

## 5G Hairpin and Interdigital Bandpass Filters

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**Abstract:** At two low 5G frequency bands: 3.7 GHz - 4.2 GHz and 5.975 GHz - 7.125 GHz, Hairpin Bandpass Filter (HPBF) and Interdigital Bandpass Filter (IBF) are designed and simulated in this paper. Both filters show good results in terms of matching and transmission responses with a wide bandwidth through the two frequency bands. HPBF with simple design resulted in good return and insertion losses, < - 10.43 dB and - 0.63 dB, and < - 14.48 dB and - 0.46 dB through frequency bands: 3.51 GHz - 4.27 GHz and 5.58 GHz - 7.24 GHz, respectively. In addition to good filter response that IBF provides, it supports high order second harmonics suppression. The simulated  $S_{11}$  and  $S_{12}$  of this filter are < - 11.15 dB and - 0.63 dB with out of band rejection up to 11.12 GHz through the frequency band 3.56 GHz - 4.25 GHz. Furthermore, at the second frequency band IBF is designed with two different grounding via hole radii ( $r_{Via}$ ), case 1:  $r_{Via} = 0.4$  mm and case 2:  $r_{Via} = 0.7$  mm. For both cases, the designed filter shows good results with high order second harmonics suppression up to 18.33 GHz and 18.96 GHz. In this paper, High Frequency Structure Simulator (HFSS) software is used to carry out the simulation.

**Keywords:** Hairpin Bandpass Filter (HPBF), Interdigital Bandpass Filter (IBF), high order second harmonics suppression, 5G, HFSS

### 1. Introduction

Filters play important role in many RF/Microwave applications in which they are used to get different responses (band-pass, band-stop, low-pass, and high-pass) [1]. Hairpin Bandpass Filter (HPBF) is simply constructed by folding the  $\lambda/2$  resonators of the parallel-coupled filter, to get the U shape [2]. HPBF has been used in many applications for different frequencies. In [3], 5.78 GHz with 10% BW HPBF was designed to work for unlicensed WiMAX. Superior harmonics suppression in the response of HPBF is obtained in [4] by adding different Defected Microstrip Structure (DMS) to the filter's resonators. The resulted suppressions were 25 dB and 40 dB for the second and the third harmonics. Authors in [5], designed a compact HPBF for 923 MHz RFID application. The compactness was 37 % and it was achieved using via hole grounding. Plackett-Burman Design of Experiment methodology (DOE) was applied in designing 2.4 GHz HPBF for further optimization. The resulted insertion and return loss of this filter were 61% and 15 % improved from the one designed with Gensys software. 2 GHz - 4 GHz HPBF was designed in [6] for satellite application. HPBF with Defected Ground Structure (DGS) for radar application was designed in [7]. In addition, this filter showed better performance with aluminum casing. In [8], X-band HPBF was designed for radar navigation. Authors in [9], designed a millimeter wave HPBF (30 GHz) on Liquid Crystal Polymer Substrate using Inkjet Printing Technology. The measured insertion and return loss at 30.4 GHz were 2.41 and 18.9 dB, respectively. Spurious harmonic response suppression was obtained by using nonuniform coupled line resonators to design 34 GHz in [10]. HPBF with tunable center frequency

650MHz to 920MHz and bandwidth 25MHz and 85 MHz was designed in [11] using Screen Printed Ferroelectric Varactors. Authors in [12], designed three different 20 GHz HPBF with different feeding techniques.

Interdigital Bandpass Filter (IBF) is considered compact because of its  $\lambda/4$  resonators length as compared to HPBF  $\lambda/2$  resonators length. Furthermore, it supports high order second harmonics suppressions since their center frequency usually occurs around three times the center frequency of the desired band [2]. IBF has been used in many applications. In [13], 900 MHz IBF was designed. The designed filter supported up to 3<sup>rd</sup> harmonic suppression using under-coupled quarter-wavelength resonator pair. 2.25 GHz IBF with multilayer folded quarter-wavelength resonators was proposed in [14]. Based on CMOS technology, high frequency 55 GHz millimeter wave IBF was designed in [15]. Authors in [16] designed a compact interdigital filter operating at L band via changing the filter coupling structure. In [17], spurlines were used to achieve up to 8 GHz in designing seventh-order IBF. Sixth-order 2.25 GHz IBF was proposed in [18] to meet electromagnetic interference (EMI) or electromagnetic compatibility (EMC) issues requirements. Authors in [19], designed 2.4 GHz IBF. Ninth-order IBF with LTE duplexer band 28 was proposed in [20]. Aggressive space mapping was used to design two-layer K-band IBF in [21]. After seven iterations, good filter response was obtained and this reflects a small run time simulation as compared to the full-wave electromagnetic simulation software.

On October 24, 2018, the Federal Communication Commission (FCC) has proposed two frequency bands below 24 GHz licensed (C-Band: 3.7 GHz-4.2 GHz) and unlicensed (5.925 GHz -6.425 GHz, 6.525 GHz -6.875 GHz and 6.875 GHz – 7.125 GHz bands (totally 5.925 GHz–7.125 GHz)) spectrum for 5G technology [22]. In this paper, HPBF and IBF are designed at these two frequency bands, which is considered as a contribution at 5G technology. Furthermore, both filters provide wide bandwidth as compared to the other filters in the literature. Take in consideration that the chosen substrate material in this study is Rogers RO4003C ( $\epsilon_r = 3.55$  and  $h = 0.813$  mm).

## 2. 5G 3.95 GHz Bandpass Filters

### 2.1 Hairpin Bandpass Filter

Based on the design equations in [2], 3.95 GHz HPBF is designed. Table 1 indicates all the calculated and optimized parameters of the filter, where  $L_{res}$ ,  $W_{res}$ ,  $S$ ,  $L_t$ ,  $L_{p1}$ ,  $L_{p2}$  and  $W_p$  are the length of the resonator, width of the resonator, the space between two adjacent resonators, tapping length, length of the first and second port and width of the ports, respectively. Figure 1 shows the layout of the designed 3.95 GHz HPBF. The simulated insertion loss is less than -10 dB and simulated insertion loss is around -0.79 dB at center frequency,  $F_c = 3.89$  GHz through the frequency band (3.57 GHz – 4.32 GHz) as shown in Fig. 2. In addition, one can observe that the proposed 3.95 GHz HPBF can support up to only 7.8 GHz harmonics suppression which is not as high as 3.95 GHz IBF can support and this will be explained in the next section.

**Table 1 - Calculated and Optimized parameters of 3.95 GHz HPBF**

Parameters	Calculated	Optimized
$L_{res}$ (mm)	23.268	23
$W_{res}$ (mm)	0.595	0.45
$S$ (mm)	0.63	0.3
$L_t$ (mm)	2.06	2.7
$L_{p1}$ (mm)	-	3
$L_{p2}$ (mm)	-	3
$W_p$ (mm)	1.819	1.5

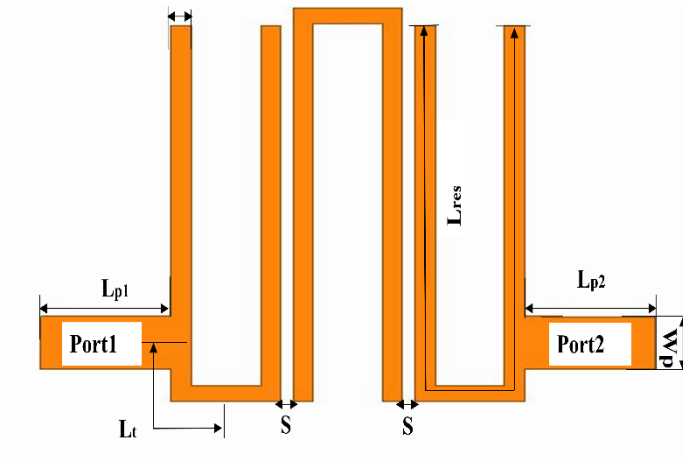


Fig. 1 - Configuration of 3.95 GHz HPBF

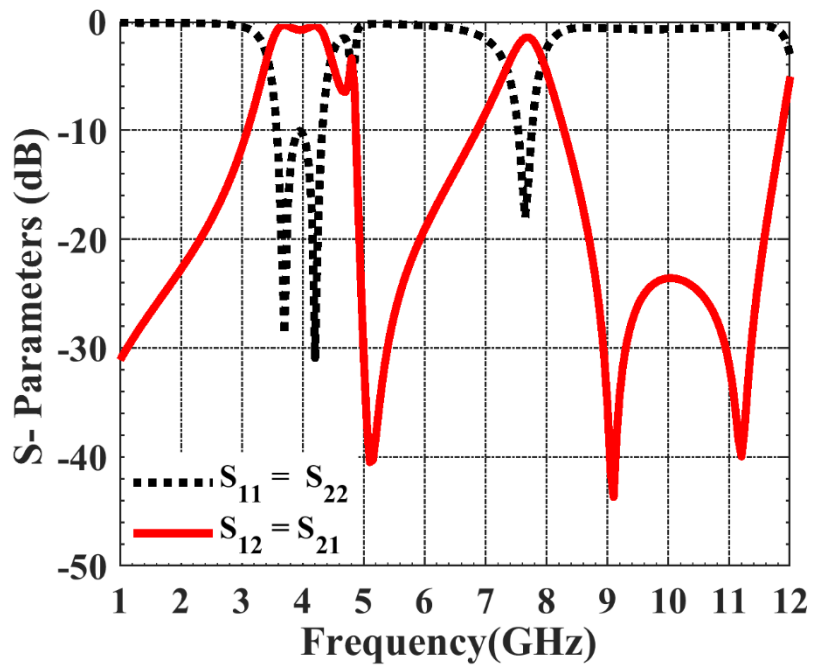


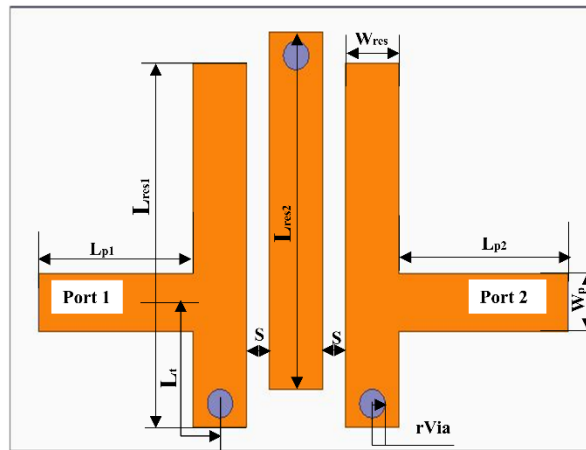
Fig. 2 - Simulated S-Parameters of the proposed 3.95 HPBF

## 2.2 Interdigital Bandpass Filter

The same procedure and design equations in [2] are used to design the three order symmetrical coupled line 3.95 GHz. The calculated and optimized parameters of this filter are shown in Table 2, where  $L_{res1}$ ,  $L_{res2}$ ,  $r_{Via}$  are the length of the first, second resonators and radius of the via hole, respectively. The designed filter is shown in Fig. 3.

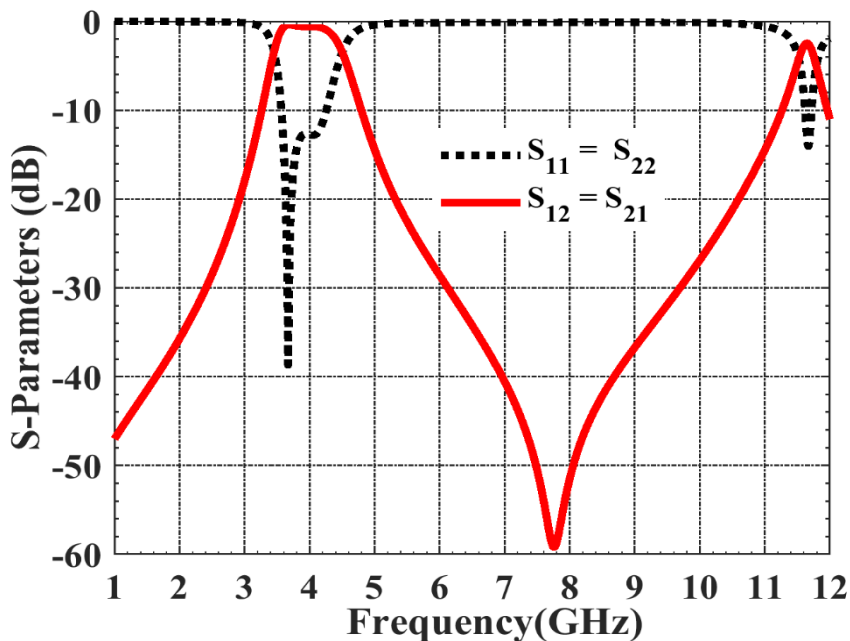
**Table 2 - Calculated and optimized parameters of 3.95 GHz interdigital filter**

Parameters	Calculated	Optimized
$L_{res1}$ (mm)	11.5796	10.2986
$L_{res2}$ (mm)	11.381	10.1
$W_{res}$ (mm)	1.843	1.9
$S$ (mm)	0.7	0.8
$L_t$ (mm)	2.332	2.75
$rVia$ (mm)	-	0.45
$L_{p1}$ (mm)	-	5
$L_{p2}$ (mm) </td <td>-</td> <td>6</td>	-	6
$W_p$ (mm)	1.819	1.819



**Fig. 3 - Configuration of 3.95 GHz interdigital filter**

The simulated reflection and transmission coefficients are demonstrated in Fig. 4. At 3.56 GHz – 4.25 GHz,  $S_{11} = S_{22}$  is  $< -11.15$  dB and  $S_{12} = S_{21}$  is approximately  $-0.63$  dB which indicates a good filter response. Up to 11.77 GHz high order second harmonics can be obtained using this filter as shown in Fig.4 which better than that of 3.95 GHz HPBF (only up to 7.8 GHz). So, 3.95 GHz IBF is preferred to be used with devices with wide bandwidth for example with Ultra Wideband (UWB) antenna to have a notch at this narrow band (3.7 GHz – 4.2 GHz).



**Fig. 4 - Simulated S-Parameters of the proposed 3.95 IBF**

### 3. 5G 6.55 GHz Bandpass Filters

#### 3.1 Hairpin Bandpass Filter

All the calculated and optimized parameters of 6.55 GHz HPBF are indicated in Table 3. The configuration of the proposed UTL HPBF is shown in Fig.5. The designed filter shows good filter response through the desired frequency band. The simulated  $S_{11} = S_{22}$  is less than -19 dB and  $S_{12} = S_{21}$  is around -0.5 dB at  $F_c = 6.61$  GHz through the frequency band 5.87 GHz – 7.35 GHz as shown in Fig. 6. In addition, harmonics at 11.1 GHz are not 100 % suppressed. However, IBF at the same frequency band can support up to 19.1 GHz and 18.35 GHz high order harmonics suppressions.

Table 3 - Calculated and Optimized parameters of 6.55 GHz HPBF

Parameters	Calculated	Optimized
$L_{res}$ (mm)	14.325	15.524
$W_{res}$ (mm)	0.5	0.6
$S$ (mm)	0.65	0.3
$L_t$ (mm)	1.267	2.9
$L_{p1} = L_{p2}$ (mm)	-	4
$W_p$ (mm)	1.819	1.819

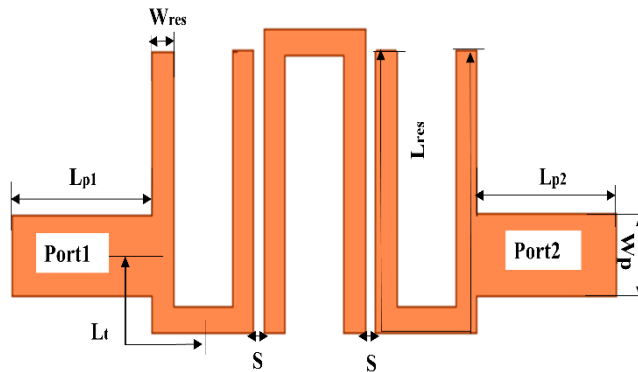


Fig. 5 - Configuration of 6.55 GHz HPBF

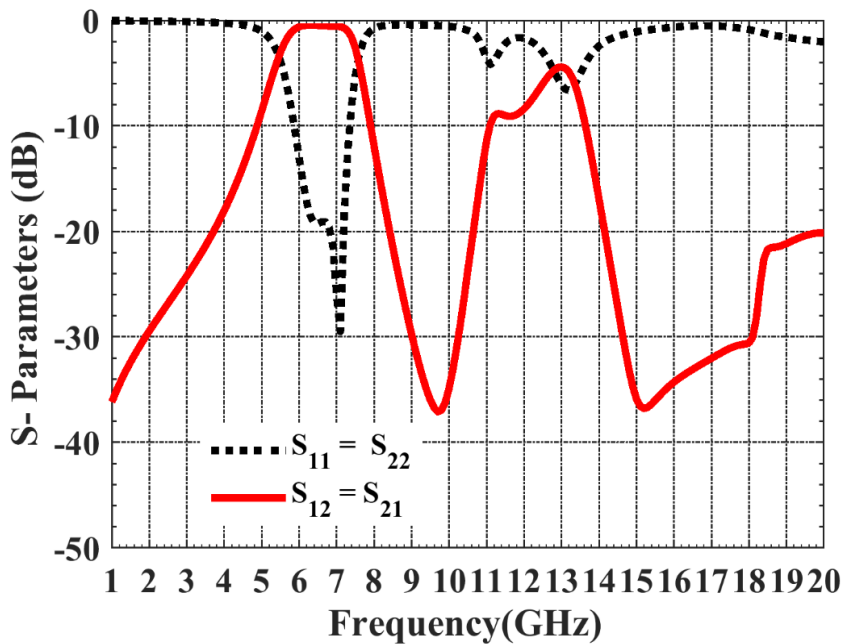


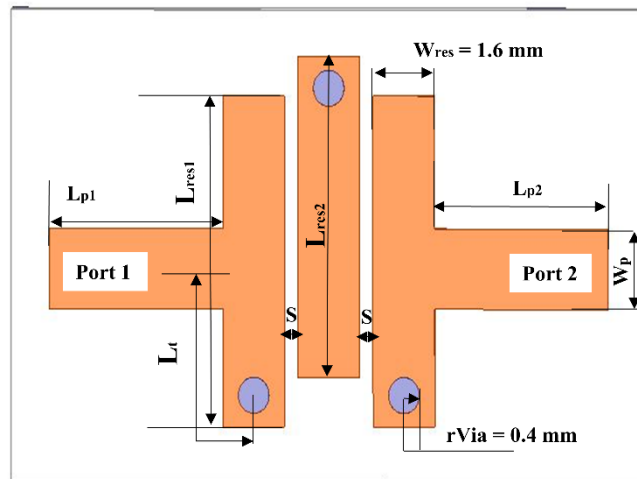
Fig. 6 - Simulated S-Parameters of the proposed 6.55 HPBF

### 3.2 Interdigital Bandpass Filter

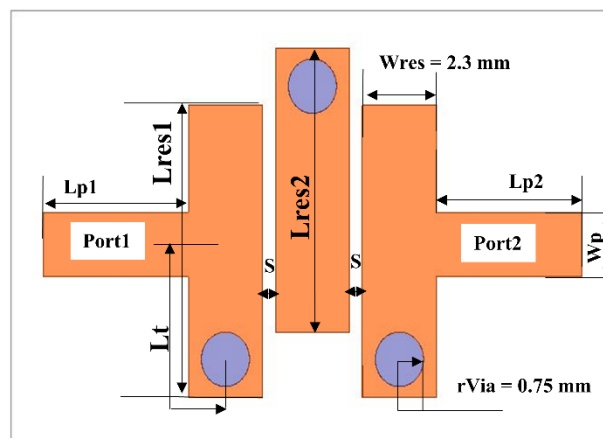
Table 4 below indicates all the calculated and optimized parameters 6.55 GHz IBF. Two different grounding via hole radii (i.e. different resonators width) are used in design this filter: Case 1 with  $r_{Via} = 0.4$  mm and  $W_{res} = 1.6$  mm and Case 2 with  $r_{Via} = 0.75$  mm and  $W_{res} = 2.3$  mm. The configuration of the designed 6.55 GHz IBF is shown in Fig. 7 and 8 for case 1 and case 2, respectively.

**Table 4 - Calculated and Optimized parameters of 6.55 GHz IBF**

Parameters	Calculated	Optimized
$L_{res1}$ (mm)	7.0382	6.2282
$L_{res2}$ (mm)	6.81	6
$W_{res}$ (mm)	2.245	<b>Case1: 1.6 &amp; Case2: 2.3</b>
$S$ (mm)	0.665	<b>Case1: 0.35 &amp; Case2: 0.4</b>
$L_t$ (mm)	1.9	2.4
$r_{Via}$ (mm)	-	<b>Case1: 0.4 &amp; Case2: 0.75</b>
$L_{p1}$ (mm)	-	4.5
$L_{p2}$ (mm)	-	4.5
$W_p$ (mm)	1.819	1.78



**Fig. 7 - Configuration of 6.55 GHz IBF (Case1)**



**Fig. 8 - Configuration of 6.55 GHz IBF (Case2)**

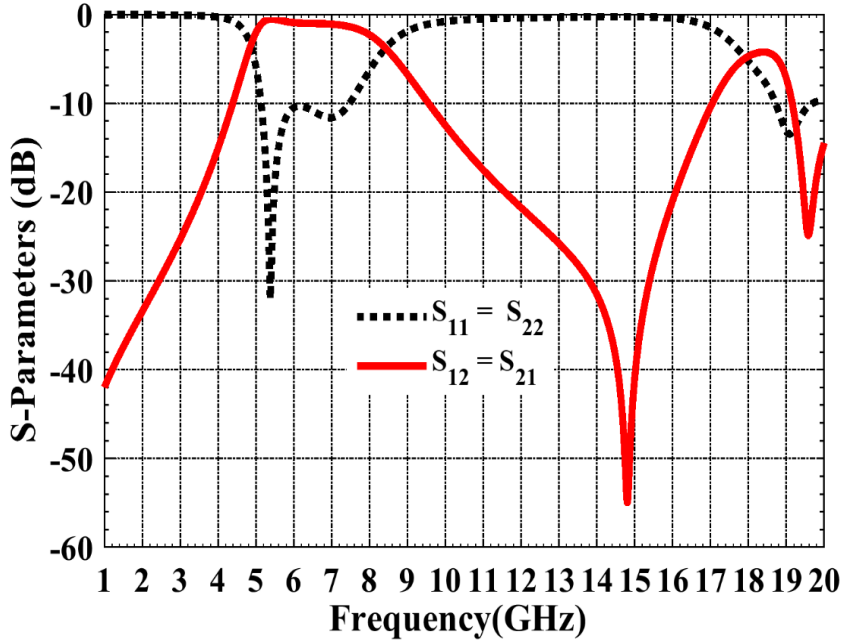


Fig. 9 - Simulated S-Parameters of the proposed 6.55 IBF (Case1)

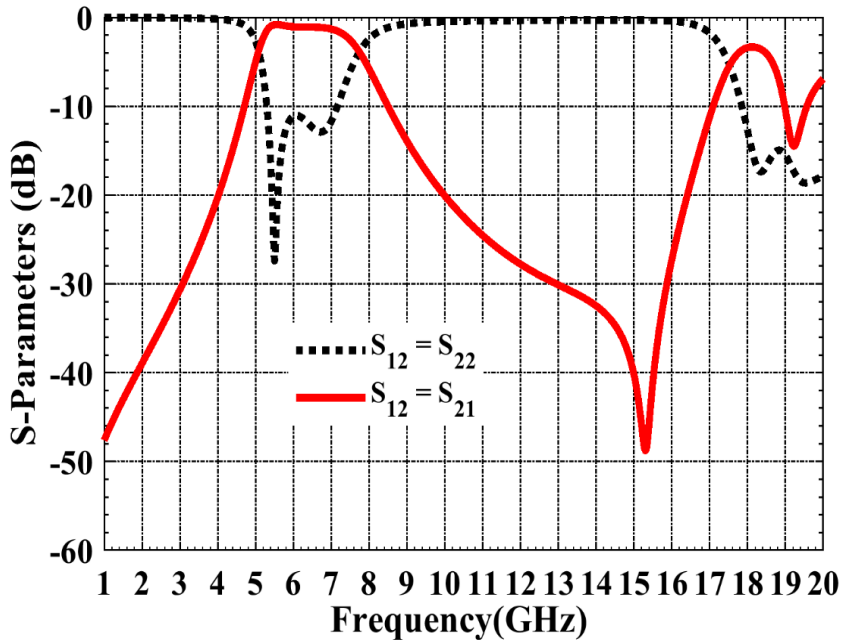


Fig. 10 - Simulated S-Parameters of the proposed 6.55 IBF (Case2)

The simulated filter responses for both cases are shown in Fig. 9 and Fig. 10 above. From Fig. 9 through the frequency band 5.14 GHz – 7.47 GHz,  $S_{11} = S_{22}$  is below -10.32 dB and  $S_{12} = S_{21}$  is approximately -1 dB at  $F_c = 6.31$  GHz in addition to up to 19.1 GHz out of band harmonics suppression. On the other hand, for case 2 the filter response is better than that of case 1 where the reflection coefficient  $S_{11} = S_{22}$  is below -11.05 dB at the frequency bands 5.3 GHz – 7.164 GHz with high order second harmonic suppression up to 18.35 GHz and the transmission coefficient is around -1.09 dB at the center frequency 6.25 GHz. Generally, the designed 6.55 GHz IBF at the two different via hole radii has good -10 impedance matching. However, its preferable to choose  $r_{Via}$  which will be suitable with the calculated  $W_{res}$ .

Finally, a comparison to the other HPBFs and IBFs designed at different frequency ranges in the literature is highlighted in Table 5. As it is shown from the table, the proposed 5G HPBF and IBF provide wider bandwidth at the two frequency bands with good impedance matching and transmission response.

**Table 5 - Comparison to other HPBFs and IBFs in the literature**

Ref.	Substrate h(mm)/ Er	order	3 dB FBW	BW GHz	FC GHz	S <sub>11</sub> = S <sub>22</sub> (dB)	S <sub>12</sub> = S <sub>21</sub> (dB)
<b>This work (HPBF)</b>	0.813 /3.55	3	18.99 % at 3.57 GHz – 4.32 GHz	0.75	3.95	< -10	-0.79
			22.39 % at 3.57 GHz – 4.32 GHz	1.48	6.61	< -19	-0.5
<b>This work (IBF)</b>	0.813 /3.55	3	17.65 % at 3.56 GHz – 4.25 GHz	0.69	3.91	< -11.15	-0.63
			Case1: 39.93 % at 5.14 GHz – 7.47 GHz	2.33	6.31	< -10.32	-1
			Case2: 29.92 % at 5.3 GHz – 7.16 GHz	1.86	6.23	< -11.05	-1.09
[3]	1.52/2.2	5	0.004% at 920 MHz -924 MHz	0.922	0.922	-18	-6.65
[5]	0.508/2.23	3	13.03% at 5.23 GHz – 5.96 GHz	0.97	5.6397	-45.91	0
[7]	0.381/9.8	5	6.67% at 2.9 GHz – 3.1GHz	0.2	3	-29.98	-0.76
[8]	1.58 /2.2	5	1.07% at 9.25 GHz – 9.35 GHz	0.1	9.3	-21.67	-0.41
[10]	0.127 /2.94	3	3.84% at 33.2 GHz -34.5 GHz	1.3	33.85	< -12	-0.37
[13]	1.524 /3.38	3	30% at 765 MHz -1035 MHz	0.27	0.9	< -20	-0.17
[17]	1.27/10.2	5	65.54% at 0.99 – GHz 1.96 GHz	0.97	1.48	< -11.24	-0.14
[21]	0.4/11.9 (two layers)	6	7.84% at 19.6-21.2 GHz	1.6	20.4	< -15	-1.2

#### 4. Conclusions

Two different 5G bandpass filters at two different frequency bands, 3.7 GHz - 4.2 GHz and 5.975 GHz -7.125 GHz are designed in this paper. The two filters are, Hairpin Bandpass Filter (HPBF) and Interdigital Bandpass Filter (IBF) and they can be used in 5G RF front end wireless communication applications, especially in filtering and reconfigurable antennas. Both filters provide wide bandwidth, good -10 dB impedance matching and good transmission coefficients through the two frequency bands. Furthermore, designing HPBF and IBF at these two-low frequency 5G bands is considered as a contribution. IBF at (5.975 GHz – 7.125 GHz) is designed with two different ground via hole radii (case 1 : rVia = 0.4 mm and case 2 : rVia = 0.75 mm) with good resulted reflection and transmission coefficients for both cases.



IBF at two frequency bands outperforms HPBF in terms of high order second harmonics suppression in which it supports up to 11.77 GHz and 19.1 GHz harmonic suppression at the frequency bands 3.56 GHz – 4.25 GHz and 5.3 GHz – 7.164 GHz, respectively. Further enhancement can be applied to these 5G filters to reduce their circuit area to be compatible with the modern communication system. In addition, many techniques can be used to overcome the second harmonic problem in 5G HPBF.

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