# A Waveguide Slot Filtering Antenna With an Embedded Metamaterial Structure

Wei Wang, Zhi Zheng, Xiaochuan Fang, Hongtao Zhang, Mouping Jin, Jiaguo Lu, *Senior Member, IEEE*, Qi Luo, *Member, IEEE*, and Steven Gao, *Senior Member, IEEE*

***Abstract*—A novel waveguide slot filtering antenna with an embedded metamaterial is presented. This filtering antenna consists of a common waveguide slot antenna with longitudinal slots cut on the top broad wall of its rectangular waveguide and a metamaterial surface embedded in the bottom broad wall. The metasurface replaces the conventional metal plane in the form of a bed of nails. In the operating frequency band, the metasurface works as a perfect electric conductor, so the antenna radiates as the traditional waveguide slot antennas. While in the stopband, the metasurface performs as a perfect magnetic conductor to suppress the propagation of electromagnetic wave in the waveguide cavity, so the interference signal is rejected and a filter function is achieved. To show the design process and verify its feasibility, a filtering antenna prototype working in the *C*-band and having a stopband in the *X*-band is designed, fabricated, and tested. A good agreement between simulation and measurement is obtained, demonstrating efficient radiations in the working band and a strong suppression of more than 35 dB in the stopband.**

***Index Terms*—Filtering antenna, metamaterial, waveguide slot antenna.**

## I. Introduction

THE current developments in wireless communication systems demand the radio frequency (RF) front end to be compact, lightweight, low cost, multifunctional, and anti-interference, especially when the device is installed on space-confined platforms such as cars, ships, planes, and satellites. The antenna and filter are the two important components for the RF front end, and the filter is usually cascaded after the antenna. Traditionally, the antenna and filter are designed individually with a common 50 Ω terminal impedance and then connected through a 50 Ω transmission line. However, this type of configuration does not ensure that the antenna and filter match well in the frequency range of interest, which increases the insertion loss of the front end. Moreover, additional space is required to accommodate the extra transmission line. To meet the demand of wireless communication, a filtering antenna, i.e., a module having radiating and filtering functions simultaneously, has been proposed and attracted significant research interests in recent years [1]–[7].

Different methods to design filtering antennas were reported in the literature. Several filtering antennas were realized by adding particular structures to antennas [8]–[12]. In [8], metal posts were inserted into a horn antenna. In [9], coupled cavities were placed into the waveguide of a leaky antenna. A parasitic loop was placed at the top of a printed antenna in [10]. In [11], four shorting pins were embedded into a via-fed monopole ultrawideband (UWB) antenna. In [12], H-shaped coupling lines and a stacked patch were used for a dual-polarized patch antenna. Although these antennas exhibit promising filtering performances, they were designed without using a systematic approach so it is difficult to tune the filtering performance, such as the bandwidth of the stopband and the attenuation level, to meet different requirements.

Various approaches were presented for integrating the filter into the feedline of the antenna [13]–[16]. Based on the multilayer low temperature co-fired ceramic technology, a quasi-elliptic filter was integrated into a microstrip line of a series-fed antenna array in the *V*-band [13]. A three-pole coplanar strip (CPS) filter was connected with a CPS-fed loop antenna to obtain a UWB antenna-filter system [14]. In [15], a bandpass filter was designed with the balun of a quasi-Yagi antenna. In [16], a third-order filtering power divider was used to feed a microstrip antenna array. In [17] and [18], evanescent mode filters were integrated to the feeding waveguide of a broadband slotted ridge waveguide antenna array [19]. Nevertheless, in these designs, the feeding network must provide enough space to include the filtering circuit, which increases the size of the front end.

Recently, a synthesis process for filtering antenna design has been presented. In these designs, the antenna not only radiates but also serves as the last resonator or the load impedance of the filter. So far, several different forms of this type of filtering antennas have been reported, such as slot antennas with 3-D cavity filters [20], microstrip filtering antennas [21], [22], and substrate-integrated waveguide filtering antennas [23]. However, due to the lack of the exact extraction of the antenna's equivalent circuit, these filtering antennas did not show a good filtering performance, especially at the band edges.

In this paper, a novel design method of a waveguide slot filtering antenna array is proposed. Different from the previous

Manuscript received February 22, 2018; revised December 25, 2018; accepted February 5, 2019. Date of publication February 13, 2019; date of current version May 3, 2019. This work was supported by the National Natural Science Foundation of China under Grant 61671416. *(Corresponding author: Zhi Zheng.)*

W. Wang, Z. Zheng, H. Zhang, M. Jin, and J. Lu are with the East China Research Institute of Electronic Engineering, Hefei 230088, China, and also with the Anhui Province Engineering Laboratory for Antenna and Microwave, Hefei 230088, China (e-mail: shu00ww@163.com; king-z-love@163.com).

X. Fang is with the School of Information and Communication Engineering, University of Electrical and Science Technology of China, Chengdu 611731, China.

Q. Luo and S. Gao are with the School of Engineering and Digital Arts, University of Kent, Canterbury CT2 7NZ, U.K.

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TAP.2019.2898989

TABLE I
DIMENSIONS OF THE FILTERING ANTENNA (SYMBOLS HAVE BEEN SHOWN IN FIG. 1)

| | | | |
|---|---|---|---|
| $a$ | 32.0 mm | $d$ | 4.0 mm |
| $b$ | 7.6 mm | $P$ | 7.6 mm |
| $L$ | 27.5 mm | $W$ | 6.1 mm |
| $L_1$ | 32.0 mm | $h$ | 8.1 mm |
| $d_1$ | 3.0 mm | | |

work, in which the filtering function is usually realized by designing the physical structure of a filtering antenna to be equivalent to the circuit model of a specified filter, the filtering function, here, is obtained by utilizing the metamaterial surface embedded in the waveguide cavity. The design process of the proposed filtering antenna is straightforward. The operating band and stopband can be easily adjusted to meet different demands. The designed filtering antenna has similar radiating performance as the common waveguide slot antenna in the operating band, while possesses a strong attenuation property in the stopband.

This paper is organized as follows. Section II shows the configuration of the proposed filtering antenna. Section III explains the filtering mechanism and the design process of the proposed filtering antenna. Section IV presents the experimental results. Section V concludes this paper.

## II. STRUCTURE OF FILTERING ANTENNA

The proposed filtering antenna has the same configuration as a conventional waveguide slot antenna, except that the smooth metal plane in the bottom wall of the rectangular waveguide is replaced with a metamaterial surface. The metasurface consists of periodic metal nails.

In this paper, a prototype is designed to radiate in the $C$-band with a stopband in the $X$-band. As shown in Fig. 1, to simplify the design without loss of generality, four longitudinal radiating slots are adopted. To facilitate the measurement, a coaxial-to-waveguide transition is used to excite the filtering antenna. The main dimensions of the prototype are listed in Table I.

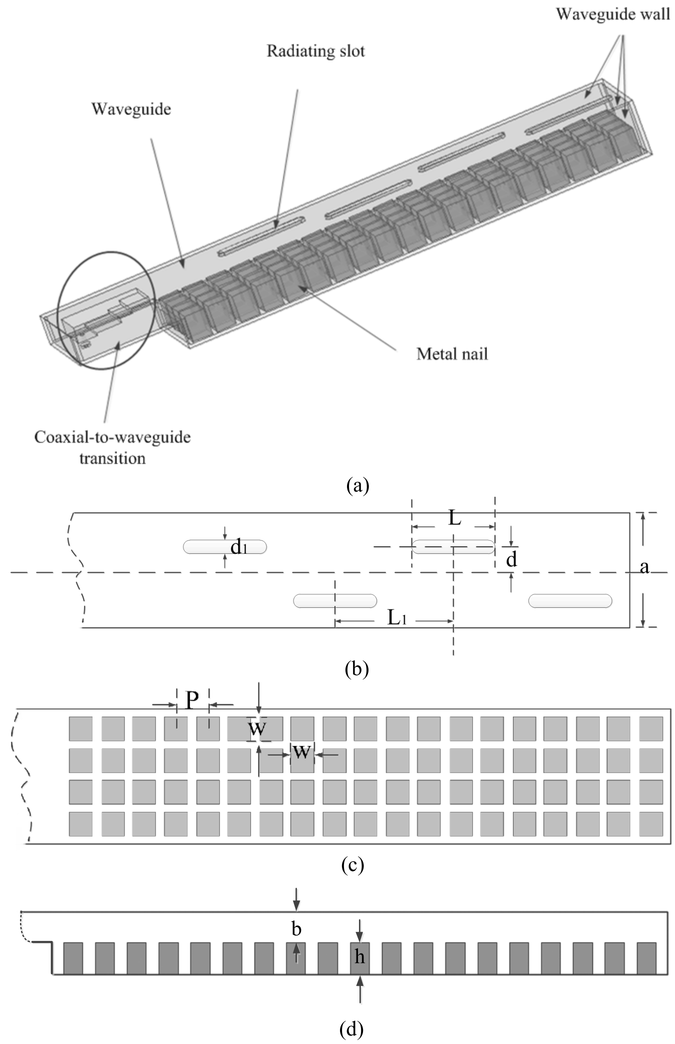



Fig. 1. Configuration of the proposed filtering antenna. (a) 3D view of the whole filtering antenna. (b) Top view of the filtering antenna. (c) Top view of the nails surface. (d) Side view of the filtering antenna.

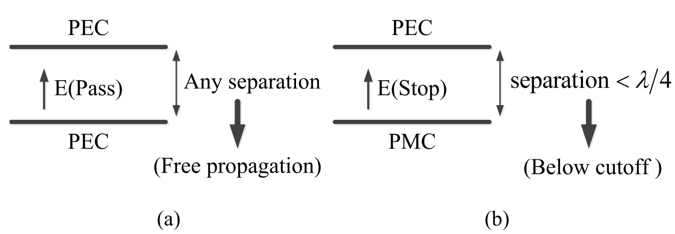



Fig. 2. Field propagation within two parallel plates. (a) One consists of two PEC plates. (b) Other consists of a PEC plate and a PMC plate.

## III. DESIGN AND ANALYSIS OF FILTERING ANTENNA

### A. Filtering Fundamental

It is well known that a vertical electric field propagates freely between two parallel perfect electric conductor (PEC) plates (alternatively called metal plates) regardless of their separation, as illustrated in Fig. 2(a). However, there is no propagated field (i.e., all modes are below cutoff frequency) between a PEC plate and a perfect magnetic conductor (PMC) plate when their separation is smaller than $\lambda/4$, where $\lambda$ is the wavelength, as illustrated in Fig. 2(b). This parallel-plate cutoff property was used in the ridge gap waveguide (RGW) technology [24]–[26]. In RGW, the PEC ridges are surrounded by a PMC surface. Providing a waveguide cavity with height less than $\lambda/4$, the PMC surface stops waves in all the directions. In such a way, the waves have to follow the PEC ridges. When designing microwave circuits, the ridges can be bent, split, or form a corner.

This paper is inspired by the fact that the parallel-plate waveguide exhibits a stopband, as shown in Fig. 2(b). Here, the bottom wall of a conventional PEC rectangular waveguide is replaced with an appropriately designed metasurface to obtain a stopband over a specified frequency range. As shown in Fig. 3, the top and bottom planes are separated by a distance

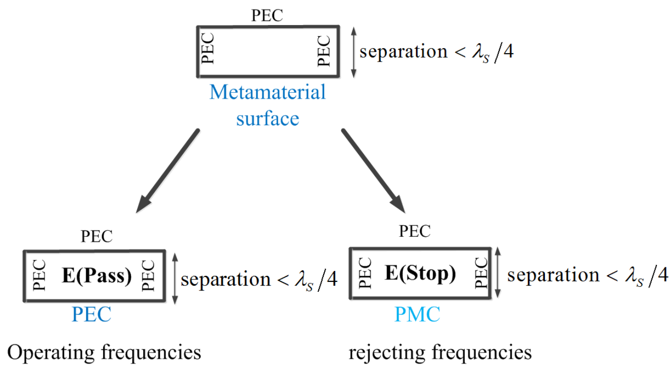



Fig. 3. Field propagation in a metamaterial-based waveguide: the metamaterial surface works as a PEC plane at operating frequencies and as a PMC plane at rejecting frequencies.

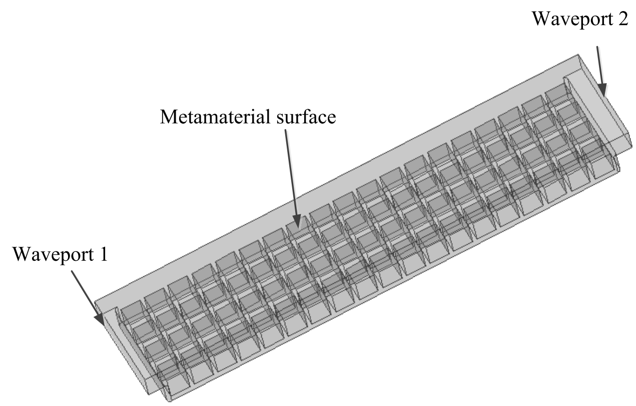



Fig. 4. Configuration of the filtering waveguide.

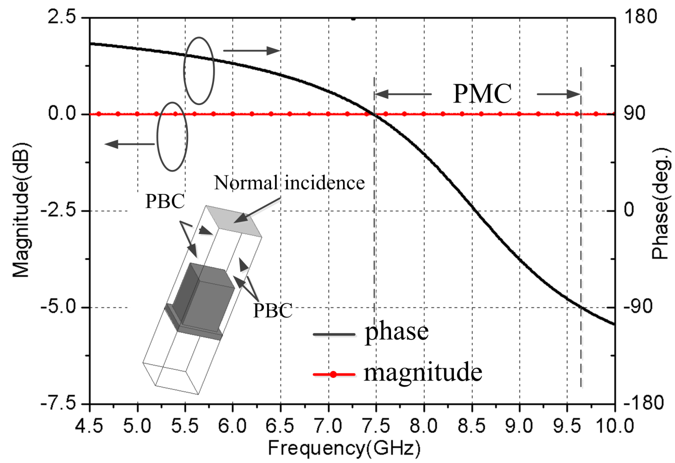



Fig. 5. Simulated reflection magnitude and phase of the metamaterial surface.

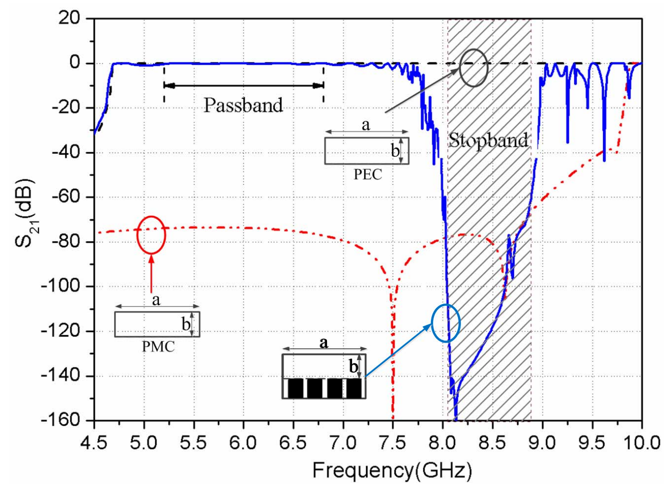



Fig. 6. Transmission coefficient of three kinds of waveguides: a common rectangular waveguide, one with a PMC bottom, and one with the proposed metasurface.

less than $\lambda_S/4$, where $\lambda_S$ is the smallest wavelength of the stopband. The response of the metasurface is designed to vary with frequency. At the operating frequencies, the metasurface performs as a PEC plane, so the waves can propagate through the waveguide. While in the stopband, the metasurface functions as a PMC plane, so the propagation of the wave is rejected. As a result, a filtering function is achieved.

## *B. Design of Filtering Waveguide*

In this section, a filtering waveguide is designed based on the principle described earlier. The configuration of the proposed filtering waveguide is shown in Fig. 4. As can be seen, the metasurface is embedded into the bottom of the waveguide in the form of bed of periodic nails. The nails have a height $h$, a square cross section with side length $W$, and a distance $P$ between two adjacent nails, as labeled in Fig. 1(c) and (d). The values of these dimensions are given in Table I.

The metasurface is simulated by applying the periodic boundary condition in the HFSS simulator, as shown in Fig. 5. The simulated reflection coefficient of the unit cell is also shown in Fig. 5. A 0 dB magnitude is obtained within the frequency band of interest, and a 0° reflection phase occurs at 8.5 GHz. This corresponds to the frequency where the metasurface behaves like a PMC. Usually, the useful bandwidth of a PMC is defined as +90° to −90° on either side of the central frequency. Thus, the designed metasurface can be considered as a PMC from 7.5 to 9.6 GHz.

The transmission coefficient ($S_{21}$) of the filtering waveguide is shown in Fig. 6. For better comparison, $S_{21}$ performances of a conventional PEC waveguide (with four PEC sides) and a waveguide with a PMC bottom wall are also shown in Fig. 6. Both of the waveguides have the same dimensions of $a$ and $b$. Here, $a$ and $b$ are set to 32 and 7.6 mm, respectively. For the conventional waveguide, this corresponds to a cutoff frequency at 4.7 GHz. While for the case of the PMC bottomed waveguide, its cutoff frequency is 9.9 GHz, and all the waves below 9.9 GHz are rejected. The cutoff frequency happens at 9.9 GHz because $b$ equals the quarter-wavelength of 9.9 GHz, just as predicted by the parallel-plate cutoff property mentioned earlier.

In summary, as shown in Fig. 6, from 4.7 to 9.9 GHz, a PEC bottom wall supports the wave propagation, whereas a PMC one stops the wave propagation. When the metasurface performs as a PEC, the $S_{21}$ response of the proposed

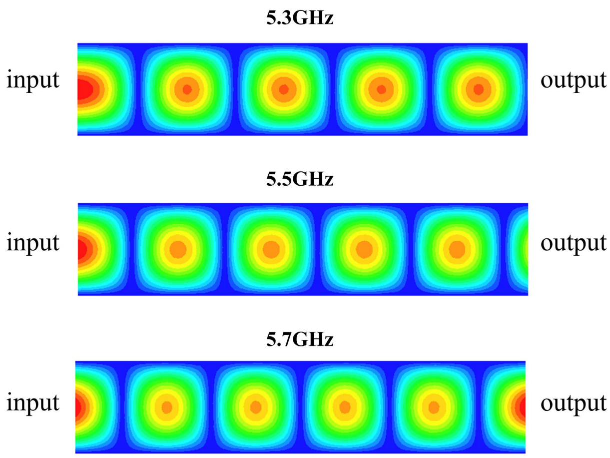



Fig. 7. Electric field distribution at the inner surface of the top broad wall of the filtering waveguide.

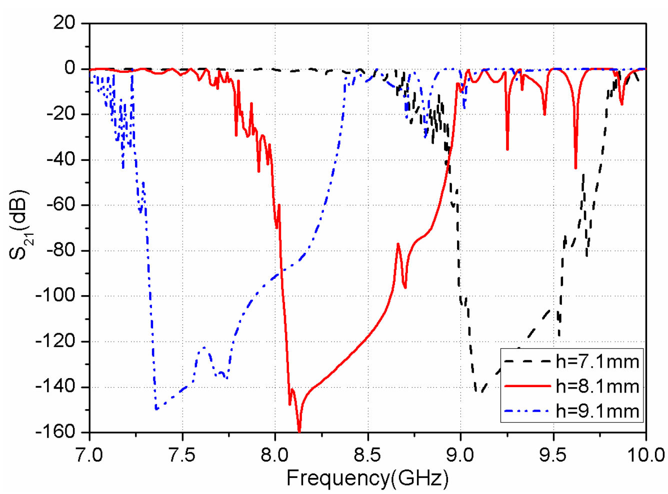



Fig. 8. Effect of the nail height on the central frequency of the stopband.

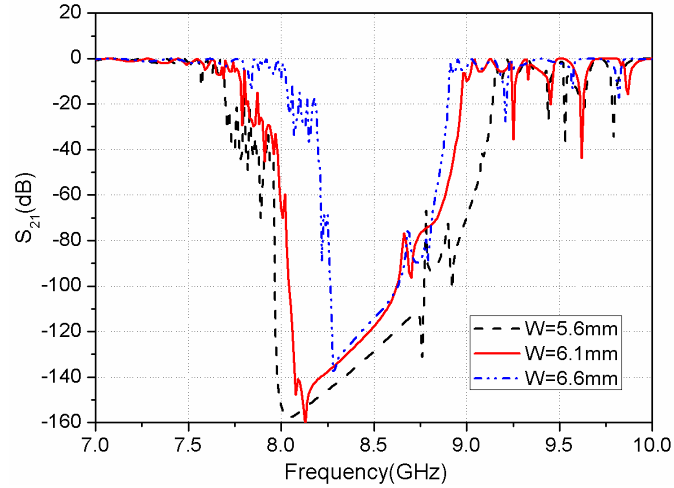



Fig. 9. Effect of the nail width on the bandwidth of the stopband.

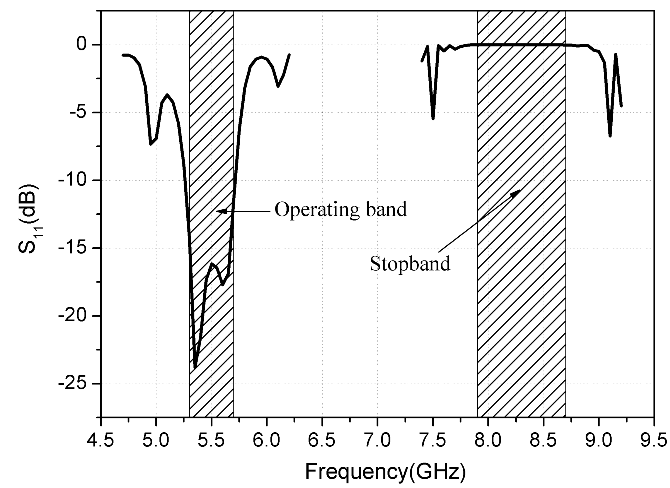



Fig. 10. Simulated reflection coefficient of the proposed filtering antenna.

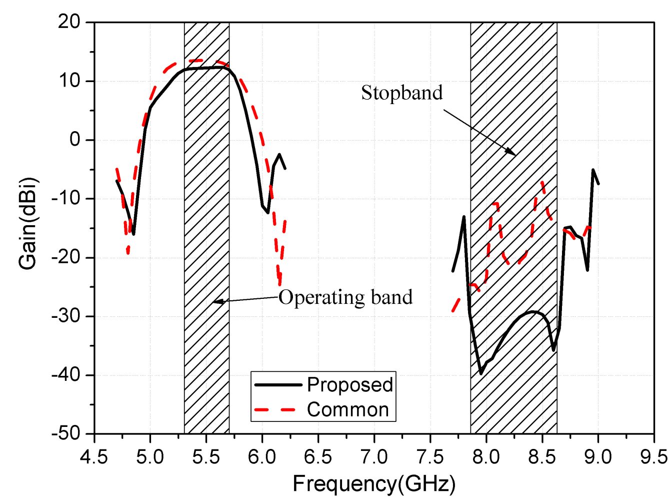



Fig. 11. Simulated broadside gain responses of the proposed filtering antenna and a common waveguide slot antenna.

waveguide is similar to that of the common waveguide. As a result, the nearly 0 dB performance is obtained over a large frequency range. From 5.2 to 6.8 GHz, the insertion loss is better than −0.5 dB, leading to a passband. There is a cutoff frequency at 4.7 GHz, which is the same as that of the common waveguide. Within the frequency band of 5.3–5.7 GHz, which is the designed operating frequency band of the presented filtering antenna, the mode of the filtering waveguide is the same as the $TE_{10}$ mode of a common waveguide. The electric field distributions in the filtering waveguide are shown in Fig. 7.

It can also be seen in Fig. 6 that there are large attenuations (stronger than 60 dB) from 8.1 to 8.9 GHz for the proposed design. This is similar to that of a PMC bottomed waveguide, resulting in a stopband. The stopband is obtained because the metasurface functions as a PMC at these frequencies. The stopband central frequency of 8.5 GHz agrees well with the 0° reflection phase location of the metasurface shown in Fig. 5. However, the bandwidth of the stopband is narrower than the PMC bandwidth of the general defined +90° to −90° shown in Fig. 5. It corresponds to the PMC bandwidth from +50° to −50°.

This presented design is flexible because the central frequency and the bandwidth of the stopband can be easily controlled to meet different antiinterference demands. Figs. 8 and 9 show the effects of the nail height and width on

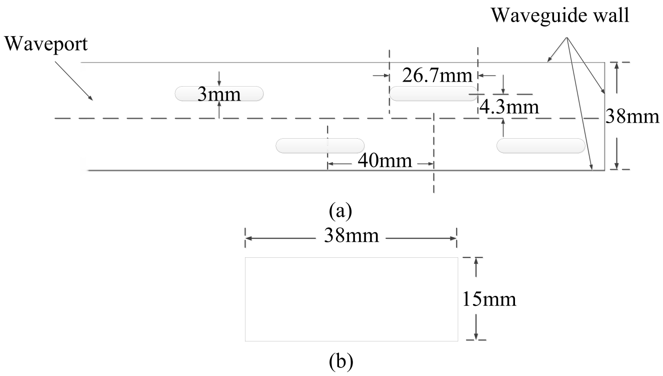



Fig. 12. Configuration and dimensions of the common waveguide slot antenna. (a) Top view. (b) Cross section.

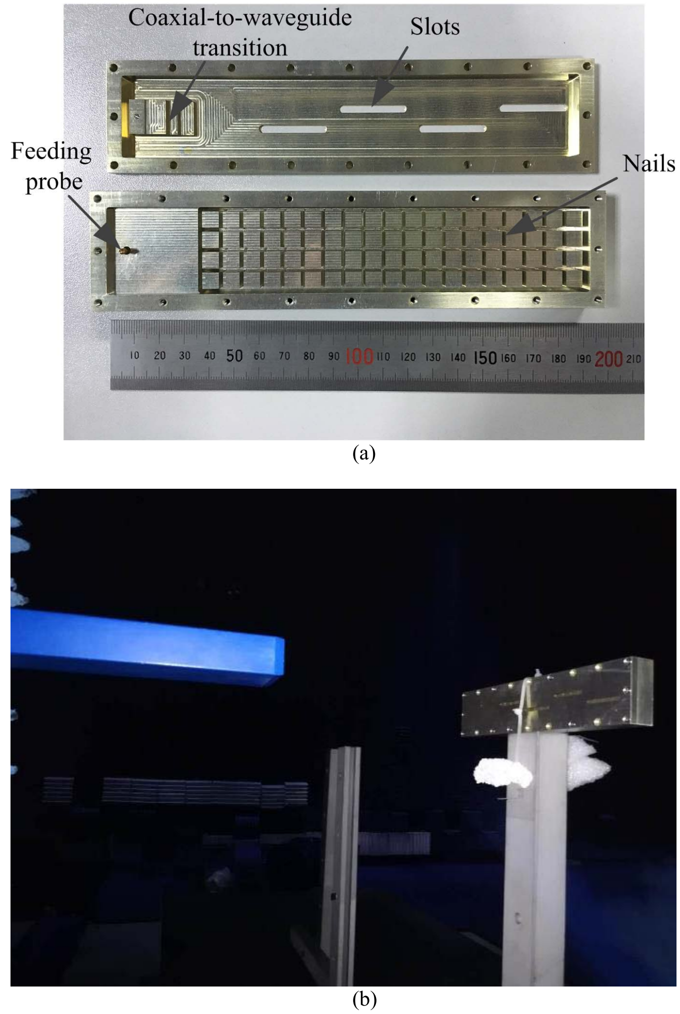



Fig. 14. Photographs of the proposed filtering antenna. (a) Inner view. (b) 3-D view in the anechoic chamber.

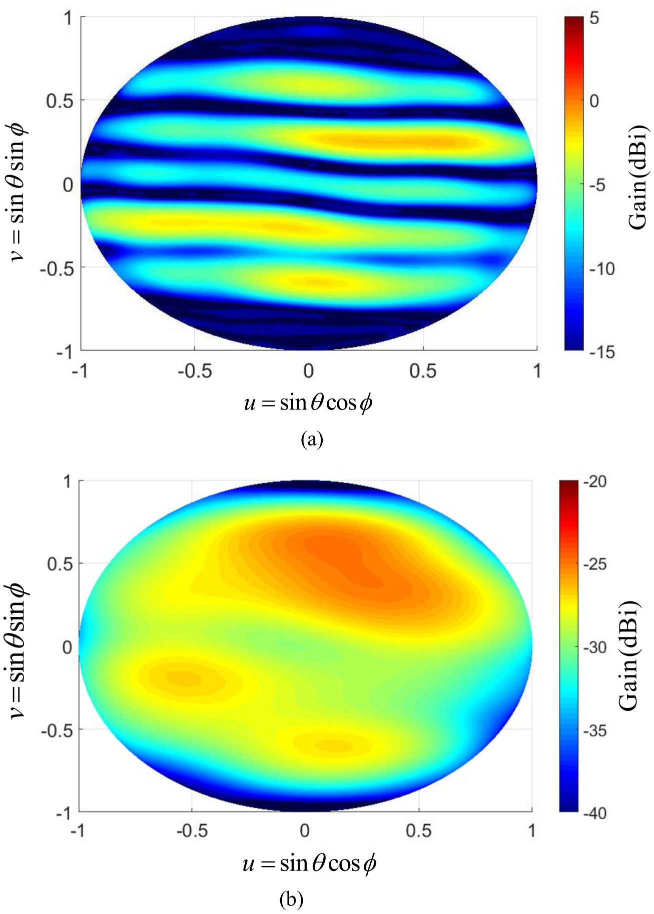



Fig. 13. Gain patterns at 8.5 GHz for (a) common waveguide slot antenna and (b) proposed filtering antenna.

the central frequency and bandwidth of the stopband, respectively. As shown, the central frequency and bandwidth change with different nail parameters. Since the central frequency and bandwidth of the stopband are consistent with that of the PMC band of the metasurface, the effects of the nail parameters on the stopband characteristic are inherently achieved by adjusting the PMC performance of the metasurface.

### C. Design of Filtering Antenna

This section presents the simulated results of the proposed filtering antenna. The structure of the proposed antenna is shown in Fig. 1. Four slots are designed on the top broad wall of the filtering waveguide. The design method of the slots is the same as that of the traditional waveguide slot antennas [27]. The offset and length of the slots are optimized to meet a good impedance matching and radiation characteristics. The operating frequencies are centered at 5.5 GHz in the passband of the proposed filtering waveguide.

Fig. 10 shows the simulated reflection coefficient of the proposed antenna. To focus on the performances of the proposed antenna in the operating band and the stopband, the data between these two bands are not given out. Within the frequency band of 5.3–5.7 GHz, good impedance matching is obtained with $|S_{11}| < -10$ dB. While in the stopband of 7.9–8.7 GHz, nearly 0 dB $S_{11}$ performance implies an almost total reflection so the signals in this band are rejected.

Fig. 11 shows the simulated broadside gain of the proposed antenna versus frequency. The gain is about 12.2 dBi in the operating band, while below $-29$ dBi in the entire stopband, corresponding to a suppression level more than 40 dB. Here, the suppression level is defined as the ratio of received electromagnetic energy in the operating band to that in the stopband. Compared with the stopband (8.1–8.9 GHz) of the

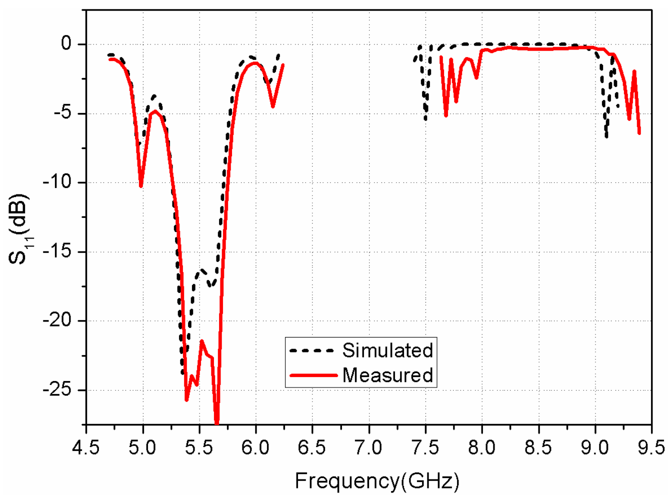



Fig. 15. Simulated and measured reflection coefficients for the filtering antenna.

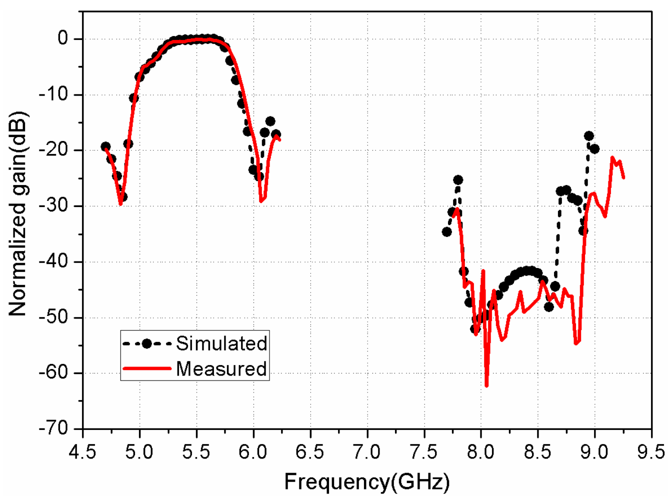



Fig. 16. Simulated and measured normalized gain for the filtering antenna.

filtering waveguide, the stopband (7.9–8.7 GHz) of the filtering antenna slightly shifts to lower frequency, and the suppression is also lower than the filtering waveguide (more than 60 dB as shown in Fig. 6). These differences are caused by the introduction of radiating slots, which affect the waveguide cavity to some degree.

As a comparison, the gain response of a common waveguide slot antenna is also shown in Fig. 11. The structure and dimensions of the common waveguide slot antenna are shown in Fig. 12. The waveguide slot antenna has the same operating band and number of radiating slots as the proposed design. As shown in Fig. 11, the gain of the common antenna is about 13.3 dBi, 1.1 dB higher than that of the proposed one. This is because the common waveguide slot antenna has a larger aperture. While in the stopband, the gain level of the common antenna is averagely 14 dB higher than that of the proposed antenna, with two peaks of −10.2 and −7.2 dBi at 8.1 and 8.5 GHz, respectively.

It should be noted that the maximum gain is usually not in the broadside direction when the frequency is far away from the central frequency, and the interference signals can come

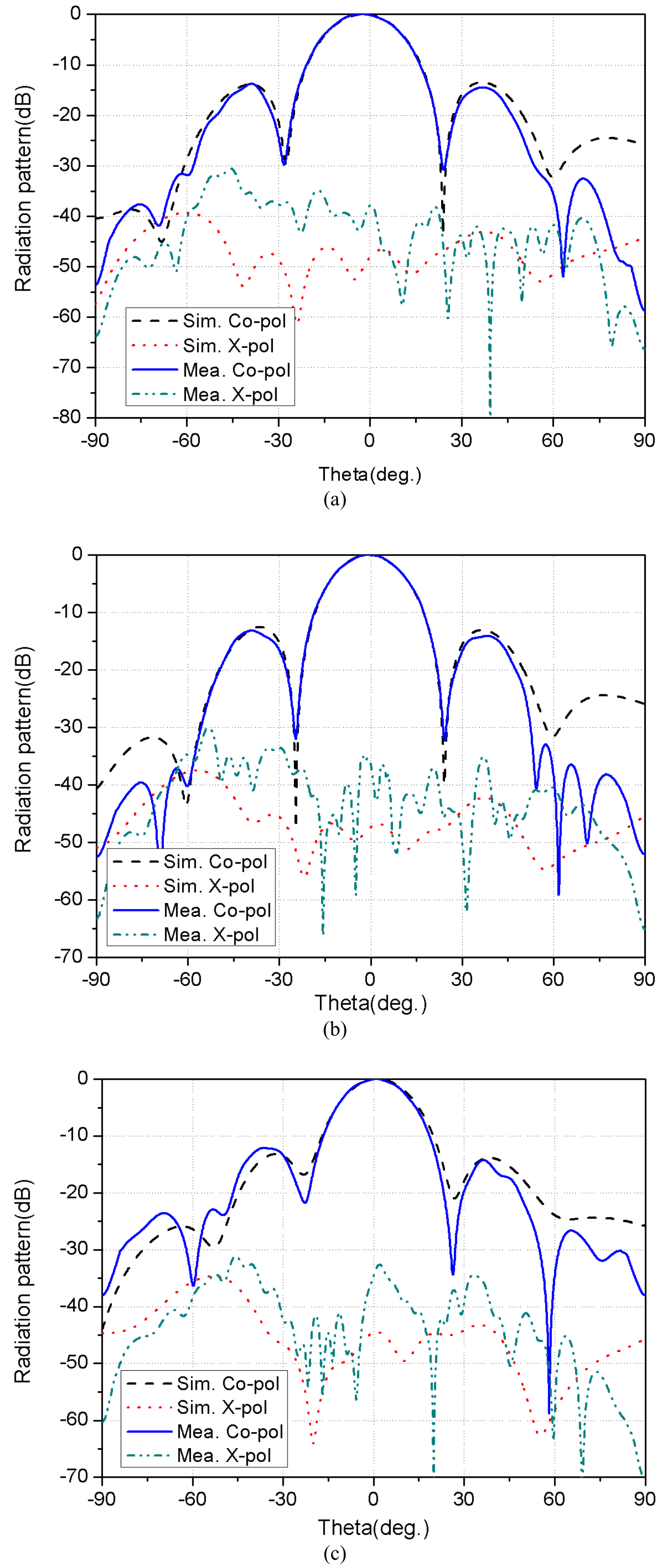



Fig. 17. Simulated and measured H-plane radiation patterns for the filtering antenna. (a) 5.3 GHz. (b) 5.5 GHz. (c) 5.7 GHz.

from any direction. Therefore, it is necessary to examine the whole gain pattern not only the broadside gain. As an example, the gain patterns at 8.5 GHz are shown in Fig. 13 for both the common and proposed waveguide slot antennas. The patterns are in the U–V coordinate system. As shown, the maximum gain is indeed not at the broadside direction (i.e., at the center of the circle). For the common case, the maximum gain is −1.4 dBi, whereas it is −24.8 dBi for our design [be note that the scales in Fig. 13(a) and (b) are different]. Taking the 12.2 dBi gain in the working band into account, a strong suppression of more than 35 dB is obtained for the proposed antenna, while the suppression is only around 15 dB for the common one. The properties of gain patterns at other frequencies in the stopband are similar. To avoid repetition, they are not shown in this paper.

## IV. Experimental Results

To verify the design method and the predicted performance of the proposed filtering antenna, the prototype antenna was fabricated and tested. First, the antenna is fabricated from two parts: a cover and a cavity. As shown in Fig. 14, the cover consists of coaxial-to-waveguide transition and radiation slots, while the cavity includes the feeding probe and nails. Then, the antenna is assembled by fixing the cover on the top of the cavity with screws.

The measured reflection coefficient of the proposed antenna is plotted in Fig. 15, and the simulated result is also given as a comparison. As shown, the measured results have a good agreement with the simulations, especially in the operating band, whereas in the stopband, the measured result slightly shifts to higher frequency. The small discrepancy may be caused by the fabrication tolerances of the height of nails since the location of the stopband is sensitive to this parameter.

Fig. 16 shows the simulated and measured broadside gain responses of the proposed antenna. They show a good agreement with each other. Comparing the gain levels in the operating band and stopband, the suppression to the interference signal is calculated to be more than 40 dB. Considering the interference signal may be not in the broadside direction, it is still reasonable that a suppression around 35 dB can be achieved, as analyzed in Section III-C. The simulated and measured H-plane radiation patterns are shown in Fig. 17. There are good agreements between the simulation and measurement results, showing classic patterns of the 1-D four-element linear array, which verifies the good radiation properties of the designed filtering antenna.

## V. Conclusion

A novel waveguide slot filtering antenna is presented in this paper. The design principle and process are explained. This type of filtering antenna consists of a common waveguide slot antenna and a metamaterial surface embedded into the bottom of the waveguide cavity. The surface is in the form of bed of nails, it works as a PEC in the operating band, while a PMC in the stopband. A prototype was fabricated and measured, and good agreements between the simulation and measurement are obtained, showing a suppression level of 35 dB to the signal in the stopband. The proposed design process is flexible, and the passband, as well as the stopband of the antenna, can be easily adjusted. Moreover, the proposed antenna can be expanded to a larger array and its all-metal structure makes itself suitable for many practical applications.

## References

[1] C.-K. Lin and S.-J. Chung, "A filtering microstrip antenna array," *IEEE Trans. Microw. Theory Techn.*, vol. 59, no. 11, pp. 2856–2863, Nov. 2011.
[2] S. Oda, S. Sakaguchi, H. Kanaya, R. K. Pokharel, and K. Yoshida, "Electrically small superconducting antennas with bandpass filters," *IEEE Trans. Appl. Supercond.*, vol. 17, no. 2, pp. 878–881, Jun. 2007.
[3] Y. Yusuf. H. Cheng, and X. Gong, "Co-designed substrate-integrated waveguide filters with patch antennas," *IET Microw. Antennas Propag.*, vol. 7, no. 7, pp. 493–501, May 2013.
[4] X. Chen, F. Zhao, L. Yan, and W. Zhang, "A compact filtering antenna with flat gain response within the passband," *IEEE Antennas Wireless Propag. Lett.*, vol. 12, pp. 857–860, 2013.
[5] C.-T. Chuang and S.-J. Chung, "Synthesis and design of a new printed filtering antenna," *IEEE Trans. Antennas Propag.*, vol. 59, no. 3, pp. 1036–1042, Mar. 2011.
[6] W.-J. Wu, Y.-Z. Yin, S.-L. Zuo, Z.-Y. Zhang, and J.-J. Xie, "A new compact filter-antenna for modern wireless communication systems," *IEEE Antennas Wireless Propag. Lett.*, vol. 10, pp. 1131–1134, 2011.
[7] L. Yang, P. Cheong, L. Han, W.-W. Choi, K.-W. Tam, and K. Wu, "Miniaturized parallel coupled-line filter-antenna with spurious response suppression," *IEEE Antennas Wireless Propag. Lett.*, vol. 10, pp. 726–729, 2011.
[8] B. Froppier, Y. Mahe, E. M. Cruz, and S. Toutain, "Integration of a filtering function in an electromagnetic horn," in *Proc. 33rd Eur. Microw. Conf.*, Oct. 2003, pp. 939–942.
[9] F. Queudet, B. Froppier, Y. Mahe, and S. Toutain, "Study of a leaky waveguide for the design of filtering antennas," in *Proc. 33rd Eur. Microw. Conf.*, Oct. 2003, pp. 943–946.
[10] J. Wu, Z. Zhao, Z. Nie, and Q.-H. Liu, "A printed unidirectional antenna with improved upper band-edge selectivity using a parasitic loop," *IEEE Trans. Antennas Propag.*, vol. 63, no. 4, pp. 1832–1837, Apr. 2015.
[11] S. W. Wong, T. G. Huang, C. X. Mao, Z. N. Chen, and Q. X. Chu, "Planar filtering ultra-wideband (UWB) antenna with shorting pins," *IEEE Trans. Antennas Propag.*, vol. 61, no. 2, pp. 948–953, Feb. 2013.
[12] W. Duan, X. Y. Zhang, Y.-M. Pan, J.-X. Xu, and Q. Xue, "Dual-polarized filtering antenna with high selectivity and low cross polarization," *IEEE Trans. Antennas Propag.*, vol. 64, no. 10, pp. 4188–4196, Oct. 2016.
[13] J.-H. Lee, N. Kidera, S. Pinel, J. Laskar, and M. M. Tentzeris, "Fully integrated passive front-end solutions for a V-band LTCC wireless system," *IEEE Antennas Wireless Propag. Lett.*, vol. 6, pp. 285–288, 2007.
[14] N. Yang, C. Caloz, and K. Wu, "Co-designed CPS UWB filter-antenna system," in *Proc. IEEE Antennas Propag. Soc. Int. Symp.*, Jun. 2007, pp. 1433–1436.
[15] C.-H. Wu, C.-H. Wang, S.-Y. Chen, and C. H. Chen, "Balanced-to-unbalanced bandpass filters and the antenna application," *IEEE Trans. Microw. Theory Techn.*, vol. 56, no. 11, pp. 2474–2482, Nov. 2008.
[16] F.-C. Chen, H.-T. Hu, R.-S. Li, Q.-X. Chu, and M. J. Lancaster, "Design of filtering microstrip antenna array with reduced sidelobe level," *IEEE, Trans. Antennas Propag.*, vol. 65, no. 2, pp. 903–908, Feb. 2017.
[17] H.-T. Zhang, W. Wang, and M.-P. Jin, "Design of a novel wideband high efficiency filtenna array," in *Proc. Int. Appl. Comput. Electromagn. Soc. Symp. (ACES)*, Suzhou, China, Aug. 2017, pp. 1–2.
[18] W. Wang, L. Li, H. Zhang, Z. Zhang, and Y. Zhang, "Frequency-selective broadband waveguide slot antenna array," China Patent 101 168 348, Oct. 14, 2009.
[19] W. Wang, S.-S. Zhong, Y.-M. Zhang, and X.-L. Liang, "A broadband slotted ridge waveguide antenna array," *IEEE, Trans. Antennas Propag.*, vol. 54, no. 8, pp. 2416–2420, Aug. 2006.
[20] Y. Yusuf and X. Gong, "Compact low-loss integration of high-$Q$ 3-D filters with highly efficient antennas," *IEEE Trans. Microw. Theory Techn.*, vol. 59, no. 4, pp. 857–865, Apr. 2011.
[21] C.-K. Lin and S.-J. Chung, "A compact filtering microstrip antenna with quasi-elliptic broadside antenna gain response," *IEEE Antennas Wireless Propag. Lett.*, vol. 10, pp. 381–384, 2011.
[22] J. Zuo, X. Chen, G. Han, L. Li, and W. Zhang, "An integrated approach to RF antenna-filter co-design," *IEEE Antennas Wireless Propag. Lett.*, vol. 8, pp. 141–144, 2009.
[23] O. A. Nova, J. C. Bohorquez, N. M. Pena, G. E. Bridges, L. Shafai, and C. Shafai, "Filter-antenna module using substrate integrated waveguide cavities," *IEEE Antennas Wireless Propag. Lett.*, vol. 10, pp. 59–62, 2011.

[24] P.-S. Kildal, A. U. Zaman, E. Rajo-lglesias, E. Alfonso, and A. Valero-Nogueira, "Design and experimental verification of ridge gap waveguide in bed of nails for parallel-plate mode suppression," *IET Microw. Antennas Propag.*, vol. 5, no. 3, pp. 262–270, Feb. 2011.

[25] P.-S. Kildal, E. Alfonso, A. Valero-Nogueira, and E. Rajo-Iglesias, "Local metamaterial-based waveguides in gaps between parallel metal plates," *IEEE Antennas Wireless Propag. Lett.*, vol. 8, pp. 84–87, 2009.

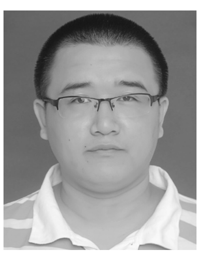
[26] P.-S. Kildal, "Three metamaterial-based gap waveguides between parallel metal plates for mm/submm waves," in *Proc. 3rd Eur. Conf. Antennas Propag.*, Berlin, Germany, Mar. 2009, pp. 28–32.

[27] R. Elliott and L. Kurtz, "The design of small slot arrays," *IEEE Trans. Antennas Propag.*, vol. 26, no. 2, pp. 214–219, Mar. 1987.

**Wei Wang** received the B.S. degree in physics from Anhui University, Hefei, China, in 1993, the M.S. degree in electrical engineering from Xidian University, Xi'an, China, in 2001, and the Ph.D. degree in electrical engineering from Shanghai University, Shanghai, China, in 2005.

From 1993 to 1998, he was an Assistant Engineer with the East China Research Institute of Electronic Engineering (ECRIEE), Hefei, where he was an Engineer from 2001 to 2002. He is a Senior Member of the Chinese Institute of Electronics, Beijing, China. He is currently a Research Professor with ECRIEE. He has authored and co-authored over 50 journal papers and 60 conference papers. He holds 30 Chinese patents. His current research interests include waveguide slot antennas, microstrip antennas for radar, compact ultrawideband for wireless communications, microwave passive devices and circuits, and microwave/millimeter systems.

Dr. Wang was a recipient of many awards, including one Second Class Award for Scientific and Technology of National Progress, two Second Class Awards for Scientific and Technology Progress of National Defense Industry, one First Class and one Third Class Awards for scientific and technology achievements in China Electronic Technology Group Corporation, one First Class Award for Electronic Information Science and Technology of China Electronic Institute, and one First Class and one Second Class Awards for Excellent Academic Papers in Natural Science of Anhui Province.

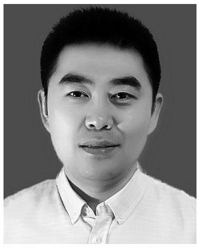


**Zhi Zheng** was born in Benxi, Liaoning, China, in 1985. He received the B.S. degree in electronic information engineering and the M.S. and Ph.D. degrees in radio physics from Sichuan University, Chengdu, China, in 2008, 2011, and 2015, respectively.

He is currently with the East China Research Institute of Electronic Engineering, Hefei, China. His current research interests include waveguide slot antennas and microstrip antennas for phased array.

**Xiaochuan Fang** received the B.S. degree from the University of Electrical and Science Technology of China, Chengdu, China, in 2015, where he is currently pursuing the M.S. degree.

His current research interests include antenna design for communications, RFID, and wireless power transfer.



**Hongtao Zhang** was born in Puyang, Henan, China, in 1980. He received the B.S. and M.S. degrees in electronic engineering from Xidian University, Xi'an, China, in 2005 and 2008, respectively.

Since 2008, he has been with the East China Research Institute of Electronic Engineering, Hefei, China, where he is currently an Antenna Research and Development Senior Engineer. His current research interests include phased array antennas, waveguide slot antennas, and ultrawideband antennas.

**Mouping Jin** received the Ph.D. degree in electromagnetic field and microwave technology from Xidian University, Xi'an, China, in 2000.

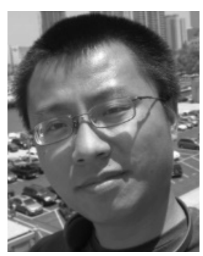
He is currently a Research Professor with the East China Research Institute of Electronic Engineering, Hefei, China. He has authored or co-authored over 20 papers in journals and conferences. His current research interests include antenna systems and microwave passive devices.

Dr. Jin was a recipient of several awards, including one Second Class Award for Scientific and Technology Progress of National Defense Industry and one third Class Award for Scientific and Technology Achievements of China Electronic Technology Group Corporation.

**Jiaguo Lu** (SM'95) received the B.S. degree in electronic engineering from Xidian University, Xi'an, China, in 1987.

He is currently the Deputy Director and Researcher of the East China Research Institute of Electronic Engineering, Hefei, China. He is also a Doctoral Supervisor with Anhui University, Hefei, and the University of Science and Technology of China, Hefei. His current research interests include the synthetic aperture radar, rain cloud measurement radar, and optically controlled phased array antenna.

Prof. Lu is a Senior Fellow of China Institute of Electronics.



**Qi Luo** (M'12) was born in Chengdu, China, in 1982. He received the M.S. degree from the University of Sheffield, Sheffield, U.K., in 2006, and the Ph.D. degree from the University of Porto, Porto, Portugal, in 2012.

From 2012 to 2013, he was a Research Fellow with the Surrey Space Centre, Guildford, U.K. He is currently a Research Fellow with the School of Engineering and Digital Arts, University of Kent, Canterbury, U.K. His current research interests include smart antennas, circularly polarized antennas, reflectarray, transmitarray, multiband microstrip antennas, and electrically small antenna design.

Dr. Luo has been serving as a reviewer for a number of technical journals and conferences. He is the outstanding reviewers of the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION in 2015.

**Steven Gao** (SM'16) received the Ph.D. degree in microwave engineering from Shanghai University, Shanghai, China, in 1999.

He is currently a Professor and the Chair of RF and microwave engineering with the University of Kent, Canterbury, U.K. His current research interests include smart antennas, phased arrays, satellite antennas, RF/microwave/millimeter-wave/terahertz circuits, satellite communications, ultrawideband radars, synthetic aperture radars, and mobile communications.