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RESEARCH ARTICLE

Coaxial Low-Pass Filter Design and Manufacture

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ABSTRACT In this study, a low-pass filter with coaxial transmission lines is designed and produced. The objective for designing a coaxial low-pass filter was to utilize both low-loss transmission and high breakdown voltage capability for high power microwave applications to enable the suppression of the second harmonic of the 4.4-6 GHz C-Band (C-Band was selected as a proof of concept) signals with minimal insertion loss. Microwave and 3D electromagnetic simulators were used in the filter design. The design was started by establishing an 11 th order Chebyshev low-pass filter prototype giving 0.05 dB ripple. Based on this prototype, a filter circuit consisting of capacitors and inductors as lumped elements was designed. The low and high impedances to be selected for the stepped impedance method, which is the basis of the transition to coaxial transmission lines, were decided and the most suitable impedances for manufacturing was determined. The filter using these impedances and designed with stepped impedance lines was transformed into the filter in which coaxial transmission lines are used. Coaxial transmission lines in the low-pass filter circuit consist of conductors with an insulating material in between. While the insulating material is selected as air in the high impedance sections of the transmission lines, it is PTFE (Polytetrafluoroethylene) with an insulating constant of 2.1 in the low impedance sections. The designed filter was manufactured. The basic properties of the manufactured filter were characterized by using RF measuring devices and compared with the designed filter. The measurements results proved that the frequency responses of the designed filter and the produced filter were very close to each other. Namely, a low-pass filter with a cutoff frequency of 6 GHz, a sharp suppression of about 45 dB at the stopband of 9 GHz and a return loss of 20 dB was designed and produced by using coaxial transmission lines. The novelty in our work can be stated that the power handling capability is increased by two techniques. The first one is that the highest transmission line radius preventing the higher order mode excitations is used to decrease the conductor loss. Teflon is covered around the low impedance lines to enhance the dielectric breakdown capability. Teflon inclusion is also used to decrease the practical low impedance level that improves the filter characteristics.

INDEX TERMS Low pass filter, coaxial filter, Chebyshev filter, return loss.

I. INTRODUCTION

Filters are used in communication systems to obtain the desired frequency response. Lumped elements such as inductors and capacitors do not satisfy the design criteria at high frequencies since they lose their linearity at these frequencies. Therefore, transmission lines are used when microwave filters are of concern.

Studies on microwave filters started before World War II. The first study was reported in 1937 by Mason and Sykes [1]. Although the study was conducted almost 85 years ago, the outcomes are still applicable today. After initial studies [1], [2], there has been enormous amount of study on filter design and manufacture which also continues with a faster speed today.

In this paper, a low pass filter with coaxial transmission lines was designed and produced. The coaxial transmission line has a closed structure. Therefore, it does not expel the wave out of the transmission line. Besides, it is suitable to operate at higher powers as compared to planar transmission lines. Before starting the design work, studies on coaxial filter design and production were examined. In this context, prominent studies on coaxial filters are summarized in the following paragraphs.

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Liu and Weinreb [3] designed a high pass filter where four parallel inductors are realized by producing short circuit coaxial cable inductors.

Benedicto et al. studied [4] an L-band filter of 6 th order to be used in space applications. The design is based on stepped impedance coaxial resonators (SIR) satisfying various electrical and dimensional requirements. Zhang et al. [5] proposed two coaxial waveguide bend mode converters which transforms coaxial transverse electromagnetic (TEM) mode to TE11 coaxial waveguide mode. Schoebel et al. [6] presented a study where the practical implementation aspects of coaxial filters are discussed by which it is shown that filters having medium and large bandwidth can be realized.

Agarwal et al. [7] designed a coaxial cavity band pass filter with large bandwidth suitable to be used in spacecraft control applications.

Martinez et al. [8] presented a sixth-order Chebyshev bandpass filter with empty substrate integrated coaxial line (ESICL) technology. The main advantage of the filter is stated to be the ability to avoid the loss due to the propagation through the dielectric material.

Sovuthy and Wen [9] investigated the design of a stepped impedance coaxial microwave filter based on TEM propagation mode. The study carried out by Zakaria et al. [10] includes a low-loss coaxial cavity microwave bandpass filter. The study started with a low-pass prototype as the initial point to achieve a bandpass response of a fourth-order filter. The study by Aouidad et al. [11] introduced a concept of stepped impedance resonators consisting of two coaxial structures fitted inside one another. The main advantage of the proposed filter is that it suppresses the first harmonic strongly without adversely affecting the quality factor.

Goulouev et al. [12] proposed a new coaxial low-pass filter (LPF) concept and design methodology. The proposed LPF consists of an array of cavity elements and operates with transverse electromagnetic (TEM) mode and transverse magnetic (TM) coupled resonators. The concept provides low insertion loss, high power and low sensitivity against production tolerances as well as maintaining an ultra-wide stopband.

Kushino and Kasai [13] developed thin semi-rigid coaxial cables to be used in low temperature experiments. Vague et al. [14] optimized and manufactured different types of wideband coaxial filters by using different materials.

Davis and Khan [15] designed a number of filters by using coaxial lines with an outer diameter of 7 mm. The designed filters were also manufactured and tested. The center frequency of the filters is reported to be 3 GHz and they exhibited an insertion loss of 2.1 dB.

Important results were obtained in these studies. One of the most important issue is the transmission of high power with little loss, besides filtering. This issue has not come to the fore in the studies carried out so far, or to the best of our knowledge, publications on this subject have been insufficient for commercial reasons. Lossless power transmission and suppression of harmonics are very important issues, especially in high-power power amplifiers. Therefore, the main motivation for our research was to design a coaxial low-pass filter to utilize both low- loss transmission and high breakdown voltage capability for high power microwave applications to enable the suppression of second harmonic of the 4.4-6 GHz C-Band (C-Band was selected as a proof of concept) signals with minimal insertion loss.

II. FILTER DESIGN AND SIMULATION STUDIES

First of all, the prototype filter which will be the baseline for the designed filter is prepared. During the preparation stage, several Chebyshev filters with different passband ripples were compared and the filter best suited to our target design was selected. A sharp attenuation is observed at the stopband as the ripple is increased and the return loss is reduced as the ripple is decreased. After the best suited prototype is selected and prepared, the filter is designed by using lumped elements. As filters with lumped circuit elements are not suitable to be used at high frequencies, the filter is redesigned by using stepped impedance method. Here, high and low impedances are specified in a way to provide the best filter characteristics and suitability for manufacturing at the same time. The bigger the ratio between the high impedance and low impedance, the closer the filter characteristics approaches the ideal filter. However, the transmission lines with high values becomes very thin which in turn makes the manufacturing process difficult. The thick transmission lines with low impedance act as capacitors while the thin lines with high impedance act as inductors.

The two stepped impedance lines are converted into three dimensional coaxial transmission lines which provides advantages in terms of losses. The coaxial transmission lines consists of nested conductors having insulating material in between. The insulation material in the low impedance section of the transmission lines is selected as PTFE (Politetrafloroetilen) having a dielectric constant $\varepsilon_r = 2.1$ whereas the insulation material in the high impedance section is selected as air. In this way, when air is used, it is possible to use longer transmission lines as compared to the transmission lines when PTFE is used as an insulator. This in turn provides convenience in production. AWR and CST software packages were used for simulation studies. While simulations are easier and faster in AWR, 3D electromagnetic simulations in CST give results being closer to practical implementation reality. Therefore, studies in AWR have shown significant differences when transferred to CST. Therefore, in order to meet the design target, the frequency response in AWR was recorded by adjusting the line measurements to catch the target in the CST.

The filter designed and manufactured has two ports. The first port starts with a serial transmission line with an impedance of 50 Ω and continues with low impedance and high impedance lines. Since the circuit is symmetrical, it ends with the 50 Ω line of the second port. While the inner conductor diameter is larger in low impedance lines, it is smaller in high impedance lines. Outer conductor diameters are kept constant for all lines.

It is very important to consider the reflection and transmission parameters in filter design. While S_{11} and S_{22} are reflection parameters, S_{12} and S_{21} are transmission parameters. For the waves returning from the second port to the first port, S_{11} is examined. While the return loss is examined, for the wave transmitted from the first gate to the second gate, S_{21} (transmission coefficient) is examined.

Coaxial transmission line filters are a common type of microwave filters. Apart from this, it is also possible to produce filters with different techniques such as microstrip, strip line, suspended strip line. The microstrip consists of a strip conductor on the upper surface of a dielectric layer and a ground plane on the lower surface of the dielectric. The production of the filters with microstrip technique is easier as compared to the filters designed by using strip line and suspended strip line. However, since the conductive strip line is not embedded between the insulators, the loss is high. Since the coaxial transmission line has a closed structure, it does not expel the wave out of the transmission line. Therefore, coaxial transmission lines are more suitable at high powers as compared to the planar transmission lines. Considering this advantage, a low-pass filter with coaxial transmission lines was designed and produced.

A. LOW PASS FILTER WITH LUMPED ELEMENTS

A prototype is prepared before moving on to low-pass filter design. In the prototype circuit, the source and load impedances are equalized to 1Ω, the circuit element values are normalized and the cutoff frequency is assumed to be 1 rad/s. The filter to be designed is reached by using the prototype. The approach for low-pass prototype filters has been simplified by Matthaei et al. [16]. This approach can be applied to filters with a specific frequency response. The "g" values known as the circuit element values in the prototype circuit can be calculated by using the network synthesis method developed by Brune and Darlington [17]. Precomputed element values for different frequency responses in terms of the ripple values for Chebyshev are given in several tables in the literature [18].

First of all, the selectivity factor (w_n) is calculated to specify the degree of the filter to be designed. The selectivity factor is obtained by equation (1).

$$w_n = (w/w_c) = (2\pi f)/(2\pi f_c) \tag{1}$$

Here, w is the working frequency and w_c is the cutoff frequency. Suppose that it is desired to design a filter having 2 GHz cutoff frequency and 45 dB attenuation at 10 GHz (w). One can see that the selectivity factor is determined as 5 rad/sec if we use equation (1). Attenuation versus normalized frequency graphs for Chebyshev filters can be found in [18]. If a vertical line starting from the normalized frequency axis at 5 rad/sec is drawn up to the point where 45 dB attenuation is achieved, the corresponding curve will give us the filter degree to meet the stated 45 dB attenuation requirement. Accordingly, it is seen that it would be appropriate to design a 3rd order filter.

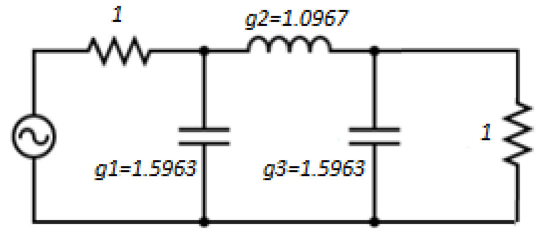

FIGURE 1. Low-pass filter prototype, n = 3.

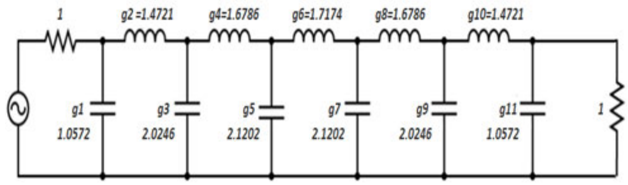

FIGURE 2. Low-pass filter prototype, n = 11.

Once the filter order is determined, the g values of the circuit elements are drawn from the tables provided in [18]. These "g" values are the coefficients of the Chebyshev polynomial. Starting from the beginning, these "g" values are assigned to the lumped elements on the prototype. The source and load side impedances are selected as 1 according to this prototype. Since the filter degree is found to be n = 3, the values in the N = 3 row in the related tables in [18] are assigned as the values of C and L sequentially. Finally, the prototype can be built as shown in Figure 1.

In filter prototypes, the number of reactive elements is equal to the filter order. In most cases, a sharp attenuation is desired between the passband and stopband. A sharp attenuation can be achieved by increasing the number of circuit elements [19].

In this study, the objective was to design a filter with a cutoff frequency of 6 GHz, which attenuates the signal by 50 dB at 9 GHz. By using the method described in the previous example, the 11 th order low-pass filter prototype in Figure 2 which gives 0.05 dB ripple, was prepared to meet the stated requirement.

B. LOW PASS FILTER WITH LUMPED ELEMENTS

First, the source/load impedance value Z_0 is converted into a circuit with 50 Ω and a cutoff frequency f_c of 6 GHz by making frequency and circuit element conversions,

Capacitor and inductor values to be used in the low-pass filter prototype are calculated by equation (2) and (3) [20]. Here, g_n is the value of the circuit element in the prototype,

TABLE 1. The calculation of capacitor and inductor values.

Circuit Element	Circuit Element Values
$C_1 = C_{11}$	0.495 pF
$L_2 = L_{10}$	1.723 nH
$C_3 = C_9$	0.948 pF
$L_4 = L_8$	1.978 nH
$C_5 = C_7$	0.993 pF
L_6	2.011 nH

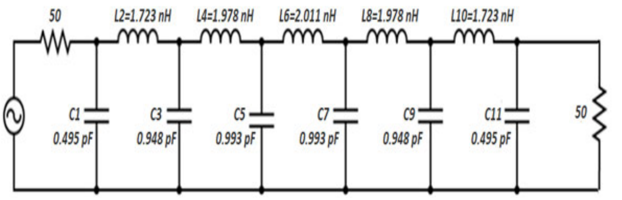

FIGURE 3. Low-pass filter design, n = 11.

$w_c = 2\pi f_c$ and the impedance value is taken as $Z_0 = 50\ \Omega$.

$$C_n = (g_n)/(Z_0 w_c) \tag{2}$$
$$L_n = (g_n Z_0)/(w_c) \tag{3}$$

Circuit elements in the LPF prototype given in Figure 2 are symmetrical. In this case, circuit elements are $C_1 = C_{11}$, $L_2 = L_{10}$, $L_4 = L_8$, $C_5 = C_7$. The specified capacitor and inductor values are calculated by equation (2) and (3) as given in Table 1. The LPF indicated in Figure 3 was designed by using the values in Table 1.

According to the calculated capacitor and inductor values, the low-pass filter is designed with lumped elements as in Figure 3.

C. STEPPED IMPEDANCE FILTER DESIGN

Almost any medium forming a transmission line can be used to create low-pass filters with stepped impedance method. A coaxial line with varying inner diameter is often preferred. A stepped low-pass filter is a series of low and high impedance lines. They are easier to design and take up less space than a similar low-pass filter using a stud. They consist of series inductors and parallel capacitors. A stepped impedance low-pass filter can be obtained if series inductors are replaced with high impedance lines and parallel capacitors with low impedance lines.

The susceptibility of the parallel capacitor is expressed by equation (4) and the reactance of the series inductor is expressed by equation (5). Here, βl is the electrical length, Y_0 is the characteristic admittance of the capacitor, Z_0 is the characteristic impedance of the inductor, B is the susceptibility of the capacitor and X is the reactance of the inductor [21].

$$B \cong Y_0 \beta l \tag{4}$$
$$X \cong Z_0 \beta l \tag{5}$$

In matrix form, these equations can be expressed as shown in Eq. (6) and (7).

$$\begin{bmatrix} 1 & 0 \\ jY_0\beta l & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ jwC & 1 \end{bmatrix}, \quad Y_0\beta l = wC = B \tag{6}$$
$$\begin{bmatrix} 1 & jZ_0\beta l \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & jwl \\ 0 & 1 \end{bmatrix}, \quad Z_0\beta l = wL = X \tag{7}$$

The advantage of using stepped impedance lines in filter structures is that the impedances can be adjusted to suppress unwanted harmonics. The disadvantage is that these filters cannot show full reflection because the input impedance never reaches zero or infinite impedance. As a result, they do not have very good stopband attenuation.

The series inductors of a low-pass prototype filter can be replaced by high-impedance line segments ($Z_0 = Z_h$) and parallel capacitors by low-impedance line segments ($Z_0 = Z_l$). The theory is based on the use of coaxial transmission lines (TL) having short electrical length. That is valid when $\beta\ell =\prec\prec \pi/2$. Here, $\beta\ell = 2\pi(\ell/\lambda)$ where β is the propagation constant, ℓ is the length of TL and λ is the wavelength. As detailed and proved in [18] for TL having short electrical length, the high characteristics impedance ($Z_0 = Z_h$) becomes equivalent to a series inductor with a reactance of $X \approx Z_0\beta\ell = Z_h\beta\ell$. On the other hand, low characteristic impedance ($Z_0 = Z_l$) can be taken as equivalent to a shunt capacitor where the susceptance $B = (1/Z_0)Sin\beta\ell \approx (1/Z_0)\beta\ell = (1/Z_l)\beta\ell$. Physically, the ratio of the characteristic impedances Z_h/Z_l must be set as high as possible that can be practically fabricated.

In this study, the impedance pair were first selected as $Z_l = 20\ \Omega$, $Z_h = 120\ \Omega$ and then as $Z_l = 20\ \Omega$, $Z_h = 80\ \Omega$. The electrical (phase difference) and physical lengths of the lines are given in Table 2 for the case where the impedances are selected as $Z_h = 120\ \Omega$, $Z_l = 20\ \Omega$ and in Table 3 for the case where the impedances are selected as $Z_h = 80\ \Omega$, $Z_l = 20\ \Omega$.

Looking at the results in Table 2 and 3, it is seen that while $Z_h = 80\ \Omega$, it is possible to design longer lines in the filter. At the same time, the frequency responses in Figure 4 show that the impedance selection does not disturb the desired result. The pink and turquoise colored curves in Figure 4 shows the state of S_{21} and S_{11} when $Z_h = 120\ \Omega$ and $Z_l = 20\ \Omega$. The red and blue colored curves show the state of S_{21} and S_{11} respectively when $Z_h = 80\ \Omega$ and $Z_l = 20\ \Omega$. In the first case ($Z_h = 120\ \Omega$, $Z_l = 20\ \Omega$), S_{21} gave better results at 9 GHz than the second case ($Z_h = 80\ \Omega$, $Z_l = 20\ \Omega$). The values of S_{11} are very close to each other in both cases. As a result, the impedance value for Z_h was selected as 80 Ω in the design using stepped impedance method. This selection facilitates the production of the filter.

TABLE 2. **Trasmission lines' electrical and physical lengths ($Z_h = 120\ \Omega$, $Z_l = 20\ \Omega$).**

i	Electrical Length	w_i(mm)	l_i(mm)
1	24.24^0	16.64	2.42
2	35.16^0	0.95	3.77
3	46.42^0	16.64	4.64
4	40.09^0	0.95	4.30
5	48.61^0	16,64	4.86
6	41.02^0	0.95	4.40
7	48.61^0	16.64	4.86
8	40.09^0	0.95	4.30
9	46.42^0	16.64	4.64
10	35.16^0	0.95	3.77
11	24.24^0	16.64	2.42

TABLE 3. **Trasmission lines' electrical and physical lengths ($Z_h = 80\ \Omega$, $Z_l = 20\ \Omega$).**

i	Electrical Length	w_i(mm)	l_i(mm)
1	24.24^0	16.64	2.42
2	52.74^0	2.31	5.56
3	46.42^0	16.64	4.64
4	60.14^0	0.95	4.30
5	48.61^0	16.64	4.86
6	61.53^0	2.31	6.49
7	48.61^0	16.64	4.86
8	60.14^0	2.31	6.34
9	46.42^0	16.64	4.64
10	52.74^0	2.31	5.56
11	24.24^0	16.64	2.42

D. COAXIAL FILTER DESIGN

TEM mode is a propagation mode in which the electric and magnetic fields are perpendicular to each other and to the propagation direction. In coaxial transmission lines, the TEM mode is the dominant mode and signals are carried in this mode. Under favorable conditions, all Electric Field lines run from the center to the outer conductor, while Magnetic Field lines draw circles around the central conductor. At high frequencies, the dimensions of the cables must be limited as higher order modes can be emitted. This limits the power capacity [18]. In order to increase the power capacity, increasing the outer radius may be the solution.

1) LINE LENGTH CALCULATION

Since stronger constraints are imposed on the transverse dimensions rather than the length in the production process,

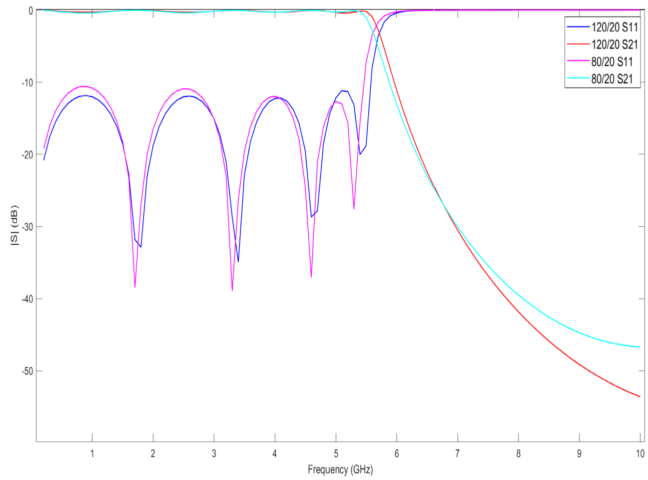

FIGURE 4. **Simulation results for the return loss and the gain values for the stepped impedance filter with two different impedances ($Z_h = 120\ \Omega, Z_l = 20\Omega$ & $Z_h = 80\ \Omega, Z_l = 20\ \Omega$).**

it is essential to determine the lengths of the transmission lines according to the selected characteristic impedances. This can be derived from equations (6) and (7). For a parallel capacitor, the electrical length of the transmission line is equal to the product of capacitor susceptance by the characteristic impedance. For a series inductor, the electrical length of the transmission line is the ratio of the inductor reactance to the characteristic impedance. The length of the capacitor, whose characteristic impedance is determined by using equation (6), (the length of the low impedance line) is calculated by equation (8) [21].

$$l = (g/2\pi)x(Z_l/Z_0)x(1/f_c\sqrt{\mu\varepsilon})x(1/\varepsilon_r) \tag{8}$$

The length of the inductor, whose characteristic impedance is determined by using equation (7) (the length of the high impedance line) can also be determined by equation (9) [21]. Here, ε is the electrical permittivity and μ is the magnetic permeability.

$$l = (g/2\pi)x(Z_0/Z_h)x(1/f_c\sqrt{\mu\varepsilon})x(1/\varepsilon_r) \tag{9}$$

2) LINE RADIUS CALCULATION

In case, the transmission line has little loss, the characteristic impedance can also be defined by equation (10) [22].

$$Z_0 = (60/\sqrt{\varepsilon_r})\ln(b/a) \tag{10}$$

The radius length of the inner and outer conductor can be determined for each line by using equation (10). Here, b is the outer conductor radius and a is the inner conductor radius.

As can be seen, the selected characteristic impedances and the dielectric coefficient of the insulator material in the coaxial line have an effect on the radius. Choosing a material with a smaller dielectric constant can be a solution for small radius lengths that may cause difficulties in the production phase. As can be seen from equation (10), the inner conductor radius (a) increases as the dielectric constant decreases at a fixed characteristic impedance Z_0.

TABLE 4. Transmission lines' dimensions ($Z_h = 80\ \Omega$, $Z_l = 20\ \Omega$, $\varepsilon_r = 2.1$).

Transmission Lines	Length (mm)	Radius (mm)
l_1	2.321	6.160
l_2	6.456	2.600
l_3	3.921	6.160
l_4	7.361	2.600
l_5	4.654	6.160
l_6	7.532	2.600
l_7	4.654	6.160
l_8	7.361	2.600
l_9	3.921	6.160
l_{10}	6.456	2.600
l_{11}	2.321	6.160

When the insulator material in the coaxial line is selected as PTFE (Politetrafloroetilen) with a dielectric constant of 2.1, the inner conductor radii within the lines are calculated as 6.16 mm and 2.6 mm. The physical dimensions of the lines determined as a result of line calculations are given in Table 4.

The low-pass filter with coaxial lines was built by using the AWR software package with the above dimensions,

In our study, analyses were made with different mesh numbers. Two different mesh structure with different mesh size (2264, 24754) are plotted in Figure 5 below. The frequency responses did not change when the mesh size is doubled. In order to keep the simulation time short, we continued to work with the mesh size of 12264.

The outer surface of the designed filter is ground. During the analysis, the results were compared by using different values in the "Boundary" and "Background" settings. In the "Boundary" settings, "Electric (Et = 0)" is selected for all axes. In another condition, Material type PEC (Perfect Electric Conductor) is selected in Background settings. It was observed that the results were the same in both settings. Therefore, we decided to choose Et = 0 as the "Boundary."

The frequency response obtained as a result of this design is given in Figure 6. Considering the frequency response, the cutoff frequency was 6 GHz and the return loss was around 14 dB. The filter suppresses the signal by 50 dB at 9 GHz.

Here, we see that targeted return loss specified to be less than 20 dB was not satisfied. Therefore, the design was optimized. The dimensions of the new transmission lines are listed in Table 5. The result obtained at the end of the optimization is shown in Figure 7. Looking at the frequency response, it is seen that the return loss has been reduced to 20 dB.

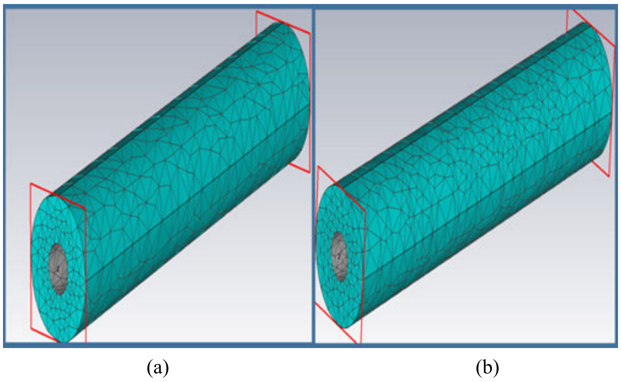

FIGURE 5. (a) Mesh size: 12264. (b) Mesh size: 24754.

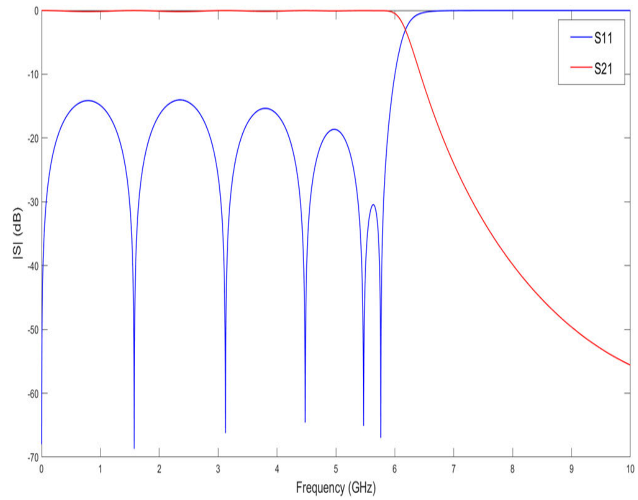

FIGURE 6. Simulation results for the return loss and the gain values for the coaxial filter design before optimization.

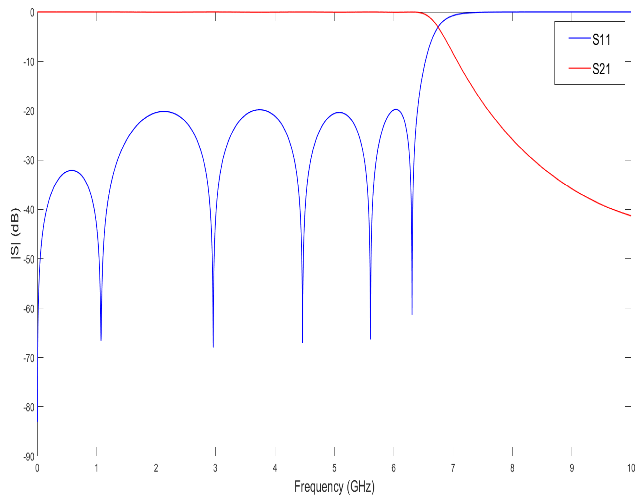

FIGURE 7. Simulation results for the return loss and the gain values for the coaxial filter design after optimization.

The cutoff frequency was kept at 6.4 GHz since there would be a shift in frequencies when the design is moved to CST after optimization. The attenuation in the stopband is

TABLE 5. Transmission lines' dimensions after optimization ($Z_h = 80\ \Omega$, $Z_l = 20\ \Omega$, $\varepsilon_r = 2.1$).

Transmission Lines	Length (mm)	Radius (mm)
l_1	2.56	5.28
l_2	6.30	2.58
l_3	4.25	5.28
l_4	7.70	2.58
l_5	4.27	5.28
l_6	8.0	2.58
l_7	4.27	5.28
l_8	7.70	2.58
l_9	4.25	5.28
l_{10}	6.30	2.58
l_{11}	2.56	5.28

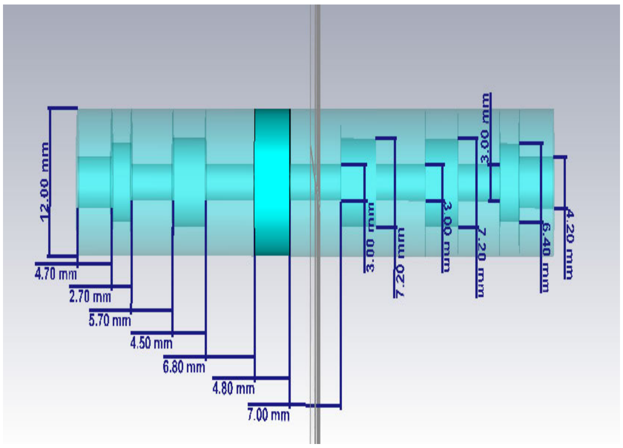

FIGURE 8. The coaxial filter structure and transmission line dimensions.

allowed to be below target. Later, the design was transferred to CST and necessary changes were made on the dimensions in order to achieve the desired results. The final state of the filter dimensions before the manufacturing process is given in Figure 8.

A question that naturally comes to mind here is to compare the frequency responses with and without the PTFE ring. Therefore, a simulation study was carried out with and without PTFE ring, including passband and wide stopband. Obtained frequency characteristics are given in Figure 9.a and Figure 9.b. As can be seen from the simulation results, using Teflon ring provides a better suppression performance as compared to the case without Teflon ring. The cutoff frequency is nearly at 6 GHz when dielectric ring is used and it is 8 GHz when there is no ring. We see that the stopband is moved 2 GHz ahead when PTFE ring is not used.

On the other hand, narrow band notches are observed beyond 15 GHz in both cases with and without dielectric

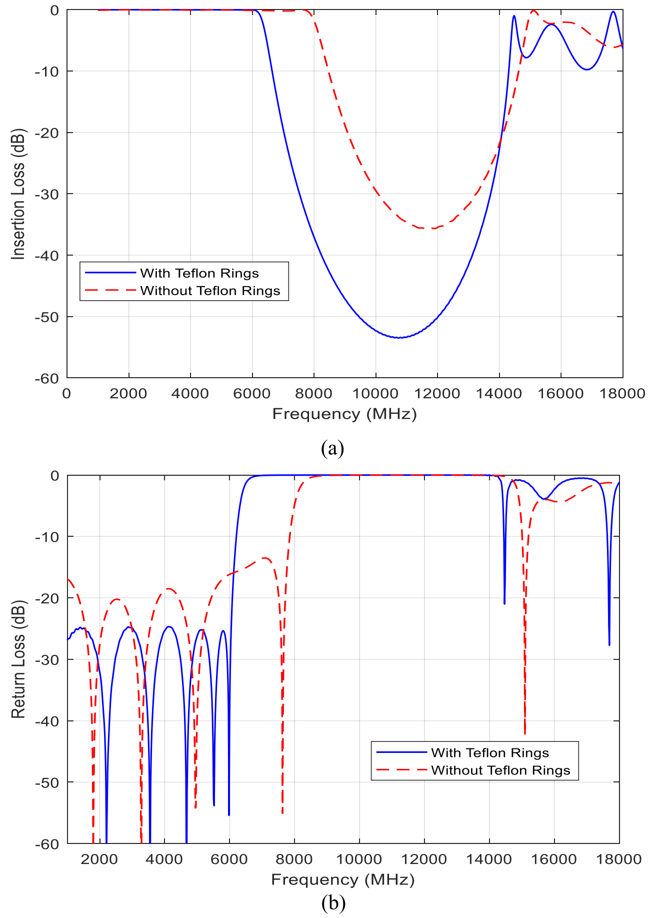

FIGURE 9. a. Simulation results for the insertion loss (S21) for the coaxial filter design with and without Teflon rings. b. Simulation results for the return loss (S11) for the coaxial filter design with and without Teflon rings.

rings. In fact, stepped impedance low-pass filter design is based on the short line approximation theory as we discussed previously. At upper frequencies, the electrical length of the lines increases and short line approximation is no longer valid. Therefore, stepped impedance low-pass filters are used to suppress the second harmonics. New passbands occur for higher harmonics. One of the objective of our filter design was to attenuate the second harmonic of the 4.4-6 GHz C-Band where there is an attenuation of more than 40 dB at this second harmonics band.

Without the Teflon rings, the lengths of the transmission lines are effectively decreased. Therefore, the filter cutoff frequency shifts to a higher frequency. When Teflon ring is not used, the low impedance lines have a higher impedance which degrades the attenuation characteristic at the second harmonic and in-band return loss as observed in Figure 9.a and Figure 9.b.

III. MANUFACTURING AND TEST

The manufactured filter is given in Figure 10. The filter structure with the case removed is shown in Figure 11. Here, the low impedance lines are wrapped with Teflon, while the

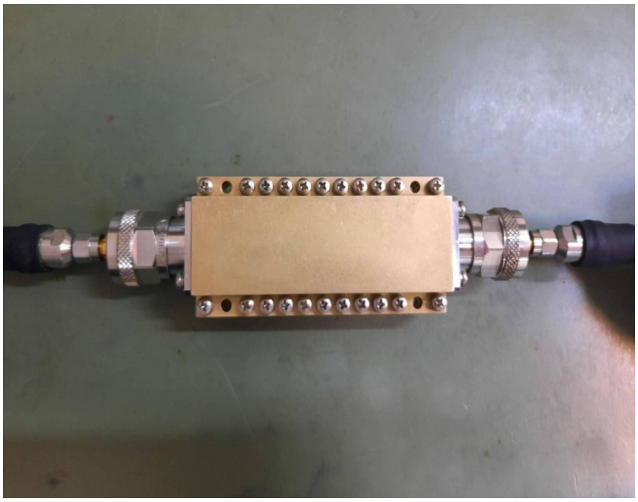

FIGURE 10. The manufactured filter.

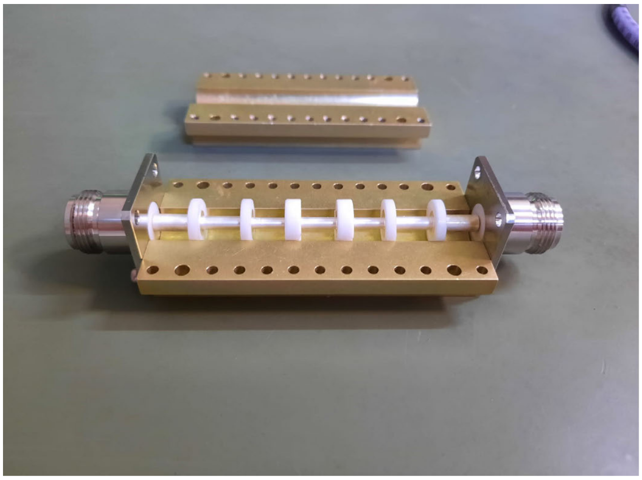

FIGURE 11. The coaxial filter with the case removed.

high impedance lines are allowed to be filled with air. Thus, high impedance lines with no Teflon wrapping selected as 80 Ω behave like a higher impedance. In this way, since the difference between high and low impedance will increase, the filter characteristic approaches the target.

After the designed filter was manufactured, its measurements were conducted by using a Network Analyzer. The network analyzer measures the scattering parameters of the filter and shows the characteristics of the filter and the losses. The simulation data and the measurement data through the network analyzer are plotted together in Figure 12.

The cutoff frequency of the filter was observed to be 6.5 GHz. The amount of attenuation at 9 GHz is measured as 46 dB. The return loss was shown to be 23 dB. The insertion loss in the passband was indicated as 0.2 dB. The value in question is a better value than similar filters.

The responses of the designed and manufactured coaxial filter values are very close to each other. While the cutoff frequency was 6.2 GHz in the simulation results, it was

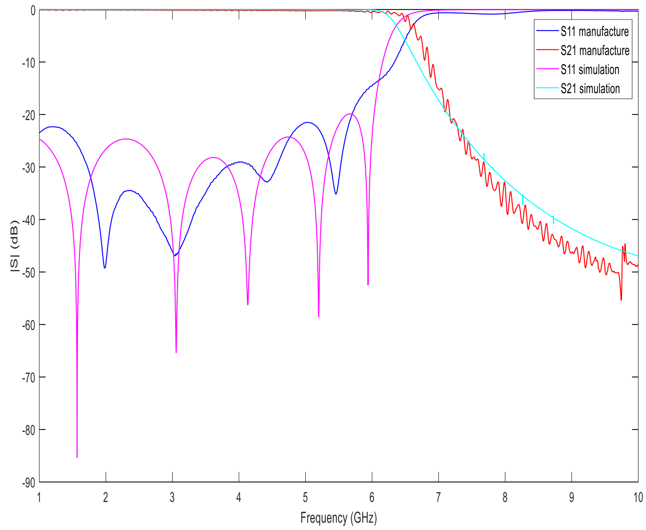

FIGURE 12. Simulation and manufacture results for S11 and S21.

TABLE 6. Comparasion of design and experimental results.

Studies	Cutoff Frequency (GHz)	Insertion Loss, dB (S21)	Return Loss, dB (S11)	Bandwidth (GHz)
Design	6.20	0.10	20	6.2
Manufactured Filter	6.50	0.20	23	6.5

observed that the manufactured filter exhibited 0.3 GHz higher cutoff frequency.

Although the insertion loss is increased by 0.1 dB at the end of the manufacture, the return loss was reduced by 3 dB after the manufacture. While the desired attenuation at 9 GHz was 40 dB in the simulation results, the attenuation was measured as 46 dB at the end of the manufacture. The design simulation and manufacture results are compared in in Table 6 in terms of the main parameters.

We observe that the insertion loss values for the design simulation and manufactured filter measurement are very close to each other. There are some deviations between the measurement and simulation data concerning the value of return loss. It is very well known that we use approximation when we design filters. In addition to that, the manufacture process depends on the production machine tolerances which are extremely challenging for small length size. This two main parameters are the main obstacles resulting in differences between the simulation and measurement data. Fortunately, the manufactured filter exhibits satisfactory insertion loss and return loss according to the stated design criteria.

The comparison of the results with other studies is given in Table 7. We see that the manufactured filter in this study provides better performance in terms of high bandwidth,

TABLE 7. Comparasion of the results with other studies.

Studies	Frequency (GHz)	Insertion Loss (dB)	Return Loss (dB)	Bandwidth (GHz)
This study	6.50	0.20	23	6.50
H. Liu (HPF) [3]	0.89	0.16	20	-
J. Vague (LPF) [14]	5.50	0.02	25	5.50
H. Aouidad (BPF) [11]	0.43-1.63	0.40	25	1.20
Z. Zakaria (BPF) [10]	2.5	0.15	15	0.16

operating frequency and losses. There was no difficulty in the production technique.

IV. CONCLUSION

In communication, filters are important in suppressing unwanted signals, noises and harmonics. In this article; a low-pass coaxial filter with a cutoff frequency of 6 GHz is designed and manufactured. By using coaxial transmission lines, the filter is aimed to provide a 20 dB return loss in the 6 GHz passband and a sharp suppression of 50 dB at 9 GHz. The objective for designing a coaxial low-pass filter was to utilize both low loss transmission and high breakdown voltage capability for high power microwave applications to enable the suppression of the second harmonic of the 4.4-6 GHz C-Band signals with minimal insertion loss.

To meet the specified design criteria; First, an 11 th order Chebyshev filter with 0.05 dB ripple is designed with lumped elements. Then, the design was transformed into stepped impedance lines by selecting low and high impedances. The last step was the transition from the stepped impedance lines to the coaxial transmission lines.

The most important point in the design with coaxial lines is the electrical properties of the insulating material between the center conductor and the shield. While the dielectric constant of the insulating material increases, the length of the transmission lines used decreases, making production difficult. While the material with high dielectric constant produces better suppression in the stopband of the filter, it causes relatively high return loss in the passband. Therefore, while designing coaxial transmission lines, low impedance lines are filled with PTFE with an insulating constant of 2.1, while spaces in high impedance lines are filled with air. In this way, when air is used, it is possible to use longer transmission lines as compared to the transmission lines when PTFE is used as an insulator. This provides convenience in production.

Simulation studies of the designs were carried out by using AWR and CST software packages. As a result of the simulations, the Chebyshev filter with a cutoff frequency of 6 GHz, a return loss of less than 20 dB, and an attenuation of around 45 dB at 9 GHz was made ready for production.

The tests carried out at the end of the manufacture proved that the filter had a cutoff frequency better than 6 GHz, the return loss was 22 dB, the insertion loss was 0.2 dB and 46 dB attenuation was obtained at 9 GHz. It has been observed that the produced filter and the designed filter simulation results are very close to each other.

The novelty enabling us to achieve these results can be stated as the capability to increase the power handling capacity with two mechanisms. One mechanism is that we used the highest transmission line radius preventing the higher order mode excitations to decrease the conductor loss. The second mechanism was that Teflon was covered around the low impedance lines to enhance the dielectric breakdown capability. Teflon inclusion was also used to decrease the practical low impedance level which improved the filter characteristics.

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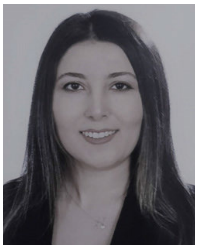

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