

# Improving Simulation Accuracy of Printed Antennas via Frequency-Dependent Permittivity Adjustment

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**Abstract**—Significant discrepancies between the simulated and measured resonant frequencies in printed antennas often originate from over-simplified dielectric modeling. We present a validation strategy based on the frequency-dependent adjustment of the real part of the relative permittivity  $\varepsilon_r(f)$ , motivated by the discrepancies between the simulated and measured return loss. We present V.N.A measurements for the return loss of micro-strip patch antennas printed on PCB and explain some details of the finite element simulations. The commercial platform employed, the materials and the boundary conditions, particularly, the implementation of a frequency-dependent permittivity function. We discuss the implications and validity of the present approach and finally show the agreement between the predicted and measured return loss in a broad frequency range. Based on the comparison between the experiment and the simulations, we discuss the limitations of the present approach and the perspective of continuation

**Index Terms**—micro-strip antenna, permittivity adjustment, simulation validation.

## I. INTRODUCTION: FREQUENCY DEPENDENT PERMITTIVITY

The design and fabrication of a multiband antenna from a printed PCB is a very challenging task. Since these type of antennas demands a sufficiently low reflection coefficient in one, two, or even three different carrier frequencies and their respective bandwidths. It is usually required return loss levels about  $-15$ , or even  $-20$  dB in different portions of the spectrum. Electromagnetic simulation software platforms are used daily for antenna design and evaluation. For return loss assessment two different methods are employed. The one (CST for instance) is modal analysis plus some loss model, that is, the auto frequencies of the system are calculated near the design frequency. One is then required to decide beforehand which and how many eigen frequencies to model. The other method (COMSOL Multiphysics) is to solve a time independent Helmholtz equation and to do a frequency sweep with an adaptive step solver. The second method can be considered as a forced resonances study, while the first resembles more natural oscillations. When electromagnetic simulation software is employed to assess on the port properties, it can be frustrating to observe that experimental return loss vs. frequency curves resemble the simulated ones in trend but fail to accurately predict the resonant frequencies and the quality factor of the peaks. Since two different simulation methods are invoked, it is of interest to investigate whether the origins of this discrepancies lies on the calculation method or

somewhere else, like for instance, a more accurate modeling of the dielectric dispersion function.

The study of dielectric permittivity in microwave substrates is essential for accurate antenna design. Coonrod[1] analyzed the variables affecting effective permittivity in PCB materials, and extended the explanation with Horn in [1], including practical simulation implications. It is well established that the real part of the permittivity in dielectric materials begins to gradually decrease from its static (DC) value as frequency enters the GHz range. This trend is often followed by subtle oscillations or transitions, typically associated with the onset of dielectric losses. Beyond this region, tends to stabilize at a lower level until a new transition may occur at higher frequencies. The specific physical mechanisms responsible for this behavior are strongly influenced by fabrication processes and micro-structural features, and are therefore considered extrinsic properties of the material. Prokopidis and Tsiboukis [2] demonstrated that substrate dispersion significantly affects the operating frequency of printed antennas.

Recently, Gluzman et al. [3] experimentally evaluated how changes in dielectric parameters—through the addition of material—affect resonance behavior. Their findings support incorporating frequency-dependent permittivity profiles to improve simulation agreement, especially below about 6 GHz, where losses are limited.

These contributions are central to justifying modeling adjustments in our current research and enhancing prediction fidelity for printed structures. Prior literature confirms the relevance of dispersion-aware modeling. This insight enables more accurate design iterations in RF systems using low-loss substrates.

## II. ANTENNA FABRICATION AND RETURN LOSS MEASUREMENTS

The micro strip patch antennas were manufactured by machining in a CNC a copper cladding covered dielectric plate made of Teflon. For this validation work, we used Rogers Corporation plates with a copper layer on both sides. We used different plates from this source, although the work presented here is performed exclusively on Duroid 6002. Further characterization will be published later. For this particular plate, Rogers Corporation reports a dielectric constant (real part) of ( $\varepsilon_r = 2.94$ ) and for this material, COMSOL Multiphysics

materials library reports in addition a Tangent Losses of 0.012. Both are reported constant, i.e., not a function of frequency.

Return loss measurements were performed using a Rhode & Schwarz ZVH8 vector network analyzer, with calibration procedures following a Full 2-Port High Accuracy protocol and a Rohde & Schwarz ZN-Z170 calibration kit. This kind of calibration was mandatory in our case since we noticed that using a quick calibration procedure instead introduced small spurious excursions into -non sense- positive values of the return loss at low frequencies. In other words, for validation against the simulated return loss, the best possible measurements are needed.

Initial measurements showed significant deviations between the simulated and measured resonance frequencies, even when the manufacturer-specified dielectric constant ( $\epsilon_r = 2.94$ ) was used. This motivated a frequency-dependent correction approach, as previous literature [1], [4] has highlighted the limitations of constant-permittivity assumptions for broadband applications.

### III. SIMULATION APPROACH

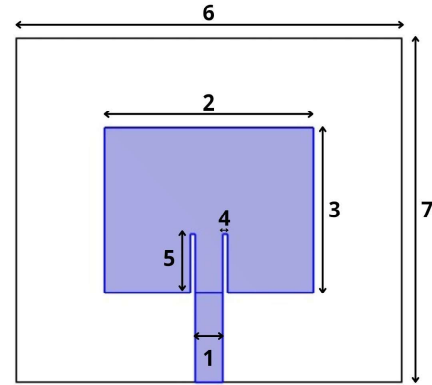
COMSOL Multiphysics 6.2, a finite element-based multiphysics software was used for simulation and validation. The RF module solves Maxwell's equations in the frequency domain by transforming the inhomogeneous wave equation into a Helmholtz equation. Thus, we convert the space-time partial differential equation into a purely spatial one for each frequency of the source term. This technique is an alternative to modal analysis, which is also possible in COMSOL. It allows the use of powerful static solvers like PARDISE using a step solver in the frequency domain. In addition, it provides an adaptive step frequency sweep that considerably reduces the calculation time. The S parameters are obtained from a lumped port from the field amplitude distributions by space integration. COMSOL allows for the direct definition of  $\epsilon_r(f)$  via interpolation functions, providing flexibility for validation purposes.

Two rectangular patch antennas on Rogers RT/duroid 6002 were modeled: a baseline geometry (first geometry) and a modified version for predictive testing (second geometry). The latter included changes in patch and feed dimensions to shift the resonant frequency. Metallic regions were set as perfect electric conductors (PEC), and the surrounding space was bounded by radiation conditions. A lumped port was defined at the feeding point and an adaptive frequency sweep was performed from 3 GHz to 8 GHz.

The dielectric properties of the substrate material were defined in two stages: first with a constant  $\epsilon_r = 2.94$  (datasheet value), and then with a fitted curve  $\epsilon_r(f)$  obtained by inverse modeling from experimental Return Loss data. This procedure enabled improved alignment between simulated and measured resonances, demonstrating the predictive value of the frequency-dependent model. For all simulations a Tangent Loss of 0.012 was employed



First geometry Patch Antenna



Dimensions in Table 1

First Geometry Patch Antenna		
Number	Name	Expression
1	w_line	4 [mm]
2	w_patch	30.3 [mm]
3	l_patch	24 [mm]
4	w_stub	0.7 [mm]
5	l_stub	8.5 [mm]
6	w_sub	56 [mm]
7	l_sub	50 [mm]

Table I: Dimensions of the First Geometry, the names: line, patch, sub and stub refer to the feeding line, the metallic patch, the dielectric substrate, and the notch that separates the feeding line from the patch respectively. W stands for width and L for length

Second Geometry Patch Antenna		
Number	Name	Expression
1	w_line	4 [mm]
2	w_patch	22.7 [mm]
3	l_patch	16.2 [mm]
4	w_stub	0.7 [mm]
5	l_stub	4 [mm]
6	w_sub	42 [mm]
7	l_sub	35.5 [mm]

Table II: Dimentions of the Second Geometry fabricated on the same Rogers Plate as the First Geometry

Function name: epsilonPrim_iso_interp	
t	f(t)
1e9	2.94
3.57e9	2.5
5.18e9	2.5
6.64e9	2.4
7.38e9	2.3

Table III: Values of the real part of the permittivity as function of frequency used for the adjustment. The polinomis interpolation can be seen in Figure 2

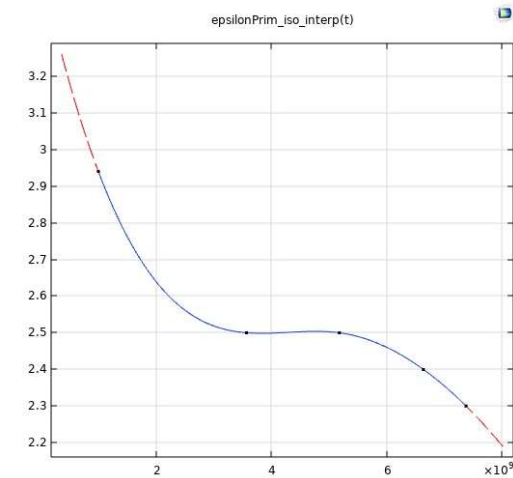


Figure 1: Polynomial interpolation of the values in Table III. This interpolation is used by the step solver to define the value of the permittivity at each frequency

#### IV. OUTLINE OF THE DESIGN METHOD BASED ON SIMULATION

The key insight guiding this work is that the discrepancies in resonance frequency prediction can be mitigated by tuning the dielectric constant as a function of frequency.

An inverse approach was employed: we iteratively adjusted the real part of  $\epsilon_r(f)$  until the simulated resonance frequencies matched the experimental ones for the First Geometry patch antenna (Table I). Once a satisfactory fit was achieved, this  $\epsilon_r(f)$  curve (Figure 1) was applied to a Second Geometry (Table II).

This allowed us to assess whether the tuned permittivity profile preserved its predictive power. As will be discussed in the results section, the strategy proved successful for the first resonance, while deviations were observed above 6 GHz, suggesting additional loss mechanisms (e.g., dielectric dispersion and/or conductor loss) not yet modeled. It is important to remark that the  $\epsilon_r(f)$  curve obtained through our adjustment process should not be regarded as an inverse measurement of the actual dielectric function. Instead, it represents a modeling tool inherently tied to the simulation platform and the chosen computational scheme. Its purpose is to enable predictive simulations with minimal iterations when designing antennas on a given substrate. Nevertheless, the fact that  $\epsilon_r(f)$  decreases with frequency aligns with well-established physical principles and supports the idea that a real dispersion mechanism is being indirectly accounted for, consistent with prior literature.

Boundary conditions included perfect electric conductors (PEC) on the metallic surfaces, and absorptive radiation boundaries enclose the whole antenna geometry. Ports were defined at the feeding point, and an adaptive frequency sweep was performed between 3 and 8 GHz.

In selecting the material properties for the dielectric substrate we defined an internal function by polynomial interpolation between some points that were systematically changed during the validation process

The first simulation set assumed a constant  $\epsilon_r = 2.94$  as per datasheet values. A second simulation set incorporated a manually fitted  $\epsilon_r(f)$  curve derived from inverse modeling based on measured S11 data.

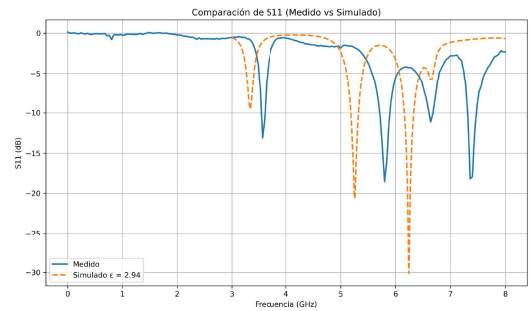


Figure 2: Simulated vs. measured return loss when using a constant, i.e, independent of frequency, permittivity

#### V. RESULTS

Four figures illustrate the outcome of the validation procedure.

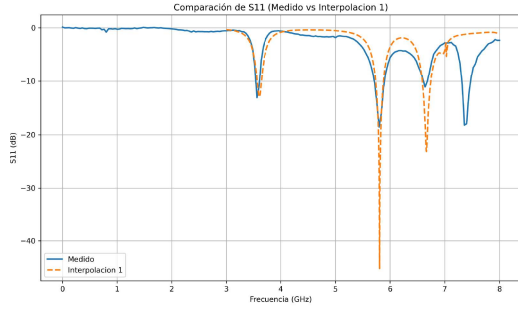


Figure 3: Measured vs simulated loss return after an adjustment of the permittivity was done in function of frequency.

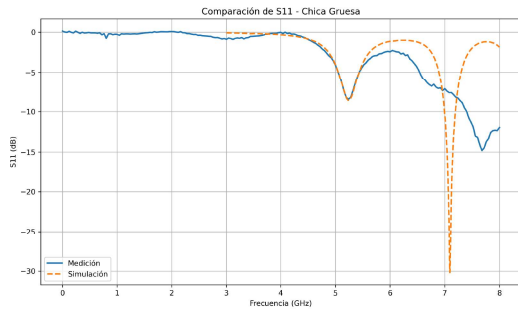


Figure 4: When the previous permittivity adjustment is employed in a newly fabricated antenna geometry, a very good agreement is obtained below about 5.5 GHz. In particular, it captured pretty well the resonance at 5.24 GHz

Figure 2 shows that when using a constant  $\epsilon_r$ , resonance frequencies are systematically shifted (underestimated) relative to the measured Return Loss minima.

Figure 3 demonstrates that tuning  $\epsilon_r(f)$  for the baseline geometry results in near-perfect alignment of the simulated and measured resonances. In addition, the losses seems well represented for the first resonance but underestimated for the following ones

Figure 4, which involves a second antenna with all dimensions altered, confirms the predictive capacity of the frequency-dependent model: the first resonance is matched with high accuracy at 5.24 GHz. However, above 5.5 GHz, the agreement deteriorates, suggesting the onset of losses not captured by  $\epsilon_r(f)$  alone. Tangent losses of 0.012 seems adequate to represent quality factor at 5.24 GHz

Figure 5 presents the second geometry simulated with constant  $\epsilon_r = 2.94$ , further confirming the need for a dispersion-aware model.

## VI. CONCLUSIONS

This work validates a methodology for improving the predictive accuracy of micro-strip antenna simulations by incorporating a manually fitted real part of frequency-dependent permittivity profile.

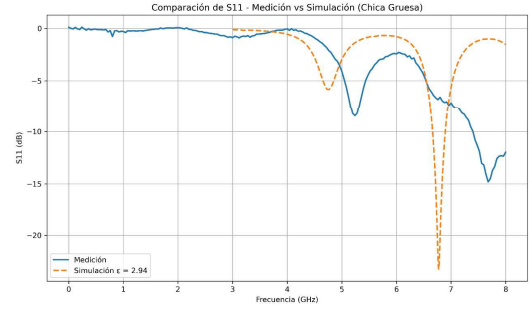


Figure 5: When a constant value of permittivity is used for the second geometry resonance frequencies are systematically underestimated.

The inverse modeling approach allows the simulated Return Loss curve to match the the experimental results for one geometry and maintain predictive capability when applied to a different structure. The main advantage is improved resonance prediction without complex complete characterization of material losses. The idea is simply to follow this approach once and every time a new kind of dielectric plate is intended for design and production

Future work will focus on modeling  $\epsilon''(f)$  more systematically on other cladding plate materials and incorporating frequency dependent dielectric losses and conductor losses to extend accuracy beyond 6.8 GHz.

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## REFERENCES

- [1] J. Coonrod and A. F. H. III, "Effect of dielectric constant and thickness on rf performance of high frequency pcb's," *Microwave Journal*, 2011, accessed: 2025-06-30.
- [2] K. Prokopidis, M. Stylianou, and T. Tsiftsis, "Moisture sensing via dielectric property variation using microstrip antennas," *IEEE Sensors Journal*, vol. 21, no. 5, pp. 6205–6213, 2021.
- [3] S. Gluzman, A. Sihvola, and J. Hansson, "A generalized mixing rule for dielectric composites based on the fractal geometry of the percolating clusters," *Journal of Applied Physics*, vol. 101, no. 8, p. 084101, 2007.
- [4] V. N. Egorov and N. I. Solomentseva, "Frequency-dependent dielectric permittivity of pcb materials: Measurement and modeling," *AIP Advances*, vol. 13, no. 2, p. 025312, 2023.