A New Perspective on Quasi-TEM Behavior in Microstrip Transmission Lines

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***Abstract*—This paper introduces a new perspective on how quasi-TEM propagation on microstrip transmission lines can impact the microstrip-based dielectric constant measurements, crosstalk, and return loss.**

***Index Terms*—Quasi-TEM, Microstrip, Effective Dielectric Constant, Crosstalk**

I. INTRODUCTION

Microstrip circuits are widely used in digital and RF circuitry. Many low-cost commercial applications use microstrip transmission lines to transmit data because of their ease of use and low manufacturing costs. Two-layer Printed Circuit Boards (PCBs) are often used to reduce the footprint, reduce cost, and ease the manufacturability of the product. Microstrip architecture is often chosen for commercial products. However, for products needing high-speed designs, where signal integrity is critical, a stripline architecture is typically chosen over microstrip architecture. Stripline architecture is usually chosen because of the perceived impact of lower emissions and TEM propagation. In fact, wave propagation on microstrip is not precisely Transverse ElectroMagnetic (TEM), but Quasi-TEM. The Quasi TEM propagation results from the in-homogeneous dielectric wrapping around the microstrip with air above the microstrip trace as shown in Fig. 1.

Fig. 1. Cross-section view of (a) microstrip and (b) Stripline.

Since the material above and below the trace is not the same, the electric and magnetic fields are never truly absent in the direction of propagation. At lower frequencies, the magnitude of the field in the direction of propagation is so small that we consider them to be of no consequence and approximate the propagation to be TEM-like or quasi-TEM.

This quasi-TEM behavior of microstrip structures has been studied computationally to show its impact on losses and dispersion [1] [2]. This paper provides a new perspective to view the relationship between the geometry of the microstrip and the non-TEM nature of the fields propagating on the line. This perspective focuses on the impact of the field distribution on dielectric constant measurements, far-end crosstalk, and the return loss of transmission lines. We also compare empirical formulae, measurements, and simulations to validate the data.

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II. THE IMPACT OF GEOMETRY ON WAVE PROPAGATION

Figure 1 illustrates the physical differences between a microstrip and a stripline. A microstrip cannot support TEM propagation, primarily because of the boundary between the air and the dielectric [3]. Figure 2 shows the field distribution for a microstrip.

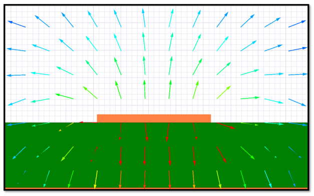


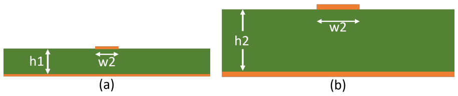
Fig. 2. Field distribution in a microstrip transmission line.

Since some fields are present in the air and some in the dielectric, we use an effective dielectric constant to capture the impact of both dielectric constants (ε_r and ε_0). A signal propagating down a microstrip line will travel at a velocity that corresponds to this effective dielectric constant.

III. OBSERVING FIELDS IN THE CROSS-SECTION

It has been shown that the charge density on a microstrip line changes with frequency. This change in charge density in the signal conductor leads to a change in the field distribution around the trace [1] [2] [3]. This change in electric field distribution can be observed in great detail using a Finite Element Method (FEM) solver such as Ansys HFSS.

As we describe in the next section, the frequency at which the quasi-TEM breakdown begins scales with the dielectric thickness. To illustrate the impact of non-TEM behavior, two different thickness microstrip lines with the same aspect ratios are compared. These are shown in Fig 3. The thinner board has a dielectric height (h1) of 10 mils and a trace width (w1) of 20 mils. The thicker board has a dielectric height (h2) of 60 mils and a trace width (w2) of 120 mils.



(a) (b)

Fig. 3. Two structures with the same aspect ratio but different dielectric heights.

The above two dielectric heights have been chosen such that the thicker board will show non-TEM dispersion above 2.5 GHz but the thinner board will not show it till 17 GHz. The estimations were performed using (4). Figure 4 shows the field distribution at different frequencies for a 50-ohm line designed with the thicker board.

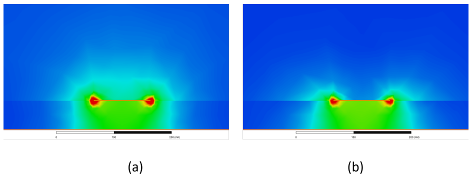

(a) (b)

Fig. 4. Field distribution in the cross-section of a microstrip transmission line at (a) a frequency of 1GHz, and at (b) a frequency of 20GHz.

It is seen that the field distribution becomes more concentrated in the dielectric under the trace as the frequency increases. At higher frequencies, this means the effective dielectric constant can not be predicted by a frequency-independent equation like Hammerstad [4]. Adding solder mask to this geometry will make this effect slightly less apparent due to less in-homogeneity but will still show very similar behavior.

IV. EXTRACTING THE EFFECTIVE DIELECTRIC CONSTANT

The phase of the S(2,1) of a transmission line can be used to extract its time delay as shown in (1).

$$TD = -\frac{\phi(S_{21})_{in\ degrees}}{360 \times f} \tag{1}$$

If L is the length of the line, and TD is the time delay, the effective dielectric constant can be calculated as (2).

$$\varepsilon_{\ eff} = \left(\frac{c_{\ vacuum}\ \times\ TD}{L}\right)^2 \tag{2}$$

Figure 5 shows the extracted effective dielectric constant of a measured transmission line using (2).

A. Quasi TEM Breakdown in Microstrip

Dispersion is a phenomenon when a signal's velocity changes with frequency. This is seen in lossy systems when the speed of an electromagnetic wave increases with frequency [5]. A similar effect happens in lossless microstrip structures, where the speed of an electromagnetic wave can start to decrease with an increase in frequency. This is clearly illustrated in Fig. 6 where the simulated time delay for a lossless microstrip transmission line is simulated using HFSS 3D.

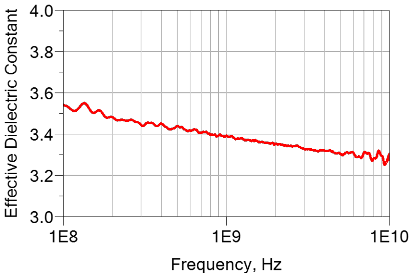


Fig. 5. Measured effective dielectric constant of a lossy microstrip line with an FR4 substrate

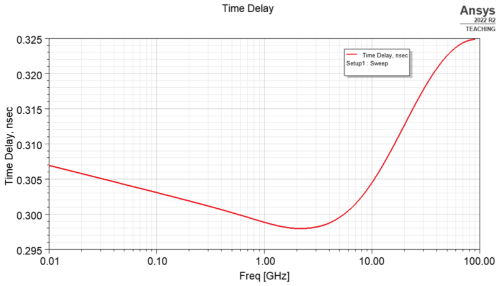


Fig. 6. Dispersion in a 2 inch long, 60 mil thick dielectric, 120 mil wide microstrip line with an ε_r of 4.6 shown with time delay.

This effect has been explored and models for predicting the phase velocity have been proposed using numerical analysis of the current distribution on the line [1] [2] [6]. The non-TEM behavior is inherently electromagnetic in nature and cannot be simulated with a quasi-static field solver which solves the electric fields and magnetic fields separately. Figure 7 shows the differences between a quasi-static 2D simulation and a full-wave 3D simulation of a microstrip line with a 60 mil thick dielectric.

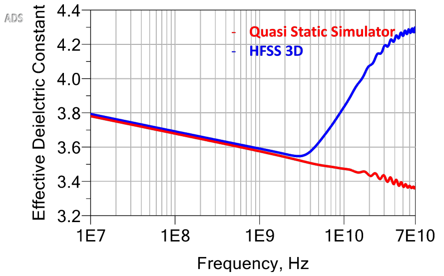


Fig. 7. Comparison of the effective dielectric constant of the same microstrip line with an ε_r of 4.6 in HFSS and a quasi-static simulation.

The extracted effective dielectric constant clearly shows the impact of non-TEM dispersion in the full-wave simulation which is missing in the quasi-static case. Schneider provides an approximation to estimate when the quasi-TEM approximation begins to break down. In Schneider's approximations to define the Quasi-TEM breakdown, a cutoff frequency, f_c, is defined in (3). This is the cutoff for the first TE mode of the dielectric slab.

$$f_c = \frac{c_0}{4h\sqrt{\varepsilon_r - 1}} \tag{3}$$

From our work [7], we propose a 1/10 factor to Schneider's cutoff frequency, where the phase distortion appears at f_{lim}. This results in a rule of thumb, in (4), that identifies the onset from the impact of Quasi-TEM breakdown.

$$h(inches) \leq \frac{0.295(inches/nsec)}{f_{lim}(GHz) \times \sqrt{\varepsilon_r - 1}} \tag{4}$$

A comparison of measurement, HFSS full-wave simulation, and Schneider's approximation is shown in Fig. 8

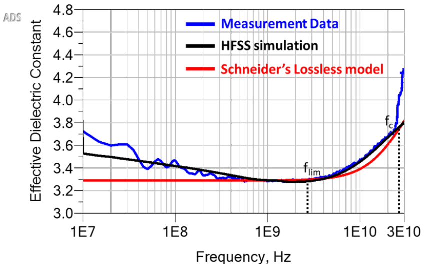


Fig. 8. Comparison of the measured and HFSS simulation of the effective dielectric constant of a microstrip in FR4.

When using a microstrip to extract the bulk dielectric properties of a Printed Circuit Board (PCB), care should be taken to be below this limiting frequency shown in (4).

V. MORE CONSEQUENCES OF FIELD DISTRIBUTION

Non-TEM dispersion is a very important phenomenon when performing material characterization using microstrip traces. This may lead one to believe that quasi-TEM limits only apply to the phase velocity, but redistribution in fields will also impact other microstrip behaviors.

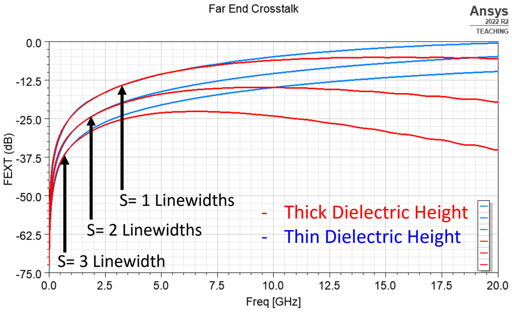


Fig. 9. Comparison of FEXT in two cases with different dielectric heights.

Figure 4 shows the field distribution in microstrip changing with frequency. This redistribution should also affect the coupling between traces. The non-TEM behavior should reduce the cross-talk at higher frequencies. The thin microstrip acts as a reference which does not show quasi-TEM breakdown until after 17 GHz. The impact is most evident in the Far End Crosstalk (FEXT) between two microstrip transmission lines with a separation equal to a multiple of their linewidth as seen in Fig.9. It is observed that the FEXT is the same for thin and thick microstrips at lower frequencies. At higher frequencies, the non-TEM behavior reduces FEXT. The FEXT in weakly coupled microstrip is more sensitive to the field re-distribution from the non-TEM behavior and diverges at a lower frequency.

A change in field distribution also results in a change in impedance, which can first be seen in the reflected signal S(1,1) in Fig.10.

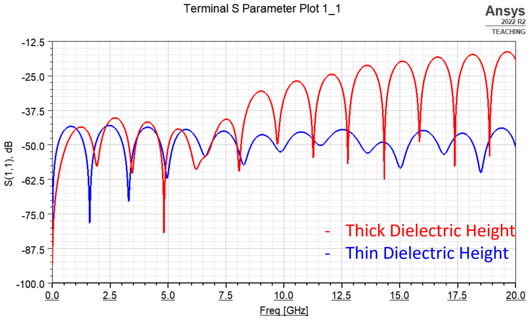


Fig. 10. Comparison of S-parameters in two structures with different dielectric heights.

VI. CONCLUSION

This paper describes how the limits of quasi-TEM propagation can impact measurements and simulations performed with a microstrip transmission line. Measurement-simulation correlation is used to propose and validate a rule of thumb to predict and identify the breakdown of the quasi-TEM approximation when using microstrip lines.

Future work on this topic includes obtaining measurement-simulation correlation for crosstalk, reflections and impedance.

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