Full Length Research Paper

Compact and Small Sized Single, Double and Multi-Folded Hairpin Line Microstrip Bandpass Filters for RF/ Wireless Communications

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Abstract

A conventional hairpin line resonator size is normally very large. The folded hairpin line resonator filters are smaller in size and easy to design, simulate/optimize and fabricate. The contents of this technical paper is to presented a new class of folded hairpin line microstrip resonator filters with great reduction (60-65\%) in size compared to the conventional hairpin line filters. The proposed single, double and multi-folded hairpin line microstrip filters are narrow band, high selectivity, small sized and low cost band pass filters for RF/wireless trans/receive communication systems for ground and space applications. The expected performance and frequency responses have been simulated/optimized by using The Agilent-make ADS/IE3D-Zealand softwares. The measured results are very close to the simulated/optimized results with great reduction in size compared to the conventional hairpin line filters.

Keywords: Substrate, folded-hairpin line resonator, miniaturized microstrip filters, coupling coefficients, narrow band, selectivity, slow wave, open-loop resonator, computed response, ADS and IE3D Softwares.

INTRODUCTION

Wireless and mobile communication systems have presented new challenges to the design of high quality miniature RF/microwave filters. Planar filters are the alternatives as they can be fabricated using printed circuit technology with low cost and size. The basic microstrip circuits consist of a single dielectric substrate, coated with a conductive material transmission line on one side and a metal ground plate on the other side. The folded-hairpin line topology has the advantage of desirable narrowband, good return loss, compact structure and low cost microstrip filters for trans/receive communication systems. The small size and compactness of the filter makes the design attractive for further development and applications in the modern mobile radio communication systems. The design of a filter having folded resonators has been accomplished in the given steps: the width of the microstrip is determined for 50 ohms, the peripheral of each resonator is made a square, length of the U-shaped coupled lines is extended to its maximum, the width of the lines is made large and the space (gap) between coupled lines is made as small as possible (Pozar, 2005; Wang et al., 2007). We have chosen the RT-Duroid-Alumina substrate of dielectric constant 10.2 and thickness of 1.27 mm to design the folded hairpin line resonators for the desired microstrip filters.

By using the empirical equations, Graphs and simulation/optimization, we have obtained the total size of a fourth-order parallel coupled bandpass filter at 1325 MHz is 95 mm x 15 mm (1425 mm\(^2\)). At the same center frequency, the total size of the fourth-order
conventional hairpin line bandpass filter is 25 mm x 25 mm (625 mm² = A). Also at the same center frequency, the total size of the fourth-order single fold, double fold and multifold hairpin line bandpass filters are 400 mm² (64 % of A), 289 mm² (47 % of A) and 225 mm² (36 % of A) respectively.

The Concept of Folded Hairpin Line Resonators

The length of parallel coupled filter is too long and the size increases with the order of filter. To solve this problem, hairpin line filter, using folded λ/2 resonator (U-shaped) structures were developed (Figure 1). Further reduction in size is made by folding again the two arms of the conventional hairpin line resonator (single-fold) to form a pair of closely coupled lines to enhance the capacitive nature of open end arms (Iliev and Nedelchev, 2002; Jovanovic and Nesic, 2005; Ruan and Chun, 2006). This structure helps reduce the size of filter upto 35-40% of the size of the conventional hairpin line bandpass filter. Even more reduction in size i.e 45-50% and 60-65% is employed by further folding the two arms of the single-folded hairpin line resonators i.e. double-folded and multi-folded hairpin line resonators (Fan et al., 2007; Alfano et al., 2005; Wu et al., 2003; Pozar, 2005; Wang et al., 2007). The filters consisting the folded resonators are of moderate quality factor and high stop band attenuation compare to the filters with conventional hairpin line resonators (Jovanovic and Nesic, 2005; Shi and Zhu, 2004; Kuo and Shih, 2003; Jantaree and Akkaraekthalin, 2003; Lai et al., 2010).

Design Procedure of Folded Hairpin Line Resonator Filters

Filters with Hairpin-line resonators are relatively simple to design and build. The design methodology and supporting softwares are available to design, simulate/optimize the single, double and multi-folded hairpin line filters (Hong and Lancaster, 2006; Akkaraekthalin and Jaruek, 2006; Zhang et al., 2007; Zhu and Menzel, 2005; Kazerooni and Cheldavi, 2006). Design calculations of folded hairpin line microstrip filters can be done in the following steps:
1. Finding the element values of LPF prototype by using the approximate synthesis method. The relations between the bandpass design parameters and the lowpass elements are (Deng et al., 2007; Zhao et al., 2007; Jen-Tasi et al., 2005; Tsai et al., 2003).

\[ Q_o = Q_{eq} = \frac{C_i}{\Delta \omega} \]

\[ k_{n,n-1} = \frac{\Delta \omega}{\sqrt{C_n C_{n+1}}} , \text{ for } n = 1 \text{ to } N/2 \]

\[ k_{m,m+1} = \frac{\Delta \omega}{C_m} , \text{ for } m = N/2, \]

\[ k_{n-1,n+1} = \frac{\Delta \omega}{C_{n-1}} , \text{ for } m = N/2, \]

Where \( \Delta \omega \): fractional bandwidth of the bandpass filter, C : Capacitance of the lumped capacitor
J : Characteristic admittance of the inverter
N : degree of the filter
2. To calculate the resonator parameters: The length of the coupled lines can be calculated by:

\[ R = \frac{Z_{pe} + Z_{pc}}{\cos \theta_z} - (Z_{pe} - Z_{pc}) \]

\[ \theta_z \] : Electric length of the resonator
Zc : Characteristic impedance
Zpe : Even mode impedance
Zpc : Odd mode impedance
3. Calculations for the coupling parameters: The values of coefficient of coupling between resonators can be calculated against the distances between the resonators. The design technique uses an approximation polynomial and a low filter prototype (Zhu et al., 2007; Xiao et al., 2007; Moon-Seok et al., 2005; Wang and Zhu, 2004). The loaded Q factor and the mixed coupling coefficients between different resonators can be calculated by using the equations, graphs and commercial softwares.
4. Calculation of the input tapped electrical length (Figure 2):
5. Calculation of the geometric parameters of the filter for an exact substrate.
6. Optimization of filter parameters by varying the geometric dimensions.

In designing a resonator the width of microstrip is determined by setting its characteristic impedance to 50 ohms (Hong and Lancaster, 2004; Singh et al., 2008; Chang et al., 2003). In the design topology the source power transfer to the load is obtained by coupling to the resonator-transmission line (Tsai and Wu, 2011; Fei et al., 2012; Singh and Sinhal, 2013). The end resonators may be externally coupled by tapping instead of using a coupled section. They provide circuits of high power handling capacity and economical to produce, hybrid and monolithic Integrated Circuit (IC). The Single-fold,
designed and developed at the same common center frequency of 1325 MHz to compare their performances with reduction in size by 35-40%, 45-50% and 60-65% respectively. The external quality factor, coupling coefficients and the coupling between adjacent microstrip resonators and other elements of the filter can then be determined by

\[
Q_e = \frac{\text{FBW}}{\text{FBW}}
\]

\[
M_{12} = M_{34} = \frac{\text{FBW}}{\sqrt{Q_e}}
\]

\[
M_{23} = M_{14} = \frac{\text{FBW}}{\sqrt{Q_e}}
\]

\[
M_{ij} = \frac{f_{p1} - f_{p2}}{f_{p1} + f_{p2}}
\]

Where \(f_{p1}\) and \(f_{p2}\) are the lower and higher split resonant frequencies of a pair of coupled resonators. We have used EM simulator to model the coupling coefficient and external Q. The hairpin transmission lines and bends are realized by using the MBEND90x and MLIN elements. (ADS Agilent-make Softwares for Design and Simulation, 2011; Ansoft-HFSS-3D software for Electromagnetic modeling, 2012; Zealand Software IE3D for Simulation and Optimization, 2013)

**Desired specifications of the filter**

<table>
<thead>
<tr>
<th>Centre Frequency (CF)</th>
<th>: 1325 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insertion loss</td>
<td>: &lt; 3 dB</td>
</tr>
<tr>
<td>3 dB width (Lower side)</td>
<td>: 24 MHz w. r. t. c. f.</td>
</tr>
<tr>
<td>3 dB width (Upper side)</td>
<td>: 24 MHz w. r. t. c. f.</td>
</tr>
<tr>
<td>Lower side attenuation</td>
<td>: 32 dBc at 1265 MHz</td>
</tr>
<tr>
<td>Upper side attenuation</td>
<td>: 32 dBc at 1385 MHz</td>
</tr>
<tr>
<td>Input/output Impedance</td>
<td>: 50 Ohms</td>
</tr>
</tbody>
</table>

**Design of a single-folded resonator-filter at 1325 MHz**

The proposed single-fold hairpin line bandpass filter is shown in figure 3 to 6.

The filter has fourth-order cross coupled structure. Dimensions of resonators of the filter

\[L_1: 8.71 \text{ mm}, W_1: 1.14 \text{ mm}, G_1: 0.31 \text{ mm}, D_{12}=D_{34}:1.61 \text{ mm} \text{ and } D_{14}=D_{23}:1.81 \text{ mm}
\]

* Size of the filter: 20 mm x 20 mm (400 mm² i.e. 64% of A)

The measured results are close to the simulated response.

**Design of a double-folded resonator filter at 1325 MHz**

The proposed double-fold hairpin line bandpass filter is shown in figure 7 to 9. This filter is a fourth-order cross-coupled structure and the couplings exist between adjacent and non-adjacent resonators. Dimensions of resonators of the filter

\[L_1: 7.11 \text{ mm}, L_2: 3.63, W_1: 1.16 \text{ mm}, G_1: 0.31 \text{ mm}, D_{12}=D_{34}=1.69 \text{ mm} \text{ and } D_{14}=D_{23}=1.87 \text{ mm}
\]

* Size of the filter: 17 mm x 17 mm (289 mm² i.e. 47% of A)

The measured results are close to the simulated response.

**Design of a multi-folded resonator- filter at 1325 MHz**

\[L_1: 6.57 \text{ mm}, L_2: 4.36 \text{ mm}, L_3: 3.01 \text{ mm}, W_1: 1.31 \text{ mm} W_2: 0.51 \text{ mm}, G_1: 0.45 \text{ mm}, G_2: 0.39 \text{ mm} G_3: 0.44 \text{ mm}, G_4: 0.82 \text{ mm}, D_{12}=D_{34}=1.33 \text{ mm}, D_{23}=D_{14}=1.21 \text{ mm}
\]

* Size of the filter:15 mm x 15 mm (225 mm² i.e 36 % of A)

The measured results are close to the simulated response. Figure 10 to 12 and Table 1.

**RESULTS AND DISCUSSIONS**

At the desired center frequency of 1325 MHz, the simulated and measured 3dB bandwidths of fourth-order
**Figure 3.** Structure of a Single-folded resonator

**Figure 4.** Coupling Coefficients for end-coupled resonators

**Figure 5.** A fourth-order filter having single-folded resonators.

**Figure 6.** Simulated response and measured result of the fourth order filter having single-folded resonators.

**Figure 7.** Structure of a double-folded resonator

**Figure 8.** A fourth-order filter consisting of double-folded resonators
Figure 9. Simulated response and measured results

Figure 10. Structure of a fourth-order multi-fold

Figure 11. A fourth-order multi-folded filter resonator

Figure 12. Simulated response and measured results
bandpass filters consisting of single-fold, double-fold and multi-fold hairpin line resonators, are 3.7%/3.6%, 3.7%/3.8% and 4.3%/3.6% respectively. The simulated and measured results show minor variations in lower and upper stopband attenuation for single-fold and double-fold structures but major variations for multi-fold structure due to undesired cross-coupling between folded arms of individual resonators and non-adjacent resonators in the filters. The optimized dimensions of these filters are 20 mm x 20 mm (400 mm$^2$), 17 mm x 17 mm (289 mm$^2$) and 15 x 15 mm (225 mm$^2$).

CONCLUSION

This paper presents single, double and multi-fold hairpin line bandpass filter design techniques. The reduction in size of the fourth-order single, double and multi-fold filters are 36%, 53% and 64% of the optimized size (A) of the conventional hairpin line bandpass filter at 1325 MHz centre frequency. The measured results are close to the simulated/optimized results. There are limitations of the design in terms of inaccuracy of sharp folding and coupling between the adjacent and cross-coupled folded hairpin line resonators in the filters. The developed filters can be used for trans/receive RF/wireless/mobile communication systems.

REFERENCES


Table 1. Comparison of Simulated and Measured Results of Folded Hairpin Line Filters

<table>
<thead>
<tr>
<th>S. No</th>
<th>Parameters</th>
<th>Unit</th>
<th>Design Specs.</th>
<th>Single-fold Simulated</th>
<th>Single-fold Measured</th>
<th>Double-fold Simulated</th>
<th>Double-fold Measured</th>
<th>Multi-fold Simulated</th>
<th>Multi-fold Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Center frequency</td>
<td>MHz</td>
<td>1325</td>
<td>1325</td>
<td>1325</td>
<td>1325</td>
<td>1325</td>
<td>1325</td>
<td>1325</td>
</tr>
<tr>
<td>2</td>
<td>Insertion loss in band</td>
<td>dB</td>
<td>&lt; 3</td>
<td>2.6</td>
<td>3.2</td>
<td>2.4</td>
<td>2.5</td>
<td>2.2</td>
<td>3.0</td>
</tr>
<tr>
<td>3</td>
<td>3dB width (lower side)</td>
<td>MHz</td>
<td>25</td>
<td>24</td>
<td>23</td>
<td>26</td>
<td>24</td>
<td>33</td>
<td>24</td>
</tr>
<tr>
<td>4</td>
<td>3 dB width (upper side)</td>
<td>MHz</td>
<td>25</td>
<td>26</td>
<td>25</td>
<td>24</td>
<td>27</td>
<td>24</td>
<td>23</td>
</tr>
<tr>
<td>5</td>
<td>Stopband attenuation (lower side)</td>
<td>dBc at MHz</td>
<td>30 at 1265</td>
<td>31</td>
<td>28</td>
<td>27</td>
<td>28</td>
<td>23</td>
<td>26</td>
</tr>
<tr>
<td>6</td>
<td>Stopband attenuation (upper side)</td>
<td>dBc at MHz</td>
<td>30 at 1385</td>
<td>28</td>
<td>26</td>
<td>33</td>
<td>27</td>
<td>35</td>
<td>36</td>
</tr>
<tr>
<td>7</td>
<td>Size of filter / (Reduction in size)</td>
<td>mm$^2$ /%</td>
<td>Minimum 400mm$^2$</td>
<td>400mm$^2$ i.e. 64% of A/ (36% of A)</td>
<td>289mm$^2$ i.e. 47% of A/ (53% of A)</td>
<td>225mm$^2$ i.e. 36% of A/ (64% of A)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

# Optimized dimension of a conventional hairpin line bandpass filter: 25 mm x 25 mm : 625 mm$^2$ i.e. (A) for reference.


Ansoft-HFSS-3D software for Electromagnetic modeling (2012). by M/S Ansoft Software Corporation
