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MODELING OF CONDUCTOR SURFACE ROUGHNESS EFFECT

BY

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THESIS

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ABSTRACT

Conductor surface roughness effect refers to the influence of surface roughness on the current flow inside a conductor and the subsequent effect on electromagnetic properties of the conductor. The existence of surface roughness on a conductor disturbs current flow and results in a higher than usual ohmic loss. This, in turn, impacts the performance of a variety of high-frequency interconnect, waveguide, and signal processing passive devices. It is, thus, very important to account for the impact of conductor surface roughness on the modeling and simulation used in support of the design of such devices. This thesis focuses on methodology of conductor surface roughness effect modeling, which provides accurate and efficient prediction using currently available commercial electromagnetic solvers. A methodology to account for the impact of random conductor surface roughness in the electromagnetic analysis is proposed. A compound conductor model is constructed based on the result from power absorption analysis and is used in place of the original rough-surface conductor to account for the effect of random conductor surface roughness. The model allows convenient and accurate modeling of the impact of conductor surface roughness and facilitates electromagnetic simulation of the device using commercial electromagnetic solvers. The advantage of an equivalent model for rough-surface conductor, in general, is reduction in the complexity associated with rough-surface modeling. The use of the proposed model and its advantages are demonstrated through the electromagnetic analysis of a microstrip transmission line structure and the accuracy is verified through correlations with measurement data. In addition, a microwave filter is modeled using the compound conductor approach.

To my parents, for their love and support.

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TABLE OF CONTENTS

CHAPTER 1	INTRODUCTION	1
CHAPTER 2	POWER ABSORPTION ANALYSIS	4
2.1	Extraction of the Power Absorption Enhancement Factor . . .	5
2.2	Performing Electromagnetic Simulation	9
CHAPTER 3	COMPOUND CONDUCTOR MODEL	11
3.1	Structure of the Compound Conductor	12
3.2	Power Absorption Analysis	13
3.3	Obtaining Model Parameter	15
CHAPTER 4	MICROSTRIP TRANSMISSION LINE	19
4.1	Test Structure	19
4.2	Compound Conductor Model	20
4.3	Simulation Results	23
CHAPTER 5	MICROWAVE FILTER	27
5.1	Test Structure	27
5.2	Compound Conductor Model	27
5.3	Simulation Results	29
CHAPTER 6	CONCLUSION	34
REFERENCES		36

CHAPTER 1

INTRODUCTION

Electromagnetic waves propagating inside a medium with finite conductivity suffer attenuation due to ohmic loss. Such attenuation is measured in terms of the skin depth, δ , which is defined as the distance over which the amplitude of the wave drops by $1/e$. For a good conductor, $\delta = \sqrt{1/f\sigma\pi\mu}$, where f is the frequency, σ is the conductivity and μ is the permeability of the conductor. Skin effect describes the phenomenon that an alternating current tends to distribute within a good conductor such that current flow concentrates at the conductor surface. Contrary to the case with direct current, where the current density over the cross-section of a conductor is uniform, the current density for alternating current is greatest at the surface and decreases deeper into the conductor. The majority of the alternating current flows within a thin layer at the conductor surface, dictated by the skin depth. When the skin depth is smaller than the cross-sectional dimensions of the conductor, the skin effect reduces the effective cross-section of the conductor and increases the effective resistance.

Conductor surface roughness effect refers to the influence of surface roughness on the current flow inside a conductor and the subsequent effect on electromagnetic properties of the conductor. Surface roughness on a conductor disturbs current flow and results in a higher than usual ohmic loss. The conductor exhibits even higher effective resistance than that predicted by the skin effect model. This effect is more significant at higher frequencies due to the skin effect.

Nowadays, as the speed of electronic devices increases, the data rate and operating frequency of integrated circuits become higher. Conductor surface roughness effect modeling has become necessary due to the increasing operating frequency of integrated circuits. Substrates in printed circuit boards (PCBs) are deliberately roughened to facilitate adhesion. The roughness of the substrate surface transfers to conductor surface during the man-

ufacturing process. Non-ideality related to the conductor surface roughness has previously been neglected since its impact on attenuation was small at low frequencies. However, at higher frequencies, especially at multi-GHz range, the skin depth becomes comparable to the root-means-square height of the rough conductor surface. In such a case, conductor roughness profoundly affects the electromagnetic properties of signal transmission. Failure to address the increased attenuation caused by conductor surface roughness can result in losses beyond design margin and lead to severe signal integrity issues. Trial and error is not a preferable approach to the problem since it significantly lengthens the design cycle and increases design cost. In such contexts, methods to efficiently and accurately predict the impact of conductor surface roughness in the design phase become highly desired.

Power absorption enhancement factor characterizes the increase in power absorbed by a conductor due to surface roughness. It relates the power absorption behavior of a conductor with a rough surface to its smooth counterpart. A smooth conductor involves simpler geometry and is less costly to analyze. Thus, when modeling guided wave phenomena on planar circuits via electromagnetic simulation, it is often favorable to simulate the smooth conductor case first, and then to make corrections to obtain results for the rough conductor case. Many studies have been done to analyze the power absorption behavior of rough-surface conductor and very accurate models were proposed to calculate the power absorption enhancement factor. Despite the highly sophisticated techniques that are currently available, many things need to be further investigated to advance the state-of-the-art in conductor surface roughness modeling. So far, research has focused mostly on predicting the conductor attenuation and less so on investigating the conductor surface roughness effect on other wave-guiding properties of interconnects. Few studies have been done to address the proximity effect in the presence of conductor surface roughness. No details are available to model non-uniform roughness. Practical methods to incorporate rough conductor models in computer simulation using commercial software are also lacking. This thesis focuses on methodology of conductor surface roughness effect modeling, which provides accurate and efficient prediction using a currently available commercial electromagnetic solver.

A methodology to account for the impact of random conductor surface roughness in the electromagnetic analysis is proposed. A compound conduc-

tor model is constructed based on the result of power absorption analysis, where a compound conductor with a thin outer layer conforming to the conductor contour is used to replace the original rough-surface conductor in order to account for the effect of random conductor surface roughness. The model allows convenient and accurate modeling of the impact of conductor surface roughness and facilitates electromagnetic simulation of circuits using commercial electromagnetic solvers.

The application of the model is demonstrated through the electromagnetic analysis of a microstrip transmission line structure, and the accuracy is verified through correlations with measurement data. The application of the model to a microwave filter is also investigated.

This thesis is organized as follows. Past efforts on the analysis of power absorption behavior of conductors with rough surfaces will be covered in Chapter 2. Methods to calculate power absorption enhancement factor, both periodic-structure based and random-surface based, will be surveyed. How to make use of the power absorption enhancement factor to perform electromagnetic simulation will be discussed, and the motivation of the work will be explained. Details on the generation of a compound conductor model from calculated power absorption enhancement factor will be discussed in Chapter 3. Then, in Chapters 4 and 5, the compound conductor model will be applied to the electromagnetic analysis of wave-guiding properties of a microstrip transmission line and of the resonance behavior of a microstrip filter, respectively. Conclusions are drawn in Chapter 6, with discussion of the advantages and limitations of the compound conductor model, as well as an overview of future work.

CHAPTER 2

POWER ABSORPTION ANALYSIS

As the first step to understand the impact of conductor surface roughness, a good deal of research has been conducted on analyzing the power absorption property of rough conductors. Morgan first utilized the concept of power absorption enhancement factor to characterize the power absorption property of a rough conductor [1]. The power absorption enhancement factor, K_{sr} , is defined as the ratio of power dissipated by eddy currents in a conductor per unit area when the conductor surface is rough, $P_{a,rough}$, to the power dissipated when the surface is smooth, $P_{a,smooth}$.

$$K_{sr} = \frac{P_{a,rough}}{P_{a,smooth}} \quad (2.1)$$

K_{sr} can be used as a correction factor to account for the conductor surface roughness effect when calculating attenuation. The attenuation constant, $\alpha_{c,rough}$, for wave propagation in waveguides involving conductors with rough surfaces can be estimated by multiplying the attenuation constant calculated for a smooth conductor, $\alpha_{c,smooth}$, with K_{sr} .

$$\alpha_{c,rough} = \alpha_{c,smooth} \cdot K_{sr} \quad (2.2)$$

Many analytical equations have been proposed to calculate K_{sr} based on material and geometric properties of conductors, where K_{sr} is usually a function of conductor skin depth and root-mean-square height of the surface roughness profile. The equations are usually only valid for a certain range of frequencies. The following provides an overview of the most popular models.

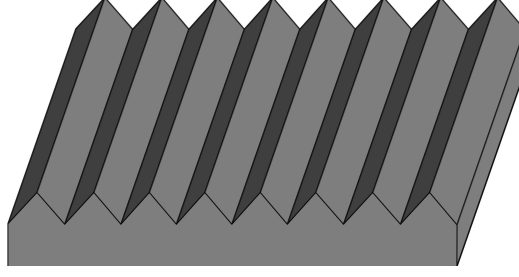


Figure 2.1: Morgan and Hammerstad model

2.1 Extraction of the Power Absorption Enhancement Factor

2.1.1 Models based on Periodic Structure Assumption

Over the years, analysis of the impact of conductor surface roughness on power absorption have relied upon the use of periodic structures. The surface of the conductor is modeled as periodic grooves or shapes protruding from a flat rectangle. The derived absorption enhancement factor is usually only valid for a certain type of surface roughness profile and does not hold for other roughness shapes.

Morgan and Hammerstad Model: Morgan's 1949 paper is probably the first power absorption analysis of the rough-surface conductor [1]. He modeled the rough conductor surface using a periodic groove profile, as shown in Figure 2.1, and evaluated the surface roughness effect by solving Maxwell's equation numerically using finite different method. Assuming current flow along the axis of periodicity, the additional power absorption caused by longer current travel path length due to surface roughness is calculated. Triangular and square grooves were considered and they gave similar results. He suggested that K_{sr} should correlate with the ratio of the root-mean-square height of surface roughness profile, Δ , to the skin depth, δ . Later, Hammerstad and Jensen proposed an empirical formula for calculating K_{sr} based on Morgan's result [2]. They ignored power absorption enhancement due to grooves parallel to the direction of current flow, and only fit Morgan's power absorption curve for grooves perpendicular to current flow. The resulting empirical equation takes the form of an inverse tangent function and pre-

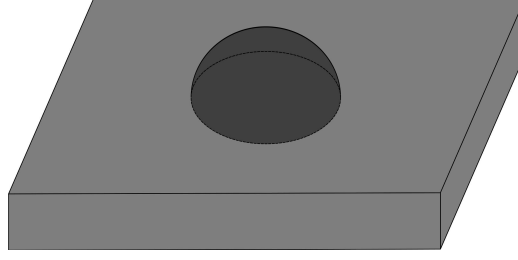


Figure 2.2: Hemispherical model

dicts that K_{sr} will saturate at higher frequencies with a maximum value of 2.

$$K_{sr} = 1 + \frac{2}{\pi} \cdot \arctan \left[1.4 \left(\frac{\Delta}{\delta} \right)^2 \right] \quad (2.3)$$

Groiss et al. measured quality factors of resonators and derived the expression for a similar factor, C_s , which is used to correct conductor loss [3]. The factor C_s they calculated also saturates with a maximum value of 2. Holloway and Kuester also verified Morgan's result using the finite element method [4]. Proekt and Cangellaris also investigated power absorption enhanced by rough conductor surface by using a perturbation method [5].

Hemispherical Model: Hallet al. modeled the rough conductor surface as conductor hemispheres protruding from a flat conductor plane, as shown in Figure 2.2, and derived an equation for K_{sr} that is accurate up to 30 GHz [6]. The hemispherical model requires additional geometrical factors like the spacing and the root-mean-square radius of hemispheres to be obtained, leading to more accurate results. Lukic and Filipovic used full-wave simulations to characterize the impact of conductor surface roughness [7]. 3-D cells of conductor surface with pyramidal, hemispherical, and cubical roughness profiles were simulated and analytical equations for K_{sr} were generated. Chen conducted full-wave simulation on rough conductors with electrolytes nickel-immersion gold plating and achieved good correlation with measured data [8]. He modeled the rough conductor surface using pyramids.

Snowball Model: Huray et al. developed a model to describe the conductor surface roughness as a pyramidal stack-up of spherical conductor snowballs on a flat conductor surface, as shown in Figure 2.3 [9, 10]. Born approximation technique was employed to calculate the K_{sr} with second order

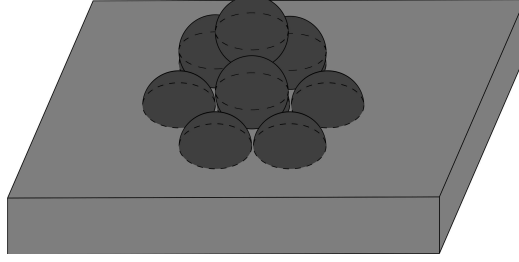


Figure 2.3: Snowball model

effects neglected. Partial wave analysis was performed on a single conducting sphere to extract the cross section for absorption. Then, maximum power absorbed by the stack-up of the spheres was calculated. They predicted that K_{sr} is independent of the stack-up form or root-mean-square height of the surface roughness profile but proportional to the total area of snowballs stacked on unit area. Fields were calculated taking into account the absorption and scattering effects of snowballs, and resulting wave losses agree with measured insertion loss up to 50 GHz. The snowball model achieves the best broadband accuracy but relies on the use of many parameters to define the surface roughness profile.

2.1.2 Models based on Random Surface Assumption

Recently, stochastic analyses were performed to investigate power absorption behavior of conductors with random surface roughness profiles. The conductor surface was modeled using random processes having certain statistical properties. Stochastic analysis was shown to be more flexible than analysis based on periodic structure assumption in the sense that results obtained from stochastic analysis are no longer subject to the specific type of surface roughness profile.

Stochastic Integral Equation Method: Chen and Wong proposed a stochastic integral equation based method, which involves the use of a surface boundary condition for a conductor with random surface roughness profile [11]. They derived the integral equation for the mean value of power loss based on a quasi-periodic assumption and solved the equation numerically using the method of moments (MoM). In a later paper, they derived a second-order correction to substantially improve the accuracy of their ap-

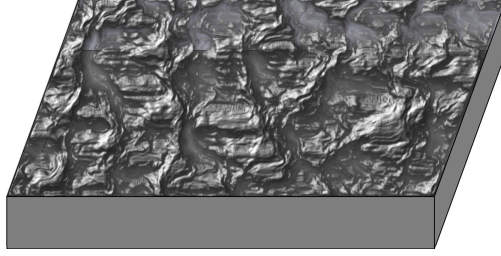


Figure 2.4: Random surface model

proach, while keeping the cost acceptable by utilizing model order reduction techniques [12]. However, the analysis was mostly restricted to the case where the conductor surface was considered to be smooth in one direction. The accuracy of the method was verified by numerical experiments.

Small Perturbation Method: Tsang et al. proposed a 2-D random rough surface model, derived closed-form K_{sr} expression by second order small perturbation method (SPM2), calculated K_{sr} for Gaussian and exponential rough surface, and numerically verified the results with MoM [13]. The resulting K_{sr} depends on root-mean-square height, correlation length, and correlation function of the random rough surface and does not saturate at high frequencies. Gu et al. [14] and Braunisch et al. [15] extracted a 2-D power spectral density (PSD) function of an isotropic rough surface from height measurements, calculated K_{sr} using the SPM2 method based on calculated PSD function, and considered the accuracy of the calculated K_{sr} in the context of attenuation loss for broadband signal transmission in microstrip lines. The estimated loss was shown to be accurate up to 20 GHz. Gu et al. extended the SPM2 method to 3-D configuration where the surface height varies in both horizontal directions as shown in Figure 2.4 [16]. Results were compared to those obtained by the T-matrix method and were found to agree well for rough surfaces with a small slope. It was also noted that saturation was observed for Gaussian rough surface but not exponential rough surface. Ding et al. put a rough conductor in a parallel plate waveguide and derived K_{sr} in guided wave environment by using SPM2 [17, 18, 19]. Higher power absorption was observed for small waveguide thickness. The result was validated with finite element method (FEM) simulation. A good summary of work done on power absorption analysis using SPM2 was provided by Tsang et al. [20] and was reiterated by Ding et al. [21].

2.2 Performing Electromagnetic Simulation

Since numerical field solvers do not have built-in support for simulating conductors with surface roughness, special techniques are necessary to incorporate the impact of surface roughness in the electromagnetic analysis. Some of the techniques used rely on the power absorption enhancement factor, K_{sr} . A summary is provided next.

2.2.1 Effective Parameters Based on Power Absorption Enhancement Factor

For the case of wave-guiding structures, K_{sr} can be used as a global correction factor for the attenuation constant in the presence of conductor surface roughness by directly multiplying with the smooth conductor attenuation constant, as shown in Equation 2.2. However, the proximity effect is neglected in such cases, which could lead to inaccuracies. Furthermore, there is a variety of passive electromagnetic devices (filters, resonator, power dividers, couplers, etc.) for which accurate modeling of the impact of roughness cannot be accomplished through a correction factor. An alternative way to include conductor surface roughness is to replace the conductor properties with an effective parameter or a set of parameters that model surface roughness in an accurate yet efficient manner.

Frequency Independent Effective Parameters: Brist et al. suggested two possible effective parameters to be used to characterize conductor surface roughness effect [22]. One suggestion was to use an effective skin depth. The extra power absorption caused by conductor surface roughness could be accounted for by a smaller than usual effective skin depth. Another suggestion was to use a higher than usual effective dielectric loss tangent. The two suggested methods were band-limited; thus, they failed to address the frequency dependent behavior of rough-surface induced loss.

Frequency Dependent Effective Parameters: Proekt and Cangellaris proposed the definition of a frequency dependent effective conductivity for the conductor to account for the impact of increased conductor resistance due to surface roughness [5]. Perturbation theory was used to find the solution

for the electromagnetic fields in the vicinity of the surface roughness and frequency dependent effective conductivity was derived for the rough-surface conductor. Braunisch et al. suggested the use of an effective conductivity to model non-uniform roughness[15]. However, his approach was tested only in the context of wave propagation in high-speed planar interconnects.

2.2.2 Motivation for the Research

This research is motivated by the limitation in using currently available field solvers to perform electromagnetic simulation on structures with rough-surface conductors. Field solvers solve Maxwell's equations without any quasi-static assumption and provide accurate simulation results. However, direct modeling of the conductor rough surface is not possible since the geometry of the rough surface is not exactly known and exhibits randomness. The high computational cost related to geometric complexity also makes the direct modeling approach prohibitive. Comparing to the direct modeling approach, the equivalent model approach is more practical, where an equivalent model with simple and deterministic geometry and material properties is derived and used in electromagnetic simulation to obtain an approximate result. However, the modeling ability greatly depends on the complexity of the equivalent model. Currently available field solvers only accept a simple description of the roughness profile during simulation and the ability to model the conductor surface roughness effect is inadequate. Methods that could describe rough conductors in great detail to give accurate simulation results, yet are easy to use under current electromagnetic solvers, are highly desired. The desire for such a method motivated this research.

CHAPTER 3

COMPOUND CONDUCTOR MODEL

Currently, methods to describe conductor roughness in electromagnetic simulation tools are limited. Direct modeling of the conductor rough surface is not possible since the geometry of the rough surface is not exactly known and exhibits randomness. In addition, the computational cost to analyze a moderate-sized structure via this manner is prohibitive. We are left with the option to use equivalent models with deterministic geometry and material properties to describe the conductor and to obtain approximate results through electromagnetic simulation. Currently available electromagnetic simulation tools only accept the root-mean-square height of the roughness profile as parameter and use it to modify the conductivity of the conductor accordingly during simulation. The method is not adequate for the accurate modeling of the conductor surface roughness effect. Alternatively, layered impedance boundary condition can be specified on the dielectric-conductor interface to account for the conductor surface roughness effect. This method provides more flexibility in the description of conductor surface roughness, but how to obtain the related parameters remains unclear. Methods that could describe rough conductors in great detail and are easy to use in electromagnetic simulation software are highly desired. To facilitate computer electromagnetic simulation of structures with rough-surface conductors, an equivalent model called the compound conductor model is proposed in [23]. Part of the original conductor with rough surface is shown in Figure 3.1. The basic idea of the compound conductor model is to replace the outer portion of the conductor where surface roughness occurs with an effective, smooth conductor layer conforming to the conductor contour, while keeping the interior of the conductor cross-section unaltered, as shown in Figure 3.2. Absence of the rough geometry in the compound conductor model simplifies electromagnetic simulation and improves efficiency. The goal of the compound conductor model is that one should be able to replace the

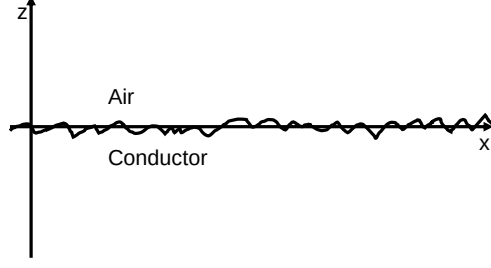


Figure 3.1: Rough-surface conductor

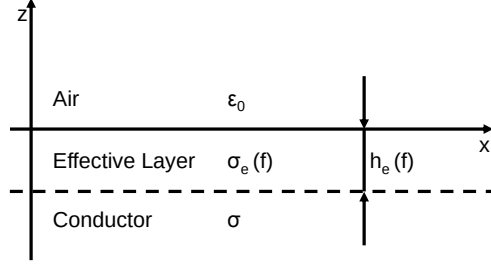


Figure 3.2: Compound conductor

rough-surface conductor with the compound conductor in electromagnetic simulation to achieve an accurate result. Since the power absorption enhancement factor, K_{sr} , is a widely accepted characterization for power absorption behavior of a rough-surface conductor, the compound conductor model is constructed to result in the same K_{sr} so that it can accurately account for the impact of conductor surface roughness.

3.1 Structure of the Compound Conductor

As shown in Figure 3.2, the proposed compound conductor model has its cross-section divided into two regions: a bulk conductor region which keeps the conductivity of original conductor, and a conformal outer layer which has different conductivity. The smooth outer layer is placed near the surface of the conductor where surface roughness occurs to mimic the behavior of conductor rough-surface. The thickness and conductivity of the outer layer could be made frequency-dependent, which provides flexibility to match the power absorption enhancement factor of the rough-surface conductor. The development of the compound conductor model amounts to the extraction of

the frequency-dependent conductivity and thickness of the outer layer. Once the frequency-dependent outer layer thickness and conductivity are extracted following the above steps, the compound conductor model could be used in field solvers to perform electromagnetic simulation.

3.2 Power Absorption Analysis

To extract the thickness and conductivity of the effective layer, we first analyze the power absorption behavior of the compound conductor, which amounts to the calculation of the power absorption enhancement factor, K_{sr} . K_{sr} for the compound conductor can be derived in terms of the thickness and conductivity of the outer layer by first deriving the expression for surface impedance, Z_s , of the compound conductor and then relating Z_s to K_{sr} .

3.2.1 Surface Impedance Calculation

The surface impedance, Z_s , of a layered conductor can be calculated by solving Maxwell's equations under plane-wave assumption, or, equivalently, as the input impedance looking into the conductor using a transmission line analogy. For the smooth conductor case, we have bulk conductor occupying a half-space, which is analogous to an infinitely long piece of transmission line. The input impedance looking into the conductor is the same as its intrinsic impedance. The surface impedance in this case is

$$Z_{s,smooth} = R_{s,smooth} + jX_{s,smooth} = \frac{1+j}{\delta\sigma} \quad (3.1)$$

where σ is the conductivity of the bulk conductor. For the rough conductor case, we have an outer layer attached to bulk conductor, which is analogous to a finite-length piece of transmission line cascaded to an infinitely long piece of transmission line. In this case, the surface impedance of the two-layer compound conductor is

$$\begin{aligned} Z_{s,rough} &= R_{s,rough} + jX_{s,rough} \\ &= \frac{1+j}{\sigma_e\delta_e} \frac{\sigma_e\delta_e + j\sigma\delta \tan(k_{1z}h_e)}{\sigma\delta + j\sigma_e\delta_e \tan(k_{1z}h_e)} \end{aligned} \quad (3.2)$$

where σ_e is the conductivity of the outer layer, $\delta_e = \frac{1}{\sqrt{\pi\mu\sigma_e f}}$ is the skin depth in it, and $k_{1z} \approx \frac{1-j}{\delta_e}$ is the propagation constant inside the outer layer in the direction perpendicular to the conductor surface.

3.2.2 Power Absorption Enhancement Factor

After calculating the surface impedance Z_s , to subsequently obtain K_{sr} , the ratio between power absorption of the rough-surface and smooth-surface cases is calculated. The rough surface case corresponds to the usual compound conductor model and the smooth surface case corresponds to the absence of the outer layer in the compound conductor model.

Assuming a planar air-conductor interface with the conductor occupying the bottom half-space, for the case of a TM-polarized plane wave of magnitude $|\mathbf{H}_{t,0}|$ on the conductor surface, the time-average power absorbed in the conductor, assuming a conductor layer of infinite extent, is calculated as

$$\begin{aligned} P_{a,smooth} &= \frac{1}{2} R_{s,smooth} |\mathbf{H}_{t,0}|^2 \\ &= \frac{1}{2\delta\sigma} |\mathbf{H}_{t,0}|^2 \end{aligned} \quad (3.3)$$

Time-averaged power absorption in the presence of surface roughness using the proposed compound conductor model can be calculated in a similar manner, where

$$\begin{aligned} P_{a,rough} &= \frac{1}{2} R_{s,rough} |\mathbf{H}_{t,0}|^2 \\ &= \frac{1}{2} \Re \left\{ \frac{1+j}{\sigma_e \delta_e} \frac{\sigma \delta + j \sigma_e \delta_e \tan(k_{1z} h_e)}{\sigma \delta + j \sigma_e \delta_e \tan(k_{1z} h_e)} \right\} |\mathbf{H}_{t,0}|^2 \end{aligned} \quad (3.4)$$

Making use of the result from above, the power absorption enhancement factor for the compound conductor model can be calculated as

$$\begin{aligned} K_{sr,c} &= \frac{P_{a,rough}}{P_{a,smooth}} \\ &= \Re \left\{ \frac{(1+j)}{\sigma_e \delta_e} \frac{\sigma \delta + j \sigma_e \delta_e \tan(k_{1z} h_e)}{\sigma \delta + j \sigma_e \delta_e \tan(k_{1z} h_e)} \right\} \end{aligned} \quad (3.5)$$

which, assuming that σ is fixed, could be further formulated to become an

expression in terms of h_e and σ_e .

3.3 Obtaining Model Parameter

K_{sr} of the actual conductor with surface roughness can be calculated based on measured roughness data using any method mentioned in the previous chapter. Take the approach in [15], for example. It is assumed that data is available for the description of the conductor surface roughness. Rough surfaces are usually characterized by their power spectral density (PSD). As first proposed in [16], K_{sr} can be calculated from the PSD by

$$\begin{aligned} K_{sr} &= \frac{\langle P_{a,rough} \rangle}{P_{a,smooth}} \\ &= 1 + \frac{2h^2}{\delta} - \frac{2}{\delta} \int_{-\infty}^{\infty} dk_x \int_{-\infty}^{\infty} dk_y W(k_x, k_y) \\ &\quad \cdot \Re \left(\sqrt{-\frac{2j}{\delta^2} - k_x^2 - k_y^2} \right) \end{aligned} \quad (3.6)$$

where h is the root-mean-square height of the rough surface, $W(k_x, k_y)$ is the PSD of the rough surface profile, and k_x, k_y are angular spatial frequencies. The root-mean-square height of the rough surface is calculated based on the PSD as

$$h^2 = \int_{-\infty}^{\infty} dk_x \int_{-\infty}^{\infty} dk_y W(k_x, k_y) \quad (3.7)$$

After calculating the K_{sr} of the actual conductor with surface roughness, h_e and σ_e are obtained by matching $K_{sr,c}$ with K_{sr} and inverting the mapping from h_e, σ_e to $K_{sr,c}$.

3.3.1 Inversion Using Minimum Possible Thickness

The combination of values for h_e and σ_e that gives the desired $K_{sr,c}$ value at given frequency is not unique. Thus, a process must be defined, where additional considerations are used to choose these parameters. To begin with, we note that, since the effective conductor layer takes up the space that is originally occupied by the bulk conductor, and the bulk conductor does not always extend to infinity, the thickness of the effective layer should

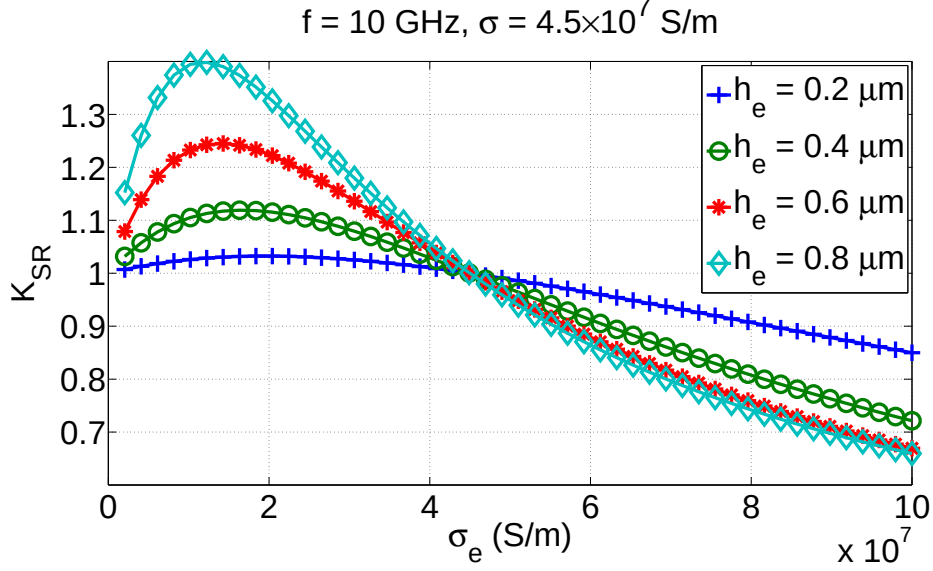


Figure 3.3: $K_{sr,c}$ vs σ_e curve for a family of h_e values at a given frequency

be constrained to be as small as possible. Therefore, we first find the smallest possible h_e and then determine the corresponding σ_e . Figure 3.3 shows the $K_{sr,c}$ vs. σ_e curve for a family of h_e values for a compound conductor with bulk conductivity $\sigma = 4.5 \times 10^7 \text{ S/m}$ at 10 GHz. Obviously, we can only achieve $K_{sr,c}$ values no more than the maximum value, $K_{sr,c,max}$, if we vary only the value of σ_e . At each frequency point, interpolation is performed on the curve $K_{sr,c,max}$ vs. h_e , as shown in Figure 3.4 to determine the minimum h_e that makes it possible to obtain the desired $K_{sr,c}$. Once the optimal value $h_{e,op}$ is found, interpolation is performed on the curve $K_{sr,c}$ vs. σ_e with the previously determined $h_{e,op}$ to determine the corresponding value $\sigma_{e,op}$ that generates the desired $K_{sr,c}$ at a given frequency, as depicted in Figure 3.5. The process can be repeated for each frequency point of interest, which leads to a compound conductor model characterized by frequency-dependent outer layer thickness and conductivity. The compound conductor generates the same power absorption enhancement factor as the actual rough-surface conductor.

3.3.2 Inversion Using Fixed Thickness

The aforementioned process generates a compound conductor model across arbitrary frequency range subject to the conditioning of the inversion pro-

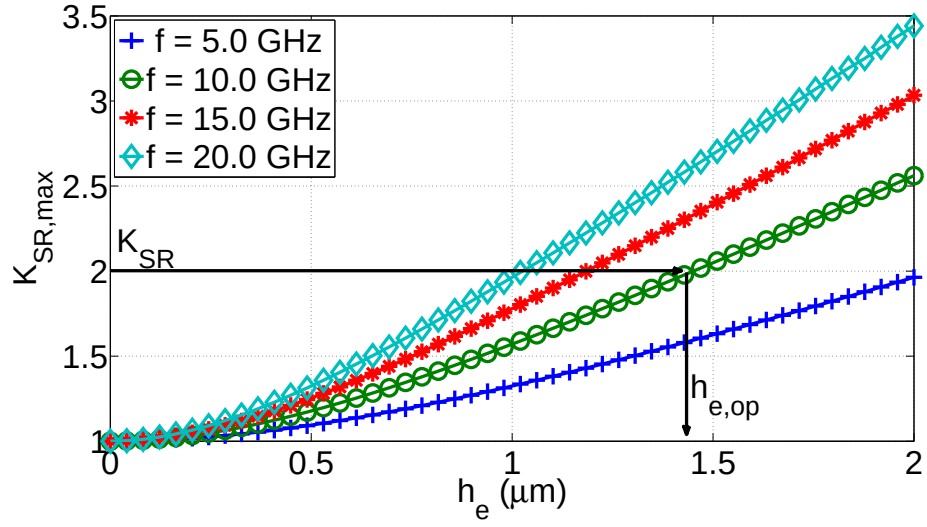


Figure 3.4: $K_{sr,c,max}$ vs h_e curve at a family of frequencies

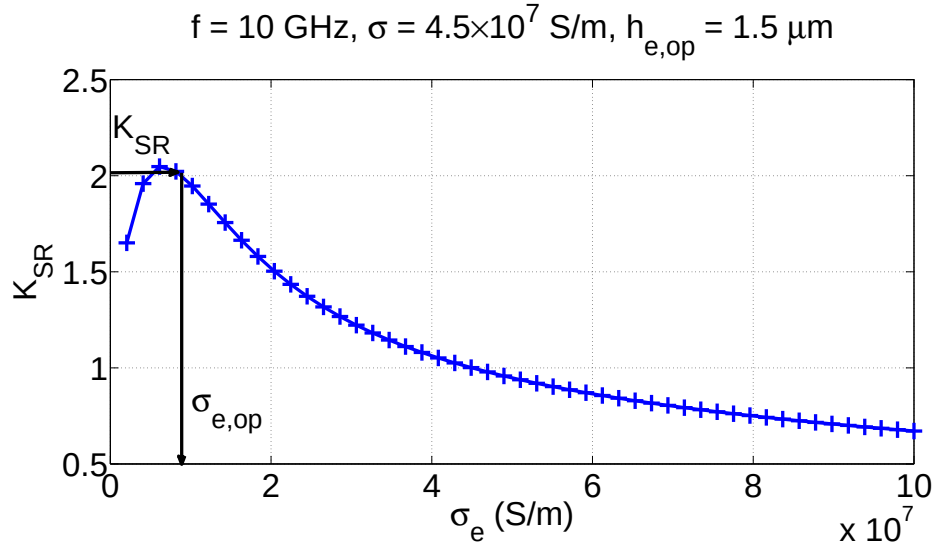


Figure 3.5: $K_{sr,c}$ vs σ_e curve with $h_{e,op}$ at given frequency

cess. However, in most applications we are only interested in simulating over a limited range of frequencies. In such cases, the thickness of the outer layer can be fixed to a chosen value and becomes frequency independent. The thickness of the outer layer has to be greater than the maximum $h_{e,op}$ value across frequency range of interests. Once the fixed thickness, h_e , is chosen, the conductivity of the outer layer, $\sigma_{e,op}$, can then be obtained following a procedure similar to that described before. The merit of this inversion strategy is that the geometry of the problem is fixed, which significantly simplifies the simulation process and increases efficiency by avoiding re-meshing.

It is worth noting that if we fix the thickness of the outer layer to be infinity, the resultant model is equivalent to replacing the conductivity of the entire conductor with an effective conductivity $\sigma_e = \frac{\sigma}{K_{sr}^2}$. The replacement of σ with σ_e is widely used as a way of simulating surface roughness and can be considered as a special case of the compound conductor model.

CHAPTER 4

MICROSTRIP TRANSMISSION LINE

To illustrate the application of the compound conductor model, the propagation properties of a microstrip transmission line with rough-surface conductor are investigated. The compound conductor model is derived following the result of power absorption analysis, and is used in subsequent electromagnetic simulation to extract the per-unit-length parameters of the transmission line. The attenuation of the transmission line modeled as a compound conductor is compared to the measurement data to verify accuracy.

4.1 Test Structure

In this chapter, the microstrip transmission line test structure in [15] is investigated. The test structure is shown schematically in Figure 4.1, where a two-line method is used to characterize the transmission line. The cross-section of the test structure is shown in Figure 4.2, with the conductor surface roughness being exaggerated. The key geometry parameters are taken to be the average of measurement values, and are listed in Table 4.1, together with key material properties. S-parameters of the two pieces of transmission line are measured, and attenuation over the length $\Delta l = l_2 - l_1$ is calculated, which

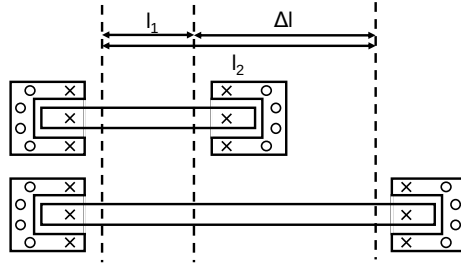


Figure 4.1: Microstrip transmission line test structure

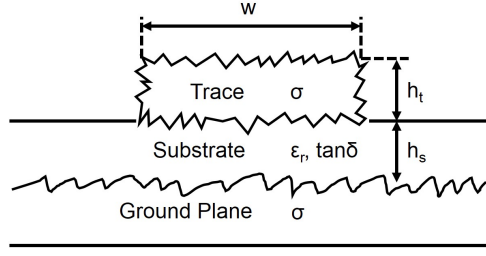


Figure 4.2: Cross-section of microstrip transmission line test structure

Table 4.1: Geometry parameters and material properties of microstrip line

Property	Symbol	Value	Unit
Short Line Width	l_1	12.3	mm
Long Line Width	l_2	24.3	mm
Line Width	w	65.5	μm
Substrate Thickness	h_s	30.6	μm
Trace Thickness	h_t	15.3	μm
Dielectric Relative Permittivity	ϵ_r	3.4	1
Dielectric Loss Tangent	$\tan \delta$	0.017	1
Metal Conductivity	σ	4.5×10^7	S/m

will be used as a reference for correlating modeling results.

The ground plane conductor is removed after S-parameter measurement and PSD for the substrate surface is measured using atomic force microscopy. It should be noted that the roughness on the substrate is transferred to the conductor during metallization and the roughness profile on the substrate suffices to represent the conductor surface roughness. After measuring PSD of the rough conductor surface, K_{sr} is calculated as documented in [15], and the K_{sr} versus frequency curve is plotted in Figure 4.3.

4.2 Compound Conductor Model

Compound conductor models are derived using the two different inversion strategies as mentioned in Chapter 3 based on the calculated K_{sr} value.

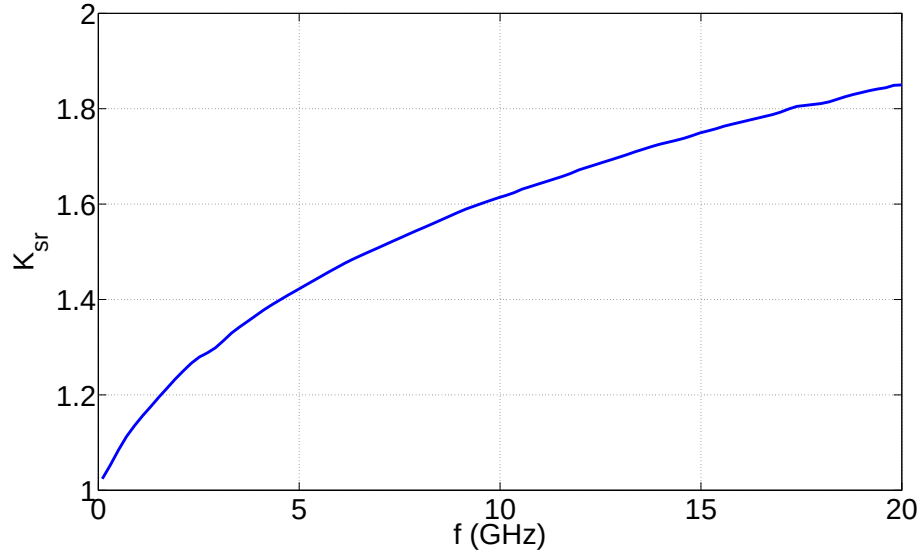


Figure 4.3: Power absorption enhancement factor for the microstrip transmission line

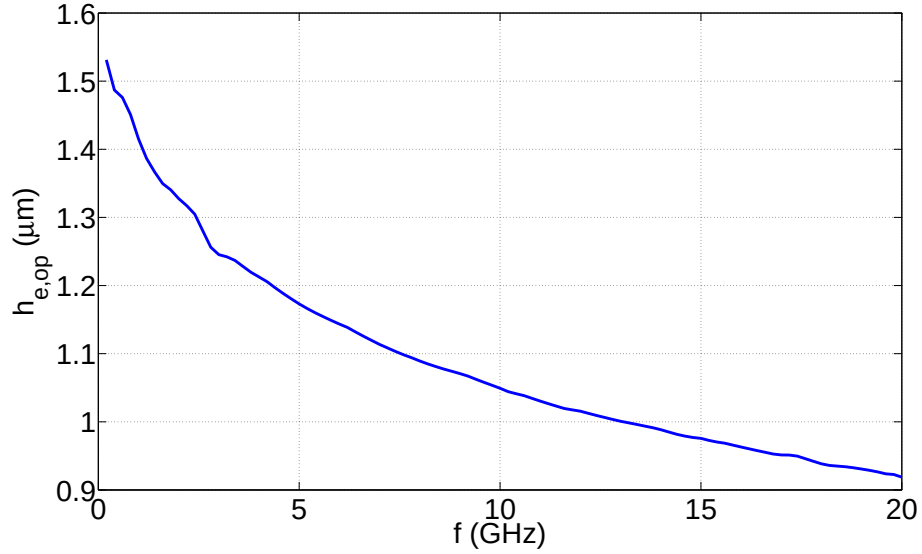


Figure 4.4: Outer layer thickness for minimum possible outer layer thickness compound conductor model for microstrip transmission line

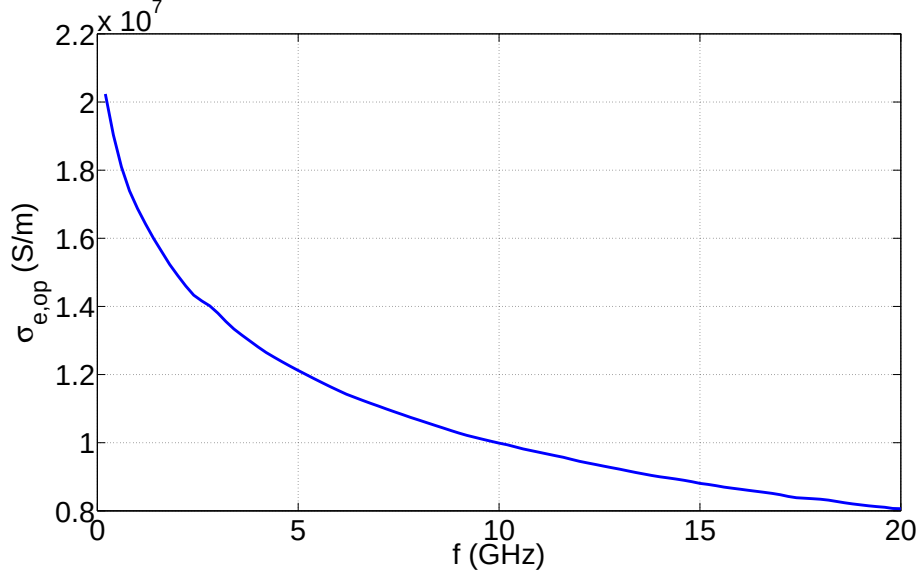


Figure 4.5: Outer layer conductivity for minimum possible outer layer thickness compound conductor model for microstrip transmission line

4.2.1 Minimum Possible Outer Layer Thickness Model

Using the methodology for deriving minimum possible outer layer thickness model from calculated K_{sr} , we get the frequency-dependent thickness and conductivity of the outer conducting layer, as shown in Figure 4.4 and Figure 4.5. Note that the frequency-dependent thickness and conductivity are calculated down to 0.2 GHz. As the frequency goes lower, the problem becomes ill-conditioned and interpolation cannot be applied. For the extreme case corresponding to zero frequency, thickness and conductivity of the outer layer could assume any value since all combinations of h_e and σ_e lead to the same desired K_{sr} , which is 1.

4.2.2 Fixed Outer Layer Thickness Model

Alternatively, if we are only interested in simulating the microstrip line structure within a limited frequency range, say, from 0.2 GHz to 20 GHz in this case, h_e could be fixed to a value greater than the maximum $h_{e,op}$ over the entire frequency range of interest. In our case, h_e is chosen to be fixed at $1.6 \mu\text{m}$. Interpolation is performed to obtain corresponding $\sigma_{e,op}$ value, which is shown in Figure 4.6. This compound model can be used in subsequent electromagnetic simulation to replace the rough-surface conductor.

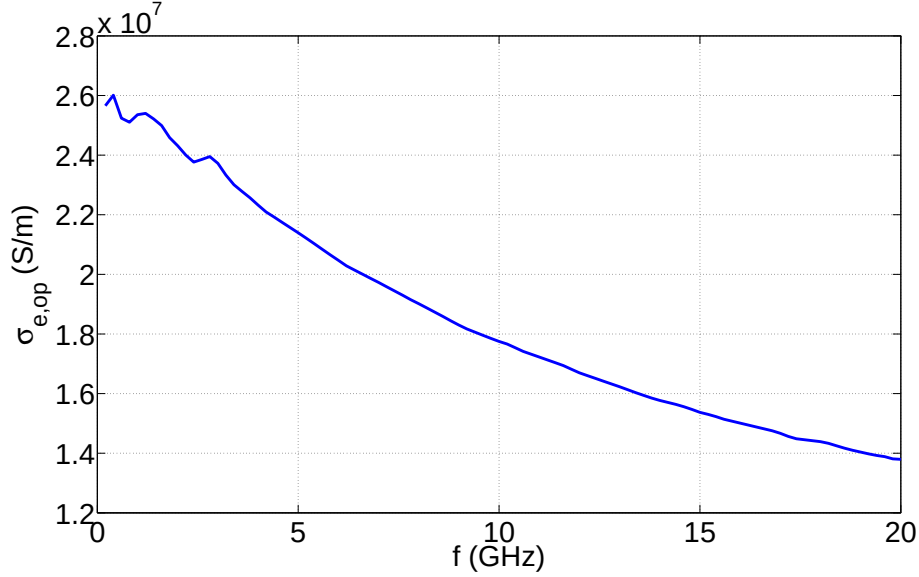


Figure 4.6: Outer layer conductivity for fixed outer layer thickness ($h_e=1.6\text{ }\mu\text{m}$) compound conductor model for microstrip transmission line

Since the geometry of the problem is no longer changing with frequency, a static model can be created with the outer layer conductor being assigned as frequency-dependent material, which dramatically cuts down the simulation time since the mesh for the highest solution frequency will be reused for simulation at lower frequency points.

4.3 Simulation Results

A 2-D cross-sectional model of the transmission line structure with its rough-surface conductor being replaced by compound conductor is created in ANSYS® Q3D Extractor® [24], as shown in Figure 4.7. The surface roughness of the microstrip conductor is assumed to be the same as that for the ground plane. Hence, the same outer layer is used to modify both the trace conductor and the ground plane. Cases corresponding to two different strategies in generating compound conductor models are simulated and results are compared to the case where conductivity for the entire metal is modified based on the power absorption enhancement factor. The case corresponding to a smooth conductor without any surface roughness is also simulated as a reference. The structure is simulated to obtain the per-unit-length resistance

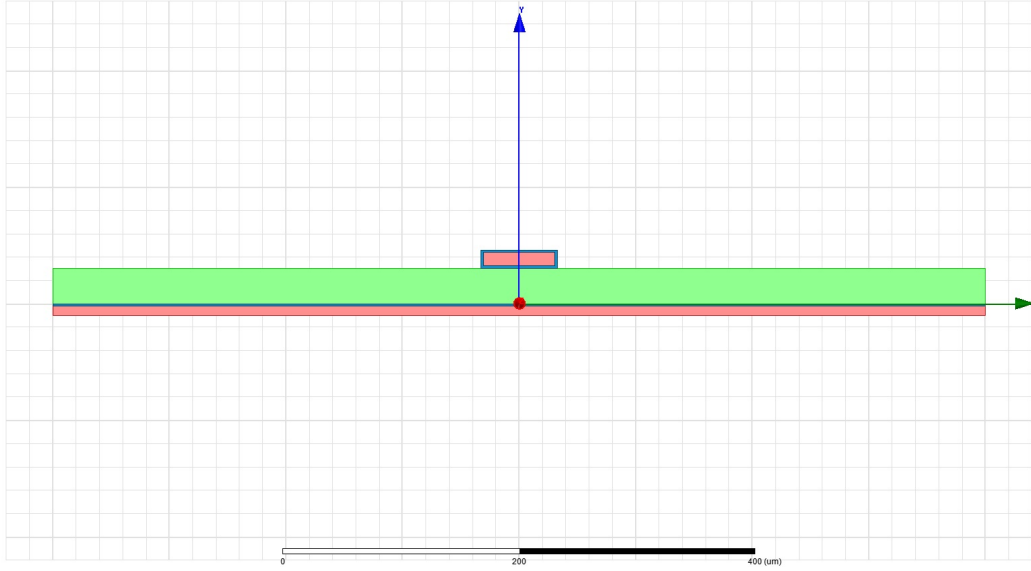


Figure 4.7: Cross-sectional model of microstrip transmission line with compound conductor in Q3D Extractor®

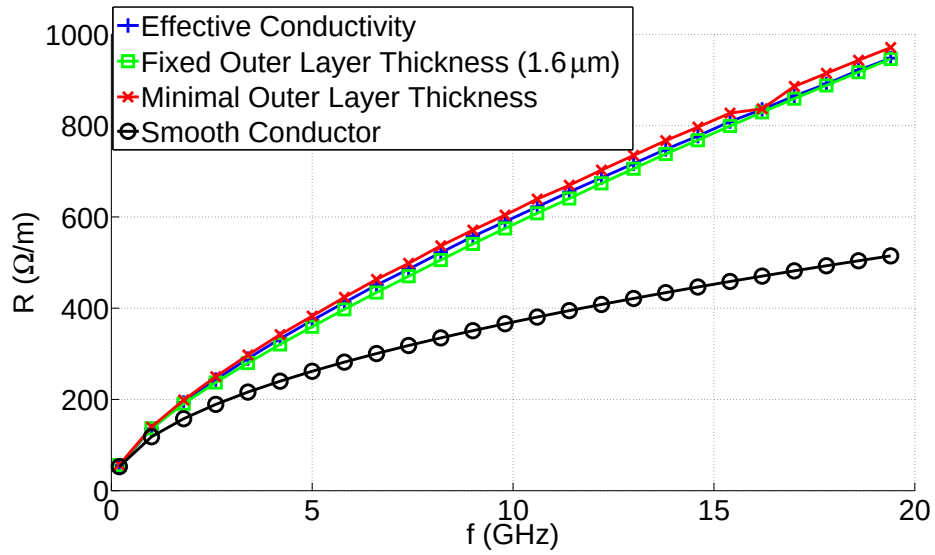


Figure 4.8: Per-unit-length resistance extracted from microstrip transmission line models

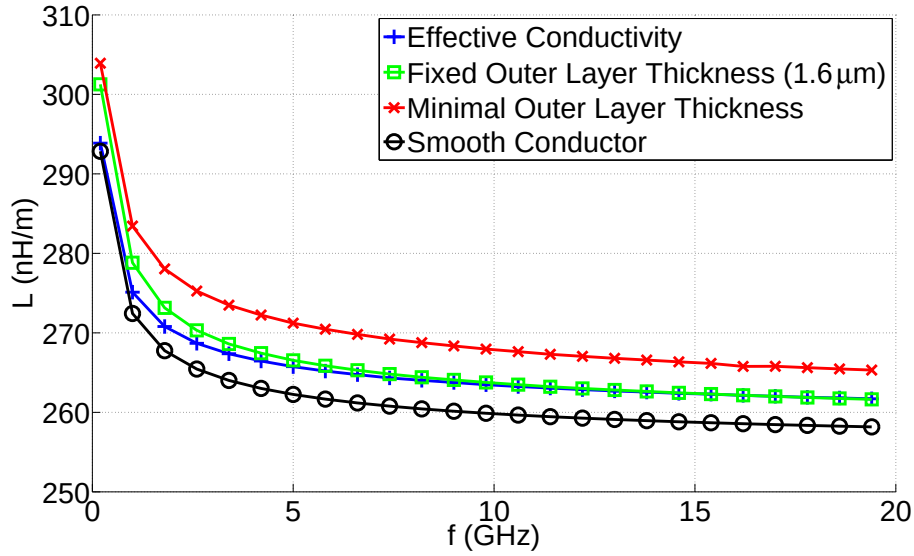


Figure 4.9: Per-unit-length inductance extracted from microstrip transmission line models

and inductance parameters, as shown in Figures 4.8 and 4.9. As can be seen from the results, the compound conductor model constructed using minimal outer layer thickness approach predicts higher per-unit-length resistance and inductance as compared to that constructed using fixed outer layer thickness approach. The effective conductivity model's prediction is close to the prediction of the minimal outer layer thickness model at low frequency. As frequency goes higher, its prediction becomes closer to the prediction of the fixed outer layer thickness model. The attenuation constant of the microstrip transmission line structure is extracted and compared to the measured attenuation constant from [15]. As shown in Figure 4.10, the attenuation predicted by all models achieves satisfactory agreement with measurement, while the minimal outer layer thickness model's predicted attenuation constant shows a closer match to that of measured data at high frequency.

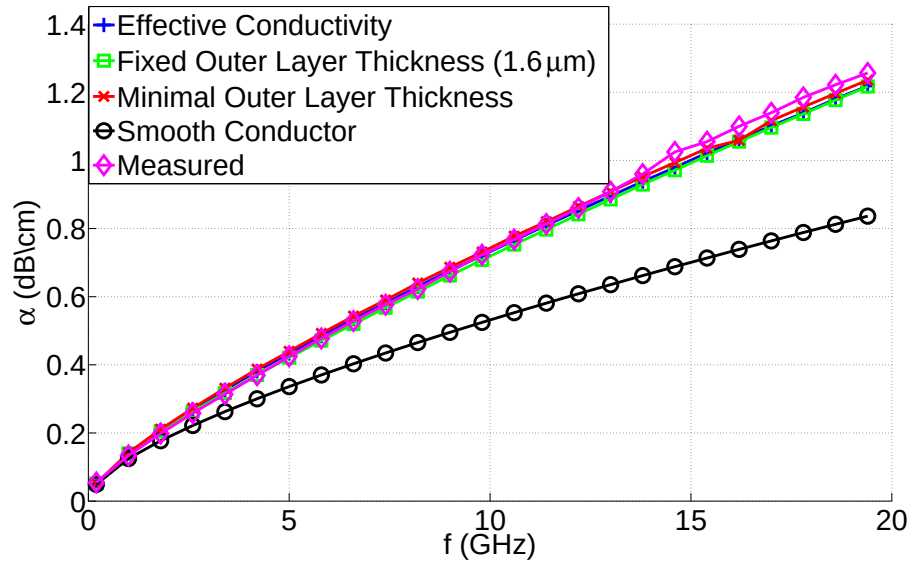


Figure 4.10: Attenuation constant extracted from microstrip transmission line models

CHAPTER 5

MICROWAVE FILTER

To further illustrate the application of the compound conductor model, a microwave filter with rough-surface conductor is investigated. The same compound conductor model as that in Chapter 4 is used in simulating the response of a 12 GHz bandpass filter. The S-parameters of the filter modeled using different approaches are reported and resultant center frequencies and bandwidths are compared.

5.1 Test Structure

In this chapter, a microstrip edge-coupled bandpass filter with center frequency at 12 GHz is considered. The filter consists of two symmetrically connected sections, and layout of the filter is shown in Figure 5.1. The stack-up view of the filter is shown in Figure 5.2. The key geometry and material parameters are listed in Table 5.1. Trace and ground conductors in the filter are assumed to have the same surface roughness profile as those in the microstrip transmission line example.

5.2 Compound Conductor Model

The surface profile of the trace and ground conductors are assumed to be the same as those in Chapter 4, which results in a similar compound conductor model being derived. Parameters for the compound conductor model are derived only in a frequency range of 8 GHz to 16 GHz since we are only interested in the S-parameters of the filter near its center frequency, 12 GHz.

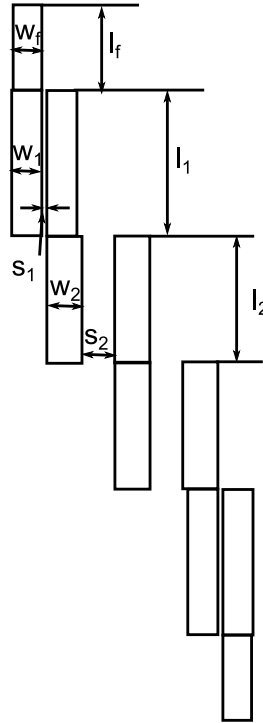


Figure 5.1: Microwave filter layout

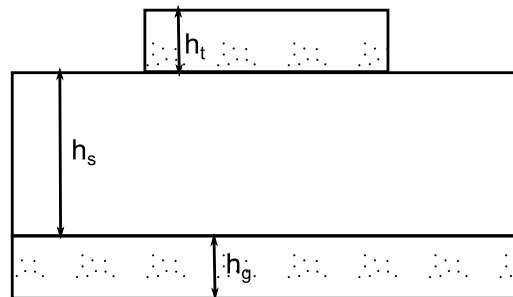


Figure 5.2: Microwave filter stack-up view (clear: dielectric; dotted: conductor)

Table 5.1: Geometry and material properties of microwave filter

Property	Symbol	Value	Unit
Feed Line Width	w_f	27.4	mil
Feed Line Length	l_f	100	mil
Coupled Line 1 Width	w_1	27.5	mil
Coupled Line 1 Spacing	s_1	3	mil
Coupled Line 1 Length	l_1	145	mil
Coupled Line 2 Width	w_2	34	mil
Coupled Line 2 Spacing	s_2	18	mil
Coupled Line 2 Length	l_2	142	mil
Substrate Thickness	h_s	15	mil
Trace Thickness	h_t	2	mil
Ground Plane Thickness	h_g	5	mil
Dielectric Relative Permittivity	ϵ_r	3.4	1
Dielectric Loss Tangent	$\tan \delta$	0.017	1
Metal Conductivity	σ	4.5×10^7	S/m

5.2.1 Minimum Possible Outer Layer Thickness Model

Frequency dependent thickness and conductivity of the outer conducting layer are shown in Figures 5.3 and 5.4.

5.2.2 Fixed Outer Layer Thickness Model

Thickness h_e is chosen to be fixed at $1.1 \mu\text{m}$. This value is different from microstrip transmission line example since we are interested in a different frequency range. Interpolation is performed to obtain corresponding $\sigma_{e,op}$ value, which is shown in Figure 5.5.

5.3 Simulation Results

A 3-D model of the microwave filter with its rough-surface conductor being replaced by compound conductor is created in ANSYS® HFSS® [25], as shown in Figure 5.6. Figure 5.7 is a close-up look at the compound conductor structure in the 3-D model. Filters modeled using different methods are simulated in ANSYS® HFSS® to obtain the S-parameters, as shown in Figures 5.8 and 5.9. The center frequency and bandwidth of the filters are

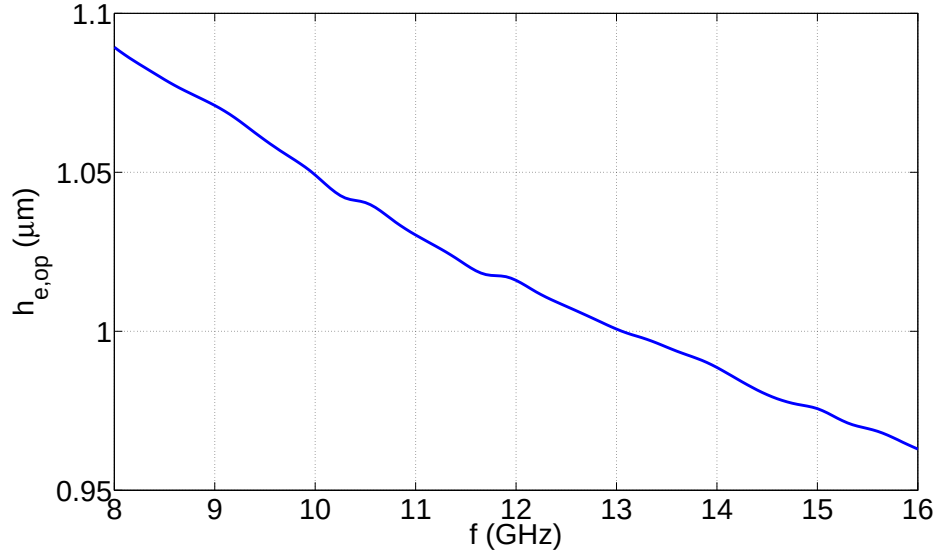


Figure 5.3: Outer layer thickness for minimum possible outer layer thickness compound conductor mode for microwave filter

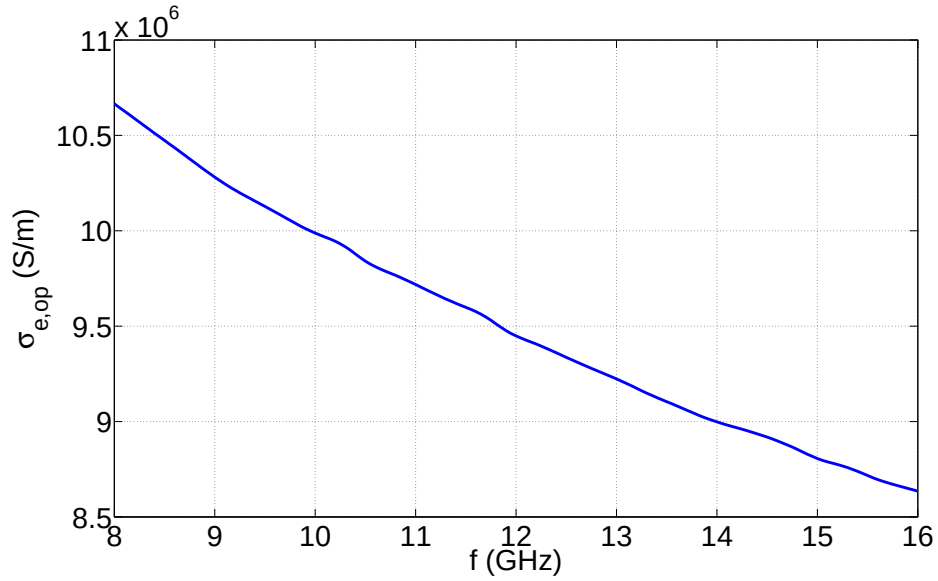


Figure 5.4: Outer layer conductivity for minimum possible outer layer thickness compound conductor model for microwave filter

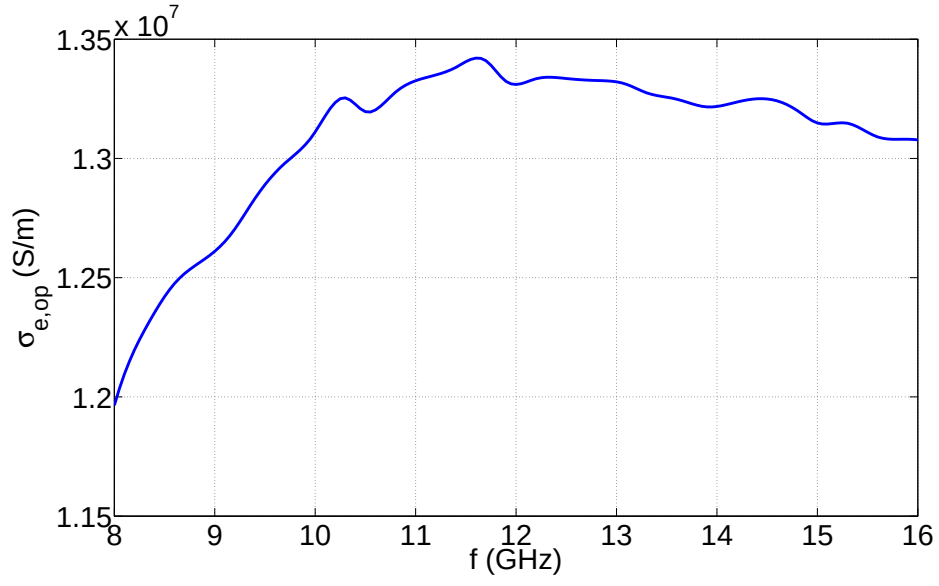


Figure 5.5: Outer layer conductivity for fixed outer layer thickness ($h_e=1.1\mu\text{m}$) compound conductor model for microwave filter

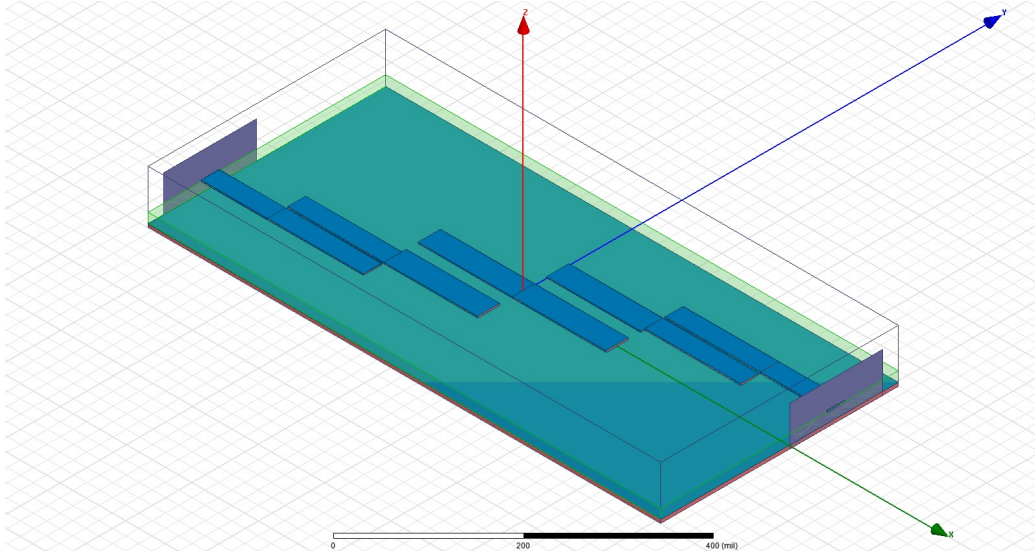


Figure 5.6: 3-D model of microwave filter with compound conductor in HFSS®



Figure 5.7: Close-up view of compound conductor structure in 3-D model of microwave filter in HFSS®

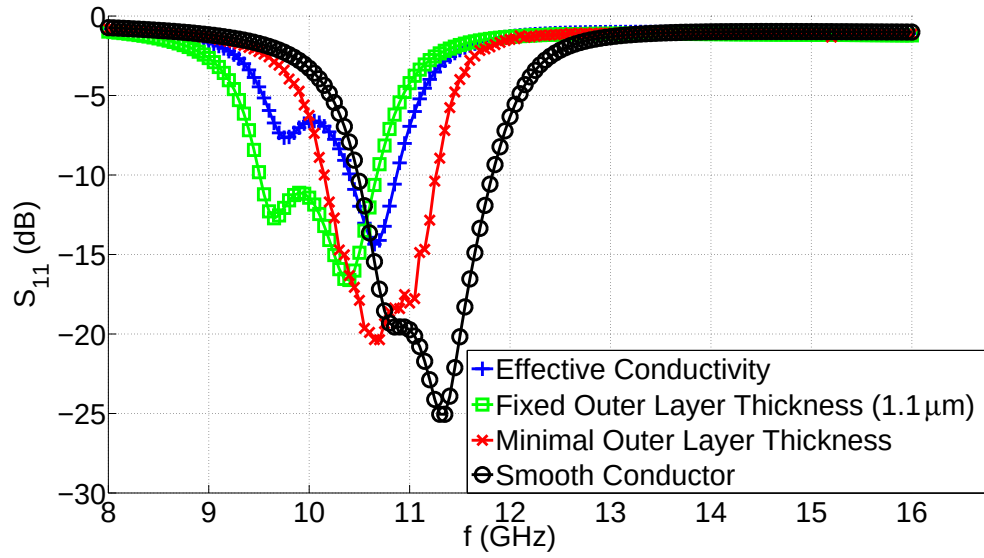


Figure 5.8: S_{11} of microwave filters from different models

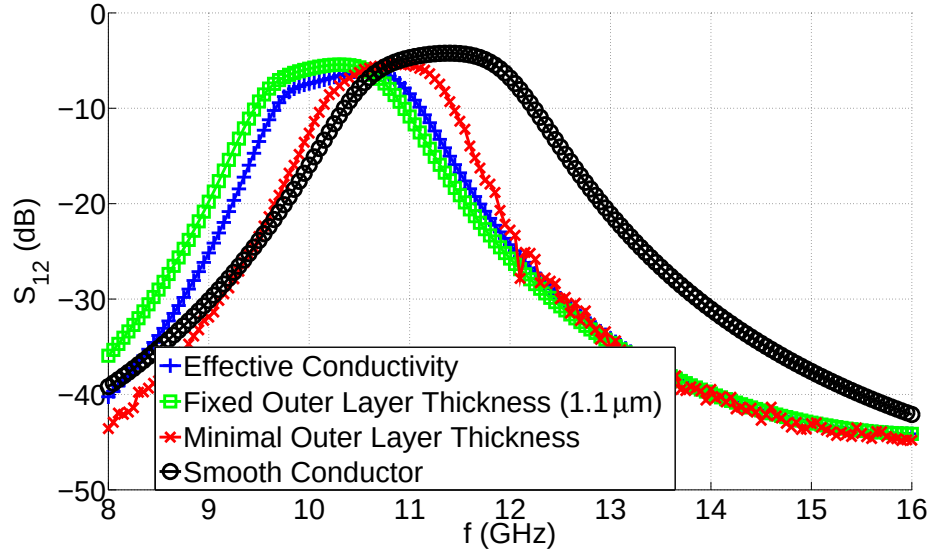


Figure 5.9: S_{12} of microwave filter from different models

Table 5.2: Microwave filter parameters

Model	Center Frequency	Bandwidth
Effective Conductivity	10.60GHz	1.30GHz
Fixed Outer Layer Thickness	10.30GHz	1.30GHz
Minimal Outer Layer Thickness	10.90GHz	1.10GHz
Smooth Conductor	11.40GHz	1.50GHz

calculated from S_{12} and then compared in Table 5.2. As can be seen from the results, the fixed outer layer thickness model predicts the lowest resonance frequency, while the minimal outer layer thickness model predicts the narrowest bandwidth. Additional studies are needed to further investigate the accuracy of models.

CHAPTER 6

CONCLUSION

In this thesis, background on conductor surface roughness effect research was reviewed, and the author's research motivation was explained. The compound conductor model was introduced for the convenient and accurate handling of conductor surface roughness in electromagnetic characterization using field solvers. The key idea of the proposed model is the replacement of the thin surface layer of the conductor within which the roughness occurs with a smooth outer layer conformal to the conductor surface. The thickness and conductivity of this outer layer are frequency-dependent and their values are obtained through a systematic process that requires that the two surfaces, the one with roughness and the one with the conformal outer layer, exhibit the same frequency-dependent power absorption behavior. The advantage of an equivalent model for a rough-surface conductor in general is to reduce the complexity induced by complex geometry, which could improve electromagnetic simulation efficiency. Specifically, the compound conductor model relates more closely to the actual physics and provides better accuracy than naive methods. The application of the compound conductor model was illustrated by electromagnetic simulation of a microstrip transmission line test structure with rough-surface conductor. The result showed good agreement between the predicted and the measured attenuation. In addition, a microwave filter was modeled using the compound conductor approach and discrepancies between the predicted center frequencies and bandwidths were observed. Even though the accuracy of the compound conductor model is validated and several applications are demonstrated, much work remains to be done. Correlation with measurement is needed to evaluate the accuracy of the compound conductor model in modeling microwave filters. Steps to model non-uniform roughness using the proposed compound conductor model need to be detailed. Especially, the power absorption property of the rough-surface conductor away from planar region needs to be discussed in further

detail, and the corresponding modeling methodology will be discussed in future work.

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