Design and fabrication of a novel multilayer bandpass filter with high-order harmonics suppression using parallel coupled microstrip filter

Esmaeil Fathi | Farbod Setoudeh | Mohammad Bagher Tavakoli

1Department of Electrical Engineering, Islamic Azad University, Arak, Iran
2Faculty of Electrical Engineering, Arak University of Technology, Arak, Iran

Abstract
This study presents a novel multilayer structure of parallel coupled-line bandpass filter centered at 2.42 GHz with a fractional bandwidth value of approximately 19.4%. The designed filter can suppress harmonics with an appropriate frequency response by incorporating different techniques based on the multilayer technique. A combination of different techniques such as radial microstrip stubs and defected ground structure (DGS) and defected microstrip structure techniques are employed to suppress harmonics up to $5f_0$. These techniques are used in two layers to suppress up to $5f_0$. In addition, in this study, the effects of different parameters, such as the width of slot-line DGS, the angle of diagonal line slots in the upper layer, and the air gap between the two layers on the filter performance, are investigated. To verify the correct circuit operation, the designed filter is implemented and tested. The measurement results of the proposed filter are compared with the simulation results.

KEYWORDS
bandpass filter, defected microstrip structure (DMS), defective ground structure (DGS), harmonics suppression, parallel coupling lines

1 | INTRODUCTION

Microstrip bandpass filters (BPFs) are fundamental parts of superheterodyne receivers that are currently used in many radio frequency and microwave communication systems [1,2]. There are several techniques for designing BPFs, such as coupled structures, stepped-impedance structures, open-circuit stubs, T-shaped resonators, substrate integrated waveguide technology, and balance differential topology [3–6]. One of the most commonly used methods for designing a BPF is the use of parallel coupled lines due to the method’s practical efficiency, high selectivity, low insertion loss, sharp skirt characteristics, flat structure, low-cost synthesis method, compactness of the coupling capacitor, easy integration, and a wide-range fractional bandwidth (FBW) [7]. In [3], coupled feed lines and rectangular stubs are used to design and fabricate BPFs [3]. In [4], a combination of a T-shaped resonator and a coupled feed line is used to design and fabricate BPFs [4]. In [5], the defected coplanar waveguide (CPW) is used to design a dual-band BPF [5]. In [6], coupled resonators are utilized to design a dual-layer balance BPF with high return loss (RL) in the passband. In [8], open-circuited stubs and coupled stubs are used to design BPFs in GSM and WLAN applications. In [9], the CPW structure is used to design tunable BPFs,
and theoretical analysis is employed to omit the second spurious passband [9]. In recent years, the defected ground structure (DGS) is used in a complementary splitting resonator [10]. In [11], multimode coupled resonators are used to design BPFs for TETRA, GSM, and GPS applications [11]. In [12], a parallel coupled-line BPF is designed by incorporating DGSs into feed and coupled lines. In [13], a modified triple-mode resonator based on a mid-coupled line between odd-mode resonances was used to design a triple-band BPF.

Transmission zeros (TZs) and transmission poles (TPs) can be used to achieve the desired filter performance in the passband and stopband [14–17]. In [14], a BPF with super high selectivity is designed using three pairs of coupled lines and two open stubs [14]. In [15], a combination of TZs and TPs is used to achieve sharp roll-off skirts in wideband BPFs based on coupled lines.

The positions of five TPs and eight TZs are calculated using odd and even methods and input impedance analysis [15]. In [16], a combination of TZs and TPs is applied to suppress up to the second harmonic [16]. In [17], to achieve the desired passband performance, a coupled-line-stub cascaded structure is used to generate TZs [17].

In [18], an ultra-wide-band BPF is designed using coupled lines for telecommunication applications. Although this kind of filter is commonly used, it has drawbacks, such as spurious responses, which are produced at and after second-order harmonic frequencies owing to the disparate even- and odd-mode phase velocities in parallel coupled lines. In other words, due to the difference in phase velocities in odd and even modes, resulting in the asymmetry of transmission electron microscopy (TEM) wave frequency response, unwanted harmonic frequencies are generated in multiples of the central frequency [19]. However, harmonic suppression is emphasized by combining edge perturbations in the conventional filter to modulate asymmetric phase velocities. One of the harmonic suppression methods in microstrip coupled-line BPFs is even- and odd-mode phase velocity compensation [20,21]. In [20], over-coupled resonators are used to compensate for the phase velocity between the even and odd modes for achieving a 50-dB suppression level. In [21], the phase velocity compensation is used in a wiggly-line filter to achieve a 30-dB rejection level. Various methods have been employed to suppress harmonics in microstrip filters, for example, microstrip coupled ring resonators, including photonic bandgap (PBG) structures [22], DGS [23–25], capacitive compensation [26], substrate suspension [27], wiggly-line structure [28], periodic groove structure [29], corrugated parallel coupled lines [30], triangular corrugation structure [31], compact fractal-shaped microstrip coupled lines [32], meandered parallel coupled lines [33], asymmetrical perturbation structure [34], band-stop filter feed lines [35], centered single groove [36], and stepped hairpin DGS [37]. Subsequently, periodic patterns etched in the ground plane based on two-dimensional uniform circular patterned PBG structures are used to suppress the second harmonic in parallel coupled-line BPFs [38]. In [39], a wide stopband coupled-line BPF centered at 1.5 GHz based on asymmetric stepped-impedance resonators is designed to suppress harmonics to achieve a suppression level of $-23.7 \, \mathrm{dB}$ up to $10.6f_0$ [39]. Subsequently, a short-circuited microstrip coupled-line hairpin resonator is used to design BPFs centered at $2.2 \, \mathrm{GHz}$ to achieve a suppression level of $20 \, \mathrm{dB}$ up to $4f_0$ [40]. A dual transmission line-based BPF centered at $1.86 \, \mathrm{GHz}$ is proposed for harmonic suppression up to the fourth order [41]. In addition, in [42], a triangular crimping technique is proposed. In this technique, with a change in the length of the coupling, two filter edges from $\lambda/4$ to $\lambda/6$, and a slight change in the type of fold can improve harmonic suppression in $4f_0$. Accordingly, a periodic triangular corrugation is used to design a parallel coupled-line BPF centered at $5.25 \, \mathrm{GHz}$ for harmonic suppression up to the second order [43]. The use of fractal shapes, such as Koch fractals and Murkowski fractals [44,45], is another harmonic elimination method.

In [46], the second and third harmonics can be suppressed using a branch-line coupler with closed-loop and open-loop resonators. Recently, to remove the second harmonic in a parallel coupled-line BPF, a coupling capacitor is used surrounding the offset gap in a compact filter. To improve the level of harmonic suppression, the incorporation of rectangular disturbances is used [47]. In this study, the effects of multilayer, DGS, and DMS techniques in parallel coupled-line filters centered at $2.42 \, \mathrm{GHz}$ with an FBW of approximately $19.4\%$ are investigated. Initially, the effects of compactness on filter characteristics have been studied by synthesizing the distributed filter network. Experimental results show an improvement in the second, third, fourth, and fifth harmonic suppression levels. The proposed method shows an improvement of more than $25 \, \mathrm{dB}$ in the suppression level using the proposed filter. Size reduction has been achieved by incorporating different techniques based on the multilayer technique.

2 | PARALLEL COUPLED-LINE FILTER DESIGN

The purpose of this study is to design a BPF with the following characteristics: a third-order $0.5\,$-dB ripple Chebyshev BPF centered at $2.42 \, \mathrm{GHz}$. The lower cutoff frequency is $f_0 = 2.2 \, \mathrm{GHz}$, and the upper cutoff
frequency is $f_{IL} = 2.6$ GHz. Figure 1 presents a third-order low-pass Chebyshev filter.

As shown in Figure 1, element values, normalized to make $g_0 = 1$ and $\omega_c = 1$ rad/s, can be calculated as follows [48,49]:

$$g_0 = g_{n+1} = 1,$$  \hspace{1cm} (1)

$$g_1 = 2\sin\left(\frac{\pi}{2n}\right),$$  \hspace{1cm} (2)

$$g_i = \frac{4\sin\left[\frac{(2i-1)\pi}{2n}\right] \sin\left[\frac{(2i-3)\pi}{2n}\right]}{\gamma^2 + \sin^2\left[\frac{(i-1)\pi}{n}\right]}$$  \hspace{1cm} \text{for } i = 2, 3, ..., n, \hspace{1cm} (3)

$$g_{n+1} = \begin{cases} 1.0 \text{ for } n \text{ odd} \\ \coth^2\left(\frac{\beta}{4}\right) \text{ for } n \text{ even} \end{cases},$$  \hspace{1cm} (4)

$$\gamma = \sinh\left(\frac{\beta}{2n}\right) \text{ and } \beta = \ln\left(\coth\left(\frac{L_{Ar}}{17.37}\right)\right),$$  \hspace{1cm} (5)

where $L_{Ar}$ denotes various ripples at the passband and $n$ is the filter order. Using (1)–(4), the element values of the third-order low-pass Chebyshev filter are computed as $g_0 = g_4 = 1, g_2 = 1.0967, $ and $g_1 = g_3 = 1.5963$. The general structure of parallel coupled microstrip BPF is presented in Figure 2 [47].

The coupled-line structure is composed of two quasi-TEM modes: even and odd. For an even-mode incitation, both microstrip lines have the same voltage potentials. To implement an odd mode, both microstrip lines should have opposite voltage potentials or carry opposite-sign charges.

$$g_{n+1} = \frac{1}{Y_0} \left[1 + \frac{J_{j+1}}{Y_0} + \left(\frac{J_{j+1}}{Y_0}\right)^2\right],$$  \hspace{1cm} (6)

where $Z_{oe}$ and $Z_{oo}$ denote the even- and odd-mode characteristic impedances and $g_0, g_1, ..., g_{n+1}$ represent the element values of the ladder structure of $n$-order low-pass prototype with $\omega_c = 1$ rad/s [48]. Based on (1) to (11), Table 1 shows the design parameters of conventional parallel coupled lines.

The proposed filter is designed on a substrate with a relative dielectric constant of 3.55 and a thickness of 0.8 mm. Thus, the width, length, and gap of each stage in parallel coupled lines can be calculated using the calculated even- and odd-mode characteristic impedances based on Table 1.

After creating the filter using the obtained values and simulating and optimizing it in the ADS software, the finalized width, gap, and length of each stage are calculated. Figure 3 shows the proposed BPF using parallel coupled lines.
The layout of the proposed filter is created in the ADS software after calculating the width, gap, and length of each stage and is then simulated using an electromagnetic simulation tool. This circuit is designed on the Rogers 4003 substrate with a thickness of 0.8 mm and $\varepsilon_r = 3.55$. Figure 4 presents the simulated $S$-parameter plots for the proposed filter.

As presented in Figure 4, the second and fourth harmonics passed through the filter. As shown in Figure 4, the values of insertion loss and RL in the passband are $-1.7$ dB and $-8$ dB, respectively.

This result is due to the nature of the filter and the difference between the even- and odd-mode characteristic impedance of each stage in parallel coupled lines.

3 | HARMONIC SUPPRESSION IN PARALLEL COUPLED-LINE BPF

3.1 | Effect of radial stub

A radial stub (RS) is used in the proposed filter configuration for harmonic suppression. An RS is used in low- and high-power microwave circuits for impedance matching. An RS is used to eliminate the effect of parasitic circuit elements, which provides a very low impedance path to ground RF signals [50,51].

An RS exhibits a short-circuit behavior at the point, where it is placed, thereby preventing these elements from placing and making metal through the Via hole in the planar circuit unnecessary [52]. Figure 5 presents the structure of an RS and the equivalent lumped circuit [53].

As presented in Figure 5, an RS can be considered a series combination of an inductor and a capacitor. The values of input impedance ($Z_{im}$), inductance ($L_e$), and capacitance ($C_e$) in this system can be calculated, as described in [53]:

$$Z_{in} \approx -j \frac{120\pi h\beta}{\theta_t\sqrt{(\varepsilon_{eff})}} \left( \ln \frac{r_1}{r_o} + \frac{1}{2} \frac{2}{(\beta r_o)^2} \right).$$

$$L_e = \frac{120\pi h}{\theta_t \varepsilon} \left[ 2.8 - 10 \frac{r_1}{r_o} \right].$$

$$C_e = \frac{\theta_t r_o^5 \varepsilon_{eff}}{240\pi h c}.$$

The resonance frequency of an RS can be calculated as
\[ \omega_0 = \frac{1}{\sqrt{L_{r1} C_{r1}}} = \frac{1}{\varepsilon \sqrt{\frac{\varepsilon + 2}{2}} \left| \ln \frac{\varepsilon}{\varepsilon + 0.5} \right|} \]  

(15)

where \( h \) denotes the dielectric thickness; \( \beta \), the phase constant; \( \theta \), the spanning angle in the RS; \( c \), the speed of light; \( \varepsilon_{\text{eff}} \), the effective dielectric constant; \( r_i \), the inner radius of the RS; and \( r_o \), the outer radius of the RS. A harmonic effect can be improved by combining RSs at the input and output of a microstrip parallel coupled-line BPF.

In this study, a combination of large RSs at the input of the proposed filter was used to create a pole at low frequencies around the frequency \( 2f_0 \), and small radials at the end of the filter are used to suppress \( 4f_0 \). In general, small RSs can be used to improve the frequency response at \( 4f_0 \).

To suppress the second harmonic, a pole must be created in the second harmonic location (\( 2f_0 \)) or 4.8 GHz; for this purpose, the RS-based filter in Figure 6 is used at the input of the proposed filter.

The poles created by the proposed circuit, as shown in Figure 6, is calculated as follows:

\[ \frac{V_{\text{out}}}{V_{\text{in}}} = \frac{\frac{1}{L_{r1}} || Ls}{\frac{1}{L_{r1}} || Ls} + \frac{1}{C_{r1}} + \frac{1}{C_{r1}} + \frac{1}{L_{q}} + \frac{1}{C_{r1}} + \frac{1}{L_{q}} \]  

(16)

where \( L_{r1} \) and \( C_{r1} \) represent the inductance and capacitance of RSS, respectively. \( L \) and \( L_q \) indicate the inductance of the microstrip stub.

The poles created by the proposed circuit can be calculated from 16; thus,

\[ P_1 P_2 P_3 P_4 = \left( L_{r1} C_{r1} L C + LL_q C_{r1} C \right)^{-1} \]  

(17)

\[ P_1 P_2 + P_3 P_4 = \frac{L_{r1} C_{r1} L C + LL_q C_{r1} C}{L_{r1} C_{r1} L C + L_q C_{r1} L + L C_{r1}} \]  

(18)

where \( P_1, P_2, P_3, \) and \( P_4 \) denote the pole of the system 16.

The structure parameters used in Figure 3 are selected to place a pole at \( f = 4.8 \) GHz. Figure 7 presents the simulated S-parameter plots for the proposed structure shown in Figure 6.

In this case, if the structure designed in Figure 3 is used at the beginning of the parallel coupled-line BPF, it can suppress the second harmonic in the designed filter. In addition, to improve the behavior of the filter in the fourth harmonic, we use the structure designed in Figure 3 at the end of the filter, and structure parameters are selected to place a pole at \( f = 9.6 \) GHz. After adding an RS to the parallel coupled-line filter, the final filter dimensions, such as the gap between two resonators and the width and length of the resonators, are calculated to adjust the filter frequency response in the desired range.

Figure 8 presents the microstrip parallel coupled-line BPF proposed on the basis of RSs. After adding an RS to the proposed parallel coupled-line filter, the final filter dimensions such as the gap between two resonators and the width and length of the resonators are calculated to adjust the filter frequency response in the desired range. Figure 9 shows the simulated S-parameter plots for the proposed filter shown in Figure 8.

Figure 6  Radial stub-based filter used at the end of the proposed parallel coupled-line filter

Figure 7  Simulation S-parameter of the proposed structure in Figure 6

Figure 8  The proposed parallel coupled-line filter based on radial stubs
3.2 Effect of the DMS and DGS techniques

As illustrated in Figure 10, there are two modes of current flow in parallel coupled lines, the first of which is the displacement current flow between each conductor carrying the same polarity with respect to the conductive ground that is common between them.

As can be seen from Figure 10, there are two excitation states can be considered in parallel coupled lines. In the even-mode excitation, the currents are in one direction in two strip conductors even though the currents in the odd mode are in an opposite direction along the conductors. The phase velocity equation is as follows:

$$\vartheta_p = \frac{c}{\sqrt{\varepsilon_{\text{reff}}}}.$$  \hspace{1cm} (19)

As can be seen from Figure 10, there are more fringing fields in the even mode than in the odd mode. Therefore, \( \varepsilon_{\text{reff}} \) in the even mode will be greater than that in the odd mode. According to (19), we will have

$$\vartheta_{\text{even}} < \vartheta_{\text{odd}}.$$  \hspace{1cm} (20)

The electrical length of a microstrip transmission line can be calculated as follows:

$$\theta = \beta l = \frac{l\omega}{\vartheta_p}.$$  \hspace{1cm} (21)

$$\theta_{\text{even}} > \theta_{\text{odd}}.$$  \hspace{1cm} (22)

Thus, it can be inferred that the electrical length of the even mode is greater than that of the odd mode in a microstrip coupled line. On the other hand, the impedance of the even mode is less than that of the even mode. The unequal electrical lengths and impedances in even–odd modes cause the resonance frequencies to have different values. As depicted in Figure 1, the current distribution in the odd mode used in the internal coupled edge position is parallel. If we increase the electric length of the odd mode to \( \theta_{\text{even}} = \theta_{\text{odd}} \), the phase velocity of even–odd modes is equal. This creates a resonator in parallel coupled lines. In this study, the DMS technique is used to equalize the phase velocity of even–odd modes.

As depicted in Figure 8, the second- and third-order harmonics are suppressed by adding RSs on the input and output of the parallel coupled-line filter, but the proposed filter does not perform well in the fourth- and fifth-order harmonics. Therefore, the DMS technique is used to solve this problem, suppressing the fourth- and fifth-order harmonics.

In this study, the DMS technique is used to suppress \( 4f_0 \) and \( 5f_0 \) harmonics, whereas the DGS technique is used to improve the RL in \( f_0 \) and \( 4f_0 \) harmonics.
3.3 Study of multilayer technique

The multilayer technique can be used to compensate for the difference between the phase velocity of the even and odd modes and to reach equal phase \[ 2,54 \]. The proposed filter consists of two layers with an air gap of 0.8 mm. In the proposed filter, the first or bottom layer is fabricated on the Rogers RO4003 substrate with the dielectric constant \( \varepsilon_r = 3.55 \), and the second layer is fabricated on the FR4 substrate with the dielectric constant \( \varepsilon_r = 4.6 \). Figure 11 shows the position of the layers in the filter fabrication process. The size of the PCB board is 121 mm \( \times 91.3 \) mm.

The layouts of these two layers are shown in Figures 12 and 13. Figure 12 presents the layout specifications of the first layer consisting of the main filter using the DMS technique. In addition, Figure 13 shows the specifications of the second layer based on the DGS technique. The optimized final physical parameters for the proposed BPF are presented in Table 2.

To investigate the effect of the multilayer technique and diagonal stubs, as shown in Figure 14, on the second layer, two lumped ports 1 and 2 are excited.

Figure 15 shows the simulated open-circuit transfer impedance (\( Z_{21} \)) in the second layer with and without an over-layer diagonal stub. Table 3 shows the comparison between the open-circuit transfer impedance in the second layer with and without an over-layer diagonal stub.

As shown in Figure 15, the use of diagonal stubs (over-layer diagonal stubs) in the second layer improves the filter performance in the second-, fourth-, and fifth-order harmonics.

The relationship between the S-parameter and Z-parameter is expressed as

\[
S_{11} = \frac{(Z_{11} - 1)(Z_{22} + 1) - Z_{12}Z_{21}}{(Z_{11} + 1)(Z_{22} + 1) - Z_{12}Z_{21}} 
\]

\[
S_{12} = S_{21} = \frac{2Z_{21}}{(Z_{11} + 1)(Z_{22} + 1) - Z_{12}Z_{21}}. \tag{24}
\]

As the value of \( Z_{21} \) increases at the second-, fourth-, and fifth-order harmonic frequencies 2, 3, and 5, the RL will decrease, whereas the insertion loss will increase. As shown in Figure 2, the diagonal stub in the second layer
has the greatest effect on the improvement of insertion loss and RL in the fifth-order harmonics.

Figure 16 shows how the layers are stacked on top of each other in the fabricated proposed BPF. Diagonal stubs with a certain length and angle are located at the bottom surface of the second layer and over the parallel coupled lines designed in the first layer. Furthermore, two circular stubs with square stubs embedded within them are located at the bottom surface of the second layer and over the RS designed in the first layer. By examining this arrangement and the related simulation results, it is concluded that the second layer with its embedded microstrip stubs will affect the electromagnetic waves of the current-carrying microstrip lines designed in the first layer so that the parallel coupled line and its resonant value are affected by the conductor fragment and the upper substrate. Figure 17 presents the layout of the proposed multilayer BPF based on the multilayer technique and groove structure based on the defected microstrip structure (DMS) and defected ground structure techniques.

Figure 18 presents the effect of a diagonal stub and a circular stub with its embedded square stub on filter
S-parameters. In this study, the multilayer technique is used to improve the insertion loss and RL performance at the second-, fourth-, and fifth-order harmonic frequencies. In this study, the multilayer technique is used to improve the overall performance of the filter as follows.

As presented in Figure 18A, the diagonal stubs designed at the bottom surface of the second layer are used to decrease the passband RL ($S_{11}$) of the proposed filter and decrease the insertion loss ($S_{21}$) in the fifth-order harmonics. As shown in Figure 18B, the two circular stubs with square stubs embedded in them are effective in improving the insertion loss ($S_{21}$) performance at the second-, fourth-, and fifth-order harmonic frequencies.

4 | RESULTS AND DISCUSSION

Figure 19 presents the effect of diagonal line slots with different angles designed at the bottom surface of the second layer on RL performance $S$-parameters. As shown in Figure 19, the diagonal line slots with $\theta = 30^\circ$ over parallel coupled lines are used to decrease the passband RL of the filter and to reduce the insertion loss at the fifth-order harmonic frequency.

Figure 20 presents the effect of the diagonal DMS slot with different angles on the RL performance ($S_{21}$). As shown in Figure 20, the diagonal DMS slot with $\theta = 30^\circ$ is used to decrease the passband RL of the filter and to decrease the RL in the fourth- and fifth-order harmonic frequencies. Figure 21 shows the effect of the air gap between the parallel coupled lines and the second layer’s structure on the insertion loss and RL performance. Figure 22 shows the effect of the slot-line DGS with different widths on the insertion loss and RL performance.

Figures 19 to 22 demonstrate that the suitable value for the angle of the diagonal stub and groove structure is $30^\circ$, the air gap between two layers is around 0.8 mm, and the width of DGS is 1 mm.

After a simulation run, the proposed BPF design is fabricated in two layers. The first and second layers of the design are shown in Figure 23. The results are measured using Network Analyzer-8720. Figure 24 presents the simulation results by the full-wave simulator in ANSYS Electronics Desktop, and the measured data of the filter proposed are presented in Figure 23.

A comparison between ANSYS Electronics Desktop simulations and the measured results shows good accordance. The measured center frequency is 2.42 GHz.
measured RL (\(S_{11}\)) is \(-24.5\) dB at 2.42 GHz (approximately \(-28\) dB in the simulation), and the FBW is almost 0.2107. The measured insertion loss (\(S_{21}\)) is 1 dB (approximately 0.7 dB in the simulation) in the passband and approximately \(-20\) dB in the entire stopband of 12 GHz.

A comparison of this work with previous works, which...
were all based on harmonic suppression in a coupled-line filter, is presented in Table 4. In this table, the central frequency in the passband and stopband and the harmonic suppression ability in previous works and this work are compared.

In [30], two different structures based on the corrugated method are used to suppress fifth-order harmonics. The geometric length of these two circuits is 160 mm and 180 mm, respectively. However, in this study, the geometric length of the proposed filter is 121 mm. As a result, in this study, the geometric size of the filter is significantly reduced using the multilayer technique.

As mentioned in [30], using a high-εr substrate can reduce the size of the filter, so in this study, a smaller size with a smaller substrate dielectric constant (εr = 3.55) is achieved. Compared with [30], the advantage of this study is the use of a simple structure with a suitable fractional band to eliminate high-order harmonics.

According to [55], the lower and upper sideband selectivities of the proposed BPF can be calculated using 3- and 20-dB amplitude responses with respect to its frequency point:

\[
\text{selectivity}_{\text{lower sideband}} = \frac{3 - 20}{f_3 - f_{20}} = 171.9 \text{dB/GHz} \quad (25)
\]

\[
\text{selectivity}_{\text{upper sideband}} = \frac{3 - 20}{f_3 - f_{20}} = 100 \text{dB/GHz}. \quad (26)
\]

As shown in Table 4, the performance of the filter designed in the passband is acceptable in terms of insertion loss, RL, and FBW.

![Comparison of simulated and measured S-parameters for the proposed bandpass filter](image)

**Figure 24** Comparison of simulated and measured S-parameters for the proposed bandpass filter

### Table 4  Comparison between related works and this study

<table>
<thead>
<tr>
<th></th>
<th>Substrate dielectric constant</th>
<th>f_c (GHz)</th>
<th>RL the passband (dB)</th>
<th>IL the passband (dB)</th>
<th>FBW (%)</th>
<th>Harmonics</th>
<th>Circuit overall length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[15]</td>
<td>2.65</td>
<td>2.05</td>
<td>20</td>
<td>0.6</td>
<td>60</td>
<td>2</td>
<td>37</td>
</tr>
<tr>
<td>[16]</td>
<td>2.65</td>
<td>2</td>
<td>20</td>
<td>1</td>
<td>35</td>
<td>2</td>
<td>59</td>
</tr>
<tr>
<td>[24]</td>
<td>10.2</td>
<td>3</td>
<td>25</td>
<td>1</td>
<td>6.7</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>[27]</td>
<td>10.2</td>
<td>2.45</td>
<td>&lt;20</td>
<td>≈1</td>
<td>10 to 25</td>
<td>2</td>
<td>62</td>
</tr>
<tr>
<td>[28]</td>
<td>10.2</td>
<td>2.5</td>
<td>&lt;15</td>
<td>≈1.3</td>
<td>10</td>
<td>2</td>
<td>66</td>
</tr>
<tr>
<td>[30]</td>
<td>10.2</td>
<td>2.45</td>
<td>30</td>
<td>1</td>
<td>0.8</td>
<td>5</td>
<td>160</td>
</tr>
<tr>
<td>[31]</td>
<td>4.4</td>
<td>5.25</td>
<td>19.66</td>
<td>2.75</td>
<td>20</td>
<td>2</td>
<td>42.76</td>
</tr>
<tr>
<td>[32]</td>
<td>2.65</td>
<td>2</td>
<td>40</td>
<td>2.1</td>
<td>5.1</td>
<td>2</td>
<td>115</td>
</tr>
<tr>
<td>[33]</td>
<td>10.2</td>
<td>1</td>
<td>40</td>
<td>≈1</td>
<td>30 to 50</td>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>[34]</td>
<td>4.4</td>
<td>5.25</td>
<td>23</td>
<td>2.8</td>
<td>20</td>
<td>2</td>
<td>42.276</td>
</tr>
<tr>
<td>[35]</td>
<td>6.15</td>
<td>1.8</td>
<td>20.3</td>
<td>1.77</td>
<td>5</td>
<td>2</td>
<td>100</td>
</tr>
<tr>
<td>[36]</td>
<td>4.4</td>
<td>2.45</td>
<td>≈15</td>
<td>≈2.5</td>
<td>-</td>
<td>2</td>
<td>100</td>
</tr>
<tr>
<td>[37]</td>
<td>3.48</td>
<td>2.4</td>
<td>26</td>
<td>3</td>
<td>29</td>
<td>2</td>
<td>4.9</td>
</tr>
<tr>
<td>[43]</td>
<td>4.4</td>
<td>5.25</td>
<td>30.02</td>
<td>2.46</td>
<td>20</td>
<td>2</td>
<td>44.736</td>
</tr>
<tr>
<td>[44]</td>
<td>4.4</td>
<td>5.25</td>
<td>15</td>
<td>2.47</td>
<td>20</td>
<td>2</td>
<td>41.016</td>
</tr>
<tr>
<td>[47]</td>
<td>4.4</td>
<td>5.25</td>
<td>20</td>
<td>2.75</td>
<td>20</td>
<td>2</td>
<td>41.7</td>
</tr>
<tr>
<td><strong>This work</strong></td>
<td><strong>3.5</strong></td>
<td><strong>2.42</strong></td>
<td><strong>24.5</strong></td>
<td><strong>1</strong></td>
<td><strong>19.4</strong></td>
<td><strong>5</strong></td>
<td><strong>121</strong></td>
</tr>
</tbody>
</table>

Abbreviations: FBW, fractional bandwidth; IL, insertion loss; RL, return loss.
5 | CONCLUSION

The design of the novel BPF based on a parallel coupled microstrip line with harmonic suppression capabilities has been demonstrated using multilayer, DGS, and DMS techniques. The purpose of this filter design is to reduce the RL and insertion loss and improve stop bandwidth ranges and harmonic suppression up to $5f_0$.

In the conventional parallel coupled-line filter, the values of the insertion loss and RL in the passband are $-1.7$ dB and $-8$ dB, respectively. In the proposed filter, the measured center frequency is $2.42$ GHz. The measured RL ($S_{11}$) is $-24.5$ dB at $2.42$ GHz (approximately $-28$ dB in the simulation), and the FBW is approximately $0.2107$. The measured insertion loss ($S_{21}$) is $1$ dB (approximately $0.7$ dB in the simulation) in the passband and approximately $-20$ dB at the entire stopband of $12$ GHz. Note that in this design, we have attempted to keep the central frequency of $2.42$ as constant as possible compared with the conventional cable line filter and then to improve its performance in the passband and suppress harmonics.

A detailed investigation of the effects of the multilayer technique around the odd-mode region of coupled lines has been conducted for harmonic suppression. In the proposed BPF filter, within an FBW value of approximately $19.4\%$, the RL has a value less than $-20$ dB in the entire rejection band. In the designed filter, the high spurious suppression efficiency in the broad range of stopband frequency response is improved. Therefore, the proposed BPF is suitable for use in WiFi applications. This study is conducted on a parallel coupled microstrip filter. There are several studies on this filter type, where only a limited number of harmonics could be eliminated using a specific technique. Furthermore, some of these studies have employed techniques that require the repetition of the geometric shape, which needs high precision to eliminate low harmonics.

The innovations of this study include the following:

1. With two diagonal slots on merely one stage of the parallel coupled line, we can improve the fourth- and fifth-order harmonics.
2. Unlike other studies, a few simple techniques are used to eliminate and control the harmonics of this type of filter.
3. In the proposed filter, an additional second layer is used. Accordingly, with regard to the specific structure of the proposed filter, we can reduce the length of the filer compared with the similar parallel coupled microstrip filters that eliminate up to the fifth-order harmonics.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest.

ORCID

Farbod Setoudeh https://orcid.org/0000-0001-5866-756X

REFERENCES

272

WILEY

FATHI ET AL.


46. A. Abdipourm, A. Abdipour, and E. Zare, A design of branch-line coupler with harmonic suppression and size reduction using closed-loop and open-loop resonators, Radioengineering 26 (2017), no. 4, 999–1005.


AUTHOR BIOGRAPHIES

**Esmaeil Fathi** received his BS degree from the University of Tehran, Tehran, Iran, in electronic engineering in 2001. He received his MS degree in electronic engineering from Islamic Azad University Science and Research Branch, Tehran, Iran, in 2013. He is currently a PhD student in electronic engineering at Islamic Azad University Arak Branch, Arak, Iran. His current research interests include microstrip filters and microstrip filtennas.

**Farbod Setoudeh** received his PhD degree in electrical engineering from the Science and Research Branch of Azad University and is currently an assistant professor at the electrical engineering department of Arak University of Technology. His research interests include chaos, intelligent system, signal processing, nonlinear system, and microwave filters. He is the author or a co-author of approximately 35 journal papers and 5 books in the area of control systems and electronic circuits.

**Mohammad Bagher Tavakoli** received his PhD degree in electrical engineering from the Science and Research Branch of Azad University in 2012 and is currently an assistant professor at the electrical engineering department of Azad University. He is the author or a co-author of approximately 40 journal papers in the area of electronic circuits.