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Design of Multilayered Strip Line Hairpin Bandpass Filter

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***Abstract*—Filtering is the process of separating the frequencies we want from a variety of frequencies in various bands, and this type of filtering can be carried out using a tool called a bandpass filter. Wireless transmitters and receivers, military applications (Radar, Electronic Warfare, Identification Friend or Foe (IFF), Submarine Communications, and a variety of other devices use bandpass filters to achieve frequency filtering. The existence of the filter in the most extreme military situations is crucial since these Bandpass filters are utilized for numerous military applications. In this paper, we presented an analysis and simulation of the Hairpin Bandpass filter using HFSS Design Software. The bandpass filter is designed to operate at a frequency of 9GHz.The FR4 substrate with a dielectric constant of 4.4 and 1.6mm thickness was used in this design. The filter that is designed is used in many 5g Applications.**

***Index Terms*— Bandpass Filters, RF applications, Half Wave Resonators, FR4.**

I. Introduction

Filters are essential in many RF and microwave applications. They are used to separate or blend different frequencies. Because the electromagnetic spectrum is limited and must be shared, filters are employed to confine RF/microwave communications to certain spectral limitations. RF/microwave filters are being put to the test by new applications like wireless communications, which have standards that are getting more and more strict. These specifications include greater performance [1], too many features like a tunable, smaller size, low weight, and lower cost. Depending on the requirements and specifications, RF/microwave filters may be created as lumped element or distributed element circuits and realized in several transmission-line topologies, including Waveguide, coaxial line, coplanar waveguide, and microstrip. The designed filter is used for 5G applications.
FR4 has the following advantages:

- Using materials in various ratios to get a range of dielectric constant materials and provide a wide scope, hence enhancing the flexibility of the circuit.
- Ceramic materials with high speed, high Q, and high-frequency capabilities may be used to create multilayer substrates by reducing the length of the conductor and connection points. They can also be used to create circuit structures with high density and many functions.
- As of now, this method can create circuits with lines less than 10 um wide and layers less than 20 um apart.
- The material has good thermal characteristics and can withstand high temperatures and strong current demands [2].

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This paper describes the parallel coupled microstrip bandpass filter as given in the figure. This is mainly based on the halfwave resonators and admittance invertors. The center frequency of 9ghz is selected first, the bandwidth is fixed to 10% and the minimum attenuation and passband ripple are counted to -30DB and 0.1DB respectively. The design methodology, parameter analysis, and the results of a 5^{th}-order bandpass filter are discussed. Firstly, we design a parallel coupled bandpass filter with the required dimensions and calculate the required dimensions and then we will convert it into a hairpin bandpass filter. These various formulas have been derived from theoretical concepts and analyzed by using online calculators.

A. Theoretical Analysis

Fig. 1 depicts the overall configuration of a parallel coupled microstrip bandpass filter. Microstrip lines that are connected in an open circuit make up the filter structure. These coupled lines are identical to shunt resonant circuits and are a quarter wavelength long ($\lambda/4$). The admittance inverters in the low-pass prototype circuit correspond to the coupling gaps. even though Admittance inverters are used to calculate the odd mode characteristic impedances of parallel-coupled half-wave resonators. The physical dimensions of the filter are then calculated using [3] these even- and odd-mode impedances. Look at Figure for an example of a bandpass filter made from a cascade of N + 1 coupled line sections. Although the load is on the right and the sections are numbered from left to right, the filter may be turned around without changing the response. The equivalent circuit of the cascade is depicted in Fig. 1 because each coupled line segment has an equivalent circuit of the type.

II. Related Works

The significance of this research lies in its rigorous literature survey, which serves to identify and evaluate the existing literature on the Microstrip Hairpin Bandpass Filter, thereby informing the direction and contributions of our study.

Jayadeep Yanapu[5] proposed a method for designing MSLHBF a 3-pole hairpin structure that was fabricated on the top of the Rogers (RT5880) substrate material and an open loop microstrip structure at the ground to give a modified triple-band BPF with a unique design. The proposed wideband BPF satisfies the International Telecommunication Union (ITU) Region 3 spectrum requirements. In transmit mode, the frequency bands used by Direct Broadcast Service (DBS) and Fixed Satellite Service (FSS), respectively, are 11.41–12.92 GHz and 14–14.5 GHz.

To analyze the various radar, surface radar, and some communications satellites Abhay Purohit [6], presented an analysis and simulation of a microwave hairpin filter designed to operate at S-Band frequency. The input and output resonators are slightly shortened to compensate for the effect of the tapping line and the adjacent coupled resonator.

In January 2019, Jagdish Shivhare[7] proposed a filter that is designed for 2.45GHz using HFSS ANSYS simulation software. Roger3003 dielectric substrate of height 1.5mm is used as substrate. Defected ground structure approach was incorporated to enhance bandwidth. With 0.2 dB insertion loss in the passband and 30 dB attenuation at 2.2 GHz, 28.57% of the fractional bandwidth (2.0720- 2.7720GHz) is attained. The pass band has a maximum return loss of -43.12 dB at 2.6290 GHz, which is more than -27 dB. This filter can be applied to terrestrial mobile communication systems in the ISM band (2.4-2.5GHz) and 2.6GHz band (2.5-2.69GHz).

In December 2021[8], Yanan Taryana, proposed and analyzed a bandpass filter using hairpin planar structures for S-band radar applications with a square groove at the middle of resonators. The designed device, which uses Roger 4350B substrate, has an operational bandwidth of 200 MHz from 2.9 GHz to 3.0 GHz based on the results of the calculations. The insertion loss is -0.76 dB, while the maximum return loss from the ADS simulation at 2.99 GHz using S11 has been measured at -29.9. The maximum S11 for the realization bandpass filter is -19.5 dB at 2.9 GHz, while the maximum S21 is -1.6 dB. The narrow bandpass filter based on the hairpin square groove with five resonators has been simulated and realized, the dimension of filter realization is 5.3 x1.6cm^2.

J.Tangjit [9] has presented a strategy for suppressing the second-harmonic response in a hairpin bandpass filter topology, and it has been effectively implemented in a microstrip construction. To account for the different phase velocities in the microstrip medium, a groove is added in the middle of a parallel-coupled line segment. This technique does not require external lumped elements such as the inductor or capacitor. The proposed hairpin BPF designed at 2.45 GHz frequency demonstrates the capability in suppressing spurious response. The proposed BPF had an insertion loss of 1.2 dB at the central frequency of 2.49 GHz.

Ved Vyas Dwivedi designed a 4th-order Chebyshev Microstrip parallel coupled band pass filter at 2.4GHz using FR4 substrate material [10]. The substrate utilised was FR4 with a dielectric constant (r) of 4.3 and a thickness of

1.6 mm. To verify the effectiveness of the suggested filter design, a comparison analysis between the simulated insertion loss and the substrate reflection coefficients of RO3003 and FR4 was carried out. Computer simulation technology (CST) and advanced design system (ADS) software are used to simulate the PCL filter. PCL filter simulation results are compared with its fabrication results. The ML Hairpin structure is designed and simulated; the size of the ML Hairpin filter is comparatively less than the PCL filter. The approximate dimension of the filter is 130 mm*30 mm. In the fabrication results, it was observed that at 2.4 GHz insertion loss is above - 5.00 dB, and reflection loss is below -20 dB.

III. DESIGN METHODOLOGY AND PROCESS

This section describes the design procedure for the realization of a parallel coupled microstrip bandpass filter for the following specifications.

Design of five-pole (n = 5) microstrip bandpass filter that has a fractional bandwidth FBW = 20% (0.2) at mid-band frequency f0 = 2 GHz. A Chebyshev prototype with a 0.1dB ripple is to be used in the design. The desired n =5 prototype parameters that are comparable may be appropriate.

TABLE I. HAIRPIN BANDPASS FILTER OVERALL PARAMETERS

Pairs	W/h	ε_{re}	l	s	w
(1,6)	1.4781mm	3.2629	4.6133mm	0.02023	0.642
(2,5)	2.1220mm	3.3589	4.5468mm	0.090974	1.6636
(3,4)	2.1844mm	3.3671	4.5413mm	0.1516	1.08

TABLE II. EVEN AND ODD IMPEDANCES OF FILTER

J	$J_{j,j+1}/y_o$	$(Z_{oe})_{j,j+1}$	$(Z_{oo})_{j,j+1}$
0	0.3701	75.35	38.34
1	0.1253	57.05	44.52
2	0.0954	55.22	45.68
3	0.0954	55.22	45.68
4	0.1253	57.05	44.52
5	0.5284	75.35	38.34

TABLE III.WIDTH CALCULATIONS OF FILTER

pairs	A_{se}	A_{so}	$(W/h)_{Se}$	$(W/h)_{so}$
(1,6)	1.192	0.685	2.977	8.200
(2,5)	0.941	0.770	4.4841	6.4843
(3,4)	0.916	0.786	4.7030	6.2340

The implementation, nevertheless, will differ in the paired strip line resonators' even- and odd-mode characteristic impedances are calculated. go, g1….,gn are elements of a ladder low pass prototype with a normalized cut-off Ω_C =1.

$$g0 = g6 = 1.0,\ g1 = g5 = 1.1468,\ g2 = g4 = 1.3712,\ g3 = 1.9750 \quad \text{and } \mathcal{E}_r = 4.4$$

To calculate the admittance inverter using $J_{n,\,n+1}/Y_o$ equations [5]. The design equations for this type of filter are given as shown in (1), (2), and (3).

g_n, g_{n+1} = components of a ladder-type low-pass prototype

$$\frac{J_{01}}{Y\,o} = \sqrt{\frac{\pi FBW}{2gog1}} \quad (1)$$

$$\frac{J_{j,j+1}}{Y\,o} = \frac{\pi FBW}{2}\frac{1}{\left(\sqrt{g_j g_{j+1}}\right)} \quad \text{for j=1 to n-1} \quad (2)$$

$$\frac{J_{n,n+1}}{Y\,o} = \sqrt{\frac{\pi FBW}{2g_n g_{n+1}}} \quad (3)$$

Where n = number of filter orders.

Ωc = Normalized cut-off value

FBW = band pass filter's fractional bandwidth

$J_{j,\,j+1}$ = J-inverter characteristic admittances.

Y0 = Terminating lines' characteristic admittance

For single-edge strip line

$$Z_{ose} = \frac{(Zoe)j,j+1}{2}, \quad Z_{oso} = \frac{(Zoo)j,j+1}{2} \quad (4)$$

Use single-line equations to find (w/h) se and (w/h) so from Zose and Zoso. With the given εr=4.4, w/h for Z =50 is approximately 1.523. Therefore, W/h ≤ 2 has been chosen. Find out value W/h from Z_{oo} and Z_{oso} as in (5).

$$W/h = \frac{8\exp(A)}{\exp(2A)-2}, \text{ where } A = \frac{Zc}{60}\left\{\frac{er+1}{2}\right\}^{0.5} + \left\{\frac{er-1}{er+1}\right\}\left(0.23+\frac{0.11}{0.42}\right) \quad (5)$$

We need to find the w/h and s/h for the desired coupled edge-strip line using a family of approximate equations as in (6).

S/h ratio for a coupled stripline

$$\frac{S}{h} = \frac{2}{\pi}\cosh^{-1}\left[\frac{\cosh\left(\left(\frac{\pi}{2}\right)\left(\frac{w}{h}\right)se\right)+\cosh\left(\left(\frac{\pi}{2}\right)\left(\frac{w}{h}\right)so\right)-2}{\cosh\left(\left(\frac{\pi}{2}\right)\left(\frac{w}{h}\right)so\right)-\cosh\left(\left(\frac{\pi}{2}\right)\left(\frac{w}{h}\right)se\right)}\right] \quad (6)$$

We find w/h and ε_{re} and the edge-strip transmission line by an overall dielectric constant for its TEM Propagation. There are a few formulas listed for the calculation of $\varepsilon_{eff.}$ [11] as in (7).

$$\varepsilon_{re} = \frac{\varepsilon r+1}{2} + \frac{\varepsilon r-1}{2}\left(\frac{1}{\sqrt{1+\frac{12h}{w}}}\right) \quad (7)$$

The effective dielectric constant of the edge strip is determined & the guided wavelength of the quasi-TEM mode of the edge strip is given by (8).

$$L = \frac{\lambda g}{4} = \frac{c}{4f\sqrt{\varepsilon re}} \quad (8)$$

Using the design equations for coupled edge-strip lines, the width and spacing for each pair of quarter wavelength couped sections are found and listed.

Based on the above calculations, the overall length, width, and spacing are determined for the filter. Now the filter is designed in HFSS by following the appropriate steps and the design is shown in Fig. 2. Based on the above calculation's overall length, width, and spacing are determined for the filter as shown in Table I. The intermediate calculations are shown in Table II and Table III respectively and in the process of design firstly parallel coupled bandpass filter is obtained [12]. They are conceptually obtained by folding the arms of normal parallel coupled λ/2 resonators into a U shape to reduce the size of the filter. However, to fold the resonators it is necessary to consider the reduction of the coupled-line lengths, which reduces the coupling between the resonators [13]. The line between two bends tends to shorten the physical lengths of the coupling sections, and the coupled section is slightly less than a quarter wavelength.

In this proposed design the width of the substrate is 3.38 mm and relative permittivity is 4.4 and the conductor thickness is 1.57 mm. Fig. 2 shows the 3-dimensional view of the proposed bandpass filter. The proposed design is simulated using HFSS [14]. Fig. 2 Indicates that the width, distance & length for section 1 & 6 are w1 = w6 = 2.03872mm, s1=s6=8.445 mm &l1=l6=2.5606 mm, for section 2 &5 are w2=w5= 3.144mm, s2=s5=6.994mm &l2=l5=4.0494mm and for section 3 &4 are w3=w4= 3.3264mm, s3=s4=6.6297mm &l3=l4=4.3554mm and the dimensions of the filter are obtained are approximately 46mm*25mm and on the conversion of hairpin filter length significantly reduced to 12mm*9mm.

IV. RESULTS

By carefully designing the filter's dimensions and component values, engineers can shape the filter's response to meet specific requirements. In this discussion, we will explore the results of hairpin bandpass filters, highlighting their performance metrics and applications in various industries.

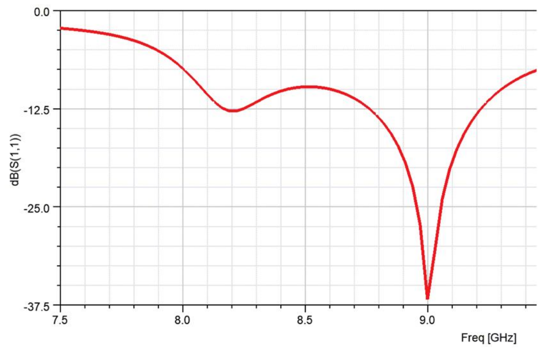

Figure 3. Return Loss

Figure 4. Fabricated Product of The Design

- Simulation results of the hairpin bandpass filter are shown in Fig 3 and Fig 5, the center frequency is 9GHz, the bandwidth of 400 MHz, the in-band insertion loss is less than -2.2dB, and the insertion loss is around 0 dB (0 GHz < f < 9GHz). The filter model is designed and modeled with the help of HFSS and for achieving the target specification as tabulated in Table III, the filter scattering parameters were computed [15].

- The insertion loss of a hairpin bandpass filter refers to the amount of signal power that is lost or attenuated when the signal passes through the filter. It is typically measured in decibels (dB) and represents the difference in signal power between the input and output of the filter.
- The simulated multilayer hairpin band-pass filter exhibits a low insertion loss of -2.2 dB. Lower insertion loss indicates that the filter is more efficient in transmitting the desired signals with minimal attenuation, whereas higher insertion loss values indicate greater signal power loss and can result in reduced signal quality or degraded performance.
- The return loss of a hairpin bandpass filter refers to the amount of reflected power at the input or output of the filter. It is a measure of how well the filter matches the impedance of the connected system or circuit.
- The hairpin bandpass filter yielded a high return loss of -24.2dB, which indicates that most of the power is being transmitted through the filter and minimal power is being reflected. This is desirable as it minimizes signal reflections, maximizes power transfer, and ensures efficient performance.
- The correct bandwidth and a superior reflection coefficient require more dimension optimisation.
- After the successful design of the required filter in HFSS [16] the results will be verified, and they will be optimized to perfect values. Then the physical product as shown in Fig 4 is obtained by the fabrication of the design by various techniques at the fabrication units.

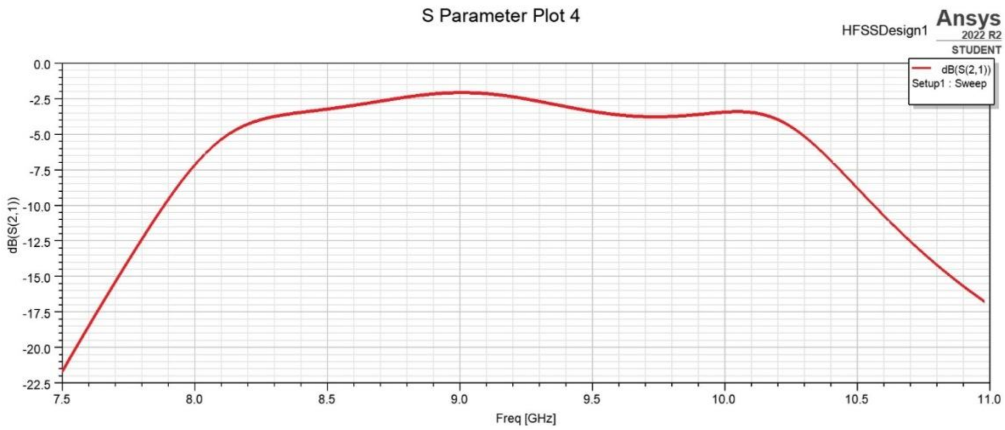

Figure 5. Insertion Loss of The Hairpin Bandpass Filter

V. CONCLUSIONS

A Microstrip Hairpin bandpass filter designed has extensive use because of its very simple structure, easy fabrication, and its integration possibility with other microwave components [17]. In this research brief discussion of the fundamental theory, equations, and steps to design a Microstrip Hairpin Bandpass Filter is shown. FR4 (permittivity = 4.4) dielectric substrate of height 1.6 mm is used to implement the proposed design. The filter is simulated using simulation software HFSS. The designed Filter has been resonated at 9.0 GHz frequency which belongs to the X Band frequency range. The simulated result show return is greater than -25 dB in the passband range. The dimension of the fabricated filter is 12mm*9mm which is compact.

Overall design, Fabrication, and processing were completed concerning the filter parameters. Mild difference between experimental and simulation results, which includes the error of ceramic dielectric materials, the processing technology, test fixture, etc [18]. However, the result tends to be consistent, comply with the design target, and can be batch production. The insertion loss and return loss are in range and hence the filter is compatible with 5G applications.

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