Measurement of the Anisotropic Dielectric Constant of a Glass Bead in a Coaxial Test Fixture

By Bruce Bullard
Atmel Corporation

Hermetic connectors are used throughout the microwave industry, in applications ranging from extreme humidity and salt fog to vacuum systems. The most widely used seal is made from glass. For frequencies below 1 GHz, most glass is interchangeable. However, for higher frequencies where insertion loss and VSWR are factors, glass types behave differently. Some are easily fired and exhibit a very repeatable dielectric constant, but with high loss. Others have low loss but exhibit variations in the dielectric constant from lot to lot and as a function of firing schedules. This results in VSWR performance variation from lot to lot.

The solution to manufacturing a high performance hermetic connector is to identify a specific glass and then optimize the glass seal process to obtain low loss material and repeatable dielectric constant.

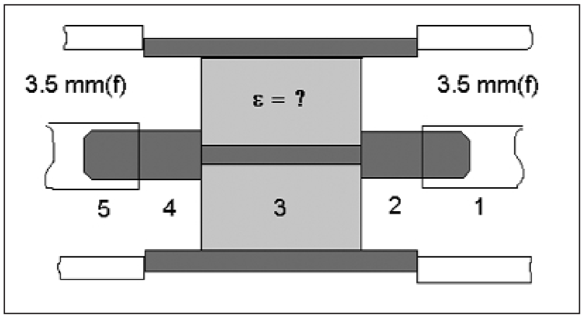
Measuring the dielectric constant poses a problem. The classical method [1, 2] places the bead in a resonant cavity, then uses the quality factor and changes in the resonant frequency to determine the properties of the bead. A drawback of this method is the bead is not measured in the configuration in which it is used. Also, when fired into the connector, the bead forms a compression seal with its surrounding body. This article will show that the compression influences the dielectric properties.

Another disadvantage of this method is that the bead should be fired into a regular shape. Since the beads are purchased in preformed shape (in this case a coaxial configuration), firing the bead into a different shape, one without an inner conductor, is cumbersome and requires undesired machining.

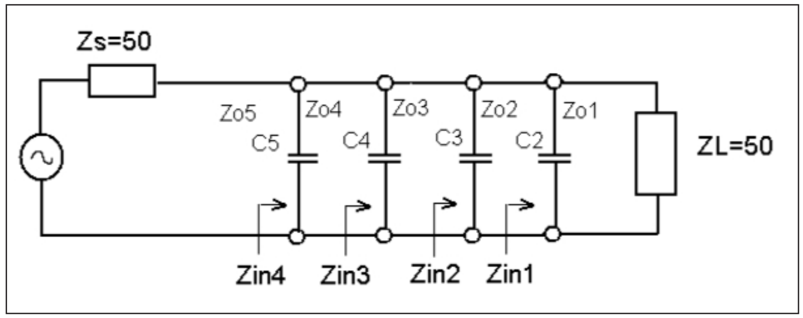
Ideally, the properties of the bead would be measured once it has been fired into the connector body. One method of achieving this is to fire a seal into a connector, perform a TDR measurement of the connector, and analyze the impedance of the connector around the glass seal. Drawbacks to this procedure are:

- The connector must be attached to a matched load for the measurement.
- The connector and matched load must operate to high frequencies (18 GHz minimum).
- The seal is on the order of 0.08 inches long. The resolution of two adjacent discontinuities by TDR is nearly equal to the width of the seal even for broadband measurements. If discontinuities adjacent to the seal are not minimized, they mask the impedance measurement of the glass.
- The TDR measurement is a broadband frequency measurement, which computes the impedance based on the response to all frequencies. Therefore, any variation with frequency is masked.
- The TDR method does not account for anisotropic dielectrics.

This article describes a method where a glass bead is fired into a coaxial test fixture configuration that is similar to the connector. The glass is assumed to be anisotropic following the firing. The parallel (to E field, $\varepsilon_{\parallel}$) relative dielectric constant is computed by comparing the theoretical VSWR to the measured VSWR. The perpendicular relative dielectric constant ($\varepsilon_{\perp}$) is computed by comparing the theoretical phase response to the measured phase response. The theoretical insertion phase is computed using established analytical methods [3, 4] for capaci-



▲ **Figure 1. Glass bead test fixture mated to 3.5 mm (*f*) connectors.**



▲ **Figure 2. Glass bead test fixture transmission line mode.**

tive discontinuities, combined with the theoretical phase response of a coaxial transmission line. Using the test fixture has the advantage that the same firing fixtures, cover gas, inner conductor, similar outer conductor, and heating schedule are used for firing the connector.

The bead is also under the same compression as when it is fired into the connector. These factors all contribute to minimizing a number of uncertainties in the firing process.

The test fixture

The glass bead is fired into the configuration shown in Figure 1. Four junction discontinuities are apparent when the fixture is mated to 3.5 mm (*f*) connectors. The dimensions of the fixture are determined based on dielectric constant estimates/values supplied by the manufacturer, or past experience. The following paragraphs and references [3, 4] provide the necessary analytical tools for design. The design should be optimized for the minimum possible VSWR, which reduces the phase measurement error.

$$ACBD_{eqv} = \begin{pmatrix} A_{eqv} & B_{eqv} \\ C_{eqv} & D_{eqv} \end{pmatrix}$$

$$= (C_5)(ABCD_4)(C_4)(ABCD_3)(C_3)(ABCD_2)(C_2)(ABCD_1)$$

$$= \begin{pmatrix} 1 & 0 \\ j\omega C_5 & 1 \end{pmatrix} \begin{pmatrix} \cos\beta_4 l_4 & jZo_4 \sin\beta_4 l_4 \\ \frac{j}{Zo_4}\sin\beta_4 l_4 & \cos\beta_4 l_4 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ j\omega C_4 & 1 \end{pmatrix}$$

$$\text{X} \begin{pmatrix} \cos\beta_3 l_3 & jZo_3 \sin\beta_3 l_3 \\ \frac{j}{Zo_3}\sin\beta_3 l_3 & \cos\beta_3 l_3 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ j\omega C_3 & 1 \end{pmatrix}$$

$$\text{X} \begin{pmatrix} \cos\beta_2 l_2 & jZo_2 \sin\beta_2 l_2 \\ \frac{j}{Zo_2}\sin\beta_2 l_2 & \cos\beta_2 l_2 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ j\omega C_2 & 1 \end{pmatrix}$$

$$\text{X} \begin{pmatrix} \cos\beta_1 l_1 & jZo_1 \sin\beta_1 l_1 \\ \frac{j}{Zo_1}\sin\beta_1 l_1 & \cos\beta_1 l_1 \end{pmatrix}$$

▲ **Equation 1.**

Device parameters

The transmission line model for the device is shown in Figure 2, and the parameters are tabulated in Table 1. The dielectric constant for section 3 is provided by the glass supplier, then refined using the following procedures. The glass dielectric is assumed to be anisotropic [5]. All dimensions are in inches; SI units are used in all calculations.

The ABCD parameters [6] are computed and converted to S parameters. The VSWR is the usual ratio of the reflection coefficient, and the phase response is the argument of the S_{21} term. The ABCD parameters for the lossless transmission line with the configuration described in Table 1 and Figure 2 are:

l_i = length of section

$$\beta_i = 2\pi f\sqrt{\mu_o \varepsilon_o \varepsilon_\perp}$$

$$Zo_i = \frac{59.96}{\varepsilon_\parallel} ln\frac{b_i}{a_i}$$

Equation 1 shows the resulting calculations.

The S_{11} and S_{21} parameters of the scattering matrix are:

$$S_{11} = \frac{A_{eqv} + \frac{B_{eqv}}{Z_o} - C_{eqv} - D_{eqv}}{A_{eqv} + \frac{B_{eqv}}{Z_o} + Z_o C_{eqv} + D_{eqv}} \quad (2)$$

$$\text{vswr} = \frac{1 + |S_{11}|}{1 - |S_{11}|}$$

$$S_{21} = \frac{2}{A_{eqv} + \frac{B_{eqv}}{Z_o} + Z_o C_{eqv} + D_{eqv}}, \quad Z_o = 50 \quad (3)$$

Section	Dia a (in)	Dia b (in)	Dielectric	Length (in)	Capacitance (in)
1	0.0598	0.1378	1	0	n/a
2	0.0360	0.1180	1	0.015	9.62
3	0.0235	0.1180	$\varepsilon_{\parallel}$, $\varepsilon_{\perp}$	0.085	1.88 $\varepsilon_{\parallel}$
4	0.0360	0.1180	1	0.015	1.88 $\varepsilon_{\parallel}$
5	0.0598	0.1378	1	0	9.62

▲ **Table 1. Glass bead fixture diameters.**

Measurement results

TDR measurement

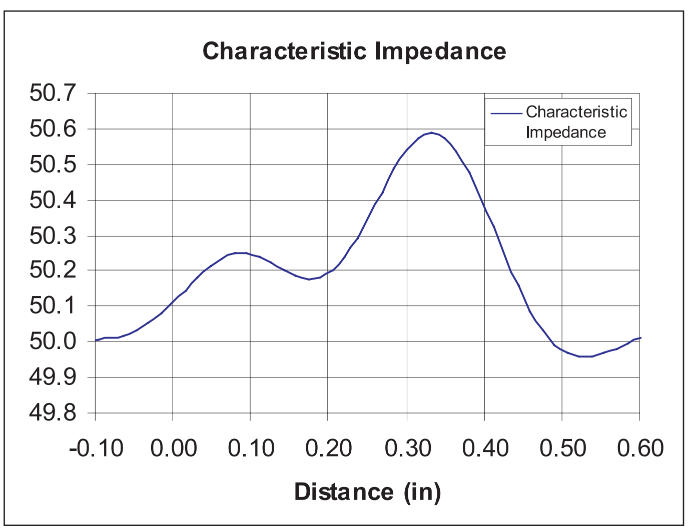
The glass bead test fixture (Table 1) was manufactured and tested at room temperature using 7070 glass. A rough estimate of the dielectric constant can be obtained using the TRD method.

Using the HP8510 network analyzer's TDR mode, the characteristic impedance of the fixture was measured and is shown in Figure 3. The first high corresponds to the mismatch caused by the glass and the discontinuities on either side. The second high is a result of the transition between the glass seal and the load. The HP8510 network analyzer settings are: frequency span = 0.045 to 18.0 GHz, window = normal, low-pass mode. For this setup, the minimum resolvable spacing between discontinuities is:

$$t_{min} = \frac{1}{2}\cdot\frac{(0.60)\cdot(1.6)}{\text{Freq Span}} = 27\text{ pS} \qquad (4)$$

$$l_{min} = \frac{t}{2\sqrt{\mu_o\varepsilon_o\varepsilon_r}}\cdot\frac{100}{2.54} \approx 0.08\text{ in} \qquad (5)$$

Note that with this setup, the difference between the discontinuities on either side of the glass seal and the seal cannot be resolved.



▲ **Figure 3. TDR for the glass bead text fixture of Figure 2 and Table 1.**

The estimate of the dielectric constant is made by ignoring the discontinuities and calculating the isotropic dielectric constant of the glass based on the impedance measured in the area, as well as the dimensions in that area. For section 3,

$$\varepsilon_r \approx \left[\frac{59.96}{50.25}\cdot ln\left(\frac{0.118}{0.0235}\right)\right]^2 = 3.71 \qquad (6)$$

Note that the impedance in sections 1, 2, 4 and 5 can skew impedance measurement. These values are:

$$Z_{o2} = Z_{o4} = 59.96\, ln\frac{b_2}{a_2} = 71.2\,\Omega \qquad Z_{o5} = 59.96\, ln\frac{b_5}{a_5} = 50\,\Omega \qquad (7)$$

For section 1, between the glass and the load, the measured value from the TRD is:

$Z_{o1} = 50.6\ \Omega$
$l_1 = 0.5$ in

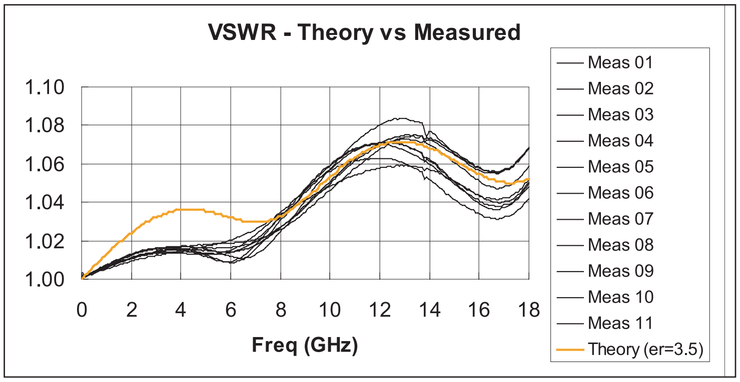
VSWR performance

The parallel dielectric constant ($\varepsilon_{\parallel}$) is estimated by comparing it to the theoretical VSWR. Equations (1) and (2) and the TDR measurement of the length and impedance of section 1 are used. Note that the parallel dielectric has the most influence on the magnitude of the VSWR, whereas the perpendicular dielectric constant ($\varepsilon_{\perp}$) has the effect of changing the phase response and, to a small extent, the spacing of the VSWR nulls. A comparison between theoretical VSWR performance and actual VSWR performance is shown in Figure 4. The estimated value for the dielectric constant is 3.5 parallel and 3.5 perpendicular. Good agreement is obtained.

Phase response

The perpendicular dielectric is determined by comparing the measured phase response to the theoretical value calculated with Equations (1) and (3). The parallel dielectric is as calculated above, $\varepsilon_{\parallel} = 3.5$. The influence of the parallel dielectric is only slightly significant. Using an isotropic dielectric changes the calculated perpendicular dielectric constant by roughly 0.03.

When manufacturing the test fixture, the lengths l_2 and l_4 are relatively easy to control, but l_3 varies because of process variations. These lengths are significant in phase calculation. Lengths l_2 and l_4 are held constant at 0.015 inches. The measured phase and calculated perpendicular dielectric constant are listed in Table 2.



▲ **Figure 4. VSWR for the glass bead fixtures from Table 1.**

Sample	Measurement Phase (degrees)	Length (in) $l_2 + l_3 + l_4$	$\varepsilon_\perp$
1	–84.985	0.1135	4.02
2	–83.767	0.1110	4.12
3	–85.591	0.1125	4.19
4	–86.670	0.1140	4.16
5	–84.346	0.1110	4.19
6	–86.626	0.1150	4.07
7	–85.850	0.1150	3.98
8	–85.000	0.1120	4.17
9	–86.640	0.1150	4.07
10	–87.163	0.1160	4.03
11	–85.368	0.1130	4.11
Average = 4.10			
STD Dev = 0.07			

▲ **Table 2. Measured phase and dielectric constant.**

Published data

Several sources were found for the dielectric constant of 7070 glass. The published values are for an uncompressed dielectric or, in this case, the perpendicular dielectric constant ($\varepsilon_\perp$). Good agreement is obtained. The results are shown in Table 3.

Measurement errors

Calculation of the perpendicular dielectric constant based on phase response is subject to several sources of error. First, the fixture must be assembled as shown in Figure 1. The steps on either side of the glass seal must be relatively flush to the glass because capacitance of the junction is based on the dielectric constant of the glass, as well as the proximity of the step to the glass. The second error lies in the physical measurement of the fixture's dimensions. These can be reduced using standard measurement techniques for small dimensions, testing a large number of devices and taking the average dielectric constant. A third consideration is the accuracy of the capacitance estimate and its variance with frequency. The capacitance is estimated to within 3 percent, and the variance with frequency should not exceed 2 percent. Another error term is estimating the phase change per length of line from Equation 1. Specifically, the loss terms were ignored. The model is estimated to be within 0.5 percent.

The network analyzer measurement error is easily reduced. It has a worst-case phase measurement error of roughly ± 2.9 degrees [8]. Plugging this into Equations (1) and (2), the error in the dielectric measurement is roughly ± 0.3. (Keep in mind this error is the worst case, and typically the accuracy will be much greater.) A rough measurement of the network analyzer phase error has been made [9] and it was shown that most measurements are within ± 0.4 degrees. The reduction in the variance is accomplished by taking several phase measurements over varying frequencies.

VSWR can also generate phase errors. For the VSWR measured, 1.10:1 the phase error is estimated as [10]:

$$\phi_{err} = \pm\sin^{-1}|\rho_1\rho_2| = 0.033° \qquad (8)$$

where

$$\rho_1 = 0.048$$
$$\rho_2 = 0.012$$

Ignoring the dimensional discrepancies, combining the capacitance errors, considering the errors in the model for phase/length and using a phase measurement error of ±0.4 degrees, the error in the dielectric measurement will be approximately ±0.08.

Because test fixture is similar, the errors from the capacitance estimates should be repeatable, as are the errors from the phase/length equations. To a lesser extent, because of the similarity of devices, one can argue that the errors in the phase measurement are also somewhat repeatable. These factors combine to yield an estimate of the dielectric constant that may have a mean error of ±0.08, but that has a low error variance.

Source	Frequency Range	Relative Dielectric Constant (room temperature)
Corning, Publish Spec	1 MHz	4.1
GBC Materials (supplier)	1 MHz	4.1
A. von Hipple	100 Hz to 10 GHz	4.0
A. von Hipple	25 GHz	3.9

▲ **Table 3. Published dielectric constant of 7070 glass [7].**

Verification using electromagnetic finite integration

A finite integration simulation/modeling program was made available by

	Δf GHz	Dielectric Constant	Phase Response
CST Microwave Studio (phase is calculated from dielectric)	13.99	3.550	86.82°
ABCD Theory (dielectric is calculated	13.99	3.627	86.82°

▲ **Table 4. Comparison to finite integration analysis.**

CST America and used to confirm the accuracy of the theory presented. The device was used as defined in Table 1. The CST model was run with a isotropic dielectric of 3.55 instead of the measured $\varepsilon_r = 3.5_{\parallel}, 4.10_{\perp}$. For comparison, the ABCD model also uses an isotropic dielectric. The results are shown in Table 4.

Frequency dependent dielectrics

Frequency dependent dielectrics can be measured as described above. The goal is to narrow the frequency span to encompass the frequency of interest. Several measurements are made over varying frequency bands that surround the frequency of interest. Using this method, the phase measurement error can be reduced, thereby reducing the error in the measured dielectric constant.

Complex dielectric constant

The basic Equation (1) still applies. Beta becomes the complex propagation constant gamma, which takes into account conductor loss and dielectric loss. The cosine terms become hyperbolic cosines, the sine terms, hyperbolic sines and the *j* is dropped. Two good sources for proceeding are [11, 12].

Conclusion

The illustrated measurements show that the dielectric constant of 7070 glass is dependent on the compression the glass is under. In the direction parallel to the electric field, the relative dielectric constant ($\varepsilon_{\parallel}$) is reduced because of increased pressure, while the relative perpendicular component ($\varepsilon_{\perp}$), which is not under compression, maintains its typical value.

The key to designing low VSWR hermetic seals is to quantify the changes in the dielectric constant as a result of the compression seal. This method gives connector manufacturers tools for monitoring the firing process and adjusting when necessary. The tools and techniques required are basic and available in most microwave manufacturing facilities.

In addition, this method allows the designer the option of testing over frequency without setting up numerous resonate cavities. Although not as accurate as the resonate cavity, the method accounts for compression and anisotropic dielectrics and can be easily implemented. ■

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Author information

Bruce Bullard is a consulting engineer in the Silicon Germanium Circuit Evaluation Laboratory at Atmel Corporation. He is also a member of the Atmel Application and Integration Team for the W-CDMA Harmony Lite Chip. He has a master of science degree in electrical engineering from the University of Colorado at Colorado Springs. He may be reached via E-mail: bruce_b37@yahoo.com; or Tel: 719-540-1517.