Guest Editorial
Special Cluster on Three-Dimensional Printed Antennas and Electromagnetic Structures

ADDITIVE manufacturing technologies, often called three-dimensional (3-D) printing, have received much attention recently with impressive applications ranging from arts, foods, medical devices, to vehicles, to housing components, or even entire buildings. Different constitutive materials including metal, polymer, ceramics, biological tissues, and even concrete, have been incorporated in various 3-D printing technologies. Printing dimension ranging from submicrons to meters has been reported, and 3-D printing has been carried out in households, schools, laboratories, factories, and even space.

Besides mechanical objects, 3-D electromagnetic (EM) structures, such as circuits, waveguides, antennas, lenses, and holographic devices for GHz to THz operation have also been demonstrated recently. What distinguish additive manufacturing technologies for antennas and electromagnetic structures from regular 3-D printing is perhaps it is not merely the ability to build objects incrementally in a voxel manner, but the merging of mechanical CAD, RF/mechanical/thermal/aerodynamic modeling, material science, and building method into a multiphysics digital workflow.

Although it has been argued that 3-D printing could be the future of manufacturing, the potential and applicability of these methods for creating advanced and integrated antenna systems still remain largely unexplored. This has to do with the methodology, the available tools, and digital workflow. For example, as we move from 2-D to 3-D, the optimization space for the voxels to build antenna and EM structures increases tremendously, design methodology typically need to couple a dedicated CAD program together with an RF modeling software. Similarly, the range of materials and resolution available for EM purpose is only starting to become available to RF modeling software natively in recent years. The ability to design efficiently at different frequencies and model the material under specific build condition and postprocessing techniques in one seamless environment will be a key step to advance the art. This is an exciting time for RF 3-D printing precisely because we are witnessing the creativity in piecing these different areas together to form an effective workflow.

Methodology aside, RF additive manufacturing also need specific areas of advancement. For example, for higher frequency (i.e., millimeter wave and THz) applications, challenges involving more stringent tolerance requirement, surface roughness, etc., need to be adequately addressed. In addition, development of various measurement techniques to validate theoretical results would be very beneficial. For example, establishment of the correlation between various printing qualities (i.e., surface roughness, printing resolution, impact of material anisotropy, etc.) with high-frequency performance of 3-D printed antennas will be necessary for practical applications.

The objective of this special issue of papers is to assemble and establish a body of work that will highlight current research involving 3-D printing technology for advanced and novel antenna applications and electromagnetic structures. There are many research groups that have started working in this area. As evidence, there have been several special sessions at major antenna conferences in the past few years. For example, the proposers (Guest Editors) have organized or participated in the following conference special sessions related to 3-D printed antennas: URSI Boulder 2016; International Workshop on Antenna Technology (iWAT) 2016; EuCAP-2015, and IET Microwave, Antennas and Propagation Special Issue on microwave components and antennas based on advanced manufacturing techniques. For the IEEE AP/URSI Symposia, 3-D printed antennas sessions have been a regular feature since 2015. The focus here is on 3-D/nonplanar devices and structures rather than those that can be designed and fabricated using conventional PCB methods. We believe that these technologies have matured to the point where they can make a serious impact on the antenna and propagation community, and now is the time to have a special issue exploring possible pathways for real applications of additive manufacturing, discussions of new techniques, and the challenges associated with them. The following describes the organization and brief introduction of the selected letters in this Special Cluster.

One of the key attractiveness of using additive manufacturing is the level of control afforded by the method to tune the local characteristics of the material. The inhomogeneity resulted is then used to control the EM properties. Dongho Kim *et al.* examine the use of sectional phase delays to improve the gain of integrated lens antennas in "3-D Printer Based Lens Design Method for Integrated Lens Antenna." Marco Pasian *et al.* incorporate the gradual change of dielectric properties directly via the build in "3-D-Printed Antenna for Snowpack Monitoring." The phase control was achieved at millimeter wave in "Design and Measurement of a 220GHz Wideband 3-D Printed Dielectric Reflectarray" by Bin Li *et al*.

Associated with the voxel control is the concern regarding the mechanical and electrical performance of the materials. Throughout the Special Cluster, the readers will see how the

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specific issues regarding tolerance, surface roughness, mechanical performance, conductivities, etc., affect the specific applications. Several papers focus on such effects. Jordi Romeu *et al.* study the surface roughness and fabrication tolerance in "Assessment of 3-D Printing Technologies for Millimeter Wave Reflectors." Jorge Teniente *et al.* compare the different attributes of 3-D printed horns and conventionally fabricated ones in "3-D Printed Horn Antennas and Components Performance for Space and Telecommunications." Rashi Mirzavand *et al.* show the effect of surface roughness on the radiation pattern of dielectric rod antenna in "Investigation of 3-D Printing Roughness Effects: Performance Analysis of a Printed Dielectric Rod Antenna."

Aside from the freedom in dielectric properties, the design of the elements by exploiting the topological and geometrical flexibility is certainly a key advantage of 3-D printing, and a significant portion of the papers are addressing that. While they addressed optimization (e.g., "A 3-D Printed W-Band Slotted Waveguide Array Antenna Optimized Using Machine Learning" by Jinpil Tak *et al.*, "Particle Swarm Optimized, 3-D-Printed, Wideband, Compact Hemispherical Antenna" by Ming-Chun Tang *et al.*), complex geometries (e.g., "Design and Fabrication of Orthogonal Mode Transducer (OMT) Using 3-D Printing Technology" by Hadi Saeidi-Manesh *et al.*), or implementation of adapted antenna topology ("Investigation of Additive Manufacturing for Broadband Choked Horns at X/Ku Band" by Andrea Giacomini *et al.*, "3-D Printing of High-Performance Feed Horns From Ku to V Bands" by Giuseppe Addamo *et al.*), the adaptation of the design to suit the manufacturing process as well as the flexibility offered by additive manufacturing was illustrated throughout.

Last but certainly not least is the vision of an antenna array system. We see the illustration of using the new methodology by Gregory Le Sage in "Dielectric Steering of a 3-D Printed Microwave Slot Array" and comprehensively in "3-D Printed Parts for Multilayer Phased Array Antenna System" by Xiaoju Yu *et al.* where the use of multilayer and embedding of different function area into the 3-D printed structure is discussed.

We hope this special cluster of papers give readers the latest in research in new antenna topologies/synthesis/design enabled by 3-D printing technology, advanced 3-D printed antenna and array systems, 3-D printable materials for antenna related applications, 3-D printed metasurfaces, and metamaterials, key fabrication challenges, and potential solutions of 3-D printing for antennas.

In terms of antenna design taking advantage of 3-D printing itself, four specific areas should see foreseeable growth in the future. They are 3-D antenna element design, multilayer structures, embedding of active components, and inhomogeneous materials. It is not possible to discuss the impact of 3-D printing without discussing the cost. With each improvement happening with the printing method, the product, at least in the prototyping regime, has entered into a competitive range. Notably, as 3-D printing technology has been growing rapidly, the researchers from academia and industrial contributors come from a diverse geographical background. 3-D printing is here to stay, and once the technology reaches a critical point, it will become another toolbox, one that broadly open up the design space.

Finally, the guest editors would like to give our sincere thanks to the reviewers and authors. Their contribution and prompt feedback have improved this Cluster and made it a reality. We would also like to thank the IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS Editor-in-Chief, Prof. C. Fumeaux, and Sideri from the editorial staff for their patience and support.

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Dr. Sharma was the recipient of the IEEE AP-S Harold A. Wheeler Prize Paper Award in 2015, the National Science Foundation's prestigious Faculty Early Development (CAREER) Award in 2009, the Young Scientist Award of URSI Commission B, Field and Waves, during the URSI Triennial International Symposium on Electromagnetic Theory, Pisa, Italy, in 2004. He was recognized as the Outstanding Associate Editor (AE) for the IEEE TRANSACTION ON ANTENNAS AND PROPAGATION (IEEE TAP) journal in July 2014. He served as the AE for the IEEE TAP and is currently serving as the AE for the IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS. He was the Chair/Co-Chair of the several Student Paper Contests in different conferences and symposia and served on the subcommittee of the Education Committee for the IEEE Antennas and Propagation Society for the organization of the Student Paper Contests. He is currently a full member of the USNC/URSI, Commission B, Fields and Waves and is currently serving as the Chair, Technical Activities for the same.

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He was the recipient of the prestigious EPSRC's Grand Challenge £5M (FEC) Award: Synthesizing 3-D Metamaterials for RF, Microwave and THz Applications (http://gow.epsrc.ac.uk/NGBOViewGrant.aspx?GrantRef=EP/N010493/1. He was the Chairman of the Executive Committee of the IET's Antennas and Propagation Professional Network in the U.K. and chaired the IEEE's Distinguish Lecturer Program of the Antennas and Propagation Society for five years. He founded the Loughborough Antennas and Propagation Conference, which has been running since 2005. He has chaired numerous IEE/IET events and has served on the Steering Committee of the European Conference on Antennas and Propagation (EuCAP). He was the General Chair of EuCAP'07. He was elected a Fellow of the Royal Academy of Engineers in 2011.

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