Tight-coupled microstrip hairpin bandpass filter

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ABSTRACT

The paper depicts a microstrip hairpin bandpass filter design, simulation, fabrication and test. The proposed microstrip filter's design is comprised of five hairpin structures separated by a tenth of a mm distance for which various parametric studies have been conducted. The simplicity of design provides inexpensive and undemanding filter. The filter is fabricated with suitable parametric results. The design is based on Chebyshev's values for the prototype, with N (the order of filter) number being equivalent to five. The final fabricated version of the project is based upon FR4 dielectric substrate with the input return loss being below -10 dB and insertion loss above – 2 dB. Approximate values of the input reflection coefficient and insertion loss are -33.34 dB and -1.72 dB respectively. Furthermore, the frequency range for the proposed geometry is between approximately 2.6 GHz and 3.6 GHz. The proposed filter is fabricated and the results measured in real life are highly correlated to the results simulated in the software. The proposed microstrip hairpin bandpass filter can be utilized in wireless internet access and communication.

Key words: Microstrip; Bandpass filter; Sonnet Suites Software; FR4; Chebyshev's values;

INTRODUCTION

The aim of the microstrip bandpass filters in microwave communication systems is to provide an enhanced and high performance of the microwave transceivers with minimal cost (A.Hasan et al, 2008). The hairpin filter design proposed in this paper can be correlated to different hairpin designs since it provides effective results, insertion losses above -3dB and return losses below -10dB. In the paper (A.Hasan et al, 2008), five-pole hairpin bandpass filter structure is designed by simply combining rectangular metals in the "U shape" configuration, however, the results obtained using the dielectric constant ($\varepsilon_r = 4.34$) were less than -3dB (slightly above -10 dB) due to the tangent losses of FR4 dielectric constant (A.Hasan et al, 2008).In addition to the rectangular design, one can utilize the combination of rectangles and triangles to construct polygons which in turn increase the complexity of the overall geometry (N.Ismail et al, 2018), such geometry proposed can provide decent results for insertion losses and return losses in the range from -1.76 to -4.62 dB and -7.92 to -2.96 dB respectively. Even though, one may increase the complexity of the design it does not necessarily have to be in a direct connection with more precise and better results (A.Hasan et al,2008;N.Ismail et al, 2018). Furthermore, the hairpin geometry can be used to make defected ground structure (DGS) microstrip filters since the results are improved in comparison to the standard microstrip hairpin filters (V.S.Kershaw et al, 2017; N.Ismail et al, 2018). As mentioned previously, the overall structure can be modified by turning the rectangles into polygons with the final and remaining resemblance of "U shape" design, such modifications can be stressed even further by the slight change in angles from 90 degrees utilized for rectangular designs (A.Hasan et al, 2008;V.S.Kershaw et al, 2017; N.Ismail et al, 2018), to quarter circle combination of the five poled "U shape design" (T.Praludi et al, 2016). The parametric studies showed that five poled hairpin filters can perform in the same range with insertion losses and return losses being somewhat close to the boundary values (T.Praludi et al, 2016). Additionally, the microstrip bandpass filter's design can be modified in terms of the number of hairpin structures utilized for the overall design, such structure can use more than five poles and as a consequence, the results obtained by the parametric study are in close proximity of the acceptable range (T.Hariyadi et al, 2018). The proposed geometry can be enhanced by using DGS and minimizing the size of the filter due to the application requirements (T.Hariyadi et al,2018; N.Ismai et al,2018).High performance can be achieved by utilization of microstrip hairpin filters with adjustment in folding the hairpin line and thus reducing the size from 60-65% (Jagdish Shiyhare et al, 2015; S.B.Jain et al, 2012). Furthermore, the conventional hairpin bandpass filter can increase the quality factor by utilizing the previously mentioned folding of hairpin line and have higher stopband attenuation higher than the one present without folding (Jagdish Shiyhare et al, 2015 S.B.Jain et al, 2012). The model of hairpin bandpass filter can be altered and mathematically designed(using Chebyshev's n number of poles) for K band frequency segment for radar applications (A.A Sulaiman et al,2008).In comparison to the geometries mentioned from different sources, we have constructed a simple rectangular structure proposed in (A.Hasan et al,2008) with modification in the height, width, separation distance, and hairpin port line connectors, leaving only the resemblance with the mentioned papers in terms of the "U shape " geometry. The cost for designing the hairpin filter can be reduced and bandwidth increased with high reliability (Cornelis Jan Kikkert,2005).The design is based on five resonator filter structures with the frequency band of 1GHz (Cornelis Jan Kikkert,2005).From the mentioned papers one may infer that the hairpin filters utilize the simplicity of design and are relatively cheap to produce with accuracy that is in a well acceptable range and the simulations for the models provide reliable geometries for which microstrip bandpass filters can be fabricated without any significant alterations between simulated and measured results. We would like to make a small digression and focus on the comparison among different types of filter designs that are different from microstrip design, in that way we may encompass the advantages and disadvantages of other technologies being used nowadays for manufacturing filters. The lumped element filters, comprised from the different combinations of capacitors, inductors and resistors and since the wavelength is larger than the size of the lumped filter, there is a negligent change in waveform from input till the output (G.T. Bharathy et al, 2019).In terms of the advantages of lumped element filters, they are usually low cost, have a wide bandwidth and does not require any additional power source due to the passive elements used for the filter design. On the other hand, the lumped filters are not implemented for narrow bandwidths and can cause unpredictable behavior at higher frequencies (G.T. Bharathy et al, 2019).Apart from lumped filters, intrinsically switchable ferroelectric bulk acoustic wave filters based upon BST (Barium, Strontium Titanate) material provides a compact and low tangent loss circuit designs, which would allow this filter to be used in reconfigurable radio designs (Victor Lee et al, 2013).The advantage of this type of filter is that if the resonators places are precisely determined, then the filter can have a wide bandwidth and low S11 parameter (Victor Lee et al, 2013).On the other hand, the insertion loss and return loss parameters depend highly on the geometry and separation distance between resonators and as such would be highly affected if the simulations were done inaccurately. Furthermore, if the design requires more simulations prior to manufacturing, then it can be argued that the designing with given technology would be time consuming. In addition to the given provided technologies, one may utilize waveguide filters.Waveguide filters designed using QWRs for the E-plane filters, can be decreased in size and utilized in ICDS miniaturized filters (Marija Mrvic et al, 2017).The center frequency is adjusted by the length and size of the QWRs (Marija Mrvic et al, 2017), if we want to compare this technology of filters with microstrip filer design, the price and size of waveguide filters are higher, however both microstrip and waveguide filters experience certain losses due to the substrate. To elaborate on this, the inadequate milling process and cheap substrates can cause degradation in the filter response graphs of S11 and S21 parameters (Marija Mrvic et al, 2017).If we were to summarize all of the mentioned technologies for the filter designs, most of the designs can be simulated prior to fabricating the prototype and thus saving time. Depending upon the geometry of the design, elements used, accuracy of the simulation, size of the filter and cost, one has to weigh all of the above in order to decide what type of filter design would suffice the requirements.

DESIGN METHODOLOGY

The design methodology was initiated by calculating Chebyshev's response of the prototype design with N = 5 order and pass ripple below 2dB.The reason we are not aiming for values too close to 0dB is that the substrate used for the proposed design is FR4 and due to the tangent losses we will be unable to make insertion loss at the range of > -0.15 dB. For such reason we have decided to operate in an acceptable range of -2dB and calculate the appropriate filter for this range, keeping in mind that even though we are limited by implementing this dielectric, we can still design a relatively cheap and effective device. Regarding the Chebyshev's values for the prototype with normalized cut off frequency $\Omega_c = 1$, it is as following : $g_0 = g_6 = 1.0, g_1 = g_5 = 1.1468, g_2 = g_4 = 1.3712 \ and \ g_3 = 1.9750$ (Wiley J,2013).

Table 1. Chebyshev values for prototype design (Wiley J., 2013)

N	g_1	g_2	g_3	g_4	g_5	g_6

1	0.3052	1.0				
2	0.8431	0.6220	1.3554			
3	1.0316	1.1474	1.0316	1.0		
4	1.1088	1.3062	1.7704	0.8181	0.3554	
5	1.1468	1.3712	1.9750	1.3712	1.1468	1.0

The microstrip bandpass filter's design is comprised of the five hairpin structures, under which FR4 dielectric substrate (er = 4.4) and above the geometry relative air dielectric constant are used, with the height and width being 13.5 mm and 5.5 mm respectively. Moreover, the thickness of dielectric substrate FR4 is 1.55 mm, whereas the thickness of the air layer is set to be 10 mm. It can be observed that separation distance is either 0.1 mm or 0.2 mm which additionally aids in manufacturing of the design. Furthermore, the inner three hairpins are increased in comparison to the outermost hairpins (leftward and rightward). Fractional Bandwidth for the bandpass filter is taken to be 15.2% with a tapping point at 6mm. Lastly, the design utilizes the simplicity of the rectangular connections and therefore does not require additional investment in the production of the filter. The design of a singular hairpin can be observed below. The formulas for calculating and obtaining the mentioned and taken values for the final design are provided below, it is worth mentioning that the software Sonnet Suites aided in establishing the most suitable results for the given geometry and to some degree provide a suitable solution to the obtained results both mathematically and in real-life measurements.

In order to calculate the prementioned microstrip's bandpass filter specifications, we have utilized the following formulas. Firstly, external quality factors for feeding the input and output ports is given by equation 1 (Mudrik A. et al 2011; Adib Belhaj et al 2017).

$$Q_{ei} = \frac{g_0 * g_1}{FBW} \; and \; Q_{ei} = \frac{g_5 * g_6}{FBW} \qquad (1)$$

where FBW is frequency bandwidth and $g_0 - g_6$ are Chebyshev's values. The reflection quality coefficient can be calculated by equation 2 :

$$Q_e = \frac{f_0}{f_{90} - f_{-90}} \qquad (2)$$

Where f_0, f_{90} and f_{-90} are frequency phases for the corresponding degrees – 0, 90 and -90.

Coupling between two hairpin structures is calculated by equation 3 :

$$k = \frac{FBW}{\sqrt{g_i * g_j}} \qquad (3)$$

where k is a coupling coefficient between the hairpin structures. The parametric studies presented in the further discussion will provide you with the suitable separation distance with respect to the coupling coefficient k. We have utilized the Sonnet Suites for this procedure and we simulated and obtained that the most suitable results occur for separation distance around the range 0.1-0.2 mm (Mudrik A. et al ;2011, Feng Y et al 2014). For small values of the separation distance between hairpin structures(resonator) as in our case, the equation 4 provides a relationship to calculate coupling factor with small value for the separation distance:

$$k = \frac{(f_1^2 - f_2^2)}{(f_1^2 + f_2^2)}, \qquad (4)$$

where k is the coupling factor and f_1 and f_2 are resonant frequencies (Mudrik A. et al,2011).

For the tapping point (t) represented in figure 2. we need to consider multiple factors such as height of the hairpin (H), impedance required for terminating (Z_o) ,impedance of hairpin line (Z_r), and external quality factors. The tapping point is inversely proportional to the quality factor, however, it is directly proportional to the height of the hairpin structure. The equation 5 relates the tapping point to the mentioned factors (Pal M. et al, 2011;Girraj Sharma et al, 2014).

$$\frac{t}{H} = \frac{2}{\pi} * \sin^{-1}\left(\sqrt{\frac{\pi}{2} * \left(\frac{Z_o}{Z_r * Q_e}\right)}\right) \to t = \frac{2H}{\pi} * \sin^{-1}\left(\sqrt{\frac{\pi}{2} * \left(\frac{Z_o}{Z_r * Q_e}\right)}\right) \quad (5)$$

The resonator's height is $H \approx \frac{\lambda_g}{4}$ (Girraj Sharma et al,2014;Kavitha K et al, 2018) and measurements are adjusted according to this relationship. The value for Z_o is taken to be 50Ω for the calculations. Moreover, the value for FBW is obtained by equation 6 (Adib B,2017) :

$$FBW = \frac{(\omega_2 - \omega_1)}{\omega_o}, \qquad (6)$$

where ω_2, ω_1 *and* ω_o are higher, lower cut off and center frequencies respectively. From equation 1 to 6 we were able to design the microstrip hairpin bandpass filter, the mathematical process with numbers have been averted due to the fact that every mathematically obtained solution was confirmed in the Sonnet and therefore, if one is willing to repeat the procedure, the mathematical equations along with simulated results are presented in the paper.

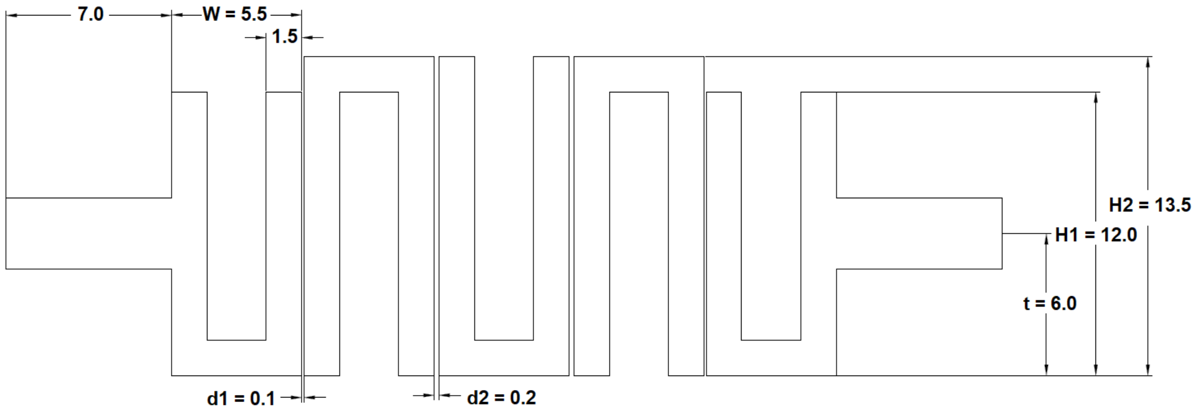

Figure 1. Proposed geometry for the compact microstrip bandpass filter

Prior to establishing the final design we have gone through multiple simulations of calculated designs and since we were only aiming to manufacture the microstrip filter with the FR4 substrate even though we have multiple simulations and results from different substrates with which results obtained provide us with a significantly better insertion loss, we still remained with FR4 substrate as a final resulting substrate with the thickness of 1.55mm.

PARAMETRIC STUDIES & COMPARISON WITH THE PREVIOUS DESIGNS

For the parametric studies, the proposed design of the microstrip filter will undergo a series of changes in height, width, separation distance and utilization of the final design with different dielectric substrates instead of FR4. The ultimate aim is to obtain the values in the acceptable range for both insertion loss (S_{21}) and input return loss (S_{11}), above -3dB and below -10dB respectively. The characteristics of the final design are mentioned in the previous section in terms of the geometry, the results of the operational performance of the microstrip filter are the following: the insertion loss (S_{21}) is **-1.72 dB,** the input return loss (S_{11}) is below -10dB with the max value of **-33.34 dB** and the filter is operating in the bandwidth of approximately 1 GHz (2.6-3.6 GHz). In order to partially convey the comprehension of the parametric study procedure, we will provide you with the figure (1) prior to each table, in that case, we want to avoid any ambiguities regarding the conducted parametric study.

Table 2. Different Heights of hairpin resonators and simulated results for S11 and S21

Height H1 (mm)	**Height H2 (mm)**	**S_{11} (dB)**	**S_{21} (dB)**	**Frequency Range (GHz)**
12	**13.5**	**-33.343234**	**-1.7200607**	**2.6 - 3.6**
11.5	13	-32.866754	-1.73425636	2.3 - 3
10.5	12	-31.035561	-1.68972451	2.4 - 3.0
13	14.5	-29.6983291	-1.96374543	2.3 - 3.25
13.5	15	-39.1022489	-2.10338924	2.5 - 3.2

From the table 2 we may depict that the minor increase in height changes the frequency range as well as the S21 and S11 parameters.

Table 3. Simulation results with different widths for the hairpin structures

Width (mm)	**S_{11} (dB)**	**S_{21} (dB)**	**Frequency Range (GHz)**
1.5	**-33.343234**	**-1.7200607**	**2.6 - 3.6**
2	-28.852375	-1.79044715	2.3 - 3
2.5	-23.468909	-1.96642981	2.4 - 3.0
0.5	-31.827960	-1.39552265	2.3 - 3.25
3	-21.135433	-2.20632201	2.5 - 3.2
1	-28.096102	-1.66278425	2.65 - 3.5

Table 3 infers that the minor increase and decrease of the width impacts the result parameters.

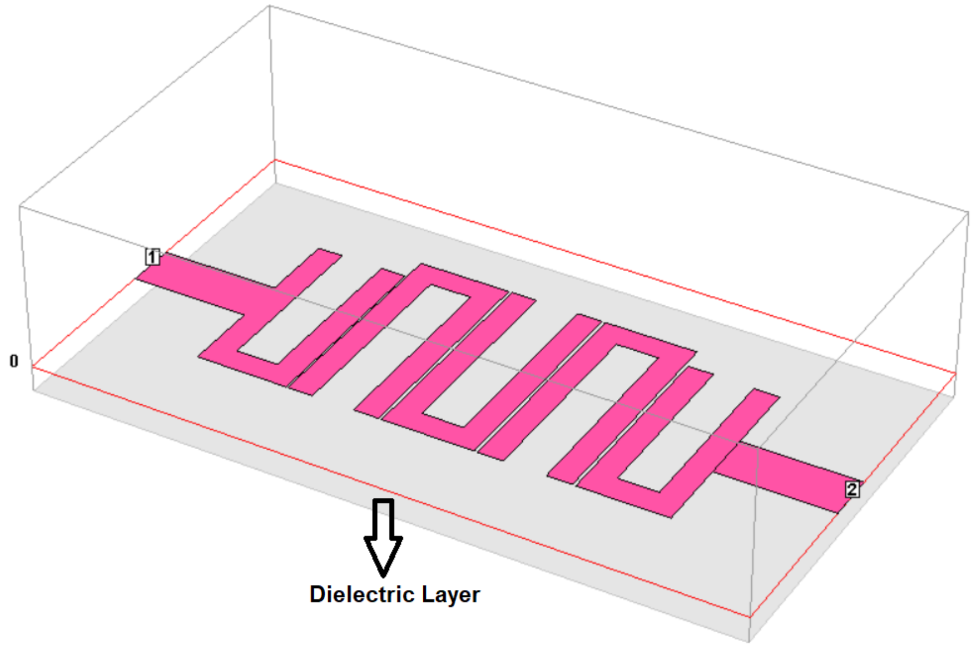

Figure 2. The dielectric layer explanation of the hairpin structures (resonators)

Table 4. Simulation results with different dielectric layers

Dielectric Layer	S_{11} (dB)	S_{21} (dB)	Frequency Range (GHz)
FR4	**-33.3432**	**-1.720060**	2.6-3.6
9.9 (Alumina 99.5%)	-45.7324	-0.329428	1.75-2.35
5.1 (Arlon AD5)	-51.5260	-0.3107159	2.5-3.4
3.38 (Arlon 25N)	-48.4774	-0.3124536	2.85-4.1
4.5 (Arlon AD450)	-45.5602	-0.3866213	2.5-3.6
7.5 (ESL41010)	-40.6831	-0.4523087	2.0-2.85
2.0 (Dupont FEP)	-44.5589	-0.3611323	3.5-4.4
2.6 (Nelco NX9260)	-43.1672	-0.1538782	3.2-4.45
10.2 (Arlon AD1000)	-16.1885	-0.6585255	1.8-2.5

6.15 (Arlon AD600)	-40.7188	-0.2810697	2.2-3.1

As mentioned previously, the dielectric FR4 does not provide the most suitable results for the given geometry due to its tangent losses and for that reason, if one is aiming to improve the design that was manufactured for FR4 substrate you may simply use one of the simulated dielectric layers since the results provided are somewhat in the more acceptable range and as a consequence, the filter will have a better performance.

Table 5. Simulation results with various separation distances between hairpins

Separation Distance d1 and d2 (mm)	S_{11} **(dB)**	S_{21} **(dB)**	**Frequency Range (GHz)**
0.1 & 0.2	**-33.343234**	**-1.7200607**	**2.6 - 3.6**
0.2 & 0.4	-28.165432	-1.9941101	2-6 - 3.55
0.2 & 0.2	-25.991671	-1.8307104	2.55 - 3.5
0.1 & 0.1	-31.005585	-1.6122356	2.65 - 3.6
0.15 & 0.2	-30.655352	-1.6610972	2.5 - 3.65
0.15 & 0.15	-28.132566	-1.7117653	2.6 - 3.6
0.15 & 0.2	-28.535813	-1.7375399	2.5 - 3.55
0.25 & 0.15	-29.245449	-1.7931815	2.5 - 3.6

Table 6. Advantages and disadvantages of our and prior designs of the different filters

Our and Prior designs	**Advantages**	**Disadvantages**
Our proposed design	- provides stable results with relatively cheap cost, compact size - provides accurate results for 1GHz range	- Tangent losses caused from the FR4 substrate.
A. Hasan et al, narrowband bandpass filter design	- simple and cheap to manufacture - provides accurate results in narrow range	- limited to the narrow range - FR4 substrate causes tangent losses that can be improved
N. Ismail et al, microstrip hairpin bandpass filter	- simple design - can be simulated and mathematically calculated in a short time	- S11 and S21 parameters can be improved.
V.S. Kershaw et al, square shape hairpin bandpass filter	- easy to simulate and modify	- S11 and S21 parameters can be

	- consistent results	improved with the change of geometry.
T.Hariyadi et al, microstrip hairpin bandpass filter with DGS at X- band frequency	- simple design, provides accurate results - weather radar application	- limited to a narrow range

SIMULATION RESULTS

In the simulation results section, we present the S parameters for the proposed microstrip filter along with explanation of the simulated results.

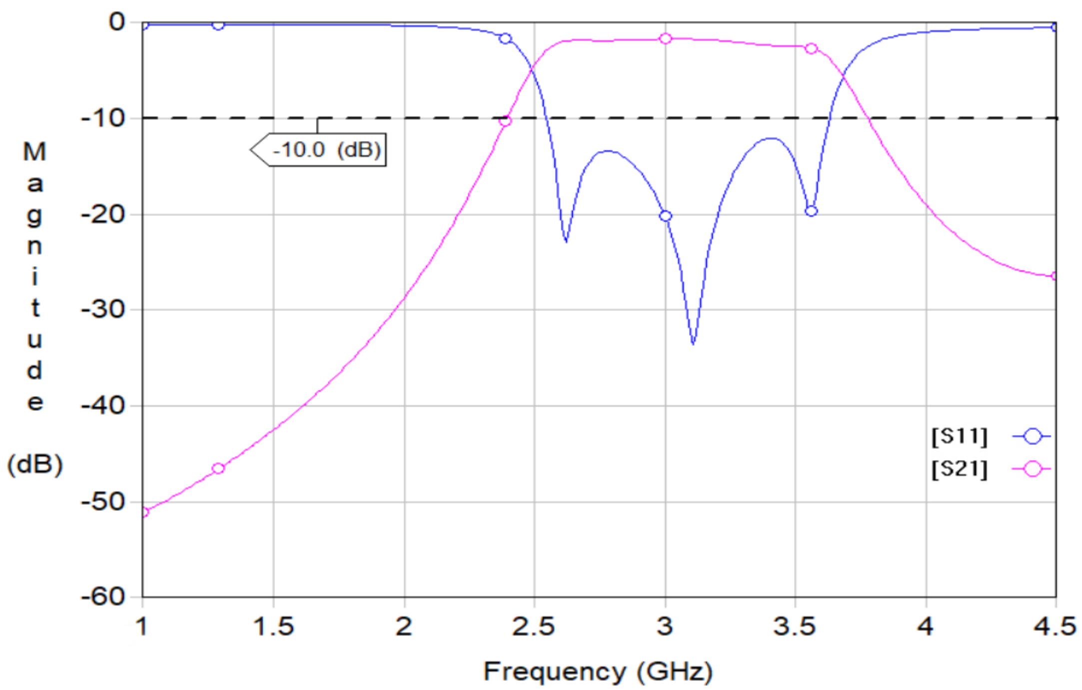

Figure 3. The S parameters for the proposed microstrip filter geometry

We have conducted various simulations and as one may notice, the bandwidth is ranging from 2.6 GHz to 3.6GHz. In addition, the insertion loss (S_{21}) and return loss (S_{11}) are in the operating range below -2 dB and above -10 dB respectively. The figure 3 depicts discussed data with the marker set at -10dB for a clear depiction of the acceptable range.

MEASUREMENTS AND ANALYSIS

The proposed model has been designed in real life and the simulations were done accordingly. Regarding the overall design, as mentioned in the paper, 1.55mm thick FR4 dielectric along with proposed separation distance, hairpin height and width was manufactured. Regarding the experimental procedure, after the manufacturing the prototype was used to measure the results and later on compare the results obtained from real life and the ones simulated in the software. For the manufacturing milling machine was utilized, after which the connectors were soldered on the microstrip design for the later testing. With regards to the measured results and comparison between real-life results and the simulated ones, in simulations, we have obtained the results for insertions loss to be approximately -1.72 dB, whereas input match was below -10dB between 2.6 - 3.6 GHz bandwidth and it's peak at -33.34 dB around 3.1 GHz. The measured results were as following : (S_{21}) was measured around -1.7dB along with input matches well below -10 dB in the range from 2.6 to 3.6 GHz at the peak at 3.1 GHz, with the approximate value of around -30dB and -45dB for S22 and S11 respectively.

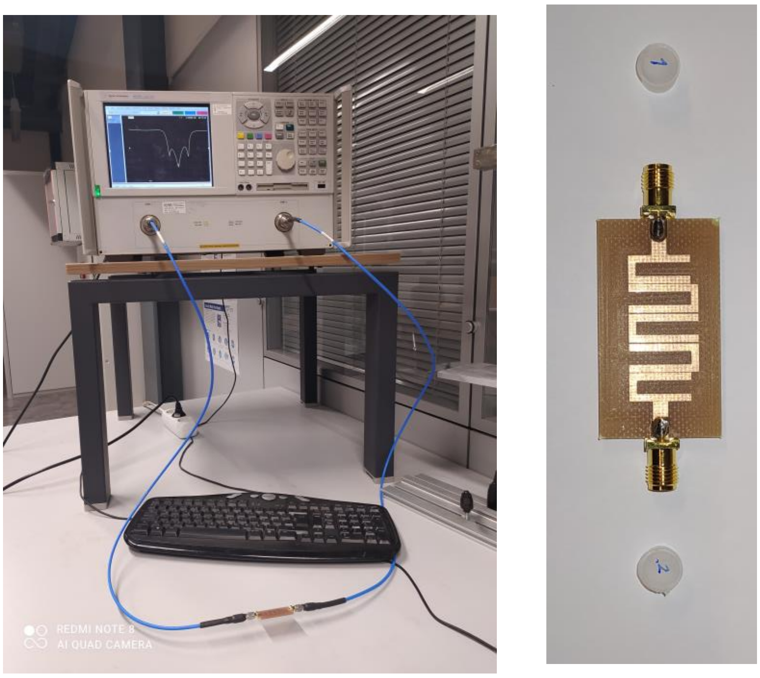

Figure 4. The manufactured and tested proposed microstrip hairpin bandpass filter

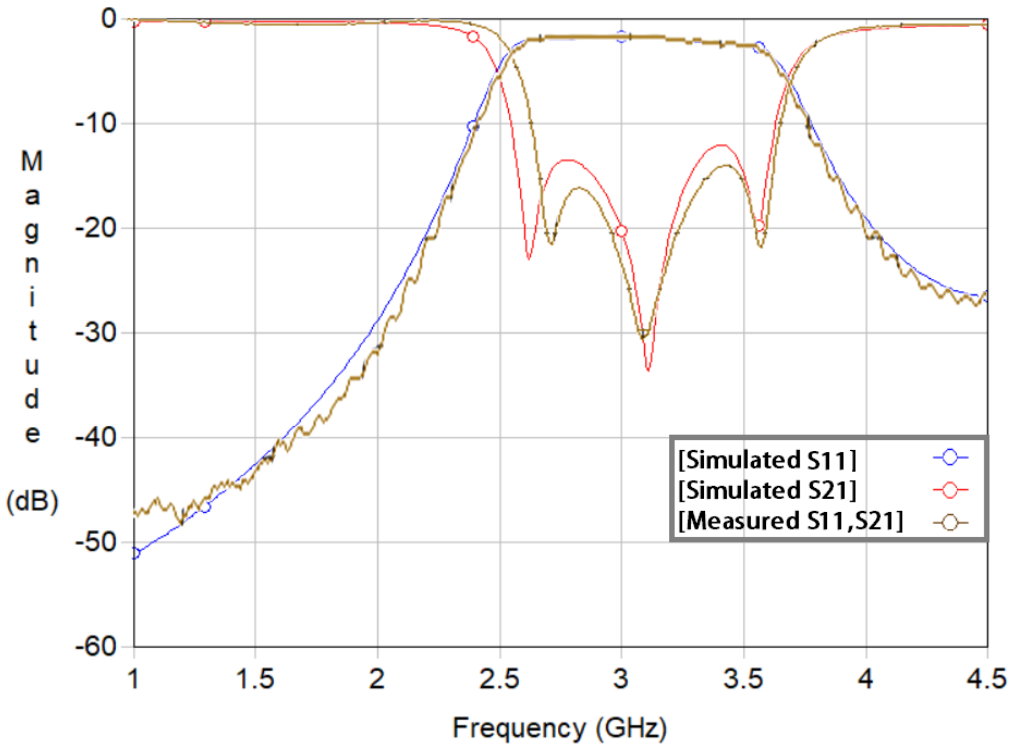

Figure 5. The comparison between simulated and measured S11 and S21 parameters

Furthermore, if we consider the tables from 2 to 5 for which values of S11 parameter are specified with respect to different factors, we can infer that the highest possible value for S11 was around -50dB, whereas for the S21 the highest value closest to zero was at approximately -0.15dB. The combined S11 and S21 parameters depicted in figure 6 imply that the data acquired through the simulation can predict the behavior of the filter in real life, in fact, the measured results have a slight deviation from the simulated ones. Despite, the frequency range, the behavior of the S22 curve resembles the behavior predicted in the simulation with a smaller peak value at the frequency of 3.1GHz, which is approximate -30dB, whereas the simulated results suggest that the peak value should be slightly higher and the expected value was -33.34dB. From the analysis, we have inferred that the fabrication of the proposed model with FR4 substrate does provide us with the expected behavior of the bandpass filter with simulation results closely resembling the measured ones. Therefore, if we were to modify our filter in order to an improve S11 and S21 parameters, we may immediately come to a conclusion that with the better tangent loss for dielectric constant we may improve the performance and obtain results that are in accord with the simulations.

CONCLUSIONS

From the proposed microstrip hairpin bandpass filter we may infer that, since parametric studies are in alignment with the acceptable range for utilization of such filter, it was manufactured such that we could compare the real-life results with the ones obtained in the simulation. In addition, the final version can be improved if we were to use different dielectric substrates. The tangent losses of FR4 are significant in comparison to the other substrate chosen for the parametric study. If we modify the separation distance, height, or width of the hairpin lines we may conclude that the proposed microstrip filter is still operating in the acceptable range with different bandwidths, which depend on the values being used for the analysis. Additionally, as the results obtained in fabricated filters measurements have a close resemblance to what we had simulated, we can imply that this proposed design will work for the proposed frequency range and the expectations will be in close relation to the results obtained in the simulations. The results of the S11 parameter for the fabricated and simulated bandpass filter suggest that the operating and acceptable range can be met (below -10dB). In addition, room for an improvement of the proposed and fabricated microstrip hairpin bandpass filter is possible by adjusting the prementioned factors. The most significant increase and improvement of S parameters were observed during the alteration of the dielectric layer. Lastly, the implementation of the mentioned geometry should not be an issue due to a simple design which ultimately leads to lower costs and more affordable devices for the customers who are willing to pay for a relatively cheap and effective device.

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