E-ISSN: 111 – 2716 P-ISSN: 3026 – 8214
MPRI-JAAER | INTERNATIONAL JOURNAL OF APPLIED & ADVANCED ENGINEERING RES.
VOL. 13 NO. 5 JULY, 2026

FABRICATION AND CHARACTERIZATION OF A COPLANAR WAVEGUIDE BANDPASS FILTER FOR 4G LTE AND 5G NEW RADIO APPLICATIONS

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DOI: https://doi.org/10.70382/mejaaer.v13i5.063

Abstract

The fast development of fourth-generation (4G) Long-Term Evolution (LTE) and fifth-generation (5G) New Radio (NR) communication systems has increased the demand for compact, low-loss, and high-performance microwave filters capable of supporting high data-rate wireless communications. Coplanar Waveguide (CPW) has attracted considerable attention due to its low radiation loss, simplified fabrication process, ease of integration with active and passive microwave components, and excellent high-frequency performance. This paper presents the design, simulation, fabrication, and experimental characterization of a printed circuit board (PCB) Coplanar Waveguide Bandpass Filter for microwave applications. The proposed filter was designed using CST Microwave Studio based on optimized CPW geometrical parameters to achieve the desired frequency response within the target operating band. Finite Integration Technique (FIT) electromagnetic simulations were performed to investigate the scattering parameters performance. The optimized design was fabricated using standard single-sided PCB manufacturing techniques and experimentally characterized using a Vector Network Analyzer (VNA). The measured S-parameter

Keywords—
Coplanar Waveguide (CPW), Bandpass Filter, Microwave Filter, CST Microwave Studio, PCB Fabrication, S-Parameters, Vector Network Analyzer, 4G LTE, 5G New Radio, Microwave Communication.

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responses demonstrated good agreement with the simulated results, confirming the effectiveness of the design methodology and fabrication process. The fabricated CPW bandpass filter exhibits satisfactory insertion loss (less than 2 dB), return loss (better than 11 dB), and passband selectivity at DC is better than 60 dB and 38.5 dB at the upper stopband frequency with centre frequency at 0.88 GHz (880 MHz), making it suitable for integration into modern 4G LTE and emerging 5G New Radio front-end microwave systems. The study further demonstrates the reliability of combining full-wave electromagnetic simulation with practical PCB fabrication to realize compact and cost-effective microwave filtering devices for contemporary wireless communication applications.

Introduction

The rapid growth in wireless communication technologies has significantly increased the demand for compact, efficient, and high-performance microwave filtering devices. Modern wireless standards, particularly Fourth Generation Long-Term Evolution (4G LTE) and Fifth Generation New Radio (5G NR), require microwave front-end components that exhibit low insertion loss, high selectivity, excellent impedance matching, and compact physical dimensions. These demands broaden research into advanced planar transmission-line technologies capable of supporting highfrequency systems while maintaining low fabrication cost and ease of integration with monolithic microwave integrated circuits (MMICs) and printed circuit board (PCB) platforms. Bandpass filters constitute one of the most critical components in microwave communication systems because they determine channel selectivity, suppress unwanted harmonic frequencies, minimize adjacent channel interference, and improve overall receiver sensitivity. In both base stations and user equipment, microwave filters are employed to isolate desired frequency bands while rejecting out-of-band signals that could degrade communication quality. As communication systems migrate toward wider bandwidths and higher operating frequencies, filter performance requirements have become increasingly stringent.

Among various planar transmission-line technologies, the Coplanar Waveguide (CPW), originally introduced as an alternative to conventional microstrip transmission lines, has emerged as an attractive solution for high-frequency microwave circuit implementation. Unlike microstrip structures, the signal conductor and the ground planes of a CPW are located on the same side of the dielectric substrate, thereby eliminating the need for plated through-holes or backside metallization interconnections. This configuration

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considerably simplifies fabrication while simultaneously reducing parasitic inductance and improving broadband performance. Several additional advantages make CPW structures particularly attractive for microwave filter applications. These include reduced radiation losses, lower dispersion characteristics, wider operational bandwidth, simplified shunt and series component integration, compatibility with active semiconductor devices, and ease of monolithic integration. Furthermore, CPW structures exhibit excellent performance at microwave and millimetre-wave frequencies, making them suitable candidates for contemporary 4G LTE and emerging 5G New Radio systems.
Recent developments in microwave filter design have focused on improving electrical performance while reducing circuit size and fabrication complexity. Various design methodologies have been reported, including coupling matrix synthesis, electromagnetic optimization, artificial intelligence-assisted design, surrogate modelling, space mapping, and full-wave numerical optimization. The integration of electromagnetic field solvers such as CST Microwave Studio has significantly enhanced the accuracy of microwave filter design by allowing designers to predict electromagnetic behaviour before hardware fabrication. Full-wave simulation enables accurate evaluation of scattering parameters, current distributions, electric-field intensity, coupling mechanisms, and impedance matching, thereby reducing development time and fabrication cost.
Coupling matrix synthesis remains one of the most widely adopted analytical approaches for microwave filter design because it provides systematic control of resonator coupling and external quality factors while allowing precise realization of specified frequency responses. Advanced optimization methods have further improved microwave filter development by combining electromagnetic simulation with modelling techniques to reduce computational complexity while preserving simulation accuracy. Such optimization strategies have been successfully employed in the design of microwave filters and multiplexers with significantly reduced design cycles.
Although numerous CPW bandpass filters have been reported in the literature, many existing designs either focus on theoretical electromagnetic optimization without practical hardware validation or require relatively complex fabrication processes involving multilayer substrates, defected ground structures, or sophisticated resonator topologies. Consequently, there remains a need for compact, low-cost, and experimentally validated CPW filter structures that can be readily fabricated using standard PCB technology while maintaining acceptable microwave performance for current wireless communication systems.
This research addresses this need by presenting the design, fabrication, and experimental characterization of a printed circuit board Coplanar Waveguide Bandpass Filter suitable for microwave communication applications. The proposed filter was designed using CST Microwave Studio through full-wave electromagnetic simulation and subsequently

fabricated using conventional PCB manufacturing techniques. Experimental measurements were performed using a Vector Network Analyzer to evaluate the scattering parameters and validate the simulation results.

Evolution of Microwave Bandpass Filters

Microwave bandpass filters are indispensable components in modern wireless communication systems because they provide frequency selectivity, suppress unwanted harmonics, and reduce interference from adjacent communication channels. Their performance directly influences receiver sensitivity, transmitter spectral purity, and the overall quality of radio-frequency (RF) communication systems. As wireless technologies have evolved from second-generation (2G) systems through 4G Long-Term Evolution (LTE) and into 5G New Radio (NR), increasingly stringent requirements have been placed on microwave filters with respect to insertion loss, return loss, bandwidth, quality factor, power handling capability, compactness, and manufacturability (Y. I. Al-Yasir, 2019).

Traditional microwave filters were predominantly realized using waveguide cavities because of their exceptionally high-quality factors and low insertion losses. Although cavity filters provide excellent electrical performance, they are generally large, expensive, and unsuitable for highly integrated wireless communication devices. Consequently, research shifted toward planar microwave technologies that offer significant reductions in size, weight, fabrication complexity, and manufacturing cost while maintaining acceptable electrical performance.

Among planar technologies, microstrip transmission lines initially dominated microwave filter implementation because of their straightforward design methodology and compatibility with printed circuit board (PCB) manufacturing (S. Marín, 2016). However, as operating frequencies increased into the microwave and millimetre-wave regions, microstrip structures exhibited increased conductor losses, parasitic effects, and fabrication challenges. These limitations motivated the development of alternative planar transmission-line technologies, particularly the Coplanar Waveguide (CPW), which has become one of the most attractive platforms for modern microwave filter design

Coplanar Waveguide Technology

The Coplanar Waveguide is a planar transmission-line structure in which the centre conductors and two ground conductors are fabricated on the same surface of the dielectric substrate. This configuration differs fundamentally from conventional microstrip structures, where the signal conductor is located on one side of the substrate while the ground plane occupies the opposite side. The coplanar configuration provides several significant advantages (D. Hua, 2016), including simplified PCB fabrication, elimination of plated through-hole vias, reduced parasitic inductance, ease of mounting

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active components, improved impedance control, lower radiation losses, and superior compatibility with monolithic microwave integrated circuits (MMICs). Because both signal and ground conductors reside on the same plane, CPW circuits also facilitate easier shunt and series connections without requiring multilayer processing.

These characteristics have made CPW structures particularly attractive for microwave integrated circuits operating above 2 GHz, where electromagnetic coupling effects become increasingly significant. Furthermore, CPW structures exhibit excellent broadband characteristics, making them suitable for both LTE and emerging 5G communication systems.

Microwave Filter Synthesis Techniques

The design of microwave filters generally begins with network synthesis, where the desired electrical response is translated into an equivalent low-pass prototype before being transformed into the required bandpass response. Classical synthesis methods based on Chebyshev, Butterworth, and elliptic transfer functions remain widely used because they provide predictable insertion loss and return loss characteristics while maintaining stable filter responses.

(Macchiarella, 2007) reviewed the evolution of microwave filter synthesis and emphasized that practical microwave filter realization generally involves two complementary stages: network synthesis and physical implementation. They observed that although network synthesis establishes the desired electrical characteristics, practical implementation requires careful optimization because distributed microwave structures cannot always be represented accurately by ideal lumped-element equivalents.

Modern microwave filter design therefore combines analytical synthesis techniques with full-wave electromagnetic simulation to compensate for parasitic coupling, discontinuities, substrate effects, and conductor losses that are not adequately represented by classical circuit models.

Coupling Matrix Approach

The coupling matrix method has become one of the most powerful analytical techniques for microwave filter design because it directly relates the required electrical response to the physical coupling between resonators. Instead of manipulating distributed transmission-line parameters directly, the coupling matrix provides a systematic mathematical framework for controlling resonator interactions, external quality factors, and transmission zeros.

Research by (Lu, 2008) demonstrated that coupling matrix techniques can be successfully extended to planar microwave diplexers by incorporating mutual coupling

effects, radiation losses, and dispersion into an extended surrogate model. Their approach significantly reduced computational requirements while maintaining high simulation accuracy by limiting the number of full-wave electromagnetic simulations required during optimization. Similarly, hybrid optimization approaches combining coupling-matrix with full-wave electromagnetic simulation have been shown to provide highly accurate filter responses while dramatically reducing computational time compared with repeated direct EM optimization (Y. Liu and W. Dou, 2009). These methods exploit the speed of coarse analytical models while retaining the accuracy of electromagnetic simulation through iterative correction matrices.

Electromagnetic Simulation in Microwave Filter Design

The rapid increase in computational power has transformed electromagnetic simulation into an indispensable component of microwave filter development. Full-wave electromagnetic solvers such as CST Microwave Studio, HFSS, Sonnet, and FEKO enable accurate modelling of complex electromagnetic interactions including fringing fields, conductor losses, dielectric losses, higherorder modes, and radiation effects. Unlike conventional equivalent circuit analysis, full-wave simulation solves Maxwell's equations numerically throughout the entire computational domain, providing accurate predictions of scattering parameters, electric-field distribution, magnetic-field intensity, current density, surface impedance, and resonant behaviour before fabrication.

The availability of full-wave electromagnetic analysis substantially reduces prototype iterations, lowers manufacturing cost, and shortens product development cycles. Furthermore, visualization of electromagnetic field distributions allows designers to identify unwanted coupling mechanisms and optimize resonator geometries prior to fabrication. Among the available software platforms, CST Microwave Studio has gained widespread acceptance because of its robust finite integration technique (FIT), adaptive mesh refinement, transient and frequency-domain solvers, and comprehensive post-processing capabilities. Consequently, CST has become one of the preferred simulation environments for the design of microwave filters intended for modern wireless communication systems.

Printed Circuit Board Fabrication of CPW Filters

Printed Circuit Board (PCB) technology provides an economical platform for implementing planar microwave filters intended for commercial communication systems. Advances in PCB manufacturing have enabled high dimensional accuracy, improved conductor surface quality, and enhanced dielectric consistency, allowing planar microwave circuits to operate efficiently at gigahertz frequencies.

The fabrication process generally involves substrate preparation, copper pattern transfer through photolithography or computer numerical control (CNC) milling, chemical

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etching, drilling, connector installation, and post-fabrication inspection. Accurate dimensional control is particularly important because relatively small deviations in conductor width or gap spacing can significantly alter characteristic impedance and resonant frequency. Experimental validation using Vector Network Analyser (VNA) remains the standard method for characterizing fabricated microwave filters. Measurements of the scattering parameters (S_{11} and S_{21}) allow direct comparison between simulation and experimental performance, thereby verifying the effectiveness of the design methodology.

CPW Filters for 4G LTE and 5G New Radio Applications

The deployment of LTE-Advanced, LTE-Advanced Pro, and 5G New Radio has created unprecedented demand for compact microwave filters capable of operating over multiple frequency allocations while maintaining low insertion loss and high selectivity. Compared with earlier communication systems, fifth-generation wireless networks require significantly wider bandwidths, improved spectral efficiency, reduced latency, and increased channel capacity. Although many published CPW filters demonstrate good simulated performance, relatively few studies present comprehensive validation through practical PCB fabrication and experimental characterization. In several cases, discrepancies between simulation and measurement arise from fabrication tolerances, dielectric constant variations, connector losses, soldering imperfections, and calibration uncertainties.

The present work contributes to this area by combining full-wave CST Microwave Studio simulation with practical PCB fabrication and Vector Network Analyzer measurements. The close agreement obtained between simulated and measured responses demonstrates the feasibility of realizing high-performance CPW bandpass filters using conventional PCB technology.

Research Gap

Considerable progress in CPW microwave filter design has been reported in the literature through modelling, full-wave numerical simulation and other methods. Nevertheless, three major research gaps remain. First, many published investigations concentrate primarily on simulation without comprehensive experimental validation. Second, several reported filter structures require complex multilayer fabrication techniques or specialized substrates that increase manufacturing cost. Third, relatively few studies integrate complete electromagnetic design, low-cost PCB fabrication, and detailed experimental characterization within a single workflow suitable for practical deployment in 4G LTE and emerging 5G New Radio systems.

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This research addresses these gaps by designing, fabricating, and experimentally characterizing a compact Coplanar Waveguide Bandpass Filter using CST Microwave Studio and conventional PCB technology. The proposed approach demonstrates that high-performance microwave filters can be realized economically while maintaining excellent agreement between simulated and measured scattering parameters, thereby supporting their application in modern wireless communication front-end systems.

Research Methodology

This study employed a combined computational and experimental methodology involving the design, optimization, fabrication, and characterization of a Coplanar Waveguide (CPW) bandpass filter intended for wireless communication applications. The overall workflow consisted of six sequential stages: (i) specification of the electrical design requirements, (ii) electromagnetic modelling using CST Microwave Studio, (iii) optimization of the CPW geometry, (iv) fabrication of the optimized design using printed circuit board (PCB) technology, (v) experimental characterization using a Vector Network Analyzer (VNA), and (vi) comparison of the measured and simulated scattering parameters to validate the proposed design

Electromagnetic Design Using CST Microwave Studio

The proposed filter was modelled using CST Microwave Studio, a three-dimensional full-wave electromagnetic simulation environment based on the Finite Integration Technique (FIT) 3D geometry computer aided design tool. CST MICROWAVE STUDIO SUITE is a window-based graphical user interface with a friendly design environment consisting of various control elements. Figure 1 shows the general interface of the CST microwave studio.

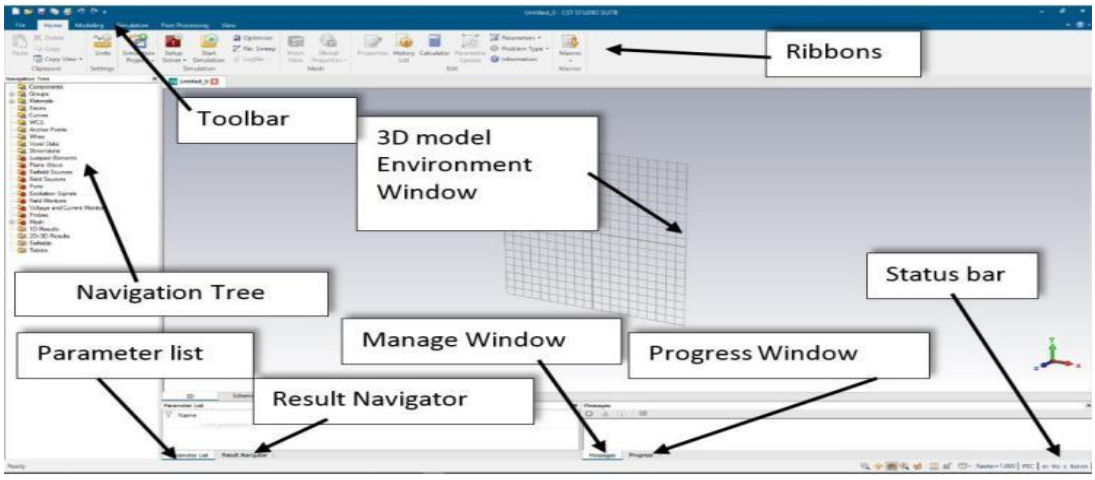

Figure 1: The general interface of the CST Microwave Studio Suit

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The workflow adopted in the 3D design and Simulation of the of the coplanar waveguide Combline bandpass filter as illustrates in Figure 2. The 3D model of the coplanar waveguide Combline bandpass filter is designed and simulated in CST microwave suite to determine its performance.

The simulation stage in the entire design process is to extract the optimized layout for fabrication.

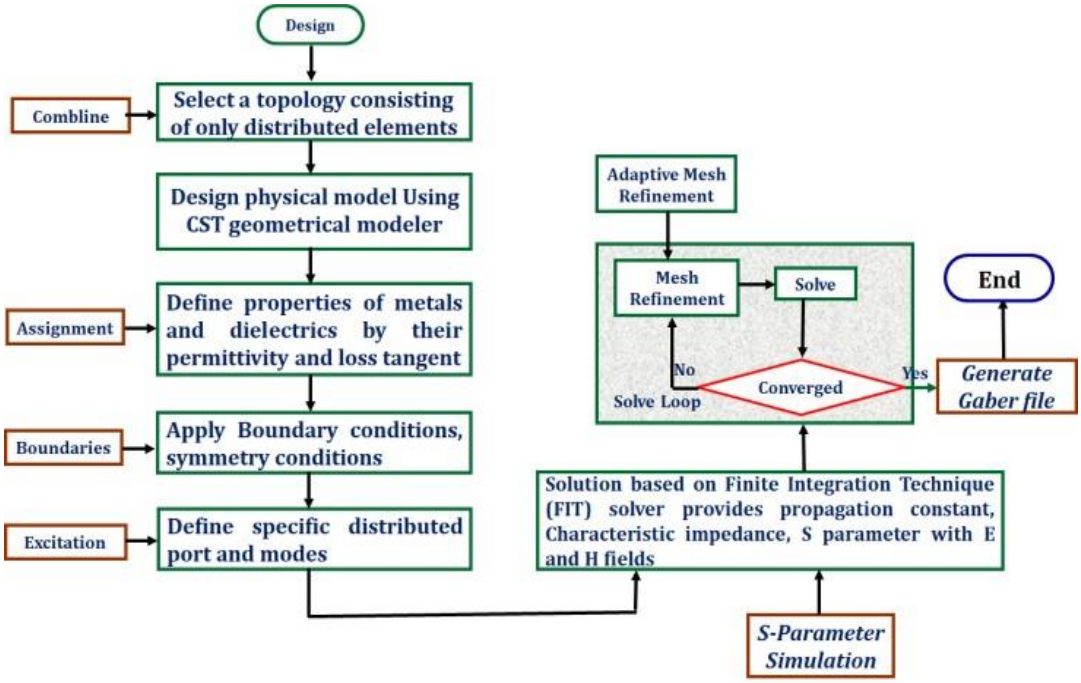

Figure 2: Flow chart of CST for the PCB CPW bandpass filter.

Simulation Settings

To maintain high numerical accuracy and reasonable computational efficiency, adaptive mesh refinement was employed throughout the simulation process. The principal simulation settings included: Frequency-domain solver, Adaptive mesh refinement, Open (add space) boundary conditions, Waveguide excitation ports and Automatic convergence criterion. Mesh refinement was repeated until successive iterations produced negligible variation in the scattering parameters, indicating numerical convergence.

Design Specifications

The proposed microwave filter was designed to satisfy the requirements of modern wireless communication front-end systems operating within the 4G LTE and sub-6 GHz 5G New Radio spectrum. The principal design objectives were: Low insertion loss within

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the passband, good impedance matching to a 50 Ω system, compact planar configuration, low cost and ease of fabrication using standard PCB technology and high passband selectivity. The filter dimensions were optimized to satisfy these electrical specifications while minimizing physical size and fabrication complexity.

Characteristic Impedance Design

Impedance matching is important for minimizing signal reflections and maximizing power transfer. The CPW dimensions were selected to realize a nominal characteristic impedance of 50 Ω, thereby ensuring compatibility with standard RF measurement equipment. The characteristic impedance of a CPW transmission line is expressed as (Simons, 2002):

$$Z_0 = \frac{30\pi}{\sqrt{\varepsilon_{eff}}} \frac{K(k')}{K(k)} \quad (1)$$

Where: (K(k)) is the complete elliptic integral of the first kind. (K(k')) is the complementary elliptic integral. (k) is determined by the conductor width and slot spacing. E_{eff} is the effective dielectric constant. The effective dielectric constant is approximated by

Resonator Design

The resonator dimensions were selected to produce resonance at the desired operating frequency while maintaining compact physical dimensions. The resonator length is determined by the equation (Balanis, 2016):

$$L_r = \frac{c}{2f_c\sqrt{\varepsilon_{eff}}} \quad (2)$$

Where: L_r is the resonator length. 'c" is the speed of light. f_c is the centre frequency.
Due to fringing fields and discontinuities that alter the electrical length of the resonator, the theoretical dimensions were subsequently optimised using CST Microwave Studio until the desired resonant frequency was obtained.

Coupling Mechanism

Energy transfer between adjacent resonating sections occurs through electromagnetic coupling generated by the spacing between the conductors. The coupling strength depends primarily on: gap spacing, overlap length, electric-field interaction, magnetic-

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field interaction. Reducing the spacing increases the coupling coefficient and broadens the passband, whereas increasing the spacing weakens the coupling and narrows the filter bandwidth. The coupling coefficient is expressed as (Cameron, 2018):

$$k = \frac{f_e^2 - f_o^2}{f_e^2 + f_o^2} \quad (3)$$

Where: f_e is the even-mode resonant frequency and f_o is the odd-mode resonant frequency.

This relationship provides a practical means of estimating coupling strength during the design stage.

Coplanar Waveguide Configuration

The filter was implemented using a Coplanar Waveguide transmission line because of its numerous advantages over conventional microstrip structures. In a CPW configuration, the signal conductor and the two ground conductors are fabricated on the same surface of the dielectric substrate, eliminating the need for plated through-hole vias and simplifying fabrication. The characteristic impedance of the CPW transmission line is determined by the conductor width, slot width, substrate thickness, and dielectric constant. Appropriate selection of these geometrical parameters ensures impedance matching with standard 50 Ω microwave measurement equipment and minimizes signal reflections. The final dimensions adopted in this work were obtained through iterative optimization in CST Microwave Studio to achieve the desired passband characteristics.

Table 1 and Table 2 show the physical dimensions of the CPW bandpass filter.

Table 1: Dimensions of the proposed filter.

Parameters	Symbols	Calculated Values	Optimized Values	Unit
Substrate Height	H	0.787	0.787	mm
Copper Thickness	t_r	0.0175	0.0175	mm
Resonator Length	L_r	55.702	55.702	mm
Resonator width	W_r	2.5418	2.5418	mm
Feeding Gap	G_f	0.2	0.900	mm
Resonator Gap	G_r	4.260	4.260	mm
Feed Line Width	F_w	4.8	3.200	mm
Feed Line length	F_L	8.094	8.094	mm
Ground width	G_w	7.000	7.000	mm
Total Filter length	L_f	74.1	74.1	mm
Total Filter Width	W_f	32.3	32.3	mm

Table 2: Dimension of the Interdigital Capacitor

Parameters	Symbols	Values	Unit
Number of fingers	N	7	mm
Finger width	W_f	0.3834	mm
Fingers Spacing	S_f	0.2556	mm
Length of fingers	L_f	2.130	mm
Terminal strip width	W_T	0.3834	mm
Input line width	W_{FI}	1.5194	mm
Output line width	W_{FO}	1.5194	mm
Output line length	L_{FI}	1.2212	mm
Finger end gap	G_{ef}	0.2840	mm
Total Capacitor length	L_c	5.2398	mm
Total Capacitor width	W_c	4.2174	mm

Layout of the Proposed Filter

The schematic consists of the three Combline resonators, loaded interdigitated capacitors, the coplanar ground plane of copper conductor and Ground-Signal-Ground

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(GSG) feedlines for SMA connector. Figure 3 and Figure 4 show the schematic design view of the PCB Combline bandpass filter components.

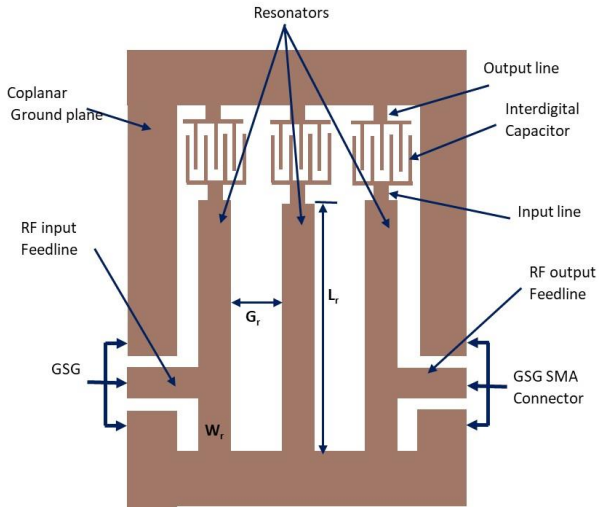

Figure 3: Schematic of the proposed Filter.

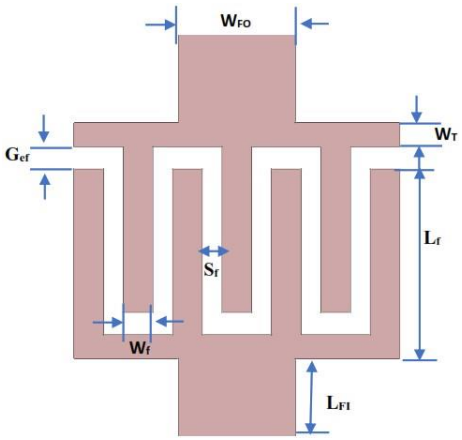

Figure 4: Loaded interdigital capacitor.

The interdigitated capacitor defines the number of fingers, finger width, spacing between fingers, length of fingers, terminal strip width, finger end gap, the input and output line width. Table 4 shows the physical dimensions of the interdigital capacitor. Figure 4 shows the loaded interdigital capacitor.

PCB Material Properties

A RT/Duroid 5880 substrate was selected for the model with copper conductor. Materials with predefined properties of the which includes conductivity, relative permittivity, relative permeability, and loss tangent have been selected and assigned from the material library to allow realistic practical model simulation. Table 3 summarised the principal substrate material properties.

Table 3: PCB Design Material Properties

Parameters	Symbol	Values	Unit
Dielectric substrate material	RT/Duriod	5880	-
Substrate permittivity	ε_r	2.2	-
Substrate thickness	H	0.031"/0.7878 0.062"/1.575	inc/mm
Copper thickness	t	17.5	µm
Minimum gap	G	10/254	mils/µm
Minimum width	W	10/254	mils/µm

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The dielectric substrate serves as the support and electromagnetic medium for the transmission line. Selection of the Duriod substrate significantly influences the resonant frequency, insertion loss, bandwidth, and impedance characteristics of the filter. The substrate was selected based on the following criteria: Stable dielectric constant, low dielectric loss tangent, good thermal stability, mechanical rigidity, availability, compatibility with PCB manufacturing. Copper cladding was employed on the substrate surface to realize the CPW metallization. The conductor thickness was selected to provide adequate current-carrying capability while minimizing conductor losses at microwave frequencies.

Model Creation and Optimization

The complete CPW filter geometry was designed in the CST studio using the optimised physical dimensions obtained during the preliminary design stage. The model is defined by primitive, assigned a unique name and material property corresponding to the selected substrate and copper metallization before simulation. Waveguide ports were introduced at both ends of the transmission line to excite the structure and to calculate the scattering parameters over the desired frequency range. Following the initial design, the CPW geometry was optimized to improve the overall filter performance. The optimization process involved systematic adjustment of: Resonator lengths, Conductor widths, Gap spacing, Feed line dimensions, Coupling distances, Ground plane dimensions. The optimization objective was to minimize insertion loss while maximizing return loss and maintaining the desired passband bandwidth. Figure 5 and Figure 6 represents the 3D view of the CPW bandpass filter.

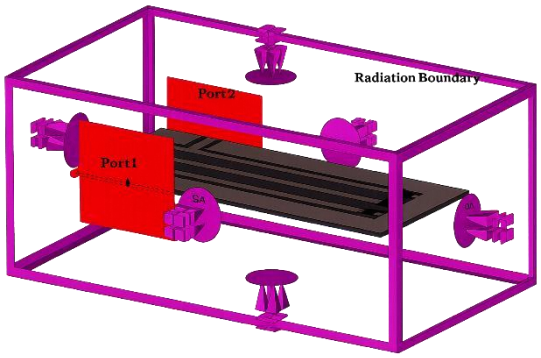

Figure 5: 3D view of the CPW bandpass filter.

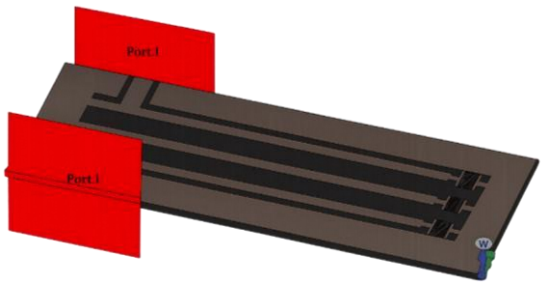

Figure 6: 3D view without the Radiation Box.

Figure 7 shows the top view of the PCB Combline bandpass filter. The filter size measures 74.1 by 32.3 mm on a Duroid substrate of height 0.787 mm. The structure is excited by input and output field lines using waveguide ports excitation. The waveguide ports have a dimension of 10mm x 10mm which was calculated using the CST port extension

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coefficient tool and is large enough to enclose the electric field around the port area. The field lines have a width of 3.2 mm and a feed gap of 0.9 mm on both sides of the feed line which provided the Ground-Signal-Ground(G-S-G) configuration. The open (add space) radiation boundary condition (metallic box around the 3D model) was used in the design.

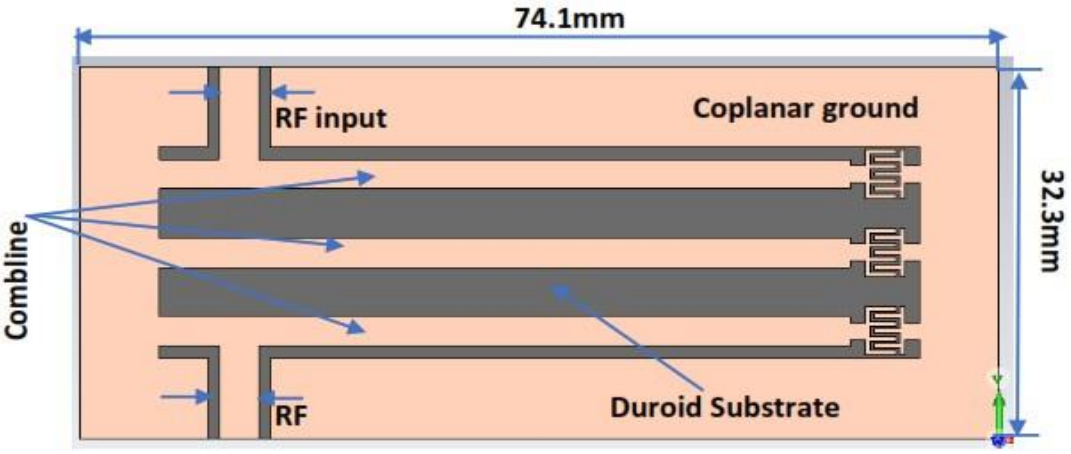

Figure 7: The top view of the PCB filter output

Figure 8 shows a cross sessional view of the filter clearly showing the Duroid substrate and the copper mentalisations. Figure 9 shows the back-side view. Unlike microstrip structures that require a ground plane on the reverse side of the substrate, the CPW back-view show that no ground plane needed and therefore the coplanar structure does not require via connection. Thus, the advantage of CPW over microstrip structure in terms of low cost, lightweight, ease of design and fabrication.

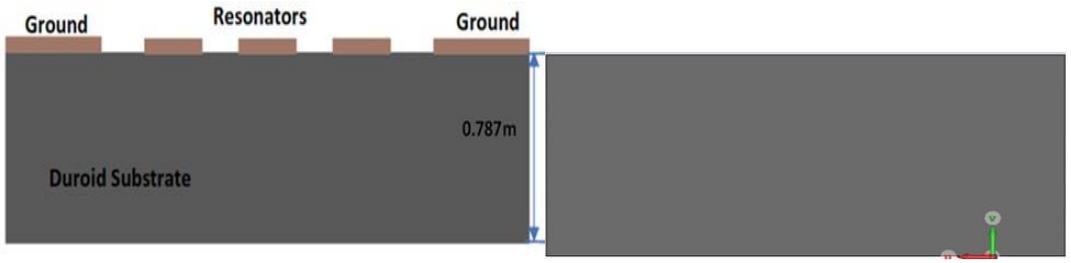

Figure 8: Cross-sectional view of the bandpass filter

Figure 9: Back side view of the bandpass filter

Analysis of the 3D Model Process

To analyse the model first a frequency sweep was defined (Min. frequency 0.0GHz; Max. Frequency 3.0GHz). This allows CST to generate the required solution within the specified range of frequency. The time domain solver parameters are also set for the accuracy level (-50dB). The inhomogeneous port accuracy enhancement is also checked. Finally, S-

parameter settings are set to normalize the port to a 50 ohms fixed impedance value. After all these settings were done, the model analysis was initialised, and the simulation results plotted to determine the S-parameter performance based on Finite Integration Technique solver.

Fabrication Process

After the simulation of the coplanar waveguide bandpass filter in CST, the next stage of the design process is the fabrication and experimentally characterised the fabricated device to verify the performance. The PCB fabrication process starts by tapping out the geometrical structure designed in CST in the Gerber file format. The Gerber (raw data) file format (RS274X) is used in the laboratory to print out the traces and components of the proposed device for artwork. The raw data with .gbr extension is edited and converted to job data with a file extension of .gbx using the GC power station software. A single sided PCB fabrication process is adopted. Figure 10 shows the single-sided PCB fabrication process adopted.

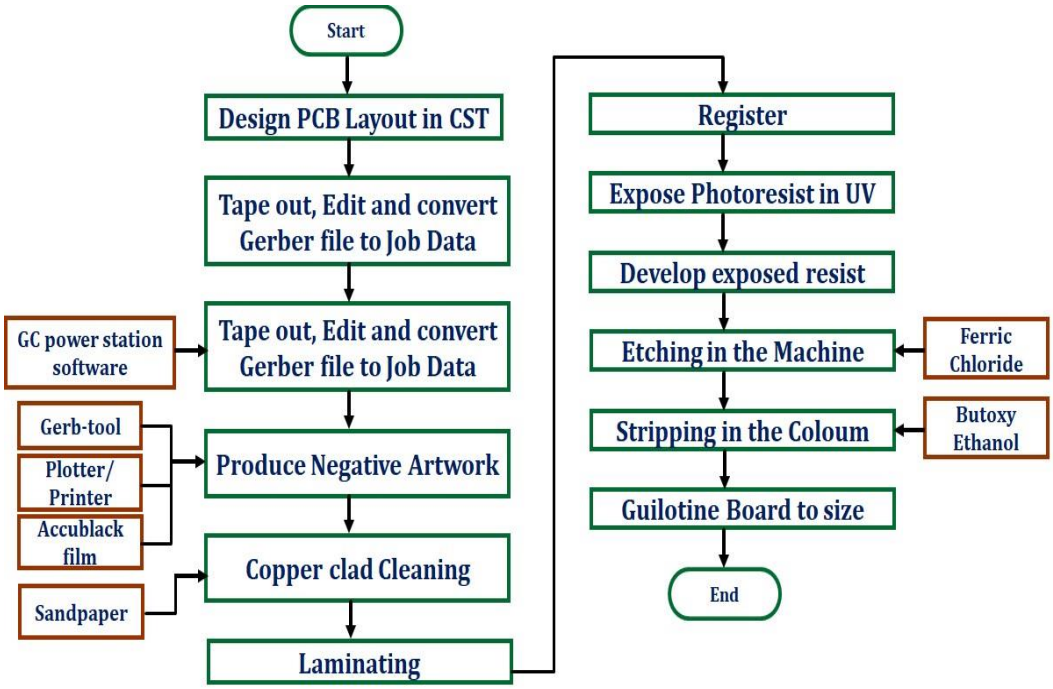

Figure 10: PCB fabrication process

Figure 11 shows the output of the GC power station. The job data is then utilized to produce the negative artwork which is known as the mask which has the PCB design printed on it using the gerb-tool software, the plotter/printer machine on Accublack film material.

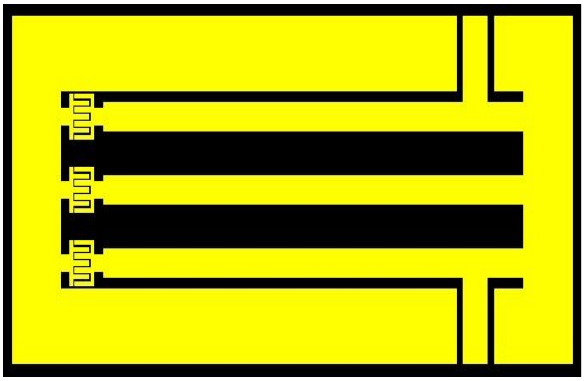

Figure 11: The output of the GC power station.

The output of the GC Cam power station is opened with a Gerb-tool to develop the negative artwork or film which is required to transfer the layout to photoresist film on the Duriod substrate (board). Figure 12 shows the development of the negative film using gerb-tool software. Figure 13 shows the negative film developed.

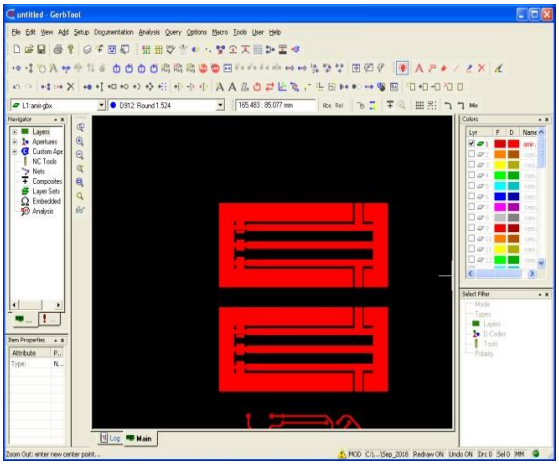

Figure 12: The development of the negative film.

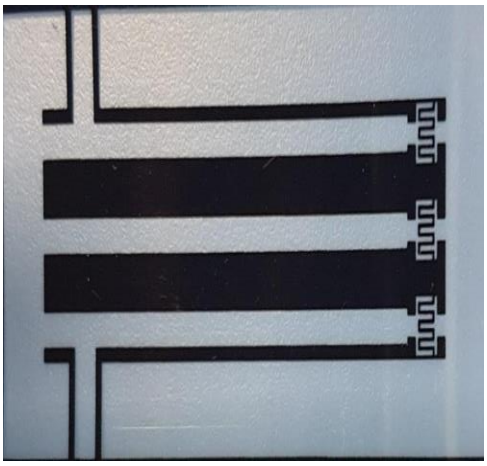

Figure 13: The negative film developed file.

After the negative film is developed, the Duriod roger substrate is then cleaned using a cleaner or sandpaper to ensure that the surface does not contain any grease, oxides or any moisture or traces to provide sufficient adhesion for the dry photoresist film before the laminating stage. The laminating stage requires a laminator machine and a photoresist film material. Figure 14 show the lamination of the Duriod board with a photoresist film.

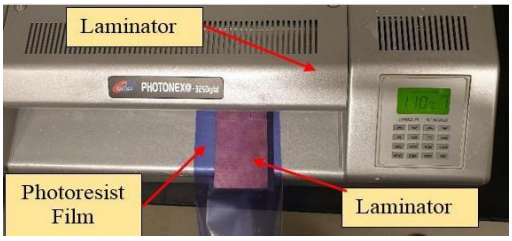

Figure 14: Lamination of the board with a photoresist film

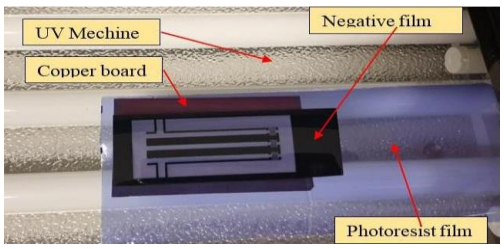

Figure 15: Register to expose photoresist to UV light.

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Figure 15 shows the register stage which exposes (makes transparent) the copper trace to the photoresist in the UV unit. The mask utilized for negative photoresist contains the inverse of the photographic "negative" of the pattern to be transferred. The exposure to UV light causes the negative resist to become polymerized and more difficult to dissolve. In order words, the areas of the copper board covered by the dark areas of the negative resist where UV cannot penetrate becomes soft and the transparent area becomes hard. After exposing the photoresist to UV unit for 30 seconds, the exposed resist (hard portion) is developed in developer solution (ethanol) for 3-5 minutes at 30°C. The developer stage removes the unexposed area (Soft portion) of the photoresist film to UV. This develops the layout on the copper board. The next stage is the etching of the copper from the board in the etching machine using ferric chloride. This takes approximately 6-8 minutes at 45°C. The final stage of the PCB fabrication involves the photoresist stripper or column using the butoxy ethanol. Lastly, the board is cut to size. The last part of the fabrication is the soldering of the SMA connector to the fabricated device for measuring the input and output RF signal and analysis of the performance of the device.

The Fabricated Bandpass Filter

Figure 16 and Figure 17 show the fabricated PCB Combline bandpass filter with the input and output connected straight 50 Ω flange mount SMA connectors, connected to the Ground-SignalGround (GSG) which are required for RF input/output and measurement of performance of the filter. The signal pins of the SMA connectors are connected to the tapped feedlines of the first and last resonators of the Combline bandpass filter. The two top arms are connected to the twowaveguide coplanar ground planes.

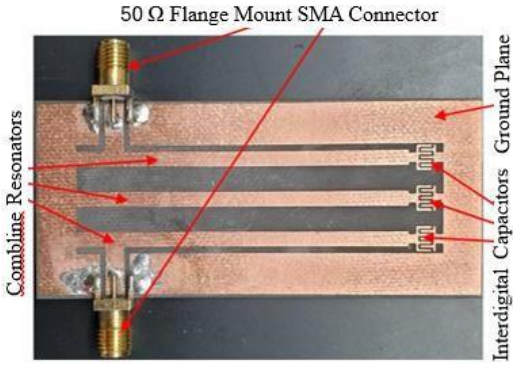

Figure 16: The fabricated bandpass filter

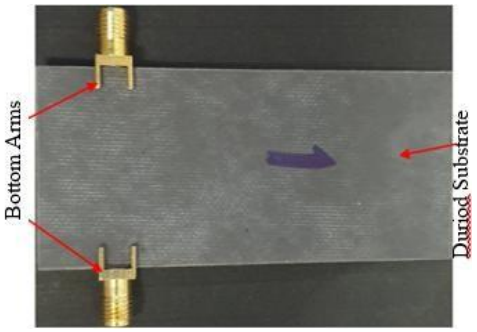

Figure 17: Back view of the fabricated filter

The backside view shows that there is no ground plane on the reverse side of the substrate, therefore vias interconnect/holes were not used during the fabrication of the

coplanar waveguide bandpass filter structure. The absence of via interconnect/holes simplified the fabrication process, reduces the cost of fabrication and losses.

Experimental Characterization

After the fabrication process was completed, the fabricated device was characterised by verifying and testing the device for performance which includes visual inspection or viewing closely the morphology of the device by checking the filter structural features such as length, width, and gaps. This is to ensure that all unwanted copper was removed, and the various components are well defined, and gaps of the interdigital filter are well spaced. The connectivity test was also done to ensure that all the components are interconnected as expected in the model design and simulation.

RF Experimental Measurement

The RF measurement is the final important experimental characterisation of the fabricated CPW bandpass filter using a calibrated Vector Network Analyzer (VNA). This characterisation was done to test and measure the performance or transmission characteristics of the filter in terms of Sparameter determination such as the S_{11} (Return Loss) and S_{21} (Insertion Loss) and the operating centre frequency. Prior to measurement, a two-port calibration procedure was performed to eliminate systematic measurement errors associated with cables, connectors, and adapters.

The fabricated Combline bandpass filter was measured using the experimental setup based on the flow chart shown in Figure 18. The experimental measurement setup consists of: Agilent Technologies E8363C PNA Network Analyser (10MHz - 40GHz), 85056D calibration kit, SCW2F2M040-F1 Coaxial (Radio Frequency) RF Cable, straight 50 Ω Flange Mount SMA Connector as shown in Figure 19.

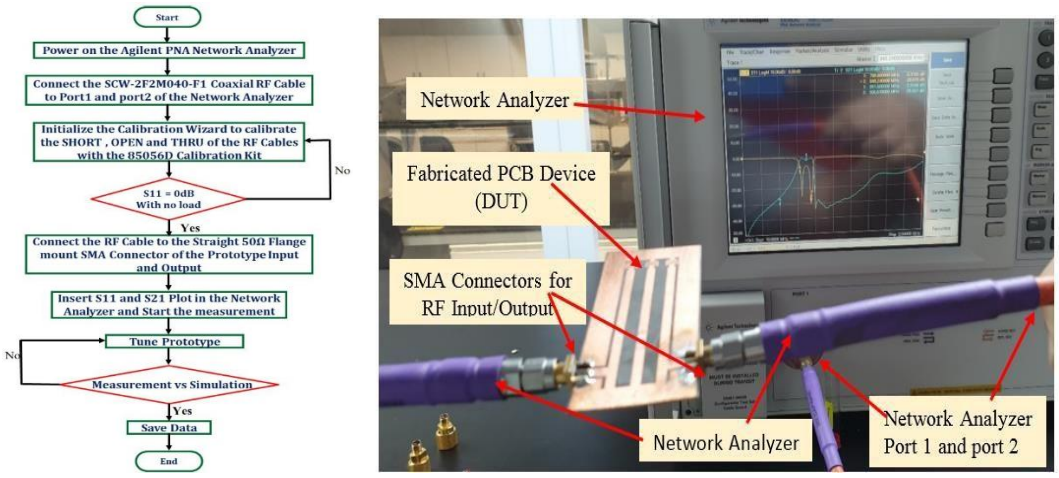

Figure 18: Flow chart of RF experimental measurement

The calibration of the network analyser was done under four conditions: short-circuit, open-circuit, fixed load condition and through connection. The prototype is measured with a frequency range of 0.01 GHz to 2.5 GHz at a centre frequency of 0.88 GHz. A piece of copper tape was used to tune the response. The S_{11} and S_{21} data were recorded when the measured and simulated response are in good agreement.

The Finite Integration Technique Simulation Result

Figure 20 shows the attenuation against frequency response of the FIT simulation result of the Combline bandpass filter with the transmission and the reflection coefficient which represents the S-parameters performance characteristics of the filter. It can be seen from the response plot that there are three reflection poles in the passband of the filter which represents the 3rd order Combline bandpass filter.

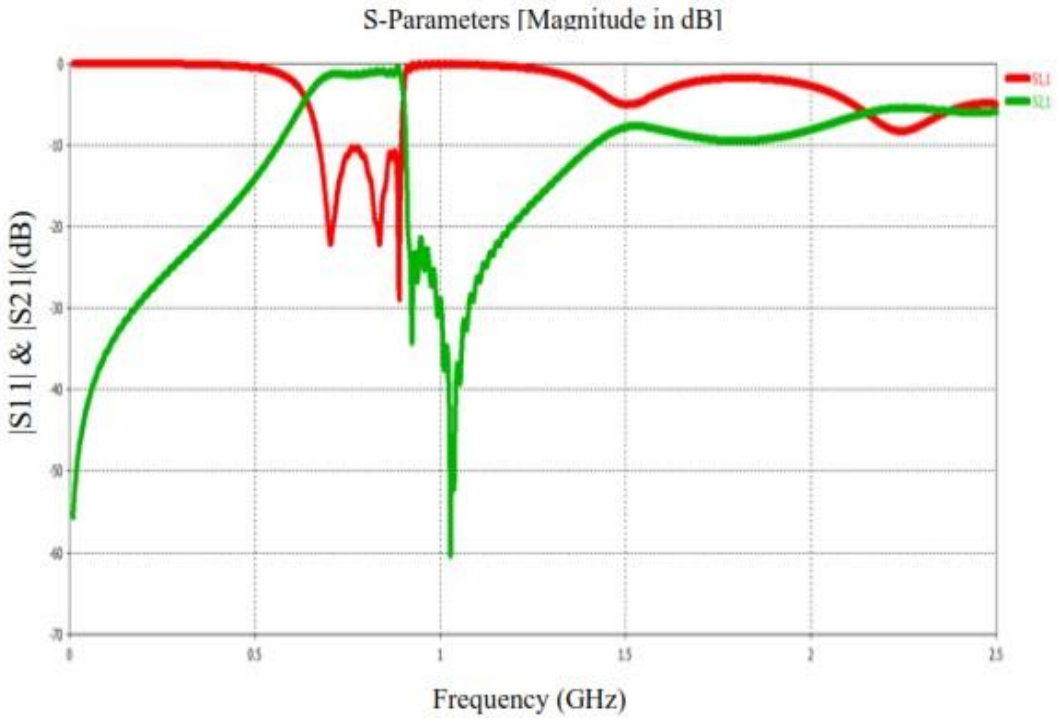

Figure 20: S-parameter simulation response of the bandpass filter.

As shown in Figure 20, the simulated S-parameter insertion loss (S_{21}) of the filter is 0.5 dB and the return loss (S_{11}) is better than 10dB. The lower passband edge frequency is at DC while there is a transmission zero (attenuation pole) at the upper passband frequency. The bandpass filter centre frequency is at 0.80 GHz. The simulated rejection of the bandpass filter at DC is 56 dB and 60.5dB at 1.25 GHz. The bandwidth measured at equal ripples of the reflection poles in the passband is 250 MHz (650 MHz - 900 MHz).

Parametric Optimization Results

Figure 21 shows the plot of the resonator length against the corresponding frequency. This shows that the longer the length of the resonator, the lower the frequency and shorter the length of the resonator, the higher the frequency.

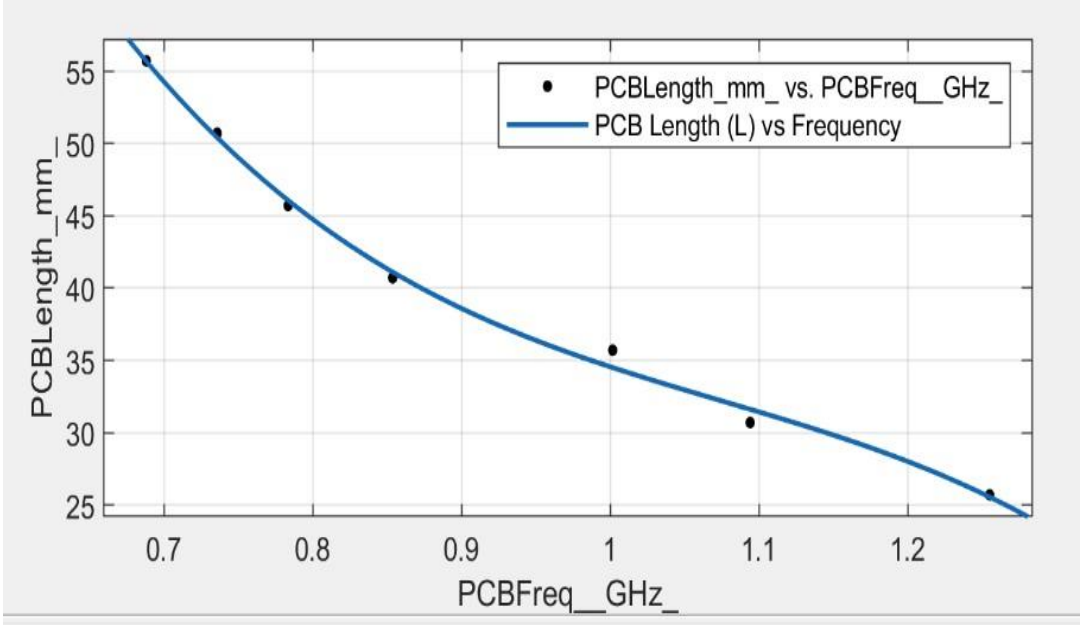

Figure 21: Plot of the Resonator length against the frequency

Figure 22 shows the attenuation against frequency response of the filter with the transmission and the reflection results as the length is varied. The response shows that, as the length is varied, the center frequency changes.

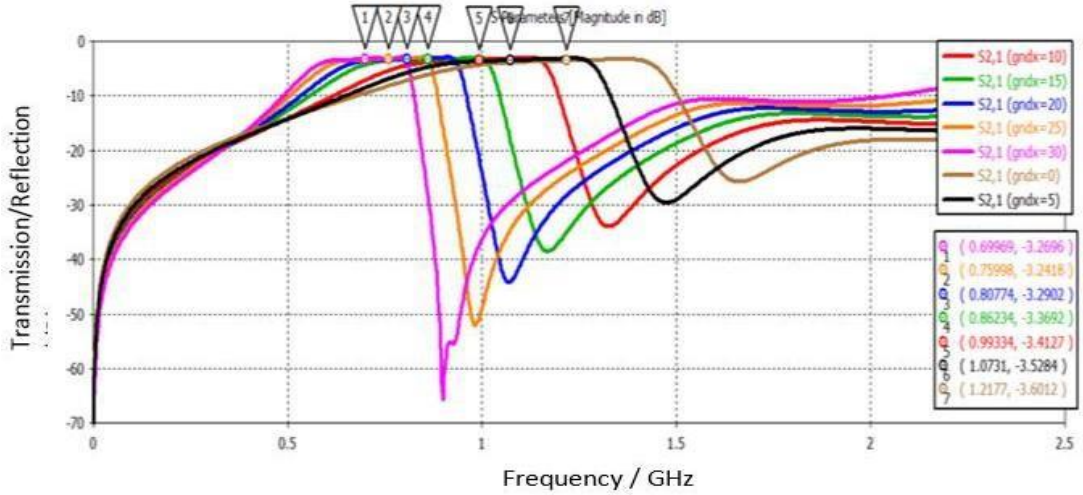

Figure 22: Effect of change in length on the centre frequency.

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Experimental Validation Measurement Result

This section presents the experimental measurement results of the fabricated coplanar waveguide Combline bandpass filter. The designed layout from the CST generated in Garber file format was fabricated at the Universiti Teknologi PETRONAS PCB Lab. The characterisation, test and measurement of the PCB prototype coplanar waveguide bandpass filter are also performed at the Universiti Teknologi PETRONAS characterisation laboratory. Figure 23 shows the attenuation against frequency response of the fabricated PCB coplanar waveguide Combline bandpass filter result with the transmission and the reflection coefficient which represents the S-parameters performance characteristics of the filter. It can be seen from the response plot that there are three reflection poles in the passband of the filter which represents the 3rd order Combline bandpass filter.

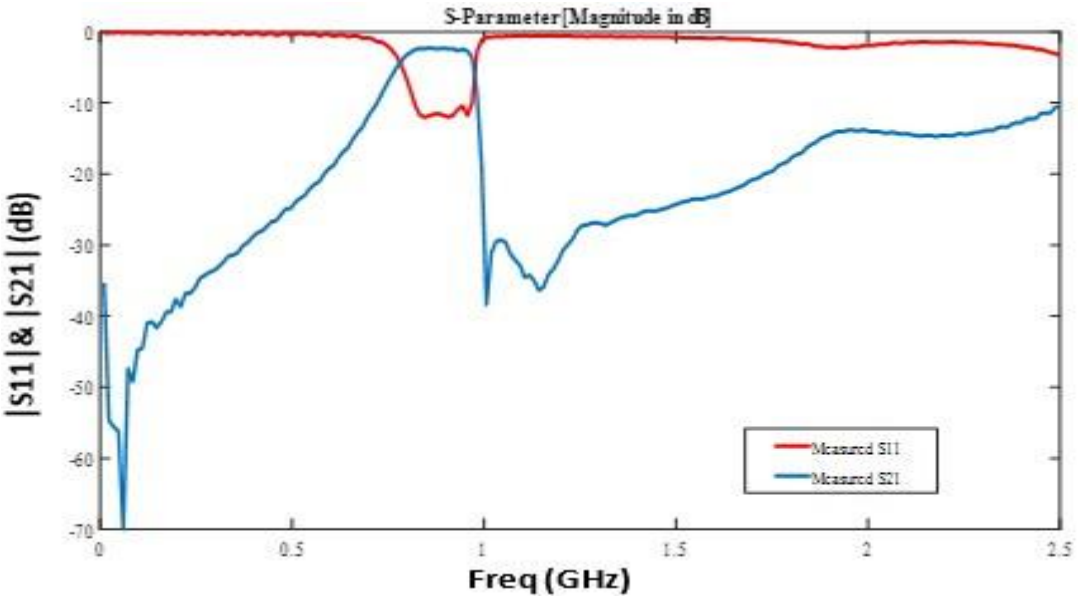

Figure 23: Measured S-parameter of the fabricated Combline bandpass filter

The measured S-parameter results insertion loss (S21) of the fabricated prototype filter is 2 dB and the return loss (S11) is better than 11 dB. The lower passband edge frequency is at 0.01 GHz while there is a transmission zero (attenuation pole) at the upper stopband frequency at 1GHz. This transmission zero at the upper passband edge causes a high selectivity in the upper stopband frequency. This can be attributed to the tight coupling between the adjacent resonators. The centre frequency is at 0.88 GHz. The measured rejection of the bandpass filter at lower edge frequency is better than 60 dB and 38.5dB at the upper stopband frequency. The bandwidth measured at equal ripples of the reflection poles in the passband is 162 MHz (832 MHz - 994 MHz).

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Comparison Between Simulated and Measured Responses

The comparison of the simulation and measurement result is shown in Figure 24. The result shows a good agreement as can be interpreted from the figure. The shift in the measured centre frequency from 0.80 GHz to 0.88 GHz can be attributed to two factors: fabrication tolerances and port definition in the simulated structure.

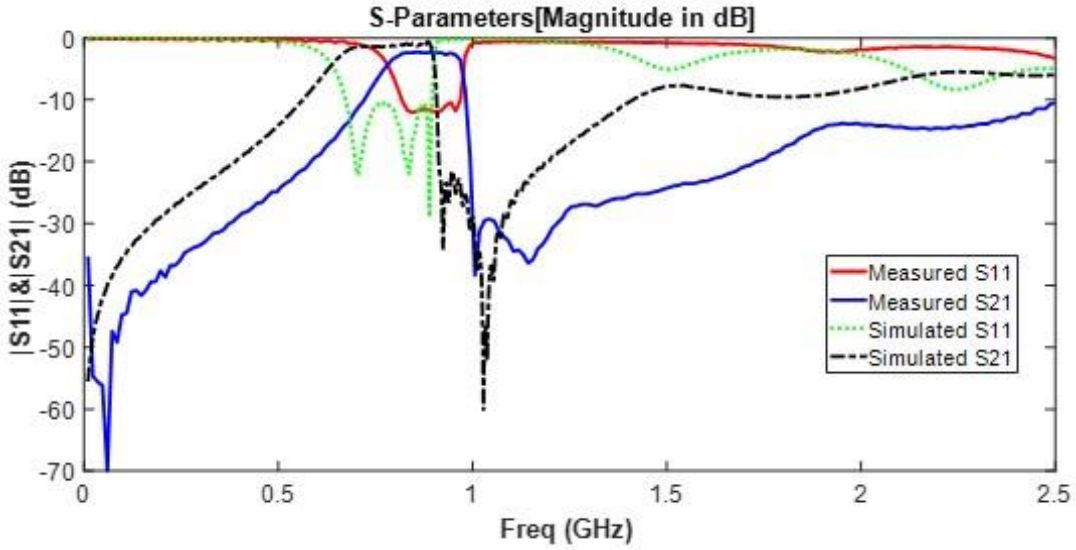

Figure 24: Comparison of simulated and measured result

Performance Evaluation

The performance of the proposed filter was evaluated using the principal microwave filter performance metrics summarized in Table 5.

Table 5: Experimental Performance Summary

Performance Parameter	Simulated	Measured
Center frequency (GHz)	0.80	0.88
Return loss (dB)	10	11
Insertion loss (dB)	0.5	2
3-dB Bandwidth (MHz)	250	162
Upper edge frequency (MHz)	900	994
Lower edge frequency (MHz)	650	832
Fractional bandwidth (%)	312.5	184
Lower Edge Rejection (dB)	56	60
Upper Edge Rejection (dB)	60.5	38.5
Characteristic impedance (Ω)	50	50

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The comparison indicates that the fabricated filter satisfies the principal design objectives established during the simulation stage.

Comparison with Published CPW Filters

To evaluate the performance of the proposed bandpass filter, its performance was compared with representative CPW bandpass filters reported in the literature.

Table 6: Comparison with Representative CPW Bandpass Filters

Reference	Technology	Operating Band (GHz)	Insertion Loss (dB)	Return Loss (dB)	Fabricated
Abada, 2026	CPW	20 - 30	2	24	Yes
Udhayasuriyan, 2022	CPW	2.23–4.2	0.2	30	Yes
Chen, 2020	CPW	8.8 - 17	0.2	15	Yes
Wen, 2020	CPW	3.29 - 3.79	2	10	Yes
Al-Naib, 2010	CPW	1 - 6	1.71	14.8	Yes
Ye, 2008	CPW	3 - 5	1	-	Yes
This Work 2026	CPW	0 - 3	2	11	Yes

The proposed filter compares favourably with previously reported designs by combining compact geometry, low-cost PCB fabrication, practical experimental validation, and satisfactory scattering parameters performance.

Discussion

The results demonstrate that full-wave electromagnetic simulation using CST Microwave Studio provides an accurate and reliable platform for the design of compact CPW bandpass filters. The optimization process successfully minimized insertion loss while maintaining satisfactory return loss and passband selectivity.

The fabricated prototype confirmed that standard PCB manufacturing techniques can be used to realize high-performance microwave filters without the need for expensive multilayer substrates or complex fabrication processes. Although small differences between simulated and measured responses were observed, these deviations are within the range typically reported for practical microwave filter implementations and do not significantly affect the intended operation of the device.

The successful validation of the proposed filter highlights the suitability of CPW technology for integration into modern RF front-end modules used in 4G LTE and sub-6 GHz 5G New Radio communication systems. The combination of compact size, ease of fabrication, and good electrical performance make the proposed design a practical

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candidate for wireless communication equipment, Internet of Things (IoT) devices, and other microwave applications.

Overall, the experimental investigation confirms that the proposed CPW bandpass filter achieves the desired performance objectives and validates the effectiveness of the combined full-wave simulation, PCB fabrication, and experimental characterization methodology adopted in this work.

CONCLUSION

This paper presented the design, simulation, fabrication, and experimental characterization of a PCB Coplanar Waveguide (CPW) Bandpass Filter intended for application in contemporary wireless communication systems, particularly 4G LTE and sub-6 GHz 5G NR front-end circuits. The study combined microwave filter design principles with full-wave electromagnetic simulation using CST Microwave Studio and practical validation through PCB fabrication and Vector Network Analyzer (VNA) measurements.

Full-wave electromagnetic simulation was employed to analyse the scattering parameters and resonance characteristics. The optimized design was subsequently fabricated using conventional PCB manufacturing techniques and experimentally characterized under controlled laboratory conditions. Experimental measurements demonstrated good agreement with the simulated results, thereby validating both the electromagnetic model and the adopted design methodology. The results further demonstrate that Coplanar Waveguide technology offers several practical advantages over conventional planar transmission-line structures for microwave filter realization.

One of the principal contributions of this work is the successful integration of full-wave electromagnetic modelling, practical PCB implementation, and experimental validation. The work demonstrates the practical realization of the proposed CPW bandpass filter and provides measured results that verify its performance under realistic operating conditions.

The satisfactory agreement between simulation and experimental measurements confirms the effectiveness of the adopted design methodology and supports the suitability of the proposed filter for deployment in RF front-end modules for 4G LTE and sub-6 GHz 5G New Radio applications.

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