APPLICATION NOTE

Properties, Test Methods, and Mounting of Dielectric Resonators

Basic Dielectric Resonator (DR) Material Properties

The most important material properties for a Dielectric Resonator (DR) are its dielectric constant (ε_r), Unloaded Quality Factor (Qu), and temperature coefficient of the resonant frequency (τ_f).

Dielectric Constant (ε_r)

The usual reason for choosing a DR as a resonating element is the size reduction afforded by the high ε_r of modern ceramics. But “dielectric constant” is a misnomer; not only does ε_r vary slightly for different temperature coefficient blends within the same material family, but lot-to-lot ceramic process variations cause ε_r to swing typically ±1 unit between lots. Within a given lot, the variation is much smaller. For example, the Trans-Tech, Inc. (TTI) catalog [reference 1] lists the ε_r of material D8371 as 35.5 ± 1.0.

TTI can help customers determine the proper resonator size for production (see “Ordering DRs to Frequency” on page 3). TTI measures the ε_r accurately using a Courtney fixture, as described in “Dielectric Constant Measurement” on page 2. TTI measures the ε_r of the ceramic lot, not of the individually-shaped DRs. Unless stipulated otherwise, TTI chooses a size for the test sample that resonates close in frequency to where the material is Qu specified.

Unloaded Quality Factor (Qu)

The measure of the DR’s ability to store microwave energy with minimal signal loss is its Qu. As discussed in "Qu Factor Measurement" on page 2, every DR application is unique, and since the RF fields of the most commonly-used $TE_{01\delta}$ mode do not end at the boundaries of the ceramic, metal wall losses lower the Qu of the shielded DR.

It is worth emphasizing that measured Qu is both mode and temperature-dependent, and the wary designer will qualify a potential ceramic supplier’s Qu claims with regard to measurement technique, temperature, and mode of operation. Higher-order modes and super-conducting temperatures can make Qu factors look phenomenal, but seldom represent the user’s application. Bear in mind that these figures are ideal, and typically apply to resonators that are isolated from conducting surfaces.

TTI characterizes and specifies Qu with the DR essentially “isolated” in an enclosure several times the size of the DR, described in "Qu Factor Measurement" on page 2. TTI’s Qu specifications apply for the $TE_{01\delta}$ mode, measured at laboratory ambient temperature.

As in the case of ε_r measurement, TTI chooses a test sample size that resonates near the frequency where the material is Qu specified. It is typical for the Microwave Integrated Circuit (MIC) environment, with thin substrate and nearby metallic enclosure, to reduce Qu to a fraction of the advertised value in the TTI catalog [reference 1]. Ultimately, Qu can and should be measured in the user’s MIC environment [reference 2].

Note: *The Qu can be degraded by inadvertently marking the ceramic with a graphite pencil.*

Temperature Coefficient (τ_f)

The time and care required to thermally stabilize the sample, as well as the test fixture, makes the temperature coefficient a time-consuming parameter to measure. An “isolated” measurement (see above) is necessary to discern the ceramic properties from other influences. Unless otherwise stipulated by a customer, TTI tests a standard-size lot sample in the $TE_{01\delta}$ mode, not parts that have been sized to f_0 for circuit application. In general, the in-circuit temperature coefficient measured by the customer will be different from TTI’s data. Proper record-keeping ensures a stable product for the DR user (see “Example” on page 3 for details).

TTI offers a standard on temperature coefficient tolerance of ± 2 ppm/°C. For example, TTI offers D8371 material with $\tau_f = 0$ ppm/°C ± 2 ppm/°C. Tighter τ_f tolerances are available on request, but the practical reproducible measurement accuracy limit is about ± 0.5 ppm/°C. Tighter τ_f tolerances drive cost, so do not over-specify this parameter.

Test Methods

Dielectric Constant Measurement

When the DR is bounded by metallic walls at its two flat faces, the dielectric constant can be determined accurately from the DR dimensions and the resonant frequency as measured on a network analyzer. The fixture, shown in Figure 1, is called a Courtney holder (described in Reference 3).

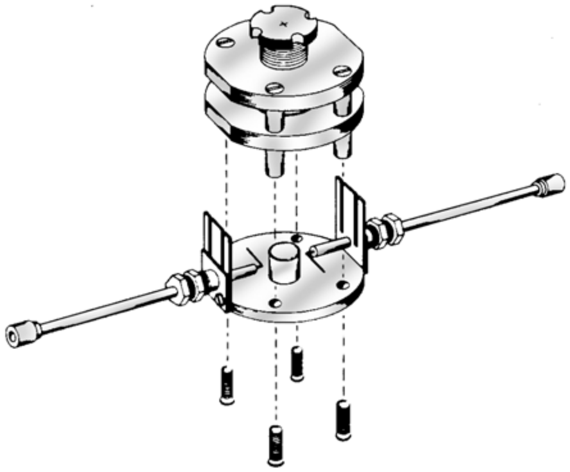

Figure 1. Courtney Holder Fixture for Dielectric Constant Measurement

Qu Factor Measurement

The Q/Qu factor is measured in a test cavity whose dimensions are at least three times the size of the DR to simulate an “isolated” but shielded resonator. Low-loss supports, such as quartz blocks or alumina wafers, suspend the DR test specimen in the middle of the cavity away from the influence of the metallic walls. TTI arranges two RF probes, connected to a network analyzer, to couple the microwave energy to and from the DR. The degree of coupling is adjusted such that the transmission loss is on the order of –40 dB. From the measured +3 dB bandwidth (BW), loss (IL), and center frequency (fo), TTI determines Qu from the relationship:

$$Q_u = \frac{\dfrac{f_0}{BW}}{1-10^{\left(\frac{IL}{20}\right)}} \qquad \textbf{(1)}$$

The test is performed at laboratory ambient conditions, and the resonance measured is the TE01δ mode.

Temperature Coefficient of Resonant Frequency (τf) Measurement

The τf is measured in a simulated “isolated” DR condition, similar to that described in “Qu Factor Measurement,” except that the TE01δ mode is observed in a reflection mode, measured with a network analyzer. The entire test cavity and DR specimen is placed in a temperature chamber, and the frequency of the resonance is measured at 25°C and at 60°C. Then τf is determined from:

$$\tau_f = \frac{\Delta f\,(\mathrm{Hz})}{f_0\,(\mathrm{MHz})} \times \frac{1}{\Delta T}\ \mathrm{ppm/°C} \qquad \textbf{(2)}$$

Where:

τf = Temperature coefficient in ppm/°C
Δf = [Resonant frequency at 60 °C] – [Resonant frequency at 25 °C in Hz]
f0 = Resonant frequency at 25 °C in MHz
ΔT = 60 °C – 25 °C = 35 °C

DR Frequency (TE01δ Mode)

For the equations in this section:

Dr = Resonator diameter (inches)
Lr = Resonator length (inches)
εr = Resonator dielectric constant

The frequency of an isolated DR in the TE01δ mode can be estimated to about 6% with a scientific calculator and the following formula:

$$f_0\,(\mathrm{GHz}) = \frac{8.553}{\sqrt{\varepsilon_r}\left(\frac{\pi}{4}D_r^2\,L_r\right)^{1/3}} \qquad \textbf{(3)}$$

Although this expression lacks high accuracy, especially when the DR is in close proximity to metal boundaries, it can still be used to estimate the sensitivity of frequency to Dr, Lr, and εr by differentiating and approximating:

$$\frac{\Delta f_0}{\Delta D_r} = \frac{-2 \times f_0}{+3 \times D_r}$$

$$\frac{\Delta f_0}{\Delta L_r} = \frac{-f_0}{+3 \times L_r}$$

$$\frac{\Delta f_0}{\Delta \varepsilon_r} = \frac{-f_0}{+2 \times \varepsilon_r} \qquad \textbf{(4)}$$

For example, using TTI’s 8371 material for a 10 GHz DR, the following estimates can be found:

Dr = 0.212"	ΔDr = ±0.001"	Df0 = ±31 MHz
Lr = 0.090"	ΔLr = ±0.001"	Δf0 = ±37 MHz
εr = 35.5	Δεr = ±1	Δf0 = ±141 MHz

This demonstrates why ordering a DR with just TTI catalog [reference 1] dimensions can result in large variances in f_0. TTI's catalog sizes are intended as guidance for beginning a DR design, to approximate the preferred frequency. See "Ordering DRs to Frequency" on page 3 for refinement.

The sensitivity formulas on page 2 can also be used to estimate the change, for example in height, required to modify the frequency of a DR. For example, if experiment shows that a 10 GHz DR frequency must be increased that f_0 changes by +31 MHz per + .001" change in height. The DR needs to be raised +500 MHz, so a simple ratio will give the change as:

$$\frac{0.001}{-31} = \frac{\Delta L_{NEW}}{+500}$$

or

$$\Delta L_{NEW} = -0.016'' \qquad (5)$$

The height of the DR should be reduced to 0.074 inches to raise the f_0 to 10.5 GHz.

Ordering DRs to Frequency

Do not order production DRs by size alone. The tolerances in dielectric constant and dimensions results in frequency variations that are unacceptable for most applications. Avoid trying to control frequency by simply imposing tight dimensions, or restricting the range of dielectric constant. This only drives yield down and cost up. Rather, specify a frequency-tuned part, one in which TTI adjusts the thickness or diameter to achieve the desired frequency and tolerance.

Ordering a DR simply by dimensions and material does not guarantee correct performance. It is not difficult to estimate DR dimensions for a target frequency when the enclosure and mounting is defined, but the choice of dimensions is not unique. Call a TTI Application Engineer for assistance in choosing the best material, size, and support. TTI can often cut weeks from your prototype development by suggesting sizes and materials already on hand, and even tailor inventoried DRs to your prototype needs.

Years of experience sizing resonators has shown that every DR application is unique, and that the best way for a designer to insure product repeatability is to follow a few basic steps.

1. Get the DR prototype circuit on frequency, or nearly so, with initial samples from the TTI catalog [reference 1] listings. DR frequency can be raised slightly by sanding the height (L_r) with fine emery paper.
2. Make a note of the:
   a. In-circuit frequency
   b. Preferred frequency
   c. TTI QC number of the prototype sample
3. Send the prototype DR with the information in Step 2 to TTI. TTI suggests that you assign a part number of your choosing to each prototype DR for correspondence and record-keeping. TTI retains this f_0 correlation sample DR, and uses it to fill next-iteration DR orders, with f_0 tuned to within 0.5% of your preferred frequency. TTI calls the difference between a) and b) the *offset*, and it is best to stipulate this offset in terms of MHz preferred above or below the correlation sample. A typical specification might read:

   "DR Frequency shall be that of correlation sample [your part number assigned to the sample] plus 120 MHz, with a tolerance of 0.5%."

When possible, it is preferable from a manufacturing standpoint to adjust f_0 by altering the height, L_r, rather than the diameter. When specifying a DR on a formal drawing, allow TTI this freedom by stating that the height L_r is nominal, and that L_r is to be adjusted to give f_0 to the frequency of the correlation sample plus offset, if any. Refer to the TTI catalog [reference 1] for typical diameter (D_r) tolerances.

Temperature Compensation

The unique nature of each DR circuit may necessitate adjustment for temperature-induced frequency drift. In an MIC environment, the expansion of the enclosure and tuning mechanism typically increases the air gap above the resonator, lowering f_0 as temperature increases. The change in f_0, in this case a negative $\Delta f_0/\Delta T$, can be compensated somewhat with a more positive τ_f of the ceramic DR. It is important to know the τ_f of the sample that was circuit-tested, so that this correction can be made. This figure is available from TTI's records if the TTI QC number, available from test data shipped with the sample, is specified. It is best to determine the DR size for frequency (f_0) first, particularly in an MIC application, because the proximity of the tuning screw can profoundly affect temperature drift. The τ_f is expressed in ppm/°C. In this context, the meaning is 1 Hz change for each MHz of operating frequency, for a given temperature range.

$$\tau_f = \frac{\Delta f\ (\text{Hz})}{f_0\ (\text{MHz})} \ \text{x}\ \frac{1}{\Delta T} \qquad (6)$$

Example

An oscillator running at 10,750 MHz (10.750 GHz) decreases in frequency by a total of 1.5 MHz over a –20 °C to +70 °C temperature range. The temperature coefficient of the entire oscillator circuit, τ_c, is:

$$\tau_c = \frac{1.5 \text{ X } 10^6 \text{ Hz}}{10{,}750 \text{ GHz}} \times \frac{1}{(70\ ^\circ\text{C} - 20\ ^\circ\text{C})}$$

$$= -1.55 \text{ ppm/}^\circ\text{C} \qquad (7)$$

This oscillator could be compensated for near-zero temperature drift by increasing the τ_f of the DR by +2 ppm/°C.

Mounting

Filter Applications

The mounting of DRs in filter applications is notoriously designer-unique and is usually proprietary. Here, the in-circuit Q is paramount and the DR is often supported with at least one DR thickness (L_r) above and below the DR, with a low-loss material having substantially lower dielectric constant than the DR's ε_r. High-purity alumina is a good choice, and the less mass the support has, the less field energy is stored in the support.

DRO Applications

MIC environments have to trade-off adequate coupling to the microstrip line versus DR height above the metal floor. The DR is sometimes placed directly on the substrate without a support for cost reduction, but f_0 drift versus temperature can be prohibitive. The large expansion coefficient of most soft substrates will effectively "lift" the DR as temperature increases, lowering frequency. Even high-volume applications such as satellite Low-Noise Block (LNB) converters use a stable ceramic support between the DR and the metal floor. The support might be 2/3 the resonator diameter. As an example, for a good trade-off between microstrip coupling and high loaded circuit Q, a 10 GHz DR is spaced 0.040 inches to 0.090 inches (0.060 inches nominal) from the floor with a diameter of 0.120 inches to support having a dielectric constant $\varepsilon_s = 6$.

Resonator Tuning

Tuning a DR means adjusting its resonant frequency by mechanical means. Several techniques can be used to achieve this:

- Changing the thickness of the DR, as previously discussed.
- Perturbing the fringing fields outside the DR with screws, tuning stubs, or dielectric material.

For example, the tuning of TE modes is easily achieved by metallic or dielectric tuning stubs placed perpendicular to the DR's top surface. Metal tuning stubs (shown as "a" in Figure 2) approaching the DR pull the frequency up and dielectric tuning stubs (shown as "b" in Figure 2) push the frequency down.

Approximately 20% of f_0 tuning can be achieved by these methods. It is, however, good practice to restrict this amount to below five percent to minimize degradation of both temperature coefficient and Qu.

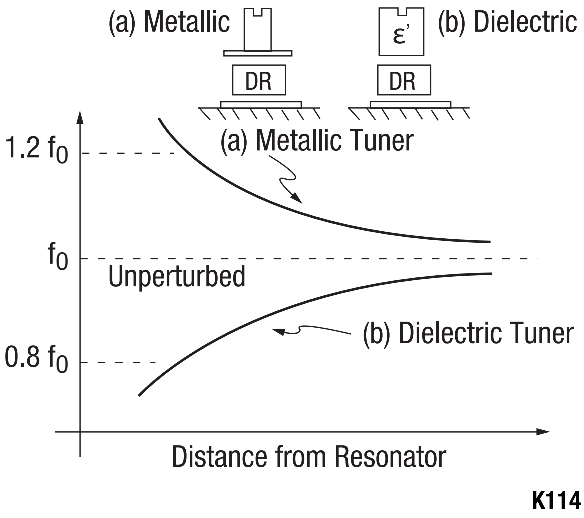

Figure 2. Tuning of TE Modes

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