

# 2

## RF.Spice A/D



Visual Software Environment For  
Analog/Digital/RF/Mixed-Signal  
Circuit & System Simulation

## System-Level Tutorial Lesson 2

### Realizing Analog Filters With Arbitrary Transfer Functions

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## 2.1 What You Will Learn

In this tutorial you will learn how to use RF.Spice's black-box virtual blocks to realize different types of filters with arbitrary transfer functions.

## 2.2 Working with Analog Filters in RF.Spice A/D

RF.Spice A/D provides you with several different ways to design, realize, build, and test analog filters. In Analog Tutorial Lessons 7 and 8, you explored active Sallen-Key filters using operational amplifiers. In RF Tutorial Lesson 5 and 7, you explored passive filters like lumped LC and distributed microstrip filters. In all of these lessons, you built your filter using discrete physical components like resistors, capacitors, Op-Amps, transmission line segments, etc.

RF.Spice A/D also offers a number of black-box virtual blocks that provide the analog filter function. These are listed below:

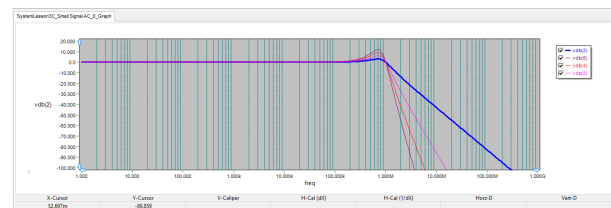
- Generic Lowpass Filter Block
- Generic Highpass Filter Block
- Generic Bandpass Filter Block
- Generic Bandstop Filter Block
- Generalized Analog Filter Block
- S-Domain Transfer Function Block

All of these parts can be accessed from **Menu > Parts > Spectral Processing Blocks > Generic Filter Blocks**. The first four blocks are basic fifth-order Butterworth filters made of LC elements. The lowpass and highpass filters give you the option to specify the cutoff frequency. The bandpass and bandstop filters give you the option to specify the center frequency and bandwidth.

Both the generalized analog filter and S-domain transfer function blocks let you define arbitrary rational transfer functions, where you need to specify the coefficients of the denominator and numerator polynomials. The generalized analog filter is an RF.Spice A/D device and is more versatile especially for time domain simulations. Its model involves analog integrator devices. The S-Domain transfer function block is an XSPICE native device that provides a convenient denormalization frequency parameter.

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### Tutorial Project: Realizing Analog Filters With Arbitrary Transfer Functions



**Objective:** In this project, you will build different types of lowpass and bandpass filters using virtual blocks.

#### Concepts/Features:

- Virtual Block
- Transfer Function Block
- Butterworth Filter
- Chebyshev Filter
- Lowpass Filter
- Bandpass Filter
- Cascaded Filter

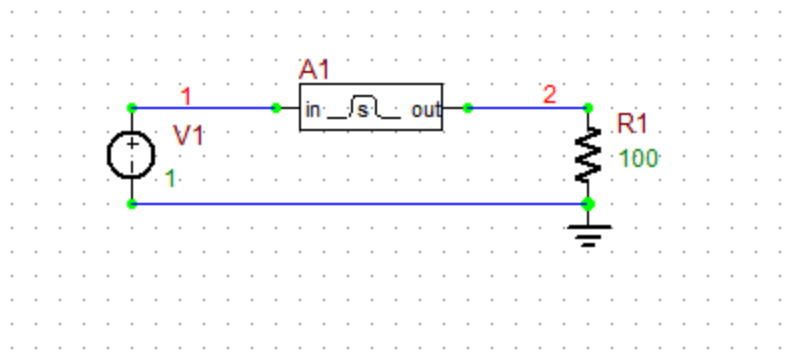
**Minimum Version Required:** All versions

## 2.3 Testing a Second-Order Butterworth Lowpass Filter

The following is a list of parts needed for this part of the tutorial lesson:

Part Name	Part Type	Part Value
V1	Voltage Source	1 V
R1	Resistor	100
A1	S-Domain Transfer Function Block	Defaults

Place and connect the part as shown in the figure below:



*A basic circuit to test the S-domain transfer function block*

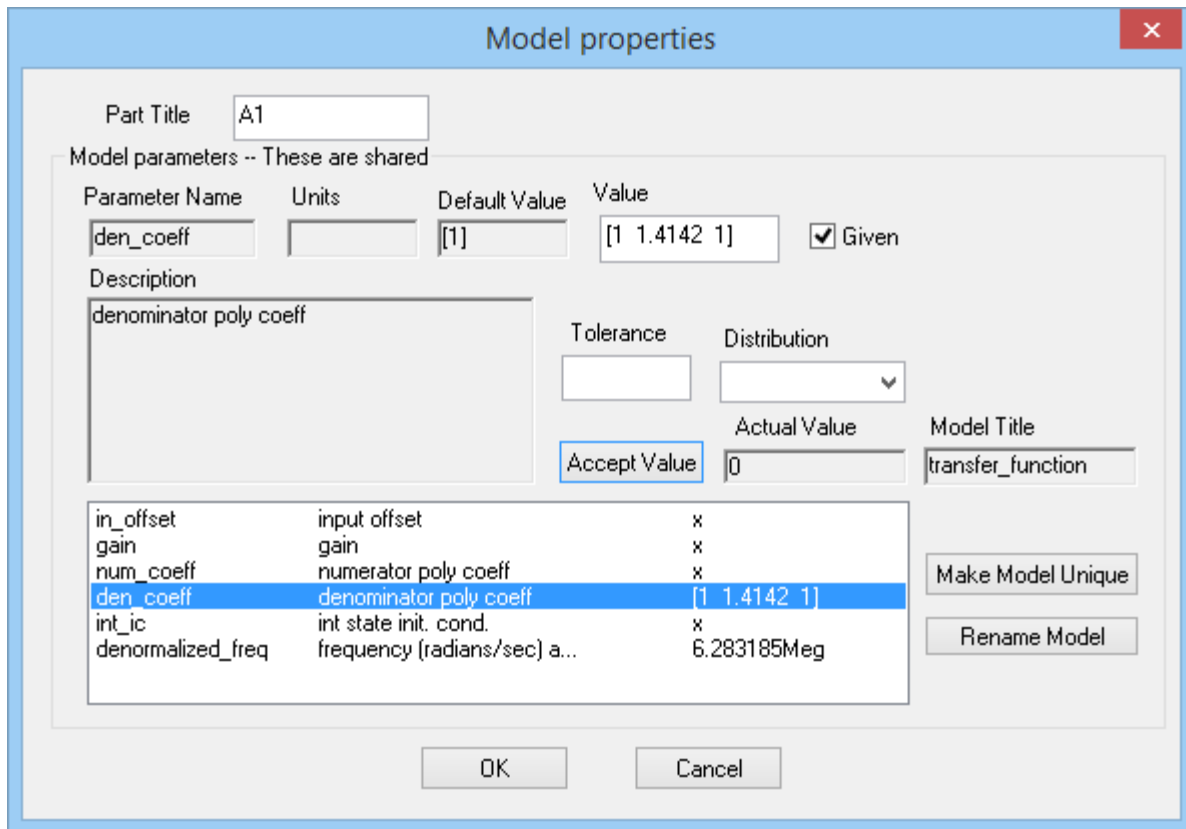
The S-domain transfer function of a second-order Butterworth filter is given by:

$$H(s) = \frac{1}{s^2 + 1.4142s + 1}$$

Open the property dialog of the transfer function block. Change the denominator polynomial coefficients to "[1 1.4142 1]" and set the value of **Denormalization Frequency** to 6.283185Meg ( =  $2\pi \times 10^6$  rad/s). In other words, you want a lowpass filter with a cutoff frequency of 1MHz.



The denormalization frequency of the S-domain transfer function block must be expressed as an angular frequency in radians/second .

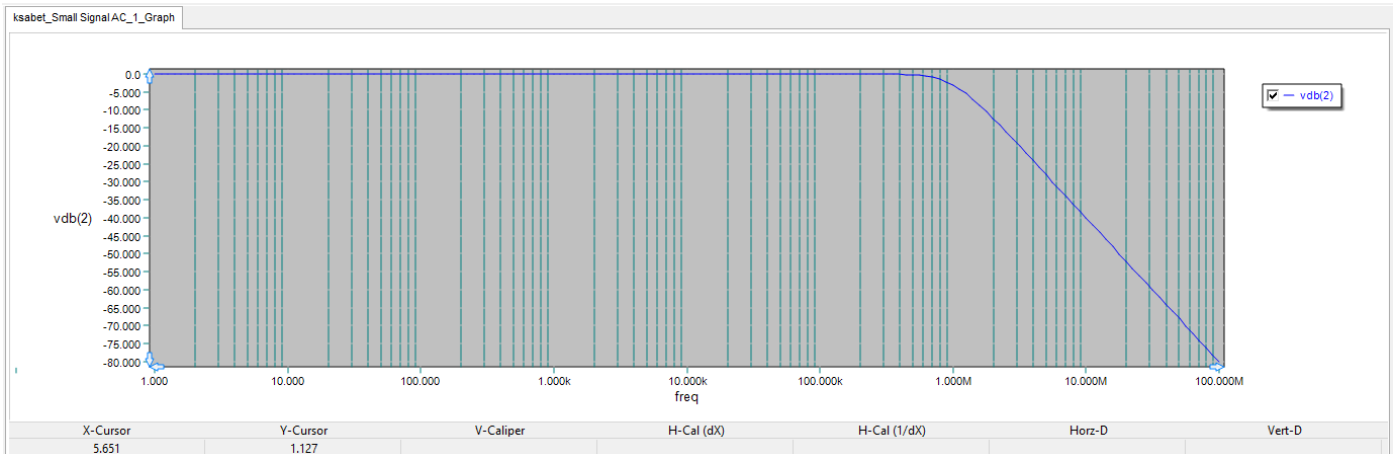


*The property dialog of the S-domain transfer function block.*

Run an AC frequency sweep of your filter with the following parameters:

<b>Start Frequency</b>	1 Hz
<b>Stop Frequency</b>	100 MHz
<b>Steps/Interval</b>	50
<b>Interval Type</b>	Decade
<b>Preset Graph Plots</b>	Custom: Gain = VDB(2)

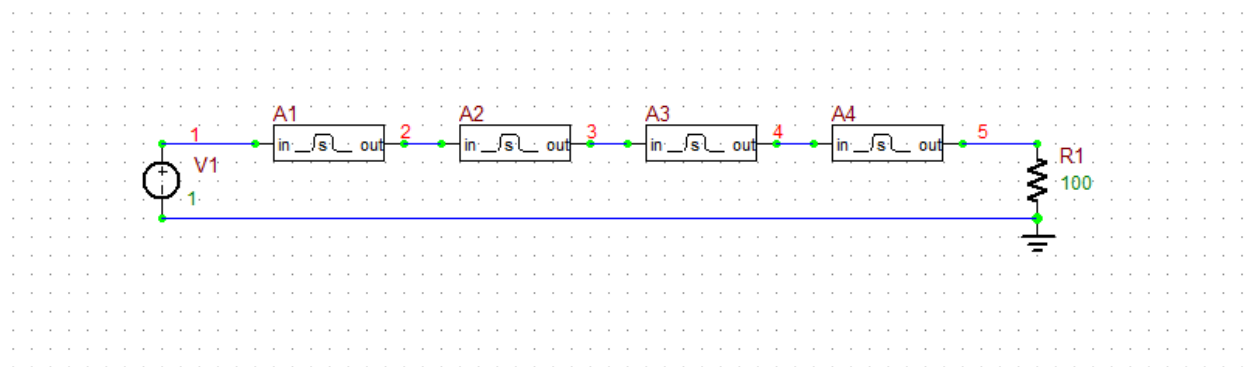
The frequency response is shown in the figure below as you should have expected:



The frequency response of the second-order Butterworth lowpass filter.

## 2.4 Exploring Higher-Order Cascaded Filters

In this part of the tutorial lesson, create three more S-domain transfer function blocks and cascade them as shown in the figure below. Copy and paste the additional parts since you want them to have the same properties as part A1.



The schematic of the cascaded lowpass filter using transfer function virtual blocks.

You will introduce four output voltages at Nodes 2, 3, 4 and 5. These correspond to second-order, fourth-order, sixth-order and eighth-order filter transfer functions, respectively. Note that the higher-order transfer functions realized in this way are different than the fourth-order, sixth-order and eighth-order Butterworth filter responses:

$$H_{B4}(s) = \frac{1}{(s^2 + 0.7654s + 1)(s^2 + 1.8478s + 1)} \neq \left( \frac{1}{s^2 + 1.4142s + 1} \right)^2$$

$$H_{B6}(s) = \frac{1}{(s^2 + 0.5176s + 1)(s^2 + 1.4142s + 1)(s^2 + 1.9319s + 1)} \neq \left( \frac{1}{s^2 + 1.4142s + 1} \right)^3$$

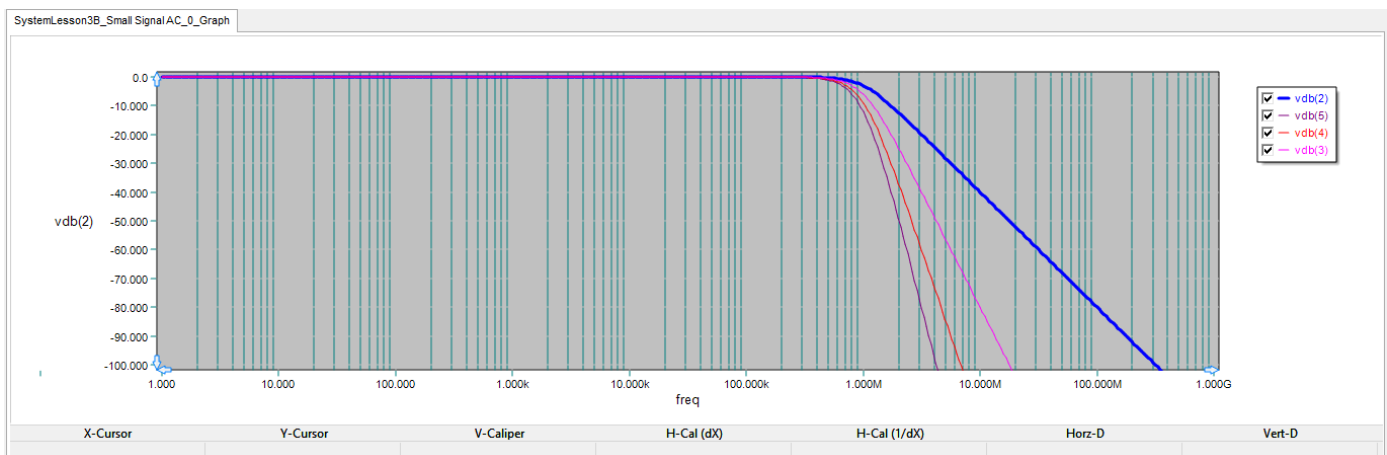
$$H_{B8}(s) = \frac{1}{(s^2 + 0.3902s + 1)(s^2 + 1.1111s + 1)(s^2 + 1.6629s + 1)(s^2 + 1.9616s + 1)}$$

$$\neq \left( \frac{1}{s^2 + 1.4142s + 1} \right)^4$$

Run an AC frequency sweep of your cascaded filter with the parameters specified below:

<b>Start Frequency</b>	1 Hz
<b>Stop Frequency</b>	1 GHz
<b>Steps/Interval</b>	50
<b>Interval Type</b>	Decade
<b>Preset Graph Plots</b>	Custom: Gain = VDB(2), VDB(3), VDB(4), VDB(5)

The results are shown in the figure below:



*The frequency response of the cascaded Butterworth lowpass filter.*

## 2.5 Testing Cascaded Chebyshev Lowpass Filter

The following is a list of parts needed for this part of the tutorial lesson:

Part Name	Part Type	Part Value
<b>V1</b>	Voltage Source	1 V
<b>R1</b>	Resistor	100
<b>A1 – A4</b>	S-Domain Transfer Function Block	Defaults

The poles of the second-order Chebyshev filter of Type I are given by:

$$s = \pm \frac{1}{\sqrt{2}} \sinh\left(\frac{1}{2} \sinh^{-1}\left(\frac{1}{\varepsilon}\right)\right) + \frac{j}{\sqrt{2}} \cosh\left(\frac{1}{2} \sinh^{-1}\left(\frac{1}{\varepsilon}\right)\right)$$

where  $\varepsilon$  is the ripple factor. The maximum passband ripple is given by:

$$R_{dB} = 20 \log\left(\frac{1}{1/\sqrt{1 + \varepsilon^2}}\right)$$

With a ripple factor  $\varepsilon = 1$ , the maximum peak-to-peak ripples would be 3dB, and the poles are given by:

$$s = \pm 0.3218 + j0.7769$$

The transfer function of the second-order Chebyshev filter with  $\varepsilon = 1$  is thus given by:

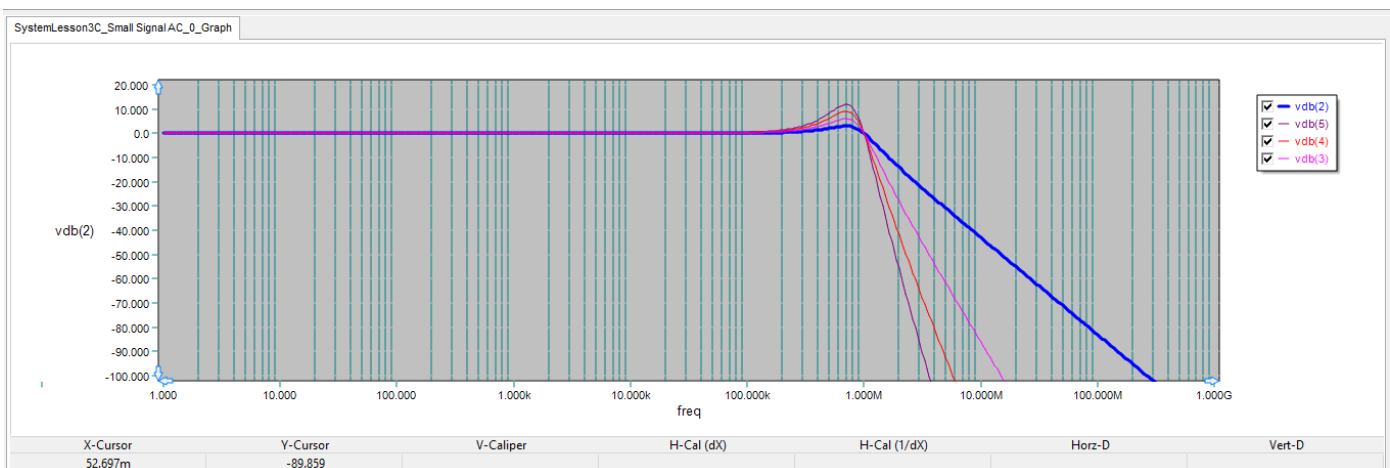
$$H(s) = \frac{1}{1.4142s^2 + 0.911s + 1}$$

Use the circuit of the previous part. Open the property dialog of the transfer function block A1 and change the denominator coefficients to "[1.4142 0.911 1]". Note that XSPICE process devices share the same modes. As you change the properties of A1, the properties of all the other transfer function blocks A2, A3 and A4 are updated accordingly unless you make their models unique.

Run an AC frequency sweep of your new cascaded filter with the parameters specified below:

<b>Start Frequency</b>	1 Hz
<b>Stop Frequency</b>	1 GHz
<b>Steps/Interval</b>	50
<b>Interval Type</b>	Decade
<b>Preset Graph Plots</b>	Custom: Gain = VDB(2), VDB(3), VDB(4), VDB(5)

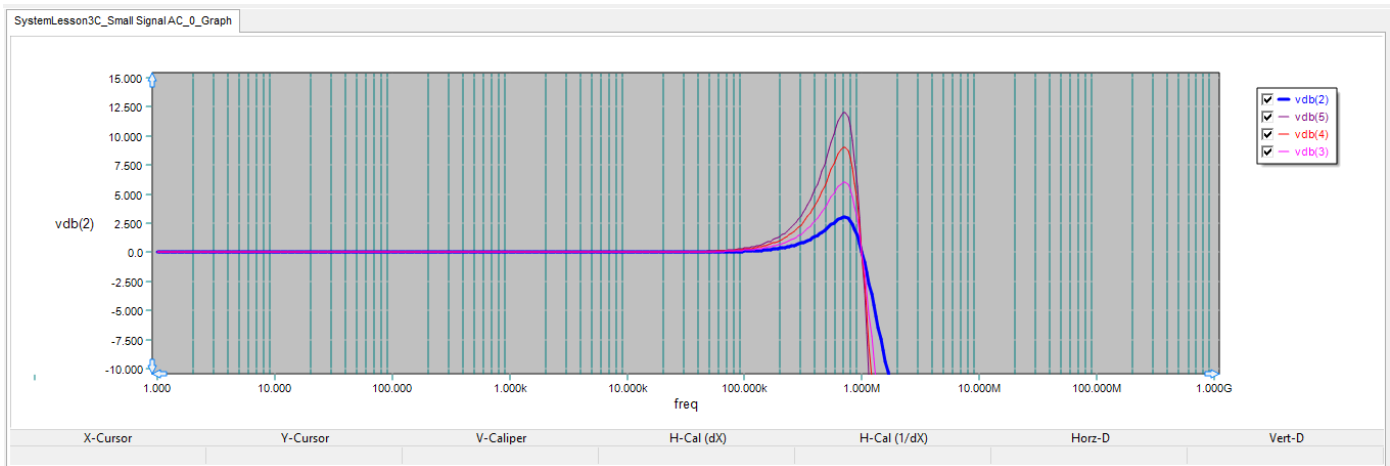
The results are shown in the figure below:



*The frequency response of the cascaded Chebyshev lowpass filter.*



You can see the ripple in the passband of the filter. To better see the details, change the left axis limits to min = -10dB and max = 15dB with 5 divisions as shown in the figure below. Note that the maximum ripple of  $v(2)$  is 3dB as expected.



*A close-up of the passband region of the cascaded Chebyshev lowpass filter.*

## 2.6 Examining a Fourth-Order Chebyshev Filter

The following is a list of parts needed for this part of the tutorial lesson:

Part Name	Part Type	Part Value
V1	Voltage Source	1 V
R1	Resistor	100
A1	S-Domain Transfer Function Block	Defaults

The transfer function of the fourth-order Chebyshev filter with  $\varepsilon = 1$  is thus given by:

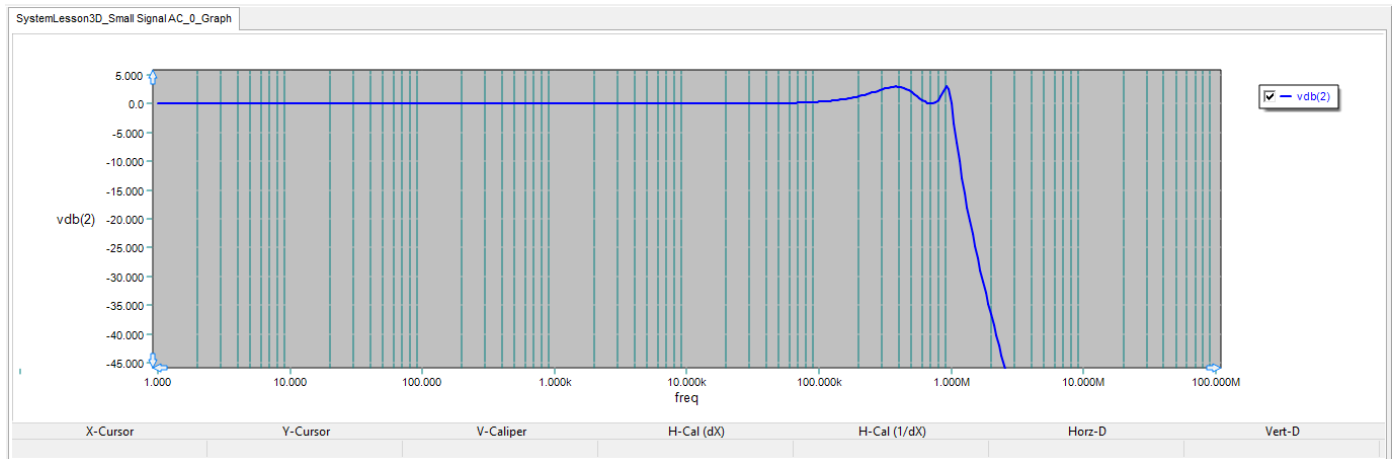
$$H(s) = \frac{1}{5.65s^4 + 3.29s^3 + 6.60s^2 + 2.29s + 1}$$

Place and connect the part similar to the first part of this tutorial with a single block. In the property dialog of the transfer function block, set the denominator polynomial coefficients to "[5.65s 3.29 6.60 2.29 1]" and set the value of **Denormalization Frequency** to 6.283185Meg.

Run an AC frequency sweep of your filter with the following parameters:

<b>Start Frequency</b>	1 Hz
<b>Stop Frequency</b>	100 MHz
<b>Steps/Interval</b>	50
<b>Interval Type</b>	Decade
<b>Preset Graph Plots</b>	Custom: Gain = VDB(2)

The frequency response of the fourth-order Chebyshev filter is shown in the figure below, where you see several passband ripples. Compare this to the single ripple of the fourth-order filter in the previous section, which was made up two cascaded second-order Chebyshev filters.



*The frequency response of the fourth-order Chebyshev lowpass filter.*

## 2.7 Realizing a Chebyshev Bandpass Filter

The following is a list of parts needed for this part of the tutorial lesson:

Part Name	Part Type	Part Value
<b>V1</b>	Voltage Source	1 V
<b>R1</b>	Resistor	100
<b>A1</b>	S-Domain Transfer Function Block	Defaults

According to the filter theory, you can use the following transformation to realize a normalized bandpass filter from a normalized lowpass prototype:

$$s \rightarrow \frac{1}{\Delta} \left( s + \frac{1}{s} \right)$$

where  $\Delta = (\omega_2 - \omega_1)/\omega_0$  is the fractional bandwidth. If you substitute the above transformation in the second-order Chebyshev s-domain transfer function, the following transfer function is obtained:

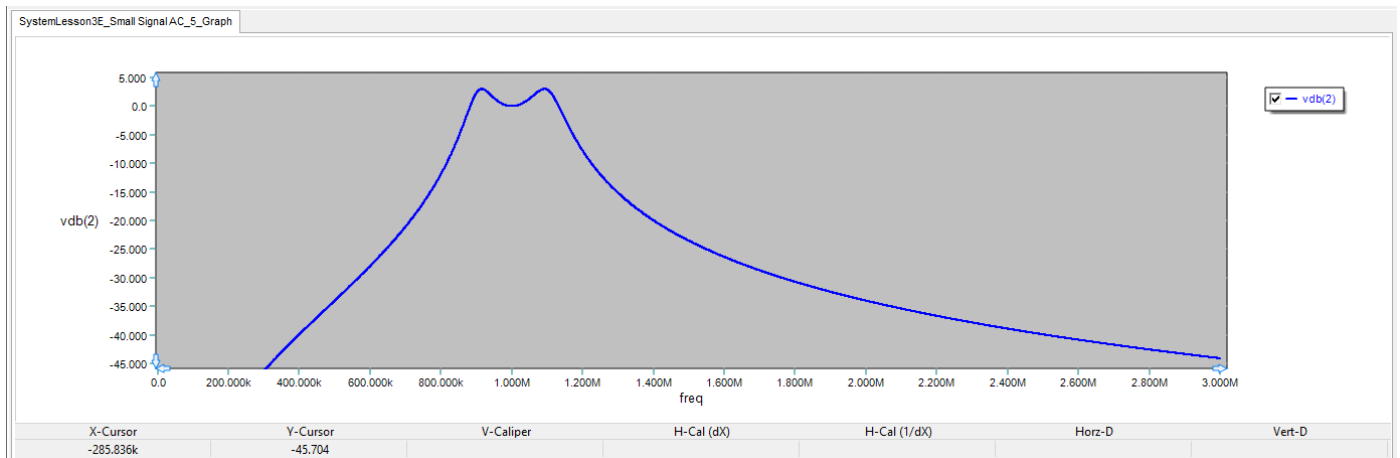
$$H(s) = \frac{s^2}{22.627s^4 + 3.644s^3 + 46.254s^2 + 3.644s + 22.627}$$

Place and connect the parts similar to the first part of this tutorial with a single block. In the property dialog of the transfer function block, set the denominator polynomial coefficients to "[22.627 3.644s 46.254 3.644 22.627]", set the numerator polynomial coefficients to "[1 0 0]", and set the value of **Denormalization Frequency** to 6.283185Meg.

Run an AC frequency sweep of your filter with the following parameters:

<b>Start Frequency</b>	1 kHz
<b>Stop Frequency</b>	3 MHz
<b>Steps/Interval</b>	1 k
<b>Interval Type</b>	Linear
<b>Preset Graph Plots</b>	Custom: Gain = VDB(2)

The frequency response of the second-order Chebyshev bandpass filter is shown in the figure below. Note that a linear frequency has been chosen as opposed to the previous graphs, which had the default logarithmic X-axis scale. As you can see from the graph, the center frequency of the filter is 1MHz and its bandwidth is about 280kHz.



*The frequency response of the fourth-order Chebyshev bandpass filter.*