Separating Dielectric and Conductor Loss for Rough Striplines in Printed Circuit Boards

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Abstract— Knowledge on dielectric constant and loss tangent of printed circuit boards (PCB) in a wide frequency range from a few MHz to tens GHz is important for modern high-speed digital design. Dielectric properties can be determined from S-parameters of a test line measured using either vector network analyzer or time-domain reflectometer. Accurate measuring of dielectric parameters requires separation of conductor loss from dielectric loss. The existing models of conductor loss in rough conductors (e.g., the most widely used empirical Hammerstad's formula [1]), have been developed for the design of microwave planar transmission line structures that require extremely smooth conductors (r.m.s. roughness $\ll 1\,\mu\mathrm{m}$). However, an amplitude of conductor roughness in PCBs is principally on the order of 1–10 μm, and Hammerstad's formula is not applicable. The conductor loss is represented as $\alpha_c = a_{c0}(1+r)$, where $\alpha_{c0} \propto \sqrt{\omega}$ is loss in a smooth conductor, and r is the roughness term, which may be a complicated function of frequency and geometry. Loss in the corresponding smooth conductor can be calculated as $\alpha_{c0} = \beta_0\eta_0\delta_s/(4PZ_c)$, where δ_s is skin depth, Z_c is the characteristic impedance of the transmission line, η_0 is the free-space impedance, β_0 is the propagation constant in free space, and P is the actual cross-sectional perimeter of the smooth conductor [2].

The ***objective of this work*** is to accurately take into account surface roughness in the stripline structure within a PCB and separate conductor loss from dielectric loss. One of the ways of accounting for surface roughness is to use Sanderson's approach [2] of electromagnetic wave propagation along a corrugated surface. The rough surface function is represented as a periodic function of coordinate of propagation and expanded into Fourier series to get spatial harmonics. In [3], different periodic surface roughness functions have been considered: sinusoidal, rectangular, and saw tooth. We have considered a peak-like periodic function, too. It turns out that the resultant conductor loss substantially depends on amplitude and period of the surface roughness function, but not on its shape. In this work, we have also analyzed random surface roughness function based on "white noise" and "Gaussian noise" formulations [2]. It is shown that random surface roughness models may substantially overestimate actual conductor loss in PCBs, especially at frequencies over 10 GHz. Also, for correct computations while using random surface roughness models, data on power spectral density, or corresponding correlation functions for surface roughness should be available through surface imaging techniques [4].

Herein, ***a new approach*** to analyze surface roughness loss has been proposed. It is assumed that surface roughness forms a high-loss composite dielectric shell around a smooth conductor. Effective permittivity of the shell is calculated using an appropriate effective medium model, e.g., Bruggeman or Maxwell Garnett rule with aligned inclusions [5]. Then the corresponding surface roughness term that depends on $\varepsilon''_{\mathit{eff}}$ is added to the characteristic impedance and propagation constant. ***Another approach*** of separating dielectric and conductor loss proposed in this work is a differential technique, which can be called "redistribution". It can be applied only if two boards with the same dielectric properties, but different conductor roughness are available. Total loss on each board α_{t1} and α_{t2} are extracted from the measured S-parameters, and the difference should be only due to the different conductor loss. In the processing algorithm, it is assumed that the conductor loss is $\alpha_{c0} = a\sqrt{\omega}$, and the dielectric loss is $\alpha_d = b\omega + c\omega^2$, which corresponds to a causal dielectric response, according to Kramers-Kroenig relations [6]. Then a curve-fitting algorithm (e.g., a genetic algorithm, or regression analysis) is applied to retrieve the coefficients a, b, and c. However, representation $\alpha_{c0} = a\sqrt{\omega}$ will result in only smooth-surface conductor loss, so that the actual conductor loss would be underestimated, while dielectric loss would be overestimated. Hence, for two boards, the calculated dielectric loss will differ, which contradicts the fact that the dielectric is the same. This urges a redistribution, which is done by introducing weight coefficients, inversely proportional to the amplitudes of surface roughness of the boards, $\nu_1/\nu_2 = A_2/A_1$, so

that $\nu_1 + \nu_2 = 1$. Then the corresponding dielectric loss for the two boards becomes equal, $\alpha_d = \nu_1\alpha_{d1} + \nu_2\alpha_{d2}$, and the corrected conductor loss is calculated as $\alpha_{c1} = \alpha_{t1} - \alpha_d$ and $\alpha_{c2} = \alpha_{t2} - \alpha_d$.

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