Design of a Simple Tunable/ Switchable Bandpass Filter

Adaptive and multimode wireless equipment can benefit from filters that can vary their center frequency and bandwidth

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As the frequency spectrum gets crowded, with an increasing number of communication devices operating in a particular band, the role of the filter is becoming more and more critical. Since multimode portable terminals and tunable transceivers are starting to appear in the market, the importance of tunable filter is gaining momentum in the area of mobile communications. What is needed is a simple, cheap and small solution. Tunable filters greatly simplify the transceiver design and play a major role, especially in the area of wideband and multimode transceivers. This article reviews some of the fundamentals of the LC tuned resonator circuit and its implementation as a tunable or switchable band pass filter and therefore provides a feasible solution for the above applications in the UHF and VHF band.

LC resonator

The simplest band pass filter is a series or parallel LC tuned circuit. Figure 1(a) shows the resonant circuit that is connected to a source of resistance of R_s. Using the voltage division rule, it can be shown that

$$V_{out} = X_t \times V_{in} / (X_t + R_s)$$

where,

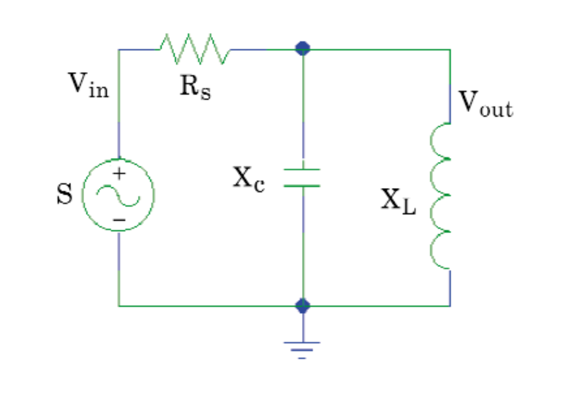
$$X_t = X_L X_C / (X_L + X_C)$$
$$X_C = 1/jwc$$
$$X_L = jwl$$

After some mathematical manipulation, we will arrive at

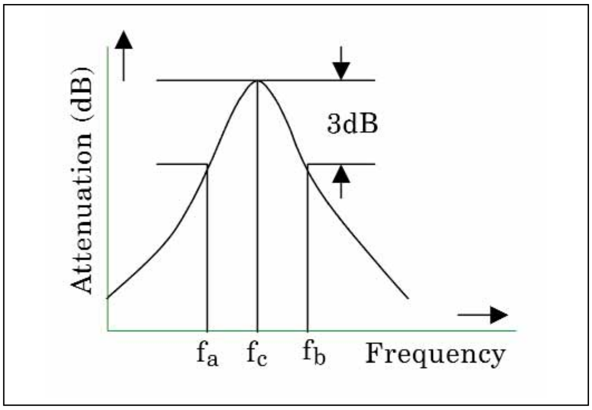
$$\frac{V_{out}}{V_{in}} = 20\log_{10}, \text{mag}\left[\frac{jwL}{(R_s - w^2 R_s LC + jwL)}\right] \quad (1)$$

Figure 1(b) shows the corresponding frequency response of the resonant circuit.

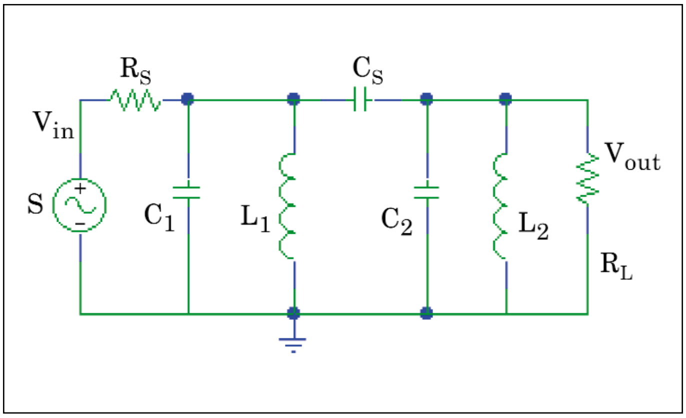
As we see, near the resonance frequency, the slope of the curve is changing at a rate of 12 dB/octave. This is caused by the presence of two



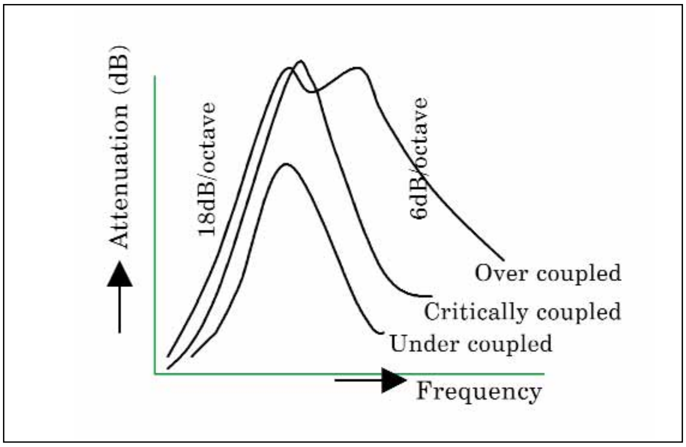
▲ **Figure 1(a). The resonant circuit connected to a source of resistance of R_s.**



▲ **Figure 1(b). Frequency response of the resonant circuit shown in Figure 1(a).**



▲ **Figure 2(a). Design of the capacitive coupling circuit.**



▲ **Figure 2(b). Frequency response of the capacitive coupling circuit shown in Figure 2(a).**

reactances near the resonant frequency. Away from the resonance, only one reactance is dominating and therefore the curve is changing at a rate of 6 dB/octave.

Loaded Q (selectivity factor)

The Q of a resonant circuit is defined to be the ratio of the center frequency to its 3 dB bandwidth. From Figure 1(b), the loaded Q (selectivity factor) of the resonant circuit is given by

$$Q = f_c / (f_b - f_a) \qquad (2)$$

where f_c is the geometric center and f_a and f_b are the lower and upper cut-off frequencies of the circuit, respectively.

The source and the load impedance also play an important part in determining the loaded Q of the resonant circuit. In fact, the loaded Q can be well explained by the following equation:

$$Q = R_p / X_p \qquad (3)$$

where R_p = equivalent parallel resistance of source and load impedances, and X_p = either the inductive or capacitive reactance at resonance.

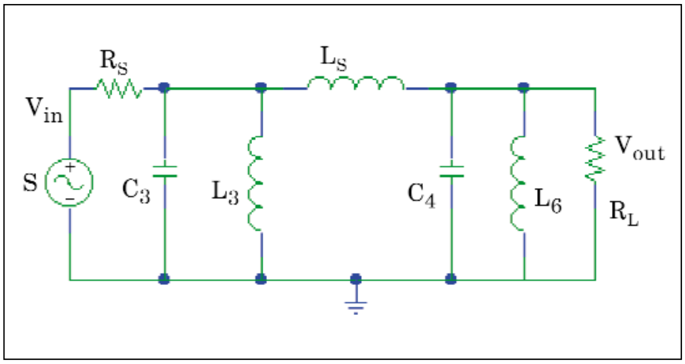
This explains that the increase in R_p will increase the Q and the selectivity of the circuit. If R_p is fixed, Q can be increased by decreasing X_p. This will require small inductance and large capacitance for the circuit.

Insertion loss

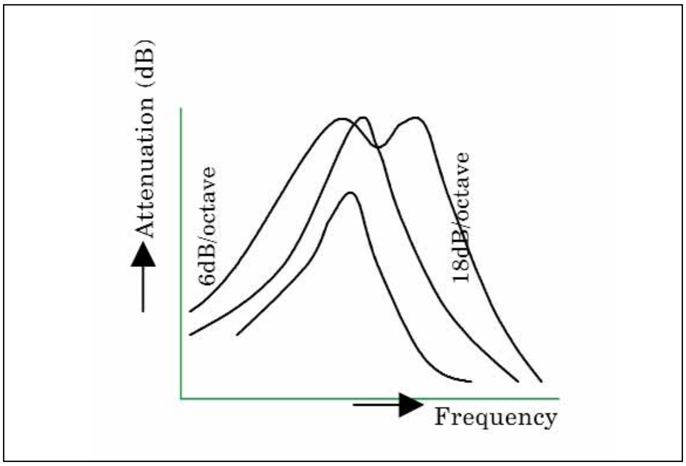
Insertion loss is defined to be the loss in the components due to their inherent resistive losses. It is a critical parameter in any electrical component. The quality factor of an inductor is defined as $Q = X/R$ where X and R are the reactance and resistance of the inductance. That is, high Q inductors are less lossy. The insertion loss in the LC resonator is mainly caused by the inductance Q as the capacitor Q is quite high over their useful frequency range.

Coupling of resonator circuits

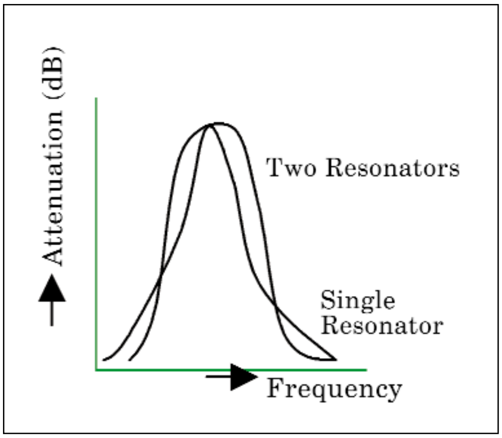
Many applications require flat response in the pass band and steeper roll-off outside the cut-off frequency. A single LC resonator circuit, such as in Figure 1(a), cannot satisfy the above requirements. It is possible, however, to obtain such a frequency response from the LC resonators if two or more such circuits are coupled prop-



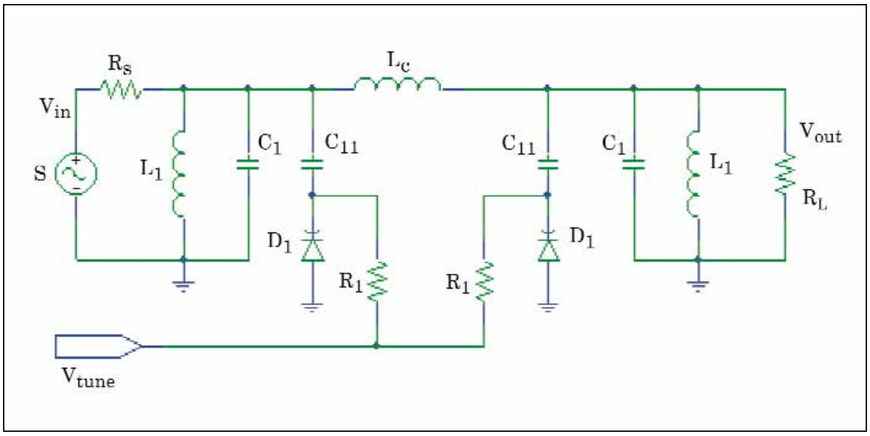
▲ **Figure 3(a). Design of the inductive coupling circuit.**



▲ **Figure 3(b). Frequency response of the inductive coupling circuit shown in Figure 3(a).**



▲ **Figure 4. Resonator response comparison of two critically coupled resonators.**



▲ **Figure 5. Configuration of a tunable/switchable filter using two identical resonators coupled inductively.**

erly. Two such circuits are given in Figure 2(a) and 3(a). They are known as capacitive coupling and inductive coupling circuit, respectively. The corresponding frequency responses are shown in Figures 2(b) and 3(b). Figure 4 compares the single resonator response with that of two critically coupled resonators.

The loaded Q of a critically coupled resonator is reduced by a factor of approximately 0.707 of a single resonator. It is obvious from Figure 4 that the coupled resonator provides wider 3-dB bandwidth in the pass band and steeper roll-off than most of the applications required. The value of the coupling components can be determined by the following formulas.

For capacitive coupling,

$$Cc = C/Q \qquad (4)$$

where C = resonance circuit capacitance, and Q= loaded Q of a single resonator.

For inductive coupling,

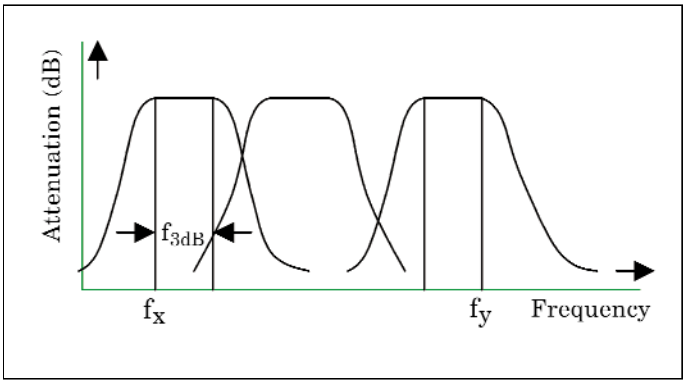
$$L_c = LQ \qquad (5)$$

where L = resonance circuit inductance, and Q = loaded Q of a single resonator.

Another form of inductive coupling is through the use of transformers. This method is not as easy as the other two methods, as many factors influence the transformer coupling.

Tuneable/switchable filter

Figure 5(a) shows a possible configuration for a tunable/switchable filter using two identical resonators coupled inductively. They can be coupled either capacitively or inductively. The response of the capacitively coupled circuit is somewhat skewed toward the lower frequency side, while the inductively coupled circuit response is skewed toward the higher end. The total capacitance of each resonator is made up of two capacitors and a varactor diode as shown in the diagram. The total capacitance (C) of each resonator is given by



▲ **Figure 6. Tuning range parameters.**

$$C = C_1 + C_{11}||C_v$$

where C_v is the varactor capacitance. Tuning or switching of the filter is achieved by applying a control voltage to the varactor. The control voltage is applied between the capacitor C_{11} and the varactor so there is no effect on the control voltage on the main line of the filter. Both varactors are controlled by a single source. The high value resistors in the circuit provide enough isolation between the resonators and the control source.

Circuit design

Assume a tunable/switchable filter from frequency f_x (MHz) to f_y (MHz) is required with a 3 dB bandwidth of f_{3dB} as shown in Figure 6.

Initially, choose L, C values to provide a resonant frequency around the middle of the desired band. Remember that the lower value of inductance and higher value of capacitance improve the loaded Q of the resonant circuit and this in turn dictates the 3-dB bandwidth of the circuit. The capacitor value is again recalculated with the previous value of L at the cut-off frequencies f_x and f_y (say C_{fx}, C_{fy}). Now, if we couple two set of L, C_{fx} resonators, it will provide a band pass filter around f_x. Similarly, two sets of L, C_{fy} resonators will provide a bandpass filter around f_y. So the prime task to tune or switch the filter between f_x and f_y is to vary the capacitance from C_{fx} to C_{fy}. This is accomplished with the help of a voltage controlled varactor as shown in the Figure 7(a). A typical varactor response is shown in Figure 7(b). The useful range of the varactor is from C_{va} to C_{vb} for the control voltage of V_{va} to V_{vb}.

The value of C1 and C11 can be calculated as follows. First, we have

$$C = C_1 + C_{11} \,//\, C_v$$

If

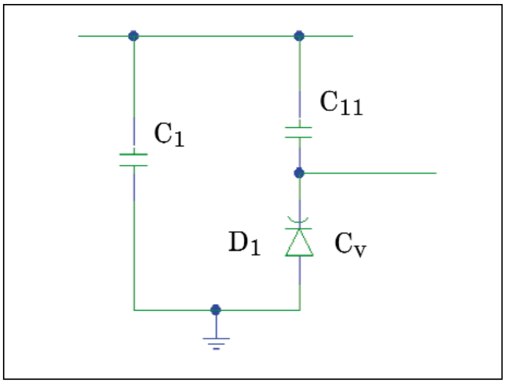
$$C_{11} >> C_{vb} \text{ (select } C_{11} >> C_{vb}\text{)},$$

then

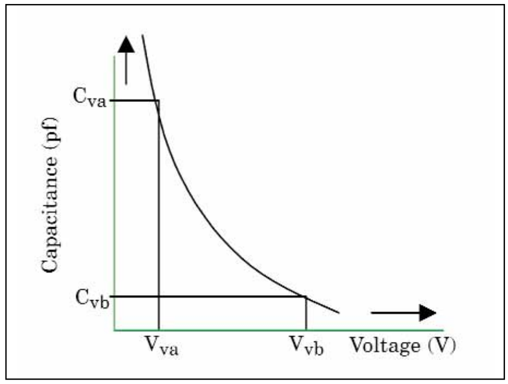
$$C_{min} = C_{f1} = C_1 + C_{vb} \qquad (6)$$

$$C_{max} = C_{f2} = C_1 + C_{11} // C_{va} \qquad (7)$$

From Equations (1) and (2), C_1 and C_{11} can be evaluated for a known value of C_{va} and C_{vb}. The coupling element can be calculated using Equation (4) or (5), depending on the type of coupling selected. This value must be compromised to provide a flat response that lies between the critical coupling and the over coupling as required. A filter design software will be very useful in this regard and to select the standard components for the filter to operate in the desired band. The resister values can be quite high (~10 kohms).

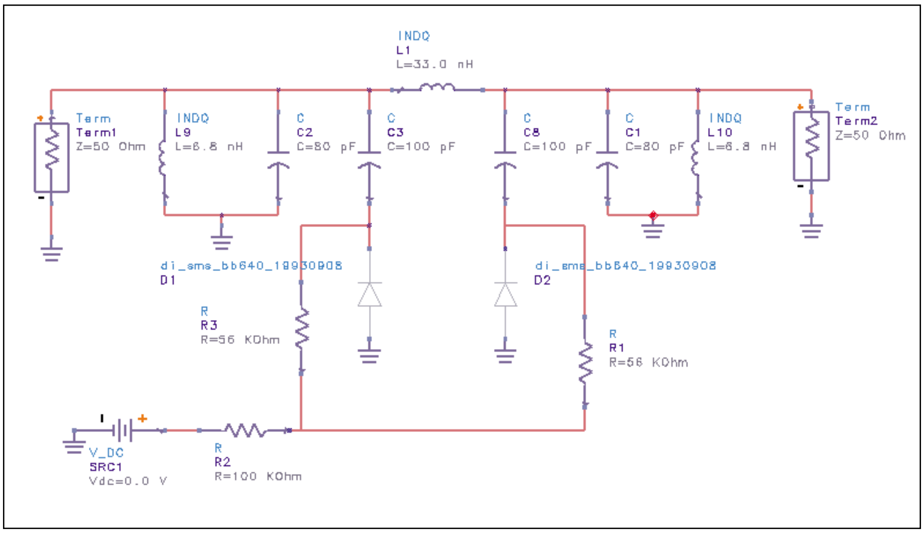


▲ **Figure 7(a). Varactor tuning circuit implementation.**

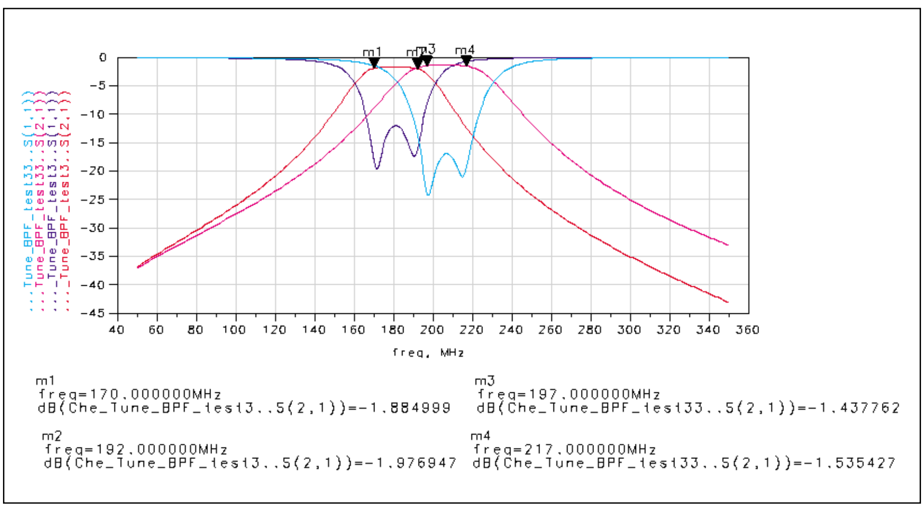


▲ **Figure 7(b). Frequency versus varactor tuning voltage.**

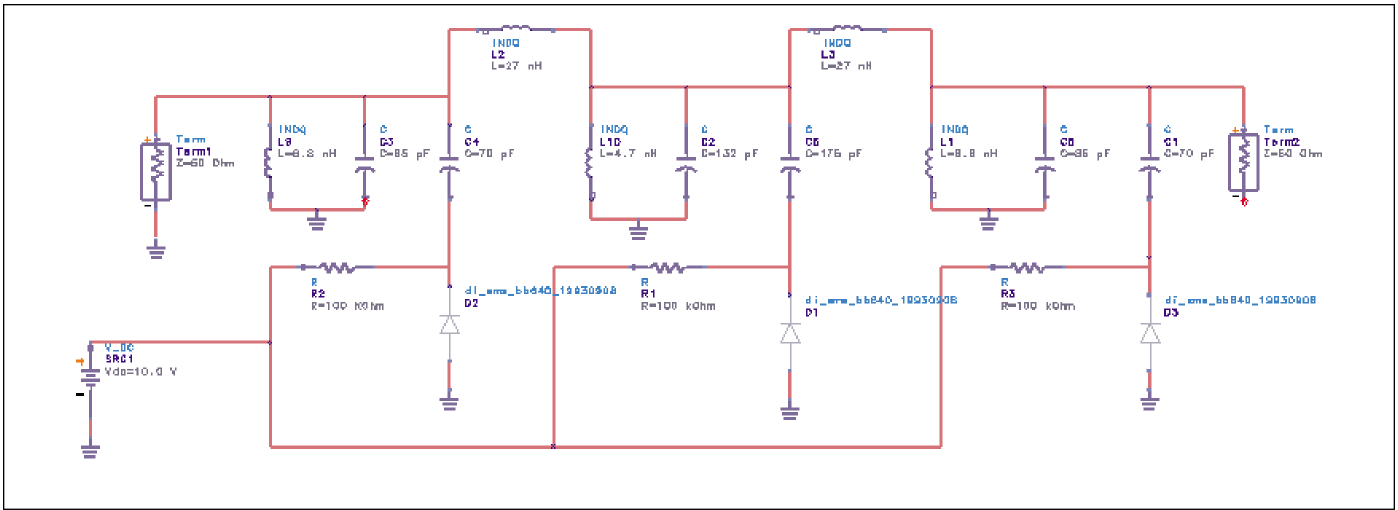
A final tune-up of capacitors may be required, due to the parasitic effects arising from the circuit, printed cir-



▲ **Figure 8(a). Design of the tunable/switchable band pass filter.**



▲ **Figure 8(b). Simulation of the tunable/switchable band pass filter.**



▲ **Figure 9(a). Complete filter circuit design with three resonators coupled inductively.**

cuit board and component tolerance.

The usable range of the varactor diode with the control voltage will limit the tuning range of the filter. More than one varactor diode can be placed in parallel to get the required capacitance. Figure 8(a) provides a tunable/switchable band pass filter with the values, which are used to simulate the circuit. The simulation result is shown in Figure 8(b). Notice that the sharpness at the cut-off frequencies increases together with the insertion loss as the frequency decreases. This is expected, as this is the inherent characteristic of a LC resonator. The flatness of the pass band and the insertion loss are controlled by the tuning range. That is, the lower the tuning range, the better the insertion loss and flatness.

The selectivity can be further improved by using more than two resonators. Figure 9(a) shows three resonators coupled inductively. Figure 9(b) shows its improved selectivity. Coupling more resonators will increase the insertion loss. Nevertheless, it is still possible to achieve a broad tuning range with reasonable insertion loss by employing high *Q* inductors and tight tolerance components.

Conclusion

A simple electrically tuned band pass filter has been presented in this article. Although the major limiting factor of this filter is the usable range of a varactor diode it is still possible to achieve more than half octave tunable range with the diodes available in the market today. This type of filter is easy to built, small sized, cost effective and consumes negligible current. Other major advantage is that the bandwidth of the filter is selectable and therefore it can be used either as tunable or switchable filter.

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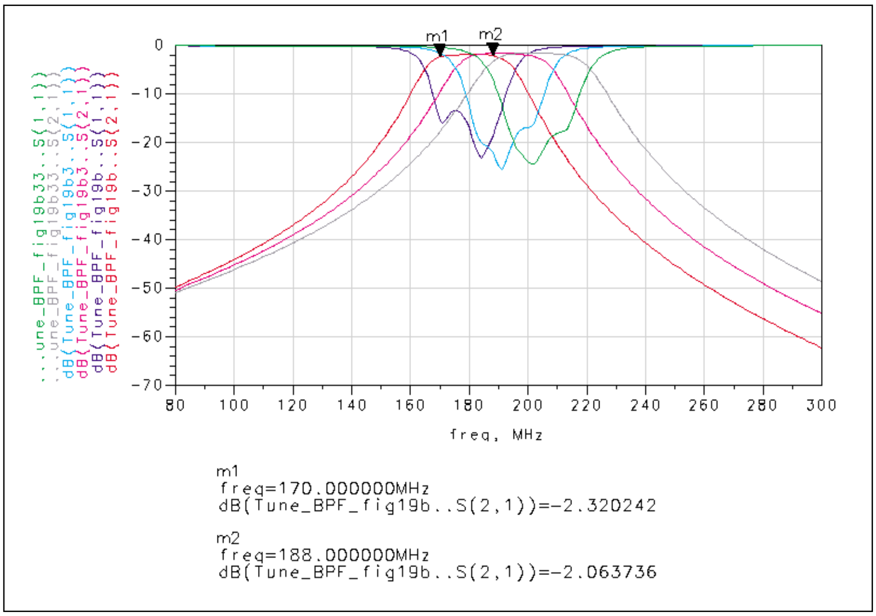

▲ **Figure 9(b). Passband and return loss performance of the filter circuit shown in Figure 9(a).**