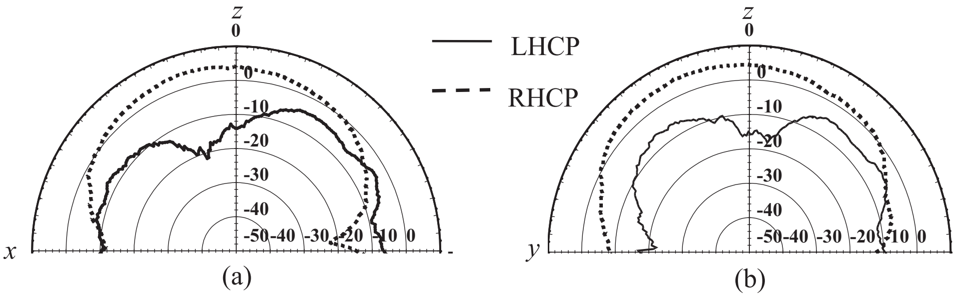

Figure 4 Radiation pattern of the proposed antenna at 3740 MHz. (a) *x-z* plane (b) *y-z* plane

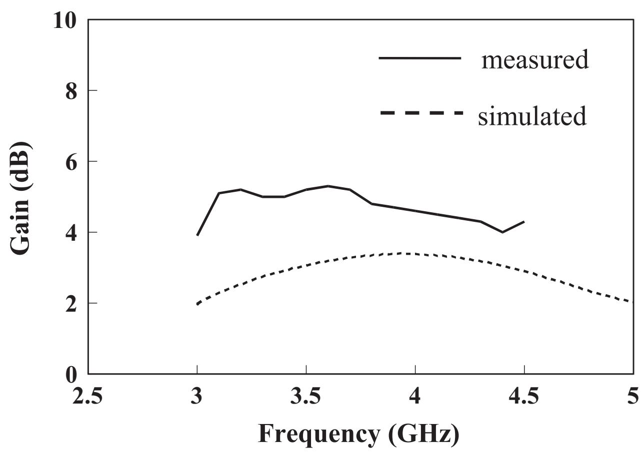

Figure 5 Gain variation against frequency for proposed antenna plane (b) *y-z* plane

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COMPACT STEPPED-IMPEDANCE LOW-PASS FILTER WITH A SLOT-BACK MICROSTRIP LINE

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ABSTRACT: *A high-performance stepped-impedance low-pass filter is proposed by using a microstrip line with a longitudinal slot in the ground plane (slot-back microstrip line). The design process is simple and yet effective in improving the performance of the filter structure. Expressions are proposed to obtain the characteristic impedance of a slot-back microstrip line. Because of the high characteristic impedance and slow-wave effect of a slot-back microstrip line, the proposed filter shows a sharper cutoff and a wider stopband with higher attenuation within a smaller circuit area when compared with a conventional stepped-impedance low-pass filter.* Microwave Opt Technol Lett 50: 1058–1061, 2008; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.23284

Key words: *stepped-impedance low-pass filters; planar passive filters; compact filters*

1. INTRODUCTION

In this fast moving age, wireless communications is increasingly demanding on new technology. The miniaturization of circuits and components becomes an important research area. Circuit board gets increasingly denser, and the requirements for devices become increasingly stringent in terms of size and performance. A filter is an essential component in any wireless communication devices. Therefore, the design of a compact filter with high selectivity and good stopband and passband performance is an essential research topic. A commonly used low-pass filter design [1] is based on the ladder LC lumped-circuit low-pass filter prototype.

Recently, a significant amount of work has been done to optimize the performance of a low-pass filter [2–6] based on this filter prototype. One of the important optimization techniques is the implementation of the inductive elements of the filter prototype using a defected ground structure (DGS) [2–5]. In Ref. 3, a DGS-base low-pass filter shows an effective suppression of the harmonic response, an improvement on the cutoff, and a reduction in circuit area. However, the design demands a complicated process to obtain the dimensions of the DGS from the circuit model. In Refs. 4 and 5, DGS-base low-pass filters obtain improvement on the cutoff and the bandwidth of the stopband while their insertion loss in the passband is considerably high. Other than a DGS, new transmission lines such as a micromachined overlay coplanar waveguide (CPW) [6] is applied for the optimization of a low-pass filter in terms of cutoff and stopband. For the optimized low-pass filter in Ref. 6, the micromachined overlay CPW is used to implement the capacitive elements of the filter prototype. This optimized filter shows improvement in terms of size, loss, cutoff, and stopband, but its structure and fabrication process are intrinsically complicated. By taking the approaches aforementioned [3, 6], low-pass filters can be effectively optimized. However, the design procedure and structure are highly complex and tedious.

Conventionally, the implementation for a ladder filter prototype is simple. It consists of the cascade of high- (narrow) and low-impedance (wide) microstrip line sections which is the well-known stepped-impedance low-pass filter [1]. Although stepped-impedance low-pass filters are simple to design and are easy to fabricate, it suffers from a flat cutoff, low attenuation of the stopband, and spurious passband that is close to the cutoff. Its disadvantages prevent the filter from being used in advanced communication systems. The problem at the cutoff and in the stopband of a conventional stepped-impedance low-pass filter can be solved by increasing the ratio of the impedances of the narrow microstrip line section to that of the wide microstrip line section. However, for a conventional substrate with perfect ground plane and perfect dielectric material, this high ratio of the impedance results in a extremely narrow high-impedance microstrip line section and/or an extremely wide low-impedance microstrip line section. This makes it hard to realize practically because of the fabrication limitation. Although this problem is addressed in Ref. 7, solutions were not provided in that paper. One solution was proposed by milling holes in the substrate to modify the substrate locally and increase the impedance of the narrow microstrip line sections [8]. In this approach, the ratio of impedance is increased, and a sharper cutoff, a wider stopband, and a smaller physical size are obtained at the same time. However, it shows much higher insertion loss in the passband because of the milled holes in the substrate. The introduction of a longitudinal slot in the ground plane of a narrow microstrip line section (named as "slot-back microstrip line" in this paper) has been shown to be an effective means to increase its characteristic impedance and wave propagation constant [9, 10]. In these papers, the characteristic impedance of the slot-back microstrip line is obtained using commercial softwares. The characteristic impedance is shown to increase as the width of the slot increases provided that the width of the microstrip line is fixed. In both papers, the slot-back microstrip line is used to implement the inductive elements of an elliptic low-pass filter, and the modified filters show a sharper cutoff and higher attenuation than the corresponding conventional filters.

In this paper, a high-performance stepped-impedance low-pass filter is proposed with a simple design procedure and a easy fabrication process by using a slot-back microstrip line section. The slot-back microstrip line sections are used to implement the inductive sections of the filter prototype. An expression is proposed to obtain its characteristic impedance. Because of the significant increase in the characteristic impedance of the slot-back microstrip line sections, the proposed filter obtains an increase in the ratio of impedances between the narrow microstrip line section and the wide one. Therefore, this proposed stepped-impedance low-pass filter obtains improved performance in terms of the cutoff, attenuation, and bandwidth of the stopband. This optimization is achieved with a reduction in circuit area and a small insertion loss in the passband. Moreover, it is noted that the proposed stepped-impedance low-pass filter shows a similar geometry to that of an electromagnetic band-gap (EBG) microstrip structure [11]. This paper indicates the intrinsic difference between an EBG microstrip structure and a stepped-impedance low-pass filter when the proposed design procedure is compared with that proposed in Ref. 11.

2. DESIGN PROCESS

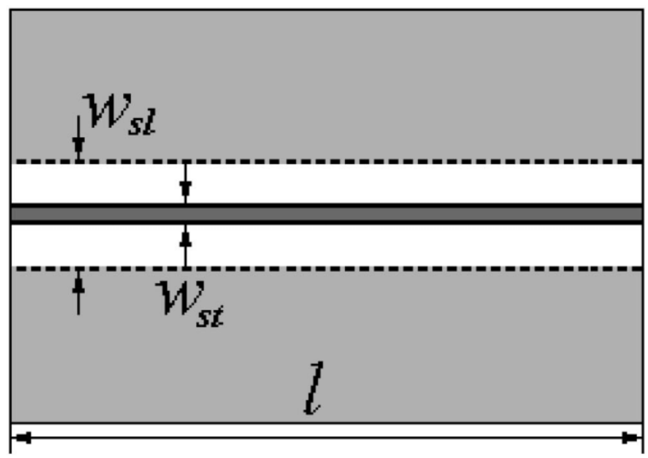
The design process of the proposed stepped-impedance low-pass filter consists of obtaining the circuit parameters of a slot-back microstrip line [9, 10] and determining the dimensions of the microstrip line sections.

2.1. Circuit Parameters of Slot-Back Microstrip Line

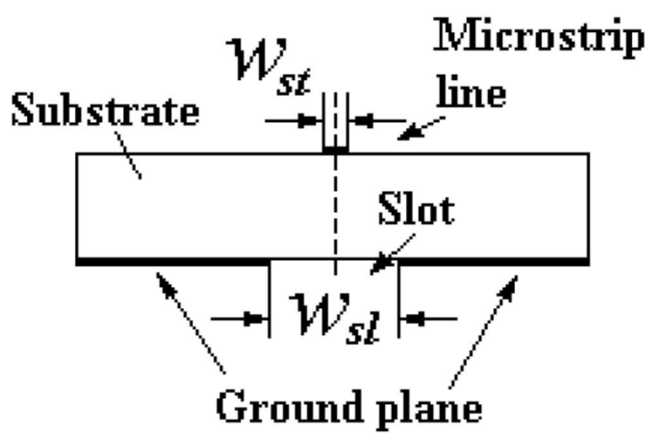
Figures 1(a) and 1(b) show the top view and cross-sectional view of a slot-back microstrip line. As can be seen in Figure 1(a), a longitudinal slot is etched in the ground plane below a conventional microstrip line. The width of the microstrip line is w_{st} and that of the slot is w_{sl}. If $w_{sl} > w_{st}$, it causes an increase in both the equivalent inductance and the characteristic impedance of the microstrip line because the coupling between the microstrip line and the ground plane is eliminated by the wide slot in the ground plane. The length of the microstrip line and that of the slot in the ground plane are the same and denoted by l. Both the microstrip line and the slot in the ground plane are symmetric to the dotted line in the middle, as shown in Figure 1(b).

For this slot-back microstrip line, the characteristic impedance, $Z_{0\text{-sl}}$, and the propagation constant, β_{sl}, can be deduced for a specified cutoff frequency. The characteristic impedance, $Z_{0\text{-sl}}$, can be obtained from (1) and (2).

$$\tau_o = \frac{\tau_i}{e^{2j\theta}}, \tag{1}$$



(a)



(b)

Figure 1 (a) The top view of a slot-back microstrip line. (b) The cross-sectional view of a slot-back microstrip line

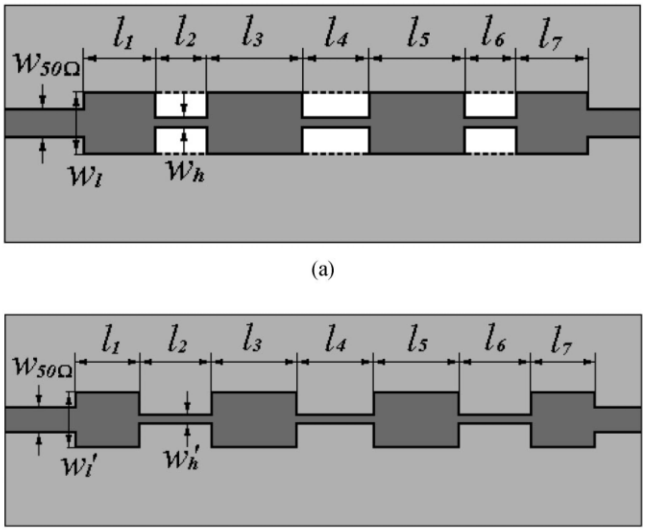


Figure 2 (a) The schematic of the proposed stepped-impedance low-pass filters with slot-back microstrip line sections. (b) The schematic of the conventional stepped-impedance low-pass filter

$$Z_{0\text{-sl}} = Z_L \frac{1 - \tau_0}{1 + \tau_0}, \tag{2}$$

where τ_o and τ_i are the reflection coefficients at the output and input port, respectively. $\theta = \beta_{sl} l$ is the phase delay at the output port with respect to the input port. $Z_{0\text{-sl}}$ and Z_L is the characteristic impedance of the targeted slot-back microstrip line and the load impedance, respectively. Z_L is set to be 50 Ω. To obtain $Z_{0\text{-sl}}$ from (1) and (2) and β_{sl}, τ_i and θ have to be found at the specified cutoff frequency. This can easily be done with the aid of commercially available simulation software such as Advanced Design System through simulation of the slot-back microstrip line shown in Figure 1. For β_{sl}, it can be extracted with a known length of the transmission line l at that specified cutoff frequency.

2.2. Dimensions of the Microstrip Line Sections

In the proposed stepped-impedance low-pass filter design, this slot-back microstrip line with tailored length will be used to implement the inductive elements in a ladder filter prototype. This will enhance the inductance and, at the same time, provides high characteristic impedance for the inductive elements. The slot-back microstrip line sections allows for a higher impedance ratio between the narrow microstrip line section and the wide microstrip line section when compared with a conventional filter with a perfect ground plane. Therefore, it results in a compact size, high-performance stepped-impedance low-pass filter. Using $Z_{0\text{-sl}}$ and β_{sl} obtained above, the length of these microstrip line sections can be determined using standard design formulae for stepped-impedance low-pass filters [12]. The length of the wide microstrip sections is also decided by the same standard design process.

3. SIMULATED AND MEASURED RESULTS

A seven-pole conventional Chebyshev low-pass filter prototype with 0.01 dB ripple is implemented to verify Eqs. (1) and (2) and to demonstrate the effectiveness of the slot-back microstrip line sections in a stepped-impedance low-pass filter. For comparison purposes, both the conventional filter and the proposed slot-back filter are simulated and measured. The cutoff frequency is set at 2 GHz. Taconic with a dielectric constant of 2.46 and a thickness of 30.5 mils is used as the substrate. According to the design process detailed earlier, a slot-back microstrip line with $w_{st} = 0.6$ mm, $w_{sl} = 10$ mm, and $l = 15$ mm is simulated using Advanced Design System. Based on the simulation results and using (1) and (2), $Z_{0\text{-sl}}$ and β_{sl} are found to be 167.0 Ω and 65.8 radian/m at 2 GHz. For comparison purposes, the characteristic impedance and wave propagation constant of the same microstrip line over a perfect ground plane Z_0 and β are obtained to be 101 Ω and 41.8 radian/m using LineCalc of Advanced Design System at the same cutoff frequency. The characteristic impedance of a microstrip line is increased significantly by introducing a longitudinal slot in the ground plane [9, 10]. Moreover, its propagation constant is increased considerably, which shows the significant slow-wave effect.

Figure 2(a) shows the schematic of the proposed stepped-impedance low-pass filter, and Figure 2(b) shows the corresponding conventional stepped-impedance low-pass filter for comparison purposes. $w_{50\Omega}$ is set to be 2.2 mm corresponding to a characteristic impedance of 50 Ω at 2 GHz for both structures. w_l and w_h are set to be equal to 10 mm and 0.6 mm, respectively, where $w_l = w_{sl}$ and $w_h = w_{st}$ corresponding to the dimensions set for the slot-back microstrip line above. $Z_{0\text{-sl}} = 167.0$ Ω and $\beta_{sl} = 65.8$ radian/m are substituted in the conventional design formulae for the inductive elements of stepped-impedance low-pass filters [12] to determine the length of the slot-back microstrip line sections. The length of the wide microstrip line sections is also determined using the standard design formulae.

For the conventional stepped-impedance low-pass filter, w_l' is set to be equal to w_l, and w_h is set to be equal to w_h' for comparison. The length of this conventional design is per normal. Table 1 shows the lengths of the two seven-pole stepped-impedance low-pass filters. As can be seen in Table 1, the lengths of the slot-back microstrip line sections in the proposed filter are reduced significantly from those of the narrow microstrip line sections in the conventional filter. The total length of the novel filter is reduced by 24.1% from the conventional filter resulting in a compact filter design. The reduction in length is due to the significant slow-wave effect of the slot-back microstrip line.

The proposed stepped-impedance low-pass filter and the conventional filter are both simulated. Figure 3 shows the simulated S_{21}-parameters of the two filter structures and the simulated S_{21}-parameter using their corresponding lumped-circuit elements. As seen in Figure 3, these two structures are working at the same cutoff frequency at 1.9 GHz. No shifting of frequency is introduced by replacing the narrow microstrip line sections with the slot-back microstrip line sections. Compared with the conventional filter, the proposed filter shows a frequency response that is more similar to the lumped-circuit elements. This is because the slot-back microstrip line provides a high characteristic impedance, and therefore, a better approximation to the inductive lumped-circuit elements. As shown in Figure 3, the proposed filter has a high selectivity of 33.8 dB/GHz, whereas the conventional filter has a selectivity of 27.7 dB/GHz. The proposed filter shows a sharper cutoff performance. It is also observed that the spurious passband of the conventional filter is effectively suppressed in the proposed filter. When comparing their ripple levels in the passband, the proposed filter has a ripple level of 0.19 dB, slightly higher than

TABLE 1 Dimension for Stepped-Impedance Low-Pass Filters

Stepped-Impedance Low-Pass Filters	L_1	L_2	L_3	L_4
Proposed filter	3.8	6.3	8.3	7.4
Conventional filter	3.8	11.8	8.3	13.8

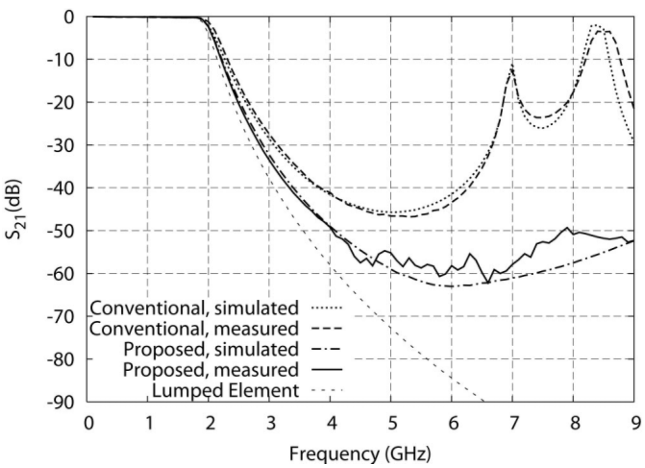


Figure 3 The simulated and measured S_{21}-parameters of the proposed and the conventional stepped-impedance low-pass filter, and the simulated S_{21}-parameter of their corresponding circuit model

the conventional filter's ripple level of 0.16 dB. This shows that the etched patches in the ground plane do not generate much additional insertion loss in the passband.

The proposed stepped-impedance low-pass filter and the conventional filter are fabricated and tested. The measured S_{21}-parameters for the two stepped-impedance low-pass filters are shown in Figure 3. The measured results are in good agreement with the simulated results for both structures. The fabricated proposed low-pass filter shows a ripple level of 0.27 dB in the passband and a selectivity of 33.5 dB/GHz, and the fabricated conventional low-pass filter shows a ripple level of 0.19 dB in the passband and a selectivity of 27.4 dB/GHz. The fabricated proposed stepped-impedance low-pass filter demonstrates superior filtering performance to the conventional filter.

4. CONCLUSION

In this paper, a stepped-impedance low-pass filter is optimized by using a slot-back microstrip line which has a high equivalent inductance and a high characteristic impedance. The design formulae and procedure for this proposed filter is presented. Because of the high characteristic impedance of the slot-back microstrip line, when it is used as the inductive elements of a ladder filter prototype, the proposed filter achieves a sharper cutoff and higher attenuation in the stopband. It provides effective suppression of the spurious passband. Moreover, the slow-wave effect of the slot-back microstrip line leads to a significant reduction in the circuit area of this proposed filter. For the performance in the passband, the increase in the insertion loss of the passband due to the slot is insignificant. The proposed stepped-impedance low-pass filter shows good filtering functions, is easy to design, and is easy to fabricate.

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AN ACCELERATING TECHNIQUE FOR ANALYZING OPEN-ENDED RECTANGULAR WAVEGUIDES

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ABSTRACT: *An accelerating technique for calculating the reflection coefficient matrix of an open-ended rectangular waveguide with infinite flange is proposed in this paper. The matrix equation, which contains double surface integrals, is initially established using the mode-matching method. To improve the computation efficiency, the double surface integral is converted to one surface integral in the spectral domain using the Sommerfeld identity. Then the matrix pencil method and the Gaussian quadrature are employed to accelerate the computation of the matrix elements, which results in the summation of a short series. An open-ended WR-90 waveguide model is analyzed to demonstrate the efficiency of the method in the calculation of the reflection coefficients.* © 2008 Wiley Periodicals, Inc. Microwave Opt Technol Lett 50: 1061–1066, 2008; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.23283

Key words: *reflection coefficient matrix; open-ended rectangular waveguide; matrix pencil method; Gaussian quadrature*

1. INTRODUCTION

Open-ended waveguides are widely used in many applications, such as aeronautics, large phased array systems, thermography, nondestructive measurement, etc. Therefore, they have received extensive attention for decades [1]. Various methods were proposed to analyze the radiation from open-ended waveguides, such as the variational principle [2], the correlation matrix method [3],