Guest Editorial Special Cluster on Recent Advances in Conformal Metasurfaces

I. Introduction to Special Cluster

EXOTIC electromagnetic applications such as cloaking and illusions, as well as antenna systems conformal to various platforms, require next-generation metasurface design approaches that can accommodate arbitrarily shaped geometries. Early examples from the mid-2000s, such as holographic impedance surfaces [1] and invisibility cloaks by J.B. Pendry and D. R. Smith, were conformal [2]. Since these examples, significant advancement has been made in the ability to control electromagnetic fields along conformal metasurfaces revealing their true potential to the research community [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15].

Conformal metasurfaces have been designed using impenetrable or penetrable boundary conditions [16], [17], [18], which can all be described using a surface boundary condition referred to as the generalized sheet transition conditions (GSTC). The GSTC is a boundary condition that includes complex electric, magnetic, and magneto-electric susceptibilities [19]. These susceptibilities can be tailored to achieve a wide range of field transformations, including extreme polarization control, seamless impedance matching between input and output fields, wide angle refraction/reflection, leaky and guided-wave control, and beamforming [18]. Most scientific works to date have focused on planar geometries. Only recently have conformal versions of the GSTC gained research interest. Several contributions to this cluster extend the classical planar GSTC to conformal geometries. Design strategies are on the horizon involving numerical techniques incorporating the GSTC, which promise to usher in the next generation of conformal antennas, electromagnetic illusions, and radar cross section reduction. Therefore, it is a pivotal time to showcase these emerging research accomplishments in this special cluster.

There are several hurdles/barriers that need to be overcome to realize the full potential of conformal metasurfaces. This special cluster showcases how various research groups at the forefront of metamaterials research tackle these issues. One major impediment to the development of conformal metasurfaces is their fabrication—an area in which additive manufacturing and other advanced manufacturing processes will play a key role. This special cluster contains contributions from leading researchers who specialize in additive manufacturing of conformal metasurfaces. The work includes the capability to both print arbitrarily shaped dielectric materials and to directly write metallization's onto them. Another hurdle is the lack of design strategies and optimization approaches for conformal metasurfaces, which take account of the added complexity that comes with nonplanar designs. This special cluster includes several new approaches for the accurate modeling and design of conformal metasurfaces of various geometry as well as their excitation.

Furthermore, the technologies that emerge from these works can be used to optimize next-generation communications channels for 5G or 6G by incorporating metasurfaces onto arbitrarily shaped walls, metropolitan infrastructure, or vehicular platforms. This special cluster showcases some recent works on conformal metasurfaces for communication system channel optimization.

In summary, conformal metasurfaces are ushering in a new generation of ultra-thin electromagnetic devices with revolutionary capabilities. Research in this area opens opportunities in applications that require electromagnetic devices with very small form factors and conformal shapes. The added degrees of freedom afforded by conformal bianisotropic sheet boundaries (GSTC) promise electromagnetic and optical systems that can be seamlessly integrated into various platforms.

II. Contributions

The special cluster includes nine submissions following a rigorous review process. The nine letters are from 32 authors of various academic institutions and industries worldwide. The papers are tabulated in Table I, indicating the authors and a short description of the letter's contribution to recent advances in conformal metasurfaces.

The first letter in the cluster is by Lee and Kwon [A1]. The letter presents a design approach for 2-D conformal leaky-wave antennas through numerical optimization of harmonic field expansion coefficients. Their design operates in circular polarization and implements the meta-atoms using printed Jerusalem crosses. One difficulty in conformal metasurface design based on boundary conditions where the total fields need to be defined is obtaining the desired tangential fields along the metasurface's conformal face. The authors present one approach based on a projection of aperture fields defined along an equivalent plane onto the conformal geometry. Techniques like these are useful for engineers looking to work with conformal metasurfaces.

Dugan et al. [A2] have extended their work on incorporating spatial dispersion modeling into the GSTC to cylindrical metasurface geometries. Their form of the GSTC incorporates rational polynomial representations of the surface susceptibilities in the wavenumber domain, which capture the spatial dispersive nature of the susceptibilities particularly problematic for larger

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TABLE I
CONTRIBUTIONS TO SPECIAL CLUSTER

No.	Authors	Topic	Ref.
1	Hakjune Lee and Do-Hoon Kwon	Circularly polarized conformal leaky wave antenna	[A1]
2	Jordan Dugan, Joao Rahmeirer, Tom Smy, and Shulabh Gupta	Extending the GSTC model to include the effects of spatial dispersion for cylindrical metasurfaces	[A2]
3	Chun-Wen Lin and Anthony Grbic	Accurate modeling of coaxial feeds for cylindrical metasurfaces	[A3]
4	Ellen Gupta, Colin Bonner, Nathan Lazarus, Mark Mirotznik, and Kelvin Nicholson	6-axis additive manufacturing of conformal metasurfaces including printing of both dielectrics and metals.	[A4]
5	Mohammadreza Imani and Idban Alamzadeh	Angle-of-Arrival (AoA) detection using cylindrical metasurfaces patterned with randomly resonant radiators.	[A5]
6	Georgios Kolezas and Grigorios Zouros	Scattering from spheres modelled using anisotropic impedance boundary conditions	[A6]
7	Mohammad Hakim, Touhidul Alam, and Mohammad Islam	Conformal FSS for 5G EMI shielding applications	[A7]
8	Michela Longhi, Stefano Vellucci, Mirko Barbuto, Alessio Monti, Zahra Hamzavi Zarghani, Luca Stefanini, Davide Ramaccia, Filiberto Bilotti, and Alessandro Toscano	Beamforming using cylindrical Huygens metasurfaces	[A8]
9	Le Jiang, Shixing Yu, and Na Kou	Conformal orbital angular momentum wave generation with asymmetric operation	[A9]

unit cells. They incorporate eigenfunction expansions in terms of cylindrical modes into their extended GSTC to design cylindrical metasurfaces, which account for inherent spatial dispersion in metallizations used to realize the metasurface. Extensions of the GSTC to conformal geometries represent another important step forward in conformal metasurface design strategies.

The third letter is by Lin and Grbic [A3]. The authors present a method to accurately model coaxial feeds that excite cascaded cylindrical metasurfaces in contrast to the typical approach assuming idealized line source feed models. Mode matching techniques are used to relate the *S*-parameters at the coaxial input port to the cylindrical-wave modes of a radial parallel plate waveguide. These *S*-parameters are then related to the *S*-parameters of the cascaded cylindrical metasurface, allowing for accurate calculation of the antenna input impedance and, hence, better matching. Accurately modeling feed networks in conformal metasurfaces allows one to excite them more efficiently and significantly improve conformal metasurface design.

A significant challenge in conformal metasurface design is their fabrication. New techniques must be developed which are capable of printing combinations of arbitrarily shaped dielectrics and metals. The letter by Gupta et al. [A4] presents two such approaches. The first approach involves laser etching of annealed copper foils, which are then pressed onto the dielectric material and affixed using adhesives. The second approach relies on a 6-axis additive manufacturing machine outfitted with an aerosol jet tool. The authors first print the dielectric support structure, then direct-write the metallic pattern via aerosol jetting of a silver conductive solution onto the 3D printed part. Finally, they use copper electroless plating to increase the conductivity of the deposited silver layer. The work in this letter marks a significant step forward in the fabrication of conformal metasurfaces.

Next in the cluster, Imani and Alamzadeh [A5] present a letter on a new approach to estimating the angle-of-arrival (AoA) of an incoming electromagnetic wave. Their design utilizes a conformal array of substrate-integrated waveguide (SIW) metamaterial radiators with randomly selected resonant frequencies. The random distribution of resonant frequencies results in different coupling strengths to an incident monochromatic wave, thus providing a different weight to each frequency component measured at the coaxial port connected to the SIW. The AoA can then be obtained by analyzing frequency samples collected from a central coaxial port. This letter marks another imaginative application of conformal metasurfaces, which can find use in civil and military scenarios.

Plane-wave scattering from spherical metasurfaces characterized by anisotropic impedance boundary conditions are analytically analyzed in the letter by Kolczas and Zouros [A6]. The incident, scattered, and transmitted fields are all expanded into spherical vector wave functions. By applying the anisotropic impedance boundary condition, the unknowns in the expansion can be determined. The team uses the approach to analyze a spherical metasurface-based mantle cloak, which can switch functions from cloaking to strong scattering depending on the incident polarization. As impedance boundary conditions are ubiquitous in metasurface design, new analysis approaches like this allow for their increased use in conformal metasurface research.

A letter by Hakim et al. [A7] appears next in the cluster. The letter presents a conformal frequency selective surface (FSS), which can be used to provide stopband filters for 5G communications system frequencies. The design shows stability over a wide range of incidence angles. The design is enabled by a dual-layer fractal-based metamaterial unit cell. The letter presents measurements of a fabricated prototype with good agreement with simulation for curved geometries. As next-generation communications systems require more line-of-sight paths between handsets and base stations, researchers are looking to the channel to optimize the communications system performance. Thus, metasurfaces that can lay conformal to the infrastructure populating the channel are finding increased demand. This letter marks one such metasurface which may find applications in these scenarios.

Longhi et al. [A8] present a letter on beamforming using cylindrical metasurfaces excited centrally by a dipolar feed antenna. The cylindrical metasurface unit cells are modeled using cascaded impedance sheets implementing Huygens sources. Cylindrical array theory is then used in conjunction with the metasurface unit cells to define circular arrays capable of beamforming. This letter presents a nice conformal application of the cascaded impedance sheet implementation of Huygens metasurfaces and marks the eighth contribution to the cluster.

The final letter in the cluster is by Jiang et al. [A9]. The authors design a conformal metasurface to generate different orbital angular momentum (OAM) beams when illuminated from different sides of a conformal metasurface. A three-layer unit cell design, which reflects one polarization and transmits the other when illuminated from above, and vice versa when illuminated from below allows for asymmetric transmission. The asymmetric unit cell is then used to design a metasurface, which generates the $l = 2$ OAM beam in transmission when illuminated from above and the $l = 1$ OAM beam in transmission when illuminated from below. OAM beams can be exploited to increase the throughput of wireless links in the radiative near field. This letter offers a means of producing them using conformal metasurface designs.

In closing, the guest editors would like to express gratitude to both Prof. Christophe Fumeaux for initially accepting the special cluster proposal and to Prof. Steven Gao for taking over the Editor-in-Chief role for IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS and seeing the cluster to completion. Special thanks also to Ms. Claire Sideri, Editorial Assistant, for her support with cluster submissions. Finally, the guest editors would like to also express gratitude to all the reviewers who helped make this special cluster possible. Enjoy the contributions!

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APPENDIX: RELATED ARTICLES

[A1] H. Lee and D.-H. Kwon, "2-D circularly-polarized printed metasurface leaky-wave antennas on a conformal aperture," *IEEE Antennas Wireless Propag. Lett.*, early access, Aug. 7, 2023, doi: 10.1109/LAWP.2023.3301547.

[A2] J. Dugan, J. G. N. Rahmeier, T. J. Smy, and S. Gupta, "Field scattering analysis of cylindrical spatially dispersive metasurfaces," *IEEE Antennas Wireless Propag. Lett.*, early access, Jul. 3, 2023, doi: 10.1109/LAWP.2023.3291868.

[A3] C.-W. Lin and A. Grbic, "A realistic coaxial feed for cascaded cylindrical metasurfaces," *IEEE Antennas Wireless Propag. Lett.*, early access, Jul. 17, 2023, doi: 10.1109/LAWP.2023.3295753.

[A4] E. Gupta, C. Bonner, N. Lazarus, M. S. Mirotznik, and K. J. Nicholson, "Multi-axis manufacture of conformal metasurface antennas," *IEEE Antennas Wireless Propag. Lett.*, early access, Jun. 9, 2023, doi: 10.1109/LAWP.2023.3282556.

[A5] M. F. Imani and I. Alamzadeh, "Conformal frequency-diverse metasurface for computational AoA detection," *IEEE Antennas Wireless Propag. Lett.*, early access, Sep. 14, 2023, doi: 10.1109/LAWP.2023.3312041.

[A6] G. D. Kolezas and G. P. Zouros, "Electromagnetic analysis of anisotropic impedance spherical metasurfaces," *IEEE Antennas Wireless Propag. Lett.*, early access, May 30, 203, doi: 10.1109/LAWP.2023.3281540.

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[A8] M. Longhi et al., "Array synthesis of circular Huygens metasurfaces for antenna beam-shaping," *IEEE Antennas Wireless Propag. Lett.*, early access, Sep. 15, 2023, doi: 10.1109/LAWP.2023.3315774.

[A9] L. Jiang, S. Yu, and N. Kou, "Asymmetric transmission of OAM vortex waves by cylindrical Janus metasurface," *IEEE Antennas Wireless Propag. Lett.*, early access, Aug. 8, 2023, doi: 10.1109/LAWP.2023.3303222.

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[6] J. Budhu, L. Szymanski, and A. Grbic, "Passive and lossless, closed metasurfaces for illusion electromagnetics," in *Proc. 17th Eur. Conf. Antennas Propag.*, 2023, pp. 1–5.

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