Design of Microstrip Parallel-Coupled Line Band Pass Filters for the Application in Fifth-Generation Wireless Communication

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***Abstract*—This article presents the design of microstrip parallel-coupled line bandpass filters (BPFs) for fifth-generation wireless communication application. The BPFs are designed and optimized at center frequencies of 5, 15, and 28 GHz via the use of Keysight's Advanced Design System (ADS) 2015 simulator. Initial lumped-element BPFs are presented prior to the realization using microstrip parallel-coupled line technique with the implementation of Rogers RO4003C substrate. Both performances are compared and discussed. The microstrip parallel-coupled line BPFs have optimal average performance of 8.59% bandwidth with insertion loss of 1.53 dB and return loss greater than 12 dB.**

***Index Terms*—Bandpass Filter; Fifth-Generation; Microstrip; Parallel-Coupled.**

I. INTRODUCTION

Over the past few years, researchers have been enforcing numerous efforts to maximize the benefits of broadband communication since the service of fourth-generation Long Term Evolution (4G LTE) started to enable the transmission and reception of hundred Mbps of data via carriers and terminals. Then, the future fifth-generation (5G) services are expected to allow a Gbps data transmission. 5G communication is basically can be called as "mm-wave communication" due to the radio waves applied are having a length in the order of millimeters. Currently, 5G cellular technology is being considered for use in 5, 15, and 28 GHz bands [1]. In order to keep the wireless communications up-to-date, numerous researches on component design being conducted including band pass filter (BPF) [2, 3].

BPF has a two-port network that is mainly used to control the frequency response at any specific point in a communication system, which providing transmissions at frequencies within the passband and attenuation in the filter stopband. Where, it allows the passing of signals within a specific band and attenuates frequencies either below a lower cut-off frequency or above an upper cut-off frequency. Generally in BPF design, the resonant parallel inductor-capacitor (LC) circuit is responsible for attenuating the frequencies outside the passband by shunting them to the ground. Whereas, the resonant series inductor-capacitor (LC) circuit is responsible for allowing the wanted frequencies to pass. As a matter of fact, in very high-frequency applications, lumped components are not practically to be implemented, therefore; the lumped-element BPF circuit is transformed to the planar microstrip transmission line circuit [4].

There are different types of microstrip line filters such as hairpin, parallel-coupled line, step impedance, and stub impedance [2, 4-9]. A parallel-coupled line microstrip bandpass filter was designed and optimized using flame retardant 4 (FR-4) substrate with a center frequency of 1.42 GHz [5] and 2.44 GHz [4]. In [5], the designed BPF demonstrated a well bandwidth performance of 300 MHz with return loss greater 10 dB and insertion loss of 2.806 dB. Meanwhile, the BPF in [4] offered narrower bandwidth of 80 MHz with return loss better than 16.1 dB and insertion loss of 3.1 dB. Another parallel-coupled line BPF design proposed in [6] for S-band application using a RT/Duriod 6010 substrate. It showed better bandwidth of 66% from 2 to 4 GHz with return loss of 11 dB and insertion loss of 1 dB. Then, a 5 GHz BPF was reported in [7] that having quite high insertion loss of 4.9 dB for a 180 MHz bandwidth with 7 dB return loss at center frequency. Furthermore, reported work in [2] proposed a BPF using stub-inserted interdigital coupled-lines using FR-4 substrate at a center frequency of 4 GHz. This BPF offered 40% bandwidth from 3.2 GHz to 4.8 GHz with very well insertion loss of 0.92 dB, and the return loss better than 15 dB. While in [8], BPF using hairpin resonator and T-feeder coupling lines was proposed, which designed at 5.205 GHz. The measured results showed that fractional bandwidth of 10.34% with return loss of 23 dB and insertion loss of 1.4 dB at resonant frequency of 5.13 GHz. A compact millimeter-wave ultra-wideband bandpass filter was introduced in [9]. The center frequency of this filter was 25 GHz with bandwidth of 20%, return loss better than 15 dB, and insertion loss of 2 dB.

In this article, microstrip parallel-coupled line BPFs are designed at 5, 15 and 28 GHz for 5G wireless applications using Rogers RO4003C substrate using Keysight's Advanced Design System (ADS) 2015 simulator. The BPF designs and the performances are presented and discussed in the following sections.

II. BANDPASS FILTER DESIGN

Chebyshev type filter with the number of order, N set to be five is chosen for this design. Whilst, the passband ripple is 0.5 dB. Its schematic of the lumped-element circuit that consists of capacitors and inductors is shown in Figure 1, which having the listed calculated element values in Table 1 for each of concerned design frequency of 5, 15 and 28 GHz with 10 % bandwidth.

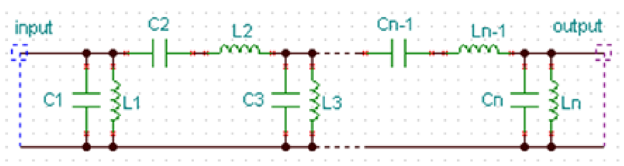


Figure 1: The schematic of the lumped-element BPF circuit with the order number, N of 5.

Table 1
Capacitor and Inductor Values of The Fifth Order BPF for 5, 15 and 28 GHz

Elements	BPF Operating Frequency		
	5 GHz	15 GHz	28 GHz
C1	2.715 pF	3.88 pF	2.07 pF
L1	373.2 pH	8.33 pH	0.40 nH
C2	0.207 pF	0.005 pF	0.17 pF
L2	4.89 nH	6.99 nH	0.10 nH
C3	4.04 pF	5.78 pF	3.07 pF
L3	250.6 pH	5.59 pH	0.29 nH
C4	0.21 pF	0.005 pF	0.19 pF
L4	4.89 nH	6.99 nH	0.10 nH
C5	2.72 pF	3.88 pF	2.07 pF
L5	373.2 pH	8.33 pH	0.40 nH

Then, the conversion to the parallel-coupled line BPF structure that having a schematic as shown in the following Figure 2 can be performed by computing the even and odd characteristic impedances of coupled-line as expressed in the following Equation (1) and (2):

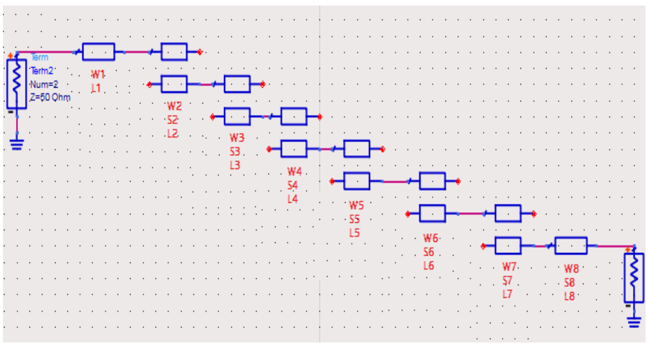


Figure 2: Schematic of the parallel-coupled line BPF

$$Z_{0e_{k,k+1}} = Z_0\left[1 + J'_{k,k+1} + {J'_{k,k+1}}^2\right] \quad (1)$$

$$Z_{0o_{k,k+1}} = Z_0\left[1 - J'_{k,k+1} + {J'_{k,k+1}}^2\right] \quad (2)$$

where, k is varied from 0 to N. While, $J'_{k,k+1}$ and Z_0 represent the respective admittance inverter and the characteristic impedance that has a typical value of 50Ω. The admittance inverter for first and last stage can be given by Equation (3), while the other stages computed using Equation (4):

$$J'_{0,1} = J'_{N,N+1} = \left\{\frac{\pi\Delta}{2g_0g_1}\right\}^{1/2} \quad (3)$$

$$J'_{k,k+1} = \frac{\pi\Delta}{2\sqrt{g_kg_{k+1}}} \quad (4)$$

where, g_k and Δ are the normalized elements obtained from the Chebyshev table and the fractional bandwidth, accordingly. The fractional bandwidth, Δ can be given by Equation (5):

$$\Delta = \frac{\omega_2 - \omega_1}{\omega_0} \quad (5)$$

where, the respective ω_0, ω_1 and ω_2 are design, lower and upper end of angular frequency, respectively. The calculated parameters obtained from the Equations (1) to (5) are tabulated in Table 2.

Table 2
The calculated parallel-coupled line BPF parameters

Stage	Normalized Element, g_k	Admittance inverter, $J'_{k,k+1}$	Even mode impedance (Z_{0e})	Odd mode impedance (Z_{0o})
1	1.7058	0.3034	69.77	39.43
2	1.2296	0.1084	56.06	45.16
3	2.5408	0.0888	54.83	45.95
4	1.2296	0.0888	54.83	45.95
5	1.2296	0.1084	56.06	45.16
6	1.7058	0.3034	69.77	39.43

Afterward, by utilizing Rogers R04003C substrate with specifications stated in Table 3 and the parameters in Table 2, the dimensions of coupled-line width, W and gap spacing, S can be calculated. While, the length, L of each coupled-line resonator at each stage can be computed from (6). The respective calculated dimensions for BPFs operate at 5, 15 and 28 GHz are tabulated in Table 4 to 6.

$$L = \frac{\lambda}{4} = \frac{3\times 10^8}{4f\sqrt{\varepsilon_r}} \quad (6)$$

Table 3
RO4003C substrate specifications

Property	Value
Conductor thickness	17 µm
Height	0.508 mm
Dielectric constant, ε_r	3.38
Loss tangent, tan δ	0.0027

Table 4
Calculated dimensions of 5 GHz BPF

Stage	Width, W (mm)	Gap, S (mm)	Length, L (mm)
1	0.91	0.14	9.43
2	1.11	0.61	9.22
3	1.12	0.75	9.21
4	1.12	0.75	9.21
5	1.11	0.61	9.22
6	0.91	0.14	9.43

Table 5
Calculated dimensions of 15 GHz BPF

Stage	Width, W (mm)	Gap, S (mm)	Length, L (mm)
1	0.93	0.15	3.11
2	1.13	0.66	3.04
3	1.14	0.81	3.04
4	1.14	0.81	3.04
5	1.13	0.66	3.04
6	0.93	0.15	3.11

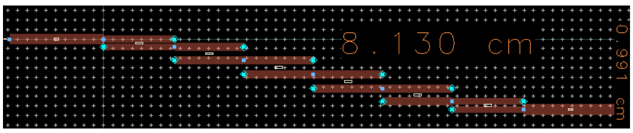
Table 6
Calculated dimensions of 28 GHz BPF

Stage	Width, *W* (mm)	Gap, *S* (mm)	Length, *L* (mm)
1	0.98	0.16	1.64
2	1.17	0.71	1.60
3	1.18	0.87	1.59
4	1.18	0.87	1.59
5	1.17	0.71	1.60
6	0.98	0.16	1.64

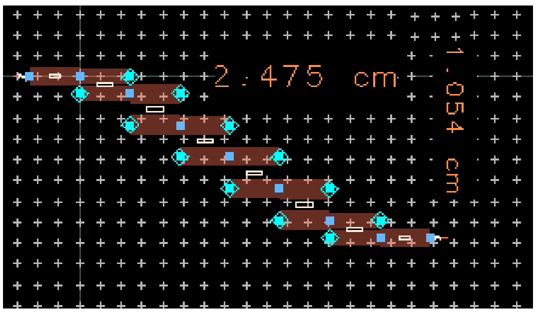
Referring to Table 4 to 6, the BPFs are designed, simulated and optimized using ADS. The optimized dimensions are summarized in the following Table 7. By using these optimized dimensions, the BPFs schematics are transformed to layouts that presented in Figure 3. The respective 5, 15 and 28 GHz BPFs have size of 0.99 cm x 8.13 cm, 1.05 cm x 2.47 cm and 1.21 cm x 1.69 cm.

Table 7
Optimized dimensions in mm of BPFs

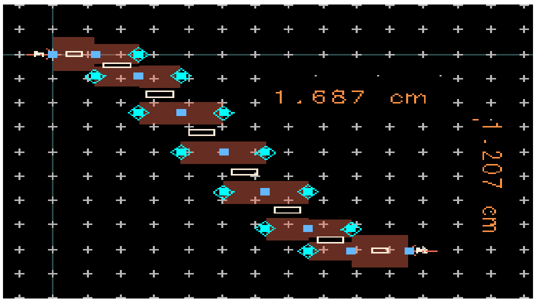
Dimension	BPF Operating Frequency		
	5 GHz	15 GHz	28 GHz
W_1	1.47	1.17	1.79
L_1	12.48	3.03	1.56
W_2	0. 92	0.93	0.98
S_2	0.14	0.15	0.16
L_2	9.43	3.08	1.64
W_3	1.11	1.24	1.18
S_3	0.61	0.66	0.71
L_3	9.23	3.04	1.60
W_4	1.12	1.14	1.18
S_4	0.75	0.81	0.87
L_4	9.21	3.04	1.60
W_5	1.12	1.14	1.18
S_5	0.75	0.81	0.87
L_5	9.21	3.04	1.60
W_6	1.11	1.24	1.18
S_6	0.61	0.66	0.71
L_6	9.23	3.04	1.60
W_7	0. 92	0.93	0.98
S_7	0.14	0.15	0.16
L_7	9.43	3.08	1.64
W_8	1.47	1.17	1.79
L_8	12.48	3.03	1.56



(a)



(b)



(c)

Figure 3: The ADS generated layout of microstrip parallel-coupled line BPFs operate at (a) 5 GHz, (b) 15 GHz and 28 GHz.

III. Results and Discussion

The performances of the lumped-element BPFs that operate at 5, 15 and 28 GHz are plotted and shown in Figure 4, 5 and 6, respectively. The BPFs have an insertion losses of approximately 0 dB across the passband. Furthermore, the 5, 15 and 15 GHz BPFs have the upper and lower frequency cut-off at -3 dB of 5.25 and 4.75 GHz, 15.75 and 14.25 GHz, and 29.4 and 26.6 GHz, according. The return losses across these ranges are having better performance than 10 dB.

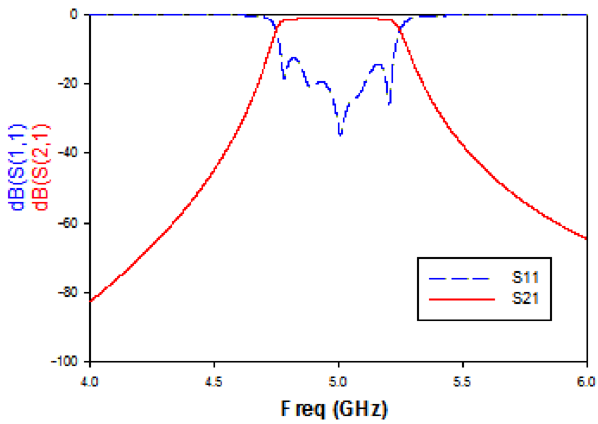


Figure 4: S21 and S11 of 5 GHz lumped-element bandpass filter

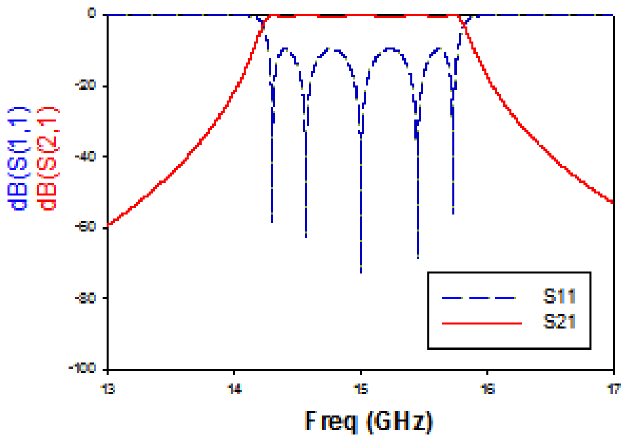


Figure 5: S21 and S11of 15 GHz lumped-element bandpass filter

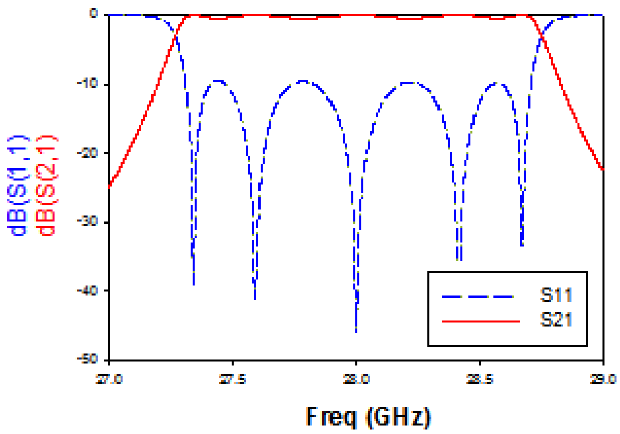


Figure 6: S21 and S11of 28 GHz lumped-element bandpass filter

The next concern is to evaluate the performances of the proposed microstrip parallel-coupled line BPFs across the designated frequency. The performances of 5, 15 and 15 GHz BPF are plotted and shown in Figure 7 to 9. Referring to Figure 7, the insertion loss across the passband is 1.1 dB depicted by 5 GHz BPF. While, its 3 dB bandwidth is 500 MHz (10%) across 4.76 to 5.26 GHz with the return loss better than 15 dB. Meanwhile, 15 GHz BPF has insertion loss of 1.9 dB as depicted by Figure 8. A 990 MHz (6.7%) of 3 dB bandwidth from 14.26 to 15.25 GHz is demonstrated by this BPF. Furthermore, it has the return loss that greater than 10 dB. Quite similar well performance can be noted from 28 GHz BPF. The performance of this BPF is shown in Figure 9. The 28 GHz BPF offers comparable insertion loss, which approximately 1.6 dB. Whilst, its 3 dB bandwidth is slightly less than 10%, which covering 2540 MHz from 26.71 to 29.25 GHz. At least 11 dB return loss is presented by this designed BPF. Then, the obtained performances of the lumped-element BPF and microstrip parallel-coupled line BPF are summarized as compared in Table 8.

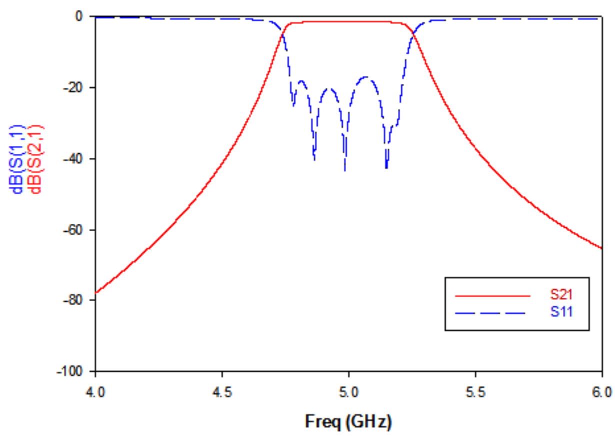


Figure 7: S21 and S11of 5 GHz parallel-coupled bandpass filter

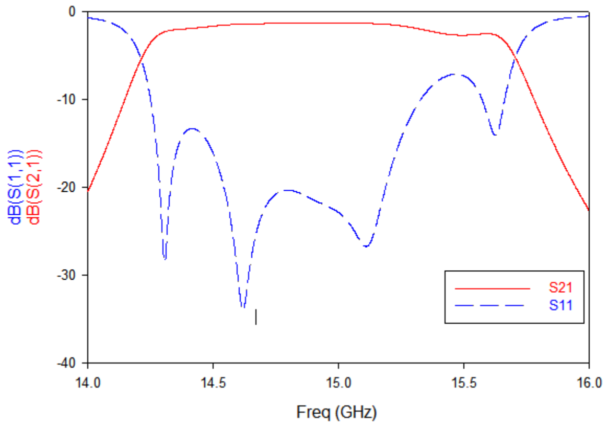


Figure 8: S21 and S11 of 15 GHz parallel-coupled bandpass filter

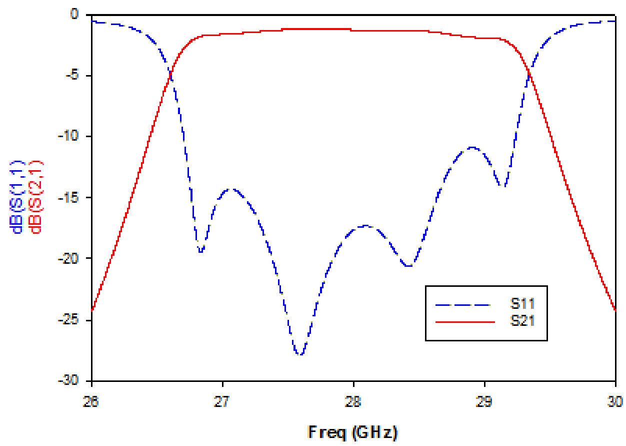


Figure 9: S21 and S11 of 28 GHz parallel-coupled bandpass filter.

Table 8
The summarized and comparison of the lumped-element BPF and microstrip parallel-coupled BPF

Parameter	Lumped-Element BPF			Parallel-Coupled BPF		
	5 GHz	15 GHz	28 GHz	5 GHz	15 GHz	28 GHz
Insertion Loss (dB)	0	0	0	1.1	1.9	1.6
Return Loss (dB)	10	10	10	15	10	11
3 dB bandwidth	10%	10%	10%	10%	6.7%	9.07%

The comparison in Table 8 shows that the lumped-element BPFs demonstrate almost ideal performances with approximately 0 dB insertion loss, good return loss of at least 10 dB and 10% bandwidth. In contrast, the parallel-coupled line BPFs have slight degraded performances due to the existence of dielectric and conductor losses. This degradation is expected from the planar microstrip technology implementation. Then, the proposed microstrip parallel-coupled line BPFs are compared to the previous discussed related works, which summarized in Table 9.

Table 9
Comparison to other previous reported works

References	f_0 (GHz)	S11 (dB)	S21 (dB)
[2]	4	≤ -15	-0.92
[4]	2.44	≤ -16.1	-3.1
[5]	1.42	≤ -10	-2.806
[6]	3	≤ -11	-1
[7]	5.12	≤ -7	-4.9
[8]	5.13	≈ -23 at f_0	-1.4
[9]	25	≤ -15	-2
This work	5	≤ -15	-1.1
	15	≤ -10	-1.9
	28	≤ -11	-1.6

The comparison does not include the bandwidth performance, as bandwidth is not a major concern in the design of the proposed BPF. The reflection coefficient performances of S11 shown by the proposed BPFs are comparable to the reported in references [2, 4-6, 9]. While, better performances are noted than [7]. As the S11 in [8] only concerns its center frequency, fair comparison cannot be made. Meanwhile, the insertion losses of the proposed BPFs quite comparable to [2, 6, 8, 9] and better than [4, 5, 7]. Even though, the proposed BPFs have shown reasonable good performances, however, there is still a room for the enhancement. Thus, to have better BPFs, the ground-slotted technique will be introduced in the next stage of design.

IV. Conclusion

The design of the microstrip parallel-coupled BPF has been presented in this article using Keysight's ADS software with the concerns of operating frequency at 5, 15 and 28 GHz. The initial design is started with the implementation of lumped-elements. Then, the conversion and design have been performed using the parallel-coupled line structures with the implementation of Rogers RO4003C substrate. The performances are quite comparable with slightly degradation observed from the proposed microstrip BPFs due to the conductor and dielectric losses. Reasonable good performances have been demonstrated by the proposed BPFs in terms of insertion loss, return loss and 3 dB bandwidth.

Acknowledgment

The authors acknowledge the financial support from Ministry of Higher Education Malaysia (MOHE) and Universiti Teknologi Malaysia (UTM) via Research University Grant with vote number of 05H43, Flagship Grant with vote number of 03G41 and HiCoE Grant with vote number of 4J212.

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