Broadband Device Modeling and Q Calculations of Barium Strontium Titanate (BST) Varactors

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[Summary] Varactors are used in a wide variety of RF and Microwave circuits. Manufacturers of these devices typically offer electrical models which Design Engineers can use to include in their design simulations to achieve first-pass design success. This paper describes the measurement, electrical model optimization and Q calculations of Barium Strontium Titanate (BST) varactors. The measurement and modeling process described can be used as a template to model any varactor technology.

1 Introduction

Barium Strontium Titanate (BST) thin film is classified as a ferroelectric material. Ferroelectric materials can be polarized with an applied external electric field then reversed. Without an applied electric field, the orientation of the materials dipole moment is in every direction. The polarity of the dipole moment changes in the direction of the applied electric field. It is this reversibility that makes ferroelectrics such a popular type of material for many applications such as tunable microwave devices.

BST is a popular thin-film material for varactors because of its relatively high capacitance tuning ratio, low loss tangent, and high thermal resistance which is a result of being a ferroelectric material with an ideal Curie temperature point. Pierre Curie, a French physicist, discovered that ferromagnetic substances exhibit a critical temperature transition, above which the substances lose their ferromagnetic behavior and become paramagnetic. This is known as the Curie temperature. In analogy to ferromagnetic and paramagnetic materials, the Curie temperature can also be used to describe the phase transition between ferroelectricity and paraelectricity. Figure 1 shows the permittivity temperature dependence around the Curie temperature (Tc). The Curie temperature is the point where the ferroelectric crystal changes phase. Below the Curie temperature, the crystal is in a polar phase and exhibits a field dependent polarization hysteresis loop. Because of this hysteresis, a given permittivity value of the crystal can have more than one applied DC field value. Above the Curie temperature, the crystal is in paraelectric phase with no hysteresis present and the permittivity of the crystal may be determined unambiguously via an applied DC field value[1]. For this reason, and that hysteresis causes an increase in dielectric loss[2], most devices are designed to operate in the paraelectric phase region.

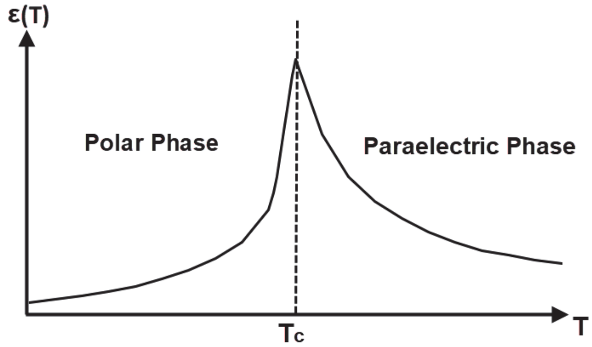

Figure 1 Permittivity temperature dependence and phase regions of a ferroelectric crystal near the Curie temperature.

The slope of the polarization vs. electric field curve gives the relative dielectric permittivity of the ferroelectric material. The advantage of having a Curie temperature point around the device operating temperature is it gives BST its highest dielectric constant, low loss tangent and linear tuning. The chemical formula of BST is $B_{ax}Sr_{1-x}TiO_3$. The Curie temperature can be adjusted by varying the barium and strontium concentrations. If the Barium concentration is kept at 0.6 and below (x<0.6), then the Curie temperature of the BST material will be well below room temperature[3]. This concentration ensures devices operate in the paraelectric phase at room temperature.

Applications for BST materials in RF/Microwave systems are numerous. BST varactors are key elements in tunable filters, frequency selectable resonators, matching networks, delay lines and steerable directional antennas. In addition to being able to change the dielectric permittivity of the material, another benefit is fast tuning speed. Tuning speeds have been reported in the nano-second range and is faster than other technologies such as MEMS, semiconductor varactor technologies and PIN-diode based structures.

With new BST interdigitated (IDC) varactor products now on the market, there is an interest in characterizing these new devices, deriving lumped element models and calculations of dielectric and total Q over a broad frequency range. The next section of this paper describes a measurement and modeling technique to derive an electrical model that system or component designers can use. From this model, varactor Q is evaluated over a broad range of frequencies.

2 VNA Calibration and Device Measurement

2.1 Device Mounting

Two IDC varactor part models were evaluated and measured[4]. Five of each varactor model part number were soldered onto a 1-cm length of 10-mil thick polished alumina Microstrip substrate. The substrate is designed as a 50-ohm thru with a 0.12 mm long metallization gap at the midpoint of the transmission line. Each varactor was installed on the substrate and centered across this metallization gap as shown in Figure 2. A total of ten substrate assemblies were prepared.

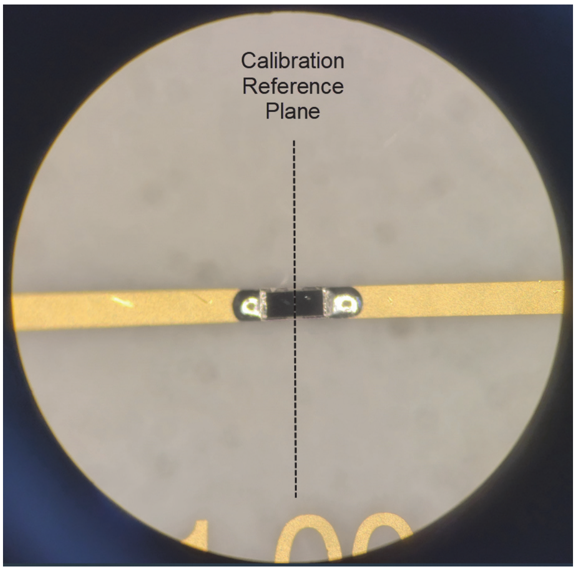

Figure 2 Tecdia Varactor soldered to 1-cm long, 10-mil thick polished alumina Microstrip substrate

2.2 Calibration

A Vector Network Analyzer (VNA) was used to provide an ultra-wideband 2-port measurement of each varactor sample device. The required measurement frequency range spans from 200 MHz to 43.5 GHz. The measurement should include only the electrical characteristics of the varactor and not any other effects such as the substrate the varactor is mounted to, test fixturing, cables, etc. One way to remove these effects from the measurement is to calibrate the system using a multi-band LRL calibration with calibrated reference planes centered at the location where the device is mounted to the substrate. A VNA[5], Universal Test Fixture (UTF)[6], test port cables[7] and a Microstrip Multi-band LRL calibration kit[8] facilitated the calibration and measurement of each prepared varactor assembly.

The calibrated frequency bandwidth ratio is about 220:1 and requires a minimum of two LRL calibration bands. Typical phase delta bounds of each band should fall in the range of 20 to 160 degrees but we extended the lower delta phase bounds to 10 degrees and still obtained a reasonable calibration. Table 1 shows the calibration line lengths chosen for each band. Table 2 shows the calibration band details with the phase delta bounds at each frequency endpoint. Note that line 1 (1-cm in length) is shared between both calibration bands 1 and 2. Also, the calibrated reference plane is defined as being located the middle of Line 1 which is also located at the middle of each varactor substrate assembly. This is the reason we chose the varactor substrate length to be 1-cm long.

Table 1 Multi-band LRL calibration band line lengths

Line #	Line Length [mm]	Band
1	10.0	1 & 2
2	10.7	2
3	17.0	1

From Table 2, the break frequency is defined to be 5 GHz. This frequency was chosen to set a reasonable maximum delta phase of Band 1 and a minimum delta phase of Band 2. This break frequency is entered into the calibration setup dialog of the VNA along with the line lengths of each band definition.

Table 2 Multi-band LRL calibration bands and delta phase bounds

Band	Freq. [GHz]	Min. Δ [deg]	Max. Δ [deg]
1	0.2 to 5.0	10	132
2	5.0 to 43.5	13	114

2.3 Device Measurement

Each varactor assembly was measured and its 2-Port S-Parameters were recorded for device biases of 0 V and +25 V. Bias to the varactor device was injected through Port 1 internal Bias-T within the VNA. Port 2 internal Bias-T was grounded. Care was taken to install each varactor assembly into the UTF without misalignment. Each varactor assembly was marked by its device part number and sample number for unique identification.

Device measurements represent the actual electrical performance. This measured data is used to fit our electrical model to. Each model element parameter value is optimized simultaneously against the measured data. In the next section, the lumped element varactor model will be developed and expressions for Q presented.

3 Model Development and Quality Factor

3.1 Lumped Element Model

The equivalent lumped element model for the varactor part is shown in Figure 3. The varactor is modeled as four lumped elements with connecting Ports 1 and 2. The capacitor C(v) models the effective capacitance of the varactor. The resistor Rp(v) is in parallel with C(v) and models the leakage conductance of the varactor. This parallel combination represents the dielectric effects of the varactor. The series resistor Rs represents the parasitic conductor and interconnect/electrode resistance and the inductance Ls which represents the parasitic conductor inductance. Parasitic elements Rs and Ls are distributed equally on either side of C and Rp but Figure 3 shows these parameters lumped on one side for simplicity.

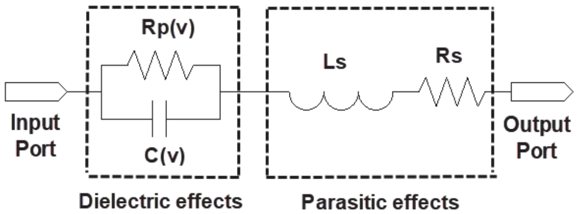

Figure 3 Equivalent schematic model for series mounted varactor

3.2 Model Parameter Optimization

The four model parameters Cp, Rp, Ls and Rs in Figure 3 are optimized simultaneously against each measured varactor assembly using Cadence AWR Microwave Office[9]. Two magnitude and phase difference equations (1) and (2) are used to optimize the four lumped element values over the frequency range of 0.2 GHz to 43.5 GHz. For both equations, the optimization goal is zero. During optimization, the lumped element parameters of the model are varied until the two magnitude and phase equations are satisfied, or more practically, when the difference error is sufficiently small.

$$|S21_{meas}| - |S21_{model}| = 0 \quad (1)$$

$$\arg(S21_{meas}) - \arg(S21_{model}) = 0 \quad (2)$$

The lumped element model is optimized against each measured varactor assembly with applied 0 V and 25 V bias. For each varactor part number, ten sets of optimized parameters were obtained: five sets at 0 V and five sets at 25 V. Each set was averaged and is shown in tables 3 and 4. As expected, the parasitic elements Ls and Rs do not change with applied bias.

Table 3 Model parameter values for 0V and 25V Biases (Tecdia PN: HBCR22AY20X10X5A02)

Parameter	Bias: 0 V	Bias: 25 V
Cp [pF]	0.2033	0.1396
Rp [kΩ]	33.77	33.29
Ls [nH]	0.0599	0.0599
Rs [Ω]	5.055	5.055

Table 4 Model parameter values for 0 V and 25 V Biases (Tecdia PN: HBC2R2KY20X10X5A02)

Parameter	Bias: 0 V	Bias: 25 V
Cp [pF]	1.958	1.145
Rp [kΩ]	30.71	31.66
Ls [nH]	0.0602	0.0602
Rs [Ω]	1.278	1.278

Although Rs may seem high and does contribute to a lower Qt value, it is attributed to the parasitic resistance of small contacts of the part itself. A larger part, having a standard 0402 (EIA) size for example, will have a larger contact area and lower parasitic resistance. This will lead to a lower Rs value and higher Qt. Further research is ongoing in reducing parasitic resistance Rs.

3.3 Quality Factor Qd and Qt

The Q factor is an important parameter since it determines the applicable frequency limit for the varactor. For oscillators used in frequency synthesizers, varactor Q will affect the noise performance. Higher Q varactors enable higher Q resonant tanks to be achieved, and in turn reduces the phase noise produced by the circuit.

Two Quality factor terms can be defined: the Quality factor due to the dielectric Qd and the total Quality Factor due to both dielectric and parasitic effects Qt. Yue[10] derives expressions for Qd and Qt based on the lumped element model in Figure 3 and are shown by equations (3) and (4) respectively. Figures 4 and 5 show plots of Qd and Qt vs. frequency vs. bias from 2 GHz to 45 GHz. These Q values are similar to those found earlier in research[10].

$$Q_d \;=\; \omega R_p C_p \qquad (3)$$

$$Q_t \;=\; \frac{\omega L_s + \frac{{Q_d}^2}{1+{Q_d}^2}\cdot\frac{1}{\omega C_p}}{R_s + \frac{R_p}{1+{Q_d}^2}} \qquad (4)$$

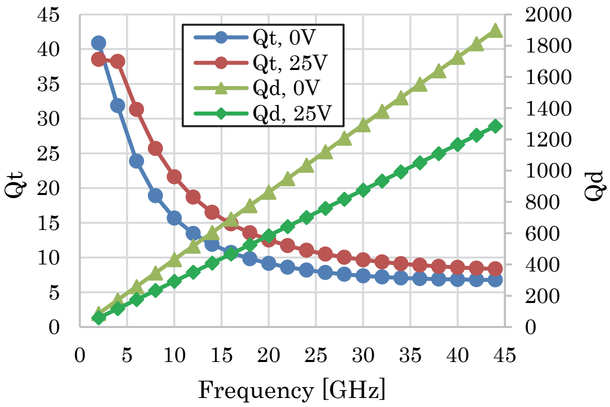

Figure 4　Qt and Qd vs Frequency vs. applied voltage (Tecdia PN: HBCR22AY20X10X5A02)

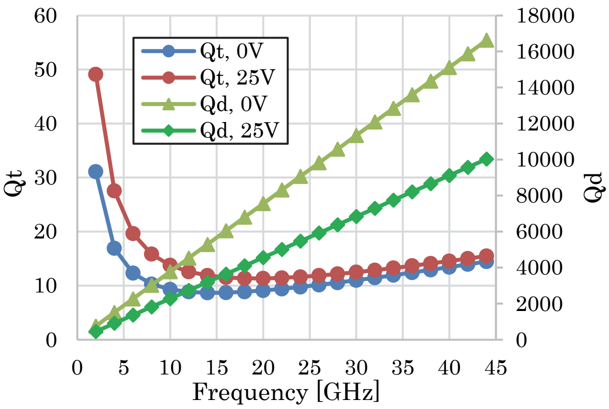

Figure 5　Qt and Qd vs Frequency vs. applied voltage (Tecdia PN: HBC2R2KY20X10X5A02)

4 Tuning Linearity

BST Varactors exhibit excellent tuning linearity. Capacitance vs. voltage data was collected on five sets of each varactor model. Data was collected using an LCR meter[11] in 2 V increments up to 25 V. For each varactor model, the measured capacitance was averaged for each bias value. A linear equation (5) was developed for each varactor model that describes device capacitance as a function of applied voltage. The coefficients for the linear equation are shown in Table 5.

$$C(V) = k * |V| + b \qquad [\text{pF}] \qquad (5)$$

Table 5　Coefficient values for use with linear equation (5)

Tecdia PN:	k (pF/V)	b (V)
HBC2R2KY20X10X5A02	−0.0423	2.1842
HBCR22AY20X10X5A02	−0.0036	0.2181

Figure 6 and 7 show tuning linearity plots for each varactor model. The tuning linearity % error is typically less than 3% and is shown in Figure 8.

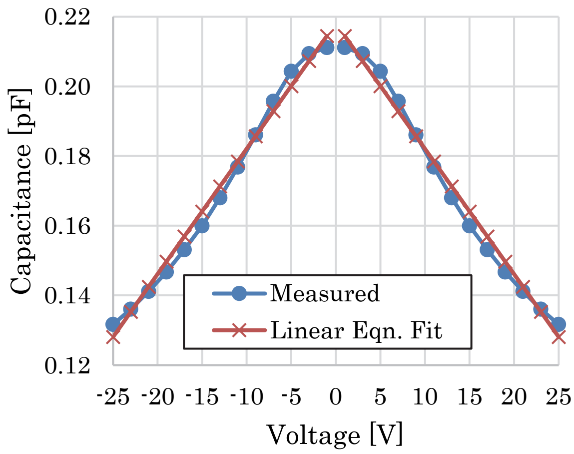

Figure 6　Capacitance vs. Voltage, Measured and Linear Eqn. Fit (Tecdia PN: HBCR22AY20X10X5A02)

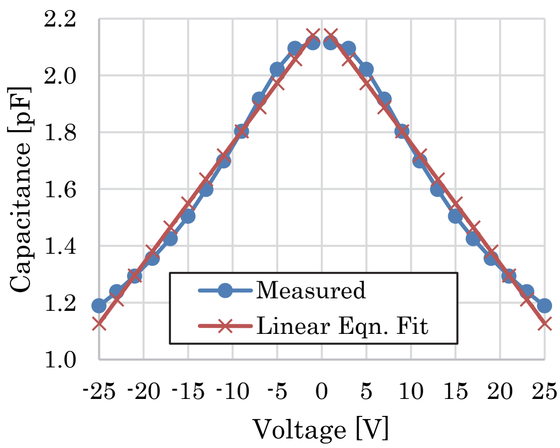

Figure 7　Capacitance vs. Voltage, Measured and Linear Eqn. Fit (Tecdia PN: HBC2R2KY20X10X5A02)

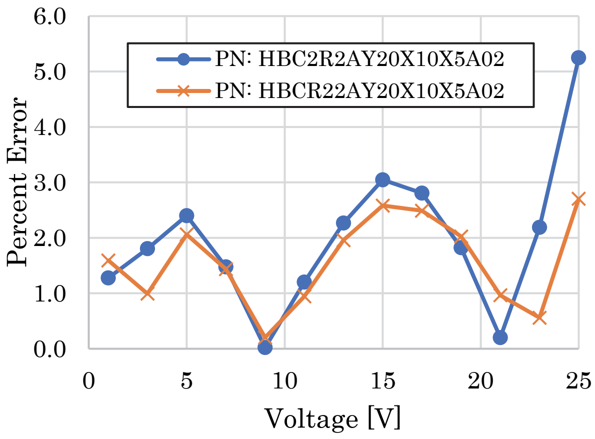

Figure 8 Percent Error of Measured vs. Linear Eqn. Fit, Tecdia 2.2 pF and 0.22 pF Varactors

5 Phase Delay

The measurements and modeling described earlier assumes the device is zero length. The parts evaluated are 0201 EIA (inch) size and have a total length of 0.02" (0.5 mm). The electrical model in Figure 3 can account for this length (L) by adding two phase delays expressed in equation (6). This phase delay is dependent on the part length and the relative dielectric constant of the substrate which the part is mounted to. In accounting for this phase delay, the reference planes are moved to the ends of the part. This phase delay is represented as two transmission lines each with length L/2 placed on either side of the lumped element model in Figure 3.

$$\emptyset(L, \varepsilon_r, f) = \frac{180 \cdot \sqrt{\varepsilon_r} \cdot L \cdot f}{c} \quad \text{[deg]} \qquad (6)$$

6 Conclusions

Quality Factor of varactor devices can be separated from its dielectric and parasitic effects. These Quality Factor expressions are derived from broadband electrical model representations of the device. The electrical model parameters Cp, Rp, Ls and Rs are optimized to varactor measurement data files. Capturing the measurement data files involves fixturing varactor devices onto a substrate and selecting a calibration that will remove the effect of the measurement system, fixture and substrate to obtain only the electrical characteristics of the varactor. Fixture removal was achieved by choosing a multi-band LRL Microstrip calibration with reference planes at the location where the part was mounted to the substrate.

One of the by-products in computing Quality Factor over a broad range of frequencies is that a simple, broadband electrical model is found which can be used in any RF/Microwave circuit simulator for component or system analysis purposes. Further, the measurement and model fitting process can be applied not only to BST type varactors but other technologies such as silicon or GaAs.

All work was performed at an ambient temperature of +25°C and the project scope did not include the effects of device temperature. Temperature effects were examined for Tecdia device models D04A1R5 and D10A1R5[12] and are available for use with modern circuit simulators.

7 References

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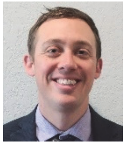

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