Proceedings of the Marina Forum on Metantennas and Multiple Antennas

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Welcome Message from Conference Chairs

On behalf of the Organizing Committee, we warmly welcome you to the 3rd Marina Forum (Mar-For 2023) on Metantennas and Multiple Antennas 2023 in Singapore!

Encouraged by the success of Mar-For 2021 (online) & Mar-For 2022 (hybrid), we are excited to organize Mar-For 2023, where we aim to demonstrate the latest progress in Metantennas & Multiple antennas. We have invited eleven renowned and active researchers from Asia, Europe, and North America to share their new findings, innovative technologies, and successful applications in antenna engineering. Additionally, senior antenna experts from the industry will be sharing the state-of-the-art antenna challenges in the market to explore opportunities for collaboration.

In particular, student sessions, including the Student Paper Contest and Student Interactive Forum, are organized to provide students with a great opportunity to demonstrate their innovative works and interact with the renowned speakers/attendees. For the first time, starting this year, speech submissions are open to the general public, and only a few selected submissions will be presented at the event as well.

Mar-For 2023 will be held in a hybrid mode from 14-16 August 2023 in Singapore at the Orchard Hotel, in the heart of the iconic Orchard Road. It will be free for all online participants and available at an affordable rate for physical participants.

The Mar-For 2023 is organized by IEEE RFID Singapore Chapter and technically sponsored by IEEE, IEEE MTT/AP and EMC Singapore Chapters, Advanced Research and Technology Innovation Center of the National University of Singapore, AIM Asia, World Scientific, Laxcen, Metamorphose Vi Aisbl, and Opto-Electronics Advances. We cordially thank our event financial sponsors - Huawei Technologies, Spring Technologies, InnoWave, Rohde & Schwarz, and Advanced Research and Technology Innovation Center of the National University of Singapore for their strong financial support!

We are looking forward to meeting you physically and virtually soon!

Zhi Ning Chen, General Chair
Xianming Qing, General Co-Chair

Program at a Glance

[ONLINE] 14 August 2023	
1400 – 1500	Student Paper Competition
1520 – 1600	Student Interactive Forum
[HYBRID] 15 August 2023	
0830 – 0900	Registration
0900 – 0930	Opening Address
0930 – 1030	Keynote: Stefano Maci, University of Siena, Italy *Reflective Intelligent Surfaces and Metasurface Antennas*
1100 – 1200	Keynote: Jiro Hirokawa, Tokyo Institute of Technology, Japan *Two Dimensional Rectangular-Coordinate Orthogonal Multiplexing Antenna Systems for Non-Far Field Region Communication*
1330 – 1430	Keynote: Yahya Rahmat-Samii, University of California Los Angeles, USA *Recent Advances in the Applications of Meta EM Structure: From 3D Printed Lenses to Lightweight Membrane Designs*
1430 – 1510	Invited: Quan Xue, South China University of Technology, China *New Progresses in CMOS Millimeter Wave Sources*
1530 – 1630	Keynote: Marco Di Renzo, Paris-Saclay University, France *Intelligent Surfaces for Wireless Communications: Living at the Interface of Electromagnetic and Communication Theories*
1630 – 1710	Invited: Yi Huang, University of Liverpool, UK *Using Metamaterials for Wireless Energy Harvesting and Power Transfer*
[HYBRID] 16 August 2023	
0830 – 0930	Keynote: John L. Volakis, Florida International University, USA *Ultra Wideband Millimeter-Wave Simultaneous Transmit/Receive Radios*
0930 – 1010	Invited: Karu Esselle, University of Technology Sydney, Australia *Antenna Beam Steering using Metasurfaces in the Near Field and Other Methods*
1030 – 1130	Keynote: Ross Murch, Hong Kong University of Science and Technology, Hong Kong S. A. R *4D Multiport Antennas: Space-Time Design*
1130 – 1210	Industry: Weihong Xiao, Huawei Technologies Co. Ltd., China *Evolution of Base Station Antennas: New Efficiency, New Intelligence, New Spectrum*
1330 – 1410	Invited: Dirk Manteuffel, Leibniz University of Hannover, Germany *Multi-Mode Multi-Port Antennas (M^3PA) for 6G Antenna Systems*
1410 – 1510	Keynote: Andrea Alù, City University of New York, USA *New Frontiers for Wave Engineering Using Metamaterials*
1530 – 1545	Feng Han Lin, ShanghaiTech University, China *Developing of Metasurface Antennas with Characteristics Mode Analysis*
1545 – 1600	Yizhu Shen, Southeast University, China *Tensor holographic Metasurface to Manipulate Multi-Mode Multibeams*
1600 – 1615	Kai-Dong Hong, Nanyang Technological University, Singapore *Isolation-Enhanced and Cross-Polarization-Reduced Half-Ring Patch Antenna Pair using Stubs and Shorting Pins*
1615 – 1630	Song Li, Freetech Intelligent Systems Co. Ltd., China *A Gradual Structure for Reducing Gain Jitter of Automotive Antenna*
1630 – 1645	Jinbo Liu, Communication University of China, China *Exact Numerical Model of Frequency Selective Surfaces using the Volume-Surface Integral Equation*

Reflective Intelligent Surfaces and Metasurface Antennas

Prof. Stefano Maci, University of Siena, Italy

The new paradigm of smart radio environment (SRE) is discussed in this talk from the perspective of metasurface-based intelligent surfaces (IS) is categorized here by using the synthetic notation RIS-n, where n counts the number of “R”-type functionalities embedded in the IS: Reflecting IS (RIS-1), Reflecting-Reconfigurable IS (RIS-2) Receiving-Repeating-Reconfigurable IS (RIS-3), Receiving-Regenerating-Repeating-Reconfigurable IS (RIS-4). For increasing n, RIS-n possess an increasing level of complexity, environmental impact, power consumption and costs, but a decreasing level of densification and standardization requirement. The deployment of RIS-n in SRE is reviewed considering the new challenges that the RIS-n technology implies when implemented through metasurfaces. Special emphasis is given to efficient ray-model for both Fresnel and far zone coverage, where the scattered field from polygonal contoured RIS-1 or RIS-2 is represented in terms of few rays. The latter formulation can be conveniently used in a ray-tracer to speed-up dramatically the calculation of the field coverage. All types of RIS are well suited to be implemented by metasurface technology, that have now reached a maturity for reconfigurable low-cost antenna implementations. Examples of RIS-1, RIS-2 and RIS-3 will be discussed.

Two-Dimensional Rectangular-Coordinate Orthogonal Multiplexing Antenna Systems for Non-Far Field Region Communication

Prof. Jiro Hirokawa, Tokyo Institute of Technology, Japan

This talk presents an orthogonal multiplexing antenna system for non-far field region communication, which is based on two-dimensional polarity in the rectangular coordinate system. In other words, it is based on two-fold symmetry and anti-symmetry between the transmission modes. The two-dimensional polarity comes from the structural symmetry of magic-T components used in the corporate-feed circuit in the antenna in the millimeter-wave band. The structural symmetry gives wideband operation. The feasibility is shown by a system where a corporate-feed waveguide slot array antenna and a monopulse circuit are combined. We experimentally confirm 4-multiplex 40cm CW transmission using an 80GHz-band 16x16-slot waveguide array, 8-multiplex 20cm CW transmission using a 60GHz-band 16x16-slot dual-polarization waveguide slot array, and 2-multiplex 40cm QPSK transmission using a 60GHz- band 16x16-slot waveguide array.

Recent Advances in the Applications of Meta EM Structures: From 3D Printed Lenses to Lightweight Membrane Designs

Prof. Yahya Rahmat-Samii, University of California Los Angeles, USA

Manipulations of EM waves through various structures have been the focus of intense research interests going back to the early history of mankind and up to now. Originally all activities were concentrated on light and after the development of Maxwell’s equations the interests evolved to all aspects of the EM frequency spectrum including light. Among the early applications, mirrors and lenses were paramount components in dealing with the light and instruments such as reflecting mirrors, optical telescopes and others demonstrated how to manipulate light waves by understanding phenomena such as reflections and refractions. The desire to further be able to manipulate EM waves received much attention since World War II due to advances in communications, radars, antennas, and many others. Novel concepts have emerged and notable among them are the recent developments of the notion of metamaterials and engineered EM structures. After some brief introductory remarks, this plenary talk will focus on recent developments in synthesizing 3-D printed and layered lenses for both ground and space applications, flat reflector antennas with unique designs, reflectarrays and transmitarrays with diverse topologies including lightweight membrane configurations and others. Some out-of-the-box features of these concepts are presented in a unified fashion and future outlook for their applications and developments are highlighted.

New Progresses in CMOS Millimeter Wave Sources

Prof. Quan Xue, South China University of Technology, China

A millimeter wave source is the heart of a CMOS millimeter wave transceiver system. Efforts have been devoted in improve the quality of CMOS sources because it directly dominates the signal quality, and hence the system performance, of communication or radar. Frequency tuning bandwidth, phase noise level at different frequency deviation, DC power consumption, etc. are key parameters concerned by the millimeter system. This talk introduces recent progresses of millimeter wave sources in the speaker's team, including varactorless VCOs, multi-core VCOs, frequency dividers, frequency multipliers, etc. Theory, simulation and experimental results will be presented.

Intelligent Surfaces for Wireless Communications: Living at the Interface of Electromagnetic and Communication Theories

Prof. Marco Di Renzo, Paris-Saclay University, France

In wireless communications, the term intelligent surface is referred to a planar metamaterial structure that is capable of generating an arbitrary current density distribution, so as to ensure the highest flexibility in generating a specified electromagnetic field and in shaping the propagation of the electromagnetic waves in large-scale networks. This presentation is aimed to report the latest research advances on analytical modeling, evaluating the ultimate performance limits, and optimizing intelligent surfaces for application to wireless communications, with focus on the synergies between electromagnetic and communication theories.

Using Metamaterials for Wireless Energy Harvesting and Power Transfer

Prof. Yi Huang, University of Liverpool, UK

In this talk, a comprehensive review and exploration of the metamaterials and metasurfaces in the field of wireless power transfer (WPT) and wireless energy harvesting (WEH) is presented. These two closely related areas have garnered significant attention due to their immense practical implications. Our focus lies in elucidating strategies to enhance the energy conversion efficiency of both systems. By harnessing the unique capabilities of metamaterials and metasurfaces, significant improvements can be achieved in RF to DC energy conversion efficiency and operational distance. Through deliberate manipulation of electromagnetic fields between the transmitter and receiver, as well as reducing the sensitivity of reception to incident wave angle and polarization, metamaterials and metasurfaces offer unparalleled opportunities for optimizing performance. These novel materials can function as either parasitic elements or loading components, effectively augmenting the overall efficiency of wireless energy harvesting. Through a systematic analysis of recent research and cutting-edge developments, we aim to provide valuable insights into the practical implementation of metamaterials and metasurfaces for WPT and WEH. The discussion will cover key methodologies, emerging trends, and potential challenges in the field. Additionally, we will explore potential applications and highlight the transformative impact of these advancements on WPT and WEH technologies.

Ultra Wideband Millimeter-Wave Simultaneous Transmit/Receive Radios

Prof. John Volakis, Florida International University, USA

Next-Generation wireless radios will rely on the millimeter-wave (mm-Wave) spectrum to deliver faster data speeds in the context of spectrally agile resource allocation for reliable communications. Realizing this promise requires high speed digital technology and wideband RF hardware that are not prone to in-band and out-of-band interferers. While modest bandwidths have been sufficient in the past, higher data rates, multiple beams, and higher transmit/receive gains are likely to be the norm for future applications. With this in mind, there is a need to develop ultra wideband hardware for full duplex radios. A technology, referred to as simultaneous time/frequency domain duplexing or simultaneous transmit and receive (STAR) or in-band full duplexing (IBFD), can enable existing and future radios to achieve two-fold improvement in spectral efficiency. Our group has been an early leader in developing and demonstrating wideband full-duplex systems for over a decade. Wideband antennas with suitable feed networks can provide 40 dB suppression of the coupled high-power self-interference Tx signal. In addition, a first-ever FIR-based wideband RF-self interference cancellation (SIC) filter with delays and attenuators was demonstrated to achieve a combined cancellation of 70dB across 500MHz bandwidth. Further analog and digital stage cancellations can allow for 120dB total self-interference cancellation. Even more, cognitive radio and customized Machine Learning (ML) and Artificial Intelligence (AI) algorithms can provide for smart and reconfigurable full duplex radios that adapt to different environment. In this presentation, we will present techniques to achieve full-duplex radios with 120dB cancellation across at least 500MHz.

Antenna Beam Steering using Metasurfaces in the Near Field and Other Methods

Prof. Karu Esselle, University of Technology Sydney, Australia

Inspired by optical Risely Prism, a modern low-profile method to steer the beam of any fixed-beam antenna by introducing two rotating metasurfaces to the near field has attracted significant attention by industry and academia since the method was first published in 2017. In this invited distinguished speech, recent advances of this method will be discussed, and some other existing beam steering methods will also be revisited.

4D Multiport Antennas: Space-Time Design

Prof. Ross Murch, Hong Kong University of Science and Technology, Hong Kong S.A.R.

Exploiting the 4th dimension (4D), time, can open up enhanced electromagnetic performance and new phenomena. For example in antenna arrays it can be used to reduce sidelobes while in electromagnetic propagation it can provide time reversal through Cauchy sources. It has not been widely utilized in multiport antenna design mainly due to the use of full digital transceivers for multiple input multiple output (MIMO) systems, which can provide all the functionality of 4D multiport design anyway. However with the advent of massive MIMO and ultra-massive MIMO in wireless communication, full digital systems are no longer possible and hybrid beamforming and antenna reconfiguration are necessary. In other words 4D multiport antenna design is becoming important. In this talk methods to perform 4D multiport antenna design are introduced. A particular focus is on methods that do not cause bandwidth expansion so that they are compatible with wireless communication spectrum requirements. Techniques to implement pulse shaping, OFDM and hybrid beamforming are described based on varactors and PIN diodes. Beamspace formulations along with far-field decompositions of scattering based on the Theory of Characteristic Modes (TCM) are harnessed for analyses of the systems. A basic introduction to 4D electromagnetic radiators is also provided as background.

Evolution of Base Station Antennas: New Efficiency, New Intelligence, New Spectrum

Weihong Xiao, Huawei Technologies Co. Ltd

Multi-Mode Multi-Port Antennas (M³PA) for 6G Antenna Systems

Prof. Dirk Manteuffel, Leibniz University of Hannover, Germany

6G mobile communications aims to provide ubiquitous connectivity in a so called “cyber-physical world”. Related applications require a merge of sensing systems (e.g. radar) and communication systems. Such Joint Communication and Sensing (JCaS) comes along with new challenges as traditionally radar and communication system are developed with different demands. They result in different requirements for the radio system in general and for the antennas in particular. Conventional antenna arrays usually consist of uniform antenna elements having a static element pattern. According to the primary beam direction, either broadside or endfire elements are chosen. Beamforming patterns then suffer from scan loss not only due to the aperture orientation but also due to the element pattern. Furthermore, co-located elements in a multi-antenna system suffer from mutual coupling that can be reduced to an acceptable level for conventional communication systems but is yet unacceptable for radar systems that require full-duplex operation. As JCaS aims at using the same common infrastructure for both communication and radar, those incompatibilities must be eliminated. In this presentation, so-called Multi-Mode Multi-Port Antenna (M³PA) elements are proposed as a unit cell for such JCaS arrays. M³PA are antenna elements having multiple uncorrelated antenna ports which are mutually uncoupled thanks to the use of symmetry properties of their modal antenna currents. The ports provide both broadside and off-broadside patterns that can be flexibly selected by the beamformer. As such, they have some potential to increase the scan range of the array when broadside modes are used for near broadside scanning and off-broadside modes are used for larger scan angles. M³PAs can also be used to generate a virtually layered array by using a certain port per element for one array layer that is used e.g. for communication while another port per element is independently used as another array layer for a radar system. Furthermore, using the orthogonality properties of M³PA already enables intrinsic decoupling of the ports of a certain element which is a prerequisite for full-duplex operation. The presentation will introduce the concept of the M³PAs and will discuss potentials and challenges when they are used in antenna arrays.

New Frontiers for Wave Engineering Using Metamaterials

Prof. Andrea Alù, City University of New York, USA

Metamaterials are engineered materials with properties that go well beyond what offered by nature, providing unprecedented opportunities to tailor and enhance the control of waves. In this talk, I discuss our recent activity at microwaves and THz frequencies, showing how suitably tailored meta-atoms and their arrangements open exciting avenues for wave manipulation. In particular, I will discuss our recent work on nonlocal metasurfaces and leaky-wave metasurfaces, which enable a new degree of control over radiated fields using engineered nonlocalities across an aperture. I will also discuss the role of time-modulation to enhance antenna bandwidth and realize efficient frequency conversion, phase conjugation, magnet-free nonreciprocity and topological phenomena. Insights into the underlying physics and new electromagnetic devices based on these concepts will be presented.

Development of Metasurface Antennas with Characterastic Mode Analysis

Feng Han Lin, Jia Fan Gao, Si Yu Miao, Yi Zheng, Yi Hui Zhu, Jian Ping Zeng, Zi Cheng Song
* *ShanghaiTech University, Shanghai, China, linfh@shanghaitech.edu.cn*

***Abstract*—This paper reviews the recent development of metasurface (MTS) antennas with the aid of characteristic mode analysis (CMA), focusing on the unique advantages and new explanations offered by CMA for modeling an MTS, simplifying the analysis, mode excitation, mode manipulation and mode synthesis. Examples of multi-mode MTS antennas are given in three different levels, including MTS antenna element, MTS antenna array and multi-port MTS antenna for bandwidth enhancement, pattern mitigation, isolation improvement, accelerated analysis and clearer physical understanding. Future directions are also briefly introduced.**

***Keywords*—Antennas; antenna array; characteristic mode analysis; metamaterials; metasurfaces; multi-port antenna; theory of characteristic modes**

SUMMARY

The development of functional metasurfaces (MTS) has gained increasing attention since 2010s. Fig. 1 illustrates the typical methods of analysis and design with applications outlined. The far-field methods are highly effective for scattering problem that aims to manipulate the outgoing waves from an electrically-large metasurface upon illumination from the far-field region, but less intuitive for near-field problems where the size of an MTS approaches a resonant size. The timely marriage of the concept of MTS and the theory of characteristic mode (TCM) has enables a new possibility of modeling and analyzing MTS resonators and arrays of finite size in arbitrary shape for developing high-performance MTS patch antennas [1]–[7], MTS wire antennas [8]–[9], MTS antenna arrays [10], multi-antenna systems [11]–[13], near-field MTS antennas [14] and meta-absorbers [15]–[16], which will be reviewed during the conference presentation with a focus on the unique advantages of CMA for solving challenging problems.

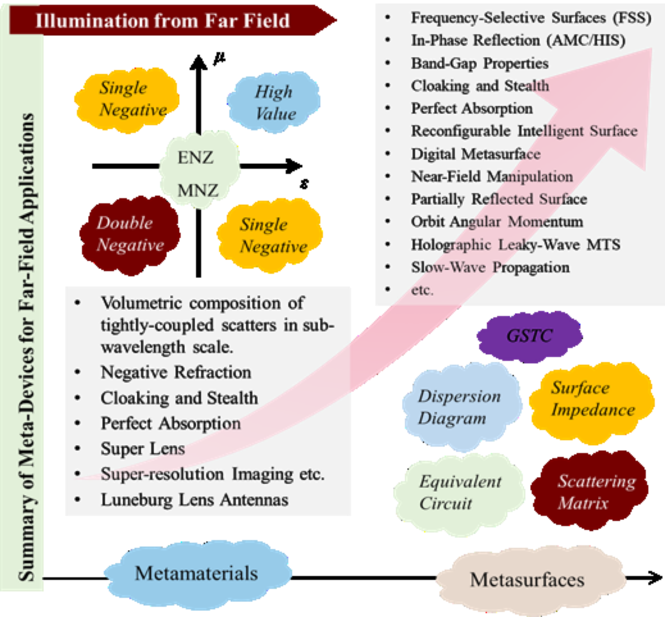


Figure 1. Summary of the characterization methods and major applications of metamaterials (MTMs) and metausrfaces (MTS).

REFERENCES

[1] F. H. Lin and Z. N. Chen, "Low-profile wideband metasurface antennas using characteristic mode analysis," *IEEE Trans. Antennas Propag.*, vol. 65, no. 4, pp. 1706–1713, Apr. 2017.

[2] F. H. Lin and Z. N. Chen, "Probe-fed broadband low-profile metasurface antennas using characteristic mode analysis," *2017 6th Asia-Pacific Conference on Antennas and Propagation (APCAP)*, Xi'an, China, 2017, pp. 1–3.

[3] F. H. Lin and Z. N. Chen, "Truncated impedance-sheet model for low-profile broadband nonresonant-cell metasurface antennas using characteristic mode analysis," *IEEE Trans. Antennas Propag.*, vol. 66, no. 10, pp. 5043–5051, Oct. 2018.

[4] F. H. Lin and Z. N. Chen, "Resonant metasurface antennas with resonant apertures: characteristic mode analysis and dual-polarized broadband low-profile design," *IEEE Trans. Antennas Propag.*, vol. 69, no. 6, pp. 3512–3516, Jun. 2021.

[5] F. H. Lin and Z. N. Chen, "Truncated impedance sheet model for low-profile broadband nonresonant-cell metasurface antennas using characteristic mode analysis," *IEEE Trans. Antennas Propag.*, vol. 66, no. 10, pp. 5043–5051, Oct. 2018.

[6] J. Zeng, X. Liang, L. He, F. Guan, F. H. Lin, and J. Zi, "Single-fed triple-mode wideband circularly polarized microstrip antennas using characteristic mode analysis," *IEEE Trans. Antennas Propag.*, vol. 70, no. 2, pp. 846–855, Feb. 2022.

[7] J. Zeng, Z. Zhang, F. H. Lin, and F. Guan, "Penta-mode ultrawideband circularly polarized stacked patch antennas using characteristic mode analysis," *IEEE Trans. Antennas Propag.*, vol. 70, no. 10, pp. 9051–9060, Oct. 2022.

[8] Y. H. Zhu and F. H. Lin, "Metasurface loaded dual-mode wideband dipole antenna using characteristic mode analysis," *2022 Int. Applied Comp. Electrom. Soc. Symp. (ACES-China)*, Xuzhou, China, 2022, pp. 1–2.

[9] Y. H. Zhu and F. H. Lin, "Metasurface-loaded tri-mode wideband monopole antenna using characteristic mode analysis," *2022 IEEE 10th Asia-Pacific Conf. Antennas and Prop. (APCAP)*, Xiamen, China, 2022, pp. 1–2.

[10] J. F. Gao and F. H. Lin, "Modeling and analysis of wideband multilayer metasurface antenna array using characteristic-mode analysis," *IEEE Trans. Antennas Propag.*, vol. 71, no. 3, pp. 2832–2836, Mar. 2023.

[11] F. H. Lin and Z. N. Chen, "A method of suppressing higher order modes for improving radiation performance of metasurface multiport antennas using characteristic mode analysis," *IEEE Trans. Antennas Propag.*, vol. 66, no. 4, pp. 1894–1902, Apr. 2018.

[12] D. Manteuffel, F. H. Lin, T. Li, N. Peitzmeier, and Z. N. Chen, "Characteristic mode-inspired advanced multiple antennas: intuitive insight into element-, interelement-, and array levels of compact large arrays and metantennas," *IEEE Antennas and Prop.n Mag.*, vol. 64, no. 2, pp. 49–57, Apr. 2022.

[13] Y. Zheng and F. H. Lin, "Compact wideband three-port metasurface antenna using characteristic mode analysis," *2022 IEEE 10th Asia-Pacific Conf. Antennas and Prop. (APCAP)*, Xiamen, China, 2022, pp. 1–2.

[14] Y. Zheng and F. H. Lin, "Enhancement of local field by using characteristic mode analysis," *2023 17th Euro. Conf. Antennas Prop. (EuCAP)*, Florence, Italy, 2023, pp. 1–5.

[15] Z. Song, P. Min, L. Yang, J. Zhu, and F. H. Lin, "A bilateral coding metabsorber using characteristic mode analysis," IEEE Antennas Wirel. Prop. Lett., vol. 21, no. 6, pp. 1228–1232, Jun. 2022.

[16] Z. Song, F. H. Lin and J. Zhu, "Recent progress in characteristic mode analysis and design of lossy structures," *2022 IEEE 10th Asia-Pacific Conf. Antennas and Prop. (APCAP)*, Xiamen, China, 2022, pp. 1–3.

Tensor Holographic Metasurface to Manipulate Multi-mode Multibeams

Song Xue, Yizhu Shen, and Sanming Hu
State Key Laboratory of Millimeter Waves
School of Information Science and Engineering, Southeast University, Nanjing, China,
230228249@seu.edu.cn, yizhu.shen@seu.edu.cn, sanming.hu@seu.edu.cn

***Abstract*—This talk will introduce recent researches on the holographic metasurface, including the optimizations of wide bandwidth, high gain, and planar integration simultaneously. Several designs will be discussed, such as a directional-fed holographic metasurface with varied modulation index, a center-fed high-gain holographic metasurface to improve the equivalent isotropic radiated power, and tensor holographic metasurface to independently manipulate multi-mode multibeams. All designs are analyzed, simulated, fabricated, and validated with matched results in simulation and measurement.**

***Keywords*—Impedance Modulation, Multibeams, Multiplexing**

SUMMARY

Multi-mode beams are with different beam types, frequency bands, polarizations, radiation directions, and focal depths. They have attracted worldwide interest, because of its flexibility and reconfigurability for different application scenarios. Additionally, multiple beams have also been widely investigated, because of its potential applications in 5G/6G wireless communication, satellite link, radar system, and so on.

Multi-mode multibeams are mostly generated by 3D bulky configuration or partitioned aperture for each beam. Holographic metasurface is a promising candidate for planar integration, since it integrates the feed at the center of the planar metasurface [1]. Several works have indicated that, the scalar holographic metasurface is with low aperture efficiency and lack of anisotropic manipulation abilities, whereas the tensor holographic metasurface is feasible to manipulate the amplitude, phase and polarization of multi-mode multibeams simultaneously [2-4].

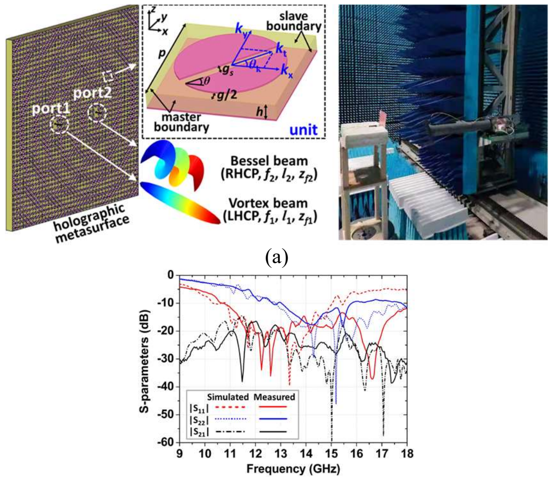
This summary introduces an addition method to generate multibeams using a planar single-layer tensor holographic metasurface with shared aperture. The underlying principle is to multiplex the holographic metasurface with a superposition of modulated impedance surface, to implement the two steps of holographic recording and holographic reconstruction. The holographic recording is to build the overall tensor surface impedance pattern of Z, which is an interference between the surface current J_{surf} and the object radiated wave E_{obj} as follow:

$$Z = j\left[X + M\,\mathrm{Re}\left(E_{\mathrm{obj}}\,J^{*}_{\mathrm{surf}}\right)\right] \tag{1}$$

where X is the average value, M is the modulation index of surface impedance, and *Re* stands for the real part. Therefore, for the multi-mode N-beams, it can be further derived as:

$$\begin{aligned}\boldsymbol{Z} &= \frac{1}{N}\sum_{i=1}^{N}\begin{pmatrix}\boldsymbol{Z}_{xxi} & \boldsymbol{Z}_{xyi}\\ \boldsymbol{Z}_{yxi} & \boldsymbol{Z}_{yyi}\end{pmatrix} \quad (i=1,2,\ldots N)\\ &= \frac{1}{N}\sum_{i=1}^{N} j\left[\begin{pmatrix}X_i & 0\\ 0 & X_i\end{pmatrix} + \frac{M_i}{2}\mathrm{Im}\left(\boldsymbol{E}_{\mathrm{obj}i}\otimes\boldsymbol{J}^{H}_{\mathrm{surf}i} - \boldsymbol{J}_{\mathrm{surf}i}\otimes\boldsymbol{E}^{H}_{\mathrm{obj}i}\right)\right]\\ &= \frac{1}{N}\sum_{i=1}^{N} j\begin{bmatrix} X_i + \frac{M_i}{2}\mathrm{Im}\left(E_{x_i}J^{H}_{x_i} - E^{H}_{x_i}J_{x_i}\right) & \frac{M_i}{2}\mathrm{Im}\left(E_{xi}J^{H}_{y_i} - E^{H}_{y_i}J_{x_i}\right)\\ \frac{M_i}{2}\mathrm{Im}\left(E_{y_i}J^{H}_{x_i} - E^{H}_{x_i}J_{y_i}\right) & X_i + \frac{M_i}{2}\mathrm{Im}\left(E_{y_i}J^{H}_{y_i} - E^{H}_{y_i}J_{y_i}\right)\end{bmatrix}\end{aligned} \tag{2}$$

To validate the proposed multiplexing method, as shown in Fig. 1(a), dual-beams with N=2 are manipulated as an example.



(a)

(b)

Fig. 1 The tensor holographic metasurface for multi-mode multibeams.

Two monopoles are employed to excite this holographic metasurface to radiate dual Bessel beams with different modes, i.e., different beam types, different frequencies, different circular polarizations, and different focal depths. Port 1 excites a first-order vortex beam with anti-clockwise impedance distribution of order of two, while port 2 generates a zero-order Bessel beam with clockwise impedance distribution of order of one. After superposition using Equation (1), an overall impedance Z is then used to implement the holographic metasurface.

This tensor holographic metasurface is full-wave simulated, fabricated, and experimentally validated. Fig. 1(b) shows the comparison between the simulated and measured two-port *S*-parameters. Other experiment results will be discussed in details in this talk. The proposed method is promising for front-ends in wireless communication with compact size, planar integration, light weight, and flexible manipulations.

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REFERENCES

[1] B. H. Fong, J. S. Colburn, J. J. Ottusch, J. L. Visher, and D. F. Sievenpiper, “Scalar and tensor holographic artificial impedance surfaces,” *IEEE Trans. Antennas Propag.*, vol. 58, no. 10, pp. 3212-3221, Oct. 2010.

[2] D. González-Ovejero, G. Minatti, G. Chattopadhyay, and S. Maci, “Multibeam by metasurface antennas,” *IEEE Trans. Antennas Propag.*, vol. 65, no. 6, pp. 2923-2930, Jun. 2017.

[3] Y. Shen, S. Xue, G. Dong, J. Yang, and S. Hu, “Multiplexing tensor holographic metasurface with surface impedance superposition for manipulating multibeams with multimodes,” *Adv. Opt. Mater.*, vol. 9, no. 22, pp. 2101340, Nov. 2021.

[4] Y. Shen, S. Xue, J. Yang, and S. Hu, “Tensor holographic metasurface using addition theory to independently manipulate orthogonally polarized Bessel beams,” *Adv. Mater. Technol.*, vol. 6, no. 4, pp. 2001047, Apr. 2021.

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Isolation-Enhanced and Cross-Polarization-Reduced Half-Ring Patch Antenna Pair Using Stubs and Shorting Pins

Kai-Dong Hong*^, Tao Yuan^
* *School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore*
^ *College of Electronics and Information Engineering, Shenzhen University, Shenzhen, China*
kaidong.hong@ntu.edu.sg

***Abstract*—A co-polarized and closely-spaced half-ring patch antenna pair (HRPAP) with loading of stubs and shorting pins is proposed for isolation enhancement and cross-polarization reduction. By inserting two stubs and adjusting gaps between the HRPAP, consistent resonant frequency and equal quality factor of the odd and even modes can be simultaneously obtained, which contributes to high isolation of the HRPAP over a wide frequency range. Furthermore, four shorting pins are elaborately loaded so as to weaken the *y*-oriented current component of the HRPAP, by which the cross-polarization level in the *H*-plane is significantly reduced. Finally, the proposed HRPAP is fabricated and measured. Both the simulated and experimental results show that the antenna has achieved an isolation level over 30 dB, cross-polarization reduction of about 8.8 dB, and consistent radiation patterns.**

***Keywords*—Half-ring patch antenna pair, isolation enhancement, cross-polarization reduction, stub loading, shorting pin loading**

SUMMARY

Patch antenna has been one of the most popular candidate in fifth-generation (5G) wireless communication system due to it attractive features including low profile, ease of integration, and mass production capabilities. However, when two or more patch antennas with same polarization are tightly arranged, the strong mutual coupling will degrade the antenna's performance, limiting its practical application in the multiple-input and multiple-output (MIMO) system [1]. Although using the traditional method based on introducing various decoupling structures can achieve the satisfactory isolation, they inevitably suffer from more complex structure, and more occupied area. In recent years, a well-known self-decoupling technique based on mode cancellation and weak-field construction has been demonstrated to be promising for mutual coupling reduction [2]. However, this method always require the special structure and arrangement of the antenna element.

This paper proposes a co-polarized and closely-spaced HRPAP with enhanced isolation, reduced cross-polarization and consistent radiation pattern [3]. The geometry of the proposed HRPAP is illustrated in Fig. 1. Two HRPAs connected by two stubs are printed on the top surface of the substrate, which is suspended above a ground plane by four plastic screws. Besides, four shorting pins with a radius of 2 mm are set along the *x*- and *y*-axis direction, respectively. As the transmission coefficients shown in Fig. 2, the odd and even modes of the HRPAP can be independently tuned by loading stubs and selecting an appropriate gap width between the HRPAP, and high isolation can be achieved when the resonant frequencies and quality factors of the two modes become equal. After that, a traditional half-ring patch antenna under full-wavelength operation usually suffer from an inherent drawback of poor polarization purity in *H*-plane. This is because the current component decomposed in the cross-polarized direction is very strong. To overcome this issue, four shorting pins are elaborately introduced to mitigate the cross-polarized current component on the patch, so that the polarization purity can be effectively enhanced by about 8.8 dB, as the cross-polarization shown in Fig 2. As compared with other reported works, our proposed antenna has some admirable features, such as simple structure, ultimate isolation, moderate bandwidth, reduced cross-polarization, and improved radiation pattern with and consistent high-gain beam.

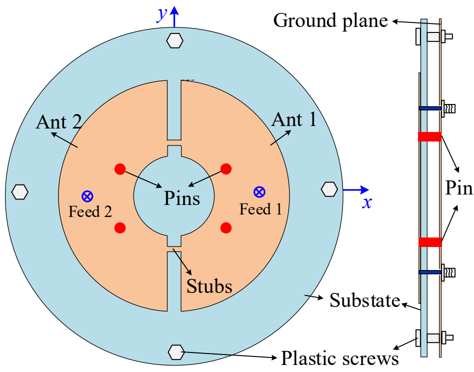

Fig. 1. Configuration of the proposed highly-isolated half-ring patch antenna pair (HRPAP).

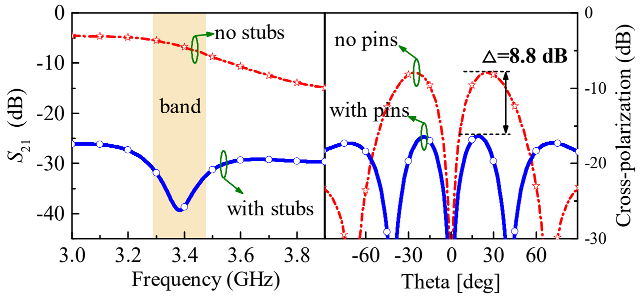

Fig. 2. Transmission coefficients and cross-polarization in the *H*-plane of the half-ring patch antenna pair with and without stubs and pins.

ACKNOWLEDEMENT

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REFERENCES

[1] M. A. Jensen and J. W. Wallace, "A review of antennas and propagation for MIMO wireless communications," *IEEE Trans. Antennas Propag.*, vol. 52, no. 11, pp. 2810–2824, Nov. 2004.

[2] H. Lin, Q. Chen, Y. Ji, X. Yang, J. Wang, and L. Ge, "Weak-field-based self-decoupling patch antennas," *IEEE Trans. Antennas Propag.*, vol. 68, no. 6, pp. 4208–4217, Jun. 2020.

[3] Q. Lai, Y. Pan, S. Zheng, and W. Yang, "Mutual coupling reduction in MIMO microstrip patch array using TM10 and TM02 Modes," *IEEE Trans. Antennas Propag.*, vol. 69, no. 11, pp. 7562–7571, Nov. 2021.

[4] K.-D. Hong, X. Zhang and T. Yuan, "Closely-spaced half-ring patch antenna pair with enhanced isolation, reduced cross-polarization, and consistent beam," *IEEE Antennas Wireless Propag. Lett.*, vol. 22, no. 2, pp. 357–361, Feb. 2023.

A gradual structure for reducing gain jitter of automotive antenna

Song Li, Chaoyang Fan, Ziqiang Tong
Freetech Intelligent Systems Co.,Ltd, shanghai, China, song.li@freetech.com
Freetech Intelligent Systems Co.,Ltd, shanghai, China, chaoyang.fan@freetech.com
Freetech Intelligent Systems Co.,Ltd, shanghai, China, ziqiang.tong@freetech.com

***Abstract*—A novel gradual structure for millimeter wave antenna is designed in this paper, which reduces the gain jitter of azimuth pattern of the antenna with radome. The simulation and measurement results show that azimuth gain jitter reduced from 15dB to 5dB within ±60°.**

***Keywords* — Comb-line antenna, Checkerboard Structure**

SUMMARY

Due to the existence of radome and bumper, gain jitter occurs on the azimuth plane of automotive radar. That's because of multiple electromagnetic reflections between antenna surface, radome and bumper, which will be superimposed on the real target echo, resulting in errors in radar ranging and angle measurement, so it is necessary to reduce the jitter of radar azimuth pattern[1].

Over the last few years periodic structures such as electromagnetic band gap (EBG) and artificial magnetic conductor (AMC) are considered to be the effective solutions. The presence of EBG is able to suppress surface waves, whereas the AMC surfaces can reflect incident waves[2]. A low RCS surface for millimeter wave radar was designed in [3], which was periodically arranged by chessboard structure composed of AMC and an ideal electrical conductor PEC. This surface uses the 180° reflection phase difference of between AMC and PEC to realize the mutual cancellation of reflected electromagnetic waves only in normal direction.

In fact, the reflection of electromagnetic waves is in not only normal direction, but also entire FOV range needs to be considered. This paper firstly select the comb-line antenna as the radiation source, which is widely used in automotive millimeter wave radar[4], then calculates the incidence angles corresponding to different areas of the antenna azimuth plane according to the electromagnetic wave propagation path, and designs the corresponding checkerboard structure for different incidence angles. Finally, different checkerboard structures are combined and arranged on the both sides of the antenna. As shown in Fig.1, checkerboard structure 0 is located at the end of the antenna, and the edge distance is approximately $\lambda_0/2$, which corresponds to the decrease of RCS on the antenna surface at vertical incidence. The checkerboard structure 1,2 and 3 are symmetrically located on both sides of antenna, corresponding to the RCS on the antenna surface when the incidence angles 1,2 and 3 decrease respectively. In the same checkerboard structure, the overall size of AMC and PEC remains the same, and the patch gap in different AMC is consistent. The size of checkerboard structure gradually increases from the center to both sides. Different AMC and PEC in gradual checkerboard structure can reduce the RCS of the antenna surface when the electromagnetic wave is incident at different angles, and further reduce the reflection between the antenna surface and radome.

Fig.2 shows the measured gain pattern of the comb-antenna with and without loading gradient checkerboard structure. It can be seen that loading this gradual checkerboard structure can reduce the jitter of the antenna azimuth pattern, azimuth gain jitter reduced from 15dB to 5dB within -60° to 60°.

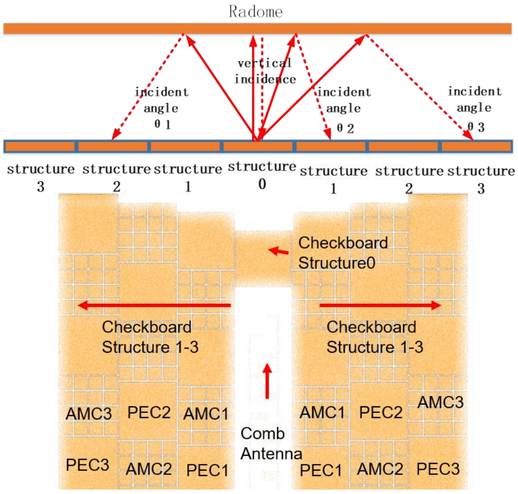

Fig.1 Gradual checkerboard structure

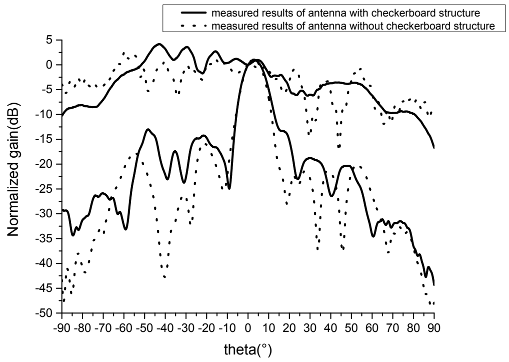

Fig. 2 Measured results of antenna with or without checkerboard structure

REFERENCES

[1] W. Menzel and A. Moebius, "Antenna Concepts for Millimeter-Wave Automotive Radar Sensors," in Proceedings of the IEEE, vol. 100, no. 7, pp. 2372-2379, July 2012, doi: 10.1109/JPROC. 2012. 2184729.

[2] Y. Sun, Z. N. Chen, Y. Zhang, H. Chen and T. S. P. See, "Subwavelength Substrate-Integrated Fabry-Pérot Cavity Antennas Using Artificial Magnetic Conductor," in IEEE Transactions on Antennas and Propagation, vol. 60, no. 1, pp. 30-35, Jan. 2012, doi: 10.1109/TAP.2011.2167902.

[3] Vasanelli C, Boegelsack F, Waldschmidt C. Design and experimental characterization of a surface with low radar cross-section at millimeter-wave frequencies[C]//2016 46th European Microwave Conference (EuMC). IEEE, 2016: 21-24

[4] Dapeng Wu, Ziqiang Tong, R. Reuter, H. Gulan and J. Yang, "A 76.5 GHz microstrip comb-line antenna array for automotive radar system," 2015 9th European Conference on Antennas and Propagation (EuCAP), Lisbon, Portugal, 2015, pp. 1-3.

Exactly Numerical Model of Frequency Selective Surfaces Using the Volume-Surface Integral Equation

Jinbo Liu[1], Zengrui Li[1], and Jiming Song[2]
[1] *Communication University of China, Beijing, China, liuj@cuc.edu.cn, zrli@cuc.edu.cn*
[2] Iowa State University, *Iowa, USA, jisong@iastate.edu*

***Abstract*—In the moment method solution of the volume-surface integral equation (VSIE) modeling composite objects, the fictitious surface electric charge accumulated on the perfect electric conductor (PEC)-dielectric interfaces is eliminated by enforcing the continuity condition (CC) of electric flux and boundary condition (BC) of electric field. Through reliable numerical experiment, it is certified that the solution accuracy during the simulation of frequency selective surfaces (FSSs) are sharply improved.**

***Keywords*—Frequency selective surface (FSS), method of moments (MoM), volume-surface integral equation (VSIE).**

SUMMARY

In the analysis of electromagnetic (EM) properties of composite perfect electric conductor (PEC)-inhomogeneous dielectric objects, the volume-surface integral equation (VSIE) is widely adopted due to its confirmed versatility and accuracy. However, to some specific applications, the accuracy of traditional VSIE is barely enough. For example, based on a large number of numerical experiments, it is found that the FSS resonant frequencies obtained by the traditional VSIE often shift to higher values. The reason is that the objects like FSSs contain large areas of PEC-dielectric interfaces (PDIs), leading to the accumulation of fictitious surface electric charge which does not exist physically.

To solve the mentioned problem, we deeply investigate how to enforce the continuity condition (CC) and boundary condition (BC) on the PDIs during the MoM solution of VSIE, to eliminate the fictitious surface charge. It is assumed that an object is profiled as a PEC surface sandwiched by two dielectric regions V_t and V_b. Excited by an EM wave, there exists the electric flux $\vec{D}_t$ and $\vec{D}_b$ flowing in top region V_t and bottom V_b and the actual surface currents $\vec{J}_{S_t}$ and $\vec{J}_{S_b}$ on the two sides of PEC surface, while $\hat{n}_{S'}$ is the outward unit normal of the PDI S' towards V_t.

Firstly, for the objects described as open PECs embedded within dielectric substrates. Based on the principle of electric flux continuity, the CC can be formed on the PDI S' as

$$\begin{cases} \mathrm{j}\omega\hat{n}_{S'}(\vec{r})\cdot\vec{D}_t(\vec{r}) = -\nabla\cdot\vec{J}_{S_t}(\vec{r}) \\ -\mathrm{j}\omega\hat{n}_{S'}(\vec{r})\cdot\vec{D}_b(\vec{r}) = -\nabla\cdot\vec{J}_{S_b}(\vec{r}) \end{cases} \quad \vec{r}\in S'. \tag{1}$$

If we respectively add the left- and right-hand sides of the two equations (1), the expression

$$\hat{n}_{S'}(\vec{r})\cdot\mathrm{j}\omega\vec{D}_t(\vec{r}) = -\nabla\cdot\vec{J}_S(\vec{r}) + \hat{n}_{S'}(\vec{r})\cdot\mathrm{j}\omega\vec{D}_b(\vec{r}) \quad \vec{r}\in S' \tag{2}$$

will be obtained with a simple transposition. That is to say, on S', $\vec{D}_t$ can be expressed by the surface summation current $\vec{J}_S$ and $\vec{D}_b$. Since $\vec{J}_{S_t}$ and $\vec{J}_{S_b}$ are not independently needed, the CC implementation is much easier compared with the approach shown in [1].

Secondly, on S', according to the BC, the tangential component of the electric field $\vec{E}$ is null as

$$\hat{t}_S(\vec{r})\cdot\vec{E}(\vec{r}) = \hat{t}_S(\vec{r})\cdot\vec{D}(\vec{r})/\varepsilon(\vec{r}) = 0 \quad \vec{r}\in S'. \tag{3}$$

The BC approach can be further improved, based on which two of the four SWG coefficients belonging to a tetrahedron terminated by a PEC triangle can be straightly determined by the other two. Moreover, the number of volumetric unknowns reduced by the improved BC is two times of that in the existing work [2].

Thirdly, the CC and BC are combined together and simultaneously enforced on the PDIs, and then the fictitious surface charge is extremely eliminated. At the same time, considerable volumetric unknowns are removed.

The backward RCS from a 10×10 FSS array is computed using the proposed approach, whose unit structure is shown in Fig. 1. The resonant frequency of the FSS unit is about 21.2 GHz. Figure 2 shows the calculated backward RCSs as functions of the frequency for the normal incidence. The curves indicate that the traditional VSIE result has an obvious high-drift of 1 GHz (22.2 GHz), while for the proposed approach, it is effectively reduced to 0.2 GHz (21.4 GHz).

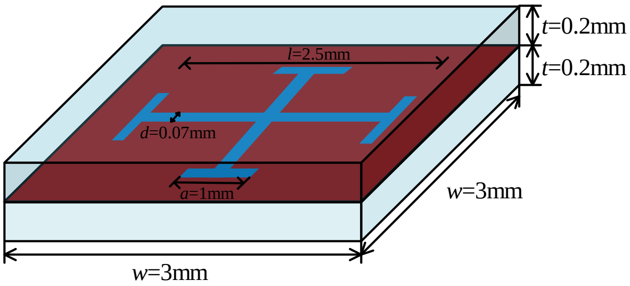

Fig. 1 Sketch of one unit in a 10×10 array of Jerusalem cross slot patch embedded in a dielectric substrate with $\varepsilon_r = 3.35$ and tan$\delta = 0.008$.

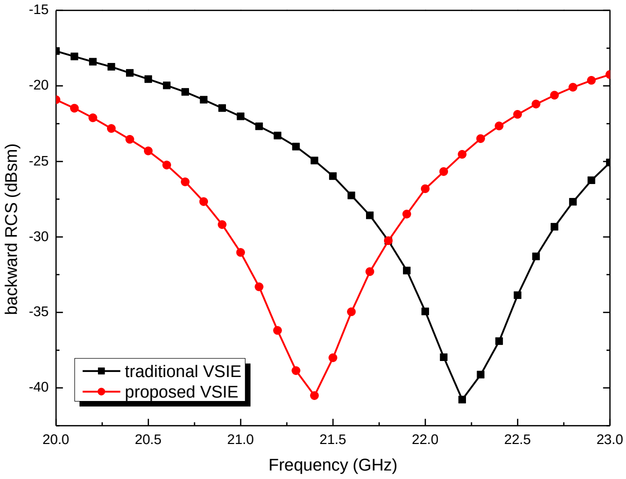

Fig. 2 The backward RCSs as a function of frequency for the normal incidence of a 10×10 array of Jerusalem cross slot FSS.

REFERENCES

[1] J. Liu, X. Men, M. He, Z. Li, and J. Song, “Improving the solution accuracy of the volume-surface integral equation for the open PEC structures embedded within dielectrics,” *IEEE Trans. Antennas Propag.*, vol. 70, no. 12, pp. 12010-12018, Dec. 2022.

[2] J. Liu, X. Men, H. Zhang, Z. Li, and J. Song, “On the enforcement of electric field boundary condition in the moment method solution of volume-surface integral equation,” *IEEE Antennas Wireless Propag. Lett.*, vol. 21, no. 9, pp. 1877-1881, Sep. 2022.

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