Communication

Narrow-Width Periodic Leaky-Wave Antenna Array for Endfire Radiation Based on Hansen–Woodyard Condition

Yuefeng Hou, Yue Li, Zhijun Zhang, and Zhenghe Feng

Abstract—**This communication presents a periodic leaky-wave antenna array with the advantages of a high endfire gain at the center frequency and a stable endfire radiation beam over the entire operating band. The antenna has a narrow width and consists of multiple monopoles located on the microstrip line. It can be fabricated by line-cutting copper strips. The antenna has a high endfire gain because it is a leaky-wave antenna designed based on the Hansen–Woodyard condition. With a length of 5.5λ_0 and a width of 0.33λ_0, a measured endfire gain of 12.9 dBi is achieved at the center frequency of 5 GHz. Good matching and stable endfire radiation beams are achieved over the entire operating band from 4.5 to 5.5 GHz. Good agreement between the measurement and the simulation has been obtained.**

Index Terms—**Endfire, Hansen–Woodyard condition, leaky-wave antenna array.**

I. Introduction

Endfire antennas mounted on a large conducting plane have received extensive attention because of their applications on the unmanned aerial vehicles, missile, and reconnaissance vehicles. In the past few years, researches have mainly focused on the realization of low-profile and wideband endfire antennas with the types of log-periodic [1], surface-wave [2], Yagi [3]–[6], and horn [7] antennas, and several well-studied designs are available in the open literature. For the log-periodic monopole antenna array in [1] and the surface-wave antenna in [2], only part of the aperture radiates the energy at one frequency point, which leads to a low endfire gain. Several Yagi antennas with different radiation elements are exhibited. In [3], a quasi-Yagi antenna consisting of eight monocones with low profile and wide bandwidth was reported. However, the radiation pattern was not exact endfire within part of bandwidth. In [4] and [5], slot Yagi–Uda arrays fed by the cavities were presented although the antennas were with narrow bandwidth because of their resonant nature. Yagi antenna based on microstrip magnetic dipole elements was introduced in [6]. The antenna has a quasi-endfire radiation pattern. However, the antenna was not suitable to be designed with a long structure, because the effect of director elements became weaker as the number of directors increased. In [7], a low-profile horn antenna was designed on a large conducting plane with a small aperture, but the beam pointed upward leading to a low endfire gain of about 5 dBi at the center frequency.

Although many researchers have made considerable efforts, it is still a tremendous challenge for endfire antenna to obtain high gain in the direction of endfire. The nonuniform energy distribution and incorrect phase constant of the traditional endfire antennas lead to a sloping-upward main-beam direction. Furthermore, the width of the traditional endfire antenna is large, which probably limits the application of the endfire antenna.

To improve the endfire gain with a narrow structure, periodic leaky-wave endfire antenna arrays are attractive substitutes for traditional endfire antenna. Compared with the other types of antennas, the periodic leaky-wave antenna arrays are more suitable to be designed with longer structure and relatively uniform aperture because each radiation element can radiate less energy [8]–[10]. Meanwhile, because the Hansen–Woodyard (H–W) antenna arrays can achieve the maximum directivity at endfire [11], the modified H–W condition has been applied for the design of the periodic leaky-wave antenna arrays [12], and the relevant theories have been acutely researched [13], [14]. However, in theory, for the periodic leaky-wave antenna array without taper, the uniform energy distribution on the aperture, which refers to one requirement of the H–W condition, corresponds to 0% radiation efficiency [13], which is not practical for application. Because, in the theoretical model, all of the energy radiated from the elements is only coupled by the feed structure leading to the actual energy distribution with the exponentially decaying distribution of the form $e^{-jk_z z}$ on the aperture [13]. $k_z = \beta - j\alpha$ is the complex longitudinal wavenumber. α and β are the attenuation constant (or leakage constant) and phase constant, respectively. That attenuation depicted by $j\alpha$ results in a lower directivity compared to the H–W antenna arrays.

In this communication, a periodic leaky-wave antenna array designed on the basis of the H–W condition is presented. It has the advantages of high endfire gain at the center frequency and stable endfire radiation beam over the entire operating band. The antenna has a narrow width of only $0.33\lambda_0$ and simple structure consisting of microstrip line and monopoles. Because the proposed antenna is a periodic leaky-wave antenna array, it can be designed with a longer structure, which is suitable to realize high endfire gain. Although the leakage constant is not 0, because the radiation elements have two paths to couple energy, the proposed antenna has almost uniform magnitude of electric-field (E-field) distribution on the monopoles, which would further improve the endfire gain. With the air substrate and periodic disturbance by the monopoles, the microstrip line can obtain a stable phase constant over the entire operating band, and the phase constant is similar to the requirement of H–W condition around the center frequency, thus achieving more stable endfire radiation beams by the proposed antenna compared with the antenna in [12]. Finally, a simple prototype with the length of $5.5\lambda_0$ is fabricated to verify the new design method.

II. Antenna Design and Analysis

The antenna array designed on the basis of the H–W condition can generate the maximum directional beam at endfire [11], theoretically. As for the H–W linear array with N radiation elements, all of the radiation elements are with the period of d and radiate the same value of power. The phase constant of the H–W antenna array is

Manuscript received December 1, 2017; revised July 19, 2018; accepted July 28, 2018. Date of publication August 8, 2018; date of current version October 29, 2018. This work was supported by the National Natural Science Foundation of China under Contract 61525104. *(Corresponding author: Zhijun Zhang.)*

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Digital Object Identifier 10.1109/TAP.2018.2864328

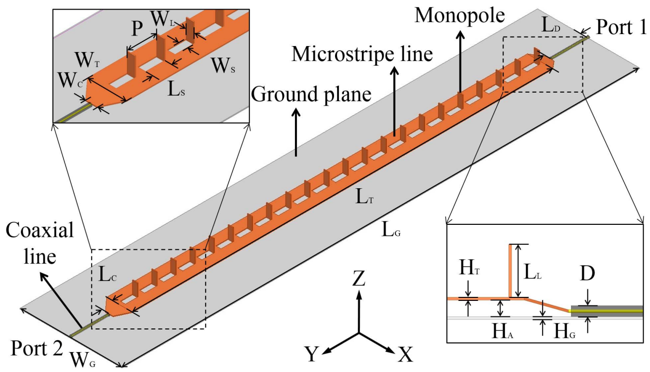

Fig. 1. Configuration of the proposed periodic leaky-wave antenna array.

TABLE I

DETAILED DIMENSION OF THE PROPOSED ANTENNA

Parameter	Value (mm)	Parameter	Value (mm)
L_G	406	W_G	80
L_T	330	W_T	20
L_D	29.5	W_L	4
L_L	9.5	W_S	4
L_S	9.5	W_C	6
L_C	8	H_A	3
P	15	H_G	0.5
D	2	H_T	0.5

presented in (1). β_0 is the propagation constant in free space, and β_h is the propagation constant of the H–W array. The following equation indicates that the phase constant inside the antenna (β_h) is larger than the one for free space (outside the antenna, β_0)

$$\beta_h = \beta_0 + \frac{2.94}{(N-1)\,d} \approx \beta_0 + \frac{\pi}{(N-1)\,d}. \tag{1}$$

Furthermore, if the backward radiation of endfire antenna array with discrete uniform aperture is negligible, the following equation is valid [15] and the period of the radiation elements is chosen as $d \approx \lambda_0/4$

$$d = \frac{\lambda}{4}\left(1 - \frac{2.94}{\pi N}\right) \approx \frac{\lambda}{4}. \tag{2}$$

According to the aforementioned analysis, to design an H–W antenna with discrete uniform aperture, the radiation elements should be arranged by the period of $\lambda_0/4$ and radiate the same energy with a special phase distribution.

To achieve a high endfire gain, the proposed antenna is designed based on the requirement of H–W condition. The configuration of the proposed antenna based on the H–W condition is illustrated in Fig. 1. The antenna consists of 22 monopoles with identical heights located on a microstrip line. The period of the monopoles is $\lambda_0/4$. The antenna has two coaxial lines as feeds. To mitigate the effect of the discontinuities between the microstrip line and the coaxial lines, tapered structures are added between them. The entire antenna is designed using 0.5 mm-thick line-cutting copper strips. In the fabrication, the model in the simulation process is used. Table I gives the detailed dimensions of the antenna.

In the proposed antenna, the energy propagates along the microstrip line. Because of the conical radiation pattern, monopoles are adopted as radiation elements in the proposed antenna to generate a good endfire radiation beam. When the height of the monopole meets the resonant condition, the maximum energy can be coupled from the microstrip line. Thus, the center frequency of the proposed antenna can be changed by modifying the height of the monopole. The width of the monopoles influences the coupling ability of the monopoles. By changing the width of the monopoles, the antenna can be designed with different lengths even as maintaining a high level of radiation efficiency.

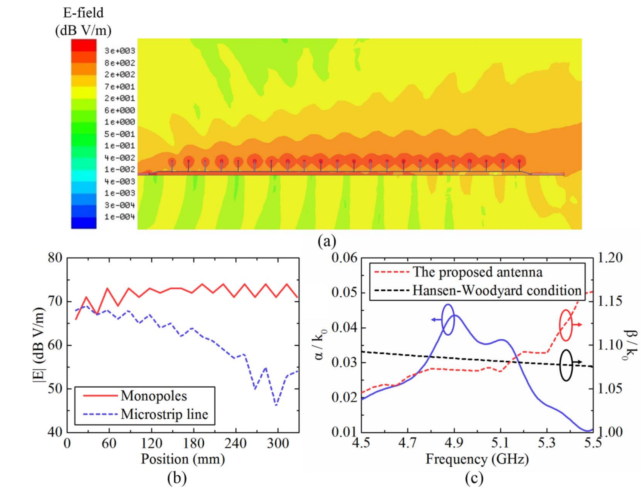

Fig. 2. Operating mechanism of the proposed antenna. (a) Magnitude of the E-field distribution in the yz plane. (b) Magnitude of the E-field distribution at the top of the monopoles and in the middle of the microstrip line at the center frequency of 5 GHz. (c) Normalized leakage constant of the proposed antenna, normalized phase constants of the proposed antenna, and the H–W conditions versus frequency.

From Fig. 2(a) and (b), it is found that the magnitude of the E-field distribution on the monopoles is almost uniform despite a gradual reduction in energy in the microstrip line at the center frequency of 5 GHz. The reason is that the monopoles form the radiated aperture of the antenna and they have two paths to couple energy. One path couples the energy from the microstrip line, and the energy gradually decreases along the propagation direction. The other path couples the energy from free space, which is similar to the Yagi antenna. Because each monopole radiates the energy coupled by the microstrip line and the energy propagates along the endfire direction, the energy is gradually gathered along the endfire direction in free space. Therefore, the monopoles far away from the feed port can couple more energy from free space. Combining the two paths of the energy, an almost uniform magnitude of the E-field distribution on the monopoles can be obtained by the antenna although obvious energy attenuation exists in the microstrip line. The normalized leakage constant of the proposed antenna is shown in Fig. 2(c). Because of the strong resonance of the monopoles around the center frequency, more energy in the microstrip line is coupled by the monopoles leading to higher leakage constants. Because the proposed antenna is with air substrate, the microstrip line works in the TEM mode. With periodic disturbance by the monopoles, the phase constant β_g in the microstrip line is slightly slower than the phase constant β_0 in free space [10]. By optimizing the dimensions of the monopoles, β_g has a small difference from the phase constant β_h of H–W condition, as shown in Fig. 2(c).

Fig. 3 presents the performance of the endfire gain and the radiation pattern of the proposed antenna with infinite ground plane. A monopole antenna array based on the H–W condition is designed for comparison. All of the monopole antennas have a height of 14 mm and width of 2 mm, and excited with the same amplitude. Meanwhile, the phase difference between two monopole antennas agrees with the

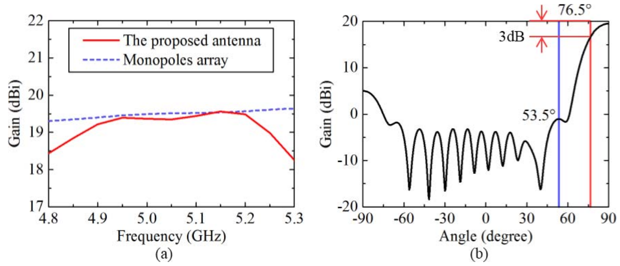

Fig. 3. Performance of the proposed antenna. (a) In the condition of infinite ground plane, the simulated endfire gain of the H–W monopole antenna array and the proposed antenna. (b) In the condition of infinite ground plane, the radiation pattern of the proposed antenna at the center frequency of 5 GHz.

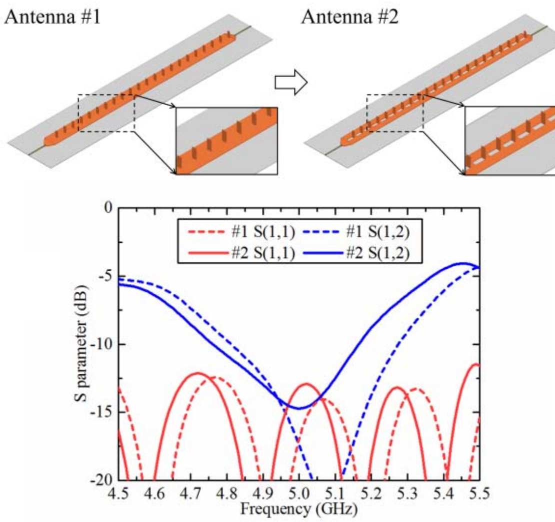

Fig. 4. Design procedure of the proposed antenna and the S-parameters of the proposed antenna with and without slots.

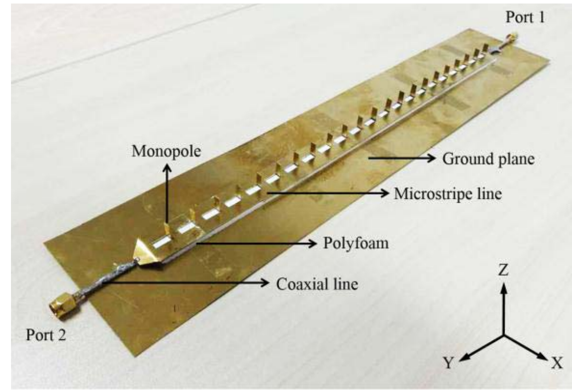

Fig. 5. Fabricated prototype of the proposed antenna.

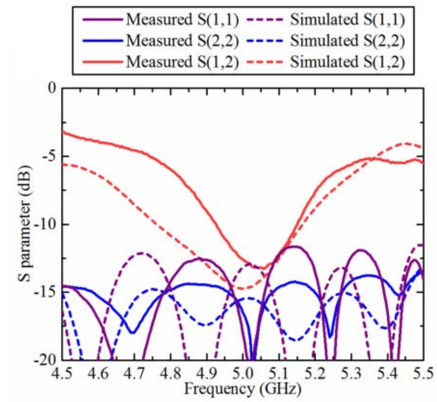

Fig. 6. Measured and simulated S-parameters of the proposed antenna.

H–W condition. To mitigate the ground effects, the monopole antenna array and the proposed antenna are simulated with infinite ground plane. The simulated endfire gain of the monopole antenna array and the proposed antenna are also shown in Fig. 3(a) for comparison. In the condition of infinite ground plane, only a small discrepancy between the endfire gains of the two antennas around the center frequency is seen. The radiation pattern of the proposed antenna with infinite ground plane is shown in Fig. 3(b). The theoretical radiation pattern performances of the H–W antenna arrays are introduced by Fuscaldo *et al.* [14] and Balanis [16]. For an H–W antenna array with the aperture length of 315 mm and the operating frequency of 5 GHz, based on the equations presented in [14] and [16], the half-power point and the first sidelobe point can be calculated as $\theta_h = 13.25^\circ$ and $\theta_{SL} = 35.24^\circ$, respectively. From the radiation pattern of the proposed antenna shown in Fig. 3(b), the half-power point is $\theta_h = 13.5^\circ$ and the first sidelobe point is $\theta = 36.5^\circ$. The results show that the beam performance of the proposed antenna is proximate to the H–W antenna array.

To simplify the fabrication, the proposed antenna is designed as #2 from #1, as presented in Fig. 4. The antenna can be fabricated from one piece of copper strip, and the monopoles can be realized by the bending part of the copper, which have been released by U-shaped slots. From the S-parameter shown in Fig. 4, the slots have slight influence on the performance of the antenna, which can be explained by two reasons. One of the reasons is that the electric current is small in the middle of the microstrip line because the H-field is stronger at the edge of the microstrip line. The other reason is that to meet the requirement of (2), the distance between the monopoles is $d = \lambda_0/4$, and the reflection from adjacent slots cancels each other around the center frequency. Therefore, a low reflection coefficient within a wide bandwidth is achieved by the proposed antenna.

III. Experimental Results

The proposed antenna has been simulated, fabricated, and measured. Geometry of the corresponding periodic leaky-wave antenna array is shown in Fig. 5. The entire antenna is designed by 0.5 mm-thick line-cutting copper strips. The antenna is excited at Port 1, and Port 2 is terminated with a match load. Reflection coefficient of the antenna is measured using a N5071B vector network analyzer (300–9 GHz); the gains and radiation patterns are measured in a far-field anechoic chamber.

Fig. 6 shows the comparison of the measured and simulated S-parameters, verifying that good matching is achieved in a band from 4.5 to 5.5 GHz. The slight difference between the reflection coefficients of Port 1 and Port 2 is mainly attributed to the asymmetric structure of the antenna. The low level of the transmission coefficient clearly indicates that most of the energy is radiated from the antenna. However, because of the resonance feature of the monopoles, the bandwidth of the proposed antenna is relatively narrow.

The comparison between the measured and simulated normalized radiation patterns of the E- and H-planes is illustrated in Fig. 7. To better evaluate the results, three scanned radiation patterns at 4.5, 5, and 5.5 GHz are chosen for presentation. Because of the existence of the finite ground plane, the radiation beam angles in the E-plane corresponding to the frequency points are about 25°, 22°, and 26° away from the endfire direction, respectively. The slight difference between the measured and simulation results around the back lobe is introduced from the shelter of the rotating platform. The deterioration of the sidelobes is mainly because of the fabrication error.

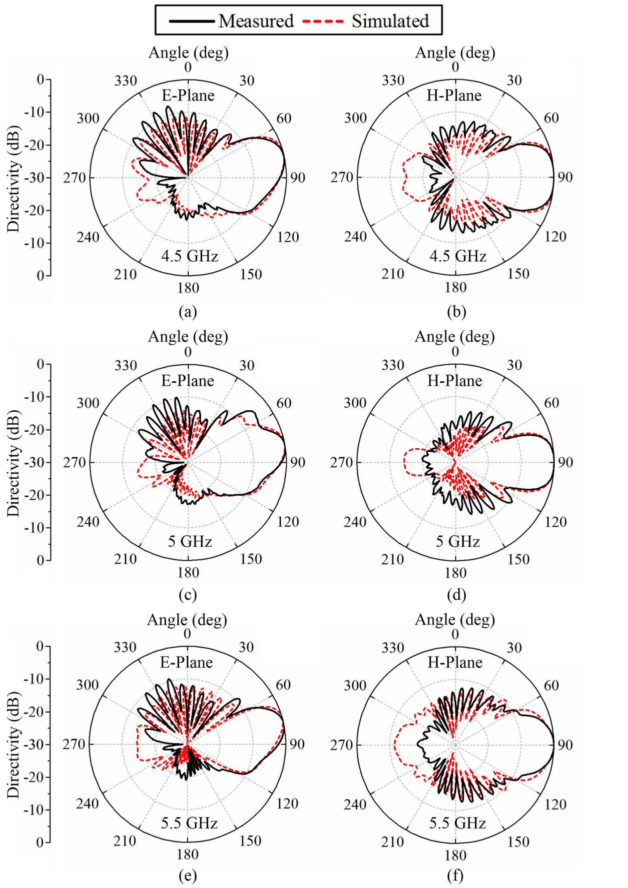

Fig. 7. Measured and simulated normalized radiation patterns of the proposed antenna at different frequencies. (a) 4.5 GHz, *yz* plane. (b) 4.5 GHz, *xy* plane. (c) 5 GHz, *yz* plane. (d) 5 GHz, *xy* plane. (e) 5.5 GHz, *yz* plane. (f) 5.5 GHz, *xy* plane.

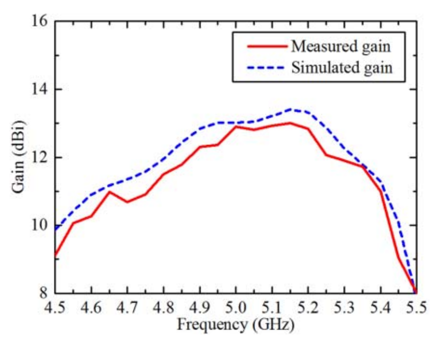

Fig. 8. Measured and simulated endfire gains for the proposed antenna.

TABLE II

COMPARISON AMONG THE PROPOSED ANTENNAS WITH ENDFIRE RADIATION

Reference	Length (λ_0)	Width (λ_0)	Height (λ_0)	Dielectric (ε_r)	Endfire Gain (dB)
[1]	3.52	0.88	0.125	2.2	4.5
[2]	1.93	2.16	0.150	1	-2
[3]	1.42	1.18	0.059	1.05	2.5
[4]	1.80	1.33	0.051	2.1	4.8
[5]	2.73	1.02	0.027	2.33	7.8
[6]	2.85	2.24	0.130	2.2	5
[7]	3.20	1.16	0.120	25	2.5
Our Work	5.50	0.33	0.217	1	12.9

Fig. 8 shows the measured and simulated endfire gains of the antenna. The measured endfire gain of the proposed antenna is better than 8 dBi over the operating band with a maximum value of 13.3 dBi at 5.15 GHz. The measured 1 and 3 dB gain bandwidths can reach 8% and 17%, respectively. Good agreement between the measurement and the simulation has been obtained.

Table II shows a comparison between existing designs in the literature and our design. λ_0 is the wavelength in free space at the center frequency, and ε_r is the dielectric constant of the material filling the antenna. It is clearly seen that our design provides a narrower width and longer structure, and a relatively higher endfire gain among all these endfire antennas, which can be mounted on a large conducting plane.

IV. CONCLUSION

This communication proposes an endfire antenna with narrow-width structure to realize a high endfire gain. The proposed antenna is a periodic leaky-wave antenna array designed on the basis of the H–W condition. Thus, a high endfire gain is achieved by the proposed antenna. Because of the simple structure composed of monopoles and a microstrip line, the antenna can be fabricated by line-cutting copper strips. With the length of $5.5\lambda_0$, the antenna achieves a measured endfire gain of 12.9 dBi at the center frequency of 5 GHz. Good matching and stable endfire radiation beams are achieved over the entire operating band from 4.5 to 5.5 GHz.

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