

RF Modeling and Simulation of Anti-reflective Coatings in View of Substrate Resonances

Jasmin Smajic¹, *Senior Member IEEE*, Hande Ibili¹, Michael Baumann¹, and Juerg Leuthold¹, *Fellow, IEEE*

¹Institute of Electromagnetic Fields (IEF), ETH Zurich, CH-8092 Switzerland, smajicj@ethz.ch

Modern communication systems for highest frequency range and bandwidths are compact solutions relying on hybrid photonic-electronic antenna integrated circuits. One of the important problems of this technology is substrate resonances at mm-wave and sub-terahertz frequencies producing highly nonlinear frequency characteristics of RF components fabricated on top of the substrate, such as antennas and electro-optical modulators. This paper presents a method for simplified modeling of anti-reflective coatings in large and detailed 3-D electromagnetic simulations by representing complicated and periodical geometrical coating features via frequency-dependent permittivity of the homogeneous coating layer. The accuracy of the proposed method is verified by comparison against detailed high-fidelity models.

Index Terms—Anti-reflective coating, substrate resonances, mm-waves, terahertz waves.

I. INTRODUCTION

THE PROBLEM OF substrate resonances at mm-wave and terahertz frequencies presently attracts a considerable attention from the wider scientific community as it is a bottleneck in developing hybrid photonic-electronic antenna integrated circuits using standard silicon technology [1]. At the bottom of this problem is the reflection of RF waves from both interfaces of a silicon substrate with air producing standing waves within the substrate [2].

To illustrate the problem, an arrangement of a silicon substrate surrounded by air is presented in Fig. 1a. The frequency characteristic of this substrate in terms of its transmission coefficient (the red line in Fig. 1b) reveals periodic peaks and dips of transmission appearing at the odd- and even multiples of $\lambda_s/4$, respectively, where λ_s is the substrate wavelength. Any electronic device on the substrate surface receiving electromagnetic waves would have those peaks in its frequency characteristic.

To mitigate the above problem various types of anti-reflective coatings (ARCs) have been considered [3]. Following a simple theory of wave reflection and transmission at the interface between two materials, it is possible to define an anti-reflective coating at a single wavelength according to the following approach [4].

$$\epsilon_{rc} = \sqrt{\epsilon_{r1}\epsilon_{r2}} \quad (1)$$

$$\delta = \lambda_0 / (4\sqrt{\epsilon_{rc}}) \quad (2)$$

where ϵ_{rc} and δ are the relative permittivity and thickness of the coating, respectively, ϵ_{r1} and ϵ_{r2} are the permittivities of the involved materials, and λ_0 is the free space wavelength.

The coating layer described by Equations (1) and (2) completely removes the reflection at the frequency of 150 GHz ($\epsilon_{r1} = 1$, $\epsilon_{r2} = 11.7$) and reduces it in the surrounding frequency range. The coating layer is applied only from one side of the substrate, which is enough to remove the resonance at 150 GHz and to offer a 3dB bandwidth of almost 100 GHz. This is clearly

visible in Fig. 1b (the solid blue line) where the amplitude of the ripples around 150 GHz drops and the mean value approaches $T = -1.55$ dB, corresponding to a single air-silicon interface.

It is worth mentioning, that several coating layers can be used in order to achieve efficient broadband operation. In the reference [3] several different ways to practically realize anti-reflective coating were described, such as layer composition-based, or surface topography-based coatings. From the hybrid photonic-electronic integrated circuits point of view, the single-layer inhomogeneous coatings are of particular interest due to their relatively simple etching into the substrate outer surface, as shown in Fig. 2.

Having such detailed and inhomogeneous coating patterns, it is almost impossible to model and simulate them in a large detailed 3-D model. This paper proposes a technique to solve this problem.

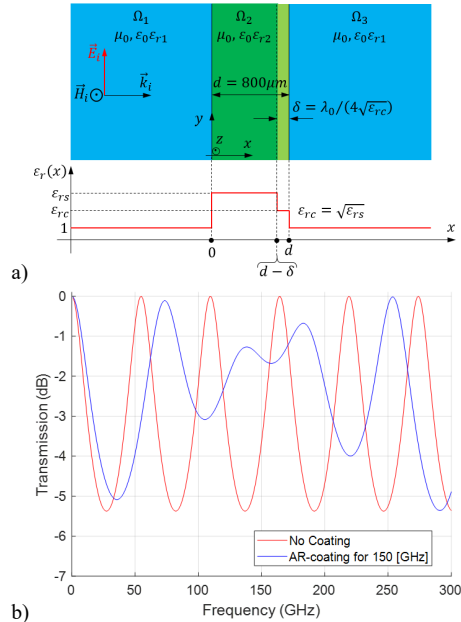


Fig. 1. (a) Arrangement of a silicon substrate (green) with an anti-reflective coating (light green) surrounded by air (blue) and illuminated by a plane wave from the left is shown. (b) The transmission coefficient of the substrate with and without the anti-reflective coating is presented. More details can be found in the text.

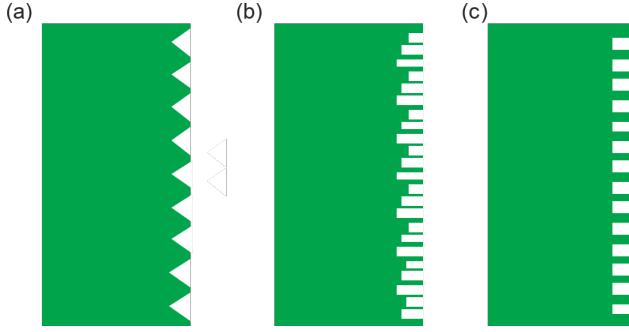


Fig. 2. Different possibilities to practically realize anti-reflective coating by using the inhomogeneous single-layer approach, i.e. pyramidal/cylindrical extraction.

II. MODELING METHODS AND INITIAL RESULTS

We propose here the following two techniques.

- a. Method 1 is based on the desired frequency curve of the coated substrate. Starting with this a homogenous single- or multi-layer coating should be developed and used in high-fidelity simulations. In addition to this, a low-complexity model of a substrate cell should be implemented to develop the real inhomogeneous coating pattern that will have the same reflection characteristic as the corresponding homogenous one. The details of this method will be presented at the conference.
- b. Method 2 starts with a possible inhomogeneous coating pattern given by the constraints of the available fabrication etching equipment. For this coating pattern a detailed 3-D model of a single cell will be simulated to obtain the coating frequency characteristic. Based on this characteristic the equivalent homogenous coating will be obtained using an analytical model and utilized in high-fidelity 3-D simulations for evaluating the coating efficiency in a real 3-D device. The details of this procedure will also be shown at the conference.

In both cases, the main idea is to have a one to one mapping of the inhomogeneous structure to a homogeneous coating, which can then be used in large high-fidelity simulations.

To illustrate this procedure, an inhomogeneous coating pattern based on Method 1 has been derived and presented in Fig. 3(a). The obtained frequency curve (green line) in Fig. 3(b) shows a very similar behavior as the reference homogenous coating (blue line) presented in Fig. 1. This result illustrates the core idea of the proposed technique and confirms its validity and accuracy.

In a more complicated situation with a 3-D substrate, the proposed technique will not be as simple as in the presented 2-D case. If the coating is, however, well designed and if the thickness of the substrate is considerably smaller than its planar dimension (see Fig. 4), the technique should still work well and yield high quality results. This will be demonstrated with a 3-D example at the conference and in the subsequent full paper.

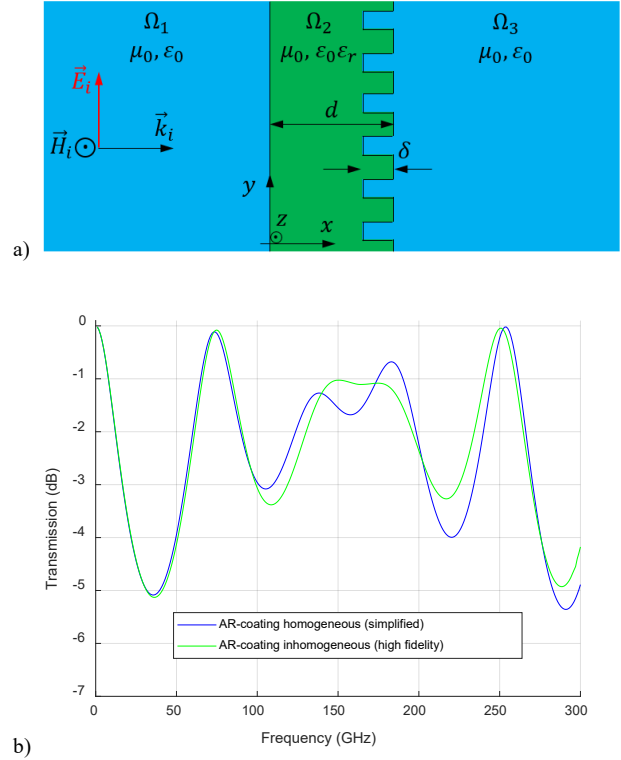


Fig. 3. Numerical results of the detailed high-fidelity 2-D model of the inhomogeneous single-layer substrate coating presented in Fig. 1. The height of the holes and teeth were $30\mu\text{m}$ and $70\mu\text{m}$, respectively.

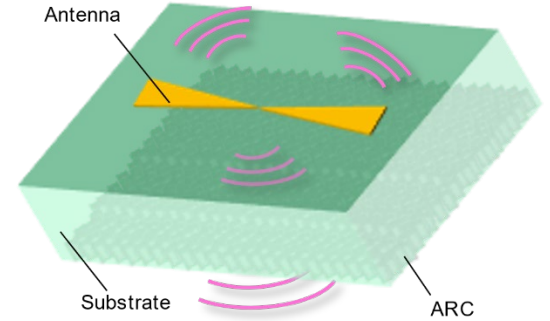


Fig. 4. Envisioned application of the proposed technique in high-fidelity 3-D models.

REFERENCES

- [1] Atif Shamim and Haoran Zhang, "On-chip antenna: challenges and design considerations," in *Antennas and Propagation for 5G and Beyond*, Q. H. Abbasi, S. F. Jilani, A. Alomainy, and M. A. Imran, Eds., Institution of Engineering and Technology, 2020, pp. 123–155. doi: 10.1049/PBTE093E_ch6.
- [2] E. R. Brown, C. D. Parker, and E. Yablonovitch, "Radiation properties of a planar antenna on a photonic-crystal substrate," *J. Opt. Soc. Am. B, JOSAB*, vol. 10, no. 2, pp. 404–407, Feb. 1993, doi: 10.1364/JOSAB.10.000404.
- [3] H. K. Raut, V. A. Ganesh, A. S. Nair, and S. Ramakrishna, "Anti-reflective coatings: A critical, in-depth review," *Energy Environ. Sci.*, vol. 4, no. 10, pp. 3779–3804, Sep. 2011, doi: 10.1039/C1EE01297E.
- [4] A. J. Gatesman, J. Waldman, M. Ji, C. Musante, and S. Yagvesson, "An anti-reflection coating for silicon optics at terahertz frequencies," *IEEE Microwave and Guided Wave Letters*, vol. 10, no. 7, pp. 264–266, Jul. 2000, doi: 10.1109/75.856983.