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Design of Wideband Bandpass and Lowpass Filters with Good Insertion Loss

*[1]Nasidi, I., [2]Idris, M. N., [2]Abu, Y. S.

[1]Department of Electrical and Electronics Engineering, Faculty of Engineering and Environmental Design, Usmanu DanFodiyo University, Sokoto.
[2]Department of Electrical and Electronics Engineering, Faculty of Engineering, Federal University Dutsin-Ma, Katsina.

*Corresponding author's email: nasidi.ibrahim@udusok.edu.ng Phone: +2348065498184

ABSTRACT

This paper proposes and demonstrates microstrip filters. A microstrip lowpass filter prototype was designed based on a maximally flat response, then transformed and scaled to step impedance and bandpass filters using a circuit theory-based method. The frequency response of all the filters shows a -3 dB insertion loss at the 1.5 GHz cutoff frequency. The lowpass and step impedance filters exhibit good insertion losses of -24 dB and -18 dB at 3 GHz, respectively. The bandpass filter exhibits a -3 dB bandwidth of 3 GHz, a wideband with potential applications in amplifiers and speakers. A finite-difference time-domain method could be employed to perform an electromagnetic analysis of the filters.

Keywords:
Bandpass,
Filter,
Insertion loss,
Lowpass,
Step impedance.

INTRODUCTION

Microwave systems have greatly impacted modern society with various applications, such as entertainment via satellite television and civil, military, and aviation communications systems. In a microwave communication network, several components are used, such as modulators (Shen, Bootsman, Alavi, & De Vreede, 2022), couplers (Bhandari et al., 2020), delay lines(Labrenz et al., 2019), amplifiers (Chen et al., 2021), and filters (Gómez-garcía & Member, 2019). A filter is widely used to separate desired and undesired signal frequencies. Microstrip is a viable candidate for filter design due to its compact size, planar shape, fabrication ease, and integration flexibility with other components (Gupta & Chaurasia, 2014; Gupta, Chaurasia, Rathor, & Singhal, 2015). Microstrip filters are two-port network devices that perform many functions, including lowpass, high-pass, bandpass, and bandstop.

Filtering characteristics have been achieved using periodic structures to improve passive component performance. An electromagnetic bandgap (EBG) structure is a valuable periodic structure for microwave antenna and filter design (Fan Yang and Yahya Rahmat-Samii, 2009). In one of our previous studies, an EBG structure was integrated into an antenna to prevent signal propagation at certain frequency bands (Nasidi & Bello, 2022). However, the design and analysis of EBG structures for antenna and filter applications are carried out in electromagnetic or finite-difference time-domain (FDTD)-based software like CST. However, EM-based software runs 3D simulations, which are computationally intensive as they require large amounts of memory and are costly to acquire. Other methods have been reported to improve filter performance. For instance, a higher-order degree filter can be used, resulting in a larger filter size and a large insertion loss. Resonant structures can be added in series or parallel to the filter circuit to enhance performance; however, this results in complex filter design and calculations(Resonators, Hsieh, Member, & Chang, 2003). Another alternative method for designing microstrip lowpass filters is a MATLAB-based algorithm (Tomar, Gupta, Tomar, & Bhartia, 2015).

In this paper, a wideband bandpass and lowpass filter with good insertion is proposed and demonstrated using a circuit theory-based method. The low pass filter is aimed to achieve a cutoff frequency of 1.5GHz and an attenuation of 20dB at 3GHz. A microstrip lowpass filter with a lumped element ladder circuit and step-impedance circuit was initially designed and then scaled and transformed into a bandpass filter. The bandpass filter is designed to have a passband in the range of 5-8GHz. A commercially available substrate with a low dielectric constant and a small thickness is used to achieve optimal filter performance.

General Filter Design Method

Generally, a lowpass filter prototype with desired passband features is designed and transformed into either a lowpass filter or a bandpass filter (Pozar, 2005). The design follows the following two steps. Firstly, the selection of the response type and the lowpass prototype. Filter response types include maximally flat response, linear phase response, and elliptic function response. This work will use a maximally flat response because it gives the flattest passband response possible for a particular filter. The lowpass prototype chosen for the work is the lumped element type, whose normalised elements g_k are obtained from the desired filter order and other constraints like attenuation. To determine the filter order or the number of elements *N*, the attenuation against normalised frequency ($\left|\frac{\omega}{\omega_c}\right| - 1$) chart is utilised (Matthaei, Young, & Jones, 1980). Using the number of elements N, the normalised element values g_k are obtained from the maximally flat response lowpass filter prototype table presented in reference (Matthaei et al., 1980). Secondly, scale and convert the network into corresponding distributed circuit elements consisting of capacitors and inductors ($L - C$ circuit). These two steps are illustrated in Figure 1.

For the simulation, circuit theory-based advanced design system (ADS) software will be used because it has the advantage of less simulation time over electromagnetic (EM)-based design and analysis software like CST or ANSYS software for filter design, and optimisation will not be required provided the $L - C$ values obtained from calculations are correct.

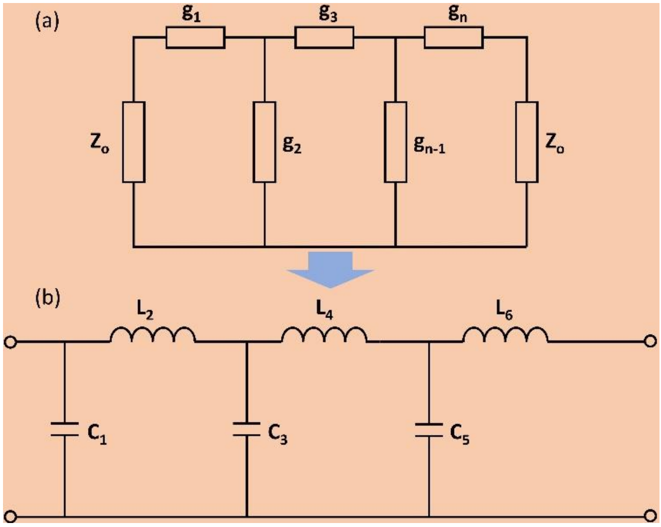

Figure 1: (a) Lumped-element lowpass filter prototype (b) distributed circuit elements.

Lowpass filter

Design and specifications

A lowpass filter consists of a series of inductors and capacitors. To design a lowpass filter, the lumped element valuesg_k $(g_1, g_2, \ldots, g_{n-1}, g_n)$ of Figure 1(a) are transformed into distributed $L - C$ circuit components, as in Figure 1(b), using the following equations.

$$L_k = \frac{g_k R}{\omega_c} \quad (1)$$

$$C_k = \frac{g_k}{\omega_c R} \quad (2)$$

WhereC_k, L_k , ω_c, and R are the capacitors, inductors, cutoff frequency, and characteristic impedance, respectively. The component index is denoted by *k*.

The microstrip lowpass filter specifications are cutoff frequency$\omega_c = 1.5GHz$, substrate thickness of 0.508mm, loss tangent $(tan\,\delta)$ 0.0027, metallisation of $35\mu m$, dielectric constant$\varepsilon_r = 3.38$, and characteristic impedance $R = 50\Omega$. The lowpass filter requires an insertion loss/attenuation of -20 dB at a frequency ω of $3GHz$.

MATERIALS AND METHODS

The number of normalised elements is obtained using attenuation against normalised frequency for a maximally flat filter prototype chart [13]. For $N = 4$ in element values for maximally flat lowpass prototype table [13], five element values g_k are obtained (i.e. g_1, g_2, g_3, g_4, g_5). Hence, $g_1 = g_4 = 0.7654$, $g_2 = g_3 = 1.8478$ and $g_5 = 1.0000$. By substituting these lump element values in equations 1 and 2, $C_1 = 1.6242pF$, $L_2 = 9.8nH$, $C_3 = 3.92pF$ and $L_4 = 4.06nH$. Figure 2(a) depicts the schematic of the lowpass filter. As can be seen, the calculated $L - C$ values are used.

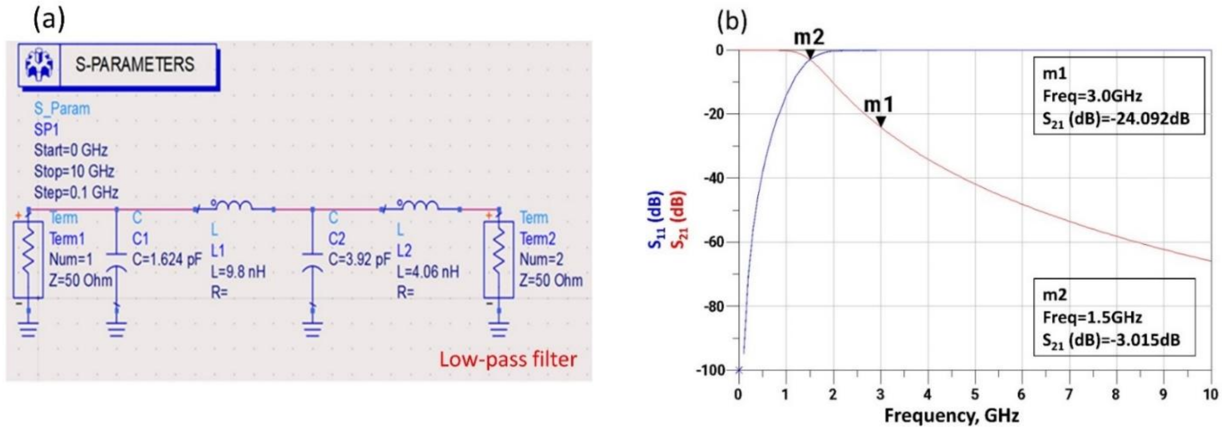

Figure 2: (a) Schematic of a lowpass filter (b) frequency response of a lowpass filter.

RESULT AND DISCUSSION

Figure 2(b) shows the frequency response of the lowpass filter simulated with calculated $L - C$ values. It can be observed that the reflection coefficient or return loss ($S_{11}(dB)$) and transmission coefficient or insertion loss ($S_{21}(dB)$) are both -3 dB at the 1.5 GHz cutoff frequency, as denoted by m2. At 3 GHz, as denoted by m1, a good attenuation/insertion loss of -24 dB was achieved. The insertion loss is even better than expected. For example, -20 dB is expected, and -24 dB is obtained. Hence, satisfying the design requirements. A lowpass filter with such a low insertion loss could be used in radio transmitters to block or suppress harmonics to prevent interference.

Step impedance lowpass filter

Design and transformation

The lowpass filter designed in Section III can be implemented as a step impedance lowpass filter. Step impedance is an alternating section of high impedance (Z_h) and low impedance (Z_l) characteristic lines, as shown in Figure 3(a). In other words, a step impedance lowpass filter is realised by cascading narrow and wide transmission line elements, as shown in Figure 3(b). The electrical length $\beta l$for high and low-impedance lines can be calculated using the expressions:

$$\beta l_i = \frac{g_k R_0}{Z_h} \quad (3)$$

$$\beta l_c = \frac{g_k Z_l}{R_0} \quad (4)$$

Where βl_i,βl_c,R_0, Z_h and Z_l are the electrical lengths for the inductor, the electrical length for the capacitor, the characteristic impedance, the high impedance line, and the low impedance line, respectively. Normalised element values obtained during lowpass filter design are used to design the step impedance circuit. Using $Z_h = 120\Omega$, $Z_l = 50\Omega$, $g_1 = g_4 = 0.7654$, $g_2 = g_3 = 1.8478$and $R_0 = 50\Omega$, the lowpass filter can be transformed into its equivalent step impedance lowpass filter. By substituting these values in equations 3 and 4, the electrical length βl for each value of the normalised element $g_k$is computed. Hence, $\beta l_1 = 17.54$, $\beta l_2 = 44.00$, $\beta l_3 = 18.27$ and $\beta l_4 = 42.00$.

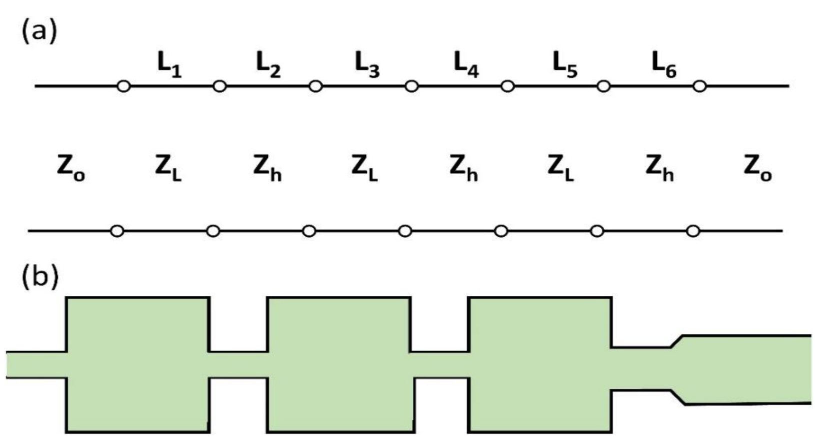

Figure 3: The layout of a step impedance lowpass filter (a) alternating high and low impedance lines (b) cascade of narrow and wide transmission lines.

Method, result, and discussion

Figure 4(a) depicts the schematic of the step impedance filter designed in ADS software. It can be observed that the electrical length $\beta l$is denoted by E, and the calculated values are used in each section.

Figure 4(b) shows the frequency response of the step impedance filter. It can be seen that the filter exhibits a -3 dB insertion loss at the 1.5 GHz cutoff frequency, as indicated by m2. Moreover, an attenuation/insertion loss of -18 dB could be observed at 3 GHz.

A comparison of the lowpass filter and step-impedance lowpass filter responses shows that they both exhibit -3 dB insertion loss at the 1.5 GHz cutoff frequency. However, the lowpass filter response shows an attenuation/insertion loss of -24 dB, whereas the step impedance response shows -18 dB at 3 GHz. This implies that the step impedance filter has poor attenuation as the power loss is large. This poor attenuation of the step impedance filter is due to the high electrical length and discontinuities. It could be overcome by optimisation or using a substrate with a thinner width. This is because physical discontinuities decrease proportionally to substrate thickness (Ma, Nomiyama, & Kobayashi, 2005). Meanwhile, our step-impedance lowpass filter response at a cutoff frequency designed using ADS gives a similar result of -3 dB as that designed using an artificial neural network (Kushwah, Tomar, & Bhadauria, 2013), with the advantage of less complexity and faster computation time.

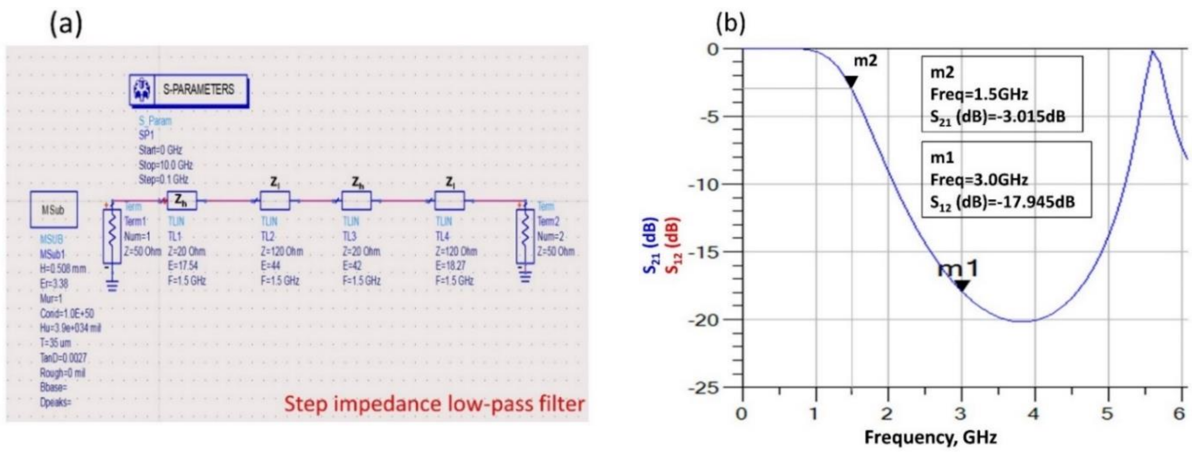

Figure 4: Step impedance filter (a) schematic diagram. TL denotes transmission line. (b) frequency response.

Bandpass filter

Design, scaling, and transformation

To convert the lowpass filter into a bandpass filter, scaling and transformation are carried out on the lowpass filter of Figure 1. The lowpass filter is transformed into a bandpass filter by replacing a series inductor $L_k$with a series $L-C$ circuit, as shown in Figure 5(a), and a shunt capacitor C_k is transformed into a shunt $L-C$ circuit, as shown in Figure 5(b). The series and shunt elements are calculated using the following expressions:

From the series inductor to the series $L-C$ circuit;

$$L_k = \frac{g_k R}{\omega_0 \Delta} \tag{5}$$

$$C_k = \frac{\Delta}{\omega_0 g_k R} \tag{6}$$

From shunt capacitor to shunt $L-C$ circuit;

$$L_k = \frac{\Delta R}{\omega_0 g_k} \tag{7}$$

$$C_k = \frac{g_k}{\omega_0 \Delta R} \tag{8}$$

$$\Delta = \frac{\omega_2 - \omega_1}{\omega_0} \tag{9}$$

Where $\omega_1$and ω_2 are the lower and higher passband frequencies. These frequencies correspond to the edges of the pass band. Using the passband edges, the centre frequency ω_0 can be computed using$\omega_0 = \sqrt{\omega_1 \times \omega_2}$.

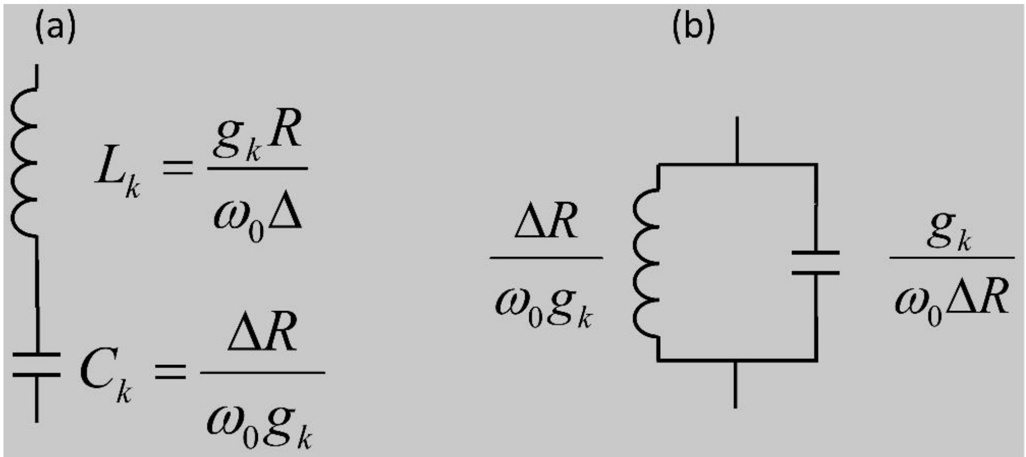

Figure 5: Filter Transformation (a) series inductor $L_k$to a series $L-C$ circuit (b) shunt capacitor C_k to a shunt $L-C$ circuit.

The bandpass filter is desired to have a passband in the 5 to 8 GHz range. Thus, $\omega_1 = 5GHz$, $\omega_2 = 8GHz$and$\omega_0 = 6.32GHz$. Using $N = 4$, the element values g_k are $g_1 = g_4 = 0.7654$ and$g_2 = g_3 = 1.8478$. The characteristic impedance $R = 50\Omega$. By substituting these values in equations (5)-(8), $L-C$ values are obtained. They are: $L_1 = 0.78nH$, $C_2 = 0.82\,pF$, $L_3 = 4.92nF$, $C_4 = 0.13pF$, $L_5 = 0.32nH$ $C_6 = 1.97pF$,$L_7 = 2.04nH$ and $C_8 = 0.312pF$.

Method, result, and discussion

Figure 6(a) depicts the schematic of the bandpass filter. A 50Ω characteristic impedance can be seen at the input (source) and output (load) terminals, and the $L-C$element values are exactly as the calculated values.

The bandpass filter frequency response is shown in Figure 6(b). The bandpass filter has a -3 dB return loss ($S_{11}(dB)$) and insertion loss $S_{11}(dB)$ and $S_{21}(dB)$ at 5 GHz and 8 GHz, denoted by m1 and m4, respectively. Moreover, it has a 0 dB insertion loss at the centre frequency$\omega_0 = 6.32GHz$, as shown by $S_{21}(dB)$ and $S_{21}(dB)$ curves. Therefore, the bandpass filter can allow frequencies between 5-8 GHz to pass and block others (below and above), as shown by the $S_{11}(dB)$ curve.

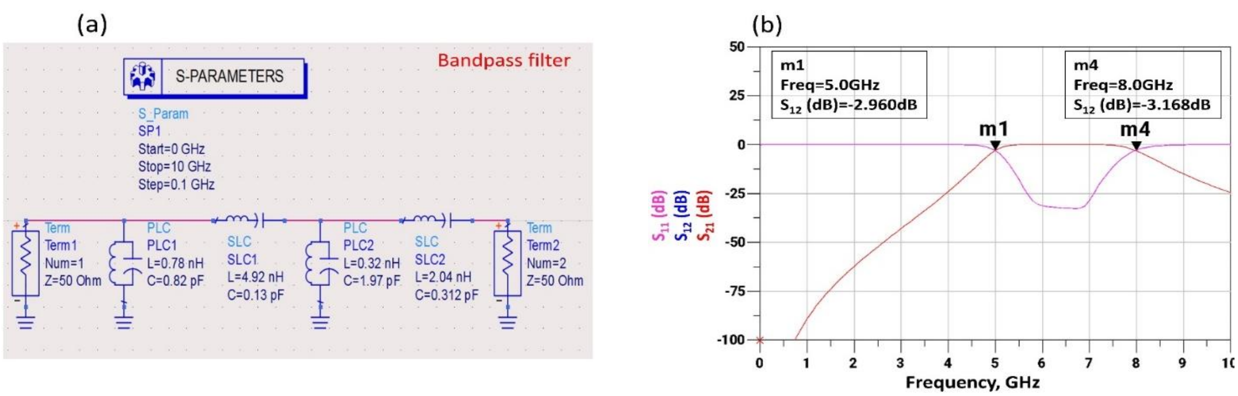

Figure 6: Bandpass filter (a) Schematic diagram (b) frequency response

CONCLUSION

This paper presents the design and analysis of microstrip filters. A microstrip lowpass filter prototype was initially designed, then transformed and scaled into a step impedance lowpass filter and a bandpass filter. The frequency responses of all the filters show -3 dB insertion loss at a 1.5 GHz cutoff frequency. The lowpass filter response shows a good insertion loss of -24 dB at 3 GHz. However, due to the high electrical length, the step impedance filter exhibits a poor insertion loss of -18 dB at 3 GHz. The bandpass filter exhibits a -3 dB bandwidth of 3 GHz within the 5-8 GHz frequency range. Our approach of using ADS for the design offers the advantages of simplicity, reduced computation time, and resources over a filter designed using an artificial neural network, which is a data-intensive method, although both results agree very well. The filters could find potential applications in audio amplifiers and speakers.

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