LETTER

Design of an ultra-compact lowpass filter with ultra-sharp roll-off for UHF application

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Abstract This letter proposes a UHF lowpass filter based on the image parameter method. This study designed, fabricated and assembled a 0.48-GHz semilumped lowpass filter using low cost FR4 substrate. It adopted a new layout concept for the air wound coils to achieve the purposes of compact size and good performances. The proposed UHF lowpass filter has the best performances for the roll-off rate and circuit size compared to previous works, and it also achieves the best figure of merit 973,369.

Keywords: air wound coil, composite filter, lowpass filter, microstrip, sharp roll-off, semilumped

Classification: Microwave and millimeter-wave devices, circuits, and modules

1. Introduction

Many researches and applications have developed in the band of Ultra High Frequency (UHF, 300 MHz to 3 GHz), such as radio astronomy [1], television broadcasting [2], Global Positioning System (GPS) [3], two-way radios [4, 5], Radio Frequency Identification (RFID) [6, 7], and radar system [8, 9]. With more and more diverse functions, it becomes harder to satisfy all the requirements with the limited circuit space. Therefore, the size of circuits has become an important parameter of system design.

Filter is one of the commonly used components in communication systems. Its function is to pass the wanted signals (pass band) and suppresses unwanted signals (rejection band). Usually, the sharp transition band between pass band and rejection band is required, and roll-off rate is an index to describe the slope of the transition band. Roll-off rate [10] is obtained by the frequency difference over attenuation level difference of 3-dB cutoff frequency point and rejection frequency point. Higher roll-off rate means sharper slope. Hence, a filter with compact size and high roll-off rate is important for systems. The goal of this letter is to design an ultra-compact lowpass filter with sharp roll-off for UHF. The specification is shown in Table I. Target of circuit size is smaller than 300 mm². The frequency of the passband is from 0 to 0.4 GHz. The insertion loss must within 0.5 dB, and the return loss should better than 10 dB. The cutoff frequency (f_c) is 0.48 GHz. The

Table I. Target of the UHF lowpass filter

Item	Specification
Frequency of passband (GHz)	0 to 0.4
Return loss (dB)	<10
Insertion loss (dB)	<0.5
Cutoff frequency of 3 dB (f_c , GHz)	0.48
Limitation of length and width (mm)	30 × 10
Roll-off rate (dB/GHz)	>1000
Rejection level (dB)	>40

Fig. 1. Traditional structure of the composite lowpass filter based on the image parameter method.

roll-off rate should as sharp as possible, and the target is higher than 1000 in this letter. The rejection level must greater than 40 dB to perform high suppression for unwanted signals.

According to the requirement of sharp roll-off and compact size, the authors would adopt the image parameter method [11] to design the lowpass filter. Compare to Chebyshev response of the insertion loss method, the structure of composite filter can achieve sharp roll-off and high rejection level with less elements [12, 13, 14, 15]. Besides, the clear division of functionality of composite filter is useful to the optimization of target specification, and is convenient for performance debugging. The traditional structure of the composite lowpass filter is shown in Fig. 1. The performance of matching is dominated by bisected π section. The slope of roll-off is dominated by the m-derived section. The rejection level is dominated by the constant-k section.

In this letter, the design of lowpass filter with coil inductors, and surface mounted devices (SMD) capacitors for UHF band is detailed. The lowpass filter was fabricated, and the performances were measured. Three duplicate lowpass filters are also implemented to validate the repeatability. This lowpass filter has the most compact circuit size,

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the sharpest roll-off rate, and the highest score of figure of merit compared to published works.

2. Circuit design

The detailed design procedure is presented in this section.

2.1 Decision of parameters of cutoff frequency and rejection frequency for the image parameter method

Intuitively, the 0.48 GHz should be chosen for the 3-dB f_c , and this means that if f_∞ is 0.527 GHz, the attenuation level must achieve 50 dB to meet the specification of roll-off rate $((50 - 3)/(0.527 - 0.48) = 1000)$. Based on this condition, the values of capacitors and inductors can be calculated for the traditional composite lowpass filter. However, this calculated capacitances and inductances are for ideal components which are no parasitic and lossless. Therefore, in the stage of design, it should be more margin for the f_c and f_∞ . In this case, 0.5 GHz is chosen for f_c to ensure the 0.48 GHz within 3-dB loss of realization. 0.52 GHz is chosen for f_∞ to ensure 1175 roll-off rate $((50 - 3)/(0.52 - 0.48) = 1175)$ in the simulated stage.

Fig. 2. Symmetric structure of constant-ks for lowpass filter.

Table II. Parameters of the composite lowpass filter

Parameters (unit: GHz, nH, pF)	Value
f_c	0.5
f_∞ (infinite attenuation pole)	0.52
L	31.83
C	12.73
$L1_{Mat}$ ($m = 0.6$)	16.98
$L2_{Mat}$ ($m = 0.6$)	9.55
$C1_{Mat}$ ($m = 0.6$)	3.82
$L3_{Con}$ ($m = 0.275$)	15.92
$L4_{Con}$ ($m = 0.275$)	15.92
$C2_{Con}$ ($m = 0.275$)	12.73
$L5_{Mde}$ ($m = 0.275$)	4.37
$L6_{Mde}$ ($m = 0.275$)	4.37
$L7_{Mde}$ ($m = 0.275$)	26.79
$C3_{Mde}$ ($m = 0.275$)	3.5
$L7_{Con}$ ($m = 0.275$)	15.92
$L8_{Con}$ ($m = 0.275$)	15.92
$C4_{Con}$ ($m = 0.275$)	12.73
$L9_{Mat}$ ($m = 0.6$)	9.55
$L10_{Mat}$ ($m = 0.6$)	16.98
$C5_{Mat}$ ($m = 0.6$)	3.82

2.2 Adopted structure of symmetric constant-k for lowpass filter

After the decisions of f_c and f_∞ , the parameters can be calculated by Eq. 1 to Eq. 10, and the ideal performance of the traditional composite lowpass filter (single constant-k) can be simulated by using a circuit design simulator (advanced design system [ADS]). All the performances are much higher than the specification except for the rejection level. Therefore, an extra constant-k is added to the traditional composite lowpass filter (single constant-k) as shown in Fig. 2. Although the added constant-k can also directly cascade to the original constant-k to form the asymmetric structure and has the same performances with the symmetric structure, the formation of symmetric constant-ks is preferred due to realization concern. In the realization stage, the set of $L4_{Con}$ and $L5_{Mde}$ and the set of $L6_{Mde}$ and $L7_{Con}$ would be combined to one kind inductor. If in the case of series constant-ks, the set of $L4_{Con}$ and $L7_{Con}$ would be combined to one kind inductor, and the $L8_{Con}$ and $L5_{Mde}$ would be combined to another kind inductor. This condition not only results higher cost, but also increases the variability of realization. Hence, the symmetric structure of constant-ks for the composite lowpass filter is adopted, and related parameters are listed in Table II. The performances are shown in Fig. 3. The symmetric constant-ks lowpass filter has better rejection level with little compromise of return loss.

$$m = \sqrt{1 - \left(\frac{f_c}{f_\infty}\right)^2} \quad (1)$$

$$L = \frac{2R_0}{\omega_c} \quad (2)$$

$$C = \frac{2}{R_0\omega_c} = C2_{Con} = C4_{Con} \quad (3)$$

$$\omega_c = 2\pi f_c \quad (4)$$

$$\frac{1 - m^2}{2m} L = L1_{Mat} = L10_{Mat} \quad (5)$$

$$\frac{mL}{2} = L2_{Mat} = L9_{Mat} = L5_{Mde} = L6_{Mde} \quad (6)$$

$$\frac{mC}{2} = C1_{Mat} = C5_{Mat} \quad (7)$$

$$\frac{L}{2} = L3_{Con} = L4_{Con} = L7_{Con} = L8_{Con} \quad (8)$$

$$mC = C3_{Mde} \quad (9)$$

$$\frac{1 - m^2}{4m} L = L7_{Mde} \quad (10)$$

2.3 Consideration for implementation of components

There are two choices for implementation of components, one is equivalent components made by printed circuit board (PCB). The effect of inductors and capacitors can be implemented by open stubs, short stubs, coupled lines, and the layout patterns of the PCB. This method would not easy to achieve compact size [16, 17, 18, 19, 20], and it may not meet the requirement of this UWB lowpass filter. Another is the use of lumped components. The commercial SMD of inductors and capacitors are compact and can be

Fig. 3. Simulated results of symmetric constant-k and single constant-k for lowpass filter, (a) insertion loss, and (b) return loss.

used to design a compact UWB lowpass filter. By this method, the performance of lowpass filter is highly depending on the quality factor (Q) of SMD inductors and capacitors. Higher quality factor means the components are more close to lossless component. In order to discuss the effect of Q on the circuit, the sweep of the Q of inductors (the capacitor is ideal) for the structure of constant-k is shown in Fig. 4. Pinky curve represents the Q is infinity for inductors, green curves represent the Q is from 50 to 100 for inductors, and the blue curves represent the Q is from 10 to 40. If the Q of inductors is larger than 50, the insertion losses are close to the ideal condition. If it changes to sweep the Q of the capacitor (inductors are ideal), the curves of a similar trend could be obtained. Therefore, the value 50 of the Q for components is the basic requirement to meet the specification of insertion loss. The next step is to find suitable components for the design of the UHF lowpass filter. After authors repeatedly surveyed and experimented, the capacitors of high Q 0603 SMD and inductors of high Q air wound coil are adopted. The S-parameters which were near to two ends of capacitors and inductors without the effect of connectors were measured by thru-reflect-line (TRL) calibration method [21], and the capacitances, inductances, and Q were calculated by ADS. For the capacitors, the commercial SMD of Multi-layer Ceramic Capacitor (MLCC) can achieve Q of 100 easily. But for the SMD inductors of MLCC, it may be

Fig. 4. Simulated result of the quality factor for the structure of constant-k.

a challenge to achieve the Q of 50. Therefore, the air wound coils with high Q are adopted. Initially, the authors used the empirical Eq. 11 to help fabricate the expected air wound coils by hands. Eq. 11 is a general form which was derived from [22] for metric unit. Finally, based on the tested results, the customized air wound coils were bought to implement the lowpass filter, and the test board of the air wound coils is shown in Fig. 5. The diameter of the coil is 2.0 mm, and the diameter of the enameled wire is 0.4 mm.

$$L = \frac{d^2 \times n^2}{b + 0.45d}, \quad \text{for } l > 0.4d \quad (11)$$

L = inductance of the coil (μH), d = diameter of the coil (m), n = turns of the coil, b = length of the coil (m).

Fig. 5. Test board of the air wound coils.

2.4 Layout of the UHF lowpass filter

After the components are determined, an elaborate layout is proposed to facilitate the compact size and good performances of the UHF lowpass filter as shown in Fig. 6. The low cost FR4 substrate ($h = 0.8$ mm, $\epsilon_r = 4.3$, and $\tan \delta = 0.018$) is used, and the transmission line is in microstrip form. The detailed dimensions are labeled

and the total size is $30\text{ mm} \times 10\text{ mm}$ ($0.100 \times 0.033 \lambda_g^2$ @ 0.48 GHz , where λ_g is the guided wavelength in substrate at a design frequency). The width of the 50Ω microstrip line is 1.4 mm for the input and output ports. The width of the interconnected line is 0.4 mm for components. Thinner interconnected lines have strong inductive, and these essential interconnected lines can be taken as a part of the lumped inductors. Therefore, no extra 50Ω microstrip line is needed to as an interconnected line for lumped components. With the tandem layout for the coils, not only the series coils but also the shunt coils can be arranged to side by side line formation. Hence, the individual magnetic flux of the coils would not interfere each other. Furthermore, this line formation is also convenient for assembling the coils. When all coils are putted in the corresponding positions, those coils can be soldered in order, and this would reduce the assembly time and complexity.

Fig. 6. The layout of the proposed UHF lowpass filter.

3. Experiments

The equivalent circuit and photograph of the fabricated UHF lowpass filter is shown in Fig. 7. Final values of components for the UHF lowpass filter are shown in Table III. The adjacent inductors are combined into one inductor. The values differ from the calculated values in Table II due to the compromises of selling values of commercial components and layout compensations.

The measured performances are shown in Fig. 8. Three duplicated circuits are fabricated to validate the repeatability. The f_c is 0.48 GHz , the calculated roll-off is larger than 1700, the suppression is larger than 40 dB, and the return losses are better than 10 dB. The performance compared to the state-of-the-art works is shown in Table IV. The related formulas are also shown. The proposed work has the sharpest roll-off rate 2285.7, high suppression level 44 dB, the most compact size $0.0033 \lambda_g^2$, and the highest figure of merit 973,369.

4. Conclusion

The proposed UHF lowpass filter is implemented by

Fig. 7. Photograph of the proposed UHF lowpass filter.

Table III. Component values of UHF lowpass filter

Parameters	Labeled value	Value, Quality factor @0.5 GHz
L1	35 nH (5 turns)	43.2 nH, 78
L2	25 nH (4 turns)	30.6 nH, 79
L3	25 nH (4 turns)	30.6 nH, 79
L4	35 nH (5 turns)	43.2 nH, 78
L5	25 nH (4 turns)	30.6 nH, 79
L6	25 nH (4 turns)	30.6 nH, 79
L7	35 nH (5 turns)	43.2 nH, 78
C1	1.5 pF	1.54 pF, 194
C2	9.0 pF	9.4 pF, 237
C3	2.2 pF	2.25 pF, 858
C4	8.0 pF	8.12 pF, 1437
C5	1.8 pF	1.84 pF, 381

the low cost FR4 substrate, low cost and high Q coils, and low cost and high Q SMD capacitors. This UHF lowpass filter has the most compact size and the sharpest roll-off rate, and can compete with previous works. Two key features necessary for this ultra-compact and good performances lowpass filter were the appropriate selection of components and layout allocation. With these, the individual series and shunt coils would not interfere each other and the process of assembly is simple.

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Fig. 8. Measured results of (a) transmission coefficient, (b) input reflection coefficient, and (c) output input reflection coefficient.

Table IV. State-of-the-art sharp roll-off rate PCB lowpass filter

Reference	Cutoff frequency (GHz)	Roll-off rate ζ (dB/GHz)	Relative stopband bandwidth	Suppression factor	Normalized circuit size (λ_g^2)	Architecture factor	Figure of merit
[23] EL2103	2.44	178.9 (–3 to –20 dB)	1.73 (–20 dB)	2	$0.168 \times 0.138 = 0.0231$	1	26,796
[24] EL2018	2.0	340 (–3 to –20 dB)	1.71 (–31 dB)	3.1	0.025	1	72,094
[25] ELEX2011	1.55	58.6 (–3 to –20 dB)	1.49 (–20 dB)	2	$0.164 \times 0.035 = 0.0057$	1	30,433
[26] MWCL2013	1.26	217 (–3 to –20 dB)	1.69 (–20 dB)	2	$0.27 \times 0.116 = 0.0313$	1	19,931
[27] ETRI2011	1.036	134.9 (–3 to –20 dB)	0.70 (–20 dB)	2	$0.22 \times 0.18 = 0.0396$	1	4,747
[28] TJES2018	2.912	1608.7 (–3 to –40 dB)	0.77 (–45 dB)	4.5	$0.238 \times 0.081 = 0.0193$	1	162,820
[29] APMC2017	2.108	544.1 (–3 to –40 dB)	1.66 (–33 dB)	3.3	$0.297 \times 0.131 = 0.0389$	1	96,359
[30] EL2015	1.513	187.8 (–3 to –40 dB)	1.71 (–35 dB)	3.5	$0.177 \times 0.097 = 0.0172$	1	65,593
[31] EL2010	1.5	257 (–3 to –40 dB)	1.57 (–15 dB)	1.5	$0.145 \times 0.108 = 0.0157$	1	38,747
[32] EL2019	1.0	123.3 (–3 to –40 dB)	0.33 (–31.3 dB)	3.13	$0.063 \times 0.055 = 0.0035$	1	37,024
[33] PIERL2014	0.86	154.2 (–3 to –40 dB)	1.44 (–40 dB)	4	$0.23 \times 0.05 = 0.0115$	1	77,228
[34] APEC2015	0.63	109.3 (–3 to –50 dB)	1.15 (–20 dB)	2	$0.092 \times 0.0537 = 0.0049$	1	50,746
This work	0.483	1740.7 (–3 to –50 dB)	0.65 (–44 dB)	4.4	0.100 $\times$ 0.033 = 0.0033	2	743,301
		2285.7 (–3 to –67 dB)					973,369

Roll-off rate (ζ)

$$\zeta = (\alpha_{\max} - \alpha_{\min}) / (f_s - f_c)$$

$\alpha_{\max}$ is the designated attenuation level

$\alpha_{\min}$ is the 3 dB attenuation level

f_s is the designated stopband frequency

f_c is the 3 dB cutoff frequency

Normalized circuit size (NCS)

NSC = physical size (length $\times$ width) / λ_g^2

λ_g is the guided wavelength at f_c

Relative stopband bandwidth (RSB)

$$\text{RSB} =$$

(stopband bandwidth) / (stopband centre frequency)

Architecture factor (AF)

AF = 1 for planar structure

AF = 2 for three-dimensional structure

Suppression factor (SF)

SF = rejection level / 10

Figure of merit (FOM)

$$\text{FOM} =$$

$(\zeta \times \text{RSB} \times \text{SF}) / (\text{NSC} \times \text{AF})$

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