

Compact Step-Impedance Hairpin Resonator (SIHR) Based Lowpass Filter for GPS Applications

Resty Amanda^{1*}, Asrizal¹, Pakhrur Razi¹, and Khairi Budayawan²

¹Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Negeri Padang, Padang, Indonesia

²Department of Computer Engineering, Faculty of Engineering, Universitas Negeri Padang, Padang, Indonesia

*Corresponding author: amandaresty1182@gmail.com

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ABSTRACT

GPS system performance often experiences degradation due to microwave signal interference, resulting in inaccurate data reception. To overcome this, a microstrip-based lowpass filter was designed for GPS, which functions to cut unwanted high-frequency signals. This study aims to analyze the effect of adding stubs, the effect of physical dimensions on filter parameter performance, and to design and characterize a lowpass filter for GPS applications. The filter is designed using a stepped impedance hairpin resonator (SIHR) structure, which is a parallel connection of one transmission channel and two parallel channels with internal coupling. The material used in the filter is NPCH-220A substrate with a dielectric constant of 2.17 and a thickness of 1.6 mm. The desired filter specifications are a cut-off frequency of 1.7 GHz, insertion loss >-3 dB, and return loss <-10 dB. The research result are based on the simulation and measurement results with VNA, a cut-off frequency of 1.79 GHz was obtained in the simulation and 1.66 GHz in the measurement, with excellent return loss of -24 dB in the simulation and -45 dB in the measurement. Insertion loss at the cut-off frequency is -3 dB (simulation and measurement). Insertion loss in the passband shows optimal performance, which is -0.1 in simulation and -1.6 dB in measurement. The size of the fabricated filter is 33.5×40 mm. The results of this study indicate that lowpass filters with SIHR structures are effective for use in GPS applications to optimize system performance.



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1 INTRODUCTION

Rapid global technological advancements in the digital age are driving major changes across all fields, particularly in the areas of navigation and information technology, one of which is the Global Positioning System (GPS). GPS is a satellite-based navigation system that transmits microwave signals to continuously provide information on position, speed, direction, and time, regardless of time of day or weather conditions. There are 31 GPS satellites orbiting the Earth. All are located in six orbits at an altitude of approximately 20,200 kilometers, with an inclination of 55 degrees and an orbital period of 11 hours and 58 minutes [1].

GPS has three main segments: the space segment, the control segment, and the user segment. The space segment (satellites) is the first component of the GPS system, responsible for transmitting signals containing time and position information. The control segment (controller) is responsible for regularly monitoring the condition of GPS satellites and sending data to the satellites for transmission to GPS receivers on Earth. The user segment (user segment) receives data and processes L-band signals to determine the PVT (position, velocity, and time) required by users [2].

GPS system performance is often degraded because the L-band signals received by the receiver can experience electromagnetic interference, resulting in inaccurate data. To support optimal GPS performance, a device is needed that can pass the desired frequency and suppress unwanted frequencies, namely a filter [3].

In navigation systems, especially in GPS receivers, filters play a very important role. In GPS receiver applications, the filters used are generally small and thin. One filter that has these characteristics is the microstrip filter. One such filter with these characteristics is the microstrip filter. Microstrip filters are currently popular due to their small size, ease of fabrication, simplicity in production, low prices, and ease of integration with other electronic devices[4]. A microstrip filter is a type of filter that is thin and capable of operating at very high frequencies. This filter consists of several components, including a resonator layer (conductor), a dielectric substrate, and a ground plane [5]. One type of filter that can be used in this study is a microstrip lowpass filter.

A lowpass filter is a filter that passes signals below the cut-off frequency and cut-off signals at the cut-off frequency [6]. The cut-off frequency is the frequency that acts as a boundary for passing or attenuating input signals that have frequencies higher or lower than the cut-off frequency [7]. One important aspect of GPS is the selection of the operating frequency. The right operating frequency can reduce noise outside the GPS signal spectrum and improve signal quality. GPS receivers operate in the L-band frequency range. The data received from satellites is in the form of radio signals, with frequencies L1 1575.42 MHz and L2 1227.60 MHz.

The QPQ1063 filter, manufactured by Qorvo, is designed for GPS and communication system applications. The insertion loss of the filter for L1/L2 is 1.6 dB and 1.3 dB [8]. Ideally, the application of a filter in a GPS system yields optimal results for system performance, such as low insertion loss (close to 0 dB), good return loss, and a wide stopband, as typically shown in simulation results. However, in real-world implementations, due to parasitic effects and fabrication tolerances, frequency shifts and a decline in filtering quality occur; for example, insertion loss values do not approach 0 dB, and measured results typically range from 1 to 3 dB.

Several previous studies have developed microstrip filter designs relevant to the present research. In 2019, Barrak et al. designed a reconfigurable dual-bandpass filter. The filter design is based on the Open-Loop Stub-Loaded Resonator (OL-SLR) topology. This filter was designed using TLY5 material with $h = 0.787$ mm and a loss tangent of 0.0017. The frequency ranges are L1 (1554–1589) MHz and L2 (1117–1245) MHz. The insertion loss values are $L1 = < 4$ dB and $L2 = < 3.5$ dB, and the return loss for both L1 and L2 is >10 dB. The fabricated filter measures 84 x 38 mm [9]. A limitation of this study lies in the insertion loss, as the recommended value is close to zero to achieve ideal filter characteristics [7].

In 2019, Jin Zhang et al. designed a lowpass filter. The results of this study showed an insertion loss of 0.38 dB and a return loss of over 20 dB [10]. The limitation of this study is the presence of sidebands and its complex design [7]. In 2021, Ogorodnikov et al. designed a compact bandpass filter. The frequency range for L1 is 1.594–1.61 GHz and for L2 is 1.237–1.254 GHz. The insertion loss values for L1 are 0.576 dB and for L2 are 1.073 dB. The return loss values for L1 are 19.3 dB and for L2 are -19.4 dB. The filter dimensions for L1 are 50 x 30 x 32.2 mm and for L2 are 50 x 30 x 34.5 mm [11]. The limitations of this study include the presence of sidebands near the operating frequency, which can reduce filter performance, and its complex design.

In this study, a microstrip-based low-pass filter was designed and fabricated with a return loss of <-15 dB, an insertion loss of >-3 dB, and a wide stopband. This filter was designed using a stepped impedance hairpin resonator (SIHR) structure. To achieve a wide stopband, a stub was incorporated into the filter design [12]. This microstrip filter was designed using CST Studio Suite software. The cutoff frequency is 1.66 GHz. The objective of this research is to achieve a high-performance LPF with a wide stopband, providing a robust solution for GPS-based communication systems.

2 MATERIAL AND METHOD

A filter requires one or more resonances to realize a filtering function. The SIHR structure is an effective way to realize a compact filter with a sharp roll-off and easy fabrication [10]. The LPF design using SIHR and its equivalent circuit is in Figure 1, and a description of the design can be seen in Figure 2 [13].



Figure 1: (a) LPF design using SIHR with internal coupling and (b) LPF equivalent circuit

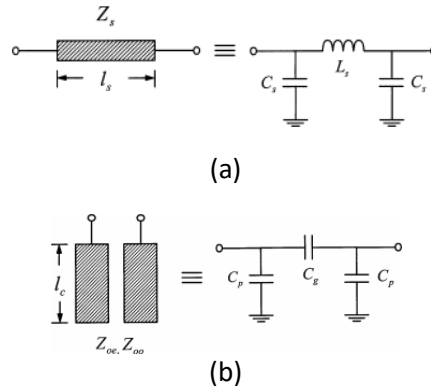


Figure 2. Equivalent circuit with: (a) single transmission line, (b) symmetric coupled lines

To design and plan the dimensions of the microstrip line, Equation (1) can be used.

$$\epsilon_e = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \frac{1}{\sqrt{1 + 12 h/W}} \tag{1}$$

The characteristic impedance can be calculated using Equation (2).

$$Z_0 = \frac{60}{\sqrt{\epsilon_e}} \ln \left(\frac{8d}{W} + \frac{W}{4h} \right) \tag{2}$$

In the design, if there is characteristic impedance and dielectric constant, then the value of W (resonator channel width) is calculated using Equation (3) [14], [15].

$$\frac{w}{h} = \frac{8e^A}{e^{2A} - 2} \tag{3}$$

Where:

ϵ_r = dielectric constant

ϵ_e = effective dielectric constant

Z_0 = impedance

h = dielectric substrate thickness

W = resonator channel width

Table 1 shows the characteristics of the NPCH-220A substrate.

Table 1. Specifications of NPCH-220A material

Specifications	Value
Substrate thickness (h)	1.6 mm
Dielectric constant (ϵ_r)	2.17
Loss tangen	0.0005
Copper thickness	0.035 mm

In designing a filter, physical dimensions must be taken into account in order to obtain results that match the parameter specifications. Once the filter has been designed, it is simulated. If the results do not match the filter performance parameter specifications, the filter design must be optimized. The expected filter specifications are in Table 2.

Table 2. Specifications of microstrip filter performance parameters

Parameters	Value
Cut-off frekuensi	1.7 GHz
Return loss	<-10 dB
Insertion loss	>-3 dB
Input impedance	50 Ω

Simulation and optimization of microstrip lowpass filter designs using CST Studio Suite software. The design and fabrication of lowpass filters follows the flowchart in Figure 3.

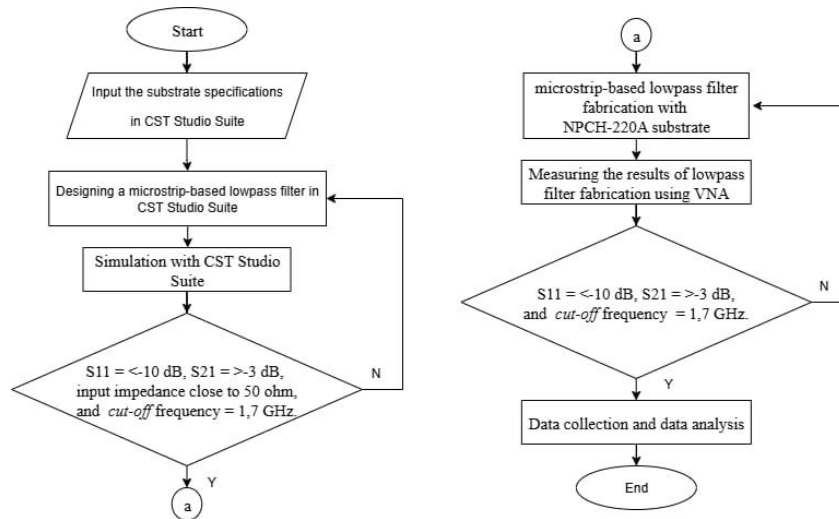


Figure 3. Flow chart diagram of filter manufacturing

Table 3 shows the physical dimensions of the lowpass filter using the optimized SIHR (in mm units).

Table 3. Optimization size of lowpass filter using SIHR

Section	L	W	Section	L	W
1.	5.5 mm	5.0 mm	8.	3.5 mm	2.0 mm
2.	2.5 mm	11 mm	9.	1.5 mm	7.5 mm
3.	2.5 mm	2.5 mm	10.	1.5 mm	4.5 mm
4.	5.0 mm	2.0 mm	11.	4.5 mm	1.5 mm
5.	4.7 mm	5.5 mm	12.	4.2 mm	8.5 mm
6.	1.0 mm	1.5 mm	13.	0.5 mm	1.0 mm
7.	2.5 mm	5.0 mm	14.	3.0 mm	8.5 mm

A lowpass filter designed using SIHR proposes the addition of a stub to the design, which are meant to optimize the performance of a filter. Figure 4 and 5 shows the equivalent circuit and design of a lowpass filter using SIHR. In this study, physical dimension parameters including L7, L9, L11, L14, W2, W3, W4, W5, and W9 were selected as optimization variables to obtain filter characteristics that meet the specified requirements.

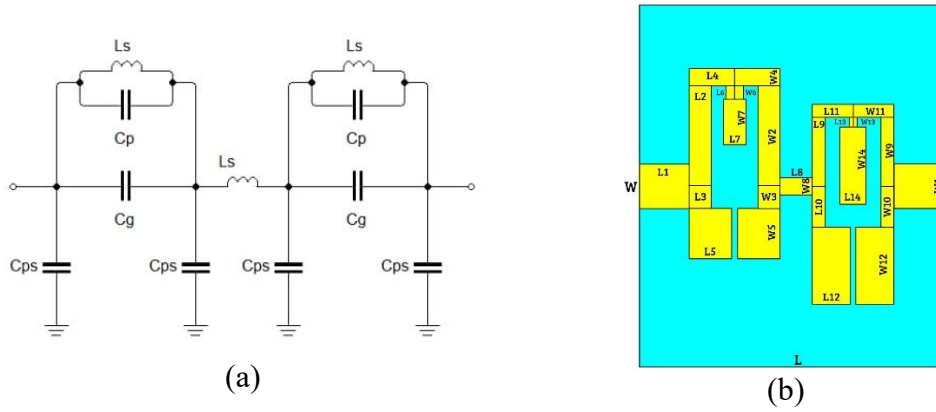


Figure 4. (a) lowpass filter equivalent circuit, (b) Lowpass filter design model

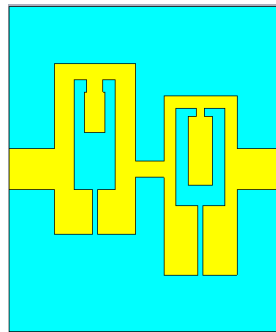


Figure 5. (a) Lowpass filter design in CST Studio Suite

3 RESULTS AND DISCUSSION

In the design of a lowpass filter using an SIHR structure, an analysis was conducted on the effect of adding stubs, The impact of changing the physical size of the filter and the properties of the lowpass filter. The results of this analysis showed the effect on the cut-off frequency, insertion loss, return loss, and stopband width. Based on the optimal analysis results, a microstrip lowpass filter was fabricated for GPS applications.

3.1 The Effect of Stub Addition on Filter Parameters

The design of filters using SIHR is an effective way to create compact filters with sharp roll-off and easy fabrication. The addition of stubs is proposed in the design of lowpass filters to improve the performance of microstrip lowpass filters for GPS applications. The addition of stubs also affects the stopband width in lowpass filter simulation results [12]. Figure 6 and 7 shows the effect of adding stubs on lowpass filter design.

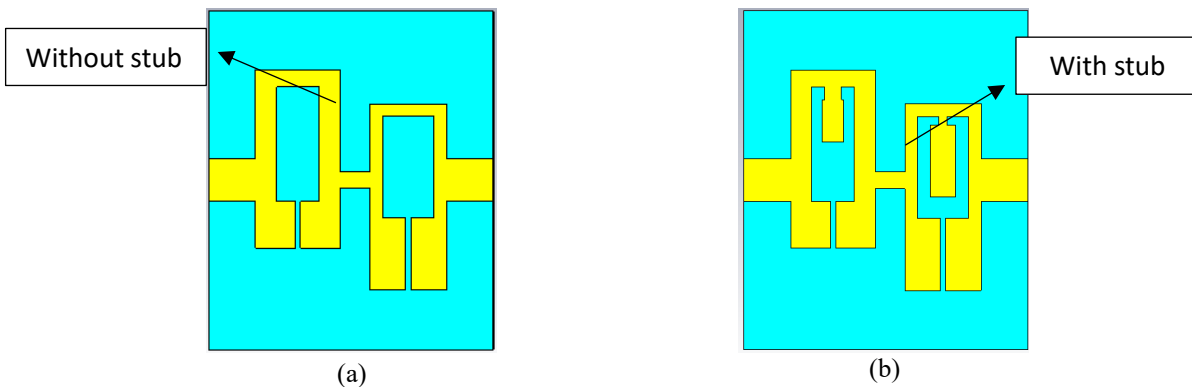


Figure 6. (a) Lowpass filter design without stub, and (b) lowpass filter design with stub

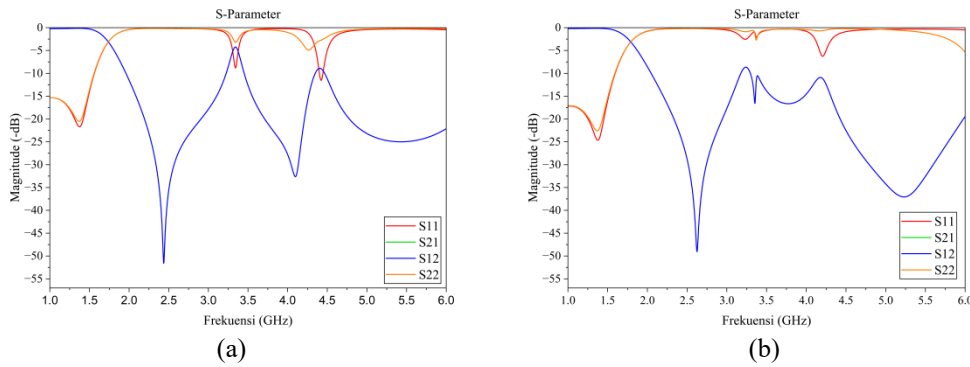


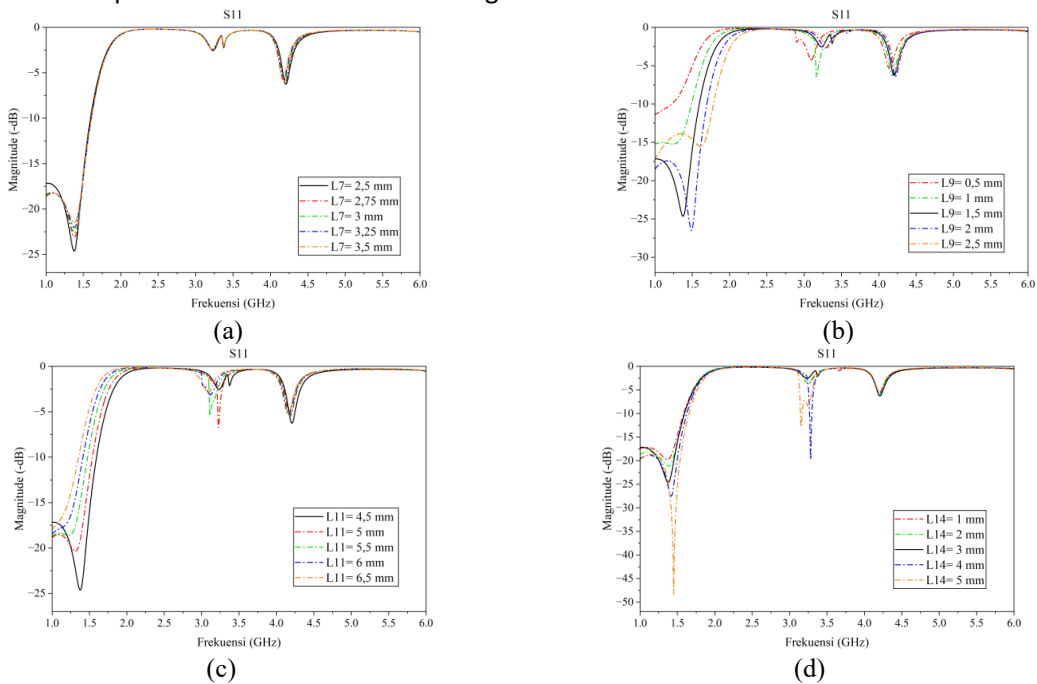
Figure 7. (a) simulation on a lowpass filter without using a stub, and (b) simulation on a lowpass filter using a stub

Figure 7 show, there is a difference between the simulation results of a lowpass filter that does not use a stub and one that does. In Figure 7(a), the simulation results show sidebands at frequencies of 3.3 GHz and 4.5 GHz. This indicates that the simulation results are not yet optimal because there is signal interference near the GPS operating frequency. In Figure 7(b), the filter design with the added stub is able to optimize the performance of the filter. The outcomes of the simulation with the stub can create a broad stopband ranging from 1.66 GHz to 6 GHz, leading to better filter efficiency.

3.2 The Effect of Filter Dimensions on Filter Performance

3.2.1 Analysis of the Influence of Physical Dimensions on Return Loss

If the size of the microstrip lowpass filter design is changed, the return loss value may also change. Incorrect dimensions can cause the return loss value to decrease (below -10 dB), while appropriate dimensions result in a higher return loss value, indicating lower reflection (less reflected power). In this research, the physical dimensions of L7, L9, L11, L14, W2, W3, W4, W5, and W9 have an effect on the return loss value. Figure 8 shows the impact of these dimensional changes.



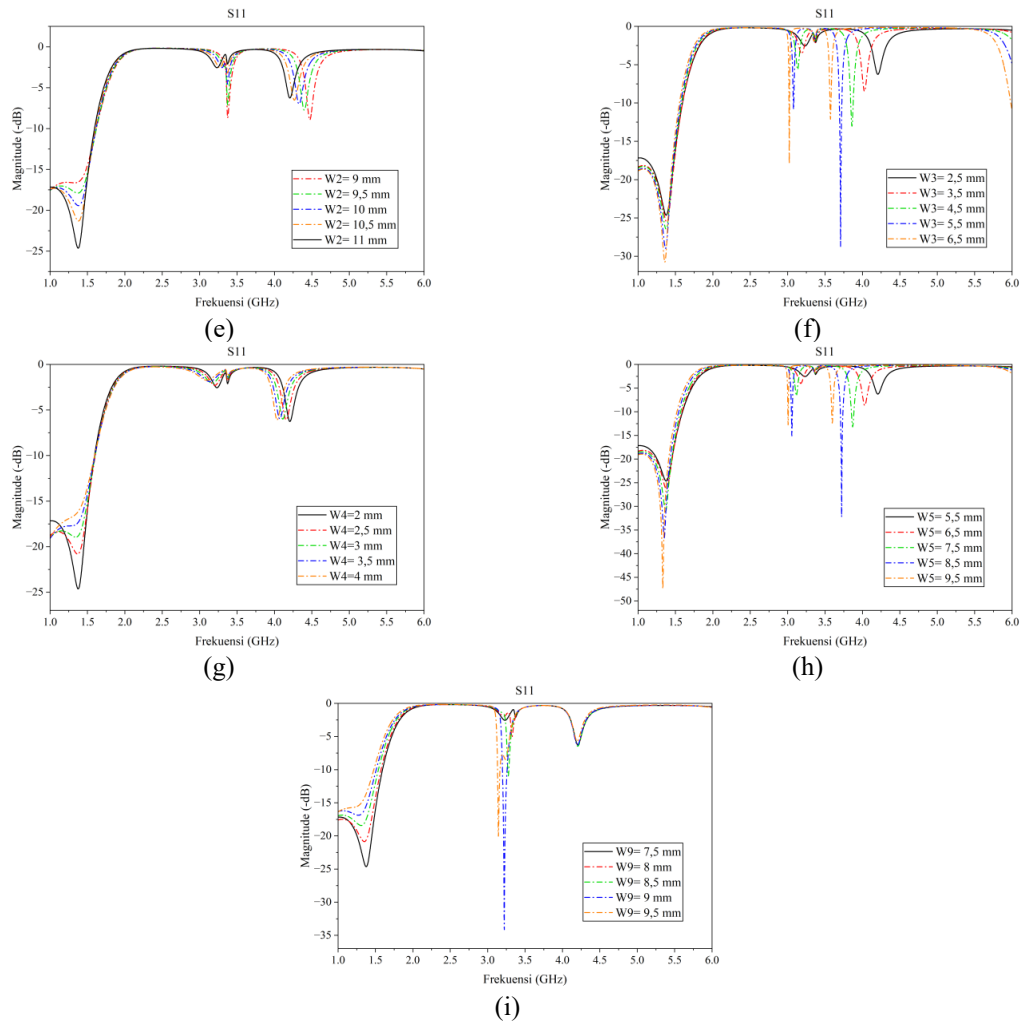


Figure 8. Results of dimension variation on S11 value (a) L7, (b) L9, (c) L11, (d) L14, (e) W2, (f) W3, (g) W4, (h) W5, dan (i) W9

Figure 8 shows the analysis of the variation in the physical dimensions L7, L9, L11, L14, W2, W3, W4, W5, and W9 of the filter affecting the return loss value, cutoff frequency, and sideband. To achieve an increasingly optimal return loss value, the dimensions of L9, L14, W2, W3, and W5 should be increased, while the dimensions of L7, L11, W4, and W9 should be decreased. This analysis shows that if the return loss value is high, less power goes back to the source [2]. Changes in physical dimensions also affect the cutoff frequency and stopband width. The cutoff frequency will shift to a higher value if L9 is increased and L11 is decreased. The presence of sidebands after the cutoff frequency can affect the performance of a filter. In the analysis of dimensional variations, sidebands are present when the W2 dimension is reduced and the L4, W3, W5, and W9 dimensions are increased.

3.2.2 Analysis of the Effect of Physical Dimensions on Insertion Loss

Insertion loss is a measure of how much signal is transmitted through the filter from the input port to the output port. If the transmission value is high (S21 is close to 0 dB) below the cutoff frequency, it means that the filter works better in transmitting signals below the cutoff frequency. On the other hand, if there is a decrease in transmission (S21 < -20 dB) after the cutoff frequency, it means that the filter successfully attenuates the signal above the cutoff frequency [3]. In this study, the physical dimensions of L7, L9, L11, L14, W2, W3, W4, W5, and W9 have an influence on the return loss value. The effect of these dimensional changes can be seen in Figure 9.

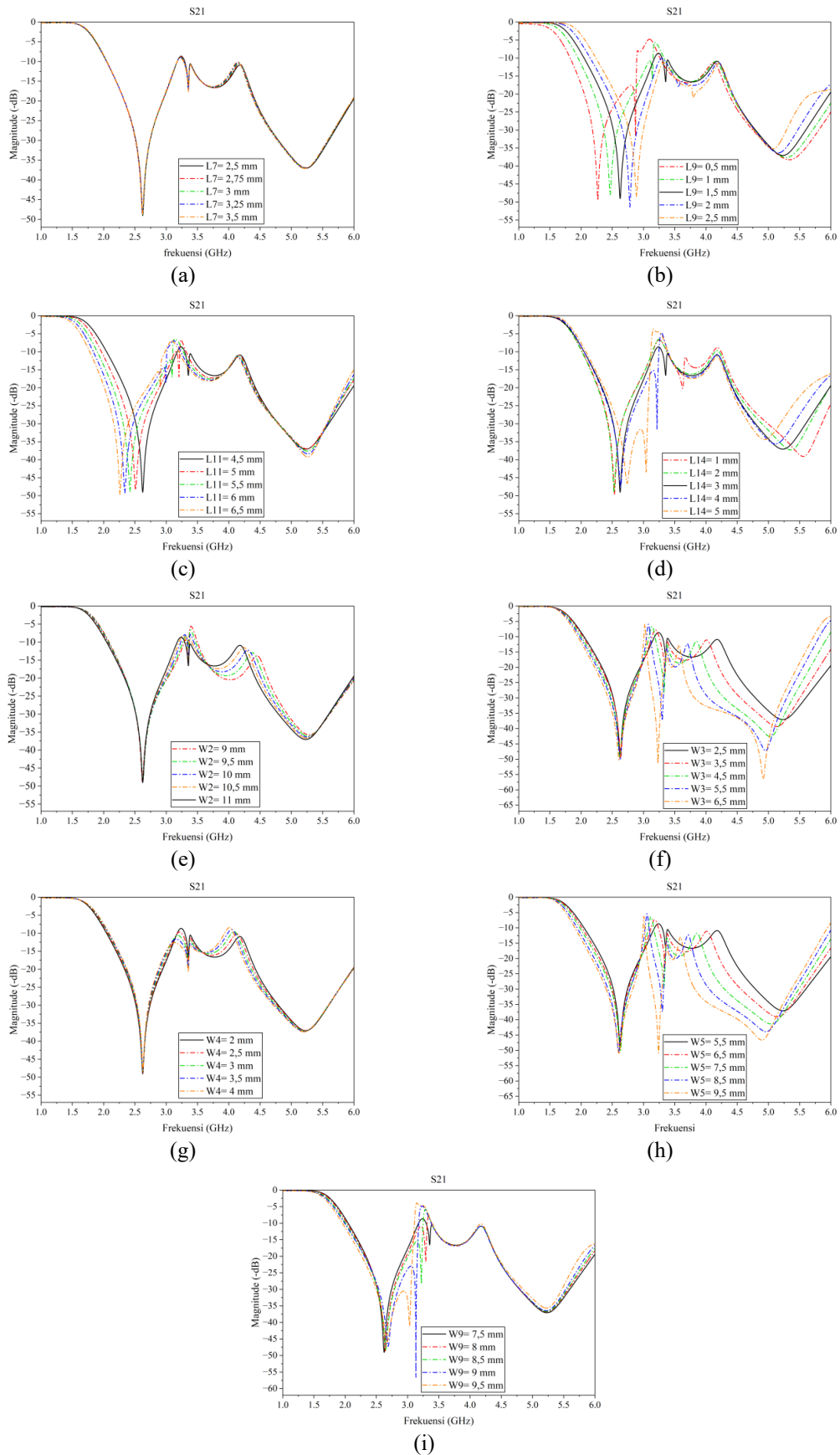


Figure 9. Results of dimension variation on S11 value (a) L7, (b) L9, (c) L11, (d) L14, (e) W2, (f) W3, (g) W4, (h) W5, dan (i) W9

Figure 9 shows the analysis of the variation in the physical dimensions L7, L9, L11, L14, W2, W3, W4, W5, and W9 on the filter affecting the insertion loss, cutoff frequency, and sideband values. To achieve a smaller insertion loss value (approaching zero dB), the dimension size of L9 is increased, while the dimension sizes of L11, W5, and W9 must be reduced. The smaller the insertion loss value (approaching zero dB), the better the filter performs in transmitting signals below the cutoff frequency [7]. Changes in physical dimensions also affect the cutoff frequency and stopband width values. The cutoff frequency value will shift upward if L9 is increased and L11 is decreased. The presence of sidebands after the cutoff frequency can affect the performance of a filter. In the analysis of dimensional variations, sidebands are present when the dimension of W2 is reduced and the dimensions of L4, W3, W5, and W9 are increased.

3.3 Characteristics of Microstrip Lowpass Filters for GPS Applications

The fabrication of the lowpass filter was carried out after designing a microstrip lowpass filter and optimizing the filter. The filter was improved by looking at and changing its physical size, which affects how well it works. Figure 10 shows the fabrication results.

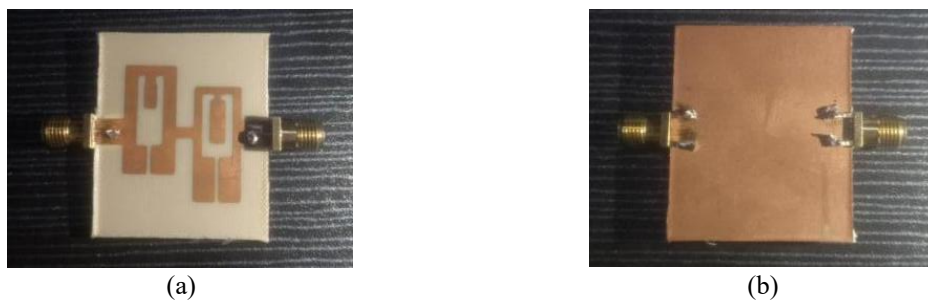


Figure 10. (a) Front view of the fabricated lowpass filter and (b) back view of the fabricated lowpass filter

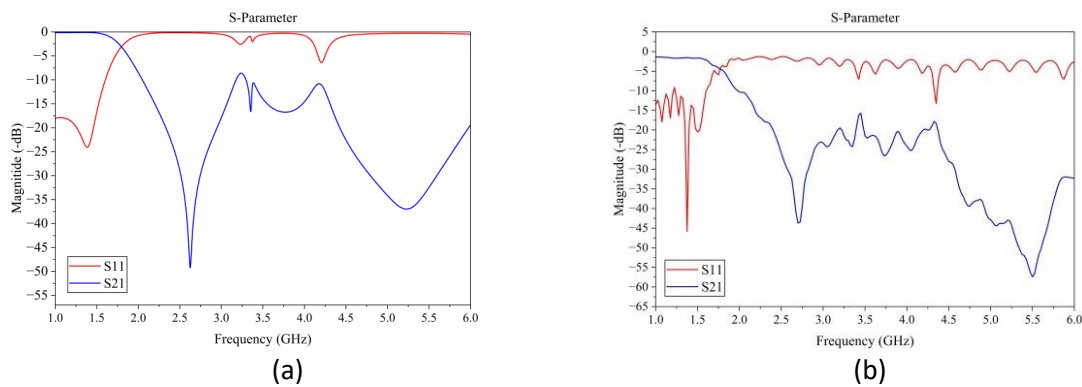


Figure 11. (a) Simulation results using CST (b) measurement results using VNA

Figure 11 shows, the performance of the lowpass filter was measured using a VNA. The results seen in the simulation and the measurements included the return loss (S11) and insertion loss (S21) figures. In Figure 12, a comparison of the simulation and measurement results.

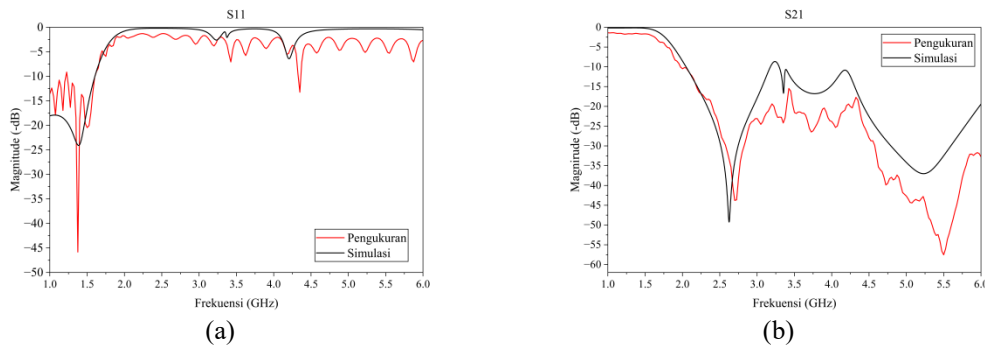


Figure 12. Comparison of simulation and measurement results (a) S11 (b) S21

Figure 12(a) presents a comparison of the results from simulations and actual measurements for the return loss value. In the simulation, the return loss value was -24 dB at a frequency of 1.38 GHz, whereas the measured value was -45 dB at a frequency of 1.37 GHz. This indicates that the lowpass filter that was made showed a notable improvement in its return loss value.

Figure 12(b) displays a comparison of the results from simulations and measurements regarding insertion loss and cutoff frequency. The simulated results indicated -3 dB at a cutoff frequency of 1.79 GHz, with the insertion loss value in the passband being -0.1 dB. On the other hand, the measurement results showed -3 dB at a cutoff frequency of 1.66 GHz, along with an insertion loss value of -1.6 dB in the passband. Therefore, the filter performs effectively for GPS uses, where the cutoff frequency is 1.66 GHz, the return loss is -45 dB, and the measured results at that cutoff frequency are -3 dB with the insertion loss in the passband being -1.6 dB.

Table 4. Comparison with some previous studies

Ref.	Filter Type	Size (mm)	Insertion loss (dB)	Return loss (dB)	Substrate
[9]	Bandpass filter	84 x 38 mm	L1= -4 dB, L2= -3.5 dB	-10 dB	TLYS
[10]	Lowpass filter	13.5 mm x unavailable	-0.38 dB	-20 dB	PTPE composite medium
[11]	Bandpass filter	50 x 30 x 32.2 mm, 50 x 30 x 34.5 mm	L1=0.576 dB, L2=1.073 dB	L1= -19.3 dB, L2=-19.4 dB	N/A
This work	Lowpass filter	33.5 x 40 mm	-1.6 dB	-45 dB	NPCH-220A

In [9] has the advantage of dual-band capability, but the resulting insertion loss is still quite high. In contrast, this study achieves lower insertion loss and significantly better return loss, even though it operates on only a single band. In [10] demonstrates very low insertion loss, but suffers from sidebands and a complex design. This study offers a simpler design with better return loss and a wider stopband, although the insertion loss value is slightly higher. In [11] has a fairly low insertion loss, but still exhibits sidebands and a complex design. This study excels in design simplicity, a more compact size, and the absence of interfering sidebands around the operating frequency.

The discrepancy between the measured and simulated results is attributed to several factors, including fabrication tolerances. While the simulation was conducted under ideal conditions, practical measurements involve inherent losses [16]. For instance, the SMA connectors and coaxial cables used during testing introduce additional insertion losses not accounted for in the numerical model. Furthermore, external electromagnetic interference during the measurement process may also affect the overall performance.

4 CONCLUSION

The microstrip low-pass filter in this study was successfully designed and fabricated using NPCH-220A substrate material. The filter design incorporates the addition of a stub to the Stepped Impedance Hairpin Resonator (SIHR) structure to optimize performance. Measurement results show excellent transmission characteristics, with a return loss of -45 dB and an insertion loss of -1.6 dB within the passband, as well as a -3 dB point precisely at the cutoff frequency of 1.66 GHz. Additionally, this filter is capable of producing a wide stopband extending up to 6 GHz. These research results confirm that the use of the SIHR structure is effective in widening the stopband without increasing the physical dimensions of the filter. The use of NPCH-220A material has also been proven to provide very low losses, making it a superior material of choice for the development of other high-frequency microstrip devices. For further development, the addition of a Defected Ground Structure (DGS) on the ground plane section is recommended to maximize selectivity and rejection effectiveness in the stopband region.

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DECLARATIONS

Authorship contribution

Resty Amanda: Conceptualization, methodology, formal analysis, software and writing—original draft.

Asrizal, Pakhrur Razi and Khairi Budayawan: Validation, writing—review and editing.

Competing Interest

The authors **declare** no conflict of interest in this study.

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Ethical Clearance

There are no human subjects in this manuscript, and informed consent is not applicable.

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