Microwave and Millimeter Wave Evaluation of Multi-Layered Structures

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Microwave and millimeter-wave signals span the frequency ranges of ~300 MHz-30 GHz and 30 GHz-300 GHz, corresponding to wavelength ranges of 1000-10 mm and 10-1 mm, respectively. Signals at these frequencies readily penetrate inside dielectric materials and composites and interact with their inner structures. The intrinsic nature of the interaction of these signals with material media, the relatively small wavelengths and wide bandwidths associated with them enable inspection of a variety of materials with high a degree of sensitivity. Pertinent to this presentation, the efficacy and utility of thickness and dielectric property characterization, using a robust open-ended rectangular waveguide technique, has been studied and substantially improved upon during the past (nearly) three decades leading to the recent development of a unique engineered waveguide probe. This technique has now fully evolved to give an accurate estimation of complex permittivity distribution and thickness of layers in a stratified composite structure. This technique is capable of evaluating coating (single- or multi-layered) thicknesses and complex permittivity properties on a variety of substrates including conducting and carbon composite substrates. Complex permittivity information can be correlated to other materials properties allowing for the evaluation of critical characteristics such as temporal property changes, cure state monitoring, volumetric porosity estimation, etc. The inherent optimization capabilities offered by this technique allow for maximizing measurement robustness as a function of undesired measurement parameters (i.e., liftoff change, composite surface roughness, etc.). This presentation gives an overview of this microwave nondestructive evaluation technique, the fundamental electromagnetic principles of the forward and the inverse (forward-iterative) calculations and the design foundation of the engineered waveguide probe. Issues related to layer property calculation accuracy with respect to several critical parameters (i.e., thickness, substrate properties, etc.) will be discussed along with several illustrative examples. In addition, recent developments in this field using open-ended circular waveguide probes with distinct advantageous practical features will also be presented.

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R. Zoughi received his B.S.E.E, M.S.E.E, and Ph.D. degrees in electrical engineering (radar remote sensing, radar systems, and microwaves) from the University of Kansas where from 1981 until 1987 he was at the Radar Systems and Remote Sensing Laboratory (RSL). He is the Kirby Gray (Battelle) Chair in Engineering and a Professor Electrical and Computer Engineering (ECpE) at Iowa State University (ISU). He is also the Director of Center for Nondestructive Evaluation (CNDE) at ISU. He served as the Schlumberger Endowed Professor of Electrical and Computer Engineering at Missouri University of Science and Technology (Missouri S&T) from January 2001 to August 2019. Prior to joining Missouri S&T and since 1987 he was with the Electrical and Computer Engineering Department at Colorado State University (CSU), where he was a professor and established the Applied Microwave Nondestructive Testing Laboratory (*amntl*) (http://amntl.mst.edu/). Dr. Zoughi held the position of Business Challenge Endowed Professor of Electrical and Computer Engineering from 1995 to 1997 while at CSU.

While at CSU he received nine teaching awards, including the State Board of Agriculture, Excellence in Undergraduate Teaching Award and the Abell Faculty Teaching Award. Since at Missouri S&T he has received seventeen Outstanding Teaching Awards & Commendations. He is the recipient of the 2007 IEEE Instrumentation

and Measurement Society Distinguished Service Award, the 2009 American Society for Nondestructive Testing (ASNT) Research Award for Sustained Excellence, the 2011 IEEE Joseph F. Keithley Award in Instrumentation and Measurement and the 2020 IEEE Instrumentation and Measurement Society Career Excellence Award. In 2013 and 2020 he and his co-authors received the H. A. Wheeler Applications Prize Paper Award from the IEEE Antennas and Propagation Society (APS). He is also the recipient of the 2023 American Society for Nondestructive Testing (ASNT) Lester/Mehl Honor Lecture Award.

He is the author of a textbook entitled "Microwave Nondestructive Testing and Evaluation Principles" KLUWER Academic Publishers, 2000, and the co-author of a chapter on Microwave Techniques in the book entitled "Nondestructive Evaluation: Theory, Techniques, and Applications" Marcel and Dekker, Inc., 2002. He is the co-author of 194 refereed journal papers, 385^{+}conference proceedings and presentations and 125 technical reports. He served as the Editor-in-Chief of the IEEE Transactions on Instrumentation and Measurement (2007-2011), three terms as an at-large AdCom member of the IEEE Instrumentation and Measurement (I&M) Society, I&M Society President (2014-2015) and serves as an I&M Society Distinguished Lecturer. He served as the General Co-Chair of the 2013 IEEE Instrumentation and Measurement Technology Conference (I^2MTC). He has been elected as an at-large member of IEEE Publications Services & Products Board (PSPB) for two terms (2016-2018 & 2019) and served on the IEEE TAB/PSPB (2015 & 2017-2019). Since 2020 he has also been serving as an *Executive Advisor* to the American Society for Nondestructive Testing (ASNT) Board of Directors.

He has twenty issued US patents to his credit (in addition to several issued abroad) in the field of microwave nondestructive testing and evaluation. He has delivered numerous Invited and Keynote presentations on the subject of microwave and millimeter wave nondestructive testing and imaging. He is a *Fellow* of the Institute of Electrical and Electronics Engineers (IEEE) and a *Fellow* of the American Society for Nondestructive Testing (ASNT).