Miniaturized composite band pass filter using folded transmission lines for wideband radar

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Abstract. A composite design of Band Pass Filter (BPF) is developed with 3-dB fractional bandwidth (FBW) of more than 140%. This BPF is suitable for the development of wideband radar, communication and EW system in 1 to 6 GHz. Composite BPF design utilizes stepped impedance Low Pass Filter (LPF) along with the quarter wavelength ($\lambda_g/4$) short circuited stub. $\lambda_g/4$ short circuited stubs incorporated High Pass Filter (HPF) response which transforms overall design into BPF. Four cases of filter have been discussed. In case-I, the proposed BPF is developed with a size of 32.6 mm X 7.0 mm. Further in case-II, design has been realized with improved roll-off at the lower edge of the bandwidth (i.e., 1GHz). In case-III, developed design is 75% length-wise miniaturized that of case-I. Further in case-IV, about 55% length-wise miniaturization is done. Case-III and IV have their response similar to that of the case-I with miniaturized design. All designs are simulated, optimized and fabricated over RT-Duroid 5880 substrate. For case-I, III and IV fabrication has been done on 20 mil thick substrate, whereas for case-II 31 mil thick substrate is used. Comparisons between all the cases have been presented in tables and S-parameter plots.

Keywords. Band pass filter; electronic warfare; radar receiver; ultra wideband; composite filter.

1. Introduction

In the ever-increasing demand for higher bandwidth to provide better services for a large number of users with high data rates led to the development of wideband design technology [1]. In radar development, wideband technology is required to develop EW application and shared aperture technique. Wideband Radars are also used in medical imaging applications like Obstetrics imaging [2], Cardiology imaging (Radar stethoscope) [3], etc. The development of wideband component emerged with the advancement of wideband technology [4]. Band pass filters are one of the fundamental components required for the wideband design like Ultra Wide Band (UWB) receivers. The fractional bandwidth for a wideband BPF may vary from 50 to 100% or more. The conventional parallel coupled three-line microstrip structure in [5] has a fractional bandwidth of not more than 70%. In [6], BPF has inter digital configuration which is compact in size but limited up to 80% of the FBW. In [4], an alternate design utilizing a direct cascade of LPF and HPF to save circuit area has been developed. This

design has been optimized to make composite BPF which shows a significant improvement in fractional bandwidth of more than 100%.

This paper presents design of four different cases of BPF configurations based on the composite BPF configuration of [4], with higher FBW and miniaturized size. In case-I, proposed BPF is developed with a size 32.6 mm $\times$ 7.0 mm.

Case-II is designed with size 55.0 mm $\times$ 18.0 mm and developed with an improved roll-off compared to that of case-I at the lower edge of the bandwidth (i.e., 1GHz). It is found that Case-III and IV having their S-parameter response much similar to that of case-I with 75% and about 55% of length-wise miniaturization, respectively. In order to minimize insertion loss (IL), designs have been fabricated on RT- Duroid 5880. This substrate has very low loss tangent even at higher frequency up to 40 GHz (i.e., $\tan\delta = 0.0009$). For case-I, III and IV 20 mil thick substrate is used whereas case-II uses 31 mils thicker substrate. The novelty of the configurations presented in this manuscript, is its compactness, larger bandwidth, good roll off and acceptable insertion loss. Typical ultra-wideband receivers use Band Pass Filter to pass the RF signals into the receive module and rejects out of band signals. This kind of BPF is suitable for Electronic Warfare (EW) systems. Hence the proposed filter design is for wideband radar and EW application.

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2. Composite BPF design and calculation

The proposed composite BPF is developed using similar technique as in [4], stepped impedance LPF design along with the quarter wavelength ($\lambda g/4$) short circuited stubs at extremes of a stepped impedance LPF design, as shown in figure 1. For stepped impedance LPF design low-Z and high-Z values have been chosen as $20\ \Omega$ and $120\ \Omega$, respectively for cut-off frequency (f_c) of 6 GHz. The series inductor and shunt capacitor arrangement in conventional LPF design is replaced by high-Z and low-Z, respectively in stepped impedance LPF design [7], as shown in figure 2. In this design short circuited stubs incorporate HPF action along with the LPF for obtaining a BPF response. Short circuited stubs are separated to emulate overall structure to respond as BPF with pass band of 1 GHz to 6 GHz.

The above filter is designed with the Chebyshev prototype (the g_k) values for 0.1 dB pass band ripple and 7th order of LPF are [7]:

$$g_1 = g_7 = 1.1812, g_2 = g_6 = 1.4288, g_3 = 2.0967, g_4 = g_5 = 1.5734.$$

Lumped components values for LPF designs are given in [7] as:

$$\text{Inductor: } L_k = \left(\frac{g_k}{2\pi f} \right) Z_0 \quad (1)$$

$$\text{Capacitor: } C_k = \left(\frac{g_k}{2\pi f} \right) Z_0^{-1} \quad (2)$$

$$\text{Components : } L_1 = L_7 = 1.567\text{nH}, C_2 = C_6 = 0.758\text{pF}, \\ L_3 = L_5 = 2.781\text{nH}, C_4 = 0.835\text{pF}$$

Length of transmission lines [7]:

$$l_{\text{inductor}} = \frac{LZ_0}{Z_{hi}} \quad (3)$$

$$l_{\text{capacitor}} = \frac{CZ_{low}}{Z_0} \quad (4)$$

Where, L and C are the LPF prototypes (the g_k) values for a given pass band ripple and order of filter. Z_0 is the characteristic impedance of transmission line (i.e., $50\ \Omega$).

Figure 1. Layout of proposed BPF.

Figure 2. Conversion of lumped design to microstrip layout of LPF for proposed BPF. (a) Lumped Design using ADS, (b) Equivalent microstrip LPF design with $l_1 = 2.55$, $l_2 = 2.73$, $l_3 = 4.52$, $l_4 = 3.02$, $W_{lo} = 5.22$, $W_{hi} = 0.30$, all in mm. (c) Simulated Response of lumped design and its equivalent microstrip design.

Width (W) and Characteristic Impedance (Z_C) for microstrip (stub and transmission) lines are related as [8]:

$$Z_C = \frac{120\pi}{\sqrt{\epsilon_{eff}} \left(1.393 + \frac{W}{H} + \frac{2}{3} \ln \left(\frac{W}{H} + 1.444 \right) \right)} \quad (5)$$

Where,

Z_C = Characteristic Impedance of the transmission line

W = Width of the transmission line

ϵ_{eff} = Effective permittivity

H = Substrate height (thickness)

Effective permittivity for high-Z ($\epsilon_{hi,eff}$) and low-Z ($\epsilon_{low,eff}$) lines are defined [8], as:

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(1 + \frac{12H}{W} \right)^{-0.5} \quad (6)$$

$$\text{For } \left(\frac{W}{H}\right) < 2; \frac{W}{H} = \left(\frac{8e^A}{e^{2A} - 2}\right) \quad (6.a)$$

$$\text{Where, } A = 2\pi \left(\frac{W}{H}\right) \sqrt{\frac{\epsilon_r + 1}{2}} + \frac{\epsilon_r - 1}{\epsilon_r + 1} \left(0.23 + \frac{0.11}{\epsilon_r}\right) \quad (6.b)$$

$$\text{For } \left(\frac{W}{H}\right) > 2; \quad \frac{W}{H} = \frac{2}{\pi} (B - 1 - \ln(2B - 1)) \quad (6.c)$$

$$+ \frac{\epsilon_r - 1}{2\epsilon_r} \left(\ln(B - 1) + 0.39 - \frac{0.61}{\epsilon_r} \right)$$

$$\text{Where, } B = \frac{60\pi^2}{Z_0 \sqrt{\epsilon_r}} \quad (6.d)$$

Length of short circuited quarter wavelength stub of high-Z at center frequency (f_c) is:

$$l_{\text{stub}} = \frac{\lambda_0}{4\sqrt{\epsilon_{\text{hi,eff}}}} \quad (7)$$

Where, λ_0 is free space wavelength at f_c .

As shown in figure 3, Quarter wavelength stub indicates a flat response for a wide range of frequency (~ 1 to 6 GHz) and also it has a symmetric response about its resonating frequency (i.e., centre frequency, $f_c = 3.5$ GHz). Hence, this response is useful to make use of this stub along with LPF resulting in BPF as shown in figure 1.

2.1 Case-I: size reduction using folded stub

The BPF, as shown in figure 1, can be further modified by folding the stubs to reduce the size of designed BPF, as shown in figure 4(a). As shown in figure 4(c), the measured response of this design matches well with the simulated response which works for the frequency range of 1 GHz-6.5 GHz. The length of the 50 Ω line is adjusted in such a way that both of the bent stubs share common via, as shown in figure 4(a).

Filter response in case-I, clearly shows that near 1 GHz roll-off is not sharp as it is near 6 GHz. For getting better

Figure 3. $\lambda_g/4$ short circuited stub layout and ADS simulation response.

Figure 4. (a) Geometry of the proposed BPF (Case-I). $W_{lo} = 5.22$, $W_{hi} = 0.30$, all in mm, circuit is symmetric about its centers. (b) Fabricated wideband BPF and (c) simulated and measured BPF performance. Both layout and simulation have been done by ADS-2016.

rejection out of the band, sharp roll-off is essential at the edges. Making a parallel structure of two individual BPF of case-I will be most effective choice in order to increase the order of the filter for making an improvement in roll-off near 1 GHz, rather than using a cascaded configuration. In a cascaded structure, overall insertion loss and input/output port reflection will be high, which degrades the performance of the filter. Filter shown in case-I is the fundamental/basic structure which is used throughout in this paper by comparing with the modified designs in different cases [9].

2.2 Case-II: improvement in roll-off at lower edge of the bandwidth

Two individual designs of case-I are combined with the help of power divider and power combiner at the input and

output port respectively to form a parallel combination of designs as shown in figure 5. For this design, $S_{11} \leq -10$ dB and $S_{21} \sim -1.6$ dB in 5.5–6 GHz. Therefore, the measured result degrades widely from the simulated value in this frequency range, as shown in figure 5.

3. Analysis and improvement of modified designs

3.1 Case-III: Lengthwise miniaturization of 75%: Reduction in filter size of case-I was achieved by using folded transmission line to replace the high impedance (hi-Z) lines used in stepped impedance design part of BPF [9]. This design is shown in figure 6(a), which gives almost similar response as of case-I with an overall miniaturization of 75% along the length of the filter as compared to that of case-I. Measured response of this design matches with its simulated result and also with that of the case-I, as shown in figure 6 (c).

Figure 5. (a) Modified filters structure for improved roll-off (Case-II), (b) fabricated design and (c) simulated and measured performance.

(a)

(b)

Figure 6. (a) Miniaturized filter layout (Case-III), (b) fabricated design and (c) simulated and measured response.

3.2 Case-IV: lengthwise miniaturization of 55%

Further size reduction is achieved using similar technique as in case-III for the length-wise miniaturization of 55% of case-I. In this case to improve S_{11} and S_{21} , 90° bend have been used for curving of stubs instead of 90° bend of chamfered type as in the previous cases. Measured response for S_{21} and S_{11} is similar to case-I and case-III, as shown in figure 7(c).

Dimension of these entire filter configurations presented here are optimized through parametric study. The main sensitive dimensional parameters from the filter performance point of view are length, width and position of the stubs, and thickness of the substrate.

4. Measured results and comparison

Main measured parameters of various filter configurations are compared in tables 1 and 2.

Figure 7. (a) Miniaturized Filter Layout (Case-IV), (b) Fabricated Design and (c) Simulated and measured response.

Table 1. Measured parameters of skirt details and roll-off improvement.

Parameters	Case-I	Case-II
S11 (Pass band)	-6 dB at 1.1 GHz -21 dB at 3.5 GHz -40 dB at 5.9 GHz	-7 dB at 1.1 GHz -21 dB at 3.5 GHz -6.7 dB at 5.9 GHz
S21 (Pass band)	< -1 dB	< -1 dB
S21 (Stop band)	-7 dB at 600 MHz -10 dB at 450 MHz -16 dB at 250 MHz (lower edge skirt) -11 dB at 6.6 GHz -30 dB at 7.0 GHz -38 dB at 10.0 GHz (upper edge skirt)	-10 dB at 600 MHz -13 dB at 450 MHz -20 dB at 250 MHz (lower edge skirt) -11 dB at 6.6 GHz -23 dB at 7.0 GHz -38 dB at 10.0 GHz (upper edge skirt)
Bandwidth	1–6.5 GHz	1–6.5 GHz

Table 2. Measured parameters in terms of miniaturization.

Parameters	Case-I	Case-III	Case-IV
Miniaturization	—	75% length-wise	55% length-wise
Size	32.0×10.0 mm	25.0×15.0 mm	20.0×20.0 mm
Bandwidth	1–6.5 GHz	1–6 GHz	~1 to 6 GHz

Figure 8. Overall comparison plot of (a) S21 plots (roll-off) and (b) S11 plots, for all four cases.

4.1 Skirt details and roll-off improvement

4.2 Miniaturization

4.3 Comparison plots for all four cases

See Fig. 8.

5. Conclusion

A novel configuration of composite band pass filter has been presented with major emphasis on the reduction in its size. In this manuscript all filters are designed for 1-6 GHz with much improved FBW of about 140%, which is much

higher than the value reported earlier. Also in case-III and IV, 75% and 55% of miniaturization have been achieved than that of the basic design of case-I. The miniaturized designs are having higher fractional bandwidth with higher compactness than that of the design presented in [10, 11]. Use of this compact filter, will lead to the development of small-sized Transmit/Receive Modules (TRM) for the Active multipurpose radars and Electronic Warfare systems.

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