PCB Conductor Surface Roughness as a Layer with Effective Material Parameters

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Abstract—A model to substitute conductor surface roughness in printed circuit boards by a layer with an effective material (lossy dielectric) is proposed and tested using the 2D finite-element method (FEM) electromagnetics numerical simulations. The results of numerical modeling of a multilayered structure corresponding to a stripline transmission line with substituted roughness are compared with the experimental results obtained on a TRL-calibrated test vehicle with significant roughness on conductors made of a standard (STD)-roughness copper foil.

I. INTRODUCTION

Designers of high-speed electronics operating over the wide frequency range from a few hundred MHz to tens GHz need to accurately predict dissipation and dispersion on transmission lines used in their designs. Conductor roughness is always present in printed circuit boards, because it is necessary for adhesion of conductors with laminate dielectrics. Adequate modeling of conductor roughness effects over a wide frequency range is known to be important from a signal integrity (SI) point of view [1].

Numerous methods and approaches to model conductor surface roughness are described in literature – some of these methods are reviewed in, e.g., [2]-[7] and references therein. All of these methods need detailed microscopic surface roughness inspection and description.

In the proposed paper, the rough boundary layer is not modeled as a corrugated or quasi-periodic surface, as is done in [8]-[11]. Roughness in this work is neither modeled as an agglomerate of "snowballs" [1] or hemispheres [12], nor are any impedance surface boundary conditions applied [3]. Instead, the inhomogeneous boundary layer, comprised of "spikes" or "islands" (inclusions) and a surrounding dielectric matrix, is homogenized using a mixing rule for aligned prolate ellipsoids [13],

\[ \varepsilon_{\text{eff},y} = \varepsilon_{\text{matrix}} \left(1 + \frac{\varepsilon_{\text{incl}} - \varepsilon_{\text{matrix}}}{\varepsilon_{\text{matrix}} + (1 - \varepsilon_{\text{incl}})N_y(\varepsilon_{\text{incl}} - \varepsilon_{\text{matrix}})} \right). \]  

The ellipsoids with the depolarization factor \( N_y \) represent roughness inhomogeneities stretching in \( y \) direction. Their volume concentration \( \nu_{\text{incl}} \) may be comparatively high, but less than the percolation threshold, i.e., the concentration where the material transforms from a dielectric to a conductor. The complex permittivity of conducting inclusions can be represented as

\[ \varepsilon_{\text{incl}} = \varepsilon_1 + j\varepsilon_2, \]  

where \( \varepsilon_1 \) is the intrinsic conductivity of inclusions (may be different from that of copper). This means that the inclusions in the mixture are conducting particles, with significant imaginary part of complex permittivity, while \( \varepsilon_2 \) is on the order of 1. The matrix material is assumed to be an epoxy resin with some ceramic particles. Its permittivity is complex,

\[ \varepsilon_{\text{matrix}} = \varepsilon'_m - j\varepsilon''_m, \]  

but in this study, for simplicity, it is assumed to be non-dispersive in the frequency range of interest [14].

The laminate fiber-glass filled epoxy resin composite dielectric in the model is taken the same as the one experimentally tested in [7]. It is important to mention that its dielectric properties have been extracted using the differential extrapolation “DERM” technique [7], which allows for separating dielectric loss from rough conductor loss. For this procedure, the three groups of test vehicles (nine boards in each group) were tested using the travelling wave technique, where S-parameters were measured using a vector network analyzer (VNA). The TRL calibration procedure was used to remove port effects when measuring S-parameters on each test vehicle. The three groups differed only in the types of foils (STD – standard, VLP – very-low-profile, and HVLP – hyper-low-profile foils). Typically, the STD foil is the roughest, VLP is of medium roughness, and the HVLP is the smoothest [7], [8].

All the test vehicles, as is required by DERM, had as close as technologically possible geometries (cross-sectional dimensions, length of the test line, TRL pattern, connectors, and via transitions) and the same laminate dielectric. The DERM procedure allowed for obtaining “pure” dielectric loss...
parameter, not affected by roughness. This data is further used in the model proposed herein.

Roughness parameters are obtained using scanning electron microscope (SEM) Hitachi S-570 and a semi-automatic image processing tool, discussed in detail in our other paper for this Symposium [15]. Table 1 summarizes the roughness parameters for the studied test vehicles.

<table>
<thead>
<tr>
<th></th>
<th>( A_r ) (m)</th>
<th>( \Lambda_r ) (m)</th>
<th>( A_r/\Lambda_r )</th>
<th>( R_p ) (m)</th>
<th>( R_q ) (m)</th>
<th>( R_{rms} ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>STD</td>
<td>7.98</td>
<td>10.62</td>
<td>0.75</td>
<td>1.56</td>
<td>8.41</td>
<td>1.91</td>
</tr>
<tr>
<td>VLP</td>
<td>3.35</td>
<td>7.28</td>
<td>0.46</td>
<td>0.75</td>
<td>4.19</td>
<td>0.92</td>
</tr>
<tr>
<td>HVLP</td>
<td>1.65</td>
<td>4.69</td>
<td>0.35</td>
<td>0.35</td>
<td>2.29</td>
<td>0.44</td>
</tr>
</tbody>
</table>

The notations use in Table I are the following. \( A_r \) is the average peak-to-valley roughness amplitude, calculated for all peaks and valleys along the chosen sample length for inspection. \( \Lambda_r \) is the average quasi-period of the roughness function along the sample length. \( R_p \) is the mean arithmetic roughness amplitude. \( R_q \) is the average peak-to-valley amplitude defined through five highest peaks and five lowest valleys on the inspected sample. \( R_{rms} \) is the r.m.s. roughness amplitude. These parameters are discussed in detail in [7] and [15].

The modeling setup corresponds to the experimentally studied structure. This is a 50-Ohm symmetric stripline with the TRL calibration pattern, whose S-parameters were measured using a VNA.

Dielectric properties (dielectric constant \( DK = \varepsilon_r \) and dissipation factor \( DF = \tan \delta \)) of the main fiber-glass filled epoxy-resin laminate dielectric, extracted using the experiment-based differential extrapolation “DERM” method [7] and the simplified “root-omega” technique [16] are presented in Fig. 2. In both techniques, the total loss on the line, calculated from the measured S-parameters over the wide frequency range of interest, is curve-fitted to \( \sqrt{\omega} \), \( \omega \), and \( \omega^2 \) frequency contributions. In the “root-omega” technique, the conductor loss is extracted from the total loss simply as its \( \sqrt{\omega} \) part, while the dielectric loss is obtained as the remaining \( \omega \) and \( \omega^2 \) parts of the total loss. Obviously, the “root-omega” procedure lacks accuracy, since it neglects conductor surface roughness: the latter turns out to be lumped in the \( \sqrt{\omega} \), \( \omega \), and \( \omega^2 \) terms. Therefore, the dielectric parameters, extracted using the “root-omega” approach, differ for three test vehicles with identical geometry and dielectric, but different types of copper foil. Actually, the dielectric parameters, if extracted correctly, should be the same.

In the DERM procedure [7], the total loss on three lines are also curve-fitted to \( \sqrt{\omega} \), \( \omega \), and \( \omega^2 \), and the auxiliary curves of those curve-fitting coefficients as functions of peak-to-roughness amplitude \( A_r \) are built. Then the smooth conductor loss and pure dielectric loss are obtained by extrapolating these auxiliary curves to zero roughness. The unique curves for DK and DF as functions of frequency are then obtained. The test vehicle with the smoothest foil, which is the HVLP, is the closest to the unique results extracted with the DERM.

In further numerical simulations, the dielectric properties are taken as those unique data extracted using the DERM technique. These are the lowest curves in Figs. 2 (a) and (b), while the other curves (extracted using “root-omega” procedure) go above them, because conductor roughness is lumped in the curves when applying the “root-omega” technique.

![Fig. 1. SEM of a signal trace of the PCB stripline embedded in the laminate fiber-glass-filled composite dielectric](image)

**II. EXPERIMENT-BASED INPUT DATA FOR MODELING**

![Fig. 2. Extracted using “root-omega” technique and the DERM dielectric parameters of a PCB laminate dielectric: (a) dielectric constant and (b) dissipation factor as functions of frequency](image)
Conductor roughness in the proposed approach is substituted with a “roughness composite dielectric” layer. The matrix to calculate the effective material properties of this “roughness composite dielectric” is epoxy resin, which contains ceramic inclusions seen as crumbs in the SEM pictures in Figs. 3-7. Its dielectric properties are calculated using the Maxwell-Garnett mixing rule for sparse dielectric mixtures with randomly dispersed inclusions of arbitrary shape [13], and estimated as $\varepsilon_{\text{matrix}} = 5.0 - j0.17$, non-dispersive over the frequency range up to 20 GHz.

The inclusions in the roughness dielectric layer are assumed to be of a cylindrical shape, so that the depolarization factor is [17]

$$N_r = \frac{1}{a} \ln(a),$$

where $a = h_c / d_r$ is an average aspect ratio of cylindrical inclusions, i.e., the ratio of their height to diameter. This aspect ratio is different for different types of foils: higher for STD, lower for VLP, and the lowest for HVLP. The “roughness dielectric” layer thickness herein is assumed to be the doubled peak-to-valley roughness height, i.e., $T_r = 2d_r$. This distance is chosen so that the probability that roughness peaks everywhere on the foil under consideration would exceed the level of $T_r$ is almost zero. Of course, the $T_r$ value determines the volume fraction of “roughness inclusions”. The latter is not known exactly. For this reason, this is a kind of a fitting parameter, analogous to such fitting parameters in Huray’s model [1] as the concentration of snowballs and their size. Nevertheless, $v_{incl}$ could be approximately estimated from the analysis of the SEM pictures as $v_{incl} \approx \frac{\text{Area}_{\text{metal}}}{\text{Area}_{\text{total}}}$ in the roughness layer of the thickness $T_r$. As for the intrinsic conductivity of “roughness inclusions”, it is also unknown and difficult to measure. However, it should be significantly less, up to a few orders, than that of pure copper, since these “inclusions” are dendrites.
which grow into the laminate dielectric, and their surfaces may be coated by a metal different from Cu metal or even have non-metallic films. For this reason, conductivity of “roughness inclusions” is also a fitting parameter.

The resultant from the mixing theory “roughness dielectric” is very lossy, but only slightly dispersive, following the initial part of the Debye curve, where the real part of permittivity is slowly, almost linearly, decreases, while the imaginary part linearly increases. However, for simplicity sake, it may be assumed as non-dispersive over the frequency range of interest for all types of foils – STD, VLP, and HVLP.

According to our numerous observations, the dominant contribution in the loss due to just conductor surface roughness behaves as $\sim \alpha$. This behavior is associated with non-dispersive effective dielectric properties of the “roughness dielectric” (see Appendix B in [7]). Strictly speaking, the “roughness dielectric” should also have a negative $\sqrt{\omega}$ part, which is responsible for the partial compensation of the skin effect at lower frequencies, as is shown in [7]. The “roughness dielectric” should also have a negative $\omega^2$ part, which opposes the linear increase of the DF of the main laminate dielectric at higher frequencies, and is explained in [7] and [18]. However, these two contributions are small compared to the $\omega$ part.

III. NUMERICAL MODEL AND DISCUSSIONS

The numerical modeling of the transmission line with the layer of “roughness dielectric” was done employing the in-house developed 2D finite-element numerical solver [19]. The cross-section of the model setup for a stripline is shown in Fig. 7. The dimensions correspond to those given in Figs. 3-5.

The peculiarities of the model are the following. The 2D problem is solved assuming a translationally invariant structure. This means that the geometry and the material are the same in every cross-section. In this modeling, only TEM propagating mode is considered. This limitation may affect the accuracy of modeling due to possible excitation of higher-order propagating and evanescent modes, surface waves in the layered structure, and possible fringing field and leaky waves at the structure edges. All the conductors in the model are smooth and made of copper with slightly reduced conductivity, $5.8 \times 10^7$ S/m, compared to the IACS value, and the pure skin effect is taken into account. The main laminate dielectric (in the current study of the fiber-glass filled epoxy resin group) is represented by the frequency-dependent tabulated data generated from applying DERM. The “roughness dielectric” is modeled as a lossy non-dispersive material, as is mentioned above. The evaluated as described above “roughness dielectrics” for three types of foils in this study have the following parameters:

- **STD**: $\epsilon_{\text{STD}} = 48.5 - j18.4 \quad (\tan \delta_{\text{STD}}=0.38)$
- **VLP**: $\epsilon_{\text{VLP}} = 33.1 - j4.97 \quad (\tan \delta_{\text{VLP}}=0.15)$
- **HVLP**: $\epsilon_{\text{HVLP}} = 28.9 - j1.73 \quad (\tan \delta_{\text{HVLP}}=0.06)$

![Fig. 7. Cross-section of the stripline in the numerical modeling setup](image)

The results of modeling and measurements of insertion loss $S_{21}$ as a function of frequency are shown in Figs. 8-10. The measured curves in these figures are the black solid lines with markers. The upper (dashed) lines correspond to the modeled magnitude of $S_{21}$, if no “roughness dielectric” is added, and the laminate dielectric has the pure dielectric loss, extracted using the DERM. Obviously, this dashed line represents significantly less loss than should be, since all roughness effects are removed.

The lowest (solid light) lines are the losses modeled with the laminate dielectric parameters extracted using the “root-omega” procedure, and the conductors are modeled as smooth. As can be seen, the “root-omega” procedure significantly overestimates loss on the line, because in this case roughness loss is lumped into the extracted laminate dielectric data.

![Fig. 8. Insertion loss in the STD test vehicle - measured and modeled by FEM without and with “roughness dielectric”](image)
The light solid lines which almost coincide with the measured data are obtained when adding the “roughness dielectric” as discussed before to the laminate pure dielectric loss extracted using DERM. The achieved agreement is excellent for all three types of test vehicles: at frequencies above 5 GHz the discrepancy is less than 0.1 dB, and below 5 GHz the discrepancy is less than 0.3 dB for STD, and less than 0.5 dB for VLP and HVLP.

The slight discrepancy in the insertion loss magnitude at the lower frequencies can be explained by the fact that the “roughness dielectric” is modeled as non-dispersive in the first-order approximation, as is discussed above. The modeled loss at lower frequencies is slightly higher than the measured loss. This is related to not modeling negative $\sqrt{\omega}$ part in “roughness dielectric”, while it was removed from the total loss by the DERM procedure. The currently used mixing rule (1) with assumptions (2) and (3) does not allow for taking into account the term behaving as $\sqrt{\omega}$, and this should be further studied.

**IV. Conclusion**

Conductor surface roughness significantly affects signal propagation in the printed circuit boards, especially at frequencies above a few GHz. A simple model to substitute conductor surface roughness in printed circuit boards by an effective “roughness dielectric” layer is proposed. This “roughness dielectric” appears due to copper particles (dendrites) penetrating into dielectrics clad with foils for adhesion purposes.

The proposed model is based on the effective medium theory, and the parameters of the “roughness dielectric” are calculated using a mixing rule for aligned cylindrical conducting inclusions, while the parameters for these calculations are estimated from the SEM cross-sectional analysis of the test vehicle. A few parameters of the model (an aspect ratio of “roughness inclusions”, their conductivity, and volume fraction) are statistical values, which cannot be determined exactly, but can be estimated approximately from the SEM pictures, so they remain fitting parameters in modeling “roughness dielectric”.

The numerical simulations of the three types of test vehicles with different “roughness dielectrics” corresponding to different foils were done by the 2D finite-element method and compared with the measured results. The experiment-based DERM technique [7] is applied to separate the rough conductor loss and the laminate dielectric loss, and the resultant “pure dielectric loss” was used in the numerical modeling of the main dielectric on the line.

The fitting parameters of the roughness dielectric model were modified within some reasonable range (according to the SEM pictures) until the simulated and measured results agree well (within a fraction of dB) over the entire frequency range. The “roughness dielectric” in each case of a foil type has its own effective dielectric properties and thickness, depending on the roughness amplitude. Currently, the “roughness dielectric” is modeled as a non-dispersive lossy material, but in future its frequency dispersion may be added.

This way, the roughness of the copper foil can be easily incorporated in the numerical simulation tools by evaluating the effective dielectric properties of “roughness dielectrics” corresponding to the existing foils with different roughnesses. If the user does not have the capability of foil roughness inspection, e.g., using an SEM or AFM cross-sectional analysis, surface profilometer data, etc., the recommended pre-computed values of complex permittivity and thickness of “roughness dielectrics” for the known types of foils may still be used in numerical modeling.

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