A New and Simple Design Method for End-Fire Dipole Antenna Array and Three Two-Element 24 GHz Planar End-Fire Dipole Antenna Arrays

Yanfei Mao 1,2, Shiju E 1,2,* and Chungeng Zhu 1,2

Abstract: For an RF system, a high-gain antenna helps to improve the equivalent isotropic radiated power (EIRP) of the transmitter and an end-fire antenna array helps to improve the directivity (D) and half power beam width (HPBW) of the antenna. This work presents a new and simple design method for end-fire antenna array design. The method states that when antenna elements are $\lambda/2$ apart, a simple end-fire antenna array could be designed and constructed easily without matching networks between antenna elements. Utilizing Rogers 4350 PCB technology, three 24 GHz high-gain, compact planar two-element end-fire dipole antenna arrays are designed to verify this new design method. The achieved results are three two-element end-fire antennas with gains of 8.8, 9.9 and 9.1 dBi. These antenna arrays are characterized by high gain and simplicity in design. They are also very compact in size, with an area of about $1.9 \times 1.7 \text{ cm}^2$. The benefit of this work is that a new and simple design for end-fire antenna design is suggested, and three two-element end-fire dipole antenna arrays in planar technology which adopt the design method are presented. A utility model patent was granted for this end-fire dipole array antenna topology, ZL 202022106332.1.

Keywords: end-fire antenna array; planar technology; on-chip antenna design; half wave dipole elements

1. Introduction

For a RF system, one difficult task is to design high-output power transmitters. A high-gain antenna helps to improve the EIRP of the transmitter. Reference [1] compared an isometric linear broadside array with an end-fire array with the same N elements. Both the directivity (D) and half power beam width (HPBW) of the end-fire array are twice that of the broadside array according to [1]. Therefore, the performance of an end-fire array is much better than that of a broadside array. This paper focuses on looking for an end-fire antenna array with a simple structure in planar technology suitable for millimeter-wave (mm-wave) and THz on-chip antenna design.

In order to fulfill the aim of the article and explain the essence of the problem, the second section presents a theory of the end-fire antenna, which includes a new and simple method for designing an end-fire antenna array. To verify this new method of the field solution, three compact planar two-element end-fire dipole antennas with high gain are designed and implemented in the third section. The fourth section verifies the results of the measurements on three 24 GHz end-fire dipole antenna arrays. In the fifth section, the achieved results are briefly commented on and compared with the state of antenna technology in this area around the world.

Various studies have been carried out on end-fire antennas in planar technology. In [2], a 60 GHz planar end-fire fan-like antenna was fabricated using RO4003 printed-circuit board (PCB) technology with a gain of 3.4–7.6 dBi. In [3], a millimeter wave end-fire...
4 element 5G beam steerable array antenna with a low-frequency planar inverted-F antenna (PIFA) was presented with 9.5 dBi gain at 28 GHz. In [4], a novel 5.8 GHz planar end-fire circularly polarized (CP) complementary antenna was given with a gain of 2 dBi. In [5], a compact 7 GHz planar printed quasi-Yagi antenna with size reduction at 7 GHz with a gain of 4 dBi was demonstrated. In this work, a new and simple design method for an end-fire antenna array design is suggested; utilizing Roger 4350 PCB technology, three 24 GHz high-gain, compact planar two-element end-fire dipole antenna arrays are designed to verify this design method. The frequency is chosen at 24 GHz for the convenience of fabrication of antenna and the measurement of the antenna. It is much cheaper to fabricate, measure and verify the antenna topology at 24 GHz than on-chip mm-wave and THz antenna such as 60, 120 or 244 GHz end-fire antenna arrays. Additionally, there are also many applications at the frequency band of 24 GHz, such as 5G communication, imaging, and so on.

2. A New and Simple Design Method for End-Fire Antenna Array Design

Figure 1a shows a basic architecture of an N-element end-fire antenna composed of dipole antennas. N stands for the number of antenna units. d is the distance between antenna elements. Usually d = M * λ/4, M = 1,2,3… [1], and M is an integer to describe the distance d. When M = 1, an end-fire antenna array: a helix antenna could be realized such as in ref. [6]. Nevertheless, when M = 2, a new and simple design method for end-fire antenna design is discovered that means that, when antenna elements are λ/2 apart, a simple end-fire antenna array could be designed and constructed easily without matching networks between antenna elements.

Figure 1. (a) N-element end-fire antenna composed of dipole antennas and (b) minimum RF interferences or best isolation when antenna elements are λ/2 apart.

From Figure 1b, we can see that because the antenna elements are λ/2 apart, RF signals received or sent from neighboring antenna elements are out of phase. For EM signals with a distance of half the wavelength, they strengthen in the direction of the +X axis, while cancelling in the direction of the −X axis. This the reason why an end-fire antenna can be constructed without matching networks when two dipole antennas are placed with a distance of λ/2. This is why antenna elements could be connected together directly to form an end-fire antenna array without any impedance matching networks.

The rule that an end-fire antenna array could be constructed without matching networks when neighboring elements are λ/2 apart could also be proved in a more rigorous analysis, as follows.

(1) First of all, let us consider the first end-fire antenna: the two dipole antenna elements are λ/2 apart, and no auxiliary dipole element is inserted between them, as shown in Figure 2a,b. In Figure 2a, at 24 GHz with Rogers 4350 technology, L = d, d = 2.3 mm, M = 2, N = 2.
In this circuit, characteristic impedance of transmission line $Z_0$ is almost equal to the load of the dipole antenna $Z_L$.

According to transmission line theory and the theory of elements current for series-fed microstrip arrays [7,8], after a transmission line of $\lambda/2$, input impedance of $R_L$ remains the same. According to the theory of the circuit model, the ratio of impedances is as follows: $Z_2i:Z_L = 1:1$; therefore, the ratio of the currents of the two dipole antennas can be obtained as follows: $I_1:I_2 = 1:1$.

Consequently pattern function of the array can be obtained as follows:

$$f(\theta) = \frac{\cos \left( \frac{\pi}{2} \sin \theta \right)}{\cos \theta} \star \left| 2 \cos \left( \frac{\pi}{2} (1 - \cos \theta) \right) \right|$$

In Equation (1), $\cos \left( \frac{\pi}{2} \sin \theta \right)$ is the pattern of the dipole antenna, while the remaining part is the array pattern. Additionally, the gain pattern of the two-element end-fire dipole antenna array in the H plane is as shown in Figure 3.

(2) Secondly, let us consider a second case of an end-fire antenna: the two dipole antenna elements are $\lambda/2$ apart, and one auxiliary dipole element, $I_{M3}$, is inserted between them, as shown in Figure 4. In Figure 4a, at 24 GHz with Rogers 4350 technology, $L = d$, $d = 2.3$ mm, $M = 2$, $N = 2$. 

![Diagram](image-url)
Figure 4. (a) Two dipole antenna elements are $\lambda/2$ apart with 1 auxiliary dipole antenna elements; (b) the circuit model.

According to the theory of the circuit model, the ratio of impedances is as follows: $Z_2:Z_3:Z_L = 2:1:1$; therefore the ratio of the currents of the three dipole antennas can be obtained as follows: $I_1:I_3:I_2 = 4:1:1$.

Consequently, the pattern function of the array can be obtained as follows:

$$f(\theta) = \frac{\cos\left(\frac{5}{2}\sin\theta\right)}{\cos\theta} \sqrt{\left(5 \sin\left(\frac{\pi}{2}\cos\theta\right) + 1\right)^2 + 3 \cos^2\left(\frac{\pi}{2}\cos\theta\right)}$$

In Equation (2), $\frac{\cos\left(\frac{5}{2}\sin\theta\right)}{\cos\theta}$ is the pattern of the dipole antenna, while the remaining part is the array pattern. Additionally, the gain pattern of the two-element end-fire dipole antenna array in the H plane is as shown in Figure 5.

Figure 5. Gain pattern of the two-element end-fire dipole antenna array with 1 auxiliary dipole antenna in H plane.

(3) Thirdly, let us consider a third case of an end-fire antenna: the two dipole antenna elements are $\lambda/2$ apart, and two auxiliary dipole elements, $I_{M3}$ and $I_{M4}$, are inserted between them, as shown in Figure 6. In Figure 6a, at 24 GHz with Rogers 4350 technology, $L = d$, $d = 2.3$ mm, $M = 2$, $N = 2$.

Figure 6. (a) Two dipole antenna elements are $\lambda/2$ apart with 2 auxiliary dipole antenna elements. (b) the circuit model.
According to the theory of the circuit model, the ratio of impedances is as follows: $Z_2:Z_3:Z_4:Z_5 = (1.47 + 0.52):(1.14 + 0.74):1:1$; therefore, the ratio of currents of the four dipole antennas can be obtained as follows: $I_1:I_2:I_3:I_4 = (5.55 + 4.4j):(2.29 + 1.48j):1:1$.

Consequently, the pattern function of the array can be obtained as follows:

$$f(\theta) = \frac{\cos(\frac{\pi}{2}\sin \theta)}{\cos \theta} \left| e^{-j\frac{\pi}{2}\cos \theta} + \frac{2.29 + 1.48j}{5.55 + 4.4j} e^{-j\frac{\pi}{2}\cos \theta} + \frac{1}{5.55 + 4.4j} e^{j\frac{\pi}{2}\cos \theta} + \frac{1}{5.55 + 4.4j} e^{j\frac{\pi}{2}\cos \theta} \right|$$ (3)

In Equation (3), $\frac{\cos(\frac{\pi}{2}\sin \theta)}{\cos \theta}$ is the pattern of the dipole antenna, while the remaining part is the array pattern. Additionally, the gain pattern of the two-element end-fire dipole antenna array with two auxiliary dipole antennas in the H plane is as shown in Figure 7.

Figure 7. Gain pattern of the two-element end-fire dipole antenna array with 2 auxiliary dipole antennas in H plane.

3. Three End-Fire Dipole Antenna Arrays in Planar Technology

Figure 8a shows a typical two-element end-fire antenna array utilizing a half-wave dipole antenna as the elementary unit in planar Rogers 4350 PCB technologies. The thickness of Rogers 4350 is 0.245 mm.

![Figure 8a](image)

(a) An two-element end-fire antenna array utilizing a half-wave dipole antenna as the elementary unit, (b) the dimensions of the two-element end-fire antenna array, and the (c) top view, (d) bottom view and (e) side view of the antenna prototype.

Figure 8b shows the dimensions of the two-element end-fire antenna array utilizing half-wave dipoles as the elementary unit in planar PCB technology. $\lambda$ is the effective wavelength at 24 GHz. The antenna array is mainly composed of three half-wave dipoles (HWDP), as shown in Figure 8b, HWDP1, HWDP2, and HWDP3. HWDP1 and HWDP3 are the two array units and two main neighboring radiating dipoles, and comprise the two-element antenna array. The distance between HWDP1 and HWDP3 is half the effective...
wavelength. HWDP2 is an auxiliary dipole antenna unit which helps to increase the gain of the two-element end-fire antenna array. HWDP2 is in the middle of HWDP1 and HWDP3.

Figure 8c–e show a top view, bottom view and side view of the antenna array prototype. In Figure 8e, the side view, a Southwest 2.4 mm end launch connector 1492-04A-6 is included to show the size of the antenna prototype.

A two-element end-fire antenna array without auxiliary dipole antennas and with auxiliary dipole antennas at greater numbers such as two distributed evenly between HWDP1 and HWDP3 are also designed, simulated and measured. Figure 9 shows the top views of the two-element end-fire antenna arrays (a) without auxiliary dipole antennas and (b) with one auxiliary dipole antenna (c) or with two auxiliary dipole antennas in HFSS software. Table 1 shows the simulation results of the three different antenna arrays in Figure 9a–c. From Table 1, all of the three antenna arrays in Figure 9 work well, and their simulated gains are comparable with the same input impedance matching network. The simulation results verify the new and simple design method of an end-fire array. Due to the fabrication and measurement cost, at first, only the two-element dipole antenna array with one auxiliary dipole antenna is fabricated and measured. Additionally, later, the other two antenna arrays without auxiliary dipole antenna and with two auxiliary dipole antennas in Figure 9 are also fabricated and measured.

![Image](image.png)

**Figure 9.** Top view of the two-element end-fire antenna arrays (a) without an auxiliary dipole antenna and (b) with one auxiliary dipole antenna (c) or with two auxiliary dipole antennas in HFSS software. (d) Side view of the end-fire antenna prototype without an auxiliary dipole antenna; (e) side view of the end-fire antenna prototype with two auxiliary dipole antennas.

| Table 1. Performance comparison of HFSS simulation results of end-fire antenna arrays with the same input impedance matching network. |
|-----------------|-----------------|
| **S11 at 24 GHz (dB)** | **Antenna Gain_Sim (dBi)** |
| 2-element end-fire antenna without auxiliary dipole antenna | <−20 | 7.7 |
| 2-element end-fire antenna with 1 auxiliary dipole antenna | <−18 | 9 |
| 2-element end-fire antenna with 2 auxiliary dipole antennas | <−20 | 8.6 |

**4. Simulation and Measurement Results**

By modifying the parameters such as W1, W2, L1, d1, d2 and d3 and so on of the end-fire antenna array a little up and down around their calculated values, performance of the antenna is optimized.

After the optimization of the parameters of the end-fire antenna arrays, Figure 10a shows the simulation and measurement results of the S parameter of the two-element end-fire antenna array without auxiliary dipole antenna. The antenna array has a bandwidth
(S11 < −10 dB) of 0.9 GHz, extending from 23.7 to 24.6 GHz. Figure 10b,c show the simulated and measured antenna gain of two-element end-fire antenna array with no auxiliary dipole antenna. The measurement results agree with the simulation results. The antenna achieves 9.1 dBi maximum gain and a 43° half power width (from −16° to 27°) in the X–Y plane. In the X–Z plane, the antenna achieves 8.8 dBi maximum gain and a 59° half power width (from −27° to 32°). The measured cross polarization ratio is below −11 dB at 24 GHz.

Figure 11a shows the simulation and measurement results of the S parameter of the two-element end-fire antenna array with 1 auxiliary dipole antenna. The antenna array has a bandwidth (S11 < −10 dB) of 1.3 GHz, extending from 23.3 to 24.6 GHz. Figure 11b,c show the simulated and measured antenna gain of the two-element end-fire antenna array with one auxiliary dipole antenna. The antenna achieves 8.8 dBi maximum gain and a 56° half power width (from −35° to 21°) in the X–Y plane. In the X–Z plane, the antenna achieves 8.8 dBi maximum gain and a 65° half power width (from −37° to 28°). The measured antenna efficiency is 0.95. The measured cross polarization ratio is about −20 dB at 24 GHz.

![Figure 10](image-url)
Figure 10. Simulation and measurement results of the (a) S parameter, (b) gain in the X–Y plane, and (c) gain in the X–Z plane of the two-element end-fire antenna array with no auxiliary dipole antenna.

Figure 11. Cont.
Figure 11. Simulation and measurement results of the (a) S parameter, (b) gain in the X–Y plane, and (c) gain in the X–Z plane of the two-element end-fire antenna array with 1 auxiliary dipole antenna.

Figure 12a shows the simulation and measurement results of the S parameter of the two–element end-fire antenna array with two auxiliary dipole antennas. The antenna array has a bandwidth (S11 < −10 dB) of 0.6 GHz, extending from 24 to 24.6 GHz. Figure 12b,c show the simulated and measured antenna gain of the two-element end-fire antenna array with two auxiliary dipole antennas. The antenna achieves 9.9 dBi maximum gain and a 52° half power width (from −23° to 29°) in the X–Y plane. In the X–Z plane, the antenna achieves 9.9 dBi maximum gain and a 72° half power width (from −37° to 35°). The measured cross polarization is about −15 dB at 24 GHz.

In Figures 10 and 12, the measured gain of antenna arrays with no auxiliary dipole antenna or with two auxiliary dipole antennas is greater than the simulated gain, while in Figure 11, the simulated gain of the antenna array with one auxiliary dipole antenna is greater than the measured gain. This is because the three antenna arrays are fabricated and measured two times—the antenna with one auxiliary dipole antenna is measured first, while the remaining two antennas are measured second time. Additionally, there are errors in measurements at different times.

The far-field antenna measurement system mainly consists of a microwave anechoic chamber, a transmitting and receiving turntable, a vector network analyzer, measurement-related connection accessories, instrument control, data acquisition, data processing software and related auxiliary equipment and so on.

The amplitude phase synthesis method is mainly used to measure the antenna, which requires the devices of the whole RF link to maintain a stable phase. In this way, according to the collected amplitude and phase information, we can calculate the antenna pattern by algorithm. The test system is carried out according to the comparison method in the antenna standard test method “ANSI/IEEE Std 149-1979”. The gain of the antenna under test is obtained by comparing the antenna under test with the standard gain antenna. Specifically, the antenna gain is also obtained by dividing the method into two steps. The first step is called calibration, that is to measure the standard antenna; the second step is to measure the antenna under test, and calculate the gain of the antenna under test according to the data obtained from the two measurements. When measuring the standard gain antenna and the antenna under test, ensure that the antenna under test and the transmitting antenna are completely aligned, that is, to align the two antennas manually or automatically to make the measurement results correct.
Figure 12. Simulation and measurement results of the (a) S parameter, (b) gain in the X–Y plane, and (c) gain in the X–Z plane of the two-element end-fire antenna array with 2 auxiliary dipole antennas.

5. More Discussions on End-fire Antenna Array

Table 2 compares the three two-element end-fire antenna arrays with zero, one, or two auxiliary dipole antennas in this work with other end-fire dipole antenna arrays
in [9–13]. All of the antennas in [9–13] are end-fire dipole antenna arrays at around 24 GHz. Compared with the antennas in [9–13], the antenna arrays in this work have comparable gain or a little higher gain but have the same number of antenna units in the array, and are simpler in design. Compared with antenna arrays in this work, the antenna array in [9] has 5 substrate layers and 10 metal layers, and is much more complicated in its design to obtain the structure of the cavity to realize impedance matching. Compared with antennas in this work, the antenna in [10] utilizes an additional director to enhance the gain; nevertheless, its gain is comparable or a little smaller than antenna arrays in this work. Therefore, above all, this newly discovered simple design method for end-fire antenna design is characterized by high gain and simplicity in design (without matching networks), and is of some research value.

Table 2. Comparison with the state of the art.

| Number of Antenna Units | Freq (GHz) | Gain (dBi) | Topology |
|-------------------------|------------|------------|----------|
| [9]                     | 2          | 24         | 8.17     | Cavity-backed end-fire dipole antenna based on SISL technology |
| [10]                    | 2          | 24         | 6        | Wideband 5G end-fire elements with a pair of dipoles on liquid crystal polymer |
| [11]                    | 2          | 24         | 7.57     | Wideband CP end-fire Magnetoelectric dipole antenna |
| [12]                    | 2          | 24         | 6.9      | End-fire ME dipole antenna |
| [13]                    | 2          | 24         | 6.7      | ME dipole end-fire antenna |
| This work               | 2          | 24         | 9.1      | End-fire dipole antenna array with no auxiliary dipole antenna |
| This work               | 2          | 24         | 8.8      | End-fire dipole antenna array with 1 auxiliary dipole antenna |
| This work               | 2          | 24         | 9.9      | End-fire dipole antenna array with 2 auxiliary dipole antenna |

6. Conclusions

A new and simple design method for end-fire antenna design is suggested that means that, when antenna elements are \( \lambda/2 \) apart, a simple end-fire antenna array could be designed and constructed easily without matching networks between antenna elements, and three two-element end-fire dipole antenna arrays in planar technology which adopt the design method are presented. The two-element end-fire antenna array composed of half-wave dipole antenna elements is characterized by high gain, compactness and simplicity in design (without matching networks). The wavelength decreases with increasing frequency and this kind of antenna is also applicable for other frequency bands with planar PCB technology and on-chip planar mm-wave and THz antenna design. Additionally, the new and simple design method is also suitable for end-fire antenna array construction for other antenna topologies, such as patch antenna and so on.

7. Patents

A utility model patent was granted for this end-fire dipole array antenna topology, ZL 202022106332.1. An invention patent is currently being applied for this end-fire dipole array antenna.

Author Contributions: Conceptualization, Y.M.; methodology, Y.M.; software, Y.M.; validation, Y.M.; formal analysis, Y.M.; investigation, Y.M.; resources, S.E.; data curation, Y.M.; writing—original draft preparation, Y.M.; writing—review and editing, C.Z.; visualization, Y.M.; supervision, S.E.; project administration, S.E.; funding acquisition, Y.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Zhejiang Provincial Natural Science Foundation, grant number LQ17F040001 and State Key Lab of Millimeter Waves Open Project Fund, Southeast University, China, grant number K201817.

Institutional Review Board Statement: Not applicable.
Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to limited resources to make the data publicly accessible.

Acknowledgments: The authors are thankful for Key Laboratory of Antennas and Microwave Components of Xidian University, China for measurements.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References
1. Zhong, S. Antenna Theory and Techniques, 1st ed.; Publishing House of Electronic Industry: Beijing, China, 2011; p. 115.
2. Mei, S.; Qing, X.; Chen, Z.N. 60-GHz End-Fire Fan-Like Antennas with Wide Beamwidth. IEEE Trans. Antennas Propag. 2013, 61, 1616–1622.
3. Mohammad, M.S.T.; Abdolali, A.; Shuai, Z.; Gert, F.P. Integrated Millimeter-Wave Wideband End-Fire 5G Beam Steerable Array and Low-Frequency 4G LTE Antenna in Mobile Terminals. IEEE Trans. Veh. Technol. 2019, 68, 4042–4046.
4. Zhang, W.H.; Lu, W.J.; Tam, K.W. A Planar End-Fire Circularly Polarized Complementary Antenna with Beam in Parallel with Its Plane. IEEE Trans. Antennas Propag. 2016, 64, 1146–1152. [CrossRef]
5. Wu, J.; Zhao, Z.; Nie, Z.; Liu, Q.H. Bandwidth Enhancement of a Planar Printed Quasi-Yagi Antenna with Size Reduction. IEEE Trans. Antennas Propag. 2014, 62, 463–467. [CrossRef]
6. Kraus, J.D.; Marhefka, R.J. Antennas: For All Applications, 3rd ed.; Publishing House of Electronic Industry: Beijing, China, 2008.
7. David, M.P. Microwave Engineering, 4th ed.; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2011.
8. Yin, J.; Liu, K. Calculation of gain and patterns for series-fed microstrip arrays. J. Natl. Univ. Def. Technol. 2000, 22, 43–46.
9. Yun, H.; Ma, K. A cavity-backed end-fire dipole antenna using SISL technology for 24 GHz automotive anti-collision radar system. In Proceedings of the 2018 IEEE MTT-S International Wireless Symposium (IWS), Chengdu, China, 6–10 May 2018.
10. Rajveer Singh, B.; Rodney, G.V.; Mark, F. Phased Arrays and MIMO: Wideband 5G End Fire Elements on Liquid Crystal Polymer for MIMO. In Proceedings of the 2019 IEEE International Symposium on Phased Array System & Technology (PAST), Waltham, MA, USA, 15–18 October 2019.
11. Min, L.; Rong, W.; Yao, H.; Bo, W. A low-profile wideband CP end-fire magnetoelectric antenna using dual-mode resonances. IEEE Trans. Antennas Propag. 2019, 67, 4445–4452.
12. Li, A.; Luk, K.M. Millimeter-wave end-fire magneto-electric dipole antenna and arrays with asymmetrical substrate integrated coaxial line feed. IEEE Open J. Antennas Propag. 2021, 2, 62–71. [CrossRef]
13. Zeng, J.; Luk, K.M. Wideband Millimeter-Wave End-Fire Magnetoelectric Dipole Antenna with Microstrip-Line Feed. IEEE Trans. Antennas Propag. 2020, 68, 2658–2665. [CrossRef]