

Bode 100 - Application Note

Passive Filter Design with QuickFil and Bode 100



By Florian Hämmerle © 2011 by OMICRON Lab – V2.1 Visit <u>www.omicron-lab.com</u> for more information. Contact <u>support@omicron-lab.com</u> for technical support.

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- **Note**: Basic procedures such as setting-up, adjusting and calibrating the Bode 100 are described in the Bode 100 user manual. You can download the Bode 100 user manual at <u>www.omicron-lab.com/bode-100/downloads#3</u>
- Note: All measurements in this application note have been performed with the Bode Analyzer Suite V3.23. Use this version or a higher version to perform the measurements shown in this document. You can download the latest version at www.omicron-lab.com/bode-100/downloads



1 Executive Summary

This application note targets the design and analysis of standard filter types such as high pass, low pass and band pass filters.

It is demonstrated how to design a passive bandpass filter using the freeware filter design software QuickFil¹.

The designed filter is realized using standard value components and the filter characteristics are then measured using the Bode 100.

Finally the measured filter characteristics are compared with the calculated values from QuickFil.

2 Task

A passive bandpass filter with the following characteristics shall be designed:

- Centre frequency: $f_c = 230 \text{ kHz}$
- Passband bandwidth: $f_p = 10\% = 23 \text{ kHz}$
- Passband loss = 0.1 dB
- Filter degree n = 6

The designed filter shall be built and the characteristics be measured. The measured characteristics will be compared with the theoretical values.



¹ More information at: <u>https://www.omicron-lab.com/quickfil.html</u>

3 Filter Design with QuickFil

3.1 About QuickFil

QuickFil is a software for designing passive electronic filters. QuickFil supports many types of filters and different approximations:

Types of Filters:

- Lowpass
- Highpass
- Bandpass
- Bandstop
- Allpass
- Asymmetric bandpass filters
- Parametric bandpass filters

Approximations:

- Butterworth (maximally-flat filters)
- Chebyshev (equal-ripple filter)
- Inverse Chebyshev
- Elliptic (Cauer)
- Bessel (maximally flat delay)
- Modified Bessel
- General Equal-ripple approximation
- General maximum-flat approximation

Note:

If you plan to run QuickFil on Windows 10 you have to use a small workaround. Details on this are described in the QuickFil Installation Guideline which is delivered within the QuickFil Folder.

3.2 Bandpass Filter Design

The following chapters are structured like a step by step guideline on how to design a filter using QuickFil.

3.2.1 Filter Type and Specifications

The first step is to define the filter type and approximation. After starting QuickFil the main screen is shown. By clicking on <Filtertype> the type of filter and the approximation method can be chosen as shown in the following figures:





In the QuickFil Main screen the option <Filtertype> can be chosen:

The Filtertype screen appears and the <Type> is set to <Bandpass> and the <Approximation > to <Chebychev>:

[
Filtertype	Approximation
Lowpass Highnass Bandpass Bandstop Allpass	General Equal-ripple General Maximally-flat Butterworth Chebychev Inverse Chebychev Elliptic (Cauer)
FILTERTYPE: <mark>Type</mark> Approximation	Quit '

Note:

By clicking on <Quit> one can return to the main screen!



In the Main screen the <Specification> option can be chosen to enter the specification values which define the filter performance:

(0)	SPECIFICATIONS to : Chebychev appnote filt	- bandpass filter er	
(A) (B) (C)	Centre frequency : Relative passband bandwidth : Relative stopband bandwidth :	230,000 000 kHz 10.00 % 30,00 %	Input values defining the filter properties.
(E) (F) (R) (G)	Passband bandedge loss:Passband bandedge return loss:Passband reflection factor:Stopband loss:	0.100 000 dB 16.43 dB 15.09 % 23.60 dB	The veriable value
(H) (T) (J)	Filter degree : Case (b, c) : Variable value (B,C,E,F,G,H,R) :	G G	is indicated by the symbol.
	Relative 3dB bandwidth : Filter quality :	13.89 % 20.67	This option enables to
SPECIFI	freqUencyrepres. bandwithrepreS	New cumment file Printer rel.bandwithrepres. Quit ?	as relative values.

As described in the beginning of the document, a filter with a centre frequency of 230 kHz is defined. The relative passband bandiwdth is defined to be 10% and the relative stopband bandwidth is defined to be 30%.

By defining the <Stopband loss> to be the variable (changing) value the filter degree can be defined to be 6. This results in a calculated stopband loss of 23.6 dB.

<Quit> returns to the Main screen and by choosing the option <passive_Design> in the Main screen, QuickFil proposes the design and values for the passive filter defined in the specification screen:





By clicking on <Dual circuit> QuickFil calculates the component values for the dual design. In this case the dual design has some advantages for later circuit manipulation.

Passive design	1R
 (1) Output circuit (1) Input circuit (2) Circuits with positive elements (3) Computer circuit (4) Dual circuit (7) Terminating resistance (A) Accuracy (W) Sign real part of reflection zeros (M) Manipulation and analysis 	2 3 4 C 5 L 6 7 8 R
PASSIVE-DESIGN: DISCDTAVM	Quit ?

Choosing the option <Output circuit> shows the current design and the calculated component values:

appr 	note fil	ter 			
1	R		50.000	000	Ohm
2	c		142.763	346	nF
3	L		3.354	037	uН
4		c	1.206	170	nF
5	•	L	396.986	807	uН
6	c		142.763	346	nF
7	L		3.354	037	uH
8	R		50.000	000	Ohm



3.2.2 Circuit Manipulation

The default design proposed by QuickFil contains three inductors with two different inductance values ($L_3 = L_7 = 3.35 \,\mu\text{H}, L_5 = 397 \,\mu\text{H}$).

QuickFil offers a Norton's transformation functionality to modify component values without affecting the filter characteristics. In the following is explained how the filter can be modified to achieve three similar inductors.

The Norton's transformation option can be found by first choosing the <Manipulation and analysis> option in the Passive design screen.



Choosing the <Norton's transformation> option opens the Norton's transformation screen:

Norton's transformation	1R
(P) Previous component combination (N) Next component combination	2 — C — — 3 — L —
Kind of circuit : PI (A) Min. factor : 70.190 113 µ	4 C
(B) Max. factor : 1.000 000	5 Ĺ
(D) Factor : 1.000 000	6 <u> </u>
(E) Component No. : 8 Current value : 50.000 000 R	7 — L—
(F) Nominal compon. : 1 (G) Nominal value : 50.000 000 R	8 - R-1
(H) Automatic Norton's transformation (U) Undo transformation	
Move circuit: [Cursor keys]	
NORTON'S TRANSFORMATION: PNABCDE	FGHUPITEE Quit?



The transformation always works from top to down. We now want to perform a transformation in a way that the inductor L5 gets the same inductance value as the inductor L3. This can be done by setting the <Component No.> to 5. This means that component No. 5 will be changed. Since we want the inductor L5 to have the same value as the inductor L3 the <Nominal compon.> has to be set to 3. QuickFil now calculates the transformation factor which is displayed in the <Nominal factor> field:



In addition the <Kind of circuit> is set to TEE as this gives a better structure for the second transformation.

The transformation now has to be made active by clicking on <Nominal factor>. This means that the calculated transformation factor is applied to the circuit. This leads to the following screen:

Norton's transformation	1R
(P) Previous component combination (N) Next component combination	2 3C
Kind of circuit : TEE (A) Min. factor : 1.000 000 (B) Max. factor : 118.360 884 (C) Nominal factor : 1.000 000 (D) Factor : 8.448 737 m	4
 (E) Component No. : 6 Current value : 3.354 037 µH (F) Nominal compon. : not defined (G) Nominal value : 3.354 037 µH (H) Automatic Norton's transformation (U) Undo transformation 	7
Move circuit: [Cursor keys] NORTON'S TRANSFORMATION: P N A B C D E	FGHUPITEE Quit?

The first two inductors now have the same inductance value. The same transformation can be applied to the third inductor as follows.



Clicking two times on <Next component combination> marks the right components. Now the <Component No.> field is set to 8 as we want to change the value of the last inductor at position 8. The <Nominal compon.> value is set to 6 as we want the inductor 8 to have the same inductance value as the inductor 6.



Performing the transformation by clicking on <Nominal factor> leads to the final circuit design. The circuit and component values can be displayed by clicking on <Quit> and <Output circuit>:

appr	ote filter			
1	R	50.000	000	Ohm
2	 L	3.354	037	uH
3	 . c	157.213	986	nF
4	 c	1.553	177	uF
5	 . L	3.354	037	uH
6	 . C	171.371	516	nF
7	 C	1.553	177	uF
8	 . C	157.213	986	nF
9	 L	3.354	037	uH
10	 R	50.000	000	Ohm

The three inductors now have the same inductance values which can be advantageous for the practical design.



The practical design is built using standard component values. The capacitance values were achieved by series and parallel combination of standard capacitors. The used component values are:

Component	Calculated Value	Used Value
L2, L5, L9	3.354 µH	3.3 µH
C3, C8	157.213 nF	158 nF
C4, C7	1.553 µF	1,55 µF
C6	171.371 nF	172 nF

Assembled bandpass filter:



3.2.3 Circuit Analysis

QuickFil offers tools to analyze the designed filter. In the Manipulation and Analysis screen the option <Circuit analysis> can be chosen.





Diagram 1: Transfer function Magnitude [dB] with stopband specification Diagram 2: Diagram 3: Diagram 4: Select diagram with [PgUp],[PgDn] -0.000 000 dB Property: Representation: Stopband spec Magnitude [1] Transfer function Input Impedance Output impedance Input reflection factor Magnitude [dB] rnase tradi Phase [°] Output reflection factor Group delay [s] Real part [1] Imaginary part [1] -80.000 000 dB 100.000 000 kHz 350.000 000 kHz Merged graphs: 0 **100** Points linear Quality factor Induct.: infinite Capacit.: infinite <mark>G</mark>raph Hold Y-from Y-to IRCUIT ANALYSIS: Property Repres. Transfer XDefault YDefault X-from X-to pOints Lin Log Ind Cap Quit

In the Circuit Analysis screen the desired property and plot settings can be set.

Clicking on <Graph> starts the plot window and shows the transfer function as shown in the following figure.





4 Filter Measurement

The assembled bandpass filter transfer function shall be measured with the Bode 100. In the following is shown step by step how to configure and calibrate the Bode 100 for the filter measurement.

4.1 Device Setup

The transfer function of the bandpass filter can be measured in the Transmission / Reflection measurement type of the Bode Analyzer Suite.

¢	Welcome, please select a measurement type
New measurement	Vector Network Analysis Depedance Analysis
Recent	✓ Transmission / Reflection
Options	Measure s-parameters with 50 Ω termination. Measure s-parameters with 1 MO termination the second secon
About	internal reference.
Read user manual	Start measurement
Exit	> Gain / Phase
	> Reflection with external coupler

Figure 1: Start menu

We want to measure the magnitude and phase of the filter. Therefore trace 1 is set to Measurement Gain, Format Mag(dB) and trace 2 to Measurement Gain, Format phase(°) as shown in the following figures:

			· · · · · · · · · · · · · · · · · · ·
		Measurement	Gain 🔻
		Display	Measurement 🔹
Trace 1	~	Format	Phase (°) 🔹
Measurement	Gain 🔻	Unwrap pha	se
Display	Measurement 🔹	🗌 Begin	Hz
Format	Magnitude (dB) 🛛 🔻	End	Hz
Y _{max}	0 dB 🛟	Y _{max}	200 ° 🜲
Y _{min}	-80 dB 韋	Ymin	-200 ° 🖨

Trac

Figure 2: Settings Trace 1

Figure	3:	Settings	Trace	2



Start and stop frequency are set to 100 kHz and 350 kHz. The attenuator for channel 1 to 0 dB and the attenuator for channel 2 to 10 dB. The receiver bandwidth is set to 30 Hz as in the following figure.

		Single			
Start frequency		100 kHz			
Stop frequency		350 kHz			
Center		225 kHz			
Span		250 kHz			
Get from zoom					
Sweep Linear	•	Logarithmic			
Number of points 201 🔹					
Level Const	ant 🔳	Variable			
Source level		0 dBm 💲			
Attenuator Ch	annel 1	Channel 2			
Gain 0	dB 🔻	10 dB 🔻			
Gain 0 Reflection 10	dB ▼)dB ▼	10 dB ▼ 10 dB ▼			
Gain 0 Reflection 10	dB ▼)dB ▼	10 dB ▼ 10 dB ▼			

The Bode 100 is now ready to perform the measurement. To remove the influence of the connection cables on the measurement results it is advisable to perform a calibration before measuring the filter.

4.2 Calibration

A thru calibration removes the influence of the cables on the measurement. To do so, the two cables from output and channel 2 have to be connected together using the thru connector as shown in the picture below or in the Bode 100 user manual (<u>https://www.omicron-lab.com/downloads/vector-network-analysis/bode-100/</u>).







After connecting the cable the thru calibration can be done by clicking on Gain calibration -> User Range.



Figure 6: perform calibration

Start the calibration by pressing Start.



Figure 7: User Range Calibration window

4.3 Measurement

After performing the calibration, the thru connection is replaced by the bandpass filter as shown in the picture below.



Figure 8: Measurement setup

Now the measurement can be started by pressing the single sweep button.



Figure 9: single sweep button



5 Results

Performing the measurement described above leads to results as shown below. The first graph shows the amplitude gain in decibel and the second graph the phase in degree.



Figure 10: Measurement result - Magnitude (dB)





Comparing these results with the calculations in QuickFil shows that the passband loss is higher than calculated. The reason for this are the limited quality factors of the components used to assemble the filter.

QuickFil offers a feature to estimate this influence. In the circuit analysis screen are input fields for the inductor quality factor and the capacitor quality factor. The components used for the assembled filter have an approximate quality factor of

Inductors: $Q \approx 55$

Capacitor combinations: $Q \approx 40$



Diagram 1: Transfe Diagram 2: Transfe Diagram 3: Diagram 4:	r function Magnitude [dB] r function Phase [°] ————————————————————————————————————	; diagram with [PgUp],[PgDn] -	
-0.000 000 ab	Property: Transfer function Input impedance Output impedance Input reflection factor Output reflection factor	Representation: Stopband spec. Magnitude [1] Magnitude [dB] Phase [rad] Phase [°] Group delay [s] Real part [1] Imaginary part [1]	Inductor quality factor
-80.000 000 dB Merged graphs:	100.000 000 kHz 0 100 Points	250.000 000 kHz linear	factor
Quality factor Inde CIRCUIT ANALYSIS: Gr Y-	aph Hold Property Repres. from Y-to X-from X-to pOints	Capacit: 40.000 000 // Transfer XDefault YDefault : Lin Log Ind Cap Quit ?	

The figure below shows how the quality factors are entered into QuickFil.

When considering the quality factors of the components the calculated transfer characteristic results as shown in the following graph:



On the next page there is a direct comparison between measured and calculated data where the quality factors are taken into consideration





6 Conclusion

The first part of this application note shows how to design passive filters using the filter design software QuickFil. QuickFil offers many functions for passive filter design e.g. Norton's transformation to optimize the filter design.

The second part of the application note shows how to measure the filter characteristics of the designed bandpass filter using the Bode 100. It is shown how to terminate the filter correctly using the internal 50 Ohm resistance of the Bode 100.

The measured and calculated results match very well when the quality factors of the used components are considered for the calculation of the transfer function. It is therefore very important to have high quality components for the passive filter design.





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