Multilayer Hairpin Bandpass Filter for Digital Broadcasting

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Abstract**—**this paper presents 2.52-2.65 GHz bandpass filter using hairpin resonator in multilayer configuration for digital broadcasting application. The four-pole hairpin resonators centered at 2.58 GHz with bandwidth of 130 MHz were designed. The best return and insertion losses in the passband are -27.828 dB and -1.5028 dB, respectively. Combination of hairpin resonator with coupled line sections operating at desired frequency has been optimized and simulated on Rogers RO3003 with dielectric constant 3.0 together with the analysis using Computer Simulation Technology (CST).

Index term**—multilayer structure, hairpin, bandpass filter, digital broadcasting.**

I. INTRODUCTION

Digital broadcasting denotes a set of standards that aim to distribute broadcast signals in digital form in a specific and standardized way. The mode of distribution can be satellite, terrestrially or through cable. Recently, many countries worldwide are moving towards a revolutionary change to digital broadcasting including Malaysia. The digital signal broadcasting begins with a transmitter located at an uplink facility and finally received radio wave from satellite transponder at downlink receiver. The digital signal at the end users' site can be fed directly into the integrated digital receivers such as TV receiver.

This project focused on design and development of bandpass filter using multilayer configuration operating at 2.58 GHz for satellite broadcasting. The analysis in terms of performance, size and cost of the filter on multilayer design using material Rogers RO3003 with dielectric constant 3.0 has been done.

Bandpass filter is an electronic device or circuit that allows signals between two specific frequencies to pass through, and discriminates unwanted signals at other frequencies. Advanced applications continue to meet the challenges of designing microwave bandpass filter with compact size, better performance and low cost requirements. Recently multilayer structure approach has been proposed to reduce the size of the planar microstrip filters. A multilayer structure approach has been proposed to reduce the size of microwave devices since most of communication systems end up with a portable device for consumer conveniences [1-2].

The design procedure of single-layer filter using symmetric couple microstrip lines is well documented in literature [3]. However, tight coupling lines between the resonators in this configuration are difficult for the fabrication to be realized. Multilayer filter overcome this kind of restriction and based on [4-6], the technical methods normally used to realize miniaturized filters is by fabricate filters on high dielectric constant substrates and implementing multilayer structure.

For multilayer construction, stripline transmission line media was used. The parallel coupled lines model is chosen to demonstrate the performance of the filter on multilayer substrate. The hairpin filter is one of the filter structures that use parallel coupled lines [7]. The conceptual idea is obtained by folding the resonators of parallel-coupled, half wavelength resonator filters into a "U" shape called hairpin filter. It is widely used due to its advantages on providing flexible coupling variation and produce compact filter with simple design procedure as in [8].

Figure 1 shows a basic multilayer construction. The structures are primarily consisting of a core material that has been laminated both sites by a thin layer of copper metal. Any circuit can be realized on the substrate using the thin layers copper metal as distributed elements. Since the circuit is needed to be grounded, then an epoxy layer was introduced to separate the signal lines and ground plane. In a practical measurement, the circuit will expose to the air. However in a simulation procedure, the part of air was recognized as a vacuum since the circuit was simulated by assuming the circuit was measured in a close boundary. This multilayer model is constructed and simulated in CST MWS to achieve the target specification as shown in Table 1.

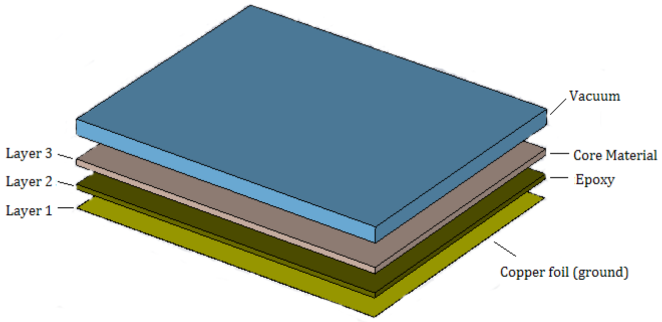

Figure 1: Multilayer construction

TABLE 1
Design Specification

Filter Specification	Values
Center frequency, f_c (GHz)	2.58
Lower cut-off frequency, f_l (GHz)	2.52
Upper cut-off frequency, f_u (GHz)	2.65
Insertion loss, *S21* (dB)	> -3
Return loss, *S11* (dB)	< -20
Bandwidth, *BW* (MHz)	130 (5%)

Table 2 shows the material properties of Rogers RO3003 used to model the filter response.

TABLE 2
Rogers RO3003 Substrate Properties

Properties	RO3003
Dielectric constant, ε_r	3
Substrate height, *h* (mm)	0.75
Loss tangent, $tan\ \delta$	0.0013
Copper thickness (mm)	0.035

II. METHODOLOGY

Figure 3 describes the methodology involved in designing the filter. The concept structure of hairpin resonator was carried out from [9]. In order to cover the whole frequency range of 2.52-2.65 GHz, 5% bandwidth at center frequency of 2.58 GHz must be achieved. A fourth-order of resonator can satisfy these requirements. By implementing multilayer structure as in [10], several optimizations on the filter dimension have been done in order to improve the response of the filter.

Figure 2 illustrate the structure of the multilayer hairpin bandpass filter in which resonator 1 and 4 are arranged on top layer of core material, while resonator 2 and 3 as an inner layer below the surface of core material depicted through the epoxy that act as a glue to combine the multilayer structure.

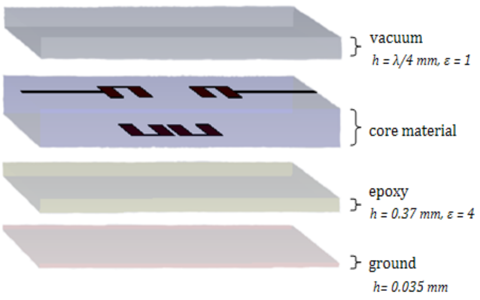

Figure 2: Fourth-order multilayer hairpin bandpass filter

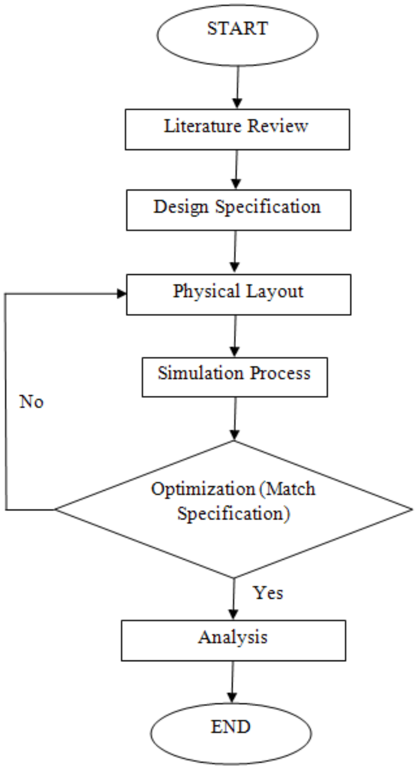

Figure 3: Design Flowchart

The physical dimension of the design was started by calculating the wavelength and line impedance. Based on center frequency and dielectric constant, the wavelength calculated is 67.06 mm. Theoretically, the characteristic impedance of microstrip and stripline can be calculated using equation in [11]. However, using analytical line impedance calculator in CST the width of the transmission line on top and inner resonator can be calculated directly to obtain 5Ω matching impedance. Length of hairpin resonator is determined by folding parallel-coupled half wavelength resonator into a "U" shape. Quarter wavelength, $\lambda/4$ is considered on the upper and lower layer of resonator to clamp the screws on the fabricated circuit and minimizing the losses that can interfere between the screws and electromagnetic waves passes through the copper resonators. Furthermore, $\lambda/10$ gap between the top adjacent resonators minimized the parasitic effects that can occur between the passive elements of the resonators. However, optimizations still need to be done to obtain desired response since the calculation is only an approximation and multilayer configuration is implemented.

By overlapping adjacent hairpin resonator on different layer, strong couplings between resonators can be achieved. The flexibility of couplings between nonadjacent resonators on different layers can also vary the coupling strength. The resonance itself can be varied by modifying overall length of the U-shaped hairpin filter and considering the length and gaps of the coupled U-shaped section.

Figure 4 and 5 shows the dimension of top and inner resonator of the multilayer structure. The overall dimension of the filter is 47.13 mm x 37.42 mm.

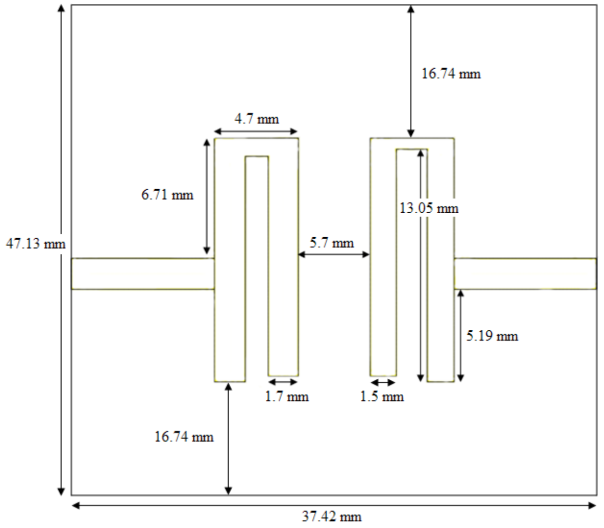

Figure 4: Dimension of three dimensional layout: top layer

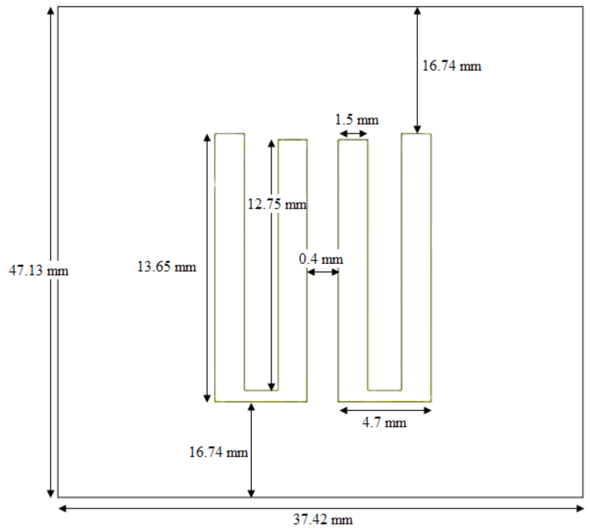

Figure 5: Dimension of three dimensional layout: inner layer

III. RESULTS AND DISCUSSION

Simulation for the design has been done by using CST MWS on transient solver to compute the required S-parameters. Transient solver is used instead of frequency solver in order to see the effect to the overall response as the pulse signal passes through the design filter and considering all the loss material used. Figure 6 and Table 3 shows the simulated frequency response and the parameters obtained. The two main parameters need to be considered in this design is the return loss, S11 and insertion loss, S21.

The return loss is a measure of the ratio of the reflected voltage amplitude to the incident amplitude. A small amount of reflected voltage is an indication of good matching impedance and represents large negative number in dB. Thus, more signals can be transmitted from input to output port with minimum power reflected back from the load. Thus, the value of -27.828 dB from the response agrees well with the specification. The insertion loss of -1.5028 dB obtained still can be accepted because of loss material consideration in the simulation.

The differences are most likely due to fringing effect and material loss. The dissipation factor or loss tangent of the material contributes the effects on insertion loss. This factor is the ratio of the energy dissipated to the energy stored in the dielectric material. If more energy is dissipated into the material, the less is going to make it to the final destination. This dissipated energy typically turns into heat or radiated into the air. A material with a large dissipation factor could result in the development of a tremendous amount of heat. However, it does not provide the insight provided by overall insertion loss because a relationship of good bond strength between the copper and dielectric must be considered.

In this design, RO3003 with loss tangent of 0.0013 is used rather than using other common substrates such as FR-4 which have wide variations of ε_r and *tan* δ even though the cost are lower compared to Rogers RO3003.

Other losses may due to the adhesive epoxy that is used to join between the filter layers. However this loss is still tolerable in multilayer filter since the target specification of passband return loss is still better than -20 dB, insertion loss less than 3dB and the measured center frequency is in good agreement with design specification. The bandwidth obtained from the -3 dB point in the simulated response is 90 MHz which is around 3.49%. Thus, further optimization need to be performed to achieve a better bandwidth.

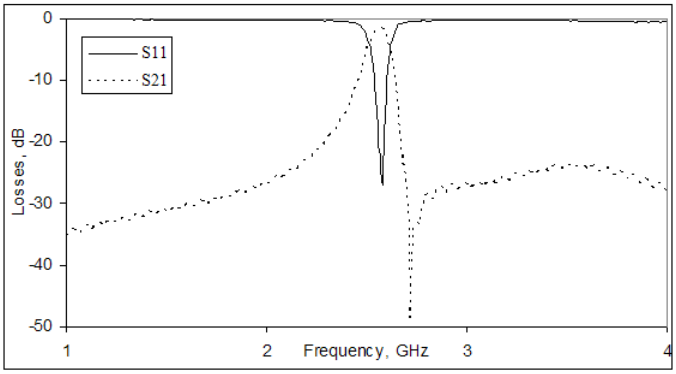

Figure 6: Simulated response on S-parameters using Rogers RO3003

TABLE 3
Results on the Simulation Response using RO3003

Properties	**Parameters**
Lower cut-off frequency, f_l (GHz)	2.53
Upper cut-off frequency, f_u (GHz)	2.62
Center frequency, f_c (GHz)	2.58
Insertion loss, *S21* (dB)	-1.5028
Return loss, *S11* (dB)	-27.828
Bandwidth, *BW* (MHz)	90
Size (mm)	47.13 × 37.42

The analysis can be divided into two parts. Firstly, analyses have been done on certain parameters that contribute major effects on the response obtained. The gap between adjacent resonators on top layer and inner layer has a large influence on the coupling property as it will affect on the performance related to insertion loss, S21 and return loss, S11. Figure 6 and Figure 7 shows the three samples of the parameter sweeps done on the gap between adjacent resonators on top layer as the response of S11 and S21 tends to vary on the coupling strength of the gap.

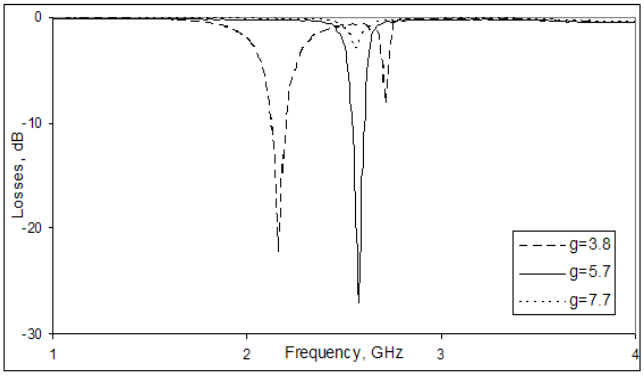

Figure 6: Parameter sweeps of S11 on gap between resonators from the top layer

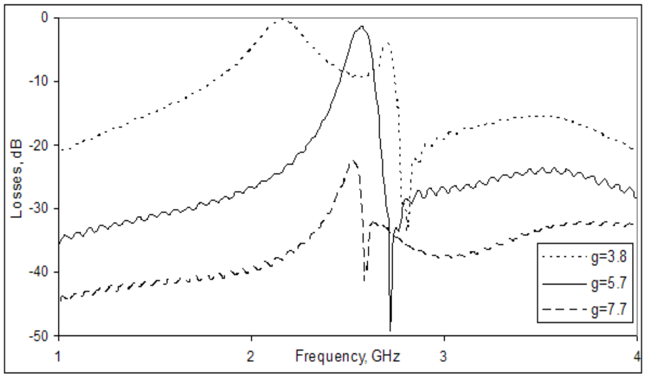

Figure 7: Parameter sweeps of S21 on gap between resonators from the top layer

Analysis also has been done on the variation of gap between resonators in the inner layer as in Figure 8 and Figure 9. As the coupling of adjacent resonators become tight, the insertion loss, S21 will decrease and return loss, S11 will increase. By increasing the gap between adjacent resonators, the insertion loss, S21 tends to become higher and making the signal not getting through and return loss will decrease. This transformation pattern is good for the filter since an ideal device is very high return loss but zero insertion loss in passband. This means that the smaller the size of the gap is better for the filter.

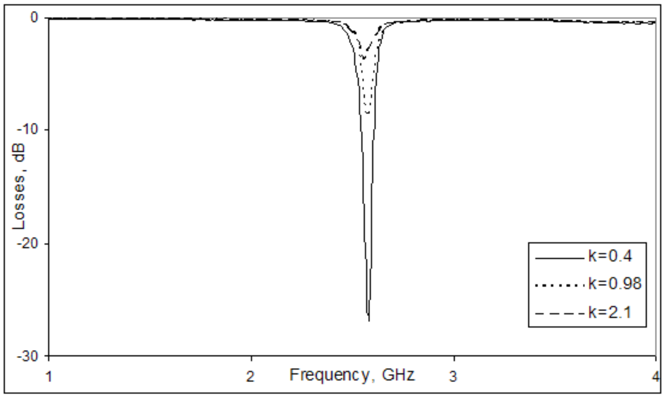

Figure 8: Parameter sweeps of S11 on gap between resonators from the inner layer

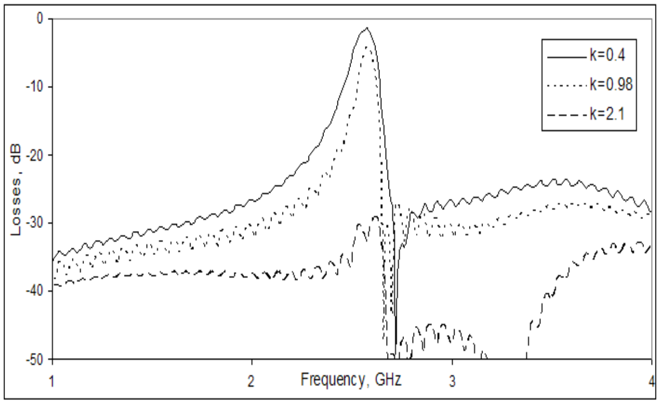

Figure 9: Parameter sweeps of S21 on gap between resonators from the inner layer

Varying the width and length of resonators also has an effect on the overall response and the physical dimension of the filter. When the width of resonators is decrease, S11 will shift to the right of higher frequency. However, when the width is increase, the return loss will shift to the left of lower frequency and the losses will decrease until at certain point the signal will lost as in Figure 10 due to the increasing gap of folded resonator. The same behaviors applied for insertion loss, S21 as shown in Figure 11.

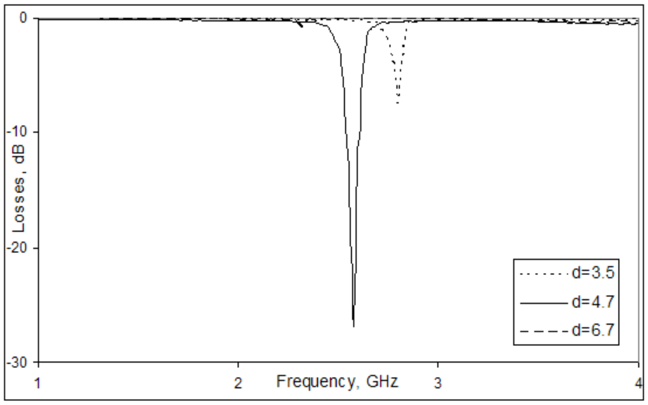

Figure 10: Parameter sweeps of S11 on width of resonators

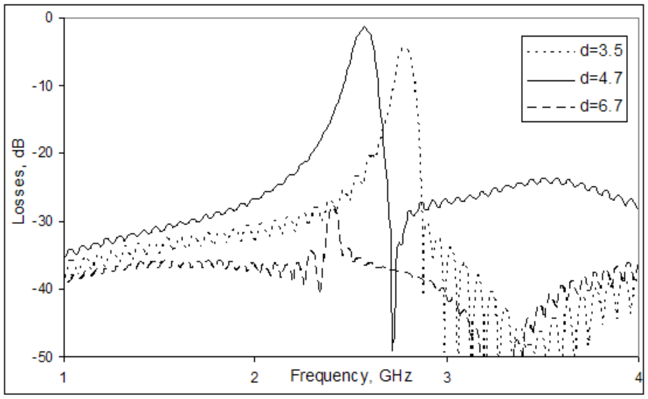

Figure 11: Parameter sweeps of S21 on width of resonators

Parameter sweeps on three sample of length of resonators in Figure 12 and Figure 13 strengthen the analysis on an effect to the physical size of the filter. When the length of resonator is increase, the response will shift to lower frequency and physical size of the filter will became bigger. At the same time, the value of return loss, S11 will be affected as well as the value of insertion loss, S21. The relationship between wavelength and frequency has known as inversely proportional according to the equation, $\lambda = c/f$. This analysis has proven that the results of the filter are agreed well to the microwave theory.

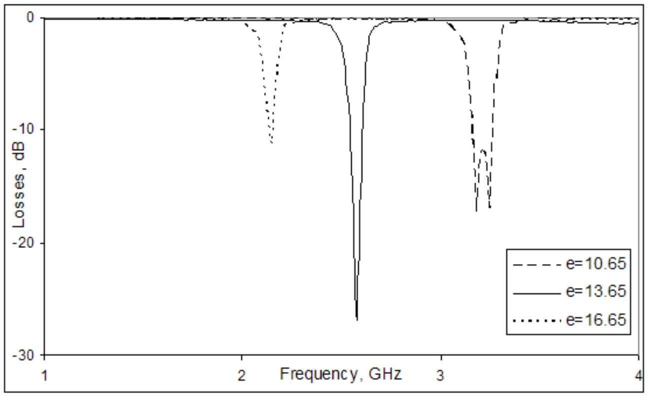

Figure 12: Parameter sweeps of S11 on length of resonators

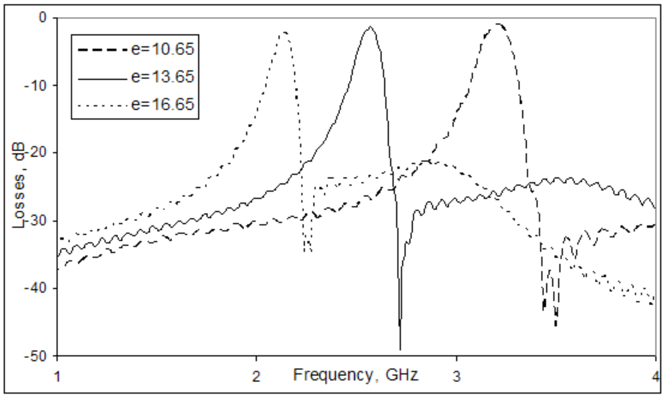

Figure 13: Parameter sweeps of S21 on length of resonators

Second analysis was carried out by using FR-4 substrates on the multilayer design to see the performance and size of the filter as compared to Rogers RO3003. Table 4 and Table 5 summarize the material properties and the comparison on parameters of simulated response using FR-4 and RO3003 respectively.

TABLE 4
FR-4 Substrate Properties

Properties	FR-4
Dielectric constant, ε_r	4.6
Substrate height, *h* (mm)	0.79
Loss tangent, *tan δ*	0.025
Copper thickness (mm)	0.035

From the simulated response using FR-4 in Figure 13 and summarization of using FR-4 and RO3003 in Table 5, the insertion loss of 2.4955 dB using FR-4 is higher compared with the insertion loss obtained by using Rogers RO3003 which is 1.5028 dB. This is due to the higher loss tangent of FR-4 that leads to high dissipation effect to the filter. The size using FR-4 is smaller than the design using Rogers RO3003 because of high dielectric constant of FR-4. The value of dielectric constant is inversely proportional to the wavelength. As the dielectric constant is high, more compact size can be achieved. However, the overall parameters obtained from the simulation agrees well with target specification set at the beginning of the design as the passband return loss is still better than -20 dB and insertion loss less than 3dB. The bandwidth obtained by using RO3003 is wider which is around 3.49% compared by using FR-4 which is only 2.33%. However, some optimization need to be performed to obtained wider bandwidth but the center frequency of 2.58 GHz still can be achieved.

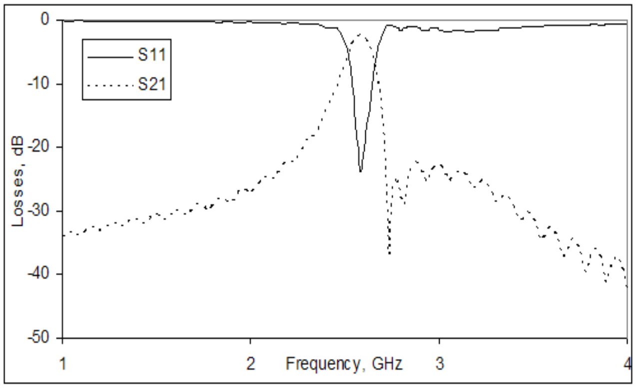

Figure 13: Simulated response on S-parameters using FR-4

TABLE 5
Response parameters using FR-4 and RO3003

Properties	**FR-4**	**RO3003**
Lower cut-off frequency, f_L (GHz)	2.55	2.53
Upper cut-off frequency, f_U (GHz)	2.61	2.62
Center frequency, f_C (GHz)	2.58	2.58
Insertion loss, *S21* (dB)	-2.4955	-1.5028
Return loss, *S11* (dB)	-23.753	-27.828
Bandwidth (MHz)	60 (2.33%)	90 (3.49%)
Size (mm)	40.04 × 32.43	47.13 × 37.42

IV. CONCLUSION

A multilayer hairpin bandpass filter has been presented based on the design specification together with the analysis of the response on the parameter sweeps of coupling gap, width and length of the resonators and the simulated response of two different substrates with different properties using Rogers RO3003 and FR-4. The analyses have proven that the design work according to the microwave theory. Further optimization need to be performed to achieve a better bandwidth but good agreement on the S-parameters has been achieved and closed to the target specification.

V. RECOMMENDATION

Multilayer is a method that able to reduce size of the overall circuit area. In future, the design is recommended to apply more than two core substrate layers. A substrate that has a high relative permittivity also can be investigated in order to improve the filter performances.

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