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Design and Fabrication of a Low-Pass Filter based on a Microstrip Resonator for Microwave Applications

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***Abstract*—This paper presents design, implementation and performance evaluation of a 2.8 GHz low-pass filter using microstrip resonator. The 3D planar electromagnetic simulator ADS Momentum is used for the layout design and the performance characterization. This filter has a Chebyshev response with 0.02 dB of ripple and a cutoff frequency located at 2.8 GHz. The attenuation of this filter is measured at 3.3 GHz. Theoretical frequency response from analytical calculations in MATLAB and ideal transmission line simulation in ADS are almost identical. The filter finds its application in telecommunication systems. Designed filter has been fabricated and measurements greatly coincide with simulation results.**

***Index Terms*—Microwave filter, planar microstrip, low-pass filter, ADS**

I. INTRODUCTION

Filters are used to select or confine the microwave signals within assigned spectral limits. Emerging applications related to wireless communications including the satellite communications continue to challenge RF filters with ever more strict requirements like smaller size, lighter weight,easy fabrication and higher performance [1], [2]. In [3] an fractional order filter are proposed to an arbitrary order $alpha$ lies in the range of 0-1 with an approximation to integer-order transfer function. The value of $alpha$ are directly obtained from colliding body optimization algorithm. Practically the approximated coefficients are deployed to match the analytical expression for curve fitting. In reference mentioned previously that approach is used to design the fractional low pass filter.

Planar microstrip filters, which possess compact size, low cost, flexible layout and easy fabrication, are preferably integrated in low power transceiver systems. Conventional procedures on the design of these filters have been discussed in [4], [5]. In lumped element model, lumped components capacitor and inductor work very well at low frequencies but at higher frequencies these lumped components don't exhibit their intrinsic properties. Hence, filter for higher frequencies is designed using distributed elements such as transmission lines. Microstrip is a type of transmission line that is used in designing planar filters. [6] Microstrip filters are preferably integrated in low power transceiver systems [7]. Conventional procedures on the design of these filters have been discussed in [8], with microstrip stepped-impedance hairpin resonators [9], microstrip low-pass filter using open loop resonators [10] and novel microstrip low-pass filter using stepped impedance resonator and spurline resonator in [11] and multimode resonator in [12]. In [13], a technique is presented where a simple open-stub microstrip line is printed on top of a substrate and the desired performance is obtained by optimizing the shape of the defected ground structure using the genetic algorithm. A low-pass filter using spiral compact microstrip resonant structure for size reduction and broad pass-band is presented in [14].

In contrast to wave guide filters [15] [16], microstrip is open and much susceptible to radiation and cross talk. Because of the high losses at microwave frequencies, microstrip devices cannot be built on FR-4 substrate. Alumina substrate is used because its dielectric constant can be controlled [17]. A strip of metal that is inserted between two ground planes is named as Stripline. It is a type of transmission line. Stripline is used in printed circuit board with minimum energy loss. The major factor that contributes towards the impedance of the strip line is strip width along with thickness and permittivity of substrate [18].

The 3D simulator called ADS Momentum is used for the layout design and the performance characterization. Momentum is the leading 3D planar electromagnetic (EM) simulator used for passive circuit modeling and analysis. [19] It accepts arbitrary design geometries and uses frequency-domain Method of Moments (MoM) technology to accurately simulate complex EM effects including coupling and parasitics. This filter has a Chebyshev response with 0.02 dB of ripple and a cutoff frequency located at 2.8 GHz. The attenuation of this filter is measured at 3.3 GHz. Theoretical frequency response from analytical calculations in MATLAB and ideal transmission line simulation in ADS are almost identical. This filter finds its application in telecommunication systems as modern wireless applications eliminate unwanted frequencies in communication systems and low pass filters play an important role to suppress high order harmonics and spurious signals [20]. Designed filter has been fabricated and measurements greatly coincides with simulation results.

TABLE I: Filter Specifications

Type of Response	Chebyshev response
Cut-off Frequency	2.8 GHz
Dielectric Constant	2.2
Substrate Thickness	62 mil
Conductor Thickness	0.035 mm

The remaining sections of the paper are organized as follows.Section II provides low-pass filter design methodology. Section III provides the design procedure for low-pass filter. Section IV provides filter's design and analysis. Section V provides stepped impedance resonator approach for low-pass filter design. Section VI provides filter response and discussion on results and Section VII concludes the paper.

II. Low-Pass Filter Design Methodology

The step by step design methodology of the low-pass filter is given in this section. The filter specifications are given in Table I.

III. Design Procedure for LPF

Step 1: At first, prototype values are calculated for cut-off frequency and load resistance of unity value. For a Chebyshev filter, attenuation can be expressed by formula [21] $\epsilon = \sqrt{10^{L_A/10} - 1}$, where L_A is ripple factor and in this case it is 0.02db. The normalized g values of nth order Chebyshev low-pass filter can be calculated from formulas

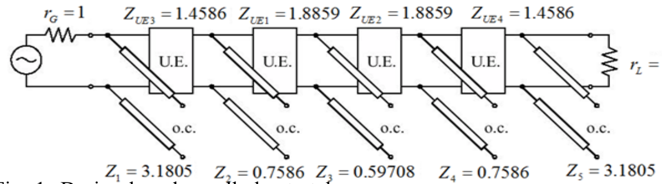

Fig. 1: Design based on all shunt stubs

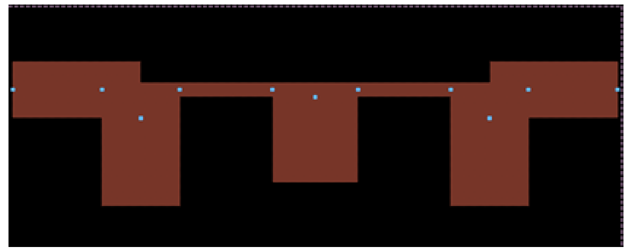
Fig. 2: Filter Layout


Fig. 3: Fabricated Filter

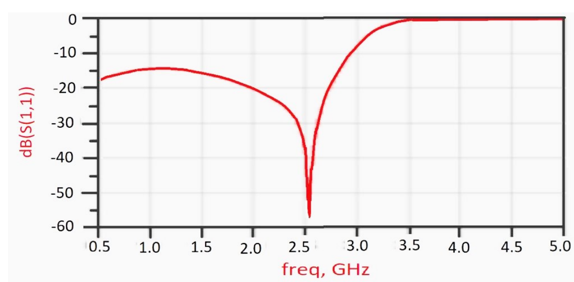

Fig. 4: Simulation Results from ADS: Return Loss

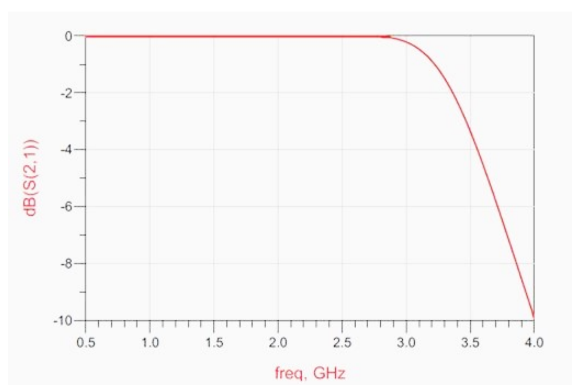

Fig. 5: Simulation Results from ADS: Insertion Loss

$g_0 = 1$, $g_1 = \frac{2a_1}{\gamma}$, and $g_k = \frac{4a_{k-1}a_k}{b_{k-1}g_{k-1}}$, where $k = 2, 3, ..., n$, $\beta = \ln(\frac{\sqrt{1+\epsilon}+1}{\sqrt{1+\epsilon}-1})$,$\gamma = \sinh(\frac{\beta}{2n})$, $a_k = \sin[\frac{(2k-1)\pi}{2n}]$ and

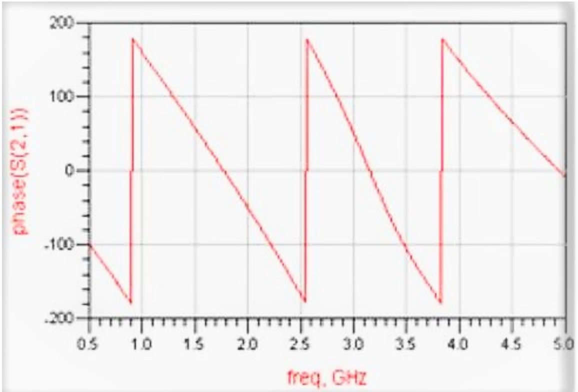

Fig. 6: Simulation Results from ADS: Phase of Insertion Loss

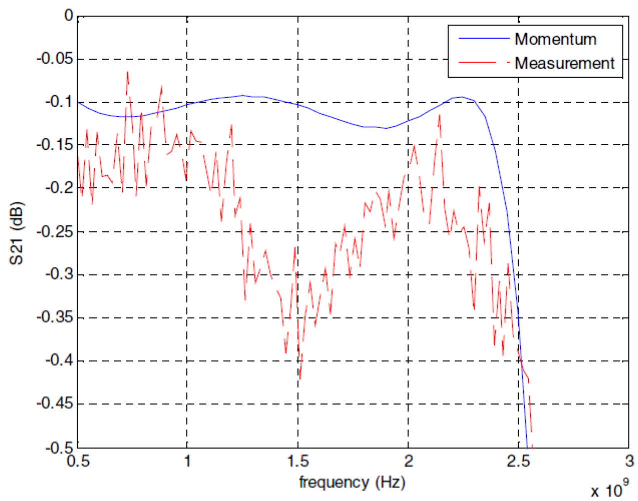

Fig. 7: S21 Measured (Passband section)

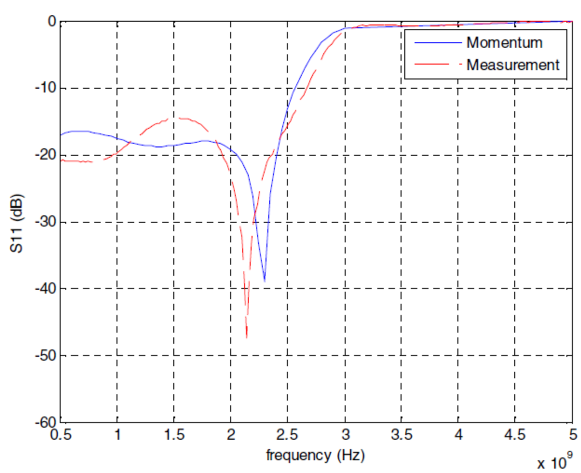

Fig. 8: S11 Measured vs. Simulated

$b_k = \gamma^2 + \sin^2(\frac{k\pi}{2n})$.

Step 2: The prototype g values calculated in step 1 are transformed into inductor L_k and capacitor C_k values for

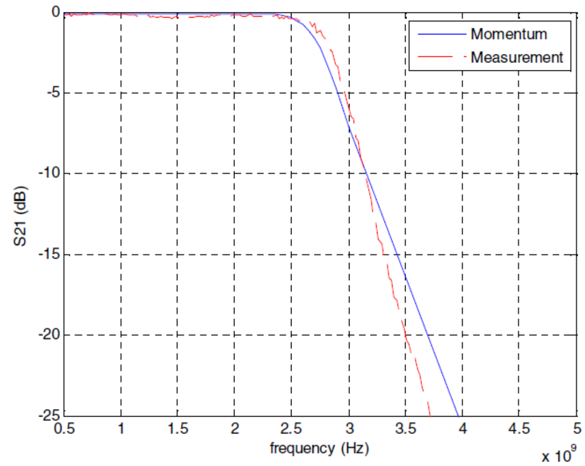

Fig. 9: S21 Measured vs. Simulated

cut-off frequency of 2.8 GHz and load resistance of 50 ohm. This is the lumped element model of low-pass filter where $C_k = \frac{1}{Z_s}\frac{g_k}{\omega_c}$ and $L_k = Z_s\frac{g_k}{\omega_c}$. Here, ω_c is cutoff frequency.The calculated values of capacitor and inductors are $L2 = L4 = 3.82nH$, $C1 = C5 = 0.96pF$ and $C3 = 1.9pF$.

Step 3: The lumped element model designed in step 2 is suitable for low frequency application. At microwave frequencies, this model is transformed into distributed element model. This transformation is accomplished using (1) Richard's Transformation and (2) Kuroda Identities. Richards Transformation allows the capacitor and inductor to emulate the open circuit stub and short circuit stub respectively. However, stubs calculated using Richard transformations are not a perfect replacement of lumped element. But this transformation is perfect in term of impedances that are same at both ends but only at one frequency (ω_c). Kuroda's Identities can be very useful in making the implementation of Richard's transformations more practicable. Kuroda's Identities essentially provide a list of equivalent two port networks. By equivalent, we mean that they have precisely the same scattering/impedance/admittance/transmission matrices.

IV. Filter Design and Analysis

In order to design low-pass prototype, at first g values are calculated for distributed element model. Richard's Transformation is used to create stubs of length $\lambda/8$ from the reactive components. A schematic is created by using Kuroda Identities, that is finally transformed into Microstrip. By using the Richard's Transformations and the Kuroda Identities the frequency shift is accounted for the final design. Impendance scaling is used to obtain desired impedances of all stubs. The normalized low-pass prototype element values $g1 = 1.0$;$g2 = 0.8472$;$g3 = 1.3449$;$g4 = 1.6748$; $g5 = 1.3449$;$g6 = 0.8472$;$g7 = 1.0$. Using Richard transformation a capacitor is replaced with open circuit stub and inductor with short circuit. Unit elements are introduced to convert series stub into shunt stub. By applying

TABLE II: Electrical Length and Characteristic Impedance

	Electrical Length	Impedance of Line	
Stub 1	45 deg	159.019 ohm	Stub 5
Stub 1	45 deg	72.932 ohm	Line 4
Stub 2	45 deg	37.964 ohm	Stub 4
Stub 2	45 deg	94.312 ohm	Line 3
Stub 2	45 deg	29.854 ohm	

TABLE III: Size of Stub:Length and Width

From Left to Right	Width of Stub	Length of Stub
Stub 1	1.0 mm	8.950 mm
Stub 2	7.669 mm	9.279 mm
Stub 3	8.661 mm	9.141 mm
Stub 4	7.669 mm	9.279 mm
Stub 5	1.0 mm	8.950 mm

TABLE IV: Size of Line:Length and Width

From Left to Right	Width of Line	Length of Line
Line 1	2.364 mm	9.054 mm
Line 2	1.221mm	9.685 mm
Line 3	1.221 mm	9.685 mm
Line 4	2.364 mm	9.054 mm

Kuroda's identity, first shunt stub is converted into series stub. Thereafter, a second set of Unit Identities is introduced in preparation for converting all series stubs into shunt stub. Finally all series stubs are converted into shunt stub. It is more convenient to design shunt stub in microstrip/stripline as compared to series stub. [22] These are normalized impedances as shown in Fig.1.

LineCalc in ADS is used to convert these values of electrical length and line impedance to dimensions. The next part was to test the design and tune it so that it still worked after incorporating discontinuities, like the T-junction. The optimization toolbox was used to help tune the design. The values are taken before the last part of the tuning. This allowed us to have the ADS software to help find suitable values. This was then converted to a layout and again tuned so that Momentum gave the best possible simulation result. Table II shows the characteristic impendance and length of each line in the ideal situation before any discontinuities have been introduced.The ADS design with ideal transmission lines is not shown in the interest of space. There is symmetry about stub 3 in the center of the layout and this is shown by each row being equal. Final design as shown in Table III and Table IV consisted of five shunt Microstrip stubs connected by four Microstrip transmission lines. There is symmetry about the center stub (stub 3). The two 50 ohm lines have been omitted because they are not specific to our design.

V. Stepped Impedance Resonator Approach for Low-pass Filter Design

In Section II, 3D electro-magnetic (EM) simulation tool such as ADS is utilized in order to design a low pass filter using particular specifications. This is highly accurate simulation tool that can predict the real-life response of a filter. The major disadvantages of these EM simulation tools are their clumsy user interfaces, time consuming for designing and higher cost. In this section, a MATLAB base algorithm is developed using circuit theory approach. In Microstrip technology, stepped impedance resonator (SIR) is widely accepted technique for low pass filter design. A combination of low impedance and high impedance microstrip lines constitutes an SIR. This SIR based filter is analyzed using ABCD matrix for multiple Microstrip lines. This ABCD matrix is calculated from equations available in [23]. The scattering parameters are extracted from ABCD matrix. These scattering parameters consist of four entities:input reflection coefficient S11, output reflection coefficient S22, forward and reverse transmission coefficient S12 and S21 respectively. There are three major steps involved in designing low pass filter using SIR. (1) Order of the filter is determined by filter response type (Chebyshev, Butterworth, elliptic or linear phase) (2) for multiple Microstrips, capacitance and inductance values are calculated. (3) These capacitance and inductance values are employed to compute physical length and width of these Microstrips. The filter designed in MATLAB is compared with the filter response of ADS 3D EM simulator. The agreement among the output response of both filters is quite good provided that the frequency does go beyond few GHz that is the limitation of circuit theory approach. The layout and fabricated filter is shown in Figs. 2 and 3.

VI. Filter Response and Results

Results from ADS Simulation: Fig. 4-6 shows the simulation of our design in ADS. The return loss for each port is shown. Since the design is symmetric about the center, the S11 and the S22 responses are the same. This is also true for the S21 and S12 responses.

Measurement Results after filter Fabrication: The frequency responses from the Momentum simulation and from measurements taken in lab were plotted in Figs. 7, 8 and 9. The final dimensions of the filter were adjusted to achieve the ripple in the passband of 0.04 dB with an attenuation of 0.09 dB; however the cutoff frequency was reduced to 2.3 GHz. For the entire frequency response, the measured response was a little bit off from the Momentum simulation. It has the higher ripple of 0.2 dB with a cutoff frequency at 2.5 GHz. The main difference is at 1.5 GHz which creates a large dip in the passband. In additional, the noisy response might be a result of limited accuracy of measurement equipment since the ideal frequency response should be smooth or of the limited modeling in Momentum compared to the real world.

VII. Conclusion

A low pass filter using stepped impedance resonator is design in ADS. The designed filter exhibits quite good agreement with the given specifications. The steps involve in designing are described in detail. LineCalc is used to extract filter parameters. This filter response is also analyzed by using circuit theory approach in MATLAB. This MATLAB algorithm is useful for RF and microwave designer in term of low cost, ease of computation and time saving. The output response of the filter using two approaches is quite similar. Fabricated filter can be used in application in telecommunication systems.

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