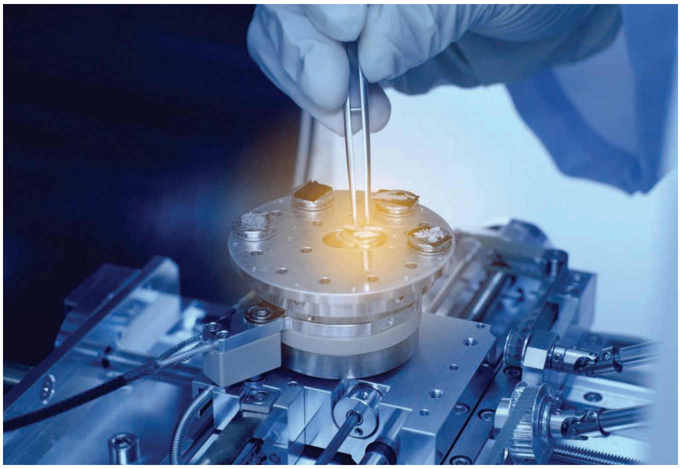
From the Guest Editors' Desk

Microwaves and Microscopy

■ Marco Farina and T. Mitch Wallis

Welcome to this special issue of *IEEE Microwave Magazine*, focused on microwaves and microscopy. As the phrase implies, the topic lies at the intersection of two technical disciplines: microwave engineering and measurements on microscopic-length scales. Within the pages of this issue are many compelling images from a wide selection of application areas, including MOS devices, biological cells, acoustic wave devices, and novel materials like graphene. Depending on your professional background, that list of application areas may entice you to dive into this issue. On the other hand, you may feel like this topic lies far from your interest and expertise. If you are in the latter category, we would like to briefly share with you a bit of our personal professional journeys that led us to this unique field of research. Perhaps you will see in our stories a connection between your own interests and microwaves and microscopy.



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Early in Marco Farina's career, after a short detour through microwave mixer design, he worked on electromagnetic theory, particularly Green's functions and analysis of planar structures. That led to the development of software for full-wave analysis of 3D passive and active linear circuits, the Electromagnetic 3D Simulator (EM3DS), as well as a book covering the underlying theory. Over time, EM3DS served as Marco's virtual lab for the simulation of different kinds of devices (including a subclass of acoustic wave devices), the calibration of "virtual" measurements, and microwave device design. In early 2000, Marco transitioned to the experimental world, working with his friend Dr. Antonio Morini on ground-penetrating radar (GPR) to address the tragic problem of landmines. During the same time, mostly by chance and thanks to coworker Dr. Andrea di Donato, he also started working on atomic force microscopes and scanning tunneling microscopes (STMs). Through these tools, Marco became fascinated by the nano world. Overall, his impression was that, on the macroscale, Maxwell's equations had been solved and leveraged in the most ingenious ways using the fruits of the microwave golden age, when microwave theory was pioneered by physicists like Julian Schwinger and Nathan Marcuvitz. On

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the other hand, as the nanoscale was becoming physically accessible thanks to scanning probe techniques, it remained mostly an unexplored land, at least in terms of electromagnetism. At that time, he started to wonder if a kind of scanning GPR could be implemented at the nanoscale, with an antenna raster scanned over dimensions on the order of a few micrometers. By merging the microwave components and software developed for the GPR with the machinery of the STM, he was able to realize a prototype of a microwave microscope. Soon after, he was amazed to discover the rich literature related to this emerging field of "scanning microwave microscopy."

Mitch Wallis's path to the field of microwave microscopy began with graduate work in nanoscale surface science. He was first exposed to STMs during his doctoral research. In addition to the capability of the STM to visualize structures at the nanoscale, the remarkable technique also enabled quantitative measurement and controlled manipulation of matter at atomic-length scales. After finishing his Ph.D., Mitch began working in the Radio Frequency Electronics division at the National Institute of Standards and Technology (NIST). In his early years there, he worked in measurement services for microwave scattering parameters and RF power. As a result, his early time there served as a crash course in precision microwave measurements and instrumentation, which proved to be intriguing and humbling for him. With experience in both nanoscale measurements and microwave measurements, Mitch naturally looked for a field of study where these two branches of metrology intersected. He was happy to discover the field of microwave microscopy, then just an emerging area of study but now the focus of this special issue of *IEEE Microwave Magazine*.

This focus issue is intended to provide a detailed description of state-of-the-art knowledge and recent innovations in the field of microwave microscopy. In a world full of macroscopic microwave transmitters and receivers, such as wireless network hubs and cellular phones, thinking about how microwaves interact with the microscopic and submicroscopic world represents a paradigm shift for many engineers. This is particularly true given that the free-space wavelength of microwave radiation is much larger than the diameter of a biological cell or the thickness of a 2D material like graphene. For readers who are curious to learn more about this nanoscale, subwavelength regime, we recommend three earlier *IEEE Microwave Magazine* focus issues: December 2010 ("RF Nanoelectronics"), December 2011 ("Microwave Nanopackaging and Interconnects"), and January 2014 ("Measurement Techniques for RF Nanoelectronics") [1]–[3]. Within the field of RF nanoelectronics, the IEEE Microwave Theory and Techniques Society's Technical Committee (TC) on RF Nanotechnology (now TC-08, formerly TC-25) provides an ongoing forum to explore nanotechnology topics of interest to the microwave engineering community.

In assembling this focused issue, we have endeavored to provide multiple perspectives, including those of industry, academia, and government laboratories. The first article is "Scanning Microwave Impedance Microscopy: Room-Temperature and Low-Temperature Applications for Device and Material Characterization" by Dr. Ravi Chandra Chintala and his colleagues at PrimeNano, Inc. Recent years have seen the accelerated development of microwave microscopy instrumentation and a corresponding expansion of the technique's application space. Dr. Chintala's article provides an industrial perspective on the current state of the art in scanning microwave impedance microscopy (sMIM), including applications spanning a wide range of environmental variables such as temperature.

The next contribution, "Nanoelectronic Characterization: Using Near-Field Microwave Microscopy for Nanotechnological Research," comes from Dr. Samuel Berweger and his colleagues at NIST. Near-field microwave microscopy is particularly useful for in operando studies of semiconducting nanoelectronic devices and their respective electromagnetic properties. Dr. Berweger's article pays particular attention to devices based on low-dimensional systems, such as carbon nanotubes, atomically thin layers of molybdenum disulfide, and tellurene.

The third article is by Prof. Farina (Università Politecnica delle Marche, Italy) and Prof. James Hwang (Cornell University). They have been collaborators for several years, and the title of their joint contribution is "Scanning Microwave Microscopy for Biological Applications: Introducing the State of the Art and Inverted SMM." After a short historical review of the origins of near-field microscopy, they address the topic of its use in the life sciences. Microwave microscopy, with its tomographic and spectroscopic abilities, is, in fact, a very promising tool for biological applications, but it still faces challenges. The relationship between the electromagnetic properties of tissues and pathological conditions was demonstrated long ago, but microwave microscopy allows us to investigate this relationship at the level of a single cell or even a cellular organelle. The authors also describe their new approach, the "inverted" scanning microwave microscope, which enables existing, conventional scanning probe microscopes to be converted into microwave microscopes.

The fourth contribution comes from Prof. Keji Lai's group at the University of Texas at Austin and their colleagues at Harvard University. Their article, "Imaging Acoustic Waves by Microwave Microscopy: Microwave Impedance Microscopy for Visualizing Gigahertz Acoustic Waves," provides an overview of sMIM's remarkable capability to image surface acoustic waves (SAWs). Devices based on SAWs have found many applications in contemporary wireless devices, including filters and delay lines. By providing direct visualization of SAWs, microwave microscopy can enable optimization and engineering of these commercially vital applications.

The final article, by Dr. Alexander Tselev (Aveiro University, Portugal), is "Near-Field Microwave Microscopy: Subsurface Imaging for In Situ Characterization." Dr. Tselev shows how the subsurface-probing capabilities of microwave microscopy can be systematically exploited to perform in situ and in operando measurements in fluids. In the first part of the work, he shows that nanometer-thin dielectric cells can be used to encapsulate fluid and samples, preventing encroachment of the microwave microscope probe into the cell. Using this method, he follows the process of silver's electrode position in a solution of silver nitrate and images living cells in a glycerol solution. Dr. Tselev also reviews how microwave microscopy can be used to probe ferroelectric material properties through naturally occurring Schottky barriers while keeping electric fields below the coercive threshold.

For those of you already familiar with microwaves and microscopy, we hope that this issue enhances your understanding and appreciation. For those new to this concept, it is our hope that you will find this focus issue interesting and informative. We welcome your feedback and comments.

Acknowledgment

Many colleagues worked very hard on this issue. We offer our sincere thanks to the authors for their efforts. Finally, we thank Sharri Shaw and Robert Caverly at *IEEE Microwave Magazine* for their support in producing this focus issue.

References

[1] L. Pierantoni, F. Coccetti, and P. Russer, "Nanoelectronics: The paradigm shift," *IEEE Microw. Mag.*, vol. 11, no. 7, pp. 8–9, Dec. 2010. doi: 10.1109/MMM.2010.938552.

[2] L. Pierantoni and F. Coccetti, "Microwave nanopackaging and interconnects," *IEEE Microw. Mag.*, vol. 12, no. 7, pp. 14–18, Dec. 2011. doi: 10.1109/MMM.2011.942694.

[3] T. M. Wallis and L. Pierantoni, "Measurement techniques for RF nanoelectronics," *IEEE Microw. Mag.*, vol. 15, no. 1, pp. 26–28, Jan. 2014. doi: 10.1109/MMM.2013.2292758.

Correction

Due to a production error, reference [7] in the September 2020 "Health Matters" column [1] was listed incorrectly. The correct reference is as follows:

[7] IARC, "Priorities for future IARC Monographs on the evaluation of carcinogenic risks to humans," *Lancet Oncol.*, vol. 20, pp. 763–764, 2019.

We apologize for any confusion.

Reference

[1] J. C. Lin, "5G communication technology and coronavirus disease," *IEEE Microw. Mag.*, vol. 21, no. 9, pp. 16–19, Sept. 2020. doi: 10.1109/MMM.2020.2999236.

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