Design of an Array-based Plane Wave Generator for Compact Field Antenna Testing

Fangyun Peng [1], Xiaoming Chen [1,2], Furong Li [1], Xiaobo Liu [1], Jiaying Zhang [3], Ming Zhang [1], and Yingsong Li [4,5]

[1] Faculty of Electronic and Information Engineering
Xian Jiaotong University, Xi'an, 710049, China
xiaoming.chen@mail.xjtu.edu.cn

[2] State Key Laboratory of Millimeter Waves
Southeast University, Nanjing, 211189, China

[3] EM-Testing, Shanghai, 200000, China

[4] College of Information and Communication Engineering
Harbin Engineering University, Harbin, 150001, China

[5] Key Laboratory of Microwave Remote Sensing
National Space Science Center, Chinese Academy of Sciences, Beijing, 100190, China

Abstract **─** A near-field planar array of wideband dual polarized antennas for plane-wave synthesis has been investigated. The paper presents a PWG with a concentric ring array of 84 Vivaldi antennas which can work at 0.6GHz-3GHz. The constraint least square (CLS) algorithm is used to optimize the weight coefficients of the array elements, which effectively reduce the influence of system uncertainty on quiet zone (QZ) ripple. To reduce the system cost and complexity, the array elements in each concentric ring form a sub-array and the elements of the same sub-array adopt a passive beam forming network. The simulation and initial test results of a circular QZ with a diameter of 600 mm are given. The results demonstrate the feasibility of our design.

Index Terms **─** Constrained Least Square (CLS), plane wave synthesis, wideband dual polarized.

I. INTRODUCTION

The fifth generation (5G) technology [1-2] has brought new challenges to radiated tests of radio frequency (RF) and antenna systems [3-22]. The integrated design of RF front-end and antenna makes the traditional conductive test no longer applicable, which puts forward new requirements for 5G testing. Various over-the-air (OTA) measurement methods have attracted great attentions in the development of wireless devices. Generally speaking, all wireless tests conducted in controllable environments, such as anechoic chamber (AC) [5, 6] or reverberation chamber (RC) [7], belong to OTA tests. Direct far-field testing dictates a long distance between the antenna under test and the measurement probe. This can impose challenging demand on the size of the AC, link budget, etc. To reduce the size of the AC (and, therefore, the system cost), various near field antenna measurement techniques have been proposed. The near field antenna measurement system collects the amplitude and phase of each point over a specific plane in the test zone and converts the near-field to the far-field through sophisticated transformation algorithms to obtain the far-field radiation characteristics of the antenna [8]. The compact antenna test range (CATR) relies on the parabolic reflector to convert spherical waves into plane waves. Good measurement performance can be achieved. However, the method is somehow limited by the construction cost and manufacture accuracy. In order to avoid the complicated near-to-far field transformation and reduce the cost, a promising solution is to synthesize plane waves in the near field using the plane wave generator (PWG) method [9-13].

The PWG can generate quasi-plane wave in short distance by optimizing the amplitude and phase of the weighting coefficient of each element, which has the advantages of high accuracy, small size and low maintenance cost. The synthesis procedures and design guidelines regarding size and shape of the PWG, as well as the number of radiating sources needed to synthesize the required plane waves were given in [14]. The

Submitted On: July 29, 2020
Accepted On: April 18, 2021

https://doi.org/10.47037/2021.ACES.J.360910

1054-4887 © ACES

research focus of PWG designs is to calculate the proper weighting coefficients and to determine the positions of the array elements given the number of radiating sources and the distance between PWG and the antenna under test (AUT). The literature proposes some algorithms, such as least square method (LSM), singular value decomposition (SVD), Genetic Algorithm (GA), Particle Swarm Optimization (PSO), etc. [15-20] to solve the optimization problem. Most of the studies on PWG lack experimental validations until very recently [21-23]. The design and measured performance of a dual-polarized PWG are reported in [22, 23].

The LS method is widely used for plane wave synthesis, but it has the disadvantage of poor adaptability of the mean square error to measurement noise. In order to obtain a stable solution to the ill-conditioned LS problem, the weighting coefficients of the array elements are calculated using the constraint least square (CLS) algorithm based on Lagrange multiplier method, which effectively reduce the influence of system uncertainty on quiet zone (QZ) ripple. And a reference area larger than QZ is introduced to reduce the reflection effect caused by the uneven distribution of the field outside QZ.

We designed a plane wave generator with 84 broadband dual polarized Vivaldi antennas, which is divided into 6 sub-arrays to reduce the system cost. Compared with the previous works [24], the presented PWG design has much fewer antennas and RF chains (and, therefore, a much lower system cost), while providing reasonably good performance. It is a reciprocal structure that can test radiated performances of the RF transceiver link, such as EIRP (Effective Isotropic Radiated Power), EIS (Electrochemical Impedance Spectroscopy), and EVM (Error Vector Magnitude). The designed prototype is validated by experiments.

The structure of the paper is as follows. Section II describes the system model of the PWG and the optimization algorithms in the synthesis processes. A PWG prototype with 84 array elements is designed. In Section III, simulation results and experimental validations show that the PWG can generate a quiet zone (QZ) in the desired frequency band with satisfactory amplitude and phase errors. Section IV draws conclusions.

II. METHOD OF PLANE WAVE SYNTHESIS

A. System model

In this paper, a PWG with a plane array of N antennas and an AUT with a square array of M samples is considered. Assuming the distance between the PWG and AUT is D. As shown in Fig. 1, the field of the m-th sample on the AUT is:

$$E_m = \sum_{n=1}^{N} I_n \frac{e^{j(2\pi/\lambda)R_{mn}}}{4\pi R_{mn}}, \tag{1}$$

where I_n is the excitation current of the n-th antenna element in the PWG, λ is the wavelength and R_{mn} is the distance between the m-th sample and the center of the n-th antenna element. Its vector-matrix representation is given as follows:

$$\mathbf{E} = \mathbf{A}\mathbf{I}, \tag{2}$$

where $\mathbf{I} = [I_1, I_2, \cdots I_N]^H$, $\mathbf{E} = [E_1, E_2, \cdots E_M]^H$ with the superscript H denoting conjugate transpose, and $\mathbf{A}$ is a $M\times N$ coefficient matrix given by:

$$\mathbf{A} = \begin{bmatrix} \frac{e^{-j(2\pi/\lambda)R_{11}}}{4\pi R_{11}} & \cdots & \frac{e^{-j(2\pi/\lambda)R_{1N}}}{4\pi R_{1N}} \\ \vdots & \ddots & \vdots \\ \frac{e^{-j(2\pi/\lambda)R_{M1}}}{4\pi R_{M1}} & \cdots & \frac{e^{-j(2\pi/\lambda)R_{MN}}}{4\pi R_{MN}} \end{bmatrix}. \tag{3}$$

The objective is to minimize the amplitude and phase error between the target field and the field sample. And the objective function can be written as

$$f = \min \| \mathbf{A}_{M\times N}\mathbf{I}_{N\times 1} - \mathbf{E}_{0_{M\times 1}} \|_2, \tag{4}$$

where $\mathbf{E}_0$ is the field of an ideal plane wave and $\|\bullet\|_2$ denotes the Euclidean norm. By taking the derivative of the cost function and forcing it equal zero, the least square (LS) solution is obtained as follows:

$$\mathbf{I} = (\mathbf{A}^H\mathbf{A})^{-1}\mathbf{A}^H\mathbf{E}_0. \tag{5}$$

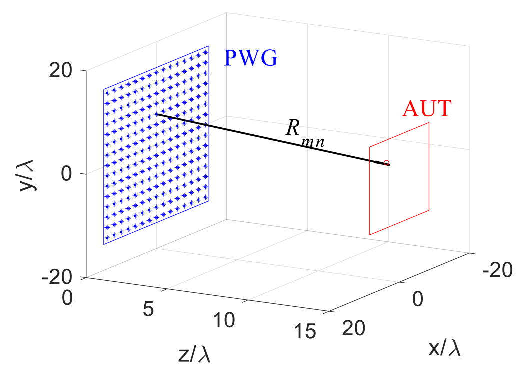


Fig. 1. Geometry of PWG and AUT.

B. The synthesis method

The LS method can find the optimal weighting coefficient of each array element by minimizing the square sum of the error. In order to synthesize a quasi-plane wave on antenna under test (AUT), we set M>>N. The LS problem is an ill-conditioned problem. Small disturbances in the coefficient matrix may cause huge disturbances in the solution, making the calculated LS solution meaningless. Especially in practical applications, the LS algorithm cannot fit well due to the uncertainty of the testing environment and the system accuracy. In order to obtain a stable solution to the ill-conditioned LS problem, we resort to the constrained least square (CLS) method.

The CLS can be expressed as:

$$\min \| \mathbf{AI} - \mathbf{E}_0 \|_2 \quad s.t.\, \mathbf{CI} = \mathbf{D}, \tag{6}$$

where $\mathbf{C}$ is a $P\times N$ matrix, and $\mathbf{D}$ is a $P\times 1$-vector. $\| \mathbf{AI} - \mathbf{E}_0 \|_2$ is the objective function and $\mathbf{CI} = \mathbf{D}$ are the equality constraints. $\hat{\mathbf{I}}$ is a solution of CLS. If $\mathbf{C}\hat{\mathbf{I}} = \mathbf{D}$, $\|\mathbf{A}\hat{\mathbf{I}} - \mathbf{E}_0\|_2 \le \|\mathbf{AI} - \mathbf{E}_0\|_2$ holds for any $N\times 1$ vector I that satisfies $\mathbf{CI} = \mathbf{D}$.

In this paper, we introduce a reference zone that is larger than the ideal QZ. $\mathbf{E}_0$ is the field of the plane wave of the ideal area, $\mathbf{D}$ is the field of the reference area, and $\mathbf{C}$ is the coefficient matrix of the PWG and the reference area. The amplitude, phase and size of the field outside the QZ and the weighting coefficient of each element on the PWG can be optimized using the global optimization algorithm.

C. Design of PWG

As shown in Fig. 2 (a), the PWG system is mainly composed of antenna array, beam forming network, polarization control turntable, test instruments, and multi-axis turntable. In this paper, a PWG with a concentric ring array of 84 probe elements is designed. The radial spacing between each ring of the PWG is 125 mm. The elements between two neighbouring rings are offset by certain degrees [see Fig. 2 (b)] to reduce to keep the mutual coupling in an acceptable level [24].

In order to improve the QZ size and accuracy, the basic idea of the PWG is to use multiple probe antennas, each of which is equipped with a phase shifter and an attenuator, to synthesize plane wave on the AUT area. However, the application of large-scale antenna arrays will increase construction and maintenance costs. A feasible solution is to divide the whole array into several sub-arrays and the elements in each sub-array share the same phase shifter and attenuator. In total, there are six concentric sub-arrays.

The elements in a concentric ring forms a sub-array and the radiating elements of the same sub-array adopt a passive beam forming network using approximately the same amplitude and phase excitation. As shown in Fig. 3, we use a multi-stage power divider network with power dividers of 1 to 2, 1 to 4, and 1 to 8 power dividers according to the number of each sub-array element.

In the near-field test, the probe has a great influence on the electrical performance of the test system. There are two methods to achieve dual polarized near-field measurement. One is to rotate a single-polarized probe mechanically and the other is to directly use a dual-polarized probe. Since the former increases the hardware complexity of the PWG and the measurement time, dual-polarized probe antennas are widely used. Preferably, the dual-polarized probe should have low cross-polarization, broadband characteristics and small size. The dual-polarized Vivaldi antenna is an ultra-wideband antenna that fulfills all the requirements [25]. Therefore, it is chosen as the radiating element of the PWG in this work.

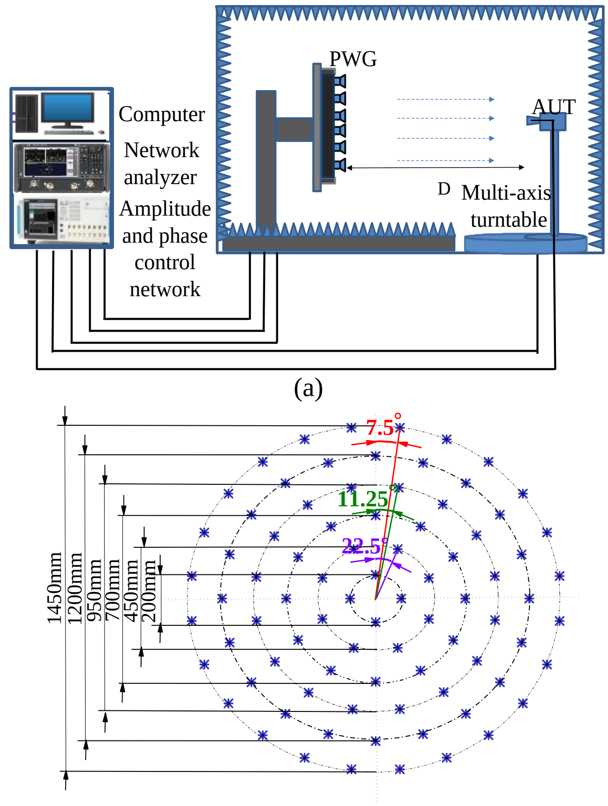


Fig. 2. (a) Structure diagram of the PWG testing system; (b) element positions (marked as asterisks) of the PWG.

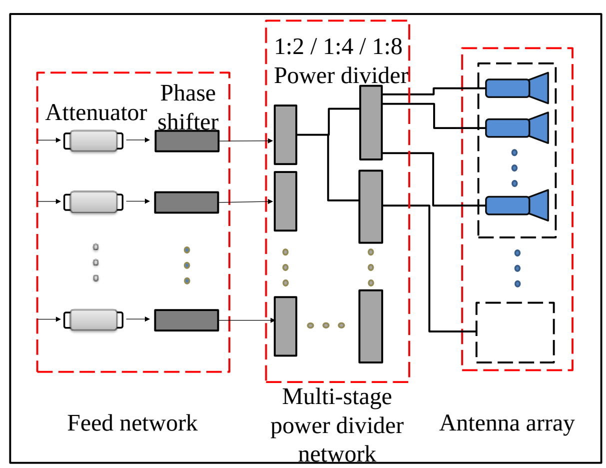


Fig. 3. The structure of the PWG.

III. SIMULATION AND MEASUREMENT RESULTS

A. Simulation

The designed PWG was simulated at 3 GHz. The circular QZ has a diameter of 600 mm. The inter-element spacing of the sampling grids in the QZ is 0.01 m. The distance between the AUT and the PWG is 1.8 m.

The reference area is a circular area with a diameter of 800 mm containing the QZ at its center. Figures 4 and 5 shows the simulation results of the PWG based on the LS and CLS methods (where the QZ is marked in a black circle). The amplitude and phase errors of the QZ generated by the CLS method are within ±0.8 dB and ±5º, respectively. Obviously, the plane waves synthesized by the CLS method are more consistent. Furthermore, compared with the LS method, it can effectively reduce the multipath scattering around the quiet zone. This indicates that the design meets the performance requirements well.

Considering the method of sub-array division, each concentric circle is used as a sub-array to match the excitation source with the same amplitude and phase. This is a trade-off between QZ performance and system complexity. The corresponding simulation results are shown in Fig. 6.

Figure 7 shows the maximum amplitude and phase errors of the QZ on the AUT with distances of 1.5m, 1.8m, 2.0m and 2.3m between the PWG and AUT. As can be seen, when the PWG works within the frequency range of 0.6 GHz-3 GHz, its maximum amplitude error is less than 1 dB and the maximum phase error is less than 2º as the distance of PWG and AUT is more than 2m.

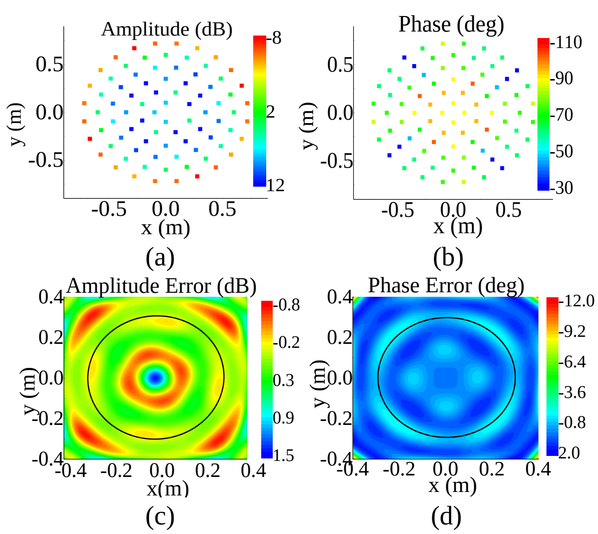


Fig. 4. Simulation results of the PWG based on the LS method at 3 GHz. The amplitude (a) and phase (b) of the excitations of the antenna elements in the PWG; the amplitude (c) and phase error (d) on the AUT.

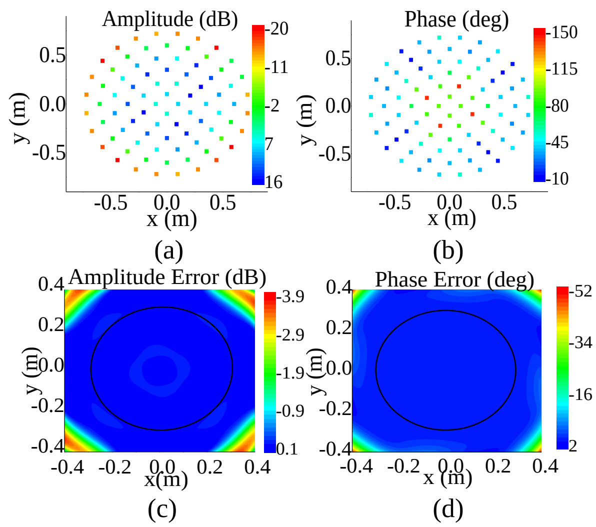


Fig. 5. Simulation results of the PWG based on the CLS method at 3 GHz. The amplitude (a) and phase (b) of the excitations of the antenna elements in the PWG; the amplitude (c) and phase error (d) on the AUT.

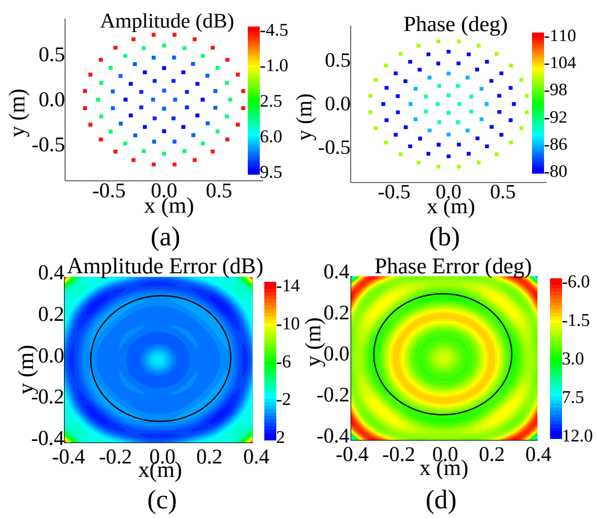


Fig. 6. Simulation results of the PWG based on the sub-array method at 3 GHz. The amplitude (a) and phase (b) of the excitations of the antenna elements in the PWG; the amplitude (c) and phase error (d) on the AUT.

B. Measurement

Figure 8 is the actual measurement setup of the PWG system. The mutual coupling between antennas is reduced by inserting absorbing materials between the antenna array elements. The vertical flatness of the QZ was measured using the scanning frame. Figures 9 and 10 present the amplitude and phase errors at the frequencies, 0.6 GHz, 1.5 GHz and 3 GHz with two different distances between the PWG and AUT of 1.8 m and 2.3 m. As can be seen, as the distance increases, the testing results have been significantly improved.

Note that due to the inconsistency of the radiation characteristics of the measurement error of the test probe, the multipath array elements, imperfect calibration of the amplitude and phase imbalance of the feeding network, reflections in the non-anechoic testing environment, etc., the measured results are not as good as the simulated ones. Nevertheless, as can be seen from Figs. 9 and 10, reasonable plane waves can be generated using the PWG at the near-field range.

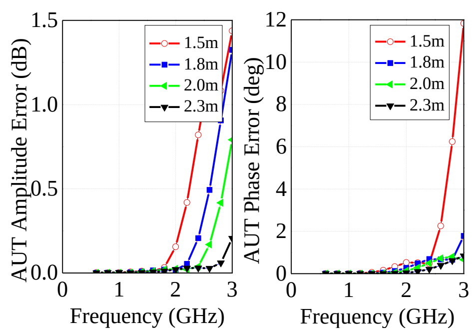


Fig. 7. Maximum amplitude (a) and phase errors (b) on the AUT as a function of frequency with a distance of 1.5 m, 1.8 m, 2.0 m and 2.3 m between the PWG and AUT, respectively.

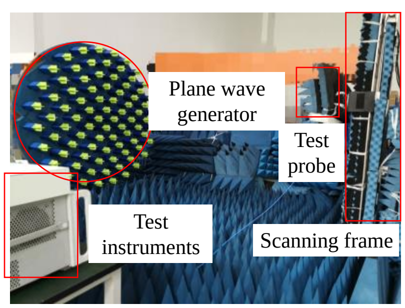


Fig. 8. Measurement setup of the PWG.

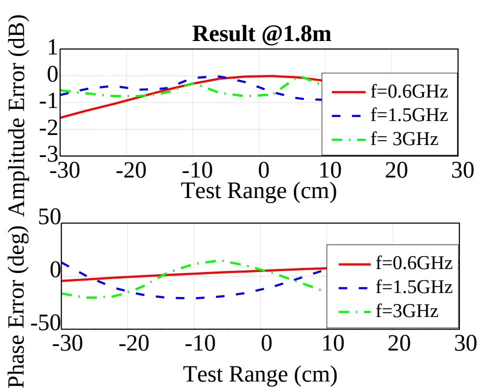


Fig. 9. Measurement results of the PWG at 0.6 GHz, 1.5 GHz and 3 GHz with a distance of 1.8 m between the PWG and AUT.

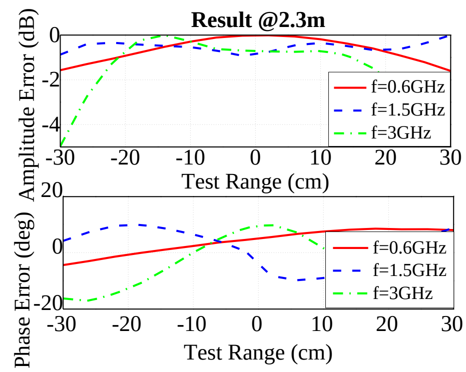


Fig. 10. Measurement results of PWG at 0.6GHz, 1.5GHz and 3GHz with a distance of 2.3m between PWG and AUT.

IV. CONCLUSION

The PWG is an effective OTA test method with the advantages of high accuracy, small size and low maintenance cost. In this paper, we designed a wideband dual-polarized PWG consisting of 84 Vivaldi antennas (divided into six concentric subarrays). In order to enhance the robustness of the system, CLS algorithm is proposed to optimize the weights of array elements. By tradeoff between QZ performance and system complexity, the design of sub-array is introduced to reduce the number of RF channels. The simulation and measurement results of the designed PWG are given in the frequency range of 0.6 GHz - 3 GHz. The test results of the amplitude and phase error in the QZ are in ±1 dB and ±10º, respectively. The unsatisfactory test environment may have a slight impact on the results.

ACKNOWLEDGMENT

This work is supported in part by the National Natural Science Foundation of China under Grants 61801366, 61901354 and by the State Key Laboratory of Millimeter Waves under Grant K201933 and Natural Science Foundation of Shaanxi Province under Grant 2020 JM-078.

REFERENCES

[1] R. He, B. Ai, G. Wang, Z. Zhong, C. Schneider, D. A. Dupleich, R. S. Thomae, M. Boban, J. Luo, and Y. Zhang, "Propagation channels of 5G millimeter wave vehicle-to-vehicle communications: Recent advances and future challenges," *IEEE Vehicular Technology Magazine*, vol. 15, no. 1, pp. 16-26, Mar. 2020.

[2] G. We and Q. Feng, "Side-frame dual-band MIMO antennas for 5G smartphone applications," *Applied Computational Electromagnetics Society (ACES) Journal*, vol. 35, no. 11, pp. 1314-1315, Nov. 2020.

[3] W. Fan, P. Kyösti, M. Romney, X. Chen, and G. F.

Pedersen, "Over-the-air radiated testing of millimeter-wave beam-steerable devices in a cost-effective measurement setup," *IEEE Comm. Mag.*, vol. 56, no. 7, pp. 64-71, July 2018.

[4] X. Chen, W. Fan, P. Kyösti, L. Hentilä, and G. F. Pedersen, "Throughput modeling and validations for MIMO-OTA testing with arbitrary multipath," *IEEE Antennas Wireless Propag. Lett.*, vol. 17, no. 4, pp. 637-640, Apr. 2018.

[5] Y. Ji, W. Fan, G. F. Pedersen, and X. Wu, "On channel emulation methods in multiprobe anechoic chamber setups for over-the-air testing," *IEEE Trans. Veh. Technol.*, vol. 67, no. 8, pp. 6740-6751, Aug. 2018.

[6] R. Johnson, H. Ecker, and R. Moore, "Compact range techniques and measurements," *IEEE Trans. Antennas Propag.*, vol. 17, no. 5, pp. 568-576, Sep. 1969.

[7] X. Chen, W. Xue, H. Shi, J. Yi, and W. Sha, "Orbital angular momentum multiplexing in highly reverberant environments," *IEEE Microw. Wireless Compon. Lett.*, vol. 30, no. 1, pp. 112-115, Jan. 2020.

[8] M. A. Qureshi, C. H. Schmidt, and T. F. Eibert, "Efficient near-field far-field transformation for nonredundant sampling representation on arbitrary surfaces in near-field antenna measurements," *IEEE Trans. Antennas Propag.*, vol. 61, no. 4, pp. 2025-576, Apr. 2013.

[9] X. H. Zhang, Z. H. Zhang, and Y. J. Ma, "5G antenna system OTA testing with plane wave generator in range-constrained anechoic chamber," *Proc. 6th Asia–Pacific Conf. Antennas Propag.*, pp. 1-3, Oct. 2017.

[10] A. Khatun, V. M. Kolmonen, V. Hovinen, D. Parveg, M. Berg, K. Haneda, K. I. Nikoskinen, and E. T. Salonen, "Experimental verification of a plane-wave field synthesis technique for MIMO OTA antenna testing," *IEEE Transactions on Antennas and Propagation*, vol. 64, no. 7, pp. 3141-3150, July 2016.

[11] R. Xie, X. Wang, R. Wang, T. Wang, D. Chen, T. Song, L. Kuang, and S. Zhu, "Synthesis of plane wave applied to 5G communication antenna measurement,"*2017 Progress in Electromagnetics Research Symposium-Spring (PIERS)*, pp. 195-198, Jan. 2017.

[12] R. Haupt, "Generating a plane wave with a linear array of line sources," *IEEE Trans. Antennas Propag.*, vol. 51, no. 2, pp. 273-278, Feb. 2003.

[13] O. M. Bucci, C. Gennarelli, and C. Savarese, "Representation of electromagnetic fields over arbitrary surfaces by a finite and nonredundant number of samples," *IEEE Trans. Antennas Propag.*, vol. 46, no. 3, pp. 351-359, Mar. 1998.

[14] O. M. Bucci, M. D. Migliore, G. Panariello, and D. Pinchera, "Plane-wave generators: Design guidelines, achievable performances and effective synthesis," *IEEE Trans. Antennas Propag.*, vol. 61, no. 4, pp. 2005-2018, Apr. 2013.

[15] D. Yu, H. Zhang, and W. Liu, "Synthesis of a plane-wave via linear array with unequal interval," *ISAPE2012*, pp. 827-829, Oct. 2012.

[16] D. A. Hill, "A numerical method for near-field array synthesis," *IEEE Transactions on Electromagnetic Compatibility*, vol. EMC-27, no. 4, pp. 201-211, Nov. 1985.

[17] A. Capozzoli, C. Curcio, G. D'Elia, A. Liseno, and P. Vinetti, "A novel approach to the design of generalized plane-wave synthesizers," *European Conference on Antennas and Propagation (EuCAP)*, Berlin, Germany pp. 3375-3379, Mar. 2009.

[18] A. Capozzoli, C. Curcio, and A. Liseno, "Singular value optimization in inverse electromagnetic scattering," *IEEE Antennas and Wireless Propag. Lett.*, vol. 16, pp. 1094-1097, 2017.

[19] M. D'Urso, G. Prisco, and M. Cicolani, "Synthesis of plane-wave generators via nonredundant sparse arrays," *IEEE Antennas and Wireless Propagation Letters*, vol.8, pp. 449-452, Mar. 2009.

[20] D. Yu, G. Xie, W. Zhai, and D. Fu, "The optimization of cosine window function using genetic algorithm and its application in plane wave synthesis," *2011 4th IEEE International Symposium on Microwave, Antenna, Propagation and EMC Technologies for Wireless Communications*, Beijing, pp. 194-197, Nov. 2011.

[21] R&S Report. Report on R&S®PWC200 Plane Wave Converter for 5G massive MIMO base station testing, March, 2019. https://scdn.rohde-schwarz.com/ur/pws/dl_downloads/dl_common_library/dl_brochures_and_datasheets/pdf_1/PWC200_fly_en_5215-5971-32_v0200.pdf

[22] F. Scattone, D. Sekuljica, A. Giacomini, F. Saccardi, A. Scannavini, N. Gross, E. Kaverine, P. O. Iversen, and L. J. Foged, "Design of dual polarised wide band plane wave generator for direct far-field testing," *European Conference on Antennas and Propagation (EuCAP)*, Kracow, Poland, pp. 1-4, Apr. 2019.

[23] Y. Zhang, Z. Wang, X, Sun, Z. Qiao, and J. Miao, "Design and implementation of a wideband dual polarized plane wave generator with tapered feeding nonuniform array," *IEEE Antennas and Wireless Propag. Lett.*, vol. 19, no. 11, pp. 1988-1992, Nov. 2020.

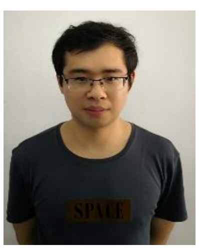
[24] X. Chen, S. Zhang, and Q. Li, "A review of mutual coupling in MIMO systems," *IEEE Access*, vol. 6, pp. 24706-24719, Apr. 2018.

[25] H. Lv, Q. Huang, J. Hou, and J. Liu, "Wideband dual-polarized Vivaldi antenna with gain enhancement," *Applied Computational Electromagnetics*

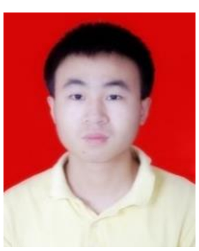
Society (ACES) Journal, vol. 33, no. 9, pp. 990-996, Sep. 2020.

Fangyun Peng received the B.Sc. degree in Electrical Information Engineering from Southwest Jiaotong University, Chengdu, China, in 2018. She is currently pursuing the M.S. degree in Information Engineering from Xi'an Jiaotong University. Her research interests include OTA test.

Xiaoming Chen received the Ph.D. degree from the Chalmers University of Technology, Gothenburg, Sweden, in 2012. From 2012 to 2014, he was a Postdoctoral Researcher at the same University. From 2014 to 2017, he was with Qamcom Research & Technology AB, Gothenburg. Since 2017, he has been a Professor with Xi'an Jiaotong University, Xi'an. His research areas include 5G multi-antenna techniques, over-the-air (OTA) testing, and reverberation chambers. Prof. Chen serves as an Associate Editor (AE) for the journal of IEEE Antennas and Wireless Propagation Letters (AWPL).



Furong Li is a Research Assistant at Xi’an Jiaotong University, Xi’an, China.



Xiaobo Liu received the Ph.D. degree in Electronic Science and Technology from Xi’an Jiaotong University, Xi’an, China, in 2018. Since 2020, he has been an Assistant Professor with Xi’an Jiaotong University. His research interests include electromagnetic and microwave theory, computational electromagnetics, antenna design, and microwave circuit.

Jiaying Zhang is the General Manager in Shanghai EM-Testing Co., LTD.

Ming Zhang received the Ph.D. degree from Xi'an Jiaotong University, Xi'an, China, in 2017, respectively. He is now an Associated Professor at Xi'an Jiaotong University.

Yingsong Li received his Ph.D. degree from both Kochi University of Technology (KUT), Japan and Harbin Engineering University, China in 2014. He is currently a Full Professor of Harbin Engineering University. His current research interests include remote sensing, underwater communications, signal processing, radar, SAR imaging, and microwave antennas. Li is an Area Editor of AEÜ-International Journal of Electronics and Communications, and he is an Associate Editor of IEEE Access and Applied Computational Electromagnetics Society Journal (ACES Journal).