Active Nanophotonics

By ANDREA ALÙ, *Fellow IEEE*
Guest Editor

HILMI VOLKAN DEMIR, *Senior Member IEEE*
Guest Editor

CHENNUPATI JAGADISH, *Fellow IEEE*
Guest Editor

Being able to manipulate and control light flows at small scales holds the promise to open groundbreaking opportunities for a variety of technologies. Consider, for instance, the challenges currently faced in the world of computing: as data rates and processing demands increase worldwide at an exponential rate, we are facing unsustainable increases in energy consumption associated with data centers and streaming providers. To address these challenges, optical computing and communications offer an interesting alternative to electronic-based systems. Using light for these purposes, however, is hindered by the fact that photons are not easily squeezed to volumes beyond the diffraction limit, i.e., below the wavelength scale, which would be required both to enable low-energy computation at sufficiently high speeds and to match the degree of integration density available in electronic systems. Today, the field of optoelectronics, which combines high-density electronic devices to process the data and low-energy data transport enabled by light, is growing at a very fast pace.

> This special issue highlights the state of the art in active nanophotonics, with an emphasis on new material platforms and metamaterial concepts to address the modern challenges in this field.

In parallel, in order to enable truly all-optical computing platforms, the field of nanophotonics has been blooming, with the goal of squeezing and processing light streams at deeply subwavelength scales, helped by tremendous technological advances in nanofabrication and in the understanding of the interaction of light with nanostructured materials. Of utmost importance is the necessity of integrating a large number of devices at the nanoscale into a platform compatible with current manufacturing processes. Ideally, within this platform, we may be able to generate, control, modulate, and process light signals at ultrafast speeds and below femtojoule/bit energy levels. This is the context behind this special issue, in which we highlight several research efforts in the broad area of active nanophotonics and in which we present 12 invited papers from leading authors in the field, highlighting opportunities, challenges, and outstanding recent questions in this area of science. A variety of exotic optical phenomena are being discovered, including the relevance of quantum phenomena as the scales of light–matter interactions becomes comparable to the atomic scale and of engineered materials and metamaterials that go beyond what natural materials offer in their interaction with light. In the following, we provide a brief overview of the articles in the special issue, with an outlook on this field of research and technology.

After an initial overview by Krasnok and Alù broadly discussing the opportunities offered by active nanophotonics and the relevance of new material platforms and metamaterial concepts to address the modern challenges in this field, the special issue can be divided into two broad areas: material platforms and metamaterial devices for nanophotonics, as described in the following.

I. MATERIAL PLATFORMS FOR ACTIVE NANOPHOTONICS

Active nanophotonic systems require the integration of optical materials capable of generating and actively manipulating light at subwavelength scales. Significant efforts are being devoted to explore various material platforms that can provide these functionalities combined with large efficiency.

Digital Object Identifier 10.1109/JPROC.2020.2986176

In this context, Sharma *et al.* discuss the implementation of arrays of atomically flat colloidal semiconductor nanocrystals and their relevance in nanophotonic applications, specifically in the realization of light-emitting diodes (LEDs), lasers, and luminescent solar concentrators. Li *et al.* review the opportunities recently put forward in the area of 2-D atomically thin and layered materials, such as transition metal dichalcogenides and semiconductors, in terms of light emission, optical gain, lasing, and enhanced Purcell phenomena. Next, Gaponenko and Guzatov discuss the use of plasmonic materials to confine light at the nanoscale and enable sensors, and light-emitting and photovoltaic devices. Plasmonics has been arguably the first material platform to be explored in the context of nanophotonics, offering opportunities for field concentration below the diffraction limit. The authors discuss their relevance in terms of enhanced light–matter interactions and various photonic processes and devices related to Raman scattering, photoluminescence and electroluminescence, photovoltaics, photochemistry, and photodetectors. Delfanazari *et al.* discuss the opportunities offered by layered semiconductors to realize sources at THz frequencies based on the stacks of intrinsic Josephson junctions, highlighting their applications for spectroscopy, imaging, and tomography. They discuss compact THz devices with subcentimeter-sized modules that act as pocket quantum THz torches. Finally, Romeira and Fiore generally discuss the fundamental limits of nanoscale light sources, such as nano-light-emitting diodes and nanolasers, based on different material platforms for active nanophotonic systems. As their size shrinks, light–matter interactions are enhanced in these devices, leading to efficient and ultrafast radiative emission. However, the authors point out that downscaling LEDs and lasers has also implications on their speed and energy limits, implying that nanoLEDs reach a fundamental energy/speed limit for data rates exceeding a few gigabits per second, whereas nanolasers may enable direct modulation rates larger than 40 Gb/s at power levels adequate for short-distance and low-energy optical interconnects.

II. METAMATERIAL DEVICES FOR ACTIVE NANOPHOTONICS

In addition to new material platforms, active nanophotonics also requires innovative electromagnetic concepts to boost light–matter interactions and confine light below the diffraction limit with large efficiency. Engineered materials and metamaterials offer a variety of tools to address these needs, as discussed by several authors in this special issue. Paniagua-Domínguez *et al.* review the use of high-index dielectric nanoantenna arrays to realize low-loss nanophotonic devices. In particular, they highlight the opportunities enabled by this platform to concentrate on the fields in semiconductor nanostructures to enhance nonlinearities and enable light emission and lasing, as well as tunable responses. Huang *et al.* also discuss tunable and reconfigurable metasurfaces based on semiconductors nanoparticles, highlighting their potential impact in interface-based nanophotonics, quantum optics, and surface engineering, fully compatible with modern semiconductor foundry processes.

In their article, Kolkowski and Koenderink generally discuss the physics of arrays of scatterers for active nanophotonic applications, including light-emitting metasurfaces with tailored emission properties and light-shaping functionalities. They highlight particularly interesting phenomena when they consider balanced combinations of gain and loss in these arrays, satisfying the condition of parity-time (PT) symmetry, including the emergence of exceptional points and nontrivial topologies of the associated photonic bands. Yoshida *et al.* discuss their experimental studies of light-emitting arrays of nanostructures to implement photonic-crystal surface-emitting lasers supporting large-area coherent lasing. They show reconfiguration of the lasing mode as a function of the current injection, reporting a transition from single-mode lasing to two-mode lasing at high injection currents. Hayenga *et al.* also discuss the impact of PT symmetry in active nanophotonics, reporting the design and implementation of nanoscale electrically pumped lasers based on microring resonators offering exceptional properties in terms of low threshold, high efficiency, and large-side-mode suppression ratio. These metrics of performance enable large-scale integrability, low-energy consumption, and stable output power, ideal for active nanophotonic applications. Finally, Blanco Redondo provides an overview of the field of topological photonics, based on the recent surge of interest in applying topological concepts to design new photonic devices with unusually robust performance to disorder and imperfections. The author focuses, in particular, on the implications of these findings for quantum photonic networks and systems, for which topologically robust transport holds important opportunities to enable scalable quantum information systems.

Overall, we believe that this special issue provides a relevant and timely snapshot of the recent efforts in the field of active nanophotonics, opening exciting research and development directions in the framework of low-energy ultrafast data manipulation, processing, and computing using light. ■

ABOUT THE GUEST EDITORS

Andrea Alù (Fellow, IEEE) received the Laurea, M.S., and Ph.D. degrees from the University of Roma Tre, Rome, Italy, in 2001, 2003, and 2007, respectively.

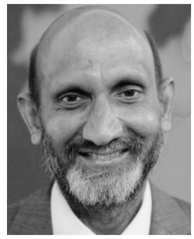
After spending one year as a Postdoctoral Research Fellow at the University of Pennsylvania, Philadelphia, PA, USA, in 2009, he joined the faculty of The University of Texas at Austin, Austin, TX, USA, where he was the Temple Foundation Endowed Professor until 2018. He is currently the Founding Director of the Photonics Initiative at the CUNY Advanced Science Research Center, New York, NY, USA. He is also the Einstein Professor of physics with the CUNY Graduate Center, New York, a Professor of electrical engineering with The City College of New York, New York, and an Adjunct Professor and a Senior Research Scientist with The University of Texas at Austin. His current research interests span over a broad range of areas, including metamaterials and plasmonics, electromagnetics, optics and nanophotonics, acoustics, scattering, nanocircuits and nanostructures, miniaturized antennas and nanoantennas, and RF antennas and circuits.

Dr. Alù is a Fellow of the American Association for Advancement of Science (AAAS), the U.S. National Academy of Inventors (NAI), the Optical Society of America (OSA), the American Physical Society (APS), and the International Society of Optics and Photonics (SPIE), and a Simons Investigator in Physics. He has been a Highly Cited Researcher since 2017. He has received several awards for his scientific work, including the NSF Alan T. Waterman Award in 2015, the Vannevar Bush Faculty Fellowship from DoD in 2019, the IEEE Kiyo Tomiyasu Award in 2019, the ICO Prize in Optics in 2016, the OSA Adolph Lomb Medal in 2013, and the URSI Issac Koga Gold Medal in 2011.

Hilmi Volkan Demir (Senior Member, IEEE) received the B.Sc. degree in electrical engineering from Bilkent University, Ankara, Turkey, in 1998, and the M.Sc. and Ph.D. degrees in electrical engineering from Stanford University, Stanford, CA, USA, in 2000 and 2004, respectively.

He is currently a National Research Foundation Fellow of Singapore and a Professor of electrical engineering, and physics and, by courtesy, of materials science and engineering at Nanyang Technological University (NTU), Singapore. He holds a chair professorship in materials science and nanotechnology at Bilkent University and UNAM—The National Nanotechnology Research Center at Bilkent (his alma mater). He is also the Founding Director of LUMINOUS! Center of Excellence for Semiconductor Lighting and Displays, NTU. As a Principal Investigator, he has published over 300 peer-reviewed research articles in major scientific journals and delivered over 250 invited conference talks, seminars, lectures, and colloquia in academia and industry around the globe. As a Principal Inventor, he has contributed to commercialization and licensing of several new enabling technologies, leading to more than 40 inventions and about 100 patent applications (granted and pending), 12 of which have currently been used, owned, or licensed by the industry. His research interests include the science and technology of semiconductor lighting, nanocrystal optoelectronics, nanoscale photonics, and implantable electronics.

Dr. Demir is a Fellow of the Optical Society of America (OSA) and an elected Associate Member of the Turkish Academy of Science (TUBA). These scientific and technopreneurship activities resulted in several important international and national awards, including the NRF Investigatorship Award, the Nanyang Award for Research Excellence, and the European Science Foundation EURYI Award.



Chennupati Jagadish (Fellow, IEEE) was the Vice-President and the Secretary of Physical Sciences of the Australian Academy of Science, Canberra, ACT, Australia, from 2012 to 2016. He is currently a Distinguished Professor and the Head of the Semiconductor Optoelectronics and Nanotechnology Group, Research School of Physics and Engineering, Australian National University, Canberra. He has published more than 940 research articles (660 journal articles), coauthored a book, coedited 15 books, and edited 13 conference proceedings and 17 special issues of journals. He holds five U.S. patents and one Australian patent.

Prof. Jagadish is a Foreign Member of the U.S. National Academy of Engineering and a Fellow of the Australian Academy of Science, the Australian Academy of Technological Sciences and Engineering, The World Academy of Sciences, the U.S. National Academy of Inventors (NAI), the Indian National Science Academy, the Indian National Academy of Engineering, the Indian Academy of Science, the European Academy of Sciences, the Andhra Pradesh Akademi of Science, the American Physical Society (APS), the Materials Research Society (MRS), the Optical Society of America (OSA), the American Vacuum Society (AVS), the Electrochemical Society (ECS), the International Society of Optics and Photonics (SPIE), the American Association for Advancement of Science (AAAS), the Electromagnetics Academy (EMA), the Asia Pacific Academy of Materials (APAM), IoP (U.K.), IET (U.K.), IoN (U.K.), and AIP. He is the past President of the IEEE Photonics Society and the Australian MRS. He has received the 2000 IEEE Millennium Medal and the Distinguished Lecturer Awards from the IEEE Nanotechnology Council, the IEEE Photonics Society, and the IEEE Electron Devices Society. He has received many awards, including the IEEE Pioneer Award in Nanotechnology, the IEEE Photonics Society Engineering Achievement Award, the IEEE Education Award from EDS, the OSA Nick Holonyak Jr Award, the Welker Award, the IUMRS Somiya Award, the UNESCO Medal for his contributions to the development of nanoscience and nanotechnologies, and the Lyle Medal from the Australian Academy of Science for his contributions to physics. He has received Australia's highest civilian honor, AC, Companion of the Order of Australia, as part of 2016 Australia day honors from the Governor-General of Australia for his contributions to physics and engineering, in particular nanotechnology. He is the Editor-in-Chief of *Applied Physics Reviews* and an editor of three book series and serves on the editorial board of 19 other journals.