Compact Water-based Microstrip Filters

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***Abstract*—Implementation of Microstrip circuits at low radio frequencies presents challenges due to the longer wavelengths, resulting in increased form factor. This can be solved by using a higher dielectric constant substrate. In this paper, we propose a novel approach of implementing microstrip circuits on a composite multilayer substrate based on water having a higher effective dielectric constant ($\epsilon_{eff} = 26$). We demonstrate the practical implementation of microstrip circuits on a composite multilayer substrate, by designing a 5th order Stepped Impedance Low Pass Filter with cut-off frequency at 350 MHz. The overall reduction in size of the filter designed on composite substrate is demonstrated by comparing it with a filter designed on a single layer dielectric medium (FR-4). Filters simulated on both the substrates have been optimized for identical electrical specifications, and prototypes have been built and measured to validate the design concept. Measurement and simulation results indicate that filter designed on the composite substrate is 2.5 times smaller in length than the filter designed on a single layer substrate. We propose to use this concept for designing compact microstrip circuits at low frequencies.**

***Index Terms*—Microstrip circuits, Transmission lines, Higher dielectric constant, Water substrate, Filters, Low pass filters. VHF, low radio frequencies.**

I. INTRODUCTION

Microstrip circuits are commonly used in RF and microwave systems for their compact size and cost-effectiveness, but, at low radio frequencies, implementation poses challenges due to long wavelengths. The dimensions of a microstrip line depends on the substrate dielectric constant, substrate height, operating frequency, and conductor thickness, etc. [1]. The electrical wavelength of a transmission line is inversely proportional to the effective permittivity of the substrate (1).

$$\lambda_g \propto \frac{1}{\sqrt{\varepsilon_{eff}}} \tag{1}$$

Consequently, implementing microstrip circuits on the higher dielectric constant substrate can reduce its length. The dielectric material of higher dielectric constant has been extensively used to make microstrip circuits compact. Ceramic substrates, characterized by their diverse mixture compositions, have been commonly used for microstrip circuit implementation. The dielectric material consisting of a mixture of Zirconium, tin, and titanium dioxide is used in [2]. They have a dielectric constant of about 38. In this paper, the authors present the design of X-band bandpass filters. However, the etching process adopted is cumbersome and the strip-line design employed has made the circuit complicated. Bandpass filters designed in [3], and [4], employ similar Zirconium / titanium-based substrates having a dielectric constant of about 32. However, these substrates are not easily available. In another study [5], a barium-titanate mixture having a dielectric constant of 80 has been used to design a hairpin filter at 900 MHz. Higher dielectric constants of about 100, have also been achieved by using ceramic substrates in which the filters are etched using photolithography techniques [6]. The comprehensive review in [7] provides an overview of various microstrip filter types that can be manufactured on ceramic substrates with very high dielectric constants. However, it is important to note that most of these high-dielectric ceramic substrates are primarily intended for mass-scale manufacturing applications, entailing significant costs, efforts, and time for production.

In our approach, we propose a novel way of developing a high dielectric constant composite material made of distilled water and FR-4 (Fire resistant woven glass-reinforced epoxy resin). The effective dielectric constant achieved is about 25. Implementing circuits on Distilled water poses numerous challenges, including the corrosion of copper traces, and the rigidity and stability of the circuit. We have successfully addressed the challenges and implemented the microstrip lines on water-based high dielectric constant composite medium using the method described in [8].In this current paper, we describe the design of a lowpass filter built on water substrate and compare its performance with a similar filter built on FR-4 material. We show that the filter built on water has similar characteristics as that of the FR-4 filter. However, the former is demonstrated to be more compact than the latter by a factor of 2.5. We have designed a 5th-order stepped impedance low pass filter with a cut-off frequency of 350 MHz both on water-based composite dielectric medium and FR-4 substrate. The circuit elements have been optimized using CST microwave for both substrates. The prototypes of both of them have been built and characterized.

Section II presents the analysis of the microstrip line on the

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multilayer dielectric medium. Section III describes the design and development of low-pass filters on single-layer as well as multilayer substrates, followed by a detailed account of their fabrication procedure in Section IV. Section V will discuss the measurement results and Section VI will provide a brief summary of the work.

II. ANALYSIS OF MICROSTRIP LINE ON MULTILAYER DIELECTRIC MEDIUM

In conventional microstrip design, the equations from [9] are used extensively. However, these equations are tailored for single-substrate microstrip configurations, and our proposed design introduces a novel composite substrate. Hence, the conventional equations cannot be applied to our microstrip design. Fig. 1 illustrates the model of our proposed substrate, where a water layer is placed below a PVC layer, with the microstrip line and ground layer conventionally positioned at the top and bottom. A detailed investigation has been carried out on the design of microstrip lines on composite substrate by J.Svacina in [10] and two fundamental equations have been derived in the article. One equation is the effective dielectric constant equation given in (2)–(4), and another equation is the characteristic impedance formula given in (5), which relates the physical dimensions and dielectric properties of the microstrip line to its impedance. These two equations have been used in our design for calculating the width of the microstrip line. The length of the microstrip line can be easily determined once the effective dielectric constant is calculated and the required phase shift is known.

The design equations adopted from [10] are given below.

$$\varepsilon_{eff} = 1 - q_1 - q_2 + \varepsilon_{r1}\varepsilon_{r2} * \frac{(q_1 + q_2)^2}{\varepsilon_{r1}q_2 + \varepsilon_{r2}q_1} \tag{2}$$

$$q_1 = aa * \left[1 + \frac{\pi}{4} - 0.5 * \cos^{-1}(bb)\right] \tag{3}$$

where,

$$aa = \frac{\ln\left(\frac{1+f_1}{1-f_1+f_2}\right)}{2 * \ln\frac{2}{f_2}}$$

$$bb = \left(\frac{1}{f_1} * \frac{f_2}{2} * \sqrt{\frac{1+f_1}{1-f_1+f_2}}\right)$$

$$q_2 = 0.5 + \left(\frac{0.9}{\pi + \ln\frac{2}{f_2}}\right) - q_1 \tag{4}$$

where,

$$f_1 = \frac{h_1}{h}, f_2 = \frac{w}{4h}$$

h=overall substrate height, h1=height of water layer, w=width of microstrip, ϵ_{r1} =dielectric constant of PVC layer, ϵ_{r2} =dielectric constant of water layer

$$Z_0 = \frac{60}{\sqrt{\varepsilon_{eff}}} * \ln\frac{8h}{w} \tag{5}$$

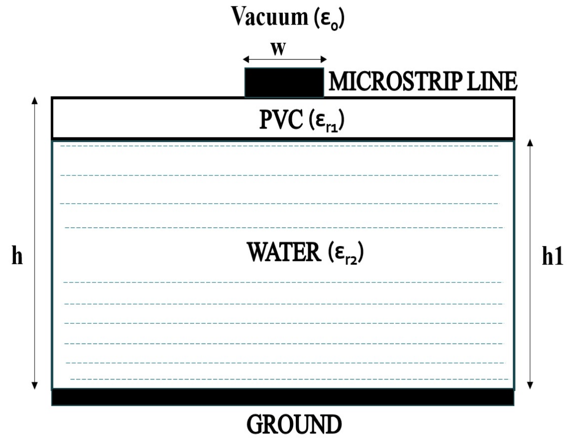
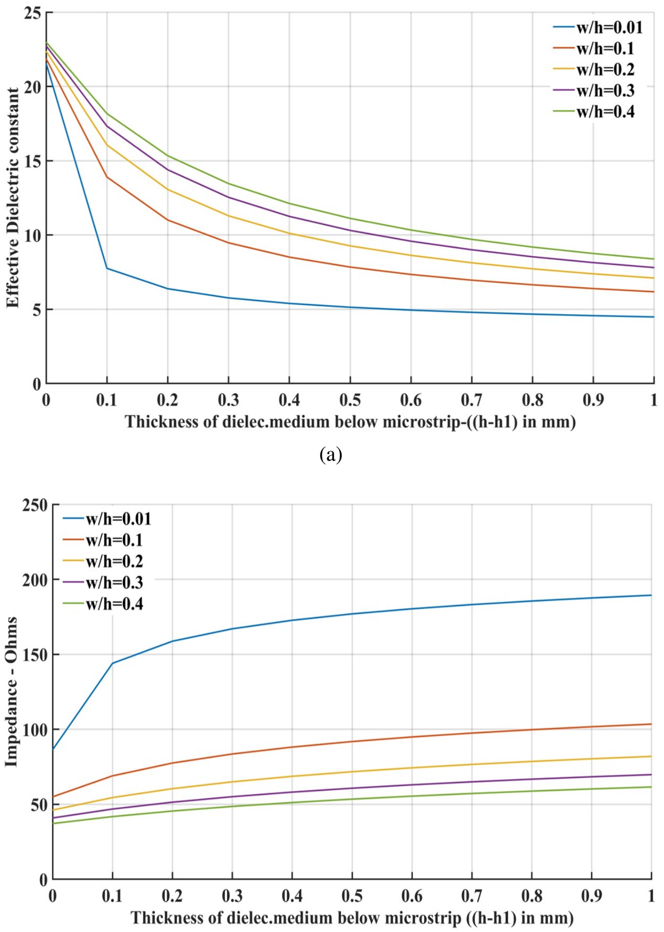


Fig. 1. Proposed model of the composite water substrate.

In the above equations, w, h, and h1 are used to calculate the effective dielectric constant and characteristic impedance. However, in our case, both the width and height of the microstrip are unknown parameters. As a result, we simulated parametric curves for effective dielectric constant and the characteristic impedance, by altering the width of the microstrip and the height of the substrates simultaneously. This approach allowed us to efficiently analyze the interdependence and identify the optimal combination of width and height that meets our specific design requirements. Fig.2 illustrates the parametric curves used for designing the microstrip line. In Fig. 2a, we observe the variation of the effective dielectric constant with respect to the height of the PVC layer for different w/h ratios. It is evident that higher w/h ratios result in a higher dielectric constant while still maintaining a limited impedance range. Similarly, in Fig.2b, the variation of impedance with the height of the PVC layer is shown, indicating that reducing the PVC layer's height leads to lower impedance values. Therefore, an optimum and practical value was selected for both the PVC layer and water layer, as detailed in our article [8], targeting a 50Ω impedance. Once the heights of the water and PVC layers are fixed, the width of the microstrip for any desired impedance value can be readily calculated from the parametric curves. The design approach for the microstrip circuits is explained in the subsequent section.

III. DESIGN OF MICROSTRIP FILTER ON SINGLE LAYER AND MULTILAYER SUBSTRATE

To demonstrate the reduction in size of a circuit at low frequency, we have designed a 5th order stepped impedance low pass filter on both single layer and multilayer medium. The following section presents a comprehensive account of the design and simulations. It commences with a concise overview of our single-layer design, followed by a detailed explanation of the design process on the multilayer substrate.



(a)

(b)

Fig. 2. a) Effective dielectric constant variation with height of PVC layer for different w/h ratio b) Impedance variation with height of PVC layer for different w/h ratio

A. *Design of stepped impedance filter on single layer substrate*

We have designed our low pass filter on single layer dielectric medium with the following specifications - Configuration: 5th order Chebyshev stepped impedance filter, Cut-off frequency: 350 MHz, Attenuation roll-off: 30dB/octave, passband ripple: 0.04 dB, and an insertion loss of 0.3 dB at 150 MHz. The filter was designed on the FR-4 substrate, with ϵ_r = 4.5 and a thickness of 1.6mm, using Genesys software [11]. Fig. 3 displays the filter's layout with the lengths ($l_1 - l_7$) and widths($w_1 - w_7$) of the lines given in Table. I. The characteristic impedance of the different sections of the filters are also mentioned in Fig.3. Subsequently, the designed filter was fabricated, and the simulation and measurement results will be presented in the sections IV and V.

B. *Design of stepped impedance filter on composite substrate*

The impedance values obtained from the FR-4 designed stepped impedance filter served as a reference for the design on the composite substrate. The dimensions of different layers on the composite substrate, as shown in Fig.1 are - height of PVC = 0.1mm, height of water = 10mm with ϵ_{r1} = 4.3, ϵ_{r2} = 80 (distilled water) respectively. Given the fixed substrate height, the width of the microstrip lines were calculated using the parametric curves (Refer Fig.2) to achieve the desired impedances. The effective dielectric constant ϵ_{eff} = 26 was taken from our earlier measurements [8] and the lengths of the microstrip lines were proportionally scaled down by ($\sqrt{\epsilon_{eff}}$). Optimization of the design was performed using CST software [12], resulting in the dimensions presented in Table I. Fig. 4 illustrates the layout of the optimized design.

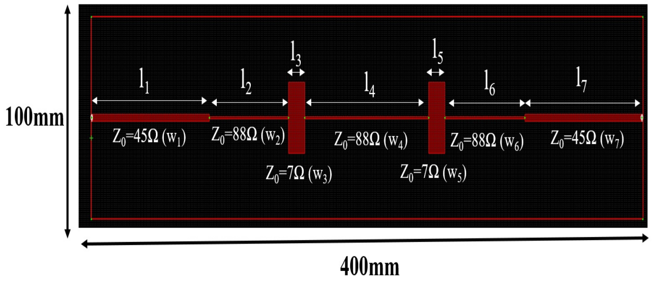


Fig. 3. Layout of the Low pass filter designed on single layer (the values $l_1 - l_7$ and $w_1 – w_7$ are given in Table I)

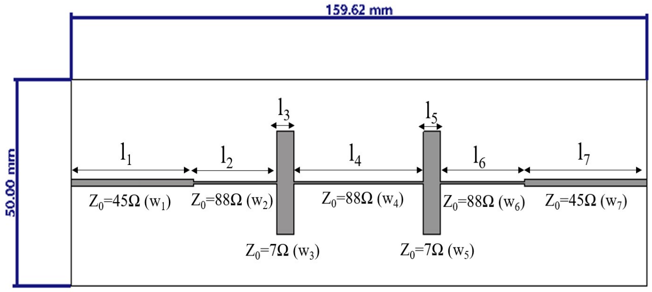


Fig. 4. Layout of the Low pass filter designed on composite substrate (the values $l_1 - l_7$ and $w_1 - w_7$ are given in Table I)

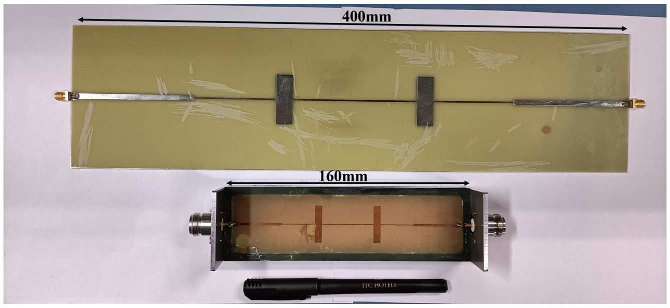


Fig. 5. Fabricated prototype of filter designed on water substrate (bottom) in comparison with filter designed on FR-4 substrate (top)

IV. FABRICATION

The filter designed on single layer was fabricated on FR-4 substrate of 1.6mm thickness. Fabrication of filter designed

TABLE I
DESIGN PARAMETERS FOR FILTERS

S.no	Design parameters		
	Variable	**Single layer**	**Multilayer**
1	l_1, l_7	85	34
2	l_2, l_6	58	23
3	l_3, l_5	11.3	4.6
4	l_4	90	36
5	w_1, w_7	3.5	1.5
6	w_2, w_4, w_6	1	0.4
7	w_3, w_5	35	25

All dimensions are in mm

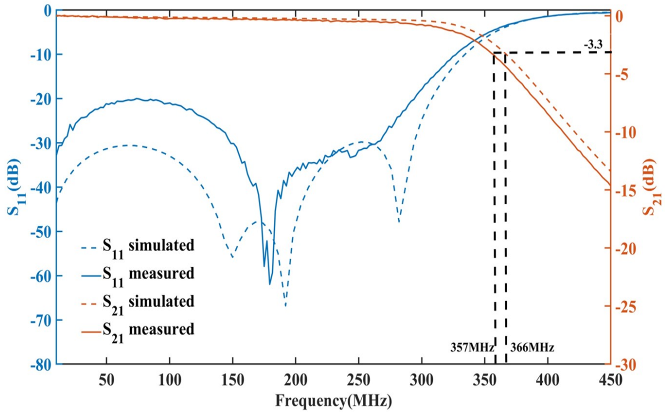


Fig. 6. Simulation and measurement results for the single layer filter (dotted line- simulated,solid line-measured)

on multilayer substrate was carried out by placing two 0.1mm thick PCB laminates on either side of water layer. This configuration was implemented to prevent any reaction between the copper metal and water. For the substrate material, we opted for distilled water, as opposed to normal water, as the latter contains minerals that exhibit good conductivity, whereas distilled water acts as a reliable insulator. The PCB laminates were ideally intended to be as thin as possible, but practical constraints led us to use a 0.1mm PCB laminate. The top PCB laminate has its top side etched with the designed filter and the bottom side copper completely etched out. Similarly, the bottom PCB laminate has its copper etched out on its top surface and retained on the bottom surface. To create a sealed environment, a custom hollow rectangular PVC frame of 5mm wall thickness and 10mm height was constructed, tailored to the dimensions of the microstrip filter PCB. The flexible etched PCB layers were then securely attached to the top and bottom of the frame using water-resistant adhesives. Subsequently, water was carefully introduced using a syringe, through a hole on top PCB, and the hole was later sealed with glue. N-type connectors were connected to the input and output of the filter, and the entire assembly was placed on a 6mm Aluminum plate for grounding purposes, ensuring an effective implementation of our microstrip filter within the water-filled enclosure. Fig.5 showcases the fabricated prototype of single layer filter in comparison with the compact filter on multilayer substrate. These filters were measured and the results are elucidated in the next section.

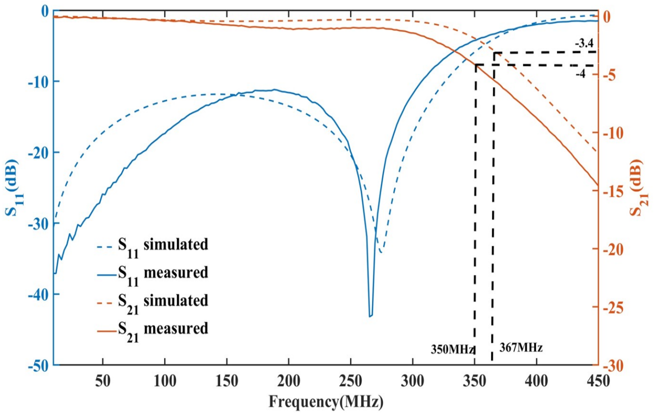


Fig. 7. Simulation and measurement results for the multilayer composite substrate filter (dotted line- simulated,solid line-measured)

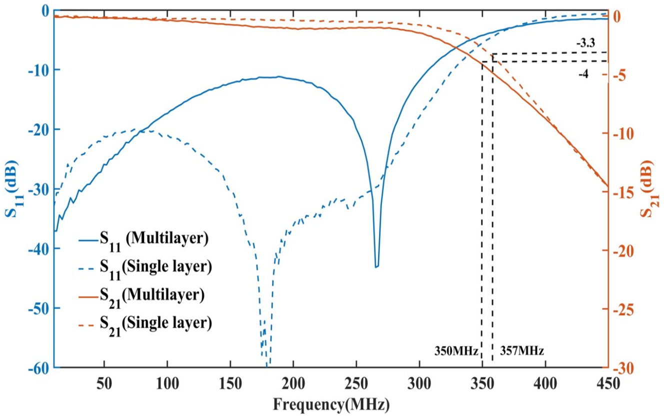


Fig. 8. Measured results comparison for the single layer and multilayer filter (dotted line – single layer, solid line – multilayer)

V. MEASUREMENT RESULTS AND DISCUSSIONS

The fabricated filters were measured using Rohde and Schwarz ZNB-20 VNA and compared with simulation results. Fig. 6 illustrates the simulated and measured results of the FR-4 filter. The measured cut-off frequency closely aligns with the simulated result, demonstrating a deviation of only 2.5%. The filter exhibits cut-off frequency at 357 MHz, with 30dB/octave roll-off and return loss greater than 20dB. In a similar vein, Fig. 7 displays the simulated and measured outcomes of the filter designed on the multilayer composite substrate. In this case, the measured cut-off frequency exhibits a close match with the simulated result, with a deviation of 4.5%, accompanied by a well-matched return loss around 15dB. The deviation is attributed to the uncertainty in the value of the dielectric constant of the composite medium. Fig. 8 shows the comparison of the measured results of both the single-layer and multilayer filters. Here, we can observe the close agreement in the measured performance of both the single-layer designed filter and the composite substrate filter. The cut-off frequency of the multilayer filter deviates by only 2% from the single-layer filter. The insertion loss of the multilayer filter is around 1dB with return loss greater than 15 dB. From these results, we conclude that our multilayer filter achieves a 2.5 times reduction in size when compared to the single-layer filter with comparable performance.

VI. CONCLUSION AND FUTURE WORK

This work presents a novel technique for implementing microstrip circuits on a multilayer composite dielectric substrate based on water. The design process uses analytical equations specifically tailored for microstrip circuits on this composite substrate. A 5th-order low pass filter was successfully designed on both single-layer and multilayer composite substrates, each with a cutoff frequency of 350 MHz and a 30dB/octave roll-off. Prototypes were constructed on both dielectric media, and measurements were carried out. The simulated and measured cut-off frequency of the single-layer filter exhibited a slight deviation of 2.5%, while the multilayer filter showed a deviation of 4.5%. Notably, the measured cut-off frequency of both single-layer and multilayer filters deviated by merely 2%, validating the efficacy of the water-based substrate approach with a significant 2.5 times size reduction. With an insertion loss of approximately 1dB, the water-based substrate demonstrated promising performance for microstrip circuit implementation. In our ongoing efforts, we are actively exploring the design of other circuits, such as beamformers, on the composite substrate. The characterization of the composite water based multilayer substrate for its loss tangent, thermal stability and vibration tolerance is under progress.

VII. ACKNOWLEDGEMENT

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