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On Conditions for Constant Radiation Characteristics for Log-Periodic Array Antennas

Jian Yang

***Abstract*—Wide frequency band antenna systems are required for many now and future applications, such as in radio astronomy and ultrawideband (UWB) technology. Constant radiation characteristics over a decade bandwidth are required for some of wide band applications, for example, feeds for reflector antennas in radio telescope. The log-periodic array antenna is one of the technologies for wideband antennas. In the present paper, an analysis on condition for constant radiation characteristics over wide bandwidth for a log-periodic array antenna is presented. From this condition, a guide rule for designing a wideband log-periodic array antenna is obtained. The Eleven antenna, a decade bandwidth log-periodic array antenna, is selected to illustrate the condition and verify the analysis in the paper.**

***Index Terms*—Constant radiation characteristics, Eleven antenna, log-periodic antenna, wideband antenna.**

I. Introduction

MANY applications require wideband or ultrawideband (UWB) antennas, such as in radio astronomy and in UWB communication or radar systems [1], [2]. Therefore, there has been extensive research on multi-octave bandwidth antennas; here we only reference representative selected works in the literature [3]–[5]. The radio astronomy applications are mainly the SKA project (SKA = Square Kilometer Array) and the VLBI2010 project (VLBI = Very Long Baseline Interferometry). Both these two projects have reflector antennas as candidates which should cover frequency band of 1–13 GHz or even higher frequency band, whereas the UWB systems require small direct radiating antennas covering typically 3–10 GHz. The requirements for radio astronomy applications are quite different from that for UWB systems. For example, it is very important in radio telescope to have a feed for a reflector antenna with constant radiation characteristics over a more-than-one-decade bandwidth.

A new technology for achieving decade bandwidth antennas with constant radiation characteristics has been developed these years at Chalmers University of Technology, which is referred to as the Eleven antenna [6]–[13]. The Eleven antenna is a cascaded log-periodic folded dipole array. The log-periodic dipole array has been widely used since it was introduced 50 years ago [14]–[16]. Folded dipoles are often used for cascading log-periodic array [17]–[19]. The Eleven antenna, which consists of pairs of parallel folded dipoles located above a ground plane, has very good features: the nearly constant beamwidth with 11 dBi directivity, almost fixed phase center location over the whole bandwidth, low profile and simple geometry.

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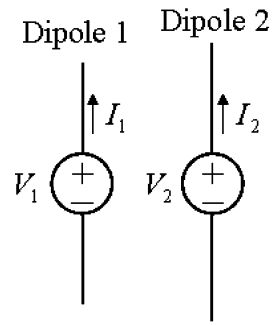

Fig. 1. Two-element log-periodic array antenna.

The purpose of this paper is to find the condition for having constant radiation characteristics for a general log-periodic array antenna. Therefore, a guide rule for designing a wideband log-periodic array with constant radiation performance is obtained.

In the paper, the theoretical derivation of the condition for having constant radiation characteristics for a general log-periodic array is presented first in Section II. Then, the condition for a cascaded log-periodic array is derived in Section III. Two examples are presented in Section IV with simulated and measured data for the sake of verifying the theoretical analysis. The reason that the Eleven antenna has constant radiation characteristics will be well explained and demonstrated in the paper.

II. Condition for Constant Radiation Characteristics

Without losing generality, we use a dipole as a symbol for a radiating element or a group of elements in a log-periodic array in our analysis model. First, we look at a two-element log-periodic array as shown in Fig. 1. We assume that $G(\theta, \varphi)$ is the radiation function of dipole 1 alone in free space at frequency f_1. Dipole 2 is a dipole scaled from dipole 1 with a scaling factor of k. Therefore, the radiation function of dipole 2 alone in free space at frequency $f_2 = f_1/k$ is also $G(\theta, \varphi)$. The equivalent circuit of this two-element log-periodic array is shown in Fig. 2. If we require the radiation function of this array kept the same as $G(\theta, \varphi)$ at f_1, the current I_2 must vanish at f_1, i.e.

$$V_2(f_1) + Z_{12}(f_1)I_1(f_1) = 0. \quad (1)$$

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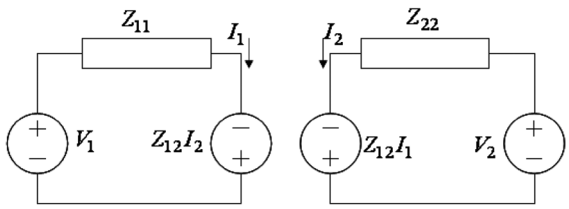

Fig. 2. Equivalent circuit of two-element log-periodic array.

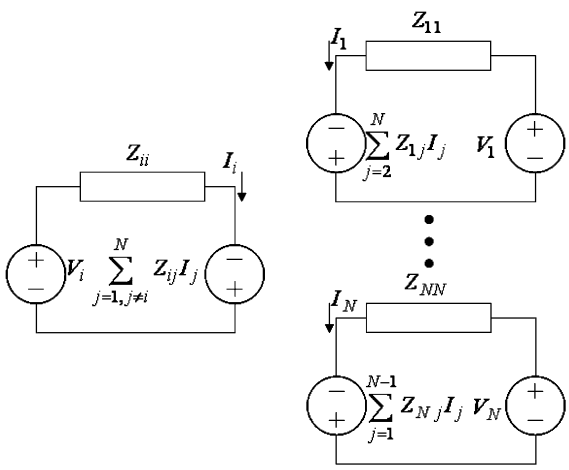

Fig. 3. Equivalent circuit of N-element log-periodic array.

With $I_2 = 0$, from Fig. 2 we can obtain

$$I_1(f_1) = \frac{V_1(f_1)}{Z_{11}(f_1)}. \tag{2}$$

From (1) and (2), we have

$$\frac{V_2(f_1)}{V_1(f_1)} = -\frac{Z_{12}(f_1)}{Z_{11}(f_1)}. \tag{3}$$

Similarly, the requirement for the array having the radiation function of $G(\theta, \varphi)$ at f_2 is

$$\frac{V_1(f_2)}{V_2(f_2)} = -\frac{Z_{12}(f_2)}{Z_{22}(f_2)}. \tag{4}$$

For N-element log-periodic array with a scaling factor k (dipole i is a dipole scaled from dipole 1 with a scaling factor k^{i-1}), we can use the equivalent circuit as shown in Fig. 3. The radiation function is required to keep the same as $G(\theta, \varphi)$ at frequencies $f_1, f_2 = f_1/k, \ldots, f_N = f_1/k^{N-1}$. By the similar procedure and reasoning as in the two-element array, we can see that at $f_i = f_1/k^{i-1}$, currents on all dipoles except for dipole i should vanish, i.e.

$$\mathbf{V}(f_i) + \mathbf{Z}_{ji}(f_i)I_i(f_i) + \mathbf{Z}(f_i)\mathbf{I}(f_i) = 0 \tag{5}$$

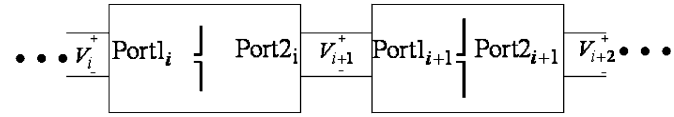

Fig. 4. Cascaded log-periodic array.

where

$$\mathbf{V} = \begin{bmatrix} V_1 \\ \vdots \\ V_{i-1} \\ V_{i+1} \\ \vdots \\ V_N \end{bmatrix}, \mathbf{Z}_{ji} = \begin{bmatrix} Z_{1,i} \\ \vdots \\ Z_{i-1,i} \\ Z_{i+1,i} \\ \vdots \\ Z_{N,i} \end{bmatrix}, \mathbf{I} = \begin{bmatrix} I_1 \\ \vdots \\ I_{i-1} \\ I_{i+1} \\ \vdots \\ I_N \end{bmatrix}$$

$$\mathbf{Z} = \begin{bmatrix} 0 & \cdots & Z_{1,i-1} & Z_{1,i+1} & \cdots & Z_{1,N} \\ Z_{21} & \cdots & Z_{2,i-1} & Z_{2,i+1} & \cdots & Z_{2,N} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ Z_{i-1,1} & \cdots & 0 & Z_{i-1,i+1} & \cdots & Z_{i-1,N} \\ Z_{i+1,1} & \cdots & Z_{i+1,i-1} & 0 & \cdots & Z_{i+1,N} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ Z_{N,1} & \cdots & Z_{N,i-1} & Z_{N,i+1} & \cdots & 0 \end{bmatrix}$$

$\mathbf{V}$ is the excitations on all dipoles except dipole i; $\mathbf{Z}_{ji}$ is the mutual impedance between dipole i and all other dipoles; $\mathbf{I}$ is the currents on all dipoles except dipole i; $\mathbf{Z}$ is the mutual impedance matrix among all dipoles except for dipole i; I_i is the current on dipole i. From (5), because $\det(\mathbf{Z}) \neq 0$, if we let

$$\mathbf{V}(f_i) + \mathbf{Z}_{ji}(f_i)I_i(f_i) = 0 \tag{6}$$

then, $\mathbf{I} = 0$. This means the currents on all dipoles except dipole i vanish. Therefore, the total radiation function of the array will be the same as $G(\theta, \varphi)$ at f_i. Because $\mathbf{I} = 0$, the induced voltage source for dipole i due to the mutual couplings is zero, i.e., $\sum_{j=1,j\neq i}^{n} Z_{ij}I_j = 0$. So we obtain from Fig. 3

$$I_i(f_i) = \frac{V_i(f_i)}{Z_{ii}(f_i)}. \tag{7}$$

Thus, from (6) and (7), the condition for constant radiation characteristics can be written as

$$\frac{V_j(f_i)}{V_i(f_i)} = -\frac{Z_{ij}(f_i)}{Z_{ii}(f_i)}, j = 1, \cdots, i-1, i+1, \cdots, N. \tag{8}$$

This means that when the above condition is satisfied, the voltage source from the feeding network and the voltage source due to the mutual couplings on all dipoles except dipole i are in the same amplitude but 180° out of phase at frequency f_i $(i = 1, 2, \cdots, N)$, which leads to currents on all dipoles except dipole i to vanish. Therefore, the radiation function of this array will be constant as $G(\theta, \varphi)$ at frequency f_i $(i = 1, 2, \cdots, N)$.

III. Cascaded Log-Periodic Array

For practical reasons, it is common to build up log-periodic array by cascading the elements one after another instead of using very complicated feeding network, see Fig. 4 where we use a symbol of a dipole to present the radiating network. We

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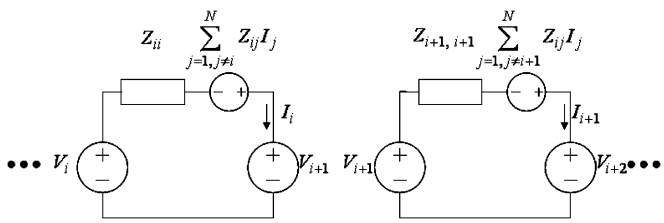

Fig. 5. Equivalent circuit of cascaded log-periodic array.

can use the equivalent circuit shown in Fig. 5 for a general cascaded log-periodic array, where Z_{ii} is the input impedance of radiating element i when the output port is shorted ($V_{i+1} = 0$) and all other radiating elements do not exist ($Z_{ij} = 0$ for all j but not $j = i$), and Z_{ij} is the mutual impedance among the radiating elements. Now comparing the equivalent circuit for a cascaded log-periodic array in Fig. 5 with the one for a general case in Fig. 3, we can see that $V_i(f_i)$ and $V_j(f_i)$ in (8) should be replaced by $V_i(f_i) - V_{i+1}(f_i)$ and $V_j(f_i) - V_{j+1}(f_i)$, respectively, for a cascaded log-periodic array. The mutual couplings among neighboring elements are much stronger than those among elements far apart. Therefore, it is important to look at neighboring radiating elements which are cascaded one after another. Then, we have the condition for having a constant radiation performance as

$$\frac{V_{i+1}(f_i) - V_{i+2}(f_i)}{V_i(f_i) - V_{i+1}(f_i)} = -\frac{Z_{i,i+1}(f_i)}{Z_{ii}(f_i)}. \tag{9}$$

We can use an ABCD matrix to describe the cascaded network in a log-periodic array as

$$\begin{bmatrix} V_{i+1} \\ I_{i+1} \end{bmatrix} = \begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix} \begin{bmatrix} V_i \\ I_i \end{bmatrix} \tag{10}$$

Then, the condition for constant radiation performance becomes

$$\frac{[A_{i+1}(f_i) - 1]\, A_i(f_i)}{A_i(f_i) - 1} = -\frac{Z_{i,i+1}(f_i)}{Z_{ii}(f_i)}. \tag{11}$$

We can also use S parameters to express the above condition by converting the ABCD matrix to an S matrix, though it is a bit complicated. For the ideal case where $S_{11,i} = S_{22,i} = 0$, we have

$$\frac{[1 - S_{21,i+1}(f_i)]^2}{2S_{21,i+1}(f_i)} \cdot \frac{1 + S_{21,i}(f_i)}{1 - S_{21,i}(f_i)} = -\frac{Z_{i,i+1}(f_i)}{Z_{ii}(f_i)} \tag{12}$$

where $S_{21,i}$ means S parameter from port 1 to port 2 in dipole i.

Now we can obtain a guide rule for designing a cascaded log-periodic array with constant radiation characteristics. The configuration of a cascaded log-periodic array should be designed in such a way that the A or S parameters satisfy (11) or (12), respectively, as much as possible. The smaller the difference between the right side and the left side in (11) or (12), the more constant the radiation characteristics. We assume here that the scaling factor k is close to 1, i.e., $0.7 \leq k \leq 1.3$, which is true for most cases. Thus, the spacing between the neighboring elements is small and the angle of $Z_{i,i+1}(f_i)/Z_{i,i}(f_i)$ is close to 0°, and also $S_{21,i+1}(f_i) \approx S_{21,i}(f_i)$. It can be also assumed that $S_{21,i}(f_i) \ll 1$ due to the radiation from dipole i. For the left side of (12), these assumptions yield

$$\frac{[1 - S_{21,i+1}(f_i)]^2}{2S_{21,i+1}(f_i)} \cdot \frac{1 + S_{21,i}(f_i)}{1 - S_{21,i}(f_i)} \approx \frac{1 - S_{21,i}^2(f_i)}{2S_{21,i}(f_i)} \approx \frac{1}{2S_{21,i}(f_i)}. \tag{13}$$

Therefore, condition of (12) requires that the angle of $S_{21,i}(f_i)$ be approximately 180°. This is the reason that the most log-periodic dipole arrays use the cross feeding as shown in Fig. 6, which was first concluded experimentally in [14].

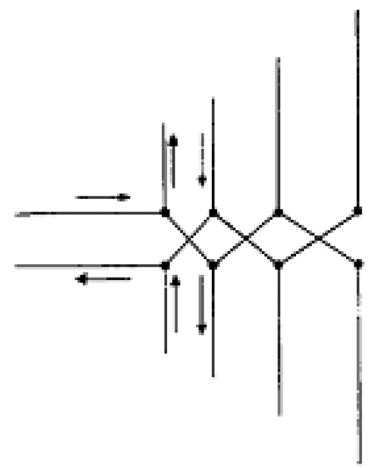

Fig. 6. Cross feeding in log-periodic dipole array [14].

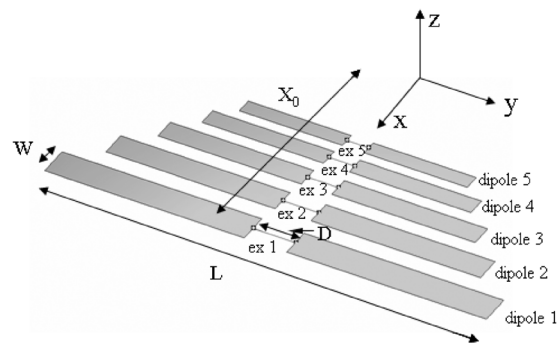

Fig. 7. Model of the five-dipole array in WILP-D.

TABLE I
DIMENSIONS OF DIPOLE i ($i = 1, \cdots, 5$) OF THE 5-DIPOLE ARRAY SHOWN IN Fig. 7 WITH THE SCALING FACTOR $k = 1/1.18$

L_i (mm)	W_i (mm)	D_i (mm)	$X_{0,i}$ (mm)
$68.63 \cdot k^{i-1}$	$4.12 \cdot k^{i-1}$	$6.60 \cdot k^{i-1}$	$40.92 \cdot k^{i-1}$

IV. EXAMPLES

Two examples of log-periodic array antennas are presented here for the sake of verifying the analysis in Section II and Section III.

A. Five Dipole Array

Fig. 7 shows the modeling of a log-periodic array consisting of five infinitely-thin PEC strip dipoles using a commercial solver WIPL-D [20]. The dimensions of the dipoles in the array are shown in Table I with the definitions in Fig. 7. The simulated H-plane (the $x - z$ plane) radiation pattern of dipole 2

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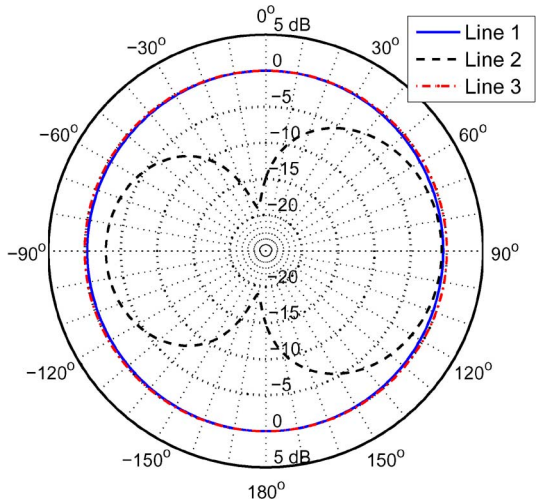

Fig. 8. Radiation patterns in H-plane at $f = 3.04$ GHz of Line 1: the 5-dipole array excited as in Table II; Line 2: the 5-dipole array excited only at dipole 2; Line 3: dipole 2 alone in free space.

TABLE II
SIMULATED MUTUAL IMPEDANCES OF THE 5-DIPOLE ARRAY USING WIPL-D AND CALCULATED VOLTAGE EXCITATIONS USING (8) FOR CONSTANT RADIATION PERFORMANCE AT $f_2 = 3.04$ GHz

	Impedance (Ohm)	Excitation Voltage (V)
Dipole 1	$Z_{12} = 250.9 - j32.1$	$-0.47 + j0.82$
Dipole 2	$Z_{22} = 161.3 + j212.4$	1
Dipole 3	$Z_{32} = 129.5 + j21.1$	$-0.36 + j0.34$
Dipole 4	$Z_{42} = 88.6 - j6.0$	$-0.18 + j0.28$
Dipole 5	$Z_{12} = 62.4 - j16.2$	$-0.09 + j0.22$

alone in free space at $f_2 = 3.04$ GHz with a voltage excitation of 1 V is shown by Line 3 in Fig. 8. When we have dipole 2 located in the array as shown in Fig. 7 with the same excitation of 1 V on dipole 2 and no excitations on other dipoles, the radiation pattern of the array in H-plane is shown by Line 2 in Fig. 8, which is very different from Line 3. We use WIPL-D to simulate the mutual impedances and the self impedances which are shown in Table II, and calculate the voltage excitation on each dipole as shown in Table II by using (8), which should give the same radiation function as that of dipole 2 alone in free space. The simulated radiation pattern with the excitations in Table II is shown by Line 1 in Fig. 8. It can be observed that Line 1 is almost the same as Line 3. By the same procedure, with the excitations defined by (8), the radiation functions of the array are almost the same for other frequencies ($f_1 = 3.04/k$, $f_3 = 3.04 \cdot k$, $f_4 = 3.04 \cdot k^2$, $f_5 = 3.04 \cdot k^3$, $k = 1/1.18$). Therefore, constant radiation characteristics can be achieved for this array by having proper excitations.

B. The Eleven Antenna—A Folded Dipole Array

The basic configuration of the Eleven antenna is two parallel folded dipoles separated by about half the resonant wavelength of the folded dipole pair and located above a ground plane. Then, the basic configuration is scaled log-periodically to a number of folded dipole pairs and these folded dipoles are cascaded one after another in each side of the pair, see Fig. 9 and Fig. 10. The origin of the coordinate system for the Eleven antenna is

Fig. 9. Photo of the linearly polarized 1–13 GHz Eleven antenna [11].

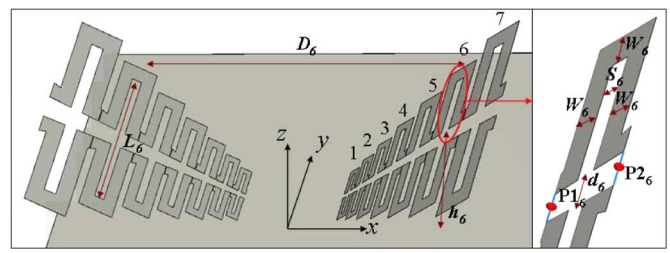

Fig. 10. Model of the 7-folded-dipole Eleven antenna in CST with the definitions of ports and dimensions.

located at the center of the ground plane as shown in Fig. 10 where the beam maximum direction is in z-direction. Successful models have been made for use in different radio telescopes: 150–1500 MHz model for Green Bank [7], 200–800 MHz for GMRT [8], and 500–3000 MHz for RATAN [9]. There is also an interest in using the Eleven antenna as a feed in reflectors for Square Kilometer Array (SKA) to cover 1–13 GHz, and for VLBI 2010 project in which case it is desirable to cover 2–14 GHz. Fig. 9 shows a photo of the linearly polarized Eleven antenna for 1–13 GHz which is a 21-folded-dipole-pair cascaded log-periodic array [11].

For the sake of convenience in the paper, we will analyze a 7-folded-dipole-pair Eleven antenna by using a commercial solver—CST Microwave Studio [21]. The folded dipoles are built up by infinitely-thin PEC strips. The model of the Eleven antenna when the folded dipoles are not cascaded is shown in Fig. 10 with the definitions of the dimensions, and their values are listed in Table III. Two ports are defined for each folded dipole for the analysis, as for example $\mathrm{P1}_6$ and $\mathrm{P2}_6$ in the figure represent port 1 and port 2 for dipole 6. Ports for other folded dipoles are defined in the same way, but not shown in the figure for the clarity. The ground plane lies on the $x - y$ plane. The Eleven antenna is excited from the innermost pair of dipoles (the first pair of dipoles) at the differential port $\mathrm{P1}_1$ with the same amplitude and phase for both the dipoles in the pair. Therefore, we set the $y - z$ plane as a PMC (perfect magnetic conductor) symmetry plane in the model. The first pair of folded dipoles are approximately halfwave dipoles at their working (resonant) frequency f_1. The next pair of dipoles work at frequency $f_2 = f_1/k$, and so on.

From [19], we can calculate the input impedance Z_{ii} of the folded dipole when the output port is shorted ($V_{i+1} = 0$) and

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TABLE III
DIMENSIONS OF DIPOLE i $(i = 1, \cdots, 7)$ OF THE 7-FOLDED-DIPOLE CASCADED ARRAY WITH THE SCALING FACTOR $k = 1.24$

L_i (mm)	W_i (mm)	S_i (mm)
$25.4 \cdot k^{i-1}$	$1.55 \cdot k^{i-1}$	$1.18 \cdot k^{i-1}$
d_i (mm)	h_i (mm)	D_i (mm)
$2.46 \cdot k^{i-1}$	$13.3 \cdot k^{i-1}$	$39.6 \cdot k^{i-1}$

without any other radiating elements existing (all $Z_{ij} = 0$), refer to Fig. 5, by

$$Z_{ii} = \frac{4Z_{T,i}Z_{D,i}}{Z_{T,i} + 2Z_{D,i}} \tag{14}$$

where $Z_T = jZ_0 \tan(kL/2)$ is the input impedance of the transmission-line mode of a folded dipole, which is the input impedance of a shorted transmission line consisting of folded dipole arm of characteristic impedance Z_0 and length $L/2$; Z_D is the input impedance of the antenna mode of a folded dipole, which is the input impedance of a linear strip dipole with an effective width $w_e = \sqrt{wS}$ and length L, please refer to [17]–[19] for the detail. Since the folded dipoles in the Eleven antenna are approximately halfwave dipoles at their working frequencies, the magnitude of $Z_{T,i}$ is very large around the working frequency. Therefore, we have

$$Z_{ii} \approx 4Z_{D,i}. \tag{15}$$

For the convenience, we analyze dipoles 4 and 5 in the 7-folded-dipole-pair Eleven antenna for illustration of the condition for constant radiation characteristics. It can be seen from Table III that the length of dipole 4 is $L_4 = 25.4 \cdot 1.24^3 = 48.4\,\mathrm{mm}$, which is about half the resonant wavelength for the folded dipole as $L_4 = 0.45 \cdot \lambda_4$. Therefore, the resonant frequency for folded dipole 4 is $f_4 \approx 2.8\,\mathrm{GHz}$. The separation between the two folded dipoles in a pair is usually chosen from 0.5 to 0.7 of the resonant wavelength [13]. In this case, the separation $D_4 = 39.6 \cdot 1.24^3 = 75.5\,\mathrm{mm} = 0.7\lambda_4$.

First, we use CST to simulate the impedances in order to calculate the right side of (12). Fig. 11 shows the equivalent dipoles of the antenna mode of dipole 4 and dipole 5 modeled in CST, and the simulated antenna mode self impedance $Z_{D,4}$ and mutual impedance $Z_{D,45}$ versus frequency. By using (15), Z_{44} can be calculated. It is known from [19] that there is no radiation from the transmission-line mode of the folded dipole. Therefore, the total mutual impedance between folded dipoles is equal to the antenna mode mutual impedance, i.e., $Z_{45} = Z_{D,45}$. Thus, the values of the right side of (12) for dipoles 4 and 5, i.e., $-Z_{45}/Z_{44}$, can be calculated and are shown by the solid lines in Fig. 13.

Second, let's look at the left side of (12) for dipoles 4 and 5. The port definition for each folded dipole can be seen in Fig. 10. Using CST, we can obtain the S parameters for each folded dipole. Fig. 12 shows the amplitudes of $S_{11,4}$, $S_{22,4}$ and $S_{21,4}$. We can see that $S_{11,4}$ and $S_{22,4}$ are below -15 dB from 2.7 to 2.9 GHz. Therefore, it is acceptable to use (12) to judge if the folded dipole array satisfies the condition for constant radiation characteristics. The calculated values of the left side of (12) are shown by the dash lines in Fig. 13.

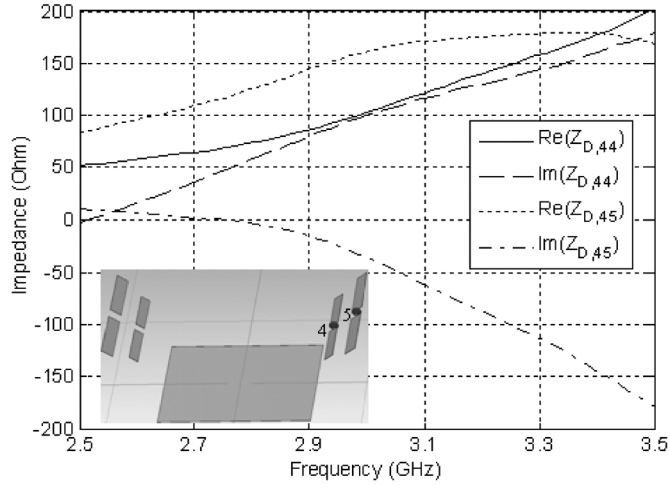

Fig. 11. Simulated antenna mode impedances of dipoles 4 and 5.

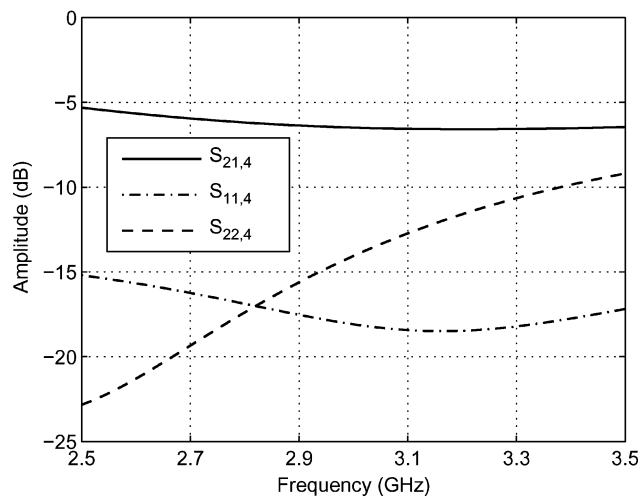

Fig. 12. Simulated S parameters of the two-port network of dipole 4.

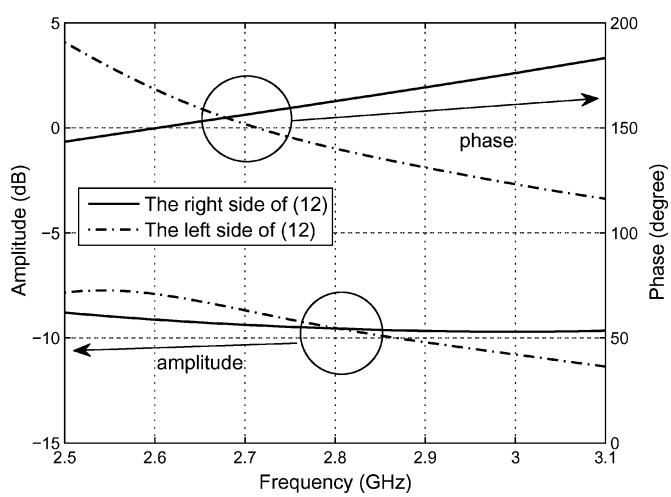

Fig. 13. Calculated values of the left and the right sides of (12) for dipoles 4 and 5 in the 7-folded-dipole-pair Eleven antenna.

Now it can be seen that the amplitudes and the phases of the left side and the right side of (12) for dipoles 4 and 5 are quite close to each other from 2.7 to 2.9 GHz. Thus, the condition

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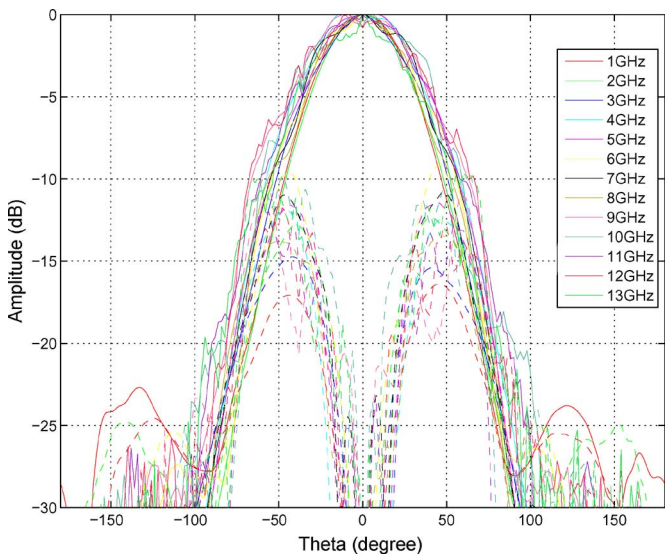

Fig. 14. Measured co- and cross-polar radiation patterns in the $\varphi = 45°$ plane of the Eleven antenna for 1–13 GHz shown in Fig. 9.

for constant radiation characteristics is satisfied for the Eleven antenna. From the physical viewpoint, it can be observed that a folded dipole makes Z_{ii} about four times of $Z_{D,i}$ and the phase of $S_{21,i}$ about 180 degrees. Therefore, the current on dipole 5 due to the transmission of the cascaded network from dipole 4 and the current induced from dipole 4 by mutual coupling have similar amplitudes, but are about 180° out of phase. This leads that, from 2.7 to 2.9 GHz, dipole 4 radiates significantly but not dipole 5. The radiation function is therefore kept constant.

Fig. 14 shows the measured radiation patterns in the $\varphi = 45°$ plane of the Eleven feed for 1–13 GHz shown in Fig. 9 [11]. It can be observed that the radiation patterns are constant over a more-than-one-decade bandwidth.

V. Conclusion

In the paper, the condition for constant radiation characteristics for log-periodic array antennas has been derived. From this condition, a general guide rule for designing a log-periodic array with constant radiation performance has been obtained. Two examples are used for verifying the analysis in the paper and the reason that the Eleven antenna has constant radiation characteristics is well explained and demonstrated.

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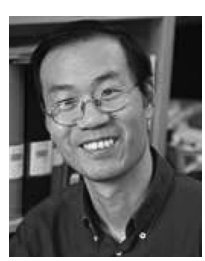

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