Sonnet Technical Focus: Are your substrates REALLY isotropic?

By

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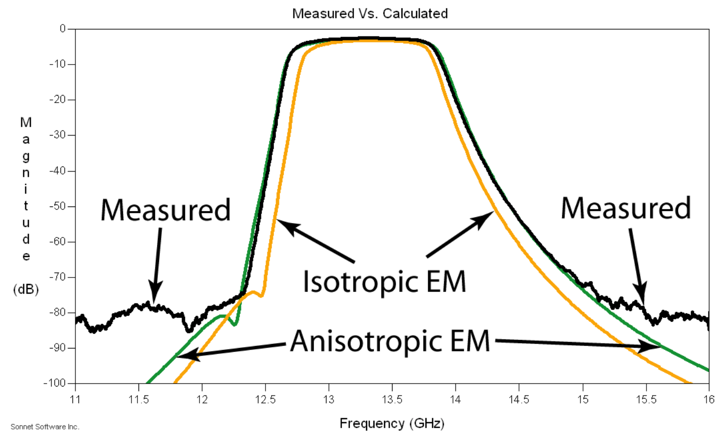

Figure 1. For this filter, pretending that the substrate dielectric constant is isotropic means a re-design is required. With anisotropy included, the filter is ready for production. From [1].

In the late 1970's, when I first got started in microwaves, one of my first tasks was to design filters on Alumina for Landsat IV. The design was carefully performed using the commonly assumed dielectric constant of 9.8. Even so, several design iterations were required. "Get used to it," I was told, "multiple design iterations are a fact of microwave design life." Or so we thought.

Fast forward to 2007. EM analysis is a mainstream design tool. Dielectric Laboratories, Casenovia, NY, is having extreme success with rapid fire design of filters using Sonnet EM analysis. Success on first fabrication is now normal, except for certain cases. The troublesome cases use a nearly exactly zero temperature coefficient ceramic, and that ceramic is anisotropic. Figure 1 illustrates the problem.

In the old days, the obvious work-around for not being able to EM analyze anisotropy is to assume isotropy (same dielectric constant in all directions) and use some kind of average dielectric constant. Anisotropy means that the dielectric constant depends on the direction of the electric field. A percentage of a transmission line's electric field is horizontal (parallel to the substrate surface) and the rest is vertical (perpendicular to the substrate surface). So we use a weighted average of the horizontal and vertical dielectric constants, and we weight the average according to the percentage of horizontal and vertical electric fields.

This works well as long as you only use single transmission lines, all with the same width. If we change the width, we change the percentage of horizontal and vertical electric field. We need a different weighted average. If the difference is not so large, maybe we can just use one isotropic dielectric constant and still get designs to work.

Assuming Isotropy Fails for Filters

The big problem comes with filters. The resonant frequencies of the resonators in our filters are determined mostly by the vertical dielectric constant. In order to get the right center frequency for our filter, we simply use the vertical dielectric constant and pretend that the substrate is isotropic. However, there is more to a filter than the center frequency; we also must nail down the bandwidth. The bandwidth depends on the coupling between resonators. The coupling between resonators depends strongly on the horizontal dielectric constant. But the horizontal dielectric constant is different!

Thus, if we try to assume an anisotropic substrate is actually isotropic, we can get the center frequency right, or we can get the bandwidth right but we cannot get both right. This was the situation when Dielectric Laboratories called in Sonnet. They showed us the "Isotropic" and the "Measured" data of Figure 1. This amount of error absolutely requires a second design iteration. That meant another two weeks of EM simulations trying to stretch the filter to an artificially wider target bandwidth, hoping that the actual realized bandwidth would end up close to requirements.

With the data of Figure 1 in hand, we modified Sonnet to include anisotropy. Specifically, we added the capability to analyze "uniaxial" anisotropy. In other words, there is one horizontal dielectric constant for all horizontal directions and a different dielectric constant for the vertical direction.

Dielectric Laboratories had measured values for the anisotropy which we plugged into Sonnet. There was no tuning of the layout, or the meshing, or the anisotropic dielectric constants provided by Dielectric Laboratories. We used exactly the information Dielectric Laboratories gave us. The "Anisotropic" curve of Figure 1 was the result, almost exactly on top of the measured data. The anisotropy problem is solved. Dielectric Laboratories now has success on first fabrication even for strongly anisotropic substrates. And the two weeks to achieve design closure? That is now down to one day using the exceptionally powerful "port tuning" technique [1]. Sweet!

Anisotropic Ceramic? Ridiculous!

It seems really strange. How can a ceramic possibly be anisotropic? We grind up some kind of material (sapphire is used to make Alumina), and then melt all the randomly oriented grains together. Even if the original material is anisotropic (as with sapphire), the resulting ceramic should be almost perfectly isotropic.

Not quite. The above reasoning works only when the grains of the ceramic are spherical. In general the grains are not spherical and the "random" orientation of the grains in the ceramic has preferences. This makes most ceramics anisotropic. For example, in the only published measurement of anisotropy in Alumina that we have been able to find [2], it was determined to be 8.607 vertically and 10.159 horizontally (manufacturing variability was not investigated). The usually assumed 9.6 to 9.9 represents a nice average of the two measured values, but the difference between the average dielectric constant and the true anisotropic dielectric constant easily explains our multiple design iterations on those Landsat IV filters.

To see why a ceramic can be anisotropic, look at Figure 2a, which illustrates a hypothetical substrate. The dark cylinders have high dielectric constant and the light areas are low, and half of the total volume is devoted to each type. The total capacitance from top to bottom is dominated by the high dielectric constant. This is just like connecting two capacitors in parallel. The total capacitance is dominated by the larger capacitor.

Next, look at Figure 2b. Here, each material still takes up the same percentage of the substrate volume. But now, the total capacitance between the terminals is dominated by the low dielectric constant. This is similar to connecting two capacitors in series. The smaller capacitor controls the total capacitance. The actual situation is similar to Figure 2c, representing particles of ceramic and air. When the ceramic grains are not spherical, then the higher dielectric constant dominates for electric field parallel to the length of the grains and the lower dielectric constant dominates for electric field parallel to the shorter grain dimensions. Thus any ceramic that has non-spherical grains will have grains tending to be preferentially oriented and is necessarily anisotropic even if the grains themselves might be perfectly isotropic.

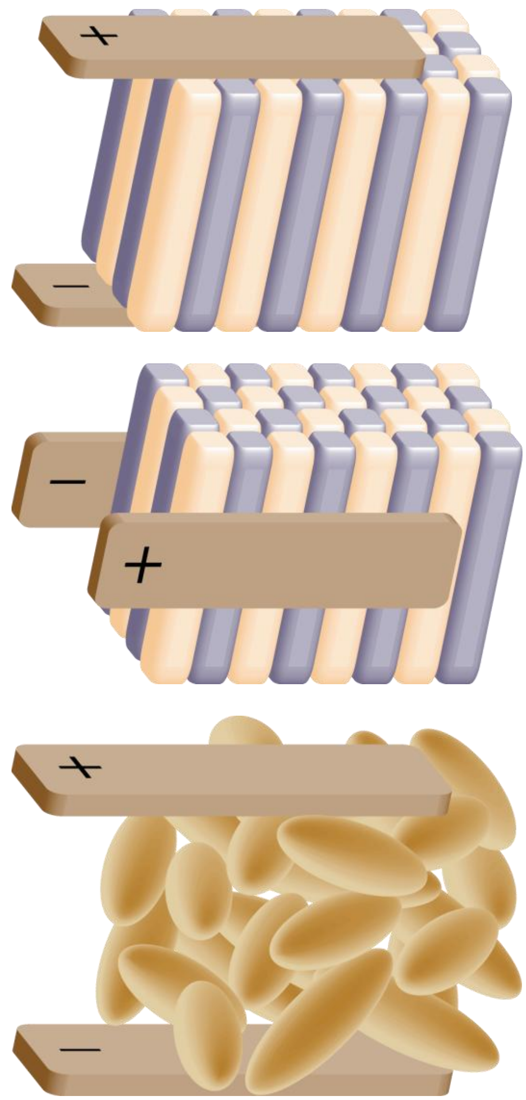

Figure 2. For (a), top, the dark, high dielectric substrate components dominate the capacitance, like capacitors in parallel. For (b), middle, the light colored, low dielectric substrate material dominates, like capacitors in series. Ceramics are like (c), bottom, where non-spherical grains cause anisotropy.

Not only are most ceramics anisotropic, composite substrates are anisotropic too. Composite substrates are formed of at least two different materials, for example PTFE and glass fiber. The reason for two materials is so that the substrate temperature coefficient matches that of the copper foil cladding. The two materials are selected for strength and durability. Each of the materials has a different temperature coefficient and they are mixed and formed so that the net temperature coefficient matches copper. The substrate dielectric constant then also becomes a weighted average of that of the two materials, which is also necessarily anisotropic for the same reason that ceramics are anisotropic, as described above.

How about semiconductors? Some common microwave RFIC semiconductors are anisotropic. Yet they are designed as if they were isotropic. With so much time and money at stake (cost of failure is very high) why do we do this? Because we do not know the numbers for the semiconductor anisotropy. At least now we can measure them. Once measured, we can then completely remove the anisotropy failure risk from the planar design cycle.

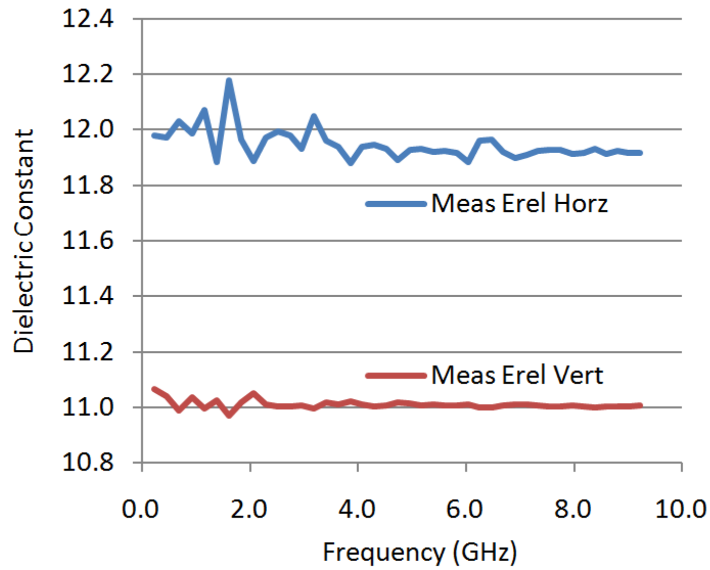

Figure 3. Measured vertical and horizontal anisotropic dielectric constants for Rogers RO3010 material. From [5].

Just Tell Me the Answer!

So now we know most substrate materials are anisotropic, and we can even do our EM analyses including the effect of anisotropy. What's missing? Measurements of anisotropy. There are many ways to measure anisotropic dielectric constants and most of them require substantial effort. The technique we have developed [3] – [6] requires initial setup effort and sample preparation. Once this is done, measurements may be taken and reduced to anisotropic dielectric constants repeatedly and quickly.

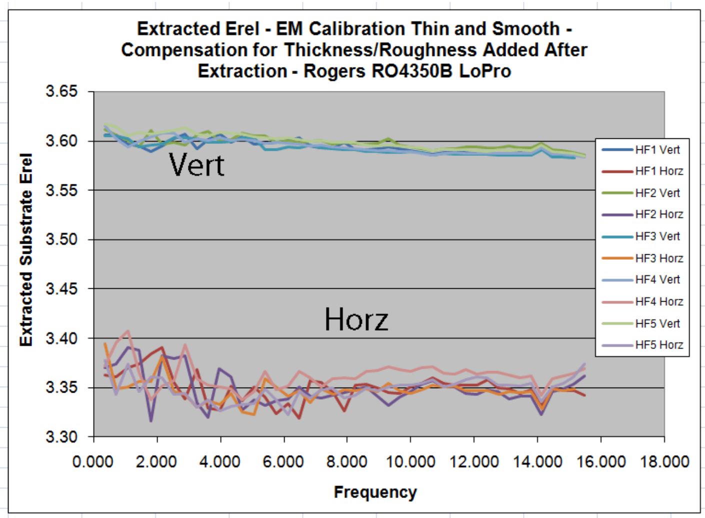

Figure 4. Extracted dielectric constants for Rogers RO4350B clad with low profile ("LoPro") copper foil shows about 7% anisotropy.

Let's start with results. If you are interested in FR-4, check out [3]. Figure 3 above shows results for one sample of Rogers RO3010, a ceramic loaded PTFE substrate up to 10 GHz. Figure 4 shows results for five samples of Rogers RO4350B, a ceramic and fiber glass weave loaded substrate.

It was expected that the horizontal dielectric constant would be higher than the vertical dielectric constant. For Rogers RO3010, that is indeed the case. RO3010 has no fiber glass weave, it is purely ceramic loaded. In contrast, RO4350B also contains a fiber glass weave. Bulk measurement suggests that the horizontal dielectric constant should be higher in this case as well. But we see in Figure 4 that it is lower.

The results of Figures 3 and 4 are obtained by measuring the resonant frequency of very long microstrip resonators. The reason Figure 4 shows a horizontal dielectric constant lower than the vertical constant is exactly because we used a microstrip resonator. The microstrip resonator concentrates electric field in the surface of the substrate where there is no fiber glass weave, just the lower dielectric constant epoxy. Thus, if you were to build a structure that excites horizontal electric field through the entire thickness of the substrate, you should use a high horizontal dielectric constant. However, if you wish to build microstrip circuits, you should use the dielectric constant that we measured by means of microstrip resonators, Figure 4.

Getting Lots of Data

One might wonder how we measure the dielectric constants at so many frequencies. Generally, resonator techniques obtain the dielectric constant at one frequency. For multiple frequencies, multiple resonators must be fabricated. Not so for this technique. We simply build a one very long resonator and we use multiple higher order resonances to measure the dielectric constant at multiple frequencies. For the RO4350B case, the resonator is 10 inches long and we measure about 50 even/odd mode resonance pairs for vertical/horizontal dielectric constant determinations at about 50 frequencies.

We use EM analysis to determine how even/odd mode resonant frequencies map into the underlying vertical/horizontal dielectric constants. Be advised that extreme accuracy for the EM analysis is absolutely critical for success in this effort. For example, the EM analysis program should be able to predict the 50^{th} resonance of a long resonator to within a few tens of kHz at 15 GHz. We think it is unlikely that any other EM analysis program can achieve the required accuracy over such a broad bandwidth.

To check our result, we took the dielectric constants that were extracted from the measurements and calculated the expected response for the resonator. Measured versus calculated is shown in Fig. 5. We show only the highest few resonances, it would be impossible to see any differences between measured and calculated if we were to show the entire frequency range. The agreement is even better at lower frequencies.

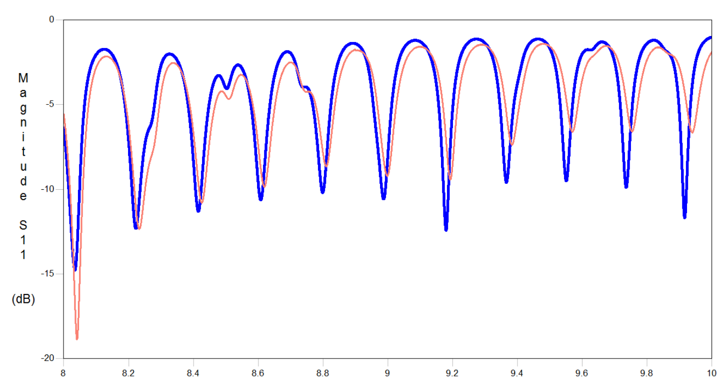

Figure 5. Measured (thin line) vs. Calculated (thick line) for 8 – 10 GHz of the nearly 25 wavelength long resonator. Calculated used the anisotropic dielectric constants extracted from the measurement. From [5].

Conclusion

Substrate anisotropy can now be accurately measured and included in our planar circuit design flow. This completely eliminates one of the few remaining major design failure risks and uncertainties, even for tight design requirements. Having to pretend that our substrates are isotropic is history.

References

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Note: A portion of this paper is based on, "Direction Matters -- Including substrate anisotropy in your planar circuit design flow," published in the February Microwave Journal, abstracted with permission.