

AN X-BAND COPLANAR WAVEGUIDE HYBRID LOWPASS FILTER WITH A COMPACT DESIGN

Dr R VENKATESH, RANI MATHEW, SANIYA SALIM, SHELJA JOSE

Department of Electrical and Electronic Engineering,

INDIRA GANDHI INSTITUTE OF ENGINEERING AND TECHNOLOGY

NELLIKUZHI P.O, KOTHAMANGALAM, ERNAKULAM (DIST) PINCODE 686691

Abstract

The article outlines the design of a small coplanar waveguide lowpass filter in the X band. The lowpass filter has a cutoff frequency of 10 GHz at which the signal is attenuated by 3 decibels. The small size is accomplished by the usage of localised surface mount capacitive loading. The use of localised loading capacitors for miniaturisation has been shown to be effective at high frequencies, marking the first instance of its successful utilisation. The developed hybrid filter demonstrates superior performance and a reduced physical footprint compared to commercially available filters that were used for comparison.

Keywords—Coplanar waveguide technique, compact lowpass filter, miniaturisation, semi-lumped, X-Band

Introduction

In microwave communication systems, lowpass filters are used in RF system design. Due to their simplicity, compactness, and cheap cost, planar filters are ideal for commercial applications and may be made using PCB technology.

Filters have focused on small size and good performance as wireless communication systems have advanced. Several miniaturisation methods exist. The most common methods include high permittivity substrates [1]-[5], tilting, folding, and meandering [6]-[7], and hybrid [8]-[15]. The next paragraphs explain the three categories.

Research suggests that substrates with high relative dielectric permittivity ($\epsilon_r > 20$) may achieve a miniaturisation rate of around 45%. [1]-[5]. The limitations of high permittivity substrates include bandwidth decrease, high cost, and difficulties obtaining high impedances. High impedances are crucial for good electrical properties.

However, meandering helps get smaller gadgets. However, this method increases circuit complexity [6]-[7]. Additionally, parasitic coupling effects of surrounding parts should be considered while designing, which might increase circuit complexity. Researchers found 50% miniaturisation using this method. Thirdly, the hybrid technique is popular owing to its simplicity. Transmission lines are loaded with lumped components (primarily capacitors) [8]-[15]. Usually called the “semi-lumped” technique. Miniaturisation is the principal benefit of the semi-lumped technique over the scattered approach (just transmission lines). Compared to the lumped technique (just capacitors and inductors), it avoids the normalised value issue. This study uses the semi-lumped technique for these reasons. In [8]-[9], lumped capacitors were added to

a transmission line to increase its characteristic impedance and minimise its length and device size. The transmission cables might have capacitors in the centre [8] or at the ends [9]. Inductors may replace capacitors, but their quality factor is low, particularly at high frequencies [9].

Miniaturisation using localised surface mount components (SMC) works well for frequencies up to 2-3 GHz. To the authors' knowledge, no research have investigated localised SMC for higher-frequency miniaturisation.

A small lowpass filter with a 3-dB cutoff frequency of 10 GHz is constructed in this study. For high-frequency performance, coplanar waveguide technology (CPW) is used.

Organisation of the paper: Section II presents the design of a hybrid lowpass filter with a cutoff frequency about 10 GHz. Section III presents and discusses fabrication and measurement data. Next, the developed filter is compared to commercial lowpass filters.

Hybrid Lowpass Filter

A. Employed Topology

Several semi-element topologies have been suggested. The topology in [8] reduces filter size efficiently. In [8], authors suggested using SMC capacitors to load transmission line portions in the middle. The equation for loading capacitance based on transmission line parameters is presented in [8]. Several 1 GHz lowpass filters were conceived, built, and tested. Good qualities of the filters include compactness, return loss, insertion loss, shape factor (selectivity), and spurious suppression. This study uses this structure to construct a 10-GHz lowpass filter with a 3-dB cutoff frequency. However, SMC capacitors have parasitic effects at high frequencies. In the next paragraph, a capacitor model is proposed and verified for filter design.

B. Modelling SMC Capacitors

When considering high frequencies, it is important to consider the parasitic effects of lumped devices such SMC capacitors. Above a predetermined nominal frequency, lumped components may cause significant design issues. To ensure precise design, simulate the soldering pads for capacitors. Numerous SMC capacitor types were described by researchers [16-18]. This study used the series RLC model. The model is based on other models [16-18]. Fig. 1 shows its simplicity and efficiency. A parasitic series resistance (R_s), inductor L_s , and shunt resistance (R_p) are utilised to simulate each SMC capacitor. These components consider high-frequency parasitic effects. A series inductor L_s represents the conduction and displacement current densities in the capacitor's metallic and dielectric components, which contribute to the surrounding magnetic field. R_s represents dielectric and Ohmic losses in the capacitor, also known as equivalent series resistance (ESR). The shunt resistance (R_p) measures coupling losses between capacitor electrodes. R_p levels are often high, even at high frequencies. When simplifying the model, R_p may be ignored. Measurement findings will validate the previous judgement.

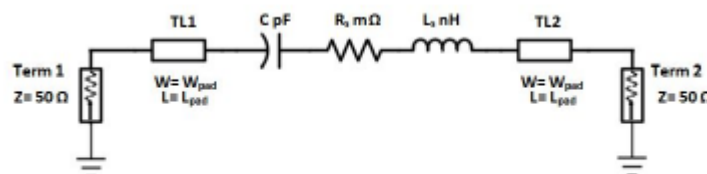


Fig. 1. Capacitor equivalent model.

For SMC capacitor soldering pads, we suggest modelling them as short transmission lines. Transmission lines representing pads should be less than $\lambda/10$ in length. The decision is reasonable since

pads are often extensions of lossy transmission lines. Neglecting pad parasitic effects affects EM wave propagation and design.

Fig. 1 displays the applied parasitic model for the SMC capacitor with a nominal capacitance of C (pF). In this scenario, the capacitor is linked in series between input and output ports. The model is created using the circuit simulator advanced design system (ADS). When simulated for frequency response, the capacitor circuit model will have a low impedance at the self-resonant frequency (SRF). The SRF may be calculated analytically using capacitance C and series parasitic inductance (L_s). At the SRF, the capacitive and inductive reactance values are identical ($1/2\pi fC = 2\pi fL_s$).

At frequencies exceeding the SRF, capacitors act as inductive devices and cannot be used. The capacitor model is derived from measurements by fitting parasitic element values R_s and L_s from Fig. 1. As illustrated in Fig. 2, the SMC capacitor is welded in the centre of a CPW transmission line between the main conductor and ground plane for measurements. This SMC capacitor features a 0.2 pF capacitance and a 0603 case size. This capacitance value is important for the LPF design in the next paragraph. The transmission line used for CPW has a modest impedance of 50. These arrangements ensure accurate model extraction. Remember that using SMC capacitors without appropriate modelling might lead to design imprecision.

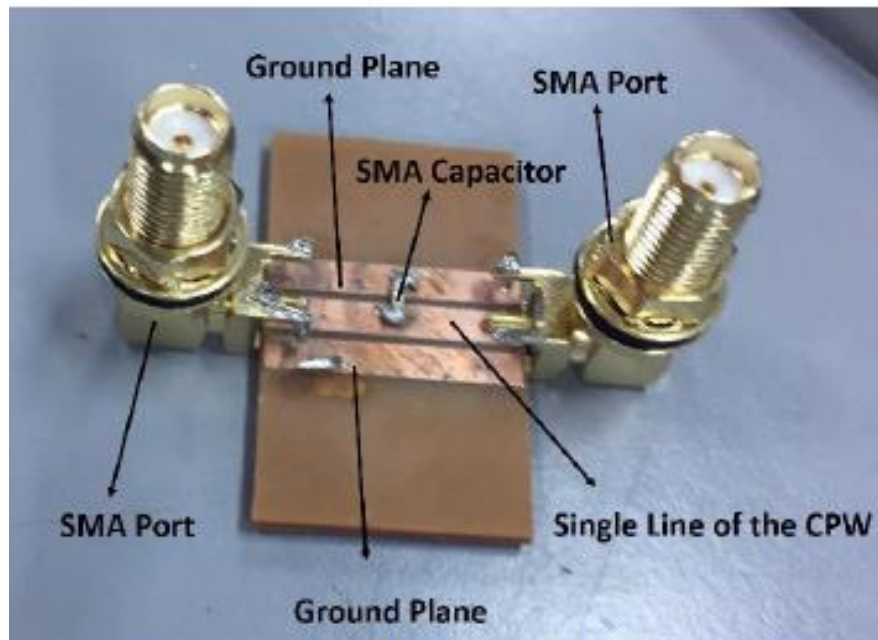


Fig. 2. Photograph of the soldered capacitor.

TRL (thru, reflect, line) calibration was done before readings. The S-parameters of the loaded transmission line were retrieved up to 13.6 GHz using the Rohde&Schwarz ZVL vector network analyzer. The next phase was fitting measurement data to model simulations by adjusting R_s and L_s values. Fig. 3 compares S-parameters from observations and model simulation.

Optimal match occurs with $L_s=0.78$ nH and $R_s=530$ m Ω . Note that the SRF of these capacitors does not show in the examined frequency region. These capacitors are safe for usage in the Xband frequency range. The process is repeated for another capacitance value. The value is 0.15 pF. See Fig. 4 for the capacitor

model optimisation findings. The figure compares S characteristics from measurements and model simulations of the 0.15 pF SMC capacitor (case size 0603).

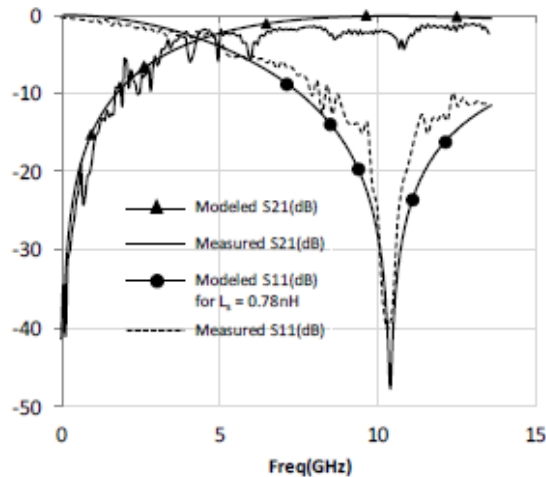


Fig. 3. Comparison of S-parameters of the 0.2 pF capacitor: Measured and modeled.

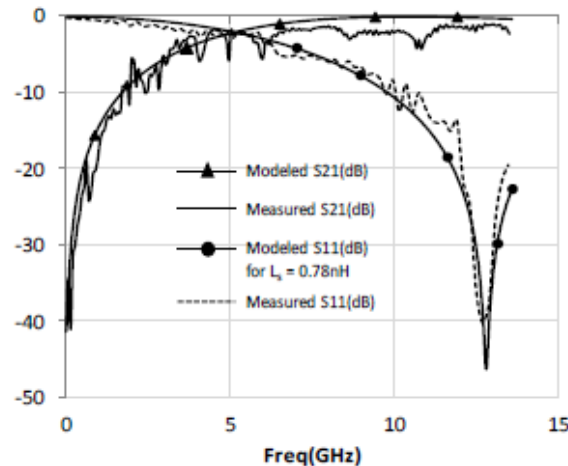


Fig. 4. Comparison of S-parameters of the 0.15 pF capacitor: Measured and modeled.

This capacitance value is important for the LPF design in the next paragraph. The series inductance L_s was measured at 0.78 nH, and the corresponding series resistance R_s was 580 m. The L_s value is the same as the previous 0.2 pF capacitor. Logic dictates that the value of L_s is determined by the case size and dimensions of the SMC (0603 in this example). As before, the SRF is absent from the band of interest. The dielectric and Ohmic losses in a capacitor, known as the equivalent series resistance (ESR), are determined by the capacitance value and manufacturing precision.

Lowpass Filter Design

The intended filter template is lowpass with a 3-dB cutoff frequency approximately 10 GHz. Commercially available filter RLPF13G09 from RF-LAMBDA© will be compared to the developed filter.

To ensure comparability, the lowpass filter template should have an insertion loss of no more than 1 dB at half the cutoff frequency f_c , and spurious should not occur until at least twice the cutoff frequency. Ensure the filter is matched (return loss < -10 dB inside working passband) and has a cutoff roll selectivity over 50 dB/GHz. The design includes both localised and dispersed features. To function in the X-band, a capacitor is used as the localised component. The rationale is because capacitors have greater quality factors than inductors. The goal is to increase the frequency of lumped SMC parts by proper design (technology and topology).

We use coplanar waveguide (CPW) technology. CPW technology is used because to its lower frequency dispersion compared to microstrip technology, particularly for thin transmission lines with high characteristic impedances. For CPW transmission lines, ground planes on both sides of the strip prevent the requirement for via holes, which need accurate modelling at high operating frequencies. The filter is constructed on Rogers RO4003® substrate with properties such as dielectric constant $\epsilon_r=3.55$, height $h=813$ μm , metal thickness $t=35$ μm , and loss tangent $\tan\delta = 0.0027$.

The suggested filter's ideal schematic is in Fig. 5. The filter has six components, establishing its order (sixth order). The sequence is adequate for achieving the desired high roll-off selectivity. Each basic part consists of two perfect transmission lines and a capacitor. For simplicity, the capacitor is connected in the centre of the transmission lines. The parasitic model of capacitors is not examined in this exploratory study. Taperization is employed to provide optimal passband matching features (Fig. 5). Taperization breaks topological periodicity by altering section characteristics at filter input and output. Taperization is performed by adjusting transmission line length (1, L_1) and/or loading capacitance (C_1) at the near and far end portions. In contrast, the intermediate parts have identical electrical length θ_2 (matching to physical length L_2) and are filled with capacitors of the same capacitance value C_2 . The characteristic impedance Z_c of all transmission line sections (middle, near, and far ends) is the same. To reduce filter size, consider using high characteristic impedance values. Due to manufacturing constraints, the maximum transmission line impedance is restricted to 120 Ohms, equating to a 0.25 mm width (W) and 1.3 mm gap (G) on the substrate. Ground plane homogeneity requires identical width W and gap G values for all transmission lines.

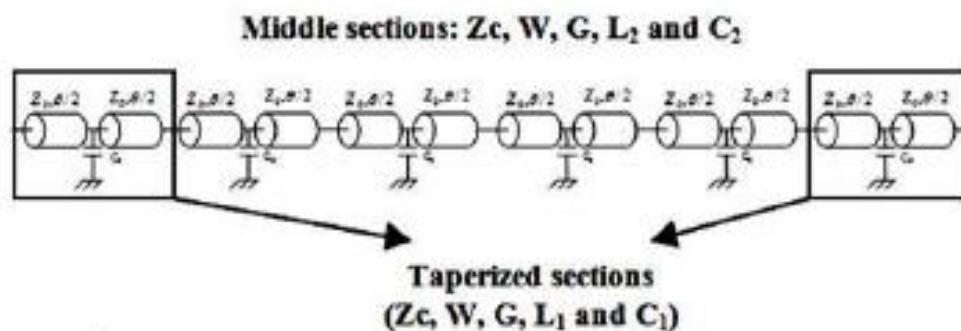


Fig. 5. Schematic of the sixth order lowpass filter.

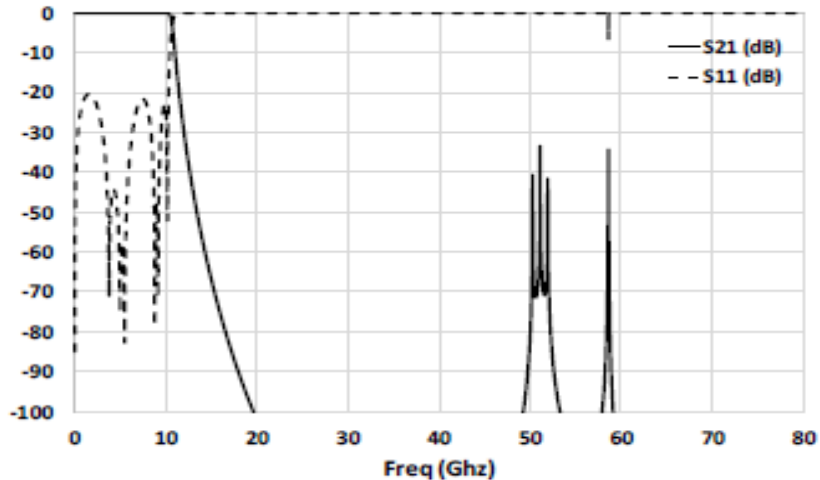


Fig. 6. Preliminary results of the return loss S11 and the insertion loss S21 in dB of the lowpass filter.

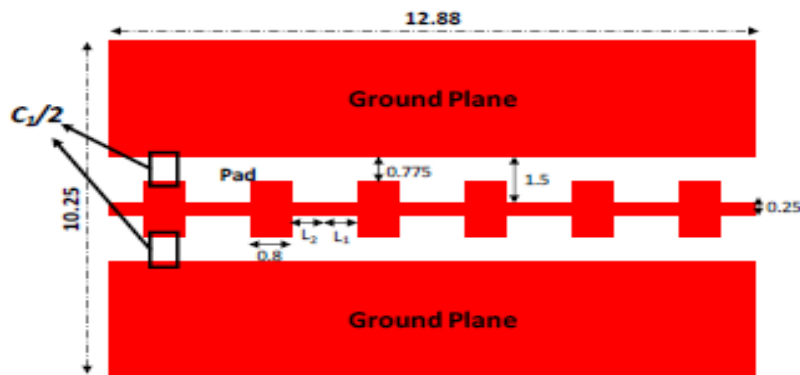


Fig. 7. Layout of the CPW lowpass filter (dimensions in mm).

As seen in Fig. 6, the first optimisation does not account for all manufacturing constraints or parasitic effects. The optimised values for L_1 , L_2 , G , W , C_1 , and C_2 are 0.96 mm, 1.29 mm, 5 mm, 1.64 mm, 0.42 pF, and 0.49 pF. Simulation results match template. The passband has better than 20 dB matching and no spurious response in the big band. Although encouraging, these findings should be considered due to significant impacts. At high frequencies, it is important to consider the parasitic effects of capacitors and soldering pads. The capacitance values must also be normalised.

The filter is optimised to suit the template by adjusting transmission line lengths and C_1 and C_2 values. The new optimisation addresses capacitor and pad models, as well as manufacturing restrictions. To get more accurate findings, the electromagnetic simulator Momentum of ADS is used for optimisation. Refer to Fig. 7 for the optimised lowpass filter architecture (mm dimensions). Note that not all capacitors are shown for clarity. Only C_1 towards the end is seen.

In Fig. 7, there are two parallel capacitors connected across the primary transmission line for C1. Doing this promotes a balanced response and reduces the impact of parasitic capacitor parts. The lowpass filter is intended to have reduced insertion loss. The capacitors have the same values as in the preceding section: $C1/2 = 0.15$ pF (taperized parts) and $C2/2 = 0.2$ pF (middle sections). The simulation results are in Fig. 8. The cut-off frequency is 9.7 GHz, return loss is -16 dB, spurious emerges at 25 GHz, and insertion loss is 0.11 dB at half the cut-off frequency and less than 0.5 dB till 9 GHz. Also, the filter has a cutoff roll selectivity of 65.8 dB/GHz. After meeting the template, the filter is made and measured for validation.

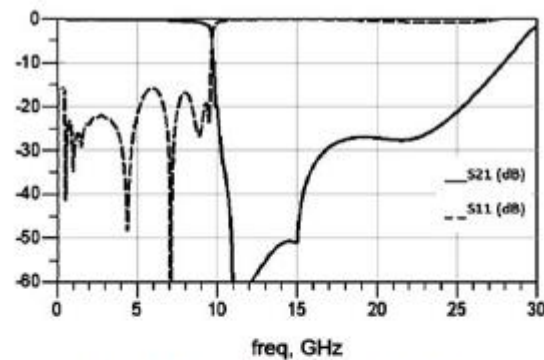


Fig. 8. Momentum Simulation Results.

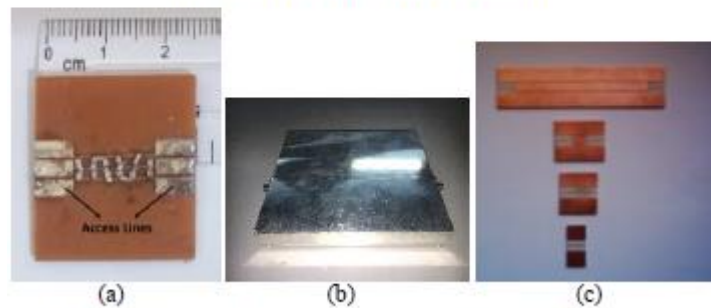


Fig. 9. Fabricated devices: (a). the realized hybrid lowpass filter (with access lines), (b). the tested filter with packaging, (c). TRL calibration set.

Fabrication and Measurements

Fig. 9 shows the filter constructed (a) and (b) and the TRL calibration kit required for measurements (c). Access lines were added to the filter's two ports for measurement. In Fig. 9 (a), the filter is shown without packaging. Figure 9 (b) shows the measured filter with packaging. The ROHDE & SCHWARZ vector network analyzer was used for measurements up to 13.6 GHz. Fig. 10 indicates a fair agreement between observations and models.

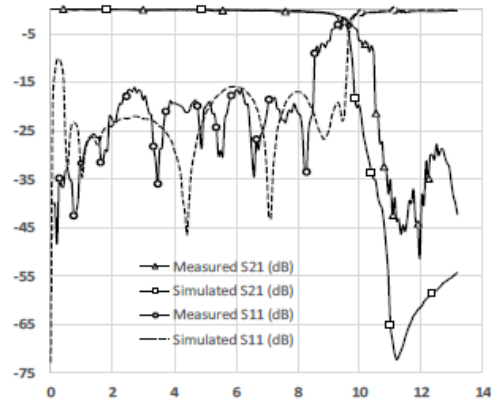


Fig. 10. Measured and simulation results of the return loss S11 and the insertion loss S21 in dB.

Fig. 10 indicates that SMC loading may be used to create small filters at high frequency (about 10 GHz) without affecting electrical performance. Surface-mounted capacitors and coplanar waveguide technologies provide compactness, performance, and cost savings. For performance assessment, the created filter is compared to a commercial one. RF-Lambda sells the filter. Choose the RLPF13G09 filter. Suspended Stripline technology was employed to create the filter. Naturally, this technology is more costly and difficult. It is also compared to state-of-the-art filters [19]-[21].

**TABLE I. COMPARISON BETWEEN DIFFERENT AVAILABLE FILTER AND
THE FILTER DESIGNED IN THIS PAPER**

Filter	[19]	[20]	[21]	RF- LAMBDA	This work
Bandpass (GHz) @ insertion loss < 1 dB	DC to 6 GHz	DC to 3.9 GHz	DC to 2.44 GHz	DC to 9 GHz	DC to 9.2 GHz
Insertion loss at $0.5 f_c$	-1 dB	-0.5 dB	-0.67 dB	-1 dB	-0.11 dB
Return loss (S_{11})	-12 dB	-13 dB	-17.7 dB	NA	-17 dB
Selectivity (dB/GHz)	12	79.5	67.27	60	65.8
Spurious ($S_{21} > -20$ dB)	35 GHz	18 GHz	16 GHz	16 GHz	25 GHz
Dimensions: $L \times W$ (mm ²) (with packaging)	22.9 × 7.5	16.8 × 7.55	17.4 × 10	26.92 × 22.09	12.88 × 10.25

Table I contrasts this paper's filter with recent ones. The comparison includes bandpass (GHz), insertion loss (dB) at half the cutoff frequency, return loss, selectivity (dB/GHz), spurious frequencies, and physical

dimensions. Both filters have a similar cutoff frequency as RF-LAMBDA. This filter has lower insertion loss than the RF-LAMBDA filter (-0.11 dB vs. -1 dB). Other filters in [19]-[21] have larger insertion loss than our design. The return loss (S11) values of all examined filters match better than 10 dB. It is correct that our work has greater out-of-band response because spurious occur at higher frequencies (25 GHz for our filter vs. 16 GHz for the RF-Lambda filter, [20] and [21]). Still, filter in [19] rejects out-of-band better. The suggested Lowpass filter is the smallest. The design is also the simplest. The lowpass filter offered has outstanding electric properties and optimal compactness. SMC components provide the filter exceptional electrical performance and compactness. These elements must be well-modeled for high-frequency use.

Conclusion

X-band small coplanar waveguide lowpass filters were designed. A 10-GHz lowpass filter has a 3-dB cutoff frequency. The small design uses localised surface mount capacitive loading components. Due to adequate characterisation, surface mount capacitors are efficient at high frequencies. Surface mount capacitors are small and electrically efficient. The developed hybrid filter was compared to a commercial filter with the same cutoff frequency. The comparison proved localised surface mount components' effectiveness at higher frequencies.

References

- [1] M. Farahani, M. Akbari, M. Nedil, A. R. Sebak, and T. A. Denidni, "Miniaturised circularly-polarised antenna with high-constitutive parameter substrate," *Electronics Letters*, vol. 53, no. 20, pp. 1343-1344, Sep. 2019.
- [2] Y. Liu, L. Shafai, and C. Shafai, "Split ring loaded dielectric resonator antenna," presented at 2017 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, San Diego, CA, 2017.
- [3] M. Hayati and F. A. Shama, "Compact lowpass filter with ultra wide stopband using stepped impedance resonator," *Radio Engineering*, vol. 26, no. 1, pp. 269-274, April. 2017.
- [4] E. Khan, J. Aktar, K. M. Parvez, and S. M. Haque, "Slot antenna miniaturization using copper coated circular dielectric material," presented at 2019 National Conf. on Communications (NCC), Bangalore, India, 2019.
- [5] C. H. Hsu, J. H. Chen, J. C. Liu, H. H. Tung, C. F. Tseng, S. H. Huang, and C. I. Hsu, "Miniaturization cross-coupled interdigital filter design using high permittivity substrate," in *Proc. Progress in Electromagnetic Research Symposium*, Shanghai, China, 2016, pp. 3496-3500.
- [6] Y. J. Li, Y. Liu, L. Y. Feng, X. Y. Liu, and D. Cheng, "Design of multi-band bandpass filters using short-circuited stub loaded meander loop resonator," presented at 2018 International Conference on Microwave and Millimeter Wave Technology, Chengdu, 2018.
- [7] E. S. Ahmed, "Design of L1/L2 GPS BPF using closed-loop rectangular ring resonator," *IETE Journal of Research*, 2019.
- [8] D. Kaddour, E. Pistono, J.-M. Duchamp, J. D. Arnould, H. Eusebe, P. Ferrari, and R. G. Harrison, "A compact and selective low-pass filter with reduced spurious responses,

based on CPW tapered periodic structures,” IEEE Trans. on Microwave Theory and Techniques, vol. 54, no. 6, pp. 2367-2375, June 2006.

- [9] Ran X, Yu Z, Xie T, Li Y, Wang X, Huang P. A novel dual-band binary branch fractal bionic antenna for mobile terminals. International Journal of Antennas and Propagation. 2020 Jan 9;2020.
- [10] Acharya AP, Das TK. Design of a modified tree-fractal antenna for RFID reader applications. In 2021 Advanced Communication Technologies and Signal Processing (ACTS) 2021 Dec 15 (pp. 1-5). IEEE.
- [11] Kaur N, Sivia JS, Kumar M. SRR and rectangular stubs loaded novel fractal antenna realization for multiband wireless applications. Wireless Personal Communications. 2021 Sep;120(1):515-33.
- [12] Ezhumalai A, Ganesan N, Balasubramaniyan S. An extensive survey on fractal structures using iterated function system in patch antennas. International Journal of Communication Systems. 2021 Oct;34(15):e4932.