^2(\omega)} \qquad (5)$$

Where:

The ripple constant ε is related to a given pass band ripple L_{Ar} in dB by:

$$\varepsilon = \sqrt{10^{\frac{L_{Ar}}{10}} - 1} \qquad (6)$$

$T_n(\omega)$ is a Chebyshev function of the first kind of order n, which is defined as

$$T_n(\omega) = \begin{cases} \cos\left(n \cos^{-1}\left(\frac{\omega}{\omega_c}\right)\right) & for \quad \left|\frac{\omega}{\omega_c}\right| \le 1 \\ \cosh\left(n \cosh^{-1}\left(\frac{\omega}{\omega_c}\right)\right) & for \quad \left|\frac{\omega}{\omega_c}\right| \ge 1 \end{cases} \qquad (7)$$

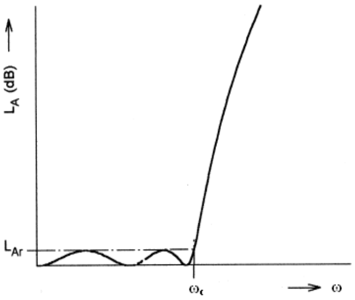


Fig. 2. Chebyshev low pass response.

II.3 Low pass prototype filter and elements

The main objective of this section is to present equations for obtaining element values of some commonly used low pass prototype filters. In addition, the determination of the degree of the prototype filter will be discussed.

In general, the design of microstrip low pass filters involves two main steps. The first one is to select an appropriate low pass prototype (figure 3). The choice of the type of response, including pass band ripple and the number of reactive elements, will depend on the required specifications. The couples [L_A; (ω/ω_c)] that we want to obtain at $\omega=\omega_a$ allows us to find the values of the order n of the filter while the L_k and C_k values are determined using the following g_k parameters.

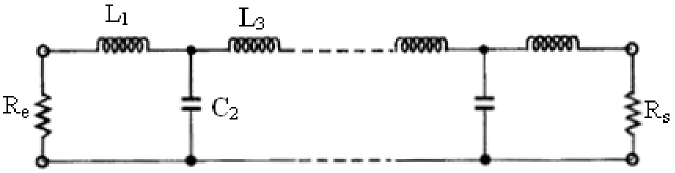


Fig. 3. Low pass prototype filter

For Butterworth or maximally flat low pass prototype filters having a transfer function given in (4), the g_k parameters may be computed using:

$$g_0 = 1$$

$$g_k = 2\sin\left(\frac{(2k-1)\pi}{2n}\right) \qquad k = 1 \; to \; n \tag{8}$$

$$g_{n+1} = 1$$

For Chebyshev low pass prototype filters having a transfer function given in (5), the element values for the two-port networks may be computed using the following g_k parameters:

$$g_0 = 1$$

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

$$g_k = \frac{1}{g_{k-1}} \frac{4\,\sin\left(\frac{(2k-1)\pi}{2n}\right)\sin\left(\frac{(2k-3)\pi}{2n}\right)}{\gamma^2 + \sin^2\left(\frac{(k-1)\pi}{n}\right)} \quad k = 2,\ldots,n \tag{9}$$

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

Where:

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

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

The input resistance R_e is given by the terms of reference since it is the characteristic impedance of the line on which the filter is inserted. Generally it is 50Ω.

The load resistance can be calculated by:

$$R_s = r.R_e \tag{10}$$

Where: for Butterworth r = 1 and for Chebyshev response $r = \begin{cases} 1.0 & for\, n\, odd \\ tgh^2\left(\frac{\beta_r}{4}\right) & for\, n\, even \end{cases}$ $with \;\; \beta_r = In\left(\coth\left(\frac{L_{Ar}}{17.37}\right)\right)$

Finally the values of the elements L_k and C_k of low pass filter are computed using relations (11) and (12):

$$L_k = \frac{R_e}{\omega_c} g_k \tag{11}$$

$$C_k = \frac{1}{R_e}\frac{1}{\omega_c} g_k \tag{12}$$

II.4 High pass filter and elements

The following figure shows the structure of a high pass filter transformed from the low pass prototype and using L-C elements.

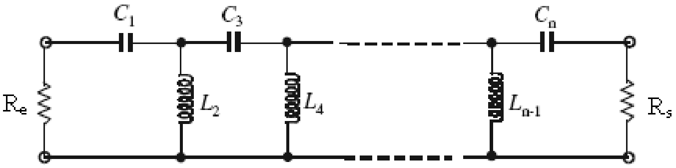


Fig. 4. High pass filter

This simple form of high pass filter consists of a series capacitor, which is often found in applications for direct current or dc block. For more selective high pass filters, more elements are required. This type of high pass filter can be easily designed based on a lumped-element low pass prototype such as one shown in figure 4 and on the following relations:

$$L_k = \frac{R_e}{\omega_c g_k} \qquad (13)$$

$$C_k = \frac{1}{R_e \omega_c g_k} \qquad (14)$$

II.5 Band pass filter and elements

Figure 5 shows the structure of a band pass filter using L-C elements.

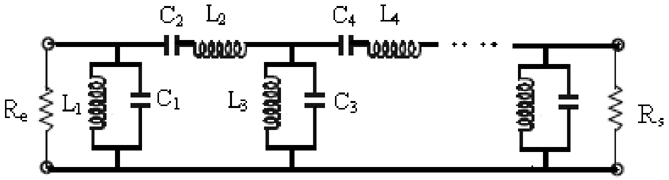


Fig. 5. Band pass filter

The Chebyshev response of this type of filter is represented in figure 6. The resonance frequency of the filter is indicated by ω_0 while the low and high pass frequencies are respectively ω_1 and ω_2.

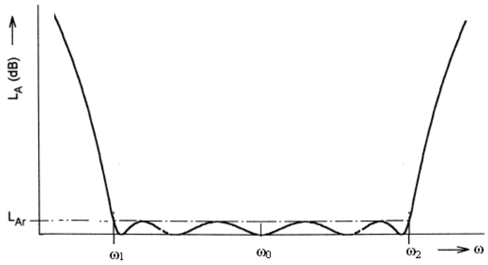


Fig. 6. Chebyshev band pass response.

This type of band pass filter can be easily designed based on a lumped-element low pass prototype and on the following expressions:

For the elements in series:

$$L_k = \frac{R_e g_k}{B\omega_0} \qquad (15)$$

$$C_k = \frac{B}{R_e g_k \omega_0} \qquad (16)$$

For the elements in parallel:

$$L_k = \frac{R_e B}{g_k \omega_0} \qquad (17)$$

$$C_k = \frac{g_k}{R_e B \omega_0} \qquad (18)$$

Where: $B = \frac{\omega_2 - \omega_1}{\omega_0}$

III. STEPPED-IMPEDANCE, L-C TYPE MICRO STRIP FILTERS

Having obtained a suitable lumped-element filter design, the next main step in the design of microstrip filters is to find an appropriate microstrip realization that approximates the lumped element filter. In this section, we concentrate on the second step.

Figure 7 shows a general structure of the stepped-impedance low pass microstrip filters, which uses a cascaded structure of alternating high- and low impedance transmission lines. The high-impedance lines act as series inductors and the low-impedance lines act as shunt capacitors. Therefore, this filter structure is directly realizing the L-C ladder type of low pass filters of figure 3.

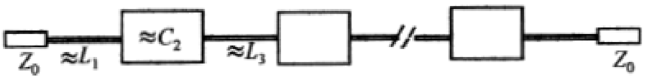
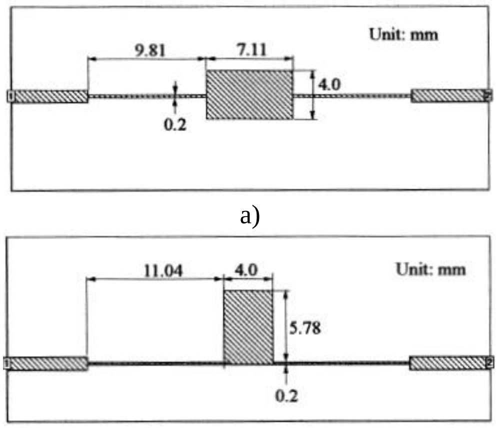


Fig. 7. General structure of the stepped-impedance low pass microstrip filters.

Figures 8 to 10 present three microstrip realizations of low pass, high pass and band pass filters.



a)

b)

Fig. 8. Layout of a 3-pole microstrip low pass filter realized on a substrate with a relative dielectric constant of 10.8 and a thickness of 1.27 mm and using: stepped-impedance on a) and open-circuited stubs on b) [5].

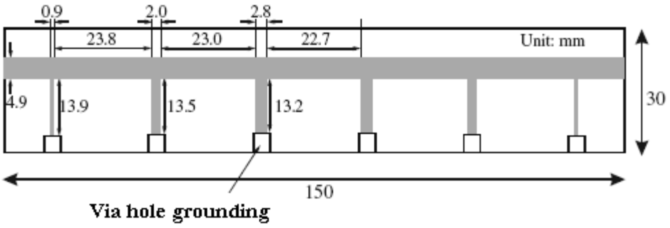


Fig. 9. A microstrip optimum high pass filter on a substrate with a relative dielectric constant of 2.2 and a thickness of 1.57 mm [5]

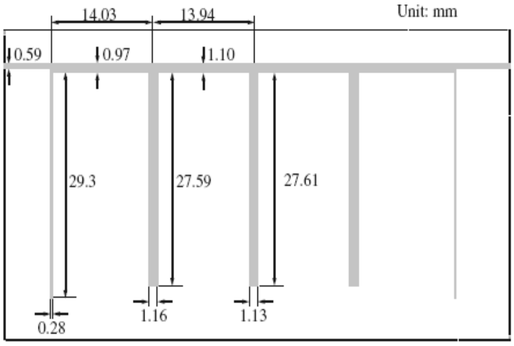


Fig. 10. Layout of a designed microstrip band pass filter with half-wavelength open-circuited stubs on a 0.635 mm thick substrate with a relative dielectric constant of 10.2 [5].

These structures have been studied and analyzed by various commercial EM simulation softwares. Their frequency responses are in good agreement with the requirements and specifications.

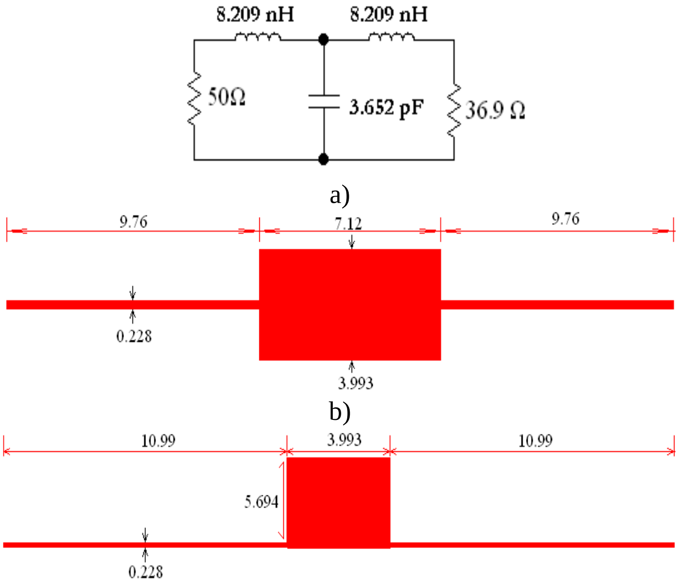
IV. EM ANALYSES AND DESIGN

Using the theory presented in this paper, we realized an accurate CAE tool which allows obtaining a suitable lumped-element filter design and finding an appropriate microstrip realization that approximates the lumped element filter. The frequency responses of our filters designs fabricated with microstrip lines can be obtained using MATPAR [6] or other software.

Our CAE tool suitable for low pass, high pass and band pass RF/microwave filters achieves a quick design according to Butterworth or Chebyshev responses and gives same results as those obtained with commercial electromagnetic (EM) simulation software. Here we applied it to the analysis and the design of an UWB band pass filter with improved upper stop band performances. The design of the UWB band pass filter is based on the use of stepped-impedance low pass filter and high pass filter constructed from quasilumped elements.

An example of design of a three-pole low pass filter is illustrated in figure 11. The specifications for the filter under consideration are: cutoff frequency f_c of 1 GHz, pass band ripple of 0.1 dB (or return loss < –16.42 dB) and source impedance of 50 Ω.

On a substrate with a relative dielectric constant of 10.8 and a thickness of 1.27 mm, figures 11-b and 11-c give two types of realizations that approximate the lumped element filter of figure 11-a. The first one uses stepped-impedance and the second one uses open-circuited stubs. Our obtained results are in good agreement with those shown in figure 8.



a)

b)

c)

Fig. 11. Lumped-element filter design on a) and layouts: stepped impedance on b) and open-circuited on c) (Unit: mm).

High pass filters constructed from quasilumped elements may be desirable for many applications, provided that these elements can achieve good approximation of desired lumped elements over the entire operating frequency band. As part of this study on UWB microstrip lines band pass filters, we examined first the design of a high pass microstrip filter having a cutoff frequency f_c of 3.1 GHz, pass band ripple of 0.1 dB and source impedance of 50 Ω. Using design procedure we find the lumped elements of the following circuit.

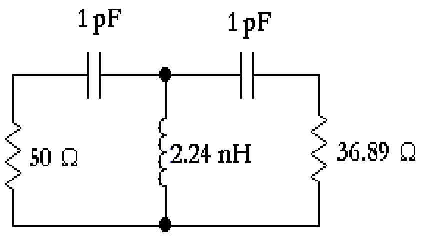


Fig. 12. Lumped-element highpass filter design.

A possible realization of such a high pass filter in microstrip, using quasilumped elements, is shown in figure 13. Here it is seen that the series capacitors are realized by two identical interdigital capacitors, and the shunt inductor is realized by a short-circuited stub. The microstrip high pass filter is designed on a commercial substrate (RT/D 5880) with a relative dielectric constant of 2.2 and a thickness of 1.524 mm.

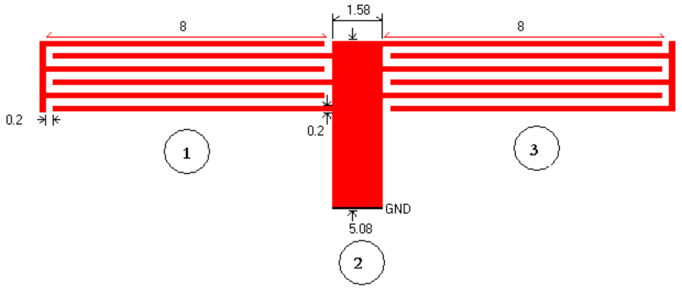


Fig. 13. A quasilumped highpass filter in microstrip on a substrate with a relative dielectric constant of 2.2 and a thickness of 1.524 mm (Unit: mm).

In order to facilitate the analysis of such structure under MATPAR environment, we divided it to three sections of lines (Figure 13). The obtained EM parameters of each section of lines using LINPAR software [7] are:

- For the interdigital capacitors (sections 1 and 3):

$$[L] = \begin{bmatrix} 772.0 & 41.38 & 28.57 & 21.24 & 16.43 & 13.10 \\ 41.38 & 763.3 & 40.97 & 28.34 & 21.12 & 16.43 \\ 28.57 & 40.97 & 761.4 & 40.89 & 28.34 & 21.24 \\ 21.24 & 28.34 & 40.89 & 761.4 & 40.97 & 28.57 \\ 16.43 & 21{,}12 & 28.34 & 40.97 & 763.3 & 41.38 \\ 13{,}10 & 16.43 & 21.24 & 28.57 & 41.38 & 771.9 \end{bmatrix} \left(\frac{nH}{m}\right)$$

$$[C] = \begin{bmatrix} 32.460 & -14.47 & -2.68 & -1.06 & -0.54 & -0.44 \\ -14.47 & 39.20 & -13.28 & -2.23 & -0.85 & -0.54 \\ -2.68 & -13.28 & 39.40 & -13.21 & -2.23 & -1.06 \\ -1.06 & -2.23 & -13.21 & 39.40 & -13.21 & -2.68 \\ -0.54 & -0.85 & -2.23 & -13.28 & 39.20 & -14.47 \\ -0.44 & -0.54 & -1.06 & -2.68 & -14.47 & 32.46 \end{bmatrix} \left(\frac{pF}{m}\right)$$

- For the shunt inductor (section 2): L = 218.0 nH/m; C = 96.8 pF/m; $Z_c = 47.52\ \Omega$ and $\varepsilon_{eff} = 1.4$.

We applied the MATPAR software in the aim of checking the electrical performance of the designed high pass filter shown in figure 13. Figure 14 illustrates the simulated response (S_{21}) of the high pass filter constructed from quasilumped elements, in the frequency band [0.2-25] GHz. It can be seen that for S_{21}=-3 dB the cutoff frequency is 2.9 GHz.

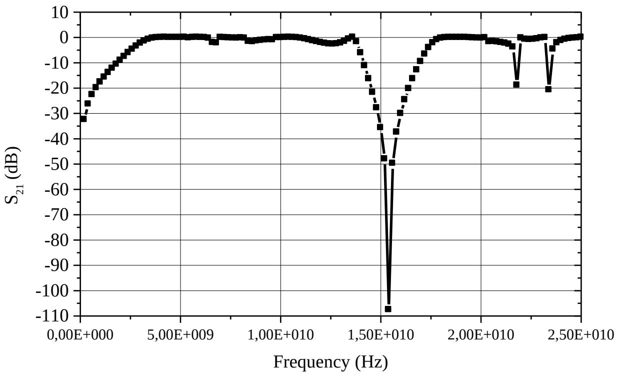


Fig. 14. EM simulated performance of the quasilumped high pass filter.

For the second part of our study on UWB microstrip lines band pass filters, we examined the design of a low pass microstrip filter having a cutoff frequency f_c of 10.6 GHz, pass band ripple of 0.1 dB and source impedance of 50 Ω. Using design procedure we find the lumped elements of the circuit shown in figure 15.

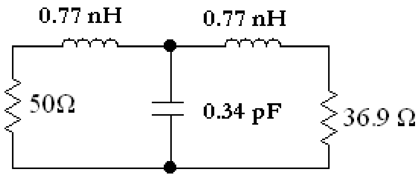


Fig. 15. Lumped-element low pass filter design.

A layout of this designed microstrip filter is illustrated in figure 16, and its performance obtained by MATPAR software is plotted in figure 17.

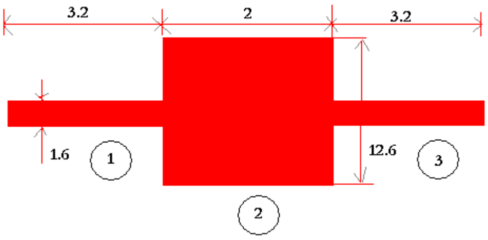


Fig. 16. Layout of the designed stepped-impedance low pass filter realized on a substrate with a relative dielectric constant of 2.2 and a thickness of 1.524 mm (Unit: mm).

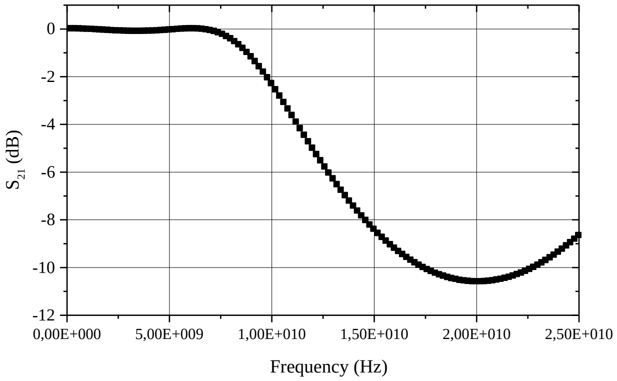


Fig. 17. EM simulated performance of the designed stepped-impedance low pass filter.

The frequency response of the stepped-impedance low pass filter was obtained for the EM parameters listed into table1 of each section of line forming the designed structure. From this response it can be seen that the cutoff frequency of the filter is 10.53 GHz obtained for S_{21}=-3 dB.

Table I. EM parameters of each section of line of the stepped-impedance low pass filter

Section of line	**[L] (nH/m)**	**[C] (pF/m)**	**Z_c (□)**	**□$_{eff}$**
1	412.4	47.95	92.8	1.78
2	113.7	196.6	24.0	2.0
3	412.4	47.95	92.8	1.78

Finally the layout of the designed UWB band pass filter using a 3-pole microstrip low pass filter is illustrated in figure 18, and its performance obtained by MATPAR software is plotted in figure 19 in the frequency band [0.2-25] GHz. This response is in reasonable agreement with results of planar structures and it also meets the requirements for UWB applications per the FCC [8]. The simulated results of stop band performances are better than 5 dB for a frequency range up to 25 GHz.

In order to increase the stop band performances of our designed structure, figure 20 gives the layout of the final UWB band pass filter using a 5-pole microstrip low pass filter. In figure 21 we present the frequency response of our designed filter.

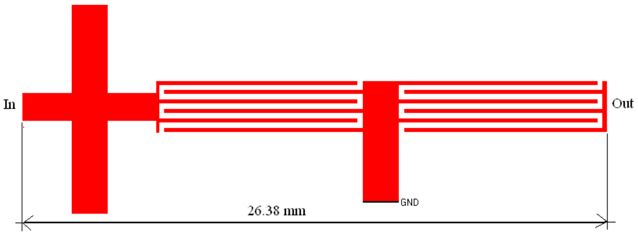


Fig. 18. Layout of the designed UWB band pass structure using a 3-pole micro strip low pass filter

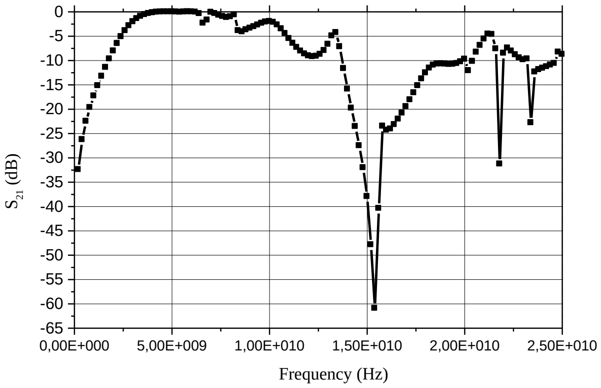


Fig. 19. EM simulated performance of the designed UWB band pass structure using a 3-pole micro strip low pass filter.

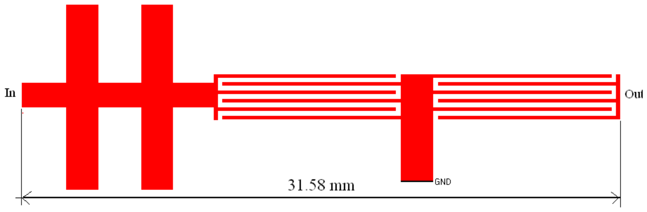


Fig. 20. Layout of the designed UWB band pass structure using a 5-pole microstrip low pass filter

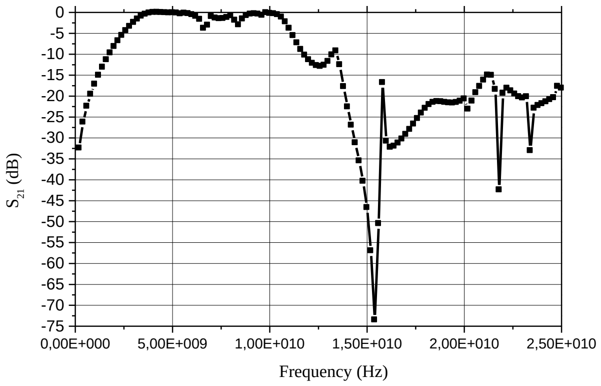


Fig. 21. EM simulated performance of the designed UWB band pass structure using a 5-pole micro strip low pass filter.

Our filter, which measures just 12.6×1.524×31.58 mm, was fabricated using RT/D 5880 substrate by means of stepped-impedance 5-pole microstrip low pass filter and high pass filter constructed from quasilumped elements. The simulated results of stop band performances are better than 15 dB for a frequency range up to 25 GHz.

V. CONCLUSION

In summary, this work presented the analysis, the design and the simulation of an ultra wideband band pass filter with improved upper stop band performances, using micro strip lines.

The filter which measures just $12.6 \times 1.524 \times 31.58$ mm, was fabricated using RT/D 5880 substrate by means of stepped-impedance 5-pole micro strip low pass filter and high pass filter constructed from quasilumped elements. The simulated results of stop band performances are better than 15 dB for a frequency range up to 25 GHz.

It was designed using our accurate CAE tools and with the aid of MATPAR software, although other commercial EM simulation software can also be used.

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