# The Effect of Dielectric Anisotropy and Metal Surface Roughness

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***Abstract* — We provide an overview of recently published research on the effect of planar substrate dielectric anisotropy and metal surface roughness. The effect of metal roughness on loss is shown to be substantially different from that predicted by commonly used models. Roughness has also been shown to have a substantial effect on velocity of propagation/effective dielectric constant due to the introduction of substantial surface inductance, far in excess of that predicted by smooth surface skin effect. We also explore a recent technique for quickly and easily measuring the dielectric constants of a uniaxially anisotropic planar substrate. Analysis of substrates using the generally incorrect assumption of isotropy can now be avoided.**

***Index Terms* — Anisotropic media, conductivity, crosstalk, dielectric measurements, electromagnetic analysis, microstrip, transmission line resonators.**

## I. Introduction

Isotropic dielectric is defined as having the same dielectric constant for all electric field, regardless of the electric field direction. Anisotropic dielectric has a dielectric constant that depends on the direction of the electric field. In this paper, we consider uniaxial anisotropy, which has one dielectric constant for vertical (perpendicular to the substrate surface) electric field and a second dielectric constant for horizontal (parallel to the substrate surface) electric field.

In present day mainstream planar microwave design methodology, dielectric substrates are assumed to be isotropic. This is because there were no planar electromagnetic (EM) tools that could include anisotropy and also because accurate values for anisotropy were typically not available. We have recently published details of a new method to easily measure uniaxial anisotropic dielectric constants [1] and we have added the capability to analyze uniaxial anisotropy to a commercial planar EM tool [2].

In addition, most of today's microwave design tools use a model of surface roughness based on an approach originally developed in the 1940's [3], recently modified [4]. We have found these models to be seriously deficient based on extensive experimental evidence [5], [6], consistent with other recent analytical, numerical, and experimental research [7], [8]. In response, we have developed a model that matches experimental data well and is based on a substantial excess inductance that is caused by the roughness.

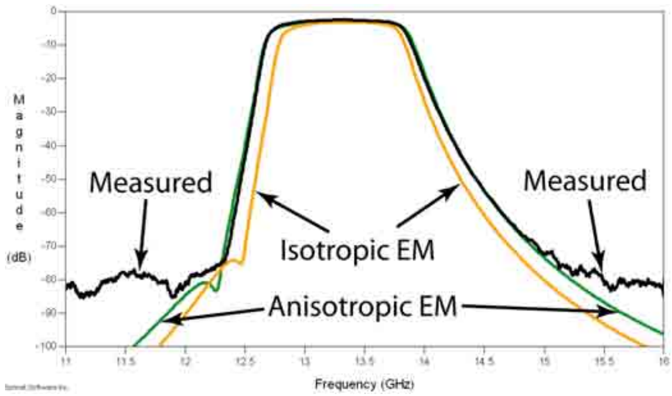


Fig. 1. When an anisotropic substrate is modeled using an isotropic dielectric constant selected to give the right center frequency necessarily yields the wrong bandwidth. From [9].

We summarize recently published results on the effects of anisotropy and metal surface roughness below.

## II. The Effect of Anisotropy

Fig. 1 illustrates the effect of anisotropy on filters. A filter based on coupled lines requires precise analysis of both even and odd coupled line modes. The even mode has positive voltage on both lines. The odd mode has positive voltage on one line and negative voltage on the other. Thus, much of the odd mode electric field goes horizontally from one line to the other. The even mode electric field starts at the lines and goes down to ground. The even mode has more vertical electric field. The odd mode has more horizontal electric field. The odd mode, with more horizontal electric field, determines the resonator coupling, and thus determines the filter bandwidth.

For a simple illustration, we assume that the vertical dielectric constant determines the filter center frequency (by means of the even mode) and the horizontal dielectric constant determines the bandwidth (by means of the odd mode). If a designer is forced to EM analyze with only one (isotropic) dielectric constant, he might select the vertical dielectric constant. Because he is forced to assume isotropy, he must make the horizontal dielectric constant the same as the vertical dielectric constant. He is forced to use the wrong horizontal dielectric constant.

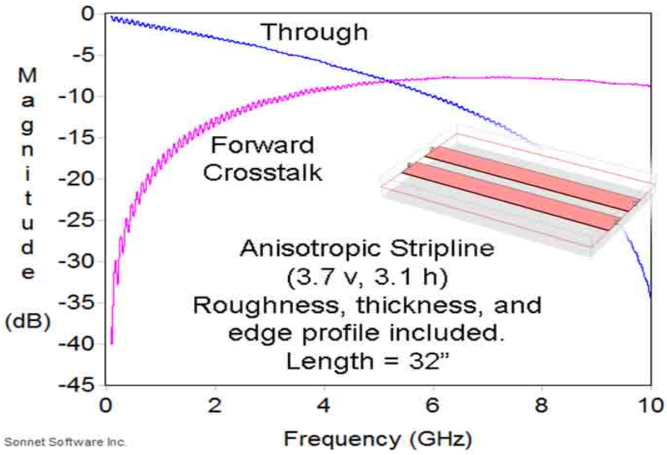


Fig. 2. Anisotropy in a stripline substrate forces the even and odd mode velocities to be different. This destroys high speed digital signal integrity at high frequencies.

Because the vertical dielectric constant is correct, the EM analysis calculates the correct filter center frequency. However, the horizontal dielectric constant, which determines bandwidth, is wrong. If the true horizontal dielectric constant is higher than the vertical, then the measured bandwidth is larger than the EM calculated bandwidth, as in Fig. 1.

In the actual situation, both vertical and horizontal dielectric constants affect both center frequency and bandwidth, but to different degrees. The result is still similar to the above illustration.

Anisotropy also has a strong effect on signal integrity. Fig. 2 shows EM analysis of a pair of high speed digital transmission lines nearly one meter long (a 2.54 cm long section is shown in the figure). For high speed digital, it is critical to keep the even and odd mode velocities exactly the same. For that reason, long digital busses use stripline. Even with ideal isotropic substrates, the even and odd mode velocities of microstrip are significantly different. Different even and odd velocities completely destroy the signal integrity of a high speed digital bus.

For Fig. 2, we plot "Forward Crosstalk". In this case a signal is applied to the input of one of two lines. The desired output ("Through") is taken from the far end of the same line. "Forward Crosstalk" is the far end output of the second line.

Ideally, we would like forward crosstalk to be zero (minus infinity dB). If we assume the substrate is isotropic (result not shown here), the forward crosstalk is about 20 dB below the through line output at 10 GHz. However, when we include anisotropy (Fig. 2), the desired through line output goes down to nothing and the forward crosstalk dominates.

This failure is because the even and odd modes have different amounts of vertical and horizontal electric fields. The vertical and horizontal electric fields experience different dielectric constants. Thus the even and odd modes have different velocities, and the signal integrity of the high speed bus is destroyed.

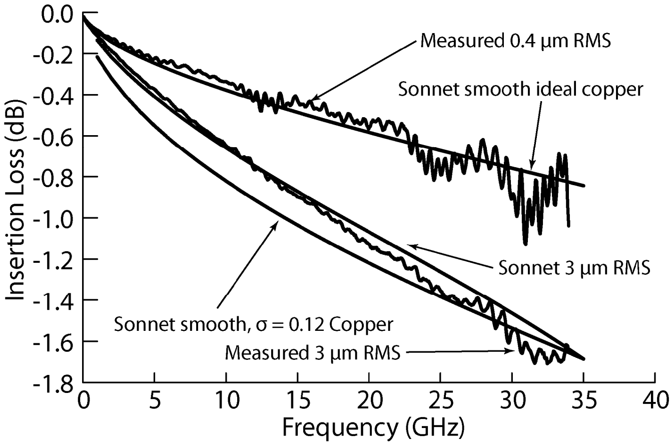


Fig. 3. Sonnet smooth and rough metal loss analysis compared to measurement. Approximating roughness loss by decreasing conductivity is unsatisfactory. From [6].

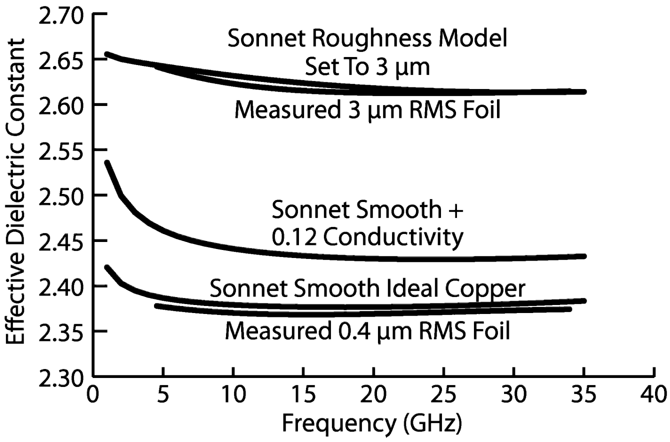


Fig. 4. Sonnet smooth and rough metal analysis compared to measurement of effective dielectric constant. Approximation by decreasing conductivity is unsatisfactory. From [6].

## III. The Effect Of Metal Surface Roughness

Metal loss increases loss and increases the series inductance of a transmission line even when the metal surface is smooth [10]. When the surface of the metal is rough, both loss and series inductance increase even more. Fig. 3 shows how loss increases due to roughness. The low loss curves are measured and EM calculated loss for smooth metal. The high loss curves are for rough metal. Approximating roughness loss by decreasing the metal bulk conductivity is unsatisfactory.

Fig. 4 shows measured and calculated results for the microstrip effective dielectric constant. The effective dielectric constant was calculated from measurements of transmission phase for a 50 Ohm line. The transmission phase is determined by the percentage of electric field in the air, the amount in the dielectric, and by the extra series inductance due to current flowing over the rough surface of the metal. Again, approximation by decreasing the metal bulk conductivity is unsatisfactory.

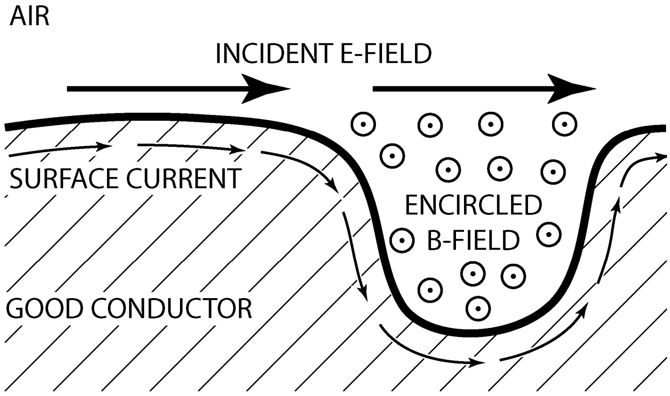


Fig. 5. Roughness inductance is caused by the loop of current in the rough metal forming a one-turn inductor excited by the incident E-field. From [6].

Typical roughness for most electro-deposited ("ED") foils is about 3 microns RMS. The effect of roughness is strongest for thin substrates. The substrate used for the measurements of Fig. 3 and 4 is 100 microns (0.004") thick. Roughness increases the measured effective dielectric constant by about 15% for this substrate.

The reason for this large increase is shown in Fig. 5. We show roughness as a "valley" in the metal surface. The loop of current flowing down one side of the valley and up the other side forms one loop of an inductor. The electric field, connecting the tops of the valley forms the voltage source exciting the one turn inductor. All the magnetic field surrounded by this loop increases the surface inductance.

Fig. 5 is a simplification of actual roughness. The roughness shown is a smooth roughness. In reality, roughness is fractal, or multi-scale. In other words, if we magnify the roughness, it still looks rough. This rough roughness increases the inductance even more.

Existing models of roughness tend to provide acceptable answers at low frequency, but they substantially underestimate loss at high frequency. In addition, they do not include the excess inductance effect at all, completely failing to show any influence on effective dielectric constant at all. Rogers and Sonnet have worked together over the past 18 months to develop a sophisticated roughness model based on extensive experimental data. The agreement between measured and calculated results in Fig. 3 and 4 are typical. The models are verified with measured data as a function of frequency, substrate thickness, and RMS roughness.

## IV. Measurement of Anisotropy

Dielectric constant can be measured by fabricating a resonator, for example [12]. Then, by comparing the measured resonant frequency against the EM calculated resonant frequency (with proper consideration for all possible error sources in the EM calculation), we can extract the dielectric constant from the measured resonant frequency.

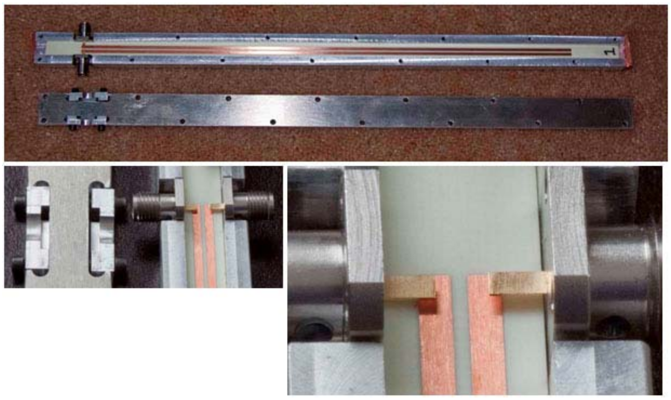

Fig. 6. The dual mode microstrip resonator. It is about 25 wavelengths long at 16 GHz. From [11].

Measurement of dielectric constant using resonators limits results to only resonant frequencies. To obtain measurement at a large number of frequencies, we use a large resonator, which has many resonant frequencies. Our typical results are obtained from microstrip resonators about 25 wavelengths long. There is a resonance every half wavelength. Thus, we obtain measurement of dielectric constant at about 50 frequencies.

For normal (single mode) resonators, it is not possible to determine anisotropy. For that reason, we use dual mode microstrip resonators. A single mode microstrip resonator is formed from a length of microstrip line. A dual mode microstrip resonator is formed from a length of coupled microstrip line, Fig. 6. This is called an "RA" resonator, named after the initials of the authors, [1].

The theory for converting coupled line microstrip resonator resonant frequencies to anisotropic dielectric constants is detailed in [1]. The process has been fully automated. One merely takes the measurement of the resonator and pushes a button on a spread sheet. A pair of vertical/horizontal dielectric constants is extracted from every pair of even/odd mode resonances.

Typical results for several dielectric substrate materials are shown in Fig. 7 and 8. Note that Rogers RO3010 has the horizontal dielectric constant higher than the vertical. We find this is typical for ceramics and for substrates that have no reinforcing fiber glass weave laminate. In contrast, Rogers 4350B, with an embedded fiber glass weave, has the horizontal dielectric constant lower. This is in direct contradiction of microwave resonator cavity measurements. We have found that this is because microstrip resonators impress horizontal electric field mainly on the surface of the substrate, where there is little fiber glass weave. Microwave cavity resonators impress horizontal electric field through the entire thickness of the substrate. Thus, when the final application of a glass fiber weave reinforced substrate is microstrip circuitry, one should use dielectric constants measured using microstrip resonators. Dielectric constant measured using microwave resonant cavities should not be

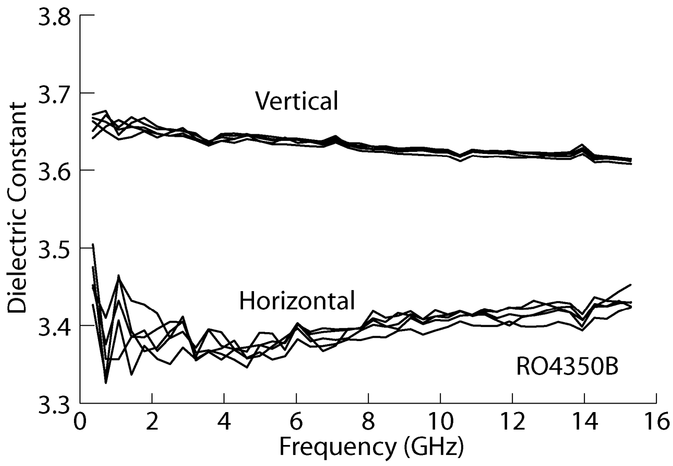


Fig. 7. Measured anisotropic dielectric constant for five samples of Rogers RO4353B. The substrate includes a glass fiber weave, and the horizontal dielectric constant is lower. Measurements of five substrates shown. From [11].

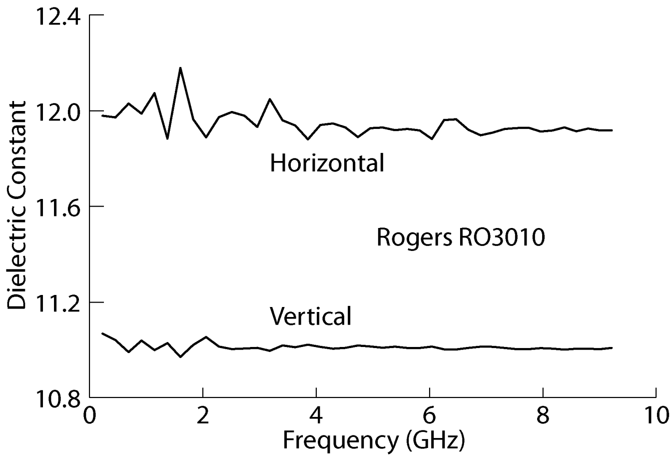


Fig. 8. Measured anisotropic dielectric constant for Rogers RO3010. The substrate has no glass fiber weave and horizontal dielectric constant is higher than vertical. From [11].

used. However, if the final application of such a substrate results in horizontal electric field impressed through the entire thickness of the substrate (for example, a radome), then microstrip resonator measurements should not be used. Instead, the microwave resonator cavity measurement [12] is appropriate.

The basic problem is that we are modeling a substrate that is really inhomogeneous as though it were homogeneous and anisotropic. An alternative model, which requires more complexity, is to model the substrate as two thin homogeneous isotropic substrates on either side of a thick anisotropic substrate that models the glass fiber region.

When a substrate is homogeneous on a macro scale, like the ceramic loaded Rogers RO3010 (no fiber glass weave), then both measurement microstrip resonator and microwave cavity resonator techniques should, and do, give essentially the same answer.

## V. Conclusion

Over the last 18 months, we have developed an extensive capability for measuring and EM analyzing the effect of substrate anisotropy. A common discrepancy seen when EM analysis incorrectly assumes an isotropic substrate is that the center frequency of a band pass filter is correctly determined, however the bandwidth is wrong. Anisotropy for several substrates have been measured and reported, with distinctly different characteristics depending on whether or not the substrate includes a glass fiber weave. We have also developed an accurate, broadband metal surface roughness model based on extensive measurements. Roughness adds both loss and series inductance, changing effective dielectric constant by up to 15% over smooth metal. Partial results have been published in a wide variety of papers. This paper provides a unified summary overview of those results.

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