Design And Implementation of Optimum-Distributed Microstrip High-Pass Filter (HPF)

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Abstract— ***This paper presents the design and implementation of a fifth-order (n = 5) optimum-distributed microstrip high-pass filter (HPF) with a cut-off frequency of 1.5 GHz. The proposed HPF is intended to posses cut-off frequency of 1.5 GHz and operates up to 6.5 GHz. It is implemented on a low-cost FR4 double-layer substrate ($\varepsilon_r = 4.4$, h = 1.6 mm). The filter consists of five shunt short-circuited stubs which is realized through via hole grounding and separated by connecting lines. The structure follows the Hong and Lancaster distributed synthesis method with an electrical length $\theta c = 33.75°$ and 0.1 dB passband ripple. After dimensional optimization in HFSS, the simulated response reached S11 = -14.46 dB and S21 = -2.9957 dB at 1.5 GHz, with nine ripples consistent with the (2n - 1) transfer-function order. The fabricated prototype that is measured with a Vector Network Analyzer (VNA), has exhibited respons which have a good agreement with the simulation ones.***

Keywords— High-pass filter; microstrip; optimum distributed; selectivity

I. Introduction

The rapid development of wireless communication technology has increased the demand for compact, low-cost, and high-performance radio-frequency (RF) and microwave components. High-performance filters with high selectivity are among the essential components in RF and microwave communication systems because they are used to control the frequency spectrum by allowing required signals to pass while attenuating undesired signals. Among various types of filters, the high-pass filter (HPF) plays an important role in eliminating low-frequency components and allowing signals above a specified cutoff frequency to propagate [1]. Therefore, the design and optimization of high-pass filters are important for improving the performance of modern communication systems.

Microstrip technology has become one of the most widely used approaches for implementing microwave filters because of its planar structure, relatively low fabrication cost, compact size, and ease of integration with other RF circuits [2]. At frequencies above 1 GHz, lumped-element realizations become impractical, so distributed-element approaches are commonly used to approximate the desired lumped-element response by means of microstrip line [3]. The performance of a microstrip HPF is strongly influenced by several design parameters, including the substrate dielectric constant, substrate thickness, conductor dimensions, transmission-line impedance, and filter geometry. Proper selection and optimization of these parameters are required to achieve the desired cutoff frequency, insertion loss, return loss, and impedance matching characteristics. Designing a high-pass filter (HPF) with a sharp cut-off is comparatively more complex than designing a low-pass filter, and the choice of filter order strongly affects the roll-off factor and out-of-band attenuation [4]. Consequently, an accurate design methodology is necessary to obtain a high-pass filter with satisfactory electrical performance.

A prior work has realized optimum distributed HPFs at various cut-off frequencies, such as a 5-pole design at 2.4 GHz [3] and a 1.3 GHz design with three short-circuited stubs [5]. This work differs by targeting a 5-pole optimum-distributed HPF at 1.5 GHz on FR4, combined with via hole grounding as the physical realization of the required short-circuit condition, and validates the design through both HFSS simulation and physical fabrication measured with a VNA. An additional comparative simulation across filter orders n = 2 to 6 is also presented to quantify the trade-off between element count and selectivity.

II. Research Methodology

A. Optimum-Distributed High-Pass Filter

In order to realize the Chebyshev fifth-order filter response, first of all, the low-pass prototype must be analyzed, then it is transformed to high-pass filter [6]. An optimum distributed HPF consists of n shunt short-circuited stubs of commensurate electrical length θc at the cut-off frequency, separated by connecting lines (unit elements) of electrical length 2θc [1]. Each short-circuited stub behaves as a shunt inductor, analogous to the lumped-element high-pass prototype. Although the structure contains only n stubs, the resulting transfer function is of order (2n-1), producing (2n-1) ripples in the passband instead of only n, which is the property that gives this topology its "optimum" designation. In physical implementation, the required short-circuit condition at each stub is realized using via hole grounding, a plated through-hole connecting the microstrip conductor to the ground plane [7].

The minimum filter order required to satisfy the specified passband ripple and stopband attenuation is determined from the Chebyshev order equation [2]:

$$n \geq \frac{\cosh^{-1}\sqrt{\frac{10^{0.1L_{As}-1}}{10^{0.1L_{Ar}-1}}}}{\cosh^{-1}\Omega_s} \quad (1)$$

The typical transmission characteristic of this type of filter, where f is the frequency variable and θ is the electrical length, which is proportional to f [3].

$$\theta = \theta_c \frac{f}{fc} \quad (2)$$

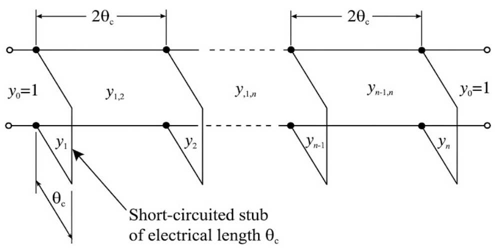

Figure 1: Optimum distributed high pass filter[2].

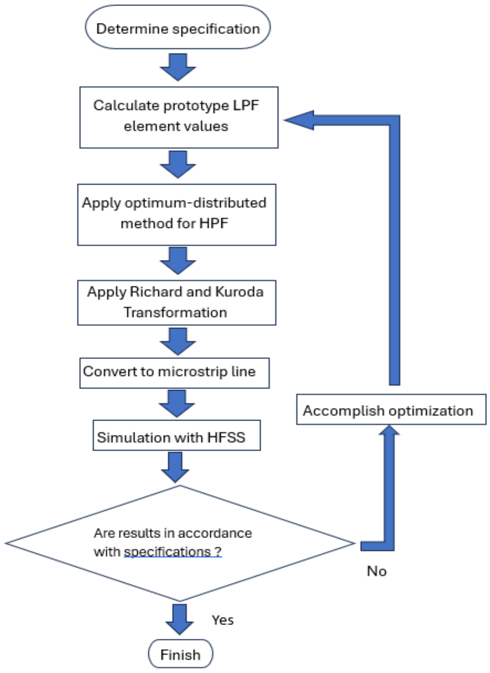

Figure 2. Flowchart design and simulation

Table 1. Element values optimum distributed filter with 0.1 dB ripple.

n	θc	y_1 / y_n	$y_{1,2}$ / $y_{n-1,n}$	y_2 / y_{n-1}	$y_{2,3}$ / $y_{n-2,n-1}$	y_3 / y_{n-2}	$y_{3,4}$
2	25°	0.15436	1.13482				
	30°	0.22070	1.11597				
	35°	0.30755	1.08967				
3	25°	0.19690	1.12075	0.18176			
	30°	0.28620	1.09220	0.30726			
	35°	0.40104	1.05378	0.48294			
4	25°	0.22441	1.11113	0.23732	1.10361		
	30°	0.32300	1.07842	0.39443	1.06488		
	35°	0.44670	1.03622	0.60527	1.01536		
5	25°	0.24068	1.10540	0.27110	1.09317	0.29659	
	30°	0.34252	1.07119	0.43985	1.05095	0.48284	
	35°	0.46895	1.02790	0.66089	0.99884	0.72424	
6	25°	0.25038	1.10199	0.29073	1.08725	0.33031	1.08302
	30°	0.35346	1.06720	0.46383	1.04395	0.52615	1.03794
	35°	0.48096	1.02354	0.68833	0.99126	0.77546	0.98381

These element values follow the optimum distributed synthesis tables presented by Hong and Lancaster [2], consistent with the synthesis approach also adopted in [8].

To design high pass filter, the cut off frequency fc = 1.5 GHz is selected with 0.1-dB ripple in the passband up to 6.5 GHz. As in figure the electrical length θc can be determined by equation (3):

$$\left(\frac{\pi}{\theta c} - 1\right) f_c = 6.5 \quad (3)$$

This yields a θ_c of 33.75°. The structural element values for the intended 5th-order high-pass filter are listed in Table 1, where Equations (4) and (5) are utilized to derive the associated impedance values relative to the terminating impedance ($Z_0 = 50\ \Omega$) [8].

$$Z_i = \frac{Z_0}{y_i} \quad (4)$$

$$Z_{i,i+1} = \frac{Z_0}{y_{i,i+1}} \quad (5)$$

A cutoff frequency of $f_c = 1.5$ GHz was selected for the HPF design. To calculate the structural parameters, the synthesis formula for the width-to-substrate-height ratio (W/h) was employed.

$$\frac{W}{h} = \frac{8e^A}{e^{2A} - 2} \quad (6)$$

with

$$A = \frac{Z_c}{60}\sqrt{\frac{\varepsilon_r+1}{2}} + \frac{\varepsilon_r-1}{\varepsilon_r+1}\left[0{,}23 + \frac{0{,}11}{\varepsilon_r}\right] \quad (7)$$

In this design, the characteristic impedance is set to Zc = Zo = 50Ω, $\boldsymbol{\varepsilon_r}$ = 4.4, W is the conductor width, and h is the substrate thickness (1.6 mm). Since the microstrip line's field is partly in the substrate and partly in air, an effective dielectric constant ($\boldsymbol{\varepsilon_{eff}}$) is used instead of εr, which is calculated by using equations (8) and (9) to determine the required W/h ratio for 50-Ω impedance [2].

For W/h ≥ 1

$$\varepsilon_{r_e} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left\{\left(1 + 12\frac{h}{w}\right)^{-0,5}\right\} \quad (8)$$

For W/h ≤ 1

$$\varepsilon_{r_e} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left\{\left(1 + 12\frac{h}{w}\right)^{-0,5} + 0{,}04\left(1 - \frac{w}{h}\right)^2\right\} \quad (9)$$

The guided wavelength was obtained from Equation (10)

$$\lambda_g = \frac{300}{f(GHz)\sqrt{\varepsilon_{re}}} \quad (10)$$

where ε_{re} is the effective dielectric constant and $f =$ 1.5 GHz.

The physical length of the short-circuited stub was determined from the electrical length θ_c and the guided wavelength λ_g, as expressed in (10). Meanwhile, the connecting line was designed with an electrical length of $2\theta_c$, and its physical length was calculated using (11).

$$l_{stub} = \frac{\theta_c}{360^0} \times \lambda_g$$

$$l_{stub} = \frac{2\theta_c}{360^0} \times \lambda_g \quad (11)$$

The normalized element values in Table 1 can be transformed to find the practical element values as they are exhibited in Table 2. Before fabricating, simulation should be accomplished which is showed in Figure 2.

Table 2. Element values of the proposed configuration

Parameters	Unit Element Short (UE)	Short Circuited Stub (SC)
Admittance values (mho)	$Y_{1,2}$ = 1,0387225 $Y_{2,3}$ = 1,0387225 $Y_{3,4}$ = 1.01187 $Y_{4,5}$ = 1,0387225	Y_1 = 0.4373425 Y_2 = 0.60563 Y_3 = 0.66389 Y_4 = 0.60563 Y_5 = 0.4373425
Impedance values (ohm)	$Z_{1,2}$ = 48,14 $Z_{2,3}$ = 49,42 $Z_{3,4}$ = 49,42 $Z_{4,5}$ = 48,14	Z_1 = 114,32 Z_2 = 82,56 Z_3 = 75,31 Z_4 = 82,56 Z_5 = 114,32
Length of the element (mm)	$l_{1,2}$ = 20,497 $l_{2,3}$ = 20,532 $l_{3,4}$ = 20,532 $l_{4,5}$ = 20,497	l_1 = 10,828 l_2 = 10,633 l_3 = 10,571 l_4 = 10,633 l_5 = 10,828
Width of the element (mm)	$W_{1,2}$ = 3,259 $W_{2,3}$ = 3,121 $W_{3,4}$ = 3,121 $W_{4,5}$ = 3,259	W_1 = 10,828 W_2 = 10,633 W_3 = 10,571 W_4 = 10,633 W_5 = 10,828

B. *Design Specifications and Calculated Dimensions*

The filter was designed for the specifications summarized in Table 3 using the FR4 substrate parameters commonly available for low-cost fabrication.

Table 3. Filter Design Specifications

Parameter	Value
Cut-off frequency, fc	1.5 GHz
Passband upper edge, fu	6.5 GHz
Filter order, n	5
Passband ripple	0.1 dB
Z0	50 Ω
Target S_{11}	≤ −10 dB
Target S_{21}	≥ −3 dB
Substrate	FR4, εr = 4.4, h = 1.6 mm
Electrical length, θc	33.75°

III. Result and Discussion

A. Simulation Results

The calculated dimensions in Table 2 were first modeled in Ansys HFSS without further adjustment. This initial simulation gave S_{11} = -10.7528 dB and S_{21} = -3.5079 dB at 1.5 GHz, meeting for the return-loss target but not yet for the insertion-loss target. Dimensional optimization was then performed to improve matching and passband flatness. Figure 3 shows the optimized filter layout, and Figure 4 shows the corresponding simulated S-parameters,

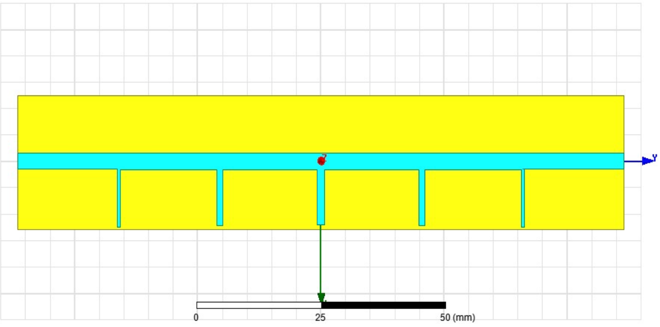

Figure 3. Layout of the optimized fifth-order optimum distributed HPF in HFSS.

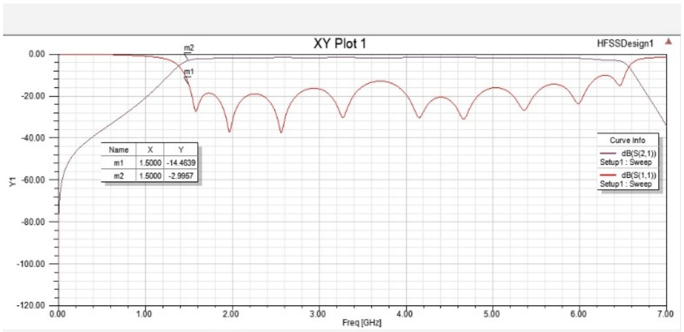

Figure 4. Simulated S_{11} (return loss) and S_{21} (insertion loss) after optimization.

After optimization, the filter achieved S_{11} = -14.4639 dB and S_{21} = -2.9957 dB at 1.5 GHz, with a simulated bandwidth of 5 GHz (1.5-6.5 GHz), satisfying both design targets. Nine minima were observed in the S11 response up to 6.5 GHz, consistent with the (2n-1) = 9 order predicted for n = 5, confirming the theoretical selectivity behavior of the optimum distributed topology.

To evaluate the effect of filter order, the same synthesis procedure (Equation (1)-(11)) was repeated for n = 2 to n = 6 at the same cut-off frequency and θc, without further per-order optimization, so as to compare the raw distributed synthesis across orders. The results are summarized in Table 4 and Figure 5.

Table 2. Comparison of Simulated S-Parameters for Orders n = 2 to 6 at 1.5 GHz

Order (n)	S21 (dB)	S11 (dB)	Ripple (2n−1)
2	−0.6642	−13.1908	3
3	−0.7747	−15.0781	5
4	−0.9285	−19.7992	7
5	−3.5079	−10.7528	9
6	−1.7474	−17.3035	11

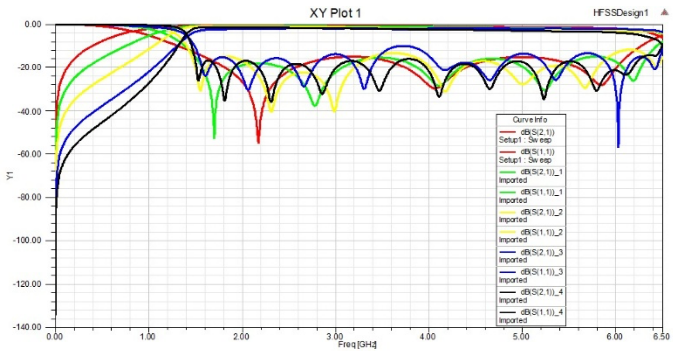

Figure 5. Simulated S_{11} and S_{21} responses for orders n = 2 through n = 6.

The results show that the number of passband minima increases as 2n - 1 with order, and that the transition (roll-off) steepness becomes sharper at higher orders, confirming that the optimum distributed topology trades circuit complexity for improved selectivity per element.

B. Fabrication and Measurement

The optimized layout was fabricated on FR4 double-layer PCB, with via holes drilled and plated at the shunt-stub ends to realize the required short-circuit ground connection, and SMA connectors soldered at both ports. Figure 6 shows the fabricated prototype (top copper pattern and bottom ground plane).

Figure 6. Fabricated fifth-order optimum distributed HPF prototype.

Finally, the fabricated filter was measured by utilizing a Vector Network Analyzer (VNA). Table 4 summarizes the measured S-parameters across the stopband and passband regions, as well as the point of the cut-off.

Table 3. Measured S-Parameters (VNA)

Region	Freq. (MHz)	S21 (dB)	S11 (dB)
Stopband	432.65	−36.7	−0.1
Stopband	897.96	−23.0	−0.2
Cut-off	1440.82	−3.0	−4.3
Passband	1518.37	−1.2	−10.3
Passband	1751.02	−0.4	−18.6
Passband	1906.12	−0.4	−12.4
Return Loss (Peak value)	-	-	−10.3
Return Loss (First Null)	-	-	-30

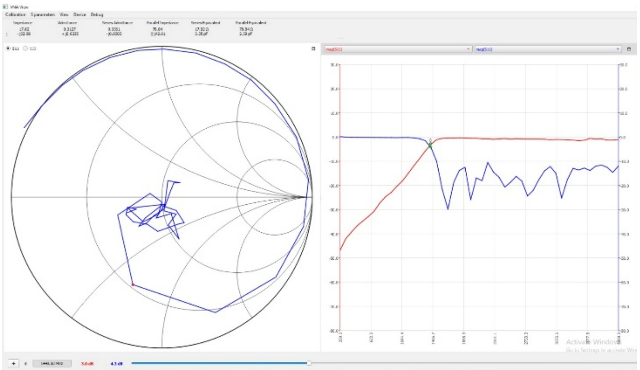

Figure 7. Measured S_{11} and S_{21} near the actual cut-off frequency (1440.82 MHz).

In Figure 7, the measured half-power point (S_{21} = -3 dB) occurred at 1440.82 MHz rather than the targeted 1.5 GHz, indicating a downward shift of about 59 MHz (≈ 3.9%). At this point S_{11} = -4.3 dB, which is above the ideal -10 dB threshold but expected within a filter's transition region. Near 1518.37 MHz, close to the original target, the filter already operates inside the passband, with S_{21} = -1.2 dB and S_{11} = -10.3 dB. Within the measurable passband ripple cycle, the worst-case S_{11} peak reached -10.35 dB, still satisfying the -10 dB matching criterion, and the estimated passband ripple near cut-off was approximately 0.7 dB. Using the measured points (1440.82 MHz, -3 dB) and (200 MHz, -47 dB), the measured roll-off rate is approximately 51.3 dB/decade.

Verification of the full nine-minima S_{11} response could not be completed because the laboratory VNA was limited to a maximum sweep frequency of 4 GHz, whereas the theoretical ninth minimum occurs near the 6.5 GHz upper passband edge. Table 6 compares the simulated and measured results.

Table 4. Comparison of Simulation and Measurement

Parameter	Simulation (HFSS)	Measurement (VNA)
Cut-off frequency	1500 MHz	1440.82 MHz
S11 (return loss)	−14.4639 dB	−4.3 dB
S21 (insertion loss)	−2.9957 dB	−3.0 dB
S11 minima count	9	Not fully verifiable (VNA limited to 4 GHz)

The frequency shift and elevated return loss at the actual cut-off point are attributed to fabrication tolerances: copper etching tolerance altering microstrip trace width, via hole position/diameter inaccuracy, parasitic inductance from uneven via plating, dielectric constant variation of the FR4 substrate, and imperfect SMA solder joints and RF cable losses during measurement. Despite these deviations, the fabricated filter retains clear high-pass characteristics consistent with the design target.

IV. Conclusion

A fifth-order optimum distributed microstrip high-pass filter with a 1.5 GHz cut-off frequency was successfully designed, simulated in HFSS, and fabricated on FR4 substrate using via hole grounding to realize the required shunt short-circuited stubs. The optimized simulation achieved S_{11} = -14.4639 dB and S_{21} = -2.9957 dB at 1.5 GHz with nine confirmed passband minima, matching the theoretical (2n-1) order. The fabricated prototype exhibited a functional high-pass response with an actual cut-off of 1440.82 MHz, shifted from the design target due to fabrication tolerances, while still showing acceptable matching and insertion loss inside the passband. A comparative study of orders n = 2 to 6 confirmed that higher filter orders yield sharper roll-off and passband ripples, ats the expense of additional stub elements. Future work should employ CNC-based vial hole drilling and a VNA with a wider sweep range to fully verify the higher-order ripple structure filter.

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