A Broadband Antenna Array Using Full-Wave Dipole

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ABSTRACT This work introduces a bandwidth broadening technique for full-wave dipole (FWD) antennas and arrays, which are realized by introducing gaps in both two arms of the dipole. Several parameters are analyzed to illustrate the change of input impedance of the proposed FWD and the moving of resonant modes. The proposed FWD array antenna shows advantages in terms of impedance bandwidth, 3-dB gain bandwidth and the complexity of the feeding network, when the four-unit FWD array antenna compares with the eight-unit half-wave dipole array antenna. The impedance bandwidth of the proposed FWD array antenna is up to 67.8% with the reflection coefficient $<-10$ dB from 3.9 to 7.9 GHz. The 3-dB gain bandwidth of the proposed antenna array is 51.4% with the maximum gain of 14.2 dBi and unidirectional radiation property across the entire operating bandwidth. The proposed methodology is good for a high-gain antenna array design through the reduction of antenna elements so as to minimize the complexity of power distributed network to the array. The ultimate goal of this work is to devote a low-cost and high-efficiency antenna array to broadband wireless communication systems.

INDEX TERMS Broadband, antenna array, full-wave dipole, unidirectional.

I. INTRODUCTION

Antenna arrays have been widely used in different communication systems nowadays. In base station of mobile communications [1], [2], high gain antenna arrays are able to cover a wide and long coverage. Due to the large attenuation in wave propagation of the millimeter-wave frequency, array configurations are a good method to establish a reliable communication link [3]–[6]. In the field of wireless energy harvest [7]–[10], the antenna array can absorb more EM energy in ambient environment than a single antenna due to a larger radiating aperture of the array.

Broadband antennas are also very popular in wireless communications because of the necessity of high data-rate transmissions. They can be applied to different communication standards and can reduce the cost and the space in the development of a wireless network owing to the advantage of multiple bands covered by the broadband antenna. A lot of researches have been demonstrated wideband antenna designs [11]–[18]. In [11]–[13], a parasitic element was closely placed to the radiating element, which adds another resonant mode in the operating band. Patch antennas with an L-shaped probe was proposed in [14] and [15] for bandwidth enhancement. In [16], the transmission line for an impedance conversion was placed between the antenna and the feeding port to realize the wide bandwidth. Using the tapered-shape antennas [17]–[19] are also an effective way to increase the bandwidth of the antenna.

The traditional half-wave dipole (HWD) is the most simple and the most popular antenna. Lots of antennas are designed based on the HWD. In this work, we propose to use full-wave dipole (FWD) elements to achieve a broadband antenna array. It is well known that the FWD has a higher gain than the HWD, which is due to the electrically large size of the FWD. However, the conventional FWD may have impedance mismatching when it is used for building up as an antenna array. In this work, we will demonstrate how to control a
good impedance matching for the FWD by introducing a gap transforming technique to the dipole arms. After that, we will exhibit a four-unit antenna array based on the FWD to be developed. The FWD array antenna has half the number of antenna elements than the HWD array antenna under the condition of same antenna gain. The complexity of the feeding network would thus also be reduced by decreasing the numbers of the antenna elements.

When dipole arms changes from half to full wavelength, the reactance of a FWD has a larger value, which makes it difficult to be matched at 50 Ω. To address this problem, we do an intensive analysis and comparison of the FWD and the HWD antenna, we find that the FWD antenna has obvious advantages in terms of the higher antenna gain and the less complexity of feeding network when compares with traditional the HWD array antenna. Thus, our work would excite antenna designers to explore a new low-cost and high-gain antenna with a simple feeding network based on the proposed FWD.

### II. GEOMETRICAL STRUCTURE OF THE PROPOSED ANTENNA ARRAY

The geometry of the proposed four-unit FWD antenna array is depicted in Fig. 1. The antenna unit is a nonuniform dipole with gaps in both arms. The dipole is printed on a dielectric substrate with a permittivity of 2.55 and a thickness of 0.8 mm. The left arm of the dipole is on the top of the substrate when the right arm is on the bottom. The length of the dipole is close to one wavelength at the center frequency. We use the parallel strip line to feed the antenna units, so the antenna array and feeding network can be fabricated in the same substrate. The characteristic impedance of two segments of the parallel strip lines are 200 Ω and 100 Ω, respectively. The outer conductor of the coaxial cable is connected to the bottom of the parallel strip line. The inner conductor is connected to the top of the parallel strip line. A metal reflector is placed under the antenna array to achieve a unidirectional radiation. All the physical dimensions of this four–unit FWD array antenna are numerically determined and they are tabulated in Table 1.

### III. ANALYSIS OF THE PROPOSED FWD UNIT

#### A. IMPEDANCE MATCHING

Figure 2 shows the structure of three types of dipoles. Both traditional dipole and the dipole with gaps have same overall antenna length of 50 mm and a feeding line width of 1.5 mm. The length of proposed FWD antenna is the same as the other two dipoles, but its width is stepped. The input impedance of the antenna unit in our design is 200 Ω. The 200 Ω is transformed to 50 Ω after four shunt connected antenna units, which enables the four elements array to match with 50 Ω feeding line easily. We studied the reflection coefficients of these three type of single element dipoles by assuming the impedance of the feeding port was perfectly matched to 200 Ω.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{d1}$</td>
<td>8.5 mm</td>
</tr>
<tr>
<td>$L_{d2}$</td>
<td>15 mm</td>
</tr>
<tr>
<td>$W_{d1}$</td>
<td>1.5 mm</td>
</tr>
<tr>
<td>$W_{d2}$</td>
<td>5 mm</td>
</tr>
<tr>
<td>$g$</td>
<td>0.7 mm</td>
</tr>
<tr>
<td>$L_r$</td>
<td>1 mm</td>
</tr>
<tr>
<td>$d_1$</td>
<td>60 mm</td>
</tr>
<tr>
<td>$d_2$</td>
<td>30 mm</td>
</tr>
<tr>
<td>$H$</td>
<td>13 mm</td>
</tr>
<tr>
<td>$X_r$</td>
<td>160 mm</td>
</tr>
<tr>
<td>$Y_r$</td>
<td>100 mm</td>
</tr>
</tbody>
</table>
when the resonant mode in high frequency has only slightly changed. The change of impedance in low frequency is more significant than the impedance change in high frequency. Two resonant modes of the dipole are close to each other after introducing the gaps, e.g. 5.5 and 8.0 GHz. The reason is that the gap cuts off the flow of current and store the electric field energy, it is equivalent to a capacitor. According to the reactance formula: \(1/j\omega C\), the reactance of the capacitor is larger in low frequency than in high frequency. It is well-known that high reactance will cause attenuation and low reactance will cause transmission. That is why the gap has a significant effect on the impedance matching of the dipole in low frequency.

The reactance of the traditional uniform dipole is closed to zero in half-wave region as shown in the shaded region in Fig. 4, which makes it easy for impedance matching. However, it is unable to radiate in full-wave region. In full-wave region, the reactance is too large, e.g. larger than 200 \(\Omega\). This will cause difficulty of impedance matching with a standard 50 \(\Omega\) port. This is also the reason why the HWD is commonly used and the FWD is rare used by antenna engineers.

In Fig. 4, the dipole with gaps has a small reactance in full-wave region and large reactance in half-wave region. This makes the dipole with gaps be more applicable to be used as a FWD. In full-wave region, the uniform dipole with gaps has a real part around 100 \(\Omega\) and an imaginary part around 0 \(\Omega\), so it is very suitable to match with a 100 \(\Omega\) feeding port. The proposed stepped dipole has the real part around 200 \(\Omega\) and the imaginary part around 0 \(\Omega\), so its impedance matching is the best among three dipoles if the feeding port is set to 200 \(\Omega\). If a four-unit FWD with 200 \(\Omega\) is designed and shunt connected as shown in Fig. 1, the FWD array antenna can be matched to a standard 50 \(\Omega\) port very easily.

The width of the gap has effect on the coupling between two segments of the dipole. It has impact to the input impedance of the dipole. Figure 5 depicts the input impedance of the proposed dipole with different gaps \(g\). When the width of the gap is reduced, the coupling becomes stronger. The equivalent capacitance of the gap increases. According to the well-known resonance equation below,

\[
f = \frac{1}{2\pi \sqrt{LC}}
\]

the resonant frequency of the FWD antenna will decrease due to the rise of the equivalent capacitor. From the Fig. 5, we can see the first peak of the real part moves toward low frequency as the \(g\) decreases. In high frequency, e.g. 8 GHz, the reactance of the equivalent capacitor is too small to affect the resonance frequency. In Fig. 5, the position of the high frequency resonant mode remains almost the same.

Figure 6 analyzes the change of the input impedance of the FWD dipole under different \(W_{d2}\). In the case of \(W_{d2} = 1.5 \text{ mm}\), the dipole is a uniform dipole. The variation of
FIGURE 6. Simulated input impedances the proposed FWD dipole under different $W_d^2$. (a) real part, (b) imaginary part.

real part around 200 $\Omega$ is so large that the broad impedance matching cannot be achieved. As $W_d^2$ increases, the real and imaginary parts become flattened since the wider dipole arms can provide more current paths. The increase of $W_d^2$ also increases the reactance value, which makes two resonant modes move towards low frequency.

B. CURRENT DISTRIBUTION

Figure 7 depicts the electric current distribution on the metallic surface of the proposed FWD antenna at different frequencies in the operating band of radiation. The gaps of the FWD have no significant influence on the direction of the current, so the current distribution of the proposed FWD is similar to the traditional FWD. The length of FWD is larger than a wavelength in high frequency, e.g. 7 GHz. The opposite current appears in the antenna, which causes the distortion of the radiation pattern and lower the antenna gain.

IV. COMPARISON OF THE FWD AND HWD ARRAY ANTENNA

The proposed FWD has obvious advantages, when it is used in array antenna. In this part, we compare the gain and reflection coefficient of the FWD array antenna and the HWD array antenna.

Figure 8 shows the geometry of a binary HWD array and the proposed single FWD antenna. Supposing they are perfectly matched in simulated frequency range. Their gains in H-plane are depicted in Fig. 9. The gain of the proposed FWD decreases quickly when the frequency is over 6.5 GHz. An antiphase current is generated in the proposed FWD antenna when its length is over a wavelength of the operating frequency as discussed in Fig. 7. From 5 to 6.5 GHz, the gain of the proposed FWD is very close to the binary HWD array antenna. It suggests that we can achieve the similar gain of a binary HWD array antenna by using just one FWD antenna unit in this frequency range. The advantage of using the proposed FWD is that the feeding network is half of the binary array HWD.
We build an eight-unit HWD array to compare its gain by adding the feeding network and matching the impedance to 50 Ω, as the Fig. 10 shows. The total length and width of the radiation units are the same as the proposed four-unit FWD array. The height of the antenna array and the size of the reflector is also the same as the proposed FWD array. In Fig. 10, we can see that the feeding network of the HWD array is more complicated. The numbers of segments are more than the proposed FWD array. The additional feeding segments will deteriorate the antenna efficiency, increase the antenna design complexity and also affect the operation bandwidth of the antenna array. Several transmission lines are needed to transform the impedance from 50 Ω to 100 Ω. The length of the impedance transformation line is 10.5 mm corresponding to the quarter wavelength of 4.5 GHz with respected to the operation frequency of the dipole.

Figures 11 and 12 plot the gain and reflection coefficient of the HWD antenna array and the proposed FWD antenna array. The proposed FWD antenna array has relative wide-band antenna gain from 4 GHz up to 6.5 GHz. While the HWD antenna array has a large variation of antenna gain from 4 to 6 GHz. Particularly, the gain drops from 13 dBi to below 9 dBi at the frequency from 4.65 to 5.75 GHz. The comparison results are listed in Table 2. The advantage of the proposed FWD array is obvious both in impedance and gain bandwidths under the condition of same overall circuit size. The maximum antenna gain (14.51 dBi) in four-unit FWD array is even higher than the gain (13.85 dBi) in eight-unit HWD array. Moreover, the proposed FWD array can achieve a broad impedance bandwidth up to 70% (3.6-7.54 GHz) with reflection coefficient <-10 dB, which is more than nine times of the eight-unit HWD array. The 3-dB gain bandwidth of the proposed array is 51.4% from 3.9 GHz to 6.6 GHz, which is also much larger than the eight-unit HWD array. The operating frequency of the HWD unit is at 4.5 GHz, but several parasitic bands appear in high frequency of the HWD array as shown in Fig. 12. It implies that the impedance transformation line has an influence to the wideband impedance matching and thus affects the reflection coefficient. Since the single FWD unit has 200 Ω input impedance, a shunt connection with four FWD antennas will automatically match to a 50 Ω feeding line. Thus in our proposed FWD array antenna, we do not need to introduce an impedance transformer. The input impedance of the transmission line at the
dividing junction is half impedance value of the divided lines. In this way, all the junctions will automatically match when the input impedance is divided by half at the junction as shown in Fig. 1(a). This makes the feeding network simple and easy to design, when compares with the feeding network in the HWD array antenna in Fig. 10(a). Moreover, the feeding network of the FWD has little impact on the wideband impedance matching. As the Fig. 12 shows, the reflection coefficient of the proposed FWD array antenna is similar to the reflection coefficient of the proposed single FWD unit in Fig. 3, in which an ideal matched port is used without feeding network. This implies that the feeding network of the FWD is almost same as an ideal matched feeding port.

V. SIMULATED AND MEASURED RESULTS
To validate the predicted performance of this proposed four-unit FWD antenna array, a prototype antenna was fabricated and measured. Figure 13 shows the photography of the fabricated antenna. Simulated results, including reflection coefficients, radiation patterns and gains, are numerically derived by using the CST studio, a commercial EM software. Measurements on the fabricated antenna were carried out by using the Agilent N5230A Network Analyzer and Satimo Antenna Measurement System. The detailed results are provided in the following for comparative study.

Fig. 14 depicts the simulated and measured reflection coefficients of the designed antenna. The measured impedance bandwidth achieved are 67.8% (3.9-7.9 GHz) under reflection coefficient $<-10$ dB. The operating frequency band in measured result slightly shifts to high frequency due to the
misalignment of the top and bottom in fabrication, but the bandwidth is still cover a wide frequency band.

The gains of the proposed FWD antenna array are measured and the results are plotted in Fig. 15. The measured and simulated results are reasonably matched with each other. The curve of measured gains has some fluctuations but the trend is consistent with the simulated gains.

Fig. 16 describes the simulated and measured radiation patterns at three discrete frequencies of 4, 5 and 6 GHz. A unidirectional radiation pattern is observed. The measured cross-polarization levels in E-plane and H-plane are below $-23$ dB and $-18$ dB, respectively. The simulated cross-polarization levels of E-plane are so small that we are unable to see it in the figure. The side lobe levels of the proposed FWD array are higher than conventional HWD array since the opposite current is more significant in FWD array.

VI. CONCLUSION

In this work, a FWD antenna array with wide impedance and gain bandwidths was presented. The introduction of gaps and the parallel connection of four FWD units is effective to solve the problem of wideband impedance matching of FWD array. Through comparison with eight-unit HWD array antenna of the same circuit size, we confirmed that the proposed FWD array receives obvious advantages in terms of the impedance bandwidth, the antenna gain bandwidth and the simplicity of the feeding network. Like the HWD, the FWD is also able to be transformed to other kind of antennas after modification. Therefore, this work can be applied to other FWD-type antenna arrays with simple feeding network.

REFERENCES


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