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S-Parameter Analysis of Parallel Coupled Line Bandpass Filter With Comsol Multiphysics

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Abstract: Nowadays as the global internet growing in high speed and the 5G flourish the demand of high-speed data transfer with low delay are still in progress. As 5G devices component, the microwave filters are functioned to transmit and to filter the signal (data) within the interest frequency range. Microwave filters are currently having problems such as insufficient of bandwidth due to the wide range of transmission signal frequency, large insertion loss. At the same time, parallel coupled line bandpass filters are being used for a wider range of frequency for passband and a more stable insertion loss, 5G parallel couple line bandpass filters with Patterned Ground Structure (PGS) technique using COMSOL Multiphysics software is designed and compared with reference filter (parallel coupled line bandpass filter). The effect of substrate size, strip/slot size and shape on S-parameter and electromagnetic field simulation results are presented and filter(s) design with better S-parameter is proposed. The small square strip medium substrate filter has 8.7% of improvement on the lowest S_{11} compared to reference filter, whereas the big O strip medium substrate has 20.3% and 8.7% of improvement for both maximum S_{11} and minimum S_{11} compared to the reference filter. The most preferable design filter is the small square strip with medium substrate having S_{21} -2 dB and S_{11} -20 dB.

Keywords: Microwave Filter, Coupled Line Bandpass Filter, Electromagnetic Field Simulation, S-Parameter

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1. Introduction

Nowadays as the global internet growing in high speed and the 5th generation (5G) flourish the demand of high-speed data transfer with low delay, related researches for improvement are just recently in progress [1]. So 5G technology is still a long way to be fully utilized in big data, industry and internet of things (IoT) [1].

Microwave filters or sometime called filters being one of the components of 5G devices such as smartphone, laptop, 5G internet modem being used for transmitting, filtering and receiving signals (data) of different frequency range. Filters can be classified into high pass, low pass, band pass and band stop filters [2]. Active filters will have at least 1 operational amplifier (op-amp), while passive filters have no op-amp within the circuit. The order of filters is based on the number of reactive components within the filter circuit, filters having 1 capacitor or inductor are called first order [3]. Parallel coupled bandpass filters and Patterned Ground Structure (PGS) technique are commonly used in filters for a wider frequency range for passband and stabler insertion loss, S21 and so high-speed 5G internet [4]. Filters are currently having problems such as insufficient of bandwidth due to the wide range of transmission signal frequency, large insertion loss S21 [5]. Filter property, scattering parameter also known as S-parameter represented by S21 and S11, the ability of a filter to transfer electrical signal throughout the filter known as the signal absorption or insertion loss being denoted by S21 having negative magnitude, while the ability for a filter to reflect electrical signal by the filter known as the reflection loss is denoted by S11 also having negative magnitude.

Simulating filter circuit through software such as Multiphysics Simulation Software COMSOL, Computer Simulation Technology (CST), Advanced Design System (ADS), Genesys and others, with electromagnetic (EM) field simulation we able to maximize the number of trials without producing filters with undesirable features, reducing yield cost and waste [4].

The research aims including designing 5G parallel couple line bandpass filters with Patterned Ground Structure (PGS) technique using COMSOL Multiphysics software. The effect of substrate size, strip/slot size and shape on S-parameter and electromagnetic field simulation results is also studied. The filter(s) design with better S_{21} and S_{11} compared to the filter from [5] is fabricated.

2. Materials and Methods

COMSOL was used for the simulation due to its availability and ease for using. In this project Patterned Ground Structure (PGS) technique is used to better enable unwanted frequency rejection and improve the electrical performances [5].

2.1 Parameter

The filter specifications are shown as Table 1 where the operating frequency referring to the signals within a range of frequency having a significant low insertion loss S_{21} expected between 6-13 GHz these frequencies also categorized as C,X, Ku band of microwave that being used by 5G devices [6]. The electrical signals simulate the microwave mentioned in Table 1. The substrate referring to the base material used in COMSOL simulation as the major part of the filter [7], in this research all the filters substrate are using Rogers 4003C (ε_r = 3.38, low loss) ; substrate thickness referring to the thickness of substrate, 0.5mm for small substrate, 0.508mm for medium substrate [5] and 1mm for big substrate; the strip referring to both microstrip (top patch) and metallic strip (ground patch), using perfect electric conductor; line impedance referring to the impedance matching [5], using 50 Ω; return loss S_{11} referring to the loss of strength of returning or reflected signals, expected to be less than -30dB; insertion loss S_{21} referring to the loss of transmitting signals power, expected to be as 0 as possible.

Table 1: Design specifications

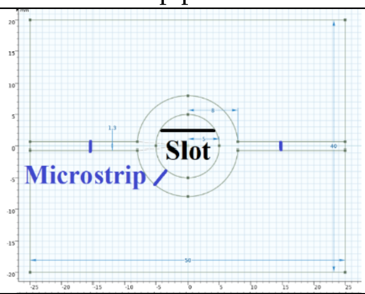
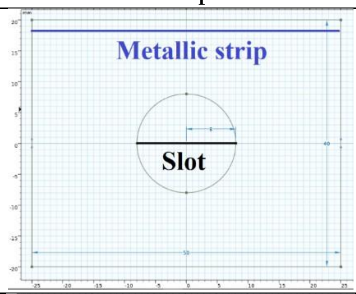
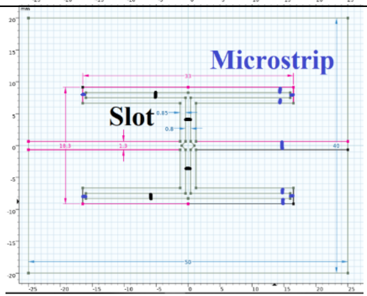
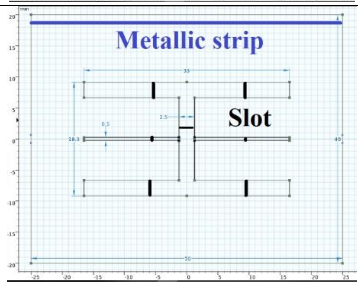
Specifications	**Value**
Operating Frequency	6-13 GHz [5]
Substrate	Rogers 4003C (ε_r=3.38 F/m)(low loss)
Substrate Thickness	0.5 mm, 0.508 mm, 1 mm
Strip	Perfect electric conductor
Line Impedance	50 Ω
Reflection loss S_{11}	≤ -30 dB
Insertion loss S_{21}	0 dB

2.2 Geometry

There are 3 sizes of filter substrate which are called as the small size, medium size (reference substrate size) [5] and big size substrate, with dimensions; length x width x thickness as following: small substrate (40mm x 20mm x 0.5mm), medium substrate (46mm x 34mm x 0.508mm) [5] and big substrate (50mm x 40mm x 1mm).

Each substrate size filter has 3 different strip/slot shapes; circular (O), E and square shape. All shapes are further categorized into 2 sizes which are big and small shape; big/small O, big/small E and big/small square. Some design filters are shown in Table 2, while Table 3 shows all the design filters' dimensions.

Table 2: Top and ground patch of some design filters

Shape	Top patch	Ground patch
Circular (O)		
E		

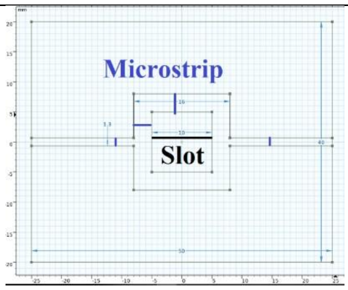
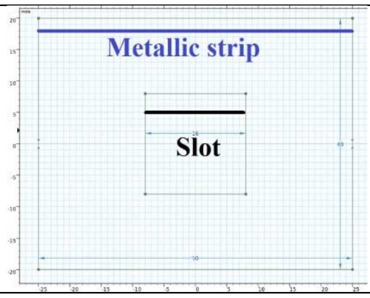
Square		

Table 3: Substrate size, strip/slot size and shape for all design filters

Substrate size (mm x mm x mm)	Shape of Strip / slot	Shape size	Top patch Microstrip size (mm)	Top patch slot size (mm)	Ground patch slot size (mm)
Small (40 x 20 x 0.5)	O (radius)	Small	1	3	4
	E		0.283	0.48	1.046
	Square (side)		1	6	8
	O (radius)	Big	3	5	8
	E		0.85	0.8	2.5
	Square (side)		3	10	16
Medium (46 x 34 x 0.508)	O (radius)	Small	1	3	4
	E		0.283	0.48	1.046
	Square (side)		1	6	8
	O (radius)	Big	3	5	8
	E		0.85	0.8	2.5
	Square (side)		3	10	16
Big (50 x 40 x 1)	O (radius)	Small	1	3	4
	E		0.283	0.48	1.046
	Square (side)		1	6	8
	O (radius)	Big	3	5	8
	E		0.85	0.8	2.5
	Square (side)		3	10	16

2.3 Patterned Ground Structure (PGS)

PGS also known as the Patterned Ground Structure technique is one of the techniques for improving the performance of microwave filter and also for enabling the unwanted frequency rejection of the signal [5]. The second column (ground patch) in Table 2 above shows the PGS for different shapes. Both metallic strip and the slot that located at the bottom part of the filter are considered as the PGS as they are contributing the electrical properties for the filter at the bottom patch [8].

2.4 Scattering boundary condition

Scattering boundary condition is to define the simulation boundary so that the EM field simulation will not run beyond the defined boundary at the same time allowing the scattering wave to pass through certain boundaries [4]. For this paper the scattering boundary condition was defined for all the domains including the surrounding and the design filter as shown as Figure 1. Whereas the scattering boundary condition is governed by the *Eq.* 2.

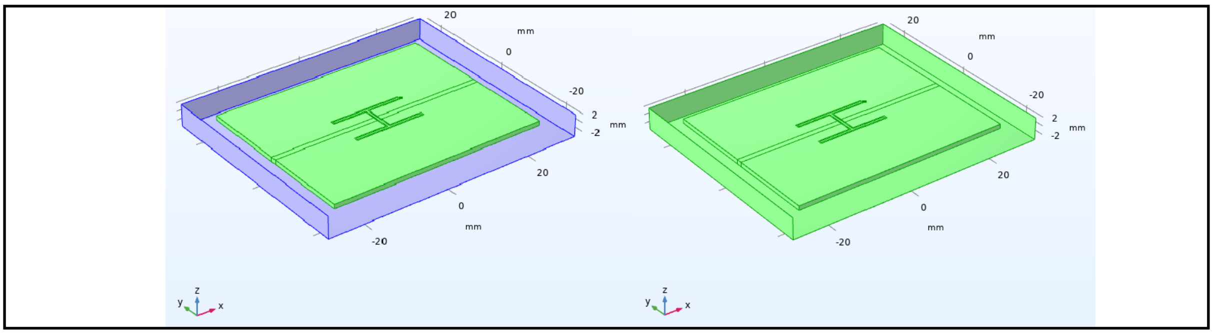


Figure 1: Left figure is the scattering boundary condition of the filter domain. Right figure is the scattering boundary condition of the surrounding domain

2.5 Meshing

Meshing also known as mesh generation representing one of the important steps in simulation that involve thousands or more of shapes for defining the physical shape of the filter [9]. A detail meshing is needed for a better accuracy of 3D CAD model [1]. After the meshing, the simulation will be run and filter property result such as S-parameter will be plotted based on the design of the filter.

2.6 Equations

The input electrical signal that passing through all of the design filters from input port shown by the blue arrow in Figure 2 is set constantly such that the voltage of input signal is 1 V and 50 Ω as reference impedance also known as characteristic impedance [10] with uniform port using cable at 0 port phase with the output signal. While the output electrical signal passing through all of the design filters out of the output port shown by blue arrow in Figure 2 is set constantly with uniform port made by cable with 1 V and 50 Ω reference impedance as well. *Eq.* 1 below showing the formulae to obtain the impedance, Z. The current set to 0.02 A for both the input and output port.

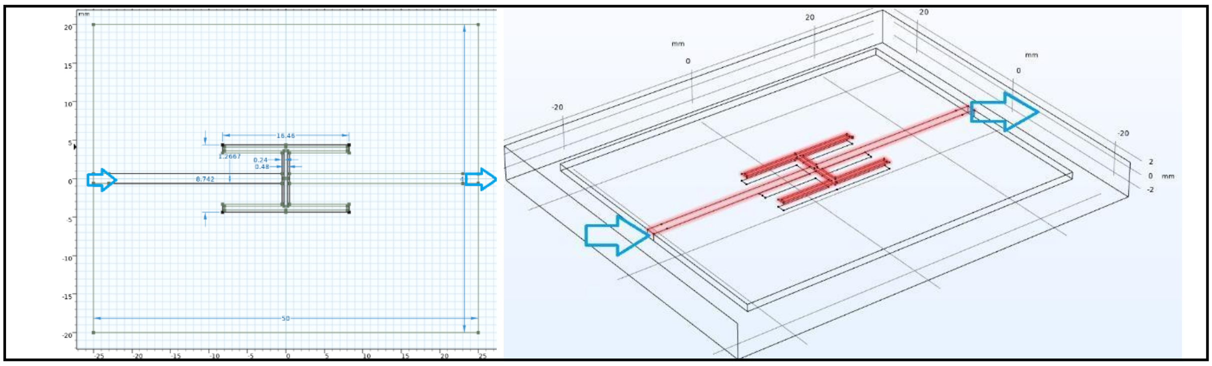


Figure 2: Left figure showing top view, right figure showing isometric view of a E strip filter with arrows indicating the direction of electric signal and the position of port 1 and port 2

$$Z = \frac{2Z_{0e} Z_{0o} \sin\theta}{\sqrt{(Z_{0e} - Z_{0o})^2 - (Z_{0e} + Z_{0o})^2 \cos^2\theta}} \qquad Eq.\ 1$$

where,

Z = Matching impedance, Ω
Z_{0e} = Even mode impedance, Ω
Z_{0o} = Odd mode impedance, Ω
θ = Signal phase

$$\nabla \cdot (\mu_r^{-1} \nabla E_z) - k_0^2 \varepsilon_r E_z = 0 \qquad Eq.\ 2$$

where,

E_z = Electric field at z-axis
μ_r = Relative permeability, H/m (equal to 1 in vacuum)
ε_r = Relative permittivity, F/m (equal to 1 in vacuum)
k_0 = Wave number

The capacitance and inductance are also the important properties of filters and being shown as *Eq.* 3 for filter capacitance and *Eq.* 4 for filter inductance.

$$C_p = \frac{f_c}{4\pi Z_e}\left(\frac{1}{f_o^2 - f_c^2}\right) \qquad Eq.\ 3$$

$$L_p = \left(\frac{1}{4\pi^2 f_o^2 C_p}\right) \qquad Eq.\ 4$$

3. Results and Discussion

By analyzing the S-parameter, the performance of design filters and also the factors effecting the performance of filter can be determined. S_{21} and S_{11} are two important parameters of filters. Insertion loss, S_{21}, known as the signal loss while signal transmitted from port 1 to port 2, so it is necessary to be stable and as low as possible (as 0 as possible), the lower the S_{21}, indicate the lower loss of signal, the stabler the S_{21}, indicate the lower discontinuity of signal, its value is negative in the S-parameter in order for considering the signal loss during the transmission.

Reflection loss, S_{11}, known as the signal loss while being transmitted to port 1 from the signal generator and reflected at port 1, so it is necessary to be as much as possible, the bigger the negative value of S_{11}, indicate more signal loss during the reflection at port 1, that's mean more signal being transmitted to the network within the filter, its value is negative in the S-parameter in order for considering the signal loss during the reflection.

Table 4 referring to the S-parameter of design filters with small strip/slot arranged based on their substrate size and strip/slot shape to analyze the effect of substrate size and strip/slot shape toward the S-parameter. While Table 5 referring to the S-parameter of design filters with big strip/slot arranged based on their substrate size and strip/slot shape to analyze the effect of substrate size and strip/slot shape toward the S-parameter.

3.1 S-parameter comparison with different substrate size

By observing the Table 4, for small strip filters, the filters with medium substrate (46mm x 34mm x 0.508mm) [5] have lower insertion loss S_{21} (less power loss during signal transmission) and higher reflection loss S_{11} (more signal able to be transmitted due to high reflection loss) compare to small and big substrate filters. Medium substrate filters (red words) have stabler S_{21} (Small O: -2dB, Small E: -3.5dB, Small square: -2dB) of insertion loss they also have larger average reflection loss S_{11} compare to small and big substrate filters (Small O: -15dB, Small E: -14dB, Small square: -20dB) meaning better performance (lower power loss for signal transmission and more signal able to be transmitted to the network within the filter due to high reflection loss) compare to other same strip/slot shape and size but different substrate size filters. When compare to reference filter that has S_{21} -1.76dB and average S_{11} -14.69dB [5], the small square is better for its S_{11} (-20dB) but not better in S_{21} (-2dB).

By observing Table 5, the filter with medium substrate (46mm x 34mm x 0.508mm) [5] having better filter performance compare to other substrate size filters in term of S_{21} and S_{11} except the big square strip filter with small substrate (Big square: S_{21} = -4.5dB and S_{11} = -14dB) (marked red star), they have relatively stable S_{21} (Big O: -4dB, Big E: -6dB) of insertion loss (less power loss during signal transmission) and larger average reflection loss S_{11} (more signal able to be transmitted due to high reflection loss). Medium substrate filters (red words) having larger average reflection loss S_{11} (Big O: -20dB, Big E: -15dB) meaning better performance (lower power loss for signal transmission and more signal able to be transmitted to the network within the filter due to high reflection loss) compare to other same strip/slot shape and size but different substrate size filters. When compare to reference filter that has S_{21} -1.76dB and average S_{11} -14.69dB [5], the big O is better for its S_{11} (-20dB) but not better in S_{21} (-4dB).

3.2 S-parameter comparison with different strip/slot shape

In case of comparing the S-parameter of design filters by its strip/slot shape in Table 4 and Table 5. For small substrate and small strip filters, O strip filter (marked blue cross) has stabler S_{21} and almost 0dB and larger average S_{11} -16dB so it has lower power loss for signal transmission and more signal able to be transmitted to the network within the filter due to high reflection loss compare to small E and small square filters. For medium substrate and small strip filters, square strip filter (marked blue cross) has more stable S_{21} and almost 0dB and larger average S_{11} -15dB so it has lower power loss for signal transmission and more signal able to be transmitted to the network within the filter due to high reflection loss compare to small O and small E filters. For big substrate and small strip filters, O strip filter (marked blue cross) has more stable S_{21} and almost 0dB and larger average S_{11} -8dB so it has lower power loss for signal transmission and more signal able to be transmitted to the network within the filter due to high reflection loss compare to small E and small square filters. For all the big strip filters with any substrate size, O strip filters (red words) are always better than other big strip filters with more stable S_{21} and almost 0dB and larger average S_{11} (small substrate: -14dB, medium substrate: -17dB, big substrate: -10dB) so they have lower power loss for signal transmission and more signal able to be transmitted to the network within the filter due to high reflection loss compare to big E and big square filters.

Table 4: S-parameter with different substrate size of small strip/slot shape

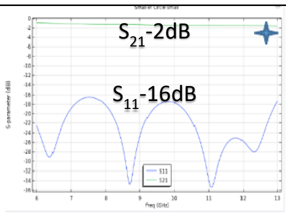
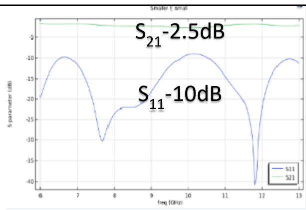
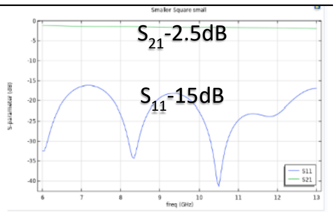
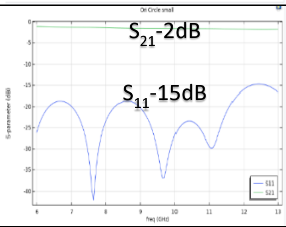
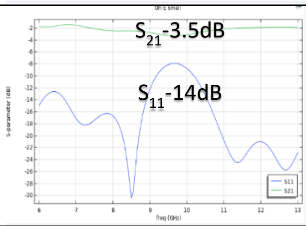
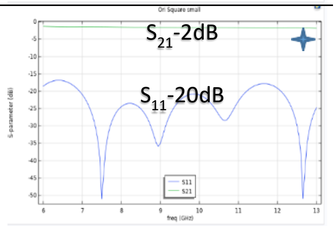
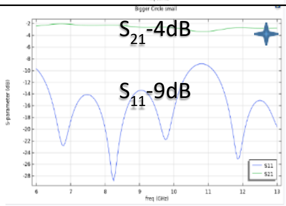
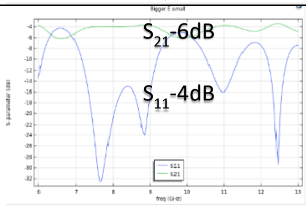
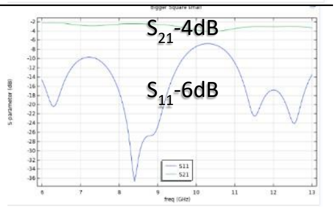
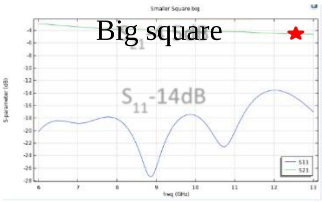
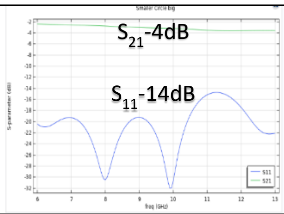
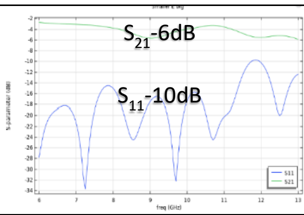
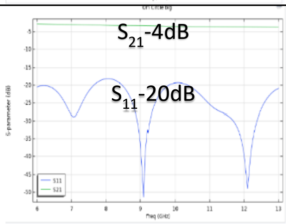
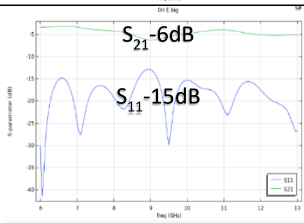
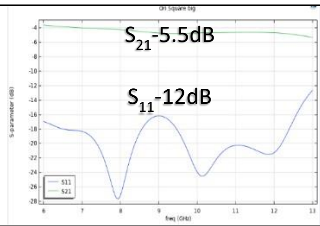
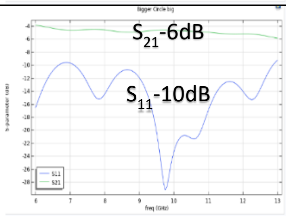
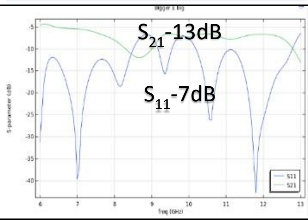
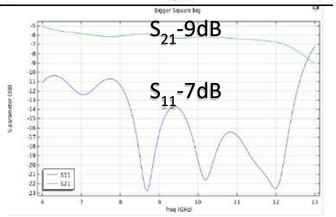
	Strip/slot shape and size		
Substrate size (mm x mm x mm)	Small O	Small E	Small square
Small (40 x 20 x 0.5)			
Medium (46 x 34 x 0.508)			
Big (50 x 40 x 1)			

Table 5: S-parameter with different substrate size of big strip/slot shape

Substrate size (mm x mm x mm)	Strip/slot shape and size		
	Big O	Big E	Big square 
Small (40 x 20 x 0.5)	 S_{21}-4dB S_{11}-14dB	 S_{21}-6dB S_{11}-10dB	S_{21}-4.5dB S_{11}-14dB
Medium (46 x 34 x 0.508)	 S_{21}-4dB S_{11}-20dB	 S_{21}-6dB S_{11}-15dB	 S_{21}-5.5dB S_{11}-12dB
Big (50 x 40 x 1)	 S_{21}-6dB S_{11}-10dB	 S_{21}-13dB S_{11}-7dB	 S_{21}-9dB S_{11}-7dB

4. Conclusion

Based on the analysis, for Table 4, the best design filter among 9 filters in term of S_{21} and S_{11} is the small square strip with medium substrate has most stable and lowest S_{21} -2dB and largest average S_{11} between -16dB to -50dB. For Table 5, the best design filter among 9 filters in term of S_{21} and S_{11} is the big O strip with medium substrate has the most stable and lowest S_{21} -4dB and largest average S_{11} between -20dB to -50dB. While the reference filter has S_{21} -1.76dB and S_{11} -16.62 as low as -46dB [5]. The small square strip medium substrate filter has 8.7% of improvement on the lowest S_{11} compared to reference filter [5], whereas the big O strip medium substrate has 20.3% and 8.7% of improvement for both maximum S_{11} and minimum S_{11} compared to the reference filter [5]. In other words, for small strip/slot shape filters those filters with square shape and medium substrate size is better and for big strip/slot shape filters those filters with O shape and medium substrate size is better, but the prior filter is the best among all the 18 design filters.

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