Guest Editorial: Programmable Metamaterials for Software-Defined Electromagnetic Control

I. Introduction

THIS Special Issue of the IEEE Journal on Emerging and Selected Topics in Circuits and Systems (JETCAS) is dedicated to novel contributions to the field of programmable metamaterials. Recent years have witnessed the emergence of this paradigm, whereby the electromagnetic response of the metamaterial can be encoded into a string of bits. This allows to control electromagnetic waves using well-defined software directives and, further, to incorporate and combine them within systems to give rise to a plethora of new applications in fields such as sensing, wireless communications, or holography.

In this Special Issue, we aim to provide a comprehensive perspective on the state of research in the field of programmable metamaterials through a selection of high-quality contributions. We start with "Programmable metamaterials for software-defined electromagnetic control: circuits, systems, and architectures," where the guest editors of this issue deliver a brief tutorial on programmable metamaterials, as well as an overview of the main research lines from the metamaterial architecture, circuits, and technology standpoints. The authors discuss the recent explosion of works that attempt to not only explore the theoretical possibilities of programmable metasurfaces across the spectrum, but also implement functional prototypes and devise new systems and applications that build upon this concept. In this article, we also discuss the potential challenges that lie ahead towards the cyber-physical system vision of software-driven, intelligent, autonomous yet interconnectable metamaterials.

The 11 selected articles are novel technical contributions that cover a wide variety of aspects related to programmable metamaterials. We briefly describe them in the next sections, distinguishing between works that include experimental prototypes, articles dealing with cross-cutting issues, and efforts dedicated to improve the modeling of metamaterials.

II. Experimental Prototypes

The research area of programmable metamaterials is maturing at a fast pace and, consequently, has recently seen a surge of experimental works that demonstrate various functionalities mainly at microwave frequencies. In this direction, the Special Issue includes four contributions with proof-of-concept implementations and experimental measurements of advanced functionalities.

The first article by Feng *et al.* "Programmable coding metasurface for dual-band independent real-time beam control" presents a metasurface prototype whose unit cells consist of two stacked layers. Each layer is designed to serve a different band (6 and 10 GHz) and contains pin diodes to provide independent reconfigurability. The authors avoid crosstalk through careful design of the structure and, through extensive simulation and measurements, demonstrate that independent control of beams is achieved at the designed frequencies.

The second article by Shuang *et al.* is titled "Programmable high-order OAM-carrying beams for direct-modulation wireless communications." This article evaluates a programmable metasurface design for the creation of beams with arbitrary orbital angular momentum (OAM) and their use for wireless communications. The metasurface allows to realize multiple topological charges, modify the vortex center of the beam, and also collimate the OAM-augmented beam. The work also experimentally demonstrates data transmission through the direct-modulation of beams with OAM, which may be of great impact due to the high multiplexing potential of the OAM technique.

The third article by Li *et al.* "SoftCharge: Software defined multi-device wireless charging over large surfaces" presents a metamaterial-inspired method that has the potential to turn any non-metallic surface into a large-area wireless charger for multiple devices located in close proximity to the surface. SoftCharge is based on the wireless interconnection of multiple tiles, where each tile contains a coil and a controller. Through the tuning of the capacitances at each tile, *energy paths* are dynamically created from the energy source to the tiles that are most appropriate for charging the device. This boosts the efficiency of wireless charging while rendering the scheme flexible to changes of position.

The fourth article by Han *et al.* "Millimeter-wave imaging using 1-bit programmable metasurface: Simulation model, design and experiment" starts off with a theoretical study, with simulations, of the use of programmable metasurfaces for imaging far-field and near-field objects. For far-field imaging, a feed antenna works in conjunction with the adaptive metasurface tunable reflector to create a scanning high-gain pencil beam to bounce electromagnetic pulses off a far-field object. A receiving antenna collects the scattered field information and is used to reconstruct to object. For near-field imaging, random complex beams are used to sample the target objects

Digital Object Identifier 10.1109/JETCAS.2020.2976077

in the time domain. Last, but not least, the hardware for a suitable programmable metasurface is presented.

III. Cross-Cutting Issues

The realization of the cyber-physical vision of programmable metamaterials across the spectrum requires addressing many questions related to their implementation. How will failures affect the behavior of deployed metasurfaces and how should they be reprogrammed to minimize the impact of faults? How can spatiotemporal programming be implemented in the terahertz band? Can we use energy harvesting to power up metasurfaces once deployed? How are we going to interconnect the different unit cells of a monolithic programmable metasurface?

This issue features four articles that touch upon cross-cutting aspects of programmable metasurface design and development in an attempt to answer some of the questions above. The first article by Taghvaee *et al.* "Error analysis of programmable metasurfaces for beam steering" investigates the impact of unit cell faults on the overall performance of the programmable metasurfaces by making error analysis on a beam-steering case. In fact, one of the challenges in realizing the programmable metasurfaces is the reliability of the vast number of unit cells or meta-atoms, which may break down due to many practical issues such as mechanical vibrations and electrical failure. In this article, the authors found that the designed functionality is robust against uncorrelated errors with random values, and could even survive when a quarter of the unit cells fail; but the clustered error which sets all unit cells to the same states has significant influence on the beam shape and should generally be avoided.

The second article by Rajabalipanah *et al.* "Reprogrammable spatiotemporally modulated graphene-based functional metasurfaces" presents a graphene-based programmable metasurface at the terahertz spectrum to realize different functionalities in both space and frequency domains. The 2-bit graphene-based meta-atom with optimized time sequence is carefully designed to obtain equivalent multi-bit phases and amplitudes at either the central frequency or a harmonic frequency. Several illustrative examples, including airy beam generation and spatial power division, are numerically presented to demonstrate that the graphene-based metasurface combined with space-time-coding strategy can perform different electromagnetic modulations for some terahertz applications, such as imaging and information systems.

Software-defined metasurfaces (SDMs) are expected to automatically control the response of numerous unit cells by building upon the unique properties of programmable metasurfaces. In the third article entitled "Idling energy modeling and reduction in energy harvesting terahertz nanonetworks for controlling software-defined metamaterials," Lemic *et al.* considered an SDM where the unit cells are controlled by a nanonetwork whose nodes are powered by means of energy harvesting. A realistic energy consumption model was proposed by taking account of the idling energy consumption of the nodes. Based on this, a new duty cycle with short wake-ups for the receiving nanonodes was used, through optimizing the wake-up time based on two algorithms, and consequently, the tolerance of idling energy consumption can increase up to three orders of magnitude.

Finally, the article by Pano *et al.* "TSV antennas for multi-band wireless communication" presents the design of an integrated on-chip antenna in the form of a vertical monopole. The antenna is based on Through-Silicon Via (TSV) and aims to enable wireless communication in multiple frequency bands among nodes within integrated environments, such as unit cells of a programmable metasurface. The article discusses the prototyping of such antenna and delivers a comprehensive simulation study of the antenna properties and potential interference of nearby antennas. Further, the impact of having multiple bands within an integrated network is evaluated in terms of performance and efficiency.

IV. Modeling Approaches

The implementation of the myriad of functionalities of programmable metasurfaces across the spectrum depends basically on the design of appropriate unit cells as well as the correct programming of the unit cells at operation. These processes hinge on the fast and accurate modeling of the response of the individual unit cells and of the full metasurface. In this regard, the Special Issue features three novel contributions.

The first article by Shao *et al.* "Coding programmable metasurfaces based on deep learning techniques" presents a design of programmable metasurfaces based on deep learning techniques for beam pattern control. The authors propose a scheme based on the application of a Convolutional Neural Network (CNN) that derives, in real time, the best metasurface code for delivering single and dual beams with various pattern gains. The key takeaway is that, after being trained with a relatively small set of coding patterns, the CNN can generalize to any single and dual-beam radiation patterns.

The second article by Liu *et al.* "A hybrid strategy for the discovery and design of photonic structures" presents a methodology for the systematic design of photonic metasurfaces, although generalizable to other photonic structures, that avoids tedious trial-and-error processes. The methodology takes as input a desired transmittance spectrum and uses an deep generative model to find a unit cell that provides the desired transmittance with low loss of accuracy. To calculate the fitness of each solution proposed by the generative model, the methodology admits either a full-wave simulator or a neural network trained beforehand that models the simulation. With an appropriate training of the model, the proposed methodology is capable of looking into a reduced space of solutions instead of having to do a more exhaustive search, thereby reducing the design time of the required structure dramatically.

Last but not least, the article by Fathizade *et al.* addresses the "analytical calculation of radiation characteristics of metasurface-based solar antennas with uniform and non-uniform cells." Solar antennas are compact combinations of antennas and solar cells that, for instance, can be found in micro-satellites. The metasurface-like arrangement of solar cells can completely distort the radiation pattern of the antenna and, thus, solar antennas need to be carefully designed. The authors of this work develop an analytical model to study the radiation pattern of solar antennas, showing close agreement with full-wave simulations with a tiny fraction of the time and memory cost. To validate its robustness, the method is tested with different types of solar unit cells.

ACKNOWLEDGMENT

The Guest Editors would like to sincerely thank the authors for their excellent technical contributions and time commitments in preparing the manuscripts for the rapid publication schedule for this Special Issue. We also thank the volunteer reviewers for their service on providing timely and valuable feedback and suggestions to comply with the high-quality standards of JETCAS. We truly appreciate the guidance and support provided by JETCAS Editors-in-Chief (EiC), Prof. Eduard Alarcón and Prof. An-Yeu (Andy) Wu, and Associate EiC, Prof. Herbert Iu, as well as the professional comments made by the Senior Editorial Board. We also thank the IEEE Publishing Operations personnel for their great efforts and patience in finalizing this Special Issue.

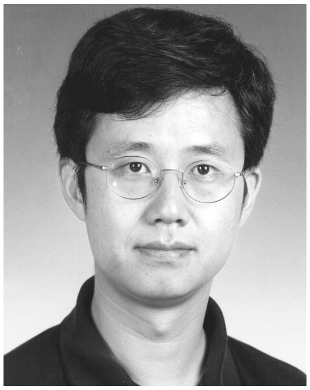
SERGI ABADAL
NaNoNetworking Center in Catalonia (N3Cat)
Universitat Politècnica de Catalunya
08034 Barcelona, Spain

TIE-JUN CUI
School of Information Science and Engineering
Southeast University
Nanjing 210096, China

TONY LOW
Department of Electrical and Computer Engineering
University of Minnesota
Minneapolis, MN 55455 USA

JULIUS GEORGIOU
Department of Electrical and Computer Engineering
University of Cyprus
1678 Nicosia, Cyprus

Sergi Abadal received the B.Sc. degree in telecommunication engineering from the Telecommunication Engineering School (Telecom BCN), Universitat Politècnica de Catalunya (UPC), Barcelona, Spain, in 2010, the M.Sc. degree in information and communication technologies (MINT) from UPC in 2011, and the Ph.D. degree in computer architecture from the Department of Computer Architecture, UPC, in July 2016. He has held several visiting positions at Georgia Tech in 2009, the University of Illinois at Urbana–Champaign from 2015 to 2016, and the Foundation of Research and Technology – Hellas in 2018. He is currently a Coordinator of the WIPLASH FET-OPEN Project. His current research interests are in the areas of chip-scale wireless communications, including channel modeling and protocol design, the application of these techniques for the creation of next-generation wireless networks for on-chip or within metamaterials, and their implications at the system design level. He has served as a TPC member for more than ten conferences and has organized three special sessions, and published over 60 articles in top-tier journals and conferences. He was a recipient of the Nano Communication Networks Young Researcher Award in 2019, the INTEL Doctoral Fellowship in 2013, the Accenture Award for M.Sc. students in 2012, and the Vodafone Fellowship for outgoing B.Sc. students in 2010. He is also an Area Editor of the *Nano Communication Networks* (Elsevier) journal, where he was named "Editor of the Year" in 2019.



Tie-Jun Cui (Fellow, IEEE) received the B.Sc., M.Sc., and Ph.D. degrees in electrical engineering from Xidian University, Xi'an, China, in 1987, 1990, and 1993, respectively.

In March 1993, he joined the Department of Electromagnetic Engineering, Xidian University, where he was promoted to an Associate Professor in November 1993. From 1995 to 1997, he was a Research Fellow with the Institut für Hochfrequenztechnik und Elektronik (IHE), University of Karlsruhe, Germany. In July 1997, he joined the Center for Computational Electromagnetics, Department of Electrical and Computer Engineering, University of Illinois at Urbana–Champaign, first as a Post-Doctoral Research Associate and then a Research Scientist. In September 2001, he was a Cheung-Kong Professor with the Department of Radio Engineering, Southeast University, Nanjing, China, where he became a Chief Professor in January 2018. He is the first author of the books *Metamaterials – Theory, Design, and Applications* (Springer, November 2009) and *Metamaterials: Beyond Crystals, Noncrystals, and Quasicrystals* (CRC Press, March 2016). He has published over 400 peer-review journal articles in *Science*, *Proceedings of the National Academy of Sciences* (PNAS), *Nature Communications*, *Physical Review Letters*, *Advanced Materials*, and the IEEE TRANSACTIONS, which have been cited more than 20 000 times (H-Factor 73). According to Elsevier, he is one of the Most Cited Chinese Researchers.

Dr. Cui received the Research Fellowship from the Alexander von Humboldt Foundation, Bonn, Germany, in 1995, the Young Scientist Award from the International Union of Radio Science (URSI) in 1999, the Cheung Kong Professorship under the Cheung Kong Scholar Program by the Ministry of Education, China, in 2001, the National Science Foundation of China for Distinguished Young Scholars in 2002, the Special Government Allowance from the Department of State, China, in 2008, the Award of Science and Technology Progress from the Shaanxi Province Government in 2009, and the May 1st Labour Medal from Jiangsu Province Government in 2010. He also received the First Prize of Natural Science Awards from Ministry of Education, China, in 2011, the Second Prize of National Natural Science Awards, China, in 2014, and the First Prize of Military Science and Technology Progress Awards in 2016. His researches have been selected as one of the "Optics in 2016" by *Optics and Photonics News Magazine* (OSA), "10 Breakthroughs of China Optics in 2016," "10 Breakthroughs of China Science in 2010," "Best of 2010" in *New Journal of Physics*, Research Highlights in *Europhysics News*, *Journal of Physics D: Applied Physics*, *Applied Physics Letters*, and *Nature China*. He is an Active Reviewer for *Science*, *Nature Materials*, *Nature Photonics*, *Nature Physics*, *Nature Communications*, *Physical Review Letters*, *Advanced Materials*, and a series of the IEEE TRANSACTIONS. He was an Associate Editor of the IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING and a Guest Editor of *Science China – Information Sciences*. He served as on the editorial staff for the *IEEE Antennas and Propagation Magazine*, and is on the Editorial Boards of *Progress in Electromagnetics Research* (PIER) and *Journal of Electromagnetic Waves and Applications*.

Tony Low received the B.Sc. and Ph.D. degrees in electrical and computer engineering from the National University of Singapore in 2002 and 2008, respectively. After that, he was a Post-Doctoral Associate with Purdue University until 2011, and then, he worked as a Theorist with various experimental groups at Columbia University, Yale University, and IBM Thomas J. Watson Research. While at IBM, from 2011 to 2014, he served as an industry liaison to various universities under the Nanoelectronics Research Initiative with the goal of finding the next electronics switch. He is currently an Associate Professor at the Department of Electrical and Computer Engineering, University of Minnesota. He was also a member of the technical program committees of over ten conferences, given more than 100 invited talks, and published over 100 articles. He has been included in the 2019 Global List of Highly Cited Researchers, compiled by the Web of Science Group. He received the Presidential McKnight Fellowship Award in 2019, the IBM Pat Goldberg Memorial Best Paper Award in 2014, the IBM Invention Award in 2013, the KITP Rice Family Fund Fellowship in 2012, the Singapore Millennium Fellowship in 2007, and the IEEE Electron Device Society Fellowship in 2005, among other honors. He leads a research group in ECE that works on expanding the understanding and design of nanomaterials and nanodevices. In recent years, they have focused on the class of two-dimensional crystals and their heterostructures, and topological and magnetic materials. His team has revealed their basic electronic and optical properties, and their opportunities for novel electronics, spintronics, optoelectronics, nanophotonics, and plasmonics. He has served as a Guest Editor for *Nanotechnology* (IOP) and an Associate Editor for the *Nanophotonics* journal (De Gruyter) and *Journal of Physics: Condensed Matter* (IOP), as well as the Co-Chair of the "2D Materials Nanophotonics" in 2017, 2019, and 2020.

Julius Georgiou (Senior Member, IEEE) received the M.Eng. degree in electrical and electronic engineering and the Ph.D. degree from Imperial College London in 1998 and 2003, respectively. He worked as the Head of Micropower Design at Toumaz Technology, a technology-based start-up company, for two years. In 2004, he joined Johns Hopkins University as a Post-Doctoral Fellow, before becoming a Faculty Member with the University of Cyprus in 2005. He is currently an Associate Professor at the University of Cyprus. His research interests include low-power analog and digital ASICs, implantable biomedical devices, bioinspired electronic systems, electronics for space, brain–computer interfaces (BCIs), memristive devices, electronics for adaptive metamaterials, inertial and optical sensors, and related systems. He is a member of the IEEE Circuits and Systems Society and the IEEE Circuits and Systems Society Analog Signal Processing Technical Committee. He was a recipient of the Best Paper Award at the IEEE ISCAS 2011 International Symposium and at the IEEE BioDevices 2008 Conference. In 2016, he received the 2015 ONE Award from the President of the Republic of Cyprus for his research accomplishments related to the development of an “Infrared Fluorescence-Based Cancer Screening Capsule for the Small Intestine.” He served as the General Chair for the 2010 IEEE Biomedical Circuits and Systems Conference, and is currently the Action Chair of the EU COST Action ICT-1401 on “Memristors-Devices, Models, Circuits, Systems and Applications - MemoCIS.” He is also the Chair of the IEEE Biomedical and Life Science Circuits and Systems (BioCAS) Technical Committee. He has been selected as an IEEE Circuits and Systems Society Distinguished Lecturer from 2016 to 2017. He is also an Associate Editor of the IEEE TRANSACTIONS ON BIOMEDICAL CIRCUITS AND SYSTEMS and the *Frontiers in Neuromorphic Engineering* journal.