

Estimation of Roughness-Induced Power Absorption From Measured Surface Profile Data

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Abstract—We present a methodology for extracting the 2-D power spectral density of a statistically isotropic random rough surface from height measurements by utilizing fast Fourier–Bessel transform. We compute the additional propagation loss due to surface roughness by integrating the extracted spectral density via the formula of absorption enhancement factor. Results for a microstrip demonstrate good correlation between measured and estimated loss up to 20 GHz. It is also possible to choose a random rough surface model for the measured surface and use it to predict the roughness effect on power loss.

Index Terms—Power absorption, power spectral density (PSD), rough surfaces.

I. INTRODUCTION

FOR interconnect waveguide structures on high-speed microelectronic package substrates and boards, the surface roughness between dielectric and conductor layers may introduce significant additional power loss that can be detrimental for insertion loss limited designs. We recently applied an analytic small perturbation method of second order (SPM2), numerical method of moments (MoM) and T -matrix method to quantify the roughness effect on power absorption [1]–[3]. The SPM2 formula of absorption enhancement factor for 2-D metallic rough surface in a 3-D problem is given in [3] in terms of the skin depth at microwave frequencies, the root-mean-square (RMS) height, and the surface power spectral density (PSD) in 2-D form. The ultimate purpose of this letter is to extract the PSD from real interconnect surfaces and use it to estimate corresponding roughness-induced power loss.

The 2-D PSD is designated as the preferred quantity for specifying surface roughness [4]. The conceptual approach to obtain 2-D PSD from measured surface height profiles is to take the magnitude squared of the 2-D Fourier transform of the data record, known as the periodogram. An ensemble average of PSD estimates needs to be taken afterwards because the periodogram estimate has large variance and makes it a noisy estimator. A simplification can be made for an isotropic surface, *i.e.*, if the topology has the same statistics regardless of direction. One can obtain the 1-D PSD from averaged periodogram estimates [5], [6] and convert it into the 2-D form [7]. However, in practice the

conversion is difficult to perform numerically due to the presence of the derivative of the inherently noisy 1-D PSD.

Our approach discussed in Section II takes an indirect route to obtain the 2-D PSD from an isotropic surface as follows.

- 1) The 1-D PSD is extracted from the averaged periodogram estimate as in [6].
- 2) The correlation function is computed by taking an inverse Fourier transform of the 1-D PSD.
- 3) The 2-D PSD is obtained by taking a fast Fourier-Bessel transform [8], also referred to as Hankel transform, of the correlation function. The procedure is valid if we assume the correlation function for a statistically isotropic surface has the same form for both 1-D and 2-D cases.
- 4) The power absorption enhancement factor is evaluated by using the extracted 2-D PSD.

In Section III, this four-step process is validated by synthetic data with given correlation function and PSD. Next, we compute the corresponding power absorption enhancement factor. Results show that the extracted PSD yields accurate roughness-induced power loss in the SPM2 model despite the bandwidth limitation due to space resolution and finite surface size. We further apply the procedures to analyze a real metal surface of an interconnect structure and demonstrate good correlation between estimated and measured loss up to 20 GHz.

II. ESTIMATING ABSORPTION WITH 2-D PSD EXTRACTION

We consider a 2-D profile of a rough surface described by a topographic height function $f(x, y)$. The expression for the 2-D PSD of the rough surface $W_{2D}(k_x, k_y)$ is defined by

$$W_{2D}(k_x, k_y) = \left\langle \lim_{L \rightarrow \infty} \frac{\left| \int_{-L/2}^{L/2} \int_{-L/2}^{L/2} dx dy f(x, y) \exp(-jk_x x - jk_y y) \right|^2}{L^2 4\pi^2} \right\rangle \quad (1)$$

where L is the surface length in both directions and $\langle \cdot \rangle$ denotes the operation of ensemble average. In practice, L is finite and the 2-D periodogram is computed by 2-D fast Fourier transform. To obtain an acceptably smooth PSD for typical 2-D surface profiles that contain 512×512 data points, normally at least a few hundred measured 2-D profiles are required for averaging. Thus, applying (1) directly to extract the 2-D PSD can be infeasible due to the time-consuming process in measurement and data processing.

Our approach of extracting the 2-D PSD is formulated by considering a 2-D profile of a statistically isotropic rough surface.

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The expression of the 1-D PSD of the rough surface, $W_{1D}(k)$, can be obtained by taking sweeps in any direction of a 2-D profile, *e.g.*, in the \hat{x} direction, and averaging the 1-D periodogram

$$W_{1D}(k) = \left\langle \lim_{L \rightarrow \infty} \frac{1}{L} \frac{1}{2\pi} \left| \int_{-L/2}^{L/2} dx f(x) \exp(-jkx) \right|^2 \right\rangle. \quad (2)$$

To get a large enough number of sweeps for averaging, we may either subdivide a long sweep into small segments as in [6] or take small segments from the 2-D profile horizontally and vertically, as long as the correlation length of the rough surface is considerably smaller than the segment size. The extracted $W_{1D}(k)$ has a bounded shape in the spatial frequency domain, where the lower bound is due to the finite surface length L and the upper bound is due to the smallest resolution Δx .

Next, we take the inverse Fourier transform of $W_{1D}(k)$ to get the correlation function of the rough surface $C(\rho)$. Note that the correlation function $C(\rho)$ does not depend on polar direction since the surface is isotropic. The bandwidth limitation of $W_{1D}(k)$ may introduce ringing artifacts in the extracted $C(\rho)$ due to the Gibbs phenomenon. This problem can be minimized by choosing a large L and a small Δx which leads to a wide-band $W_{1D}(k)$.

The third step is generally taking the 2-D Fourier transform of the correlation function to get the 2-D PSD $W_{2D}(k_x, k_y)$. For an isotropic surface where $C(x, y)$ only depends on ρ , the 2-D Fourier transform can be simplified as Fourier–Bessel transform, also referred to as Hankel transform

$$W_{2D}(k_\rho) = \frac{1}{2\pi} \int_0^\infty C(\rho) J_0(k_\rho \rho) \rho d\rho \quad (3)$$

where $k_\rho = \sqrt{k_x^2 + k_y^2}$ and $J_0(k_\rho \rho)$ is the Bessel function of zeroth order. We use a fast algorithm [8] for the numerical implementation of the transform.

The last step is substituting the extracted 2-D PSD $W_{2D}(k_\rho)$ into the formula for power absorption enhancement factor [3]. For an isotropic surface, the enhancement factor can be simplified as

$$\begin{aligned} & \frac{\langle P_{a,\text{rough}} \rangle}{P_{a,\text{smooth}}} \\ &= 1 + \frac{2h^2}{\delta^2} - \frac{4\pi}{\delta} \int_0^\infty dk_\rho k_\rho W_{2D}(k_\rho) \operatorname{Re} \sqrt{\frac{-2j}{\delta^2} - k_\rho^2} \end{aligned} \quad (4)$$

where the integrand asymptotically approaches $W_{2D}(k_\rho)/\delta^2$ as k_ρ becomes large. In the next section we select some sample results for synthetic and real rough surfaces and demonstrate how the above four-step procedure works.

III. RESULTS AND DISCUSSION

A. Estimating Loss From Synthetic Surfaces

To validate the procedure for PSD extraction, we first generate a 2-D profile of synthetic random rough surface based on the Gaussian correlation function $h^2 \exp(-\rho^2/l^2)$ with RMS height $h = 1 \mu\text{m}$ and correlation length $l = 2 \mu\text{m}$. The surface size is $150 \mu\text{m}$ by $150 \mu\text{m}$ and the number of

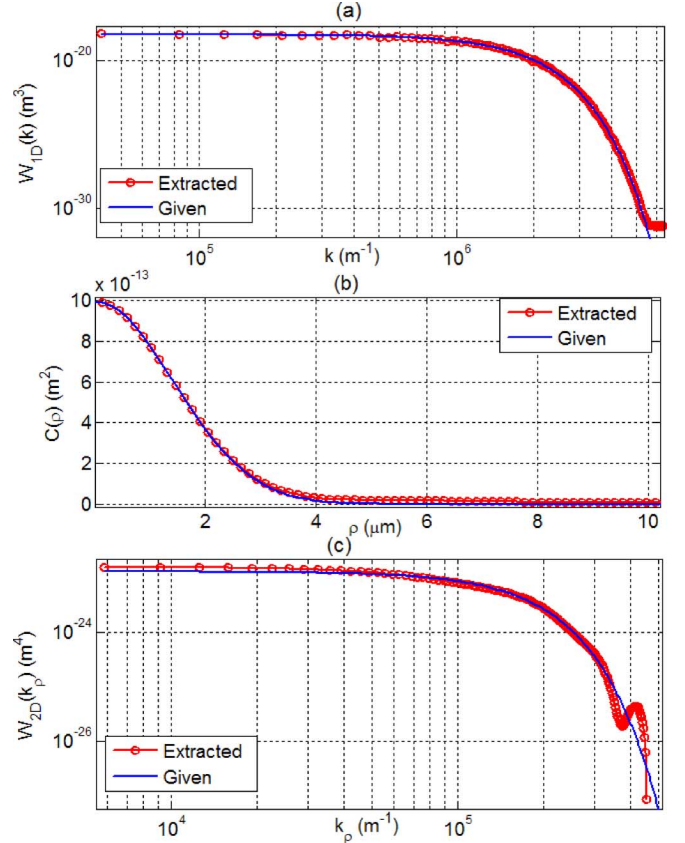


Fig. 1. (a) One-dimensional power spectral density $W_{1D}(k)$: Extracted versus synthetic model. (b) Correlation function $C(\rho)$: Extracted versus synthetic model. (c) Two-dimensional power spectral density $W_{2D}(k_\rho)$: Extracted versus synthetic model.

sample points is 1024×1024 . Fig. 1(a) illustrates the extracted $W_{1D}(k)$ compared with the given 1-D spectral density $(h^2 l / 2\sqrt{\pi}) \exp(-k^2 l^2 / 4)$. Note that the extracted $W_{1D}(k)$ is obtained by averaging periodograms from all horizontal and vertical sweeps of the given surface profile. Fig. 1(b) illustrates the extracted $C(\rho)$ compared with the given Gaussian correlation function. Some slight ringing is noticeable due to the limited bandwidth of $W_{1D}(k)$. Fig. 1(c) illustrates the extracted $W_{2D}(k_\rho)$ compared with the given 2-D spectral density $(h^2 l^2 / 4\pi) \exp(-k_\rho^2 l^2 / 4)$. Fig. 2 illustrates the absorption enhancement factor computed by the extracted $W_{2D}(k_\rho)$ and by the given 2-D PSD for two different synthetic Gaussian surfaces. The results show that the procedures are acceptably accurate and can be combined with the SPM2 formula to estimate the roughness-induced conductor loss.

B. Estimating Loss From Measured Surfaces

Here we study the metal surface of a real interconnect structure after removing dielectric materials by reactive ion etching. The 2-D profile of the surface is obtained by scanning with an atomic-force microscope (AFM). The surface size is $50 \mu\text{m}$ by $50 \mu\text{m}$ and the number of sample points is 1024×1024 . The RMS height of the surface profile is $0.85 \mu\text{m}$. Fig. 3 illustrates the extracted $C(\rho)$ and $W_{2D}(k_\rho)$, as well as the absorption enhancement factor based on the extracted $W_{2D}(k_\rho)$.

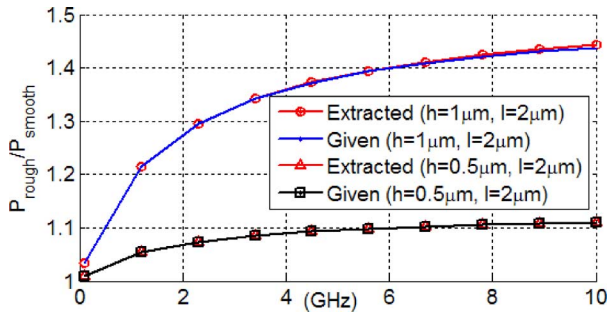


Fig. 2. Absorption enhancement factor: Extracted versus synthetic model.

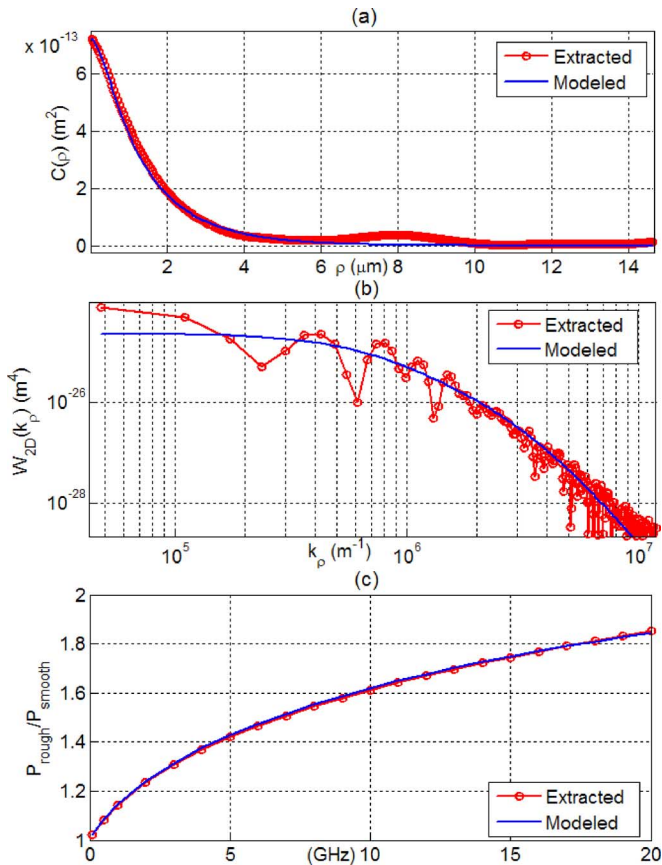


Fig. 3. (a) Correlation function $C(\rho)$: Extracted versus synthetic model; (b) 2-D power spectral density $W_{2D}(k_\rho)$: Extracted versus synthetic model; and (c) absorption enhancement factor: Extracted versus synthetic model.

In addition, we find it possible to choose a random rough surface model to approximate the measured surface profile to a large extent. Fig. 3 includes such comparison with a differentiable-exponential correlation function model given by $C(\rho) = h^2 \exp\{-(|\rho|/l_1)[1 - \exp(-|\rho|/l_2)]\}$ where $h = 0.85 \mu\text{m}$, $l_1 = 1.4 \mu\text{m}$ and $l_2 = 0.53 \mu\text{m}$.

Next, we correlate measured loss with the estimated loss, using the AFM measured surface profile data. The measured loss in terms of attenuation constant is obtained by measuring the S parameters of two microstrip lines with different length but the same metal surface characteristics [9]. As a demonstration we consider a typical organic package substrate with microstrip test structures that are not covered by any solder mask

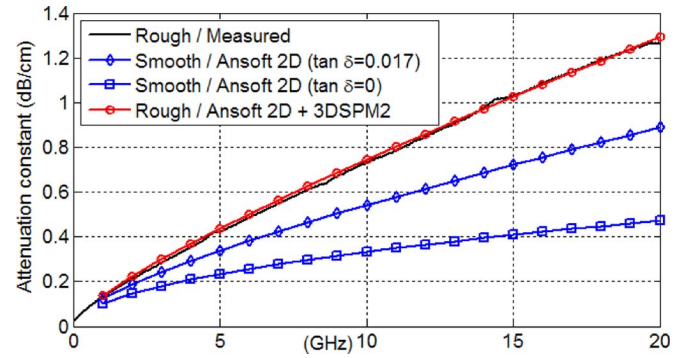


Fig. 4. Attenuation constant: Measured loss versus estimated loss.

material. The shorter line for measurements is 12.3 mm long and the longer line 24.3 mm. Estimating the loss, on the other hand, requires modeling of the smooth surface case, in which the attenuation constant can be split into conductor and dielectric loss by setting the dielectric loss tangent to zero. In our simulation, we use a commercial 2-D field solver and use the following geometric parameters from cross-sectioning of samples: trace width = $65.5 \mu\text{m}$; trace thickness = $15.3 \mu\text{m}$; dielectric thickness = $30.6 \mu\text{m}$. The relative dielectric constant and dielectric loss tangent, which were obtained from independent material characterization measurements, are equal to 3.4 and 0.017, respectively. The medium above the dielectric is air. The conductivity of metal is $4.5 \times 10^7 \text{ S/m}$. The final form of the estimated loss is obtained by multiplying the attenuation constant of smooth-conductor loss with the extracted absorption enhancement factor in Fig. 3(c) and then adding the simulated attenuation constant of dielectric loss. Fig. 4 illustrates the measured and estimated attenuation constants. The correlation between the measured loss and the estimated loss is very good up to 20 GHz.

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