A Grooved Half-Mode Waveguide Leaky-Wave Antenna for Vertically-Polarized Endfire Radiation

Xiaopeng Zhang, Libin Sun, Graduate Student Member, IEEE, Yue Li, Senior Member, IEEE, and Zhijun Zhang, Fellow, IEEE

Abstract—A high-gain low-profile leaky-wave antenna (LWA) for vertically-polarized (VP) fixed-beam endfire radiation is proposed in this article. The LWA is composed of two back-to-back half-mode waveguides with grooves etched at the margins of both radiation edges. By etching grooves, the phase velocity of the traveling wave can be tailored to slower than the wave velocity in free space for fitting the Hansen-Woodyard condition. Compared with periodic LWAs, the proposed antenna continuously radiates at two symmetric apertures, contributing to a high endfire gain. A prototype is fabricated and tested to validate the concept. The measured and simulated results are in good agreement. A simulated gain of 14.29 dBi and a measured gain of 13.37 dBi are achieved within an antenna length of 3.05λ0. Moreover, a measured overlapping bandwidth of 2.74–3.17 GHz (14.3%) is realized with S11 < −10 dB and gain variation less than 3 dB. To the best of the authors’ knowledge, the proposed VP endfire LWA realizes the highest aperture efficiency and shows great advantages in high profile, and wide bandwidth.

Index Terms—Endfire, grooved half-mode waveguide (G-HMWG), high gain, leaky-wave antenna (LWA), vertically-polarized (VP).

I. INTRODUCTION

HIGH-GAIN endfire antenna is widely applied in radar, wireless directional communication, objective detection systems, and many other domains. In order to be more suitable for these space-limited applications, endfire antennas with higher gain and lower profile have been investigated in the past few decades. In numerous scenarios, the endfire antennas should be mounted on the ground plane of platforms, so vertically-polarized (VP) radiation is necessary. Recently, there are many types of antennas proposed for VP endfire radiation, such as Yagi–Uda antennas, log-periodic antennas, surface-wave antennas, and leaky-wave antennas (LWAs).

Yagi–Uda antenna is a kind of classic endfire antenna that has been invented for nearly a century [1]. The conventional Yagi–Uda antenna is composed of dipole elements, and VP radiation can be realized by placing the dipoles vertically, but at the cost of high profile. Therefore, numerous new types of radiation elements, which could realize VP radiation within a low profile, were introduced into Yagi–Uda antennas. In [2]–[4], low-profile patch elements are utilized as drivers, directors, and reflectors to realize the VP endfire radiation. In [5]–[7], open-ended cavities are employed as drivers to generate vertical E-field. Meanwhile, the reflectors and directors are I-shaped resonators [5], patches [6], and open-ended cavities [7]. Moreover, monopole [8] and monocone [9] elements could also be utilized in Yagi–Uda antennas to reduce the antenna profile. The above Yagi–Uda antennas have the advantages of low-profile and low cost. However, the endfire gain cannot be further enhanced and the aperture efficiency will be decreased when the array length is large [7].

Log-periodic antenna could also realize endfire radiation in a simple manner. Because of the log-periodic distribution of radiation elements, the log-periodic antenna could work in an ultrawide frequency band. Similar with the low-profile Yagi–Uda antennas, the top-hat monopoles [10], [11], and open-ended cavities [12] can also be used in log-periodic antennas to substitute the dipole elements to realize a low-profile VP endfire radiation. However, the endfire gain of log-periodic antenna is limited since only part of the radiating aperture contributes to the endfire gain.

Endfire radiation can also be realized by utilizing surface-wave that transmitted on the surface of dielectrics [13], [14]. The surface-wave antennas in [13] and [14] have the advantages of wideband and low profile, while at the expense of gain reduction and beam tilt.

By adjusting the phase constant β to be approximately equal to the free-space wavenumber k0, LWAs could also realize the endfire radiation [19]. Moreover, according to the Hansen–Woodyard condition [15], the phase constant β slightly larger than the free-space wavenumber k0 is optimal for a maximum endfire gain. In [16]–[18], planar inverted-L antennas (PILAs) [16], resonant cavities [17], and folded monopoles [18] are introduced to couple energy from air-filled microstrip lines, which has a quasi-TEM transmission property with β ≈ k0. For antennas mentioned above, wideband and low-profile performance are achieved, but the endfire gain is reduced caused by finite ground and inexact endfire radiation. In order to achieve exact endfire beam and further enhance the endfire gain, endfire LWAs based on waveguides and parallel-strip lines are validated [19]–[23]. In [19], double-sided transverse slots are etched on a substrate integrated waveguide (SIW) to realize endfire radiation. An exact endfire beam is obtained, but the aperture efficiency is not very high. Parallel-strip lines supporting quasi-TEM
wave could also be used to excite dipoles [20], [21] to realize high-gain endfire radiation. However, horizontally-polarized (HP) radiation is realized by horizontal dipoles [20] and employing vertical dipoles [21] to realize a VP radiation will significantly increase the antenna profile. It is worth mentioned that endfire radiation could also be realized only utilizing curving [24] or loaded [25] parallel-strip lines without introducing extra radiation elements. These antennas have a very narrow metal width, but a wide dielectric slab is essential. Hence, it is still a great challenge to realize high-gain endfire radiation and high aperture efficiency. Even if a high endfire gain is achieved in [23], the 3 dB gain bandwidth of 5.8% in [23] is extremely narrow.

To tackle the challenges mentioned above, a high-gain, low-profile, VP endfire LWA is proposed in this article. The proposed antenna is composed of two back-to-back grooved half-mode waveguides (G-HMWGs). It is proven in this article that the grooves could slow down the phase velocity of the fast traveling wave in waveguide to realize an endfire radiation with \( \beta \approx k_0 \). The symmetric G-HMWG LWA is designed to enable two symmetrical continuous radiation apertures, which avoids beam tilt and effectively enhance the endfire gain. Different from other LWAs, the proposed antenna could realize endfire beam without any extra radiation elements. To the best of our knowledge, the highest gain per unit area (G/A) is achieved. Moreover, the overlapping bandwidth of \(-10\) dB impedance matching and 3 dB gain variation is 14.3%, which is much wider than that in [23].

II. G-HMWG LWA

A. HMWG LWA

An HMWG with a size of \(0.3\lambda_0 \times 0.1\lambda_0 \times 3.05\lambda_0\) (30 mm × 10 mm × 305 mm) operating at 3 GHz is shown in Fig. 1(a). The HMWG can be regarded as half of the waveguide with similar properties. The quasi-TE_{1,2,0} mode is the fundamental mode of the HMWG, which can be equivalent to the half of the TE_{10} mode of waveguide. In the HMWG, the traveling wave can be radiated at the open side, so it could be regarded as a continuous LWA to generate a directive beam.

In LWAs, the beam pointing could be approximately calculated by [19]

\[
\theta \approx \arcsin(\beta/k_0) \tag{1}
\]

where \( \beta \) is the phase constant, \( k_0 \) is the wavenumber in free space, and \( \theta \) is the beam pointing. According to (1), the endfire radiation can be realized when the phase constant \( \beta \) is equal to the wavenumber \( k_0 \). In the HMWG, the width \( W \) affects the phase velocity of the traveling wave

\[
\beta = k_0 \sqrt{1 - \left(\frac{\lambda}{2W}\right)^2} \tag{2}
\]

where \( \lambda \) is the wavelength in the free space. In terms of (2), the wider of the HMWG, the slower of the phase velocity. However, the phase velocity of the traveling wave transmitted in the HMWG is always faster than that transmitted in the free space, which is a fast-wave mode with \( \beta < k_0 \). Therefore, the beam pointing is always tilt for the HMWG LWA. In order to realize an endfire radiation, the traveling wave with \( \beta \approx k_0 \) is necessary. Hence, some more effective approaches need to be proposed to slow down the phase velocity of the HMWG LWA.

B. G-HMWG LWA

To slow down the phase velocity in the HMWG, here, we introduce an approach of etching the grooves in the HMWG [26]. As shown in Fig. 1(b), a G-HMWG LWA with the same size as the intact HMWG LWA is illustrated. The operating mechanism of the phase velocity reduction by the proposed etching grooves is illustrated in Fig. 2. Etching grooves at the radiation edge can extend the path of maximum current, thus slows down the equivalent phase velocity along the propagation direction.

The groove depth \( d \) is a key parameter to slow down the phase velocity of the HMWG LWA. Fig. 3(a) shows the simulated curves of the phase constant \( \beta \) and the leaky rate \( \alpha \) versus groove depth. With the increasing of \( d \), the phase constant increases gradually, and transforms from fast-wave region to slow wave region. The leaky rate is also impacted by the groove depth as shown in Fig. 3(a). As groove depth increases, the leaky rate decreases generally owing to the poor radiation ability of the slow wave. However, when
Fig. 3. (a) Normalized phase constant and leaky rate versus the groove depth \(d\) at 3 GHz. (b) Normalized radiation pattern versus the groove depth \(d\) at 3 GHz. 

When \(d\) is small, the leaky rate slightly increases with the increase of \(d\). The reason is that the discontinuity introduced by grooves enhances the radiation of the LWA. Fig. 3(b) shows the beam pointing with the variation of \(d\) in \(xoy\) plane. The beam gradually tilts as \(d\) increases and endfire radiation is realized while \(d = 12\) mm. The phase constant is slightly larger than \(k_0\) in this case, as shown in Fig. 3(a), which will meet Hansen–Woodyard condition [15]. Therefore, we choose \(d = 12\) mm as the optimal groove depth for endfire radiation.

The \(E\)-field distribution for the intact HMWG LWA and the G-HMWG LWA at 3 GHz is illustrated in Fig. 4. It is obvious that the traveling wave transmitted in the G-HMWG is much slower than that transmitted in the intact HMWG.

The G-HMWG LWA could realize endfire radiation by optimizing the size of grooves, but the maximum endfire gain is limited due to the \(E\)-field cancellation. As shown in Fig. 4(c), the \(E\)-field directions at the open side and the back side are opposite, which will cancel each other out.

III. ANTENNA DESIGN

A. Antenna Configuration

In order to enhance the maximum gain and eliminate the tilt of endfire beam, a symmetric G-HMWG LWA is proposed. As shown in Fig. 5(a) and (b), the proposed antenna could be regarded as a back-to-back connection of two G-HMWG LWAs and Fig. 5(c) shows the detailed structure of the radiation part. The electromagnetic wave is transmitted in two G-HMWGs, respectively, and radiated symmetrically at both open sides.

In order to feed two G-HMWG LWAs in-phase, two same transitions are designed between G-HMWGs and ports as shown in Fig. 5(d) and (e). The transitions are approximately air-filled parallel-plate waveguides. The height gradually transitions from \(H_p\) to \(T\), while the width transitions from \(L_p\) to \(W\). All the parameters are optimized to realize a good impedance matching. Two short sticks are extended from transitions for easily fixing of feeding cables. The energy is fed by the coaxial line and divided equally by intermediate vertical plate into two parts. The vertical plate extends a length of \(L_e\) to adjust the impedance matching, which is also utilized.
The vector two open sides are consistent, thus enhance the endfire gain. The antenna is shown in Fig. 6(a). The directions of $E$-field with HP working mechanism of our proposed antenna is different from the work in [20] which excites horizontal dipoles by parallel-strip lines with TEM mode transmitted in it to realize HP radiation. But, it is distinct that our proposed antenna is based on the HMWG with the quasi-TE$_{1,2,0}$ mode and the VP radiation is realized as explained above. Fig. 6(b) illustrates the $E$-field distribution in $xoy$ plane of the proposed antenna. The injected energy is divided equally into two parts by the transition, feeding two G-HMWGs with the quasi-TE$_{1,2,0}$ mode. The traveling wave radiates at two open sides evenly and endfire radiation is realized. The traveling wave transmitted in symmetric G-HMWG LWA is a slow wave with a wavelength slightly less than $\lambda_0$ due to the etch of grooves.

The impact of groove size and waveguide width is studied in detail as shown in Fig. 7. Waveguide width $W$ is a significant parameter to tune the phase constant and leaky rate. As shown in Fig. 7(a), with the increasing of $W$, the phase constant increases and the phase velocity slows down; meanwhile, the leaky rate decreases gradually because of the poor radiation ability of the slow wave. Fig. 7(d) shows the curve of endfire gain versus $W$. Maximum gain of 13.95 dBi is achieved when $W = 19$ mm. The groove depth $d$ is another important parameter for adjusting the phase constant and leaky rate as discussed in Section II. As shown in Fig. 7(b), $d$ has a similar effect on the phase constant and leaky rate with that of $W$. As $d$ increases, the phase constant increases from fast-wave region to slow wave region and the leaky rate decreases gradually. Fig. 7(e) shows that the approximate maximum endfire gain is obtained when $d = 15$ mm. Even if endfire gain is higher when $d = 16$ mm, the leaky rate of $d = 15$ mm is less than that of $d = 15$ mm, which causes an unexpected efficiency reduction. The phase constant and leaky rate are also impacted by the groove width $r$. Note that the spacing of grooves $s$ is equal to $r$ to simplify the design. The groove width has an inverse impact on the phase constant and leaky rate as that of $W$ and $d$, as shown in Fig. 7(c). As $r$ increases, the phase constant decreases and the leaky rate increases. However, the impact of $r$ is not as dramatic as that of $W$ and $d$. Fig. 7(f) shows that the endfire gain changes a little with the increase of $r$. Therefore, $r = 5$ mm is adopted with a tradeoff of the endfire gain and the leaky rate.

The optimal values of $W$, $d$, and $r$ are presented in Table I. The maximum endfire gain of 13.95 dBi is achieved when $r = 5$ mm, $d = 15$ mm, and $W = 19$ mm at 3 GHz. In this case, the antenna works in the slow wave mode and the normalized phase constant is 1.058, which approximately meets Hansen–Woodyard condition [15].

### IV. Simulated and Measured Results

Fig. 8 shows a prototype of the fabricated antenna to verify the performance. The proposed antenna is divided into four parts for manufacture, the top layer, the bottom layer, the intermediate vertical plate, and the reflector. All of them are made of brass plates ($\sigma = 1.5 \times 10^7$ S/m) with a thickness of 0.5 mm. Port1 is excited by a semirigid cable through reflector with outer conductor and inner conductor soldered to the proposed antenna is VP radiation. Besides, the structure and working mechanism is also quite different from the work in [20] which excites horizontal dipoles by parallel-strip lines with TEM mode transmitted in it to realize HP radiation. But, it is distinct that our proposed antenna is based on the HMWG with the quasi-TE$_{1,2,0}$ mode and the VP radiation is realized as explained above. Fig. 6(b) illustrates the $E$-field distribution in $xoy$ plane of the proposed antenna. The injected energy is divided equally into two parts by the transition, feeding two G-HMWGs with the quasi-TE$_{1,2,0}$ mode. The traveling wave radiates at two open sides evenly and endfire radiation is realized. The traveling wave transmitted in symmetric G-HMWG LWA is a slow wave with a wavelength slightly less than $\lambda_0$ due to the etch of grooves.

The impact of groove size and waveguide width is studied in detail as shown in Fig. 7. Waveguide width $W$ is a significant parameter to tune the phase constant and leaky rate. As shown in Fig. 7(a), with the increasing of $W$, the phase constant increases and the phase velocity slows down; meanwhile, the leaky rate decreases gradually because of the poor radiation ability of the slow wave. Fig. 7(d) shows the curve of endfire gain versus $W$. Maximum gain of 13.95 dBi is achieved when $W = 19$ mm. The groove depth $d$ is another important parameter for adjusting the phase constant and leaky rate as discussed in Section II. As shown in Fig. 7(b), $d$ has a similar effect on the phase constant and leaky rate with that of $W$. As $d$ increases, the phase constant increases from fast-wave region to slow wave region and the leaky rate decreases gradually. Fig. 7(e) shows that the approximate maximum endfire gain is obtained when $d = 15$ mm. Even if endfire gain is higher when $d = 16$ mm, the leaky rate of $d = 16$ mm is less than that of $d = 15$ mm, which causes an unexpected efficiency reduction. The phase constant and leaky rate are also impacted by the groove width $r$. Note that the spacing of grooves $s$ is equal to $r$ to simplify the design. The groove width has an inverse impact on the phase constant and leaky rate as that of $W$ and $d$, as shown in Fig. 7(c). As $r$ increases, the phase constant decreases and the leaky rate increases. However, the impact of $r$ is not as dramatic as that of $W$ and $d$. Fig. 7(f) shows that the endfire gain changes a little with the increase of $r$. Therefore, $r = 5$ mm is adopted with a tradeoff of the endfire gain and the leaky rate.

The optimal values of $W$, $d$, and $r$ are presented in Table I. The maximum endfire gain of 13.95 dBi is achieved when $r = 5$ mm, $d = 15$ mm, and $W = 19$ mm at 3 GHz. In this case, the antenna works in the slow wave mode and the normalized phase constant is 1.058, which approximately meets Hansen–Woodyard condition [15].

### TABLE I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value(mm)</th>
<th>Parameter</th>
<th>Value(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W$</td>
<td>19</td>
<td>$W_p$</td>
<td>32</td>
</tr>
<tr>
<td>$\tau$</td>
<td>5</td>
<td>$L_p$</td>
<td>10</td>
</tr>
<tr>
<td>$s$</td>
<td>5</td>
<td>$H_p$</td>
<td>4</td>
</tr>
<tr>
<td>$d$</td>
<td>15</td>
<td>$L_r$</td>
<td>2</td>
</tr>
<tr>
<td>$L$</td>
<td>305</td>
<td>$D_r$</td>
<td>10</td>
</tr>
<tr>
<td>$T$</td>
<td>10</td>
<td>$L_r$</td>
<td>70</td>
</tr>
</tbody>
</table>

![Cross section](image)

Fig. 6. Simulated $E$-field distribution of the symmetric G-HMWG LWA at 3 GHz. (a) Vector $E$-field distribution in the cross section ($xoz$ plane). (b) Magnitude of the $E$-field distribution in $xoy$ plane.

to determine the inclination of the top and bottom slabs in fabrication.

The antenna is fed through Port1 by the coaxial line, whereas Port2 is connected to a 50 $\Omega$ matched load to absorb the residual energy. A square reflector is placed 10 mm behind to suppress the backside radiation. The dimension of symmetric G-HMWG LWA is $0.3\lambda_0 \times 0.1\lambda_0 \times 3.05\lambda_0$ at 3 GHz. The detailed dimensions optimized by HFSS are presented in Table I.

### B. Radiation and Dispersion Analysis

According to the analysis in Section II-B, the opposite $E$-fields at the open side and the back side deteriorate the maximum endfire gain. To eliminate the opposite $E$-field in the back side, the completely symmetrical structure is designed. The vector $E$-field distribution in cross section of the proposed antenna is shown in Fig. 6(a). The directions of $E$-field at two open sides are consistent, thus enhance the endfire gain. The vector $E$-field distribution in Fig. 6(a) indicates that the working mechanism of our proposed antenna is different from the work in [26]. In [26], the surface wave transmitted in the metal strip with HP $E$-fields outside the edges is slowed down by etching grooves and the HP radiation is realized. However, as shown in Fig. 6(a), the quasi-TE$_{1,2,0}$ mode is excited in each HMWG and the traveling wave can be radiated at the open sides with VP $E$-fields which determine that our
Fig. 7. (a) Simulated normalized phase constant and leaky rate at 3 GHz versus (a) HMWG width $W$ when $d = 15$ mm and $r = s = 5$ mm. (b) Groove depth $d$ when $W = 19$ mm and $r = s = 5$ mm. (c) Groove width $r$ when $s = r$, $W = 19$ mm, and $d = 15$ mm. (d) HMWG width $W$ when $d = 15$ mm and $r = s = 5$ mm. (e) Groove depth $d$ when $W = 19$ mm and $r = s = 5$ mm. (f) Groove width $r$ when $s = r$, $W = 19$ mm, and $d = 15$ mm. Blue region is fast-wave region and white region is slow wave region in (a)–(c).

Fig. 8. Photograph of the proposed symmetric G-HMWG LWA.

Fig. 9. Simulated and measured S-parameters of the proposed antenna.

two short sticks, respectively. Port2 is connected to a matched load to absorb the residual energy.

A. S-Parameters

The simulated and measured S-parameter of the proposed antenna is illustrated in Fig. 9. It is shown that the measured results are in agree with the simulated results. The measured $-10$ dB impedance bandwidth is approximately 2.74–3.17 GHz (14.3%), close to the simulation result of 2.80–3.19 GHz (13.0%). The measured $S_{21}$ is varied from $-18.91$ to $-6.96$ dB in the operating band. There are small deviations between the measured and simulated results, which are caused by the manual fabrication error.

B. Radiation Performance

Fig. 10 shows the simulated and measured realized gains of the proposed antenna. Both measured and simulated maximum endfire gains are obtained at 3.05 GHz, which are 13.37 and 14.29 dBi, respectively. The simulated 3 dB gain bandwidth is 2.77–3.19 GHz (14.0%), while the measured result is 2.70–3.18 GHz (16.0%). The 3 dB gain bandwidth is approximately coincided with the $-10$ dB impedance bandwidth, making an overlapping operating bandwidth of 2.74–3.17 GHz (14.3%). The measured gain is slightly lower than the simulated result due to the manual fabrication errors. More energy is transmitted to another port instead of being radiated into space. The simulated total efficiency is illustrated in Fig. 10. The total efficiency is above 70% in the operating band, which indicates a good radiation performance of the proposed antenna.
Radiation patterns are measured in a far-field anechoic chamber. The simulated and measured normalized radiation patterns in E- and H-plane at 3.0 GHz are depicted in Fig. 11. The measured co-polarization results in E- and H-planes agree with the simulated ones. The front-to-back ratio level is 12 dB in E-plane and 19 dB in H-plane, respectively. Because of the measurement errors, the front-to-back ratio level in E-plane deteriorates slightly. The half-power beam widths (HPBWs) in E- and H-planes are 12° and 14°, respectively. With the completely symmetric structure, the simulated cross-polarization level is lower than −30 dB, which is neglected in Fig. 11. The measured cross-polarization of E-plane is lower than −24 dB and that of H-plane is lower than −15 dB due to the measurement errors.

C. Discussion

The simulated endfire gain versus antenna length is presented in Table II. The proposed antenna shows great ability in realizing higher endfire gain by extending the length of antenna.

The influence of the reflector size on endfire gain is also studied as shown in Table III. The endfire gain decreases very slightly with the reduction of the reflector size. Even if the width of the square reflector is the same as the radiation part (\(L_r = 38\) mm), a high gain of 13.45 dBi is achieved.
The comparisons between the proposed antenna and other designs for VP radiation are listed in Table IV. In [7] and [12], the low-profile Yagi–Uda antenna and log-periodic antenna are proposed; however, the endfire gains are not very high due to the tilt beams, leading to a low G/A. In [18] and [22], the folded monopoles and slots are utilized to couple energy from transmission lines, respectively. The gains are also not high enough due to the tilt beams. In [19], a slot-loaded SIW LWA is proposed with a gain of 14.8 dBi, but the length is as large as 14.6 λ₀. In [25], a novel phase loading technique is introduced in double-side parallel strip lines to adjust the phase distribution for endfire radiation. The highest gain is achieved with a long length, but the overlapping bandwidth is narrow. Very recently, a high-gain endfire LWA with periodic-arranged open cavity elements exciting by parallel-strip line is proposed in [23], which has the highest G/A at that time, but the overlapping bandwidth is only 5.8%. Our proposed symmetric G-HMWG LWA not only breaks the G/A record in [23], but also has a wider overlapping bandwidth of 14.3%. Therefore, the proposed symmetric G-HMWG LWA shows good performances with a measured high gain of 13.37 dBi, a wide overlapping bandwidth of 14.3%, and the highest G/A.

V. CONCLUSION

In this article, a high-gain, low-profile, VP endfire LWA is proposed. By etching grooves on HMWs, the phase velocity of traveling wave transmitted in two symmetric HMWs is slowed down and the endfire radiation is realized. We design a completely symmetric antenna structure in order to realize a higher endfire gain. The measured results show that the proposed antenna can realize a measured high gain of 13.37 dBi and a wide overlapping bandwidth of 14.3% with S₁₁ < −10 dB and gain variation less than 3 dB. Compared to the up-to-date endfire antennas, the proposed antenna realizes the highest G/A and a much wider overlapping bandwidth than the antenna [23] with a similar endfire gain.

REFERENCES


Xiaopeng Zhang received the B.S. degree from Xidian University, Xi’an, China, in 2011. He is currently pursuing the Ph.D. degree with the Department of Electrical and Engineering, Tsinghua University, Beijing, China.

His current research interests include leaky-wave antennas, antenna decoupling, and MIMO.
Libin Sun (Graduate Student Member, IEEE) received the B.S. degree from Xidian University, Xi’an, China, in 2016. He is currently pursuing the Ph.D. degree with the Department of Electrical and Engineering, Tsinghua University, Beijing, China.

He has authored over ten journal articles and holds five granted Chinese patents. His current research interests include antenna design and theory, particularly in 5G mobile phone antennas, antenna decoupling, MIMO and diversity antennas, circularly-polarized antennas, leaky-wave antennas, and surface-wave antennas.

Mr. Sun was a recipient of the Top Reviewer Award for the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION in 2019 and the Honorable Mention in 2020 IEEE AP-S Student Paper Competition. He serves as a reviewer for several international academic journals such as the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS, IEEE ACCESS, IET Microwaves, Antennas & Propagation, IET Electronics Letters, and Microwave and Optical Technology Letters.

Yue Li (Senior Member, IEEE) received the B.S. degree in telecommunication engineering from Zhejiang University, Hangzhou, China, in 2007, and the Ph.D. degree in electronic engineering from Tsinghua University, Beijing, China, in 2012.

In June 2012, he joined the Department of Electronic Engineering, Tsinghua University, as a Post-Doctoral Fellow. In December 2013, he joined the Department of Electrical and Systems Engineering, University of Pennsylvania, Philadelphia, PA, USA, as a Research Scholar. He was also a Visiting Scholar with the Institute for Infocomm Research (I2R), A*STAR, Singapore, in 2010, and the Hawaii Center of Advanced Communication (HCAC), University of Hawaii at Manoa, Honolulu, HI, USA, in 2012. Since January 2016, he has been with Tsinghua University, where he is currently an Assistant Professor and an Associate Professor with the Department of Electronic Engineering. He has authored or coauthored over 160 journal articles and 50 international conference papers, and holds 24 granted Chinese patents.

His current research interests include metamaterials, plasmonics, electromagnetics, nanocircuits, mobile and handset antennas, MIMO and diversity antennas, and millimeter-wave antennas and arrays.

Dr. Li was a recipient of the Issac Koga Gold Medal from URSI General Assembly in 2017, the Second Prize of Science and Technology Award of China Institute of Communications in 2017, the young scientist awards from the conferences of PIERS 2019, ACES 2018, AT-RASC 2018, AP-RASC 2016, EMTS 2016, and URSI GASS 2014, the best paper awards from the conferences of APCAP 2020/2017, UCMMT 2020, ISAP 2019, CSQWR 2018, NCMMW 2018/2017, NCANT 2019/2017, ISAPE 2016, and ICMMT 2020/2016, the Outstanding Doctoral Dissertation of Beijing Municipality in 2013, and the Principal Scholarship of Tsinghua University in 2011. He is serving as an Associate Editor for IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS, Microwave and Optical Technology Letters, and Computer Applications in Engineering Education, and also serving as the Editorial Board of Scientific Report and Electronics.

Zhijun Zhang (Fellow, IEEE) received the B.S. and M.S. degrees from the University of Electronic Science and Technology of China, Chengdu, China, in 1992 and 1995, respectively, and the Ph.D. degree from Tsinghua University, Beijing, China, in 1999.

In 1999, he joined the Department of Electrical Engineering, The University of Utah, Salt Lake City, UT, USA, as a Post-Doctoral Fellow, where he was appointed as Research Assistant Professor, in 2001. In May 2002, he joined the University of Hawaii at Manoa, Honolulu, HI, USA, as an Assistant Researcher. In November 2002, he joined Amphenol T&M Antennas, Vernon Hills, IL, USA, as a Senior Staff Antenna Development Engineer and then was promoted to the position of Antenna Engineer Manager. In 2004, he joined Nokia Inc., San Diego, CA, USA, as a Senior Antenna Design Engineer. In 2006, he joined Apple Inc., Cupertino, CA, as a Senior Antenna Design Engineer and then was promoted to the position of Principal Antenna Engineer. Since August 2007, he has been with Tsinghua University, where he is currently a Professor with the Department of Electronic Engineering. He has authored Antenna Design for Mobile Devices (Wiley, 1st ed. 2011, 2nd ed. 2017).

Dr. Zhang served as an Associate Editor for the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION from 2010 to 2014 and the IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS from 2009 to 2015.