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A Digital Metamaterial of Arbitrary Base Based on Voltage Tunable Liquid Crystal

YIZHE ZHAO[1,2], CHENG HUANG[2], ZELIN SONG[3], CHENGYONG YU[3], SHUO LIANG[1], XIANGANG LUO[2], AND ANYONG QING[4,1], (Senior Member, IEEE)
[1]School of Physics , University of Electronic Science and Technology of China, Chengdu 610054, China
[2]The State Key Laboratory of Optical Technologies on Nano-Fabrication and Micro-Engineering, Institute of Optics and Electronics, Chinese Academy of Sciences, Chengdu 610209, China
[3]School of Electronic Science and Engineering, University of Electronic Science and Technology of China, Chengdu 610031, China
[4]School of Electronical Engineering, Southwest Jiaotong University, Chengdu 610054, China

Corresponding authors: Yizhe Zhao (zhaoyz91@163.com) and Anyong Qing (qinganyong@tsinghua.org.cn)

ABSTRACT In this paper, a digital metamaterial of arbitrary base based on liquid crystal (LC) is proposed. The digital metamaterial can be multiplexed for different desirable functions by properly biasing the LC for different code patterns. Simulation results of two common functions, beam steering with a steering elevation angle 27° and RCS reduction of at least 10 dB from 51 to 56 GHz, have been presented to prove the concept. The feasibility has been further confirmed by preliminary measurement.

INDEX TERMS Coding metamaterial, digital metamaterial, liquid crystal (LC), coding particle, beam steering, RCS reduction.

I. INTRODUCTION

Currently, metamaterials [1] have become a research hotspot due to their special electromagnetic properties which are inexistent in natural materials. They have been applied to realize some amazing functions such as invisible cloaking [2], negative refraction [3] and perfect lens [4].

In the past decades, metamaterials have been designed to control phase of electromagnetic waves [5], [6]. Very recently, coding metamaterials (CMM) [7], [8], or more general digital metamaterials [9], have been proposed for this purpose. CMM are only composed of two types of unit cells, namely 0 and 1 elements. The phase difference between 0 and 1 elements is approximately 180°. Terahertz anomalous reflections [10] and broadband diffusions [11] were achieved.

In the seminal innovation [7], "a subwavelength square metallic patch printed on a dielectric substrate" is utilized to realize the binary elements. Consequently, although CMM encoded with different patterns might correspond to different functions, instant switching of coding patterns for different functions is a very tough challenge.

In the community of frequency selective surfaces, reconfigurable antennas, and metamaterials, tunable structures play a critical role to achieve dynamic performance. One of the common tunable structures is switches such as PIN diodes, varactor diodes [12], [13], microelectromechanical systems (MEMS) devices. It is noticed that PIN diodes have later been used to "digitally control the '0' and '1' responses" [7], the binary characteristics of PIN diodes seriously limits the coding freedom of CMM. CMM might be very complicated and bulky. In addition, tuning switches usually result in parasitic resistances, electrostatic forces [14], losses [15], cost, etc., especially at higher frequencies.

Liquid crystal (LC) is an emerging tunable dielectric whose effective permittivity can be continuously tuned by applying a bias voltage to orient LC molecules [16]–[18]. It has attracted increasing attention in electromagnetic community due to its experimentally verified low loss, liquid state, low profile and low cost, especially at higher frequencies. Material characterization of LC has been extensively carried out in microwave and millimeter-wave frequencies. Prominent functions with the help of LC include phase shifter [19], [20], leaky-wave antennas [21], [22], and metasurface [23], [24].

As far as we know, nobody else has ever studied digital metamaterial [7]–[13] based on LC. All known LC-based microwave devices [19]–[26] are analog ones, while LC has never been involved in any known digital metamaterials.

In this paper, LC is introduced to develop a novel digital metamaterial of arbitrary base for multifunctional applications. General coding elements or codes of specific base are designed by selecting appropriate LC and carefully designing geometrical configuration. Switching between custom applications corresponding to different coding patterns is

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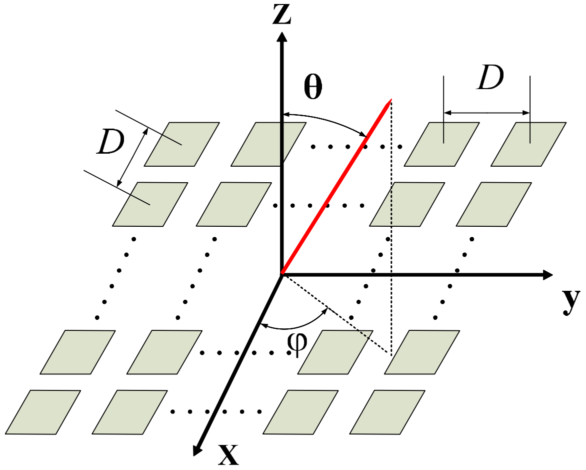


FIGURE 1. The far pattern of an digital metamaterial.

made simple. As a proof of concept, our digital metamaterial can be instantly tuned amount base 2, base 4 and base 8 for beam steering or RCS reduction.

II. THEORY OF DIGITAL METAMATERIAL

The far pattern of a digital metamaterial as shown in Fig. 1 is

$$f(\theta,\varphi)=\sum\nolimits_{m=1}^{M}\sum\nolimits_{n=1}^{N}\exp\{j\{\phi(m,n)+kD\sin\theta[m\cos\varphi+n\sin\varphi]\}\} \quad (1)$$

where θ and φ are the elevation and azimuth angles, $\phi(m, n)$ is the phase difference between reflection and incident waves arising from the digital coding particle, D is the periodicity in x and y.

Obviously, in digital metamaterials, the digital state $\phi(m, n)$ of particle (m, n) plays a critical role. The digital metamaterial can be multiplexed for different functions by properly changing $\phi(m, n)$ to achieve different far patterns.

Ideally, for a digital particle of base B,

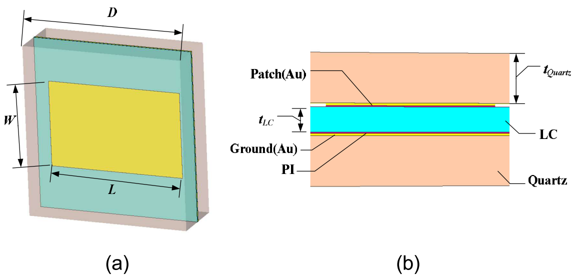
$$\phi\,(m,n)\in\left\{\phi_i\,|\,\phi_i=\frac{i}{B}360^o,0\leq i\leq B-1\right\} \quad (2)$$

Traditionally, different digital states correspond to different geometries of passive coding particles or ON/OFF states of PIN diodes of active coding particles [6]–[8]. Obviously, PIN diode-based active binary particles can only achieve 1-bit CMM. On the other hand, although multi-bit CMM can be realized by applying passive multi-bit coding particles, each passive coding particle corresponding to a specific digital state has to be independently designed. The design process is therefore much more tedious. What's worse, it is impossible to multiplex a passive CMM once finalized.

III. LC-BASED DIGITAL PARTICLE OF BASE B

A. CONFIGURATION

In this work, LC is introduced to develop active digital particles of base B and accordingly multifunctional base-B digital metamaterials for different applications. The configuration of the active digital particle is shown in Fig. 2. It is composed of a top layer of quartz (relative permittivity of $\varepsilon_r = 3.75$ and loss tangent of 0.0004), a rectangular patch, a bottom layer of LC, and an Au ground. The digital particle is supported by another layer of quartz below the Au ground.



(a) (b)

FIGURE 2. Geometry of LC-based coding particle (a) 3-dimensional and (b) Cross Section.

The LC exhibits different dielectric characteristics depending on different bias voltages. When no bias voltage is applied, LC molecules are aligned parallel by using a polyimide layer. Consequently, the LC shows the minimum permittivity $\varepsilon_{\mathrm{r},\perp}$. At maximum bias voltage V_{max}, the effective permittivity of LC is $\varepsilon_{r,//}$. Increasing the bias voltage would rotate the LC molecules and change the effective permittivity of LC continuously from $\varepsilon_{\mathrm{r},\perp}$ to $\varepsilon_{r,//}$. In accordance, ϕ or equivalently the digital state of the active digital particle depends on the applied bias voltage.

By properly selecting LC and tuning the geometrical parameters of the digital particle, the digital particle will achieve maximum phase difference $\Delta\phi$ and B digital states if

$$\Delta\phi\geq\frac{B-1}{B}360^\circ$$

B. PARAMETRIC STUDY

Two representative applications, namely beam steering and RCS reduction, will be presented to preliminarily prove our concept. The former application requires a phase gradient (0°, 90°, 180°, 270°) while the latter one expects alternating phase distribution (0° and 180°). A digital metamaterial of base 4 is therefore sufficient for both applications.

GT3-23001 manufactured by Merck [27] has been well known for its excellent tunability ($\varepsilon_{r,\|} = 3.2$, $\varepsilon_{\mathrm{r}\perp} = 2.4$, $tan\delta_{\|} = 0.002$, and $tan\delta_{\perp} = 0.006$, $V_{max} = 14\mathrm{V}$). Therefore, it is chosen in this study.

There are 5 geometrical parameters for us to determine: periodicity D, superstrate thickness t_{quartz}, LC thickness t_{LC}, patch length L and patch width W. A series of parametric studies has been carried out to determine their values numerically.

The optimized values are $D = 3$ mm, $L = 2.5$ mm, $W = 1.5$ mm, $t_{LC} = 0.05$ mm, $t_{Quartz} = 0.5$ mm. The corresponding maximum phase difference $\Delta\phi$ of the optimized digital coding particle at normal incidence ($\theta = 0^\circ$, $\varphi = 0^\circ$) is shown in Fig. 3. $\Delta\phi \geq 270^\circ$ from 52.1GHz to 53.1GHz.

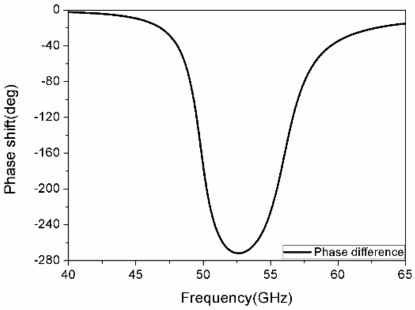


FIGURE 3. Maximum phase difference for the coding particle at normal incidence ($\theta = 0°$, $\varphi = 0°$).

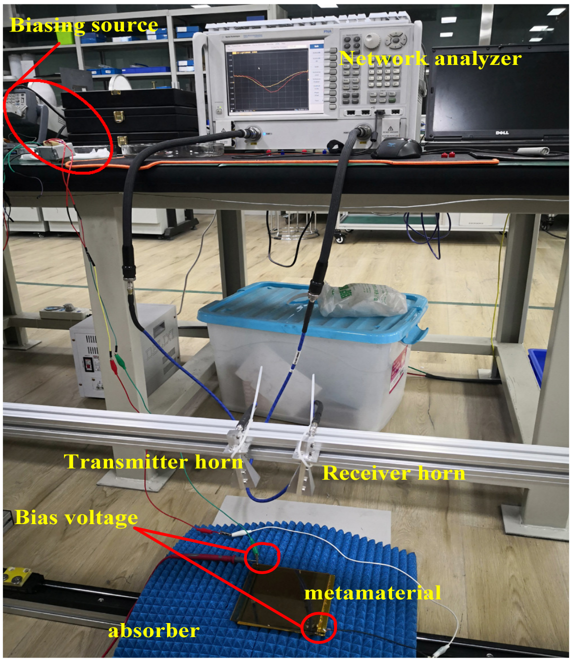


FIGURE 4. Fabricated metamaterial and experimental setup.

C. PRELIMINARY EXPERIMENTS

For a proof of concept, a LC-based metamaterial is fabricated and measured. Due to availability problem of GT3-23001 manufactured by Merck, it is replaced by a commercial LC, TIANMA9 whose tunable range ($\varepsilon_{r,\parallel} = 2.815$, $\varepsilon_{r,\perp} = 2.76$, $tan\delta_{\parallel} = 0.024$, and $tan\delta_{\perp} = 0.04$, $V_{max} = 7$ V) falls in that of GT3-23001 but is significantly smaller than that of GT3-23001. All optimized geometrical parameters are kept intact. Consequently, the measured phase shift is much weaker than designed. A photograph of the fabricated metamaterial and the experimental setup is given in Fig. 4 while the measured and simulated maximum phase difference $\Delta\phi$ is shown in Fig. 5. Good agreement is very clear.

IV. REPRESENTATIVE FUNCTIONS

To justify our LC-based digital metamaterial, two representative applications of digital metamaterials, namely beam steering and RCS reduction, have been numerically studied.

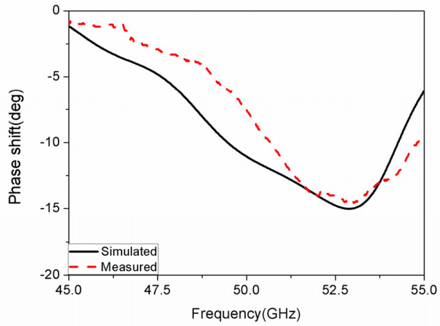


FIGURE 5. Measured and simulated maximum phase difference of the fabricated metamaterial.

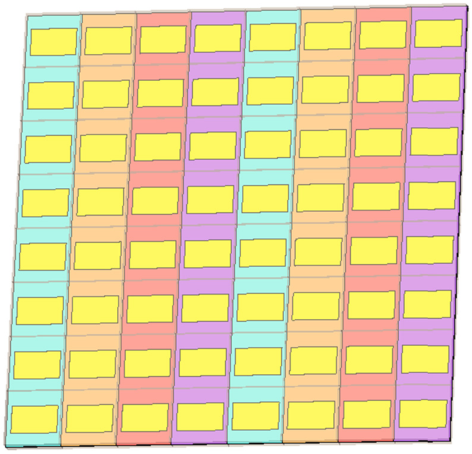


FIGURE 6. The periodic coding pattern of metamaterials for beam steering, in which the blue region represents "0", the orange region represents "1", the red region represents "2", and the Purple Region Represents "3".

A. BEAM STEERING

Beam steering is one of the most common applications of digital metamaterials. It has been known that phase gradient in metamaterials results in re-directing the outgoing beam.

According to [28], in our study, the beaming direction

$$\theta \propto \arcsin\left(-\frac{1}{B}360°/\beta d\right)$$

where B is the base for the digital particle, d is the distance between adjacent digital particles and β is the wavenumber. Therefore, θ can be tuned by changing B. Coding base $B = 3$ or larger is absolutely necessary for phase gradient in digital metamaterials.

To multiplex our digital metamaterial, the coding base $B = 4$ is chosen. The four digital states 0, 1, 2, and 3 corresponding to phase difference 0°, 90°, 180° and 270° can be obtained by biasing the digital coding particles with different voltages. Under periodic coding pattern of 0123/0123... as shown in Fig. 6, the outgoing beam at 54 GHz is re-directed to 27° by our digital metamaterial as shown in Fig. 7. Then, one more beam steering example of $\theta = 15°$ with $B = 8$ has been presented. The seven digital states 0, 1, 2,..., 6 correspond to phase difference 0°, 45°, 90°, 135°, 180°, 225° and 270°. Under periodic coding pattern

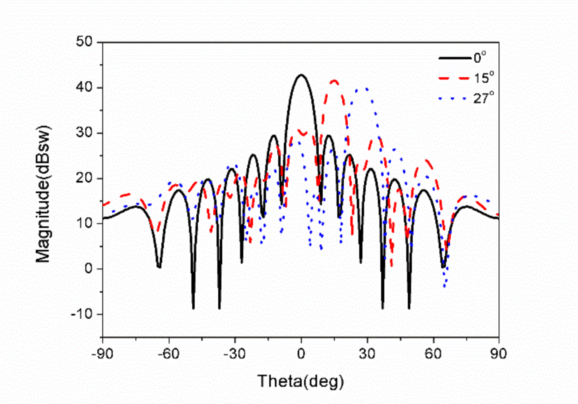


FIGURE 7. Beam steering performance of the LC-based metamaterial at 54 GHz.

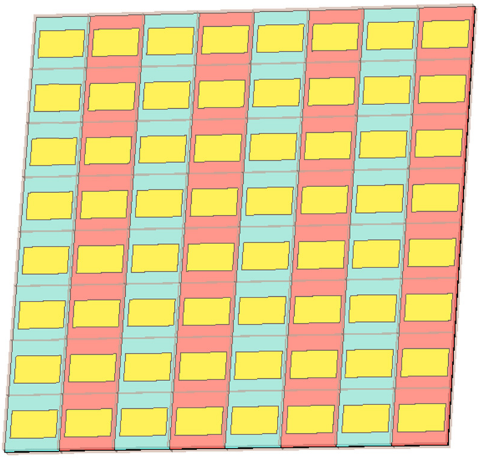


FIGURE 8. The periodic coding pattern of metamaterials for RCS reduction, in which the blue region represents "0", and the red region represents "1".

of 0123456/0123456..., the outgoing beam at 54 GHz is re-directed to 15° by our digital metamaterial as shown in Fig. 7 too.

Obviously, the outgoing beams can be re-directed to other desirable directions if the digital metamaterial is otherwise encoded. Further studies will be reported in future publications.

B. RCS REDUCTION

RCS reduction is another very important application for digital metamaterial. By diversifying the incoming beam to as many outgoing beams as possible, the RCS at a specific direction can be significantly reduced, even if there is no loss in the digital metamaterials.

Without loss of generality, alternating code pattern 010101/010101...as shown in Fig. 8 is studied. The simulated RCS of the proposed LC-based digital metamaterial under normal incidence is shown in Figs. 9-10. At least 10dB reduction is observed.

It is very interesting to point out that the binary states of our digital coding particles can be obtained in many different biasing schemes because the maximum phase difference of our digital coding particles is much larger than 180°. From this point of view, although our digital metamaterial with a specific biasing scheme can only reduce RCS in a limited frequency band, our digital metamaterial is able to reduce RCS by at least 10dB from 51 GHz to 56 GHz by biasing it differently in different frequency bands.

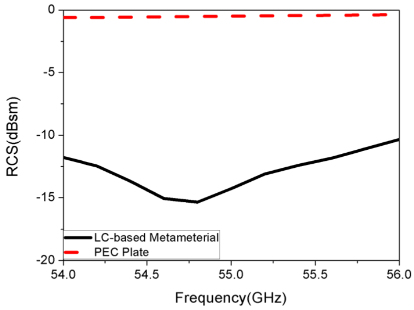


FIGURE 9. Low- RCS property of the LC-based metamaterial from 54 to 56 GHz under biasing scheme 1.

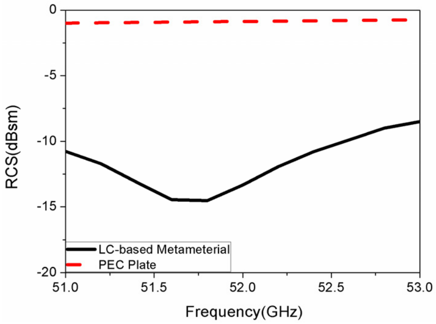


FIGURE 10. Low- RCS Property of the LC-based metamaterial from 51 to 52.4 GHz under biasing scheme 2.

V. CONCLUSIONS

In this paper, a digital metameterial of arbitrary base based on LC is proposed. It is composed of a superstrate of quartz, an array of metallic patches, a substrate of LC, and a ground. Encoding is realized by biasing LC to shift phase of incoming waves. The novel coding mechanism has been proven by both numerical simulation and preliminary experiment.

Two representative applications of digital metamaterials, namely beam steering and RCS reduction, have been presented to justify the novel digital metamaterial. The coding freedom of the LC-based digital metamaterial is demonstrated very clearly. It has also been observed that the LC-based digital metamaterial provides a very feasible solution for broadband applications.

It is regretful to point out that the desirable LC, GT3-23001 manufactured by Merck, is yet not available to the authors by the time this paper is submitted. Purchase has been in progress. Progress will be timely updated in following publications.

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REFERENCES

[1] D. R. Smith, J. B. Pendry, and M. C. K. Wiltshire, "Metamaterials and negative refractive index," *Science*, vol. 305, no. 5685, pp. 788–792, 2004.

[2] D. Schurig, J. J. Mock, J. B. Justice, S. A. Cummer, J. B. Pendry, A. F. Starr, and D. R. Smith, "Metamaterial electromagnetic cloak at microwave frequencies," *Science*, vol. 314, no. 5801, pp. 977–980, Oct. 2006.

[3] R. A. Shelby, D. R. Smith, and S. Schultz, "Experimental verification of a negative index of refraction," *Science*, vol. 292, no. 5514, pp. 77–79, Apr. 2001.

[4] J. B. Pendry, "Negative refraction makes a perfect lens," *Phys. Rev. Lett.*, vol. 85, no. 18, pp. 3966–3969, Oct. 2000.

[5] S. Lim, C. Caloz, and T. Itoh, "Metamaterial-based electronically controlled transmission-line structure as a novel leaky-wave antenna with tunable radiation angle and beamwidth," *IEEE Trans. Microw. Theory Techn.*, vol. 52, no. 12, pp. 2678–2690, Dec. 2004.

[6] S. Liu, L. Zhang, Q. L. Yang, Q. Xu, Y. Yang, A. Noor, Q. Zhang, S. Iqbal, X. Wan, Z. Tian, W. X. Tang, Q. Cheng, J. G. Han, W. L. Zhang, and T. J. Cui, "Frequency-dependent dual-functional coding metamaterials at terahertz frequencies," *Adv. Opt. Mater.*, vol. 4, no. 12, pp. 1965–1973, Dec. 2016.

[7] T. J. Cui, M. Q. Qi, X. Wan, J. Zhao, and Q. Cheng, "Coding metamaterials, digital metamaterials and programmable metamaterials," *Light, Sci. Appl.*, vol. 3, p. e218, Oct. 2014.

[8] S. Liu and T. J. Cui, "Concepts, working principles, and applications of coding and programmable metamaterials," *Adv. Opt. Mater.*, vol. 5, no. 22, Nov. 2017, Art. no. 1700624.

[9] C. D. Giovampaola and N. Engheta, "Digital metamaterials," *Nature Mater.*, vol. 13, pp. 1115–1121, Dec. 2014.

[10] L. Liang, M. Qi, J. Yang, X. Shen, J. Zhai, W. Xu, B. Jin, W. Liu, Y. Feng, C. Zhang, H. Lu, H.-T. Chen, L. Kang, W. Xu, J. Chen, T. J. Cui, P. Wu, and S. Liu, "Anomalous terahertz reflection and scattering by flexible and conformal coding metamaterials," *Adv. Opt. Mater.*, vol. 3, no. 10, pp. 1374–1380, 2015.

[11] L. H. Gao, Q. Cheng, J. Yang, S.-J. Ma, J. Zhao, S. Liu, H.-B. Chen, Q. He, W.-X. Jiang, H.-F. Ma, Q.-Y. Wen, L.-J. Liang, B.-B. Jin, W.-W. Liu, L. Zhou, J.-Q. Yao, P.-H. Wu, and T.-J. Cui, "Broadband diffusion of terahertz waves by multi-bit coding metasurfaces," *Light: Sci. Appl.*, vol. 4, 2015, Art. no. e324.

[12] B. Ratni, A. de Lustrac, G.-P. Piau, and S. N. Burokur, "Electronic control of linear-to-circular polarization conversion using a reconfigurable metasurface," *Appl. Phys. Lett.*, vol. 111, no. 21, Nov. 2017, Art. no. 214101.

[13] B. Ratni, A. de Lustrac, G.-P. Piau, and Sh. N. Burokur, "Reconfigurable meta-mirror for wavefronts control: Applications to microwave antennas," *Opt. Express*, vol. 26, no. 2, pp. 2613–2624, 2018.

[14] P. Farinelli, S. Bastioli, E. Chiuppesi, F. Di Maggio, B. Margesin, S. Colpo, A. Ocera, M. Russo, and I. Pomona, "Development of different K-band MEMS phase shifter designs for satellite COTM terminals," *Int. J. Microw. Wireless Tech.*, vol. 2, p. 263, Aug. 2010.

[15] G. Houzet, L. Burgnies, G. Velu, J.-C. Carru, and D. Lippens, "Dispersion and loss of ferroelectric $Ba_{0.5}Sr_{0.5}TiO_3$ thin films up to 110 GHz," *Appl. Phys. Lett.*, vol. 93, Jul. 2008, Art. no. 053507.

[16] S. Bulja, D. Mirshekar-Syahkal, R. James, S. E. Day, and F. A. Fernandez, "Measurement of dielectric properties of nematic liquid crystals at millimeter wavelength," *IEEE Trans. Microw. Theory Techn.*, vol. 58, no. 2, pp. 3493–3501, Dec. 2010.

[17] F. Yang and J. R. Sambles, "Resonant transmission of microwaves through a narrow metallic slit," *Phys. Rev. Lett.*, vol. 89, no. 6, Aug. 2002, Art. no. 063901.

[18] F. Yang and J. R. Sambles, "Determination of the permittivity of nematic liquid crystals in the microwave region," *Liq. Cryst.*, vol. 30, no. 2, pp. 599–602, 2003.

[19] S. Mueller, F. Goelden, P. Scheele, M. Wittek, C. Hock, and R. Jakoby, "Passive phase shifter for W-band applications using liquid crystals," in *Proc. 36th Eur. Microw. Conf.*, vol. 15, Sep. 2006, pp. 306–309.

[20] A. Moessinger, C. Fritzsch, S. Bildik, and R. Jakoby, "Compact tunable Ka-band phase shifter based on liquid crystals," in *IEEE MTT-S Int. Microw. Symp. Dig.*, May 2010, pp. 1020–1023.

[21] B.-J. Che, T. Jin, D. Erni, F.-Y. Meng, Y. Lyu, and Q. Wu, "Electrically controllable composite right/left-handed leaky-wave antenna using liquid crystals in PCB technology," *IEEE Trans. Compon. Packag. Manuf. Technol.*, vol. 7, no. 8, pp. 1331–1342, Aug. 2017.

[22] S. Ma, G.-H. Yang, D. Erni, F.-Y. Meng, L. Zhu, Q. Wu, and J.-H. Fu, "Liquid crystal leaky-wave antennas with dispersion sensitivity enhancement," *IEEE Trans. Compon. Packag. Manuf. Technol.*, vol. 7, no. 5, pp. 792–801, May 2017.

[23] M. Maasch, M. Roig, C. Damm, and R. Jakoby, "Voltage-tunable artificial gradient-index lens based on a liquid crystal loaded fishnet metamaterial," *IEEE Antennas Wireless Propag. Lett.*, vol. 13, pp. 1581–1584, 2014.

[24] A. Couch and A. Grbic, "A phase-tunable, liquid crystal-based metasurface," in *Proc. 10th Int. Congr. Adv. Electromagn. Mater. Microw. Opt. (METAMATERIALS)*, Sep. 2016, pp. 94–96.

[25] A. Moessinger, R. Marin, S. Mueller, J. Freese, and R. Jakoby, "Electronically reconfigurable reflectarrays with nematic liquid crystals," *Electron. Lett.*, vol. 42, no. 16, pp. 899–900, Aug. 2006.

[26] G. Perez-Palomino, M. Barba, J. A. Encinar, R. Cahill, R. Dickie, P. Baine, and M. Bain, "Design and demonstration of an electronically scanned reflectarray antenna at 100 GHz using multiresonant cells based on liquid crystals," *IEEE Trans. Antennas Propag.*, vol. 63, no. 8, pp. 3722–3727, Aug. 2015.

[27] S. Bildik, S. Dieter, C. Fritzsch, W. Menzel, and R. Jakoby, "Reconfigurable folded reflectarray antenna based upon liquid crystal technology," *IEEE Trans. Antennas Propag.*, vol. 63, no. 1, pp. 122–132, Jan. 2015.

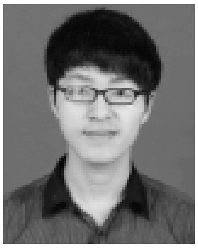
[28] W. Pan, C. Huang, P. Chen, M. Pu, X. Ma, and X. Luo, "A beam steering horn antenna using active frequency selective surface," *IEEE Trans. Antennas Propag.*, vol. 61, no. 12, pp. 6218–6223, Dec. 2013.

YIZHE ZHAO received the B.E. degree in information engineering from the Chengdu University of Technology, Chengdu, China, in 2014, and the master's degree in electronics and communication engineering from the School of Physics, University of Electronic Science and Technology of China, Chengdu, China in 2016, respectively, where he is currently pursuing the Ph.D. degree. His current research interests include metamaterials, metasurfaces, beam-steering antenna, active frequency selective surface, and tunable microwave device and antenna.

CHENG HUANG received the B.Eng. degree in electronics and information engineering from Wuhan University, Wuhan, China, in 2006, and the Ph.D. degree in optical engineering from the University of Chinese Academy of Sciences, Beijing, China, in 2011. He joined the State Key Laboratory of Optical Technologies on Nano-Fabrication and Micro-Engineering, Institute of Optics and Electronics, Chinese Academy of Sciences, and was promoted to Associate Professor in 2013. He has authored and coauthored more than 50 technical journal articles and conference papers. His research interests include metasurface, and subwavelength electromagnetics and their applications.

ZELIN SONG was born in Tianjin city, China, in 1991. He received the B.S. degree in physics and the M.D. degree from the University of Electronic Science and Technology of China (UESTC), in 2015 and 2018, respectively, where he is currently pursuing the Ph.D. degree with the School of Electronic Science and Engineering. His research interest includes the design of microwave- and millimeter-wave integrated circuits.

CHENGYONG YU received the B.Sc. degree in electronic science and technology from Guilin University of Electronic Technology, Guilin, China, in 2014. He is currently pursuing the Ph.D. degree in electromagnetic fields and microwave technology from the University of Electronic Science and Technology of China (UESTC), Chengdu, China. His research interests include electro-magnetic properties measurement of materials, design of microwave device, and automatic microwave test system.



SHUO LIANG was born in Sichuan Province, China, in 1990. He received the B.S. degree from the School of Electronic Engineering, HUAT, Hubei, in 2014, and the M.D. degree from the University of Electronic Science and Technology of China (UESTC), in 2017. His research interests include microwave planar filters, and microwave- and millimeter-wave circuits and systems design.

XIANGANG LUO received the B.E. degree in physics from Sichuan Normal University, in 1993, the M.S. and Ph.D. degrees from the Institute of Optics and Electronics, Chinese Academy of Sciences, in 1998 and 2001, respectively.

Currently, he is a Professor with the Institute of Optics and Electronics, Chinese Academy of Sciences. His research interests include microfabrication technology, subwavelength electromagnetics, micro-nano optics, electromagnetic metasurface, and surface plasmon optics.

ANYONG QING (SM'05) received the B.E. degree from Tsinghua University, in 1993, the M.E. degree from Beijing Broadcasting Institute (Communication University of China now), in 1995, and the Ph.D. degree from Southwest Jiaotong University, in 1997.

He was a Lecturer and Postdoctoral Fellow with Shanghai University from September 1997 to June 1998, a Research Fellow with Nanyang Technological University, Singapore, from June 1998 to June 2000, a member of Scientific Staff with the University of Kassel, Germany, from July 2000 to May 2001, and an RF Design Engineer with VS Electronics Pte Ltd, Singapore, from June 2001 to September 2001. He joined Temasek Laboratories, National University of Singapore, in September 2001, as a Research Scientist and was promoted as a Senior Research Scientist in 2010. After granted National Young Thousand Talent Professorship in September 2011, he joined the University of Electronic Science and Technology of China, in November 2012. He is currently chairing the Department of Electrical and Electronics, Southwest Jiaotong University.

He has involved in various areas of research in terahertz theory and technology, photoacoustic theory and technology, compressive sensing, natural optimization, computational acoustics and electromagnetics, inverse acoustic and electromagnetic scattering, electromagnetic composite materials, antennas and antenna arrays, millimeter wave and terahertz imaging, and biomedical imaging. He has been very active in industrializing millimeter wave and terahertz technology for security, medical, and industrial applications. He has authored two books, one book chapter, more than 60 peer-reviewed journal papers, and more than 70 conference presentations. His publications have been cited by other researchers more than 2000 times.

He is very active in voluntary services as Editors, Reviewers of funding and papers, and Organizers of conferences. He was appointed as an Associate Editor for Radio Science in 2017. He has also been invited to give numerous talks in different institutions and conferences.

Dr. Qing received numerous awards including National Young Thousand Talent Professorship, Sichuan Thousand Talent Professorship, Chengdu Talent Entrepreneurship, Changzhou Talent Entrepreneurship, Xuzhou Talent Entrepreneurship, and so on.

He is a member of Material Research Society Singapore, and a member of Chinese Institute of Electronics.

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