

# Design of a Constant Insertion Loss Variable Frequency LC Band Pass Filter

By Victor Koren  
Tioga Technologies Ltd.

This article will show how to design a variable frequency band pass filter that will have constant characteristics across the frequency range.

A common way to design LC band pass filters is to use parallel LC resonators with some coupling mechanism at the ends, to the source on one side, to the load on the other side and between the resonators.

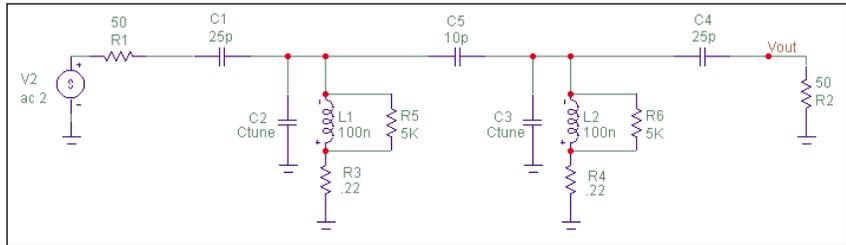
The  $Q$  of the resonators control the characteristics of the Band Pass Filter (BPF): The  $Q$  loaded /  $Q$  unloaded ratio controls the insertion loss of the BPF, while the  $Q$  loaded controls the fractional bandwidth. ( $Q$  unloaded: the parallel loss resistance of the resonator divided by the reactance of one of the elements of the resonator, at resonant frequency;  $Q$  loaded: the parallel connection of the parallel loss resistance of the resonator with the parallel value of the load across the resonator divided by the reactance of one of the elements of the resonator).

Frequently used BPF uses capacitors or inductors as top coupling elements between the resonators and terminations. Varying the center

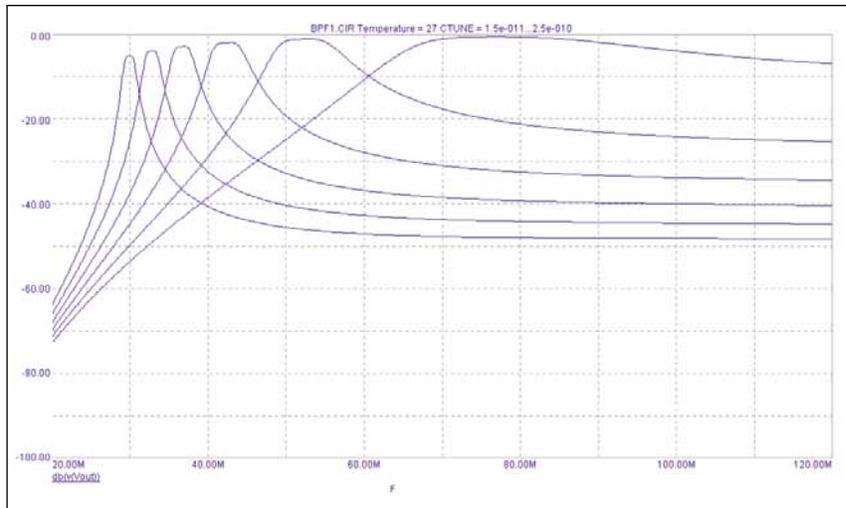
frequency of the BPF by changing the value of the resonators capacitor, will affect strongly the coupling between the BPF resonators and terminations, changing its characteristics.

### Conventional capacitor coupling

Figure 1, for example, shows a capacitor coupled 30 MHz BPF, with 5 percent  $-3$  dB points



▲ Figure 1. A capacitor coupled BPF.



▲ Figure 2. The frequency graph of the capacitor coupled BPF.

bandwidth, 5 dB insertion loss and flat bandpass response.

Each inductor is modeled with a series and parallel resistors. These resistors model the losses in the inductor. At low frequencies the loss is mainly the Ohmic wire loss. This loss is modeled by the small value series resistor. At high frequencies the loss is mainly core and parasitic capacitance losses. These losses are modeled by the parallel resistor.

These resistor values in the schematic were chosen to get an inductor  $Q_{ul}$  ( $Q$  unloaded) of around 70, or more precisely 65 at 30 and 90 MHz, and peaking a  $Q_{ul}$  of 75 at 50 MHz.

These  $Q_{ul}$  values represent very well a medium  $Q$  inductor, optimized to work around 50 MHz. Only the inductor loss is represented as in most cases the inductor loss is the dominant loss in the resonator.

Changing the tuning capacitor from 250 pF ( $f_o = 30$  MHz) to 15 pF ( $f_o = 77$  MHz), results in the frequency response graphs represented in Figure 2.

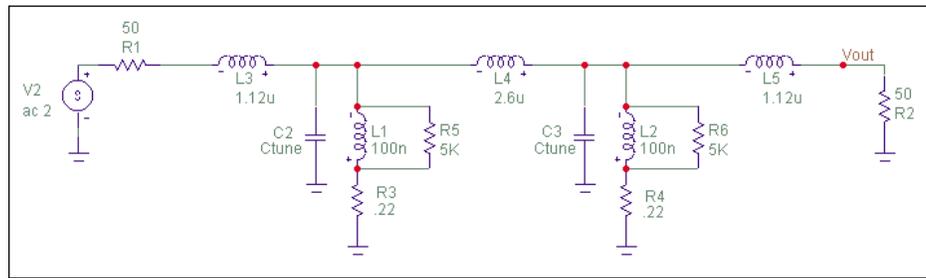
This filter performs well according to the design goals at 30 MHz, however, as the tuning capacitors decrease in value, the coupling elements reactance decrease, and so the insertion loss gets lower, the bandwidth wider and generally the filter loses its typical BPF curve.

## Conventional inductive coupling

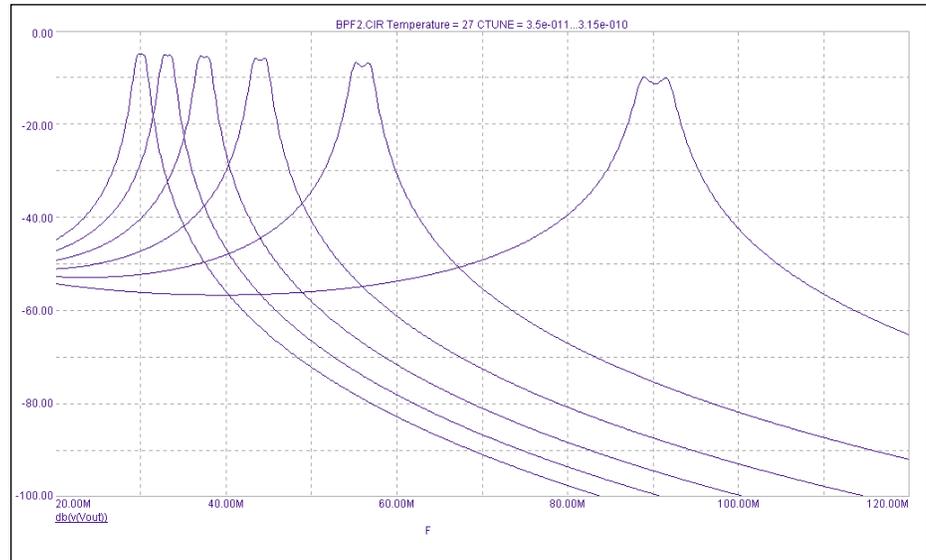
A BPF designed with inductive coupling elements results in the coupling ratios between all the inductors remaining constant. As the varying element is a capacitor, it will have lesser influence on the characteristics of the filter.

The filter in Figure 3 was designed with a center frequency of 30 MHz, with 5 dB insertion loss and 1.5 MHz bandwidth, which indeed it performs.

When the tune capacitor decreases in values, the termination inductive coupling elements reactance now increase too much and the insertion loss gets higher. The filter shows much better BPF shape at higher frequency, but we still do not get the required design goals at the higher frequencies: an insertion loss of 5 dB and a 5 percent bandwidth with a flat bandpass response. Instead, we get above 10 dB attenuation at 90 MHz, close to 5 percent bandwidth but with a 1.4 dB ripple at the passband.



▲ Figure 3. An inductive coupled BPF.



▲ Figure 4. The frequency graph of the inductive coupled BPF.

Note that the problem is only with the end termination coupling elements. The coupling between the resonators stays at the right value because the frequency control element is the capacitors, and the ratio between the resonators inductance and inter-resonator coupling inductance do not change.

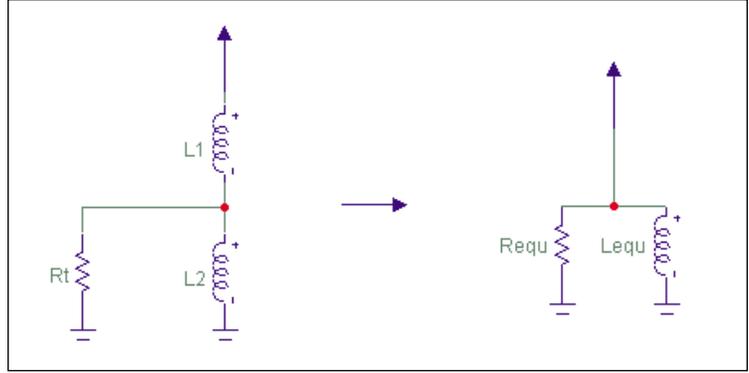
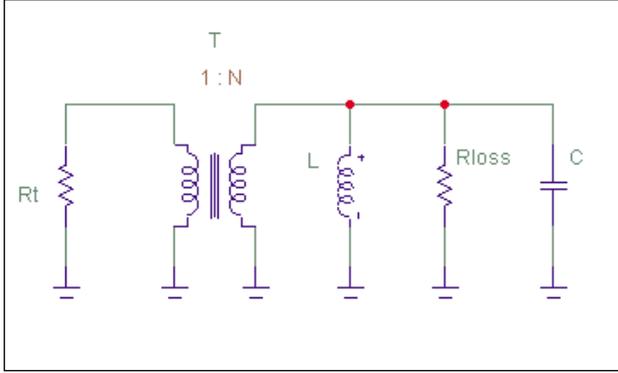
## Proper end termination loading

To get a BPF with similar characteristics at both frequency range ends, the resonators should be loaded to get the same  $Q_1$  ( $Q$  loaded) at both frequencies.

The end termination connection to the resonator can be modeled as a resistor connected to the resonator through a transformer. The transformer ratio controls the degree of loading.  $R_t$  is the termination resistance (usually 50 Ohm),  $R_{loss}$  is the resonator loss represented as a parallel resistor:

$$Q_{ul} = \frac{R_{loss}}{X_1} \quad (1)$$

$$X_1 = 2 \times \pi \times F \times L \quad (2)$$



▲ Figure 5. A resistor connected to the resonator through a transformer.

▲ Figure 6. A transforming circuit for equalizing frequency range ends.

$$Q_1 = \frac{(R_{\text{loss}} \parallel (R_t \times N^2))}{X_1} \quad (3)$$

After some manipulation:

$$N^2 = \frac{(Q_1 \times Q_{\text{ul}} \times X_1)}{(R_s(Q_{\text{ul}} - Q_1))} \quad (4)$$

Example:

- $R_t = 50 \text{ Ohm}$
- $L = 100 \text{ nHy}$
- $F_1 = 30 \text{ MHz}$   
 $Q_{\text{ul}} (@30\text{MHz}) = 65$   
 $Q_1 (@30\text{MHz}) = 30$
- $F_2 = 90 \text{ MHz}$   
 $Q_{\text{ul}} (@90\text{MHz}) = 65$   
 $Q_1 (@90\text{MHz}) = 30$

Results:

- $N_1^2 (@30\text{MHz}) = 21$
- $N_2^2 (@90\text{MHz}) = 63$

The transforming ratio squared changes proportional with the frequency. The question arises how to implement the transformation with the right ratio values at both frequency range ends.

The proposed transforming circuit is a pair of inductors, with calculated inductor values to get the right transformations at both frequencies.

Analysis of the left circuit in order to get equivalent parallel resistance and reactance as in the right circuit results in:

$$R_{\text{equ}} = N^2 \times R_t = (1 + \frac{L_1}{L_2})^2 \times R_t + (\frac{X_{11}^2}{R_t}) \quad (5)$$

Or:

$$N^2 = (1 + \frac{L_1}{L_2})^2 + (\frac{X_{11}}{R_t})^2 \quad (6)$$

The left part of the equation  $(1 + L_1/L_2)$  is the expression known for the transformation ratio, and it indeed is a good approximation if  $XL_1 \ll R_t$ , which is true in most cases.

However, if we use much higher value inductors for  $L_1$  and  $L_2$ , we can get a transformation ratio that changes with frequency, as required.

The  $L_{\text{equ}}$  calculation is close to  $L_1 + L_2$  and is not so important, because if  $L_1$  and  $L_2$  are large value inductors and are much larger in value than the resonator inductance, their influence on the resonance frequency of the resonator is small and can be trimmed by adjusting the resonator inductance value.

Using two equations that calculate  $N^2$ , each equation for a different frequency ( $F_1$  for the first equation and  $F_2$  for the second equation), with the needed transformation ratios for the two frequencies ( $N_1$  and  $N_2$ ), we can find  $L_1$  and  $L_2$  with:

$$L_1 = \frac{R_t \times \sqrt{(N_2^2 - N_1^2)}}{2 \times \pi \times \sqrt{(F_2^2 - F_1^2)}} \quad (7)$$

$$L_2 = \frac{L_1}{\sqrt{N_1^2 - (2 \times \pi \times F_1 \times \frac{L_1}{R_t})^2 - 1}} \quad (8)$$

## Design of new topology filter

Using the parameters from the last example:

- $R_t = 50 \text{ Ohm}$
- $L = 100 \text{ nHy}$

- $X_{L_1}(@30\text{MHz}) = 18.85 \text{ Ohm}$
- $X_{L_2}(@90\text{MHz}) = 56.55 \text{ Ohm}$
- $F_1 = 30 \text{ MHz}$   
 $Q_{ul}(@30\text{MHz}) = 65$   
 $Q_1(@30\text{MHz}) = 30$
- $F_2 = 90 \text{ MHz}$   
 $Q_{ul}(@90\text{MHz}) = 65$   
 $Q_1(@90\text{MHz}) = 30$
- $N_1^2(@30\text{MHz}) = 21$
- $N_2^2(@90\text{MHz}) = 63$

Results:

- $L_1 = 607.8 \text{ nHy}$
- $L_2 = 204.7 \text{ nHy}$

The values of the resonator inductors  $L_1$  and  $L_2$  were increased in order to include the influence of the inductance of the end matching sections ( $L_3 + L_4$  and  $L_5 + L_6$ ).

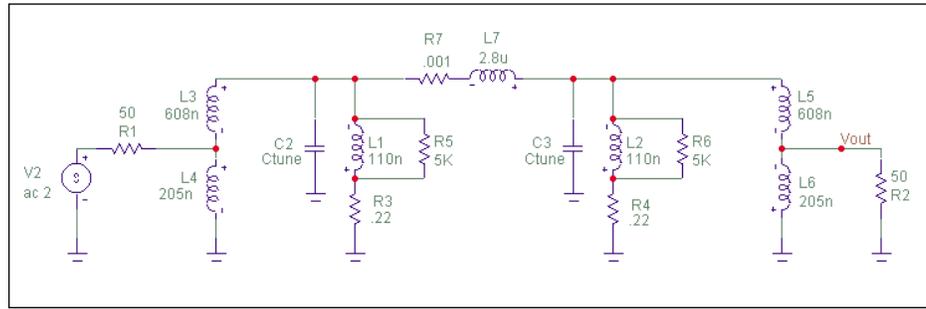
$R_7$  is included to break an inductors loop that the simulation software (Micro Cap VI Demo) could not handle.

As can be seen, the frequency response is a clean BPF response with almost constant insertion loss and fractional bandwidth, at any center passband frequency varying at a ratio of 1:3.

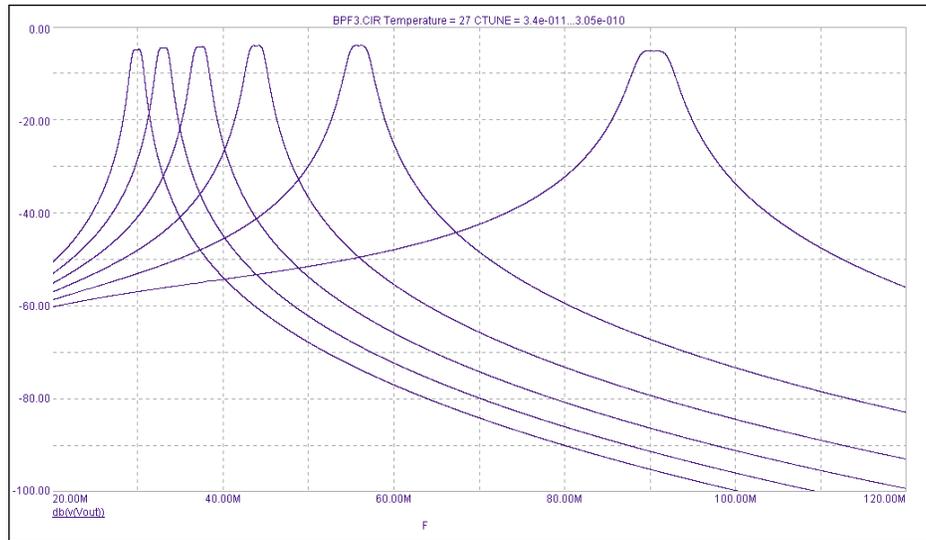
Another point to notice is that as the only capacitors at the circuit are the variable capacitors, without having to add any more coupling capacitors, the variation ratio of the capacitor is exactly the frequency ratio squared. This maximizes the frequency ratio with a given variable capacitor.

## Summary

A new way of coupling terminations to the end resonators of inductive coupled Band Pass Filter was presented. Calculation of the termination coupling inductors was shown. The same procedure of termination coupling can be used with higher order inductive cou-



▲ Figure 7. The new BPF.



▲ Figure 8. The new filter frequency response.

pling BPF to get a high performance wide frequency tuning range Band Pass Filter. ■

## Author information

Victor Koren received his BSEE from Tel Aviv University in 1982. He formerly worked with Tadiran Communications and Motorola and was with Orckit Communications from 1990 until earlier this year. He is now a Senior Analog Designer with Tioga Technologies Ltd., a spinoff of Orckit. He may be reached at victork@tiogatech.com.