

High-Q Resonators on FR4

By Randy Rhea
Eagleware Corporation

FR4 material is inexpensive, readily available and is processed using inexpensive techniques. However, the dielectric constant is poorly controlled and the dielectric material is lossy. A loss tangent, δ , of 0.008 is typical in the UHF frequency range, resulting in resonator unloaded Q under 150. This design idea explains how to build microstrip resonators with unloaded Q over 400 on FR4. At the same time, the sensitivity of the resonant frequency to dielectric constant variation is reduced.

Unloaded and loaded Q

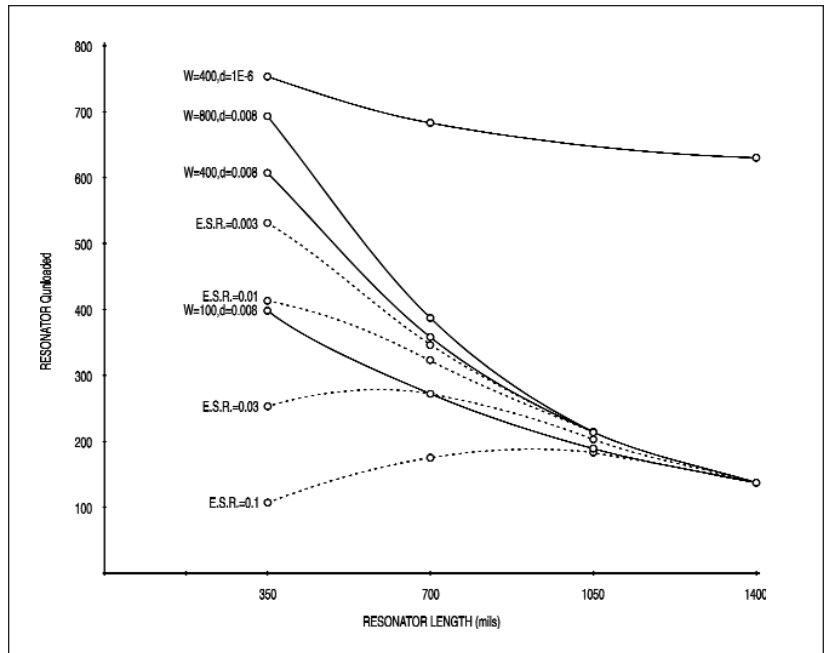
Unloaded Q is the ratio of stored energy to dissipated energy in a reactor or resonator. The unloaded Q , or Q_u , of an inductor or capacitor is X/R_s , where X represents the reactance, and R_s represents the series resistance. The loaded Q , or Q_l , of a resonator is determined by how tightly the resonator is coupled to its terminations. Q_l is equal to f_0/BW where f_0 represents the center frequency of a resonator and BW represents the response bandwidth. High resonator Q_l results in improved phase-noise for oscillators and is needed for narrow bandwidth filters. But high Q_l results in significant insertion loss unless component Q_u is much higher than Q_l . The insertion loss of a resonator is

$$I.L. = 20 \log \frac{Q_u}{Q_u - Q_l}$$

For example, if Q_u is only twice Q_l , the insertion loss is 6.02 dB. The insertion loss of an Nth order filter is typically a little more than N times this formula.

The quarter-wavelength resonator

In a quarter-wavelength resonator, one end is grounded and the other end is open. The current is maximum at the grounded end and minimum at the open end (it would be zero at the open end if not for end-effect capacitance). The voltage is maximum at the open end and minimum at the grounded end (it would be zero at the grounded end if



▲ Figure 1. 901 MHz resonator unloaded Q (Q_u) versus length in mils for 100, 400 and 800 mil line widths. Solid lines are with lossless loading capacitors and dashed lines with lossy loading capacitors for a 400 mil wide line. “d” is δ , the material loss tangent.

not for for via-hole inductance). We will refer to this resonator as full-length because it resonates without lumped elements.

In a full-length resonator, some of the loss is in the dielectric and some is in the conductors (we assume that the resonator is enclosed and radiation is not a factor).

Figure 1 shows Q_u at 901 MHz of a microstrip resonator on 60 mil thick copper plated FR4 with a relative dielectric constant of 4.8 and a dielectric loss tangent of 0.008. The test circuit is shown in Figure 2. The resonator is grounded at the bottom by contact with the enclosure wall. Terminations are coupled to the top of the resonator via capacitors. These coupling capacitors are small but they load the resonator to a small degree, and the transmission line is slightly less than quarter-wavelength. The response bandwidth is used to find Q_l , and the insertion loss is measured. Q_u is then found by solving the previous loss equation.

The physical length corresponding to full-length with coupling capacitance loading is 1400 mils, the data points on the far right of the graph. The top trace is for a resonator transmission line width of 400 mils and assumes a lossless dielectric. Q_u is 630. The remaining traces assume an FR4 loss tangent of 0.008, and Q_u is 138. The dielectric loss is primarily responsible for destroying the Q_u of the resonator.

Mitigating the effects of the dielectric

Most dielectric loss occurs near the open end of the resonator where the voltage (E-field) in the dielectric is highest. If the resonator is shortened and resonance is re-achieved with capacitive loading then dielectric loss is reduced. The solid curves in Figure 1 represent transmission line widths of 100, 400 and 700 mils with no loss in the loading capacitors. With a transmission line width of 400 mils, Q_u increases from 138 for a full-length resonator to 607 for a 350 mil long resonator.

Decreasing the resonator length places heavier demands on the capacitors. The dashed traces are for a 400 mil wide resonator with a total capacitor effective series resistance, ESR, of 0.1 to 0.003 ohms. Good RF ceramic capacitors have an ESR of approximately 0.1 ohms at 900 MHz, suggesting an optimum resonator length of 1050 mils and only a small increase in Q_u . But several capacitors may be placed in parallel to decrease the ESR. For example, with 10 capacitors in parallel, an ESR of 0.01 results in a Q_u of more than 400.

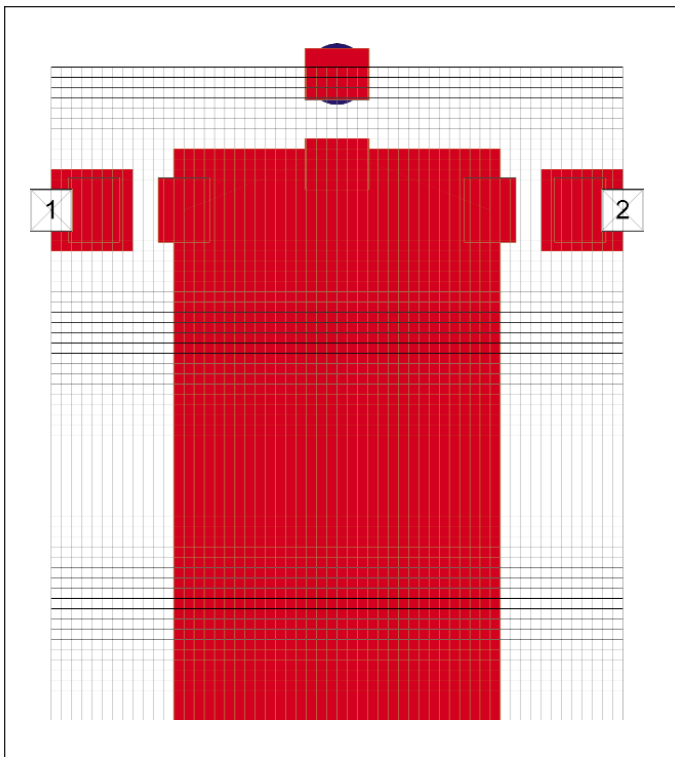
Because the dielectric is effectively removed from the system, not only is loss reduced but variations in the relative dielectric constant have a smaller effect on the resonant frequency.

Transmission line width

With coax, a ratio of the outer to inner conductor diameter of 3.6 results in minimum loss and maximum Q . This corresponds to a characteristic impedance of 76.8 ohms in air and 51.8 ohms with PTFE, with $\epsilon_r=2.2$. Loss in strip type transmission lines tends to decrease with increasing line widths. Widths of 100, 400 and 700 mils on 60 mil thick, $\epsilon_r=4.8$, material are characteristic impedances of 52.1, 19.8 and 12.4 ohms respectively.

A comment on simulators

Circuit theory simulators compute the loss, and therefore the unloaded Q , based on a natural distribution of



▲ **Figure 2. Test circuit for the microstrip resonator. The grid contains cells for the electromagnetic simulation.**

dielectric and conductor loss. This occurs with any line length that is a multiple of quarter-wavelength and asymptotically for any length of a long line. For short lines such as those discussed here, the loss reported by a circuit theory simulator will be too high and Q_u will be too low. Data in Figure 1 were generated using the electromagnetic simulator =EMPOWER=, which does not suffer from this restriction. ■

Author information

Randy Rhea is the founder and chairman of Eagleware Corporation. He received his BSEE from the University of Illinois and his MSEE from Arizona State University. He has been an RF and microwave design engineer for nearly 30 years. He may be reached at 770-939-0156.

