A Wide-Beam Array Antenna Using Shorted-End Curved Dipoles On a Reflector Plane

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Abstract: - This paper presents a wide-beam array antenna for broadcasting station by using two curved dipoles, which its both ends of each dipole are electrically shorted on the surface of a square conducting reflector and connected to the ground system and the feed point is excited at the center of each one. Advantage of this antenna should possess physically strong structure, easy fabrication, and cost effectiveness. Because of the elements of array are made of the straight dipoles, which their arms are curved for enlarging the beamwidth and shorted on a metallic reflector for increasing total directive gain and robusting the structure. The Method of Moment (MoM) is utilized to solve numerically the electrical currents that distribute along the curved dipole, which are used to determine the impedance characteristics and the radiation patterns of this antenna. The beamwidth of azimuth pattern of the proposed antenna is around 120°, which is suitable for achieving omnidirectional pattern for TV broadcasting station by placing them around the tower at least three panels. Having confirmed the validity of this approach, the UHF-band antenna prototype is fabricated, tested experimentally and shows good performance.

Key-Words: - curved dipole, array antenna, wide-beam antenna, broadcasting antenna, method of moment

1 Introduction

Broadcasting system has been extensively and continuously used for distributing information over wide range of the service area. The antenna applied for the broadcasting station of the ultra high frequency television (UHF TV) requires either unidirectional or omnidirectional beam with sufficient gain, high power handling, and bandwidth of each channel is at least 6 MHz [1]. Moreover, the antenna should possess physically strong structure, easy fabrication and cost effectiveness.

Most manufacturers offer configurations that can be used to broadcast a wide variety of azimuth and elevation patterns at either low or high power with their simple feeding system, low windload, and ability to be side- or top-mounted. Conventionally, the popular antenna utilized for this purpose is the UHF antenna panel system [2] is one type of broadcasting antennas that contains horizontally polarized wire/patch dipoles as an array arrangement. However, to achieve omnidirectional pattern, the panel system must be placed around the tower at least four panels, because of the beamwidth of each panel is not much wide. In addition, the structure of conventional panel system is probably complex and required the fully feed system.

From these aforementioned literatures of the conventional UHF TV broadcasting antennas, it is obvious that the antenna which possesses simple structure and simple feeding system is desirable. An antenna made of curved-wire dipole, which the both ends are shorted on the metallic reflector plane, is an attractive one since the structure and feed system is very simple. Moreover, the beamwidth of curved-wire dipole is larger than straight dipole.

Most of substantial works related to the shaped or curved dipole structures. Krishnan *et al.* [3] presented a V-shaped wire-loop with a butterfly-like structure. The elliptically polarized radiation of S-shaped dipole antenna was presented by Elkamchouchi and Nasr [4]. Besides these, Dubost [5] presented the radiation impedance and bandwidth of a short-circuited dipole parallel to a perfect reflector plane. Other wide-beam antenna designs of our previous works were shown in [6]-[8]. As far as we know, there is no information about the curved dipole that the both ends are shorted on a metallic reflector plane, which is necessary for the structure that requires the simple fabrication, simple feeder, and high power handling.

Since impedance, radiation pattern and beamwidth are the important characteristics that determine the efficiency of the antenna. Therefore, this paper focuses on these characteristics of a shorted-ends curved dipole. Theoretical background of this antenna will be determined by using Method of Moments (MoM). The Pocklington's integral equations for total filed are first formulated and are subsequently solved by using Method of Moments to calculate the unknown current densities, which are used to determine the input impedance of the antenna at the center feed, the radiation patterns and beamwidth. Finally, the performances of wide-beam array antenna using two shorted-end curved dipoles will be determined and validated by measurement.

2 Antenna Configuration

The structure of the proposed array antenna is composed of two curved-wire dipole, which both ends of each element are short-circuited on a metallic reflector plane and connected to the ground system as shown in Fig.1. Each curved-wire dipole of the length L, the wire radius $b(b \ll \lambda)$, and the curved radius a is aligned along ϕ-direction at which the feed center of this curved dipole is located at $\phi = \lambda/2$. The dimension of a square reflector plane of the width W is one wavelength as shown in Fig.2.

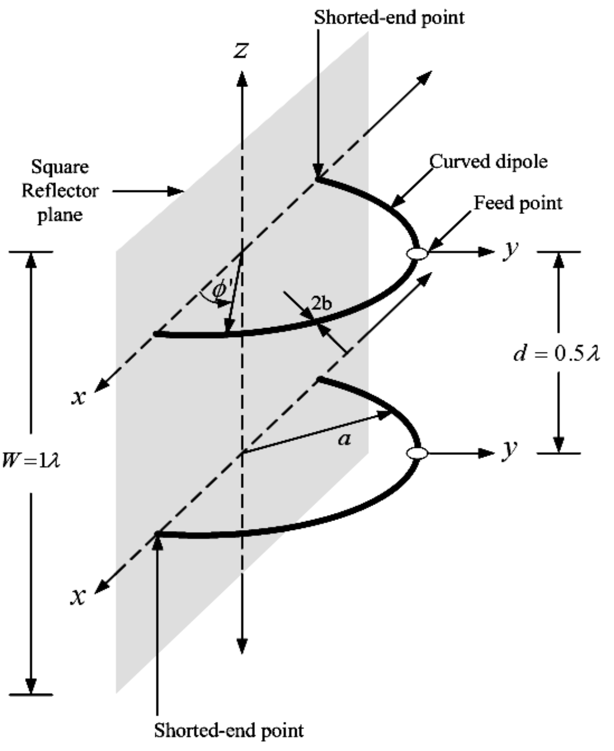


Fig.1 Geometry of two shorted-end curved dipoles on a reflector plane.

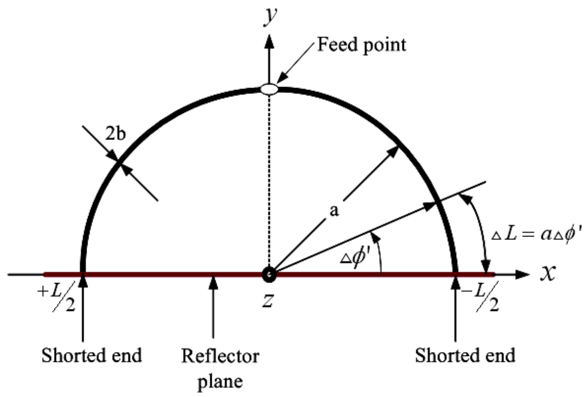


Fig.2 Analysis model of a shorted-end curved dipole on a reflector plane.

3 Theory

The current distribution of each shorted-end curved dipole can be obtained by using the Pocklington's integral equation and solved numerically using the method of moments. The point-matching technique is then used to satisfy the integral equation at discrete points on the axis of curved dipole rather than attempting to satisfy this equation everywhere on its surface [9]-[10]. Thus, a system of linear algebraic equations is generated to form the matrix model and the inversion of this matrix can realize the current distribution on the curved dipole, which is used to first determine the characteristics of input impedance of this proposed antenna.

In this work, the Pocklington's integral equation for the total field calculation, which are generated by an electric current source radiating in an unbounded free space [8], which can be written in the form of

$$\int_{-L/2}^{+L/2} I_n(\phi') \left(\frac{\partial^2}{\partial_\phi^2} + k^2 \right) \frac{e^{-jkR}}{R} d\phi' = j4\pi\omega\varepsilon_0 E_\phi^t, \qquad (1)$$

where E_ϕ^t is the total radiated field due to the current $I_n(\phi')$. Resulting from a source field E_ϕ, that could be caused by voltage applied at the antenna feed point or incident plane wave $E_{\phi'}^i$. Here ϕ' and ϕ are the source location variable and the observation location variable, respectively, and R is the distance from any one point on the source to the observation point. For small diameter wires, the current on element can be approximated by a finite series of odd-order even modes [10]-[11]. Thus, the current on the element can be written as a Fourier series expansion of the form:

$$I_n(\phi') = \sum_{m=1}^{M} I_{nm} g_n(\phi') \tag{2}$$

where $g_n(\phi')$ is entire domain basis functions [8], which is given by

$$g_n(\phi') = \cos\left[\frac{(2m-1)\pi\phi_n'}{L_n}\right], \quad 0 \le \phi_n' \le \pi, \tag{3}$$

where L_n is the corresponding length of the n element.

After some rigorous derivations and using entire domain functions with Pocklington's integral equation, the integral equation for each element of the proposed antenna can be written as [11]

$$E_\phi^t = \frac{1}{j4\pi\omega\varepsilon_0}\sum_{m=1}^{M} I_{nm}\left\{(-1)^{m+1}\frac{(2m-1)\pi}{L_n}G_2\left(\rho,\rho',\phi,\phi'/z,\frac{L_n}{2}\right)\right.$$
$$+\left[k^2 - \frac{(2m-1)^2\pi^2}{L_n^2}\right]\times\int_0^{L_n/2} G_2\left(\rho,\rho',\phi,\phi'/z,\phi_n'\right)$$
$$\left.\times\ \cos\left[\frac{(2m-1)\pi\phi_n'}{L_n}\right]d\phi_n'\right\}, \tag{4}$$

where I_{nm} represents the unknown current coefficient of mode m on element n. Because of each element of array antenna comprises two elements such as driver and reflector. Therefore, n = 2 is the total number of elements. Green's functions is given as

$$G_2\left(\rho,\rho',\phi,\phi'/z,\phi_n'\right) = \frac{e^{-jkR_-}}{R_-} + \frac{e^{-jkR_+}}{R_+}, \tag{5}$$

where $R_\pm$ represents the distance from each wire radius to the center of any other wire which can be shown by

$$R_\pm = \sqrt{(a-a')^2 + (z-z')^2 + b^2 + (\phi \pm \phi')^2}. \tag{6}$$

From (4), in according with referred to as point-matching method, in matrix form can be expressed as

$$[V_m] = [Z_{nm}][I_{nm}], \tag{7}$$

where

$$Z_{mn} = \left\{(-1)^{m+1}\frac{(2m-1)\pi}{L_n}G_2\left(\rho,\rho',\phi,\phi'/z,\frac{L_n}{2}\right)\right.$$
$$+\left[k^2 - \frac{(2m-1)^2\pi^2}{L_n^2}\right]\times\int_0^{L_n/2} G_2\left(\rho,\rho',\phi,\phi'/z,\phi_n'\right)$$
$$\left.\times\ \cos\left[\frac{(2m-1)\pi\phi_n'}{L_n}\right]d\phi_n'\right\} \tag{8}$$

and

$$V_m = 4\pi\varepsilon_0. \tag{9}$$

Then, the unknown coefficients I_{nm} can be obtained from the matrix model in (7) by using a number of matrix inversion techniques. Finally, the total electric fields plotting the azimuth patterns can be expressed in (10).

$$E_\phi = j\omega\frac{\mu e^{-jkr}}{4\pi r}\sin\theta\sum_{n=1}^{N}\left\{ e^{jk(\rho_n\sin\theta\cos\phi+\phi_n\sin\theta\sin\phi)}\right.$$
$$\left.\times\sum_{m=1}^{M} I_{nm}\left[\frac{\sin(\phi^+)}{\phi^+}+\frac{\sin(\phi^-)}{\phi^-}\right]\frac{L_n}{2}\right\}. \tag{10}$$

The total field radiated by the two elements array, assuming no coupling between the elements, is equal to the sum of the two and in the *y*-*z* plane it is given by

$$E_t = E_1 + E_2 = j\omega\frac{\mu e^{-jkr}}{4\pi r}\sin\theta\sum_{n=1}^{N}\left\{e^{jk(\rho_n\sin\theta\cos\phi+\phi_n\sin\theta\sin\phi)}\right.$$
$$\left.\times\sum_{m=1}^{M} I_{nm}\left[\frac{\sin(\phi^+)}{\phi^+}+\frac{\sin(\phi^-)}{\phi^-}\right]\frac{l_n}{2}\right\}$$
$$\times\left\{\frac{e^{-j[kr_1-(\beta/2)]}}{r_1}\cos\theta_1 + \frac{e^{-j[kr_2+(\beta/2)]}}{r_2}\cos\theta_2\right\} \tag{11}$$

where β is the difference in phase excitation between two elements. The magnitude excitation of the radiators is identical. Assuming far-field observations,

$$\theta_1 \simeq \theta_2 \simeq \theta, \tag{12a}$$

$$\left.\begin{aligned} r_1 &\simeq r - \frac{d}{2}\cos\theta \\ r_2 &\simeq r + \frac{d}{2}\cos\theta \end{aligned}\right\} \text{ for phase variations,} \tag{12b}$$

$$r_1 \simeq r_2 \simeq r \qquad \text{for amplitude variations.} \tag{12c}$$

Therefore, from (11) reduces to

$$E_t = j\omega \frac{\mu e^{-jkr}}{4\pi r^2} \sin\theta \sum_{n=1}^{N} \left\{ e^{jk(\rho_n \sin\theta\cos\phi + \phi_n \sin\theta\sin\phi)} \times \sum_{m=1}^{M} I_{nm} \left[\frac{\sin(\phi^+)}{\phi^+} + \frac{\sin(\phi^-)}{\phi^-} \right] \frac{l_n}{2} \right\} \times |\cos\theta| \, 2\cos\left[\frac{1}{2}(kd\cos\theta + \beta) \right], \quad (12)$$

where d and β are the separation and phase between elements, respectively. Note that in (12), the total pattern of the array is obtained by multiplying the pattern of the single element from (10) by that of the array factor, which is the last term of (12).

4 Numerical Results

For illustration, this array antenna with the two shorted-end curved dipoles was designed to operate at the center frequency of 470 MHz. From the preliminary study it was found that, at this operating frequency, the radius of curvature a and the wire radius b should be 10.15 cm and 0.005 λ, respectively, therefore, the good matching condition and the proper gain of this antenna could be obtained. Computations for this proposed antenna have been made using the formulas of previous section. For the current itself, convergence was about 5.5 percent change in going from 30 to 50 segments. In our case, 40 segments for a half-wave length of antenna will give the accurate results as shown in Fig.3. It is found that the appropriate length of this curved dipole should be half-wavelength due to the current magnitude at the both ends is zero.

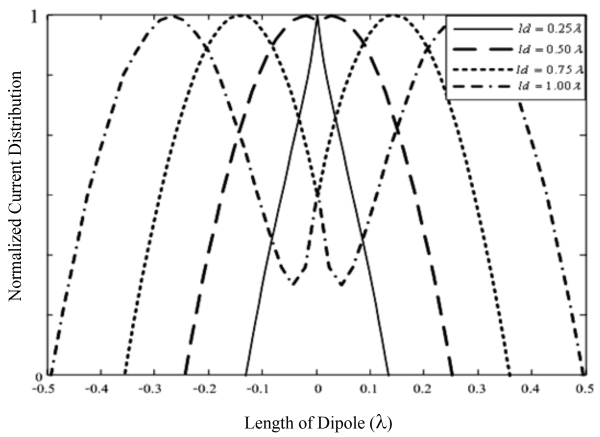
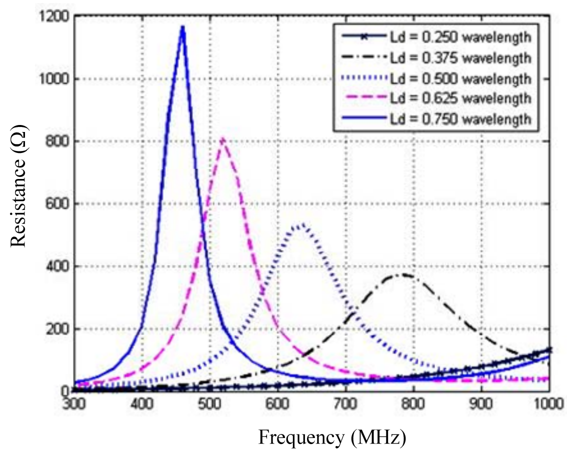
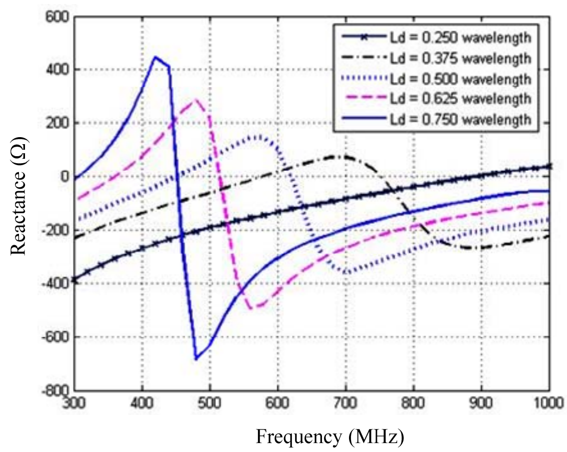


Fig.3 Current distribution versus various lengths of a curved dipole on reflector plane.

The simulated real and imaginary parts of the input impedance are shown in Fig.4. Next, the return loss, and radiation patterns for the single curved dipole on reflector plane are shown in Fig.5 through 6. In Fig.4, it is noted that the length of a curved dipole is the important parameter to characterize the impedance characteristics. The curved dipole length is varied from 0.25 λ to 0.75 λ while other parameters are fixed. The numerical results of the input resistance and reactance of a shorted-end curved dipole as a function of the frequency are illustrated in Fig. 4. It is obvious that the larger the length, the larger the resistance and the reactance. For the resonant frequency observed from the zero reactance, it can be seen that the resonant frequency will be higher when the dipole length is shortened. The resonant frequency of 470 MHz is realized when the dipole length is around 0.5 λ.



(a) Input resistance



(b) Input reactance

Fig.4 Impedance characteristic versus frequency for a curved dipole on reflector plane.

In Fig.5, the return loss of single curved dipole on a reflector plane is depicted in Fig. 5. It is found that the most proper length L_d of curved dipole at the operating frequency $(f_0 = 470\ \text{MHz})$ is also 0.5λ, because of it will yield the lowest return loss$(\sim 25\ \text{dB})$. While its bandwidth is between 425 MHz and 480 MHz at return loss is -10 dB.

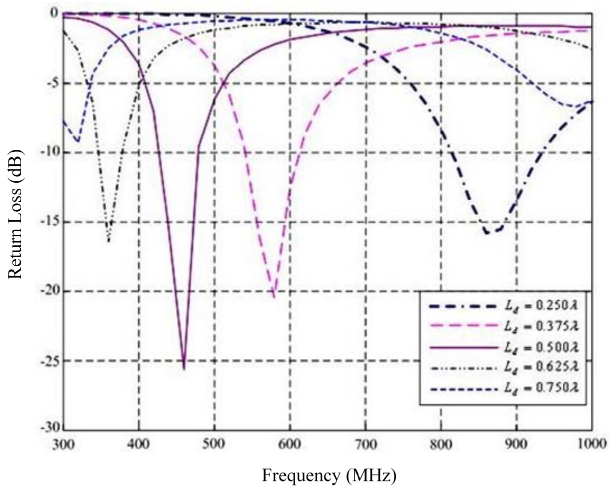
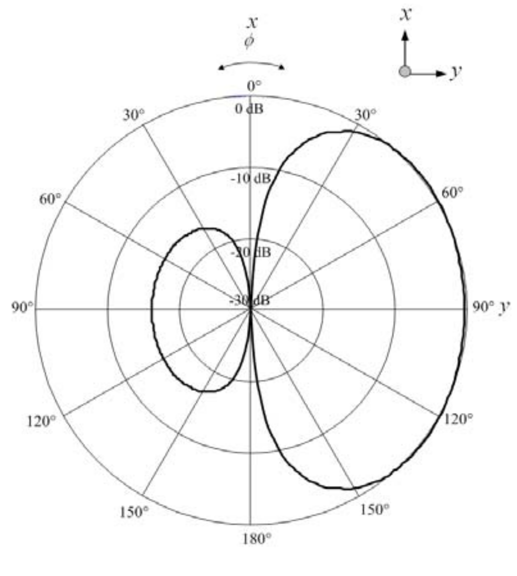
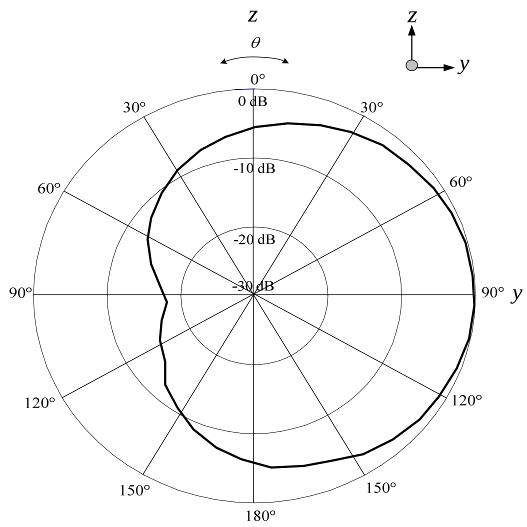


Fig.5 Simulated return loss versus frequency for a curved dipole on reflector plane

The numerical results from (10) for the azimuth patterns in E-plane and H-plane of single curved dipole on a reflector are shown in Fig. 6 (a) and (b), respectively. Note that the radiation patterns in both planes are approximately directional and similar to Yagi-Uda antenna but it yields wider beamwidths (approx. 120 degrees in both planes), which accorded to our assumption.



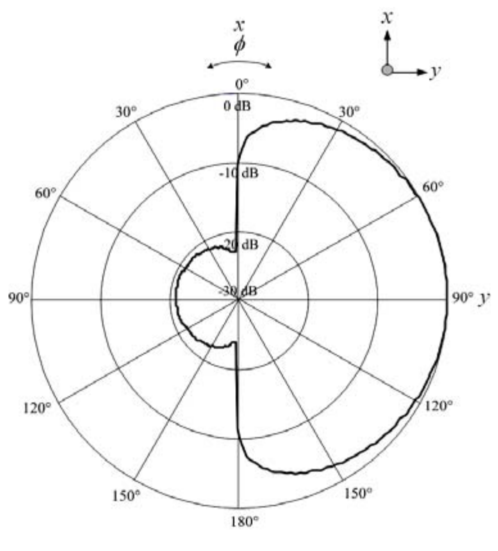
(a) E-plane



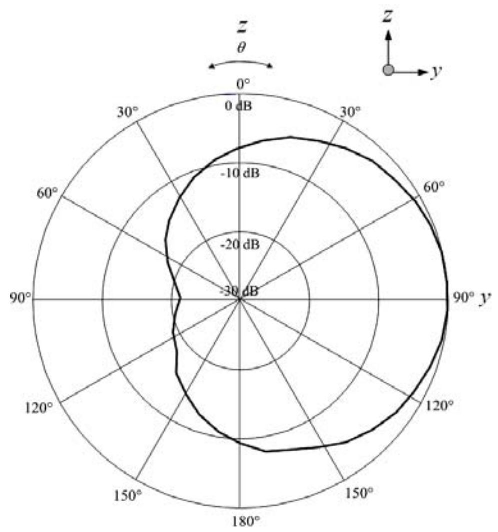
(b) H-plane

Fig.6 Radiation pattern of a curved dipole on reflector plane

In case of the two curved dipoles are installed on a square reflector plane as proposed array antenna, the total patterns of this array are obtained from (12). The separation and phase between elements are given by $d = \lambda/2$ and $\beta = 0$, respectively, as broad- side array. Then the numerical results from (12) for the total patterns both in E-plane and H-plane of the array antenna with two curved dipoles on a reflector are shown, respectively, in Fig. 7 (a) and (b). It is noted that the half-power beamwidth in E-planes still be approx. 120°, while the beamwidth in H-plane will be small reduced.



(a) E-plane



(b) H-plane

Fig.7 Radiation pattern of the array antenna with two curved dipoles on a reflector plane.

Fig.8 shows a plot of directive gain versus frequency for the shorted-end curved dipoles on a reflector plane. The simulated results for one element and two elements are compared. It is found that the array antenna using two elements will yields the directive gain around 8.6 dB at the operating frequency, which is higher than of single element about 2.6 dB. While the directive gain for the single element is around 5.9 dB.

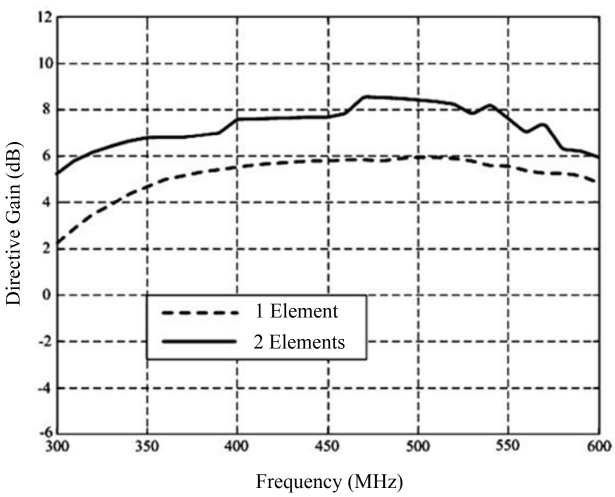


Fig.8 Directive gain versus frequency of shorted-end curved dipole on a reflector plane. Results for single and two elements are compared.

From all numerical results as mentioned above, this proposed array antenna can be realized for meeting our requirement. Therefore, the prototype of this array antenna will be implemented and manufactured to verify with such simulated results.

3 Experimental Results

To verify the theoretical calculation, the two curved dipoles, which their both ends are short-circuited on the metallic reflector plane is fabricated with the parameters of antenna at the operating frequency of 470 MHz as shown in Table 1.

Table 1 The parameters of curved dipole on the square reflector plane.

Antenna Parameters	Electrical Dimension	Physical Dimension
Dipole Length (L)	0.5λ	31.90 cm
Dipole Radius (a)	0.159λ	10.15 cm
Wire Radius (b)	0.03λ	1.91 cm
Reflector Width (W)	1λ	63.80 cm
Feed Position (ϕ)	90°	90°

The prototype of the two elements array antenna is shown in Fig.9 (for the single element has been shown in the small photo at top-left side). To achieve impedance matching, the $\lambda/4$ coaxial balun (1:1) is mounted at the center gap $(\phi = 90^\circ)$ of curved dipole to balance inherently unbalanced system as shown in Fig.10. At first, the input impedance of each element is measured by using an HP8720C Network Analyzer. The measured results are superimposed together with the theoretical results as dashed line in Fig.11. It should be pointed out that the good agreement between theory and experiment can be observed that the input impedance is around 50 Ω at the operating frequency of 470 MHz as shown in Fig.10.

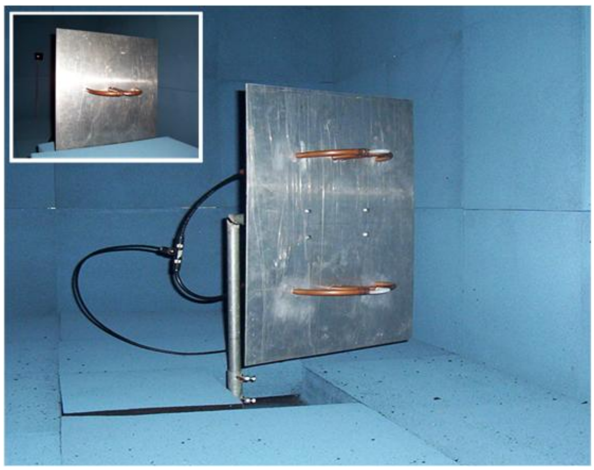


Fig.9 Photograph of the prototype of array antenna using two shorted-end curved dipoles on a reflector.

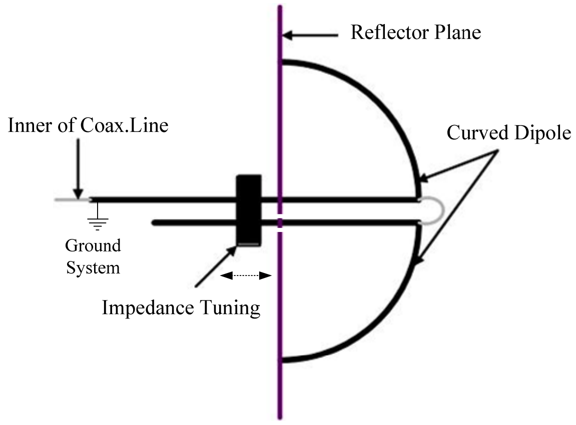
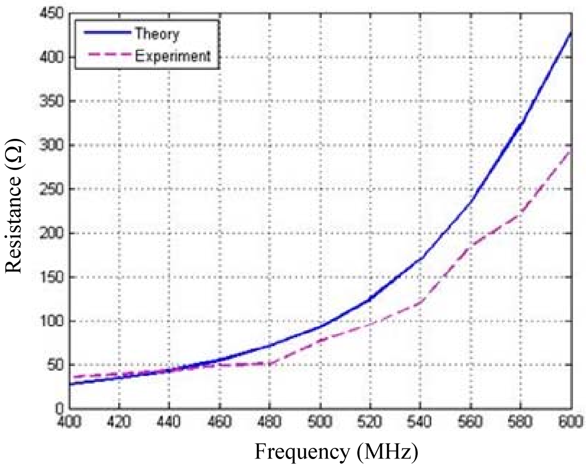
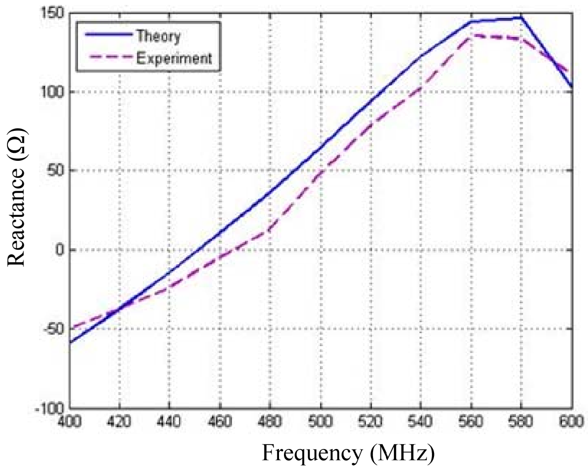


Fig.10 Impedance matching using the $\lambda/4$ coaxial balun (1:1) is mounted at the center gap $(\phi = 90^\circ)$ of curved dipole



(a) Input resistance



(b) Input reactance

Fig.11 Theoretical and experimental results of the real and imaginary parts of input impedance for the single curved dipole on reflector plane.

The matching technique using $\lambda/4$ coaxial balun (1:1) as shown in Fig.10, the indirect parallel-conductor connection of this structure will provide the desired current cancellation without eliminating the radiation [11]. The current flow on the outer shield of the main line is canceled at the position of impedance tuning approx. $\lambda/4$, which measured from feed position of curved dipole. Therefore, this technique can prevent the upsetting of the normal operation of the antenna. Besides, the other advantages of this matching technique are easier for manufacturing and impedance tuning, which can be observed from the measured results after the optimum tuning of input impedance, return loss and standing wave ratio (SWR) as shown in Fig.12, 13 (a) and 13 (b), respectively.

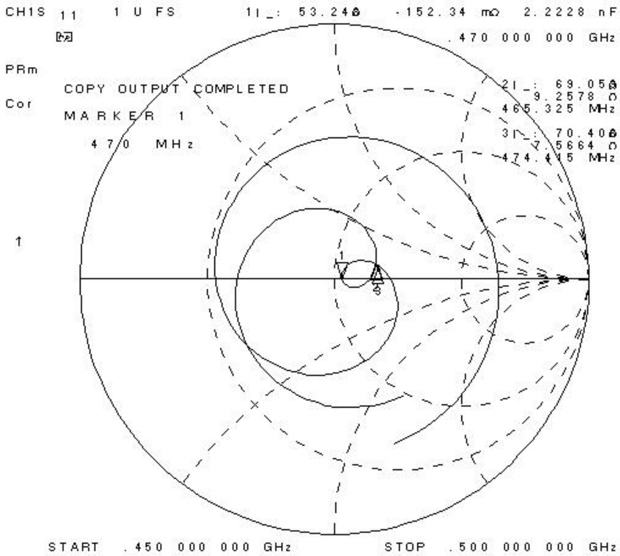
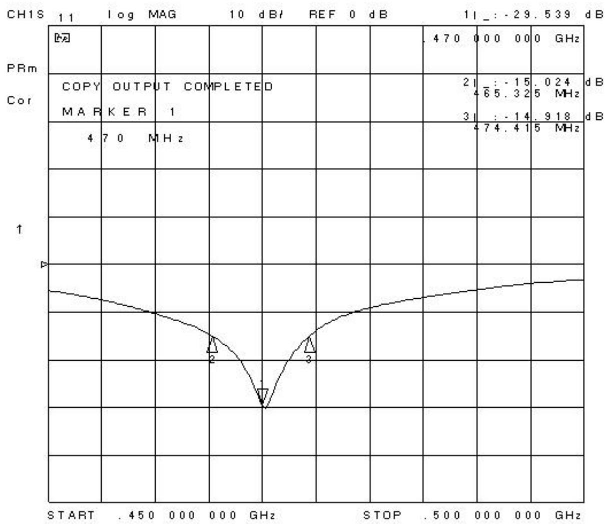
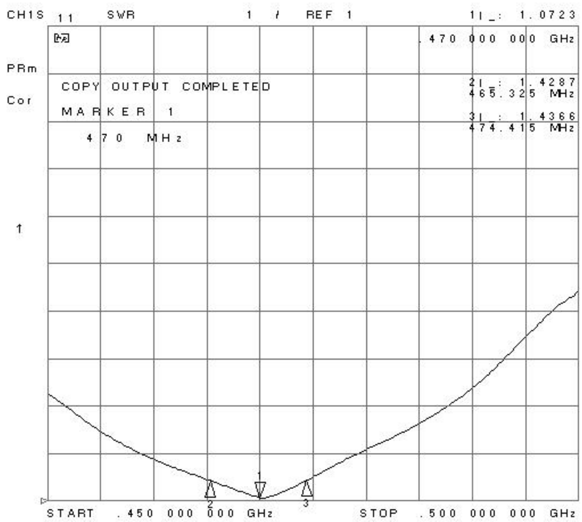


Fig.12 The input impedance of single curved dipole on reflector with $\lambda/4$ coaxial balun (1:1).



(a) Return loss.



(b) Measured SWR.

Fig.13 The impedance characteristics of single curved dipole on reflector with $\lambda/4$ coaxial balun (1:1).

In Fig.12, the measured input impedance of single curved dipole on reflector with the matching device is $53.246 - j0.152\,\Omega$ at the center frequency of 470 MHz. However, it is observed that its bandwidth, which is measured at the end of matching device, will be reduced to around 9.09 dB as shown in Fig.13 (a) and (b). Comparing to the approximated bandwidth as shown in Fig.5, the measured bandwidth, in Fig.13, is narrower than the theoretical bandwidth without matching device. It is shown that the matching technique using $\lambda/4$ coaxial balun (1:1) does not probably encourage any broad-band antennas.

The experiment setting for array antenna using the two shorted-end curved dipole on a square reflector will be done by connecting two elements together with the phasing coaxial-line (as power divider), which shows behind the reflector in Fig.9. The impedance characteristics of the proposed array antenna such as the input impedance, return loss, and SWR are measured through the power divider or phasing coaxial-line as shown in Fig.14, 15 (a) and 15 (b), respectively. In Fig.14, the measured result of input impedance at the input terminal of phasing line is about $46.85 + j0.785\,\Omega$ at 470 MHz. From Fig.15 (a) and (b), it is obvious that the antenna bandwidth will be affected from the phasing coaxial-line that used to provide the power for each curved dipole of array. The bandwidth of array antenna measured at the input terminal of phasing line is about 7.07 dB, which is narrower than the measured bandwidth at the input terminal of each curved dipole as mention above (Fig.13).

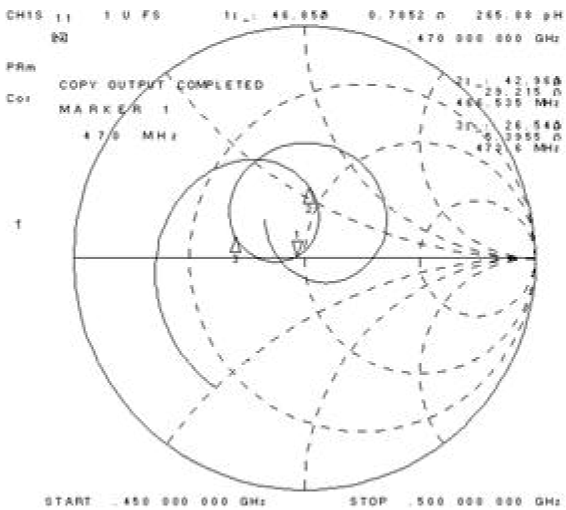
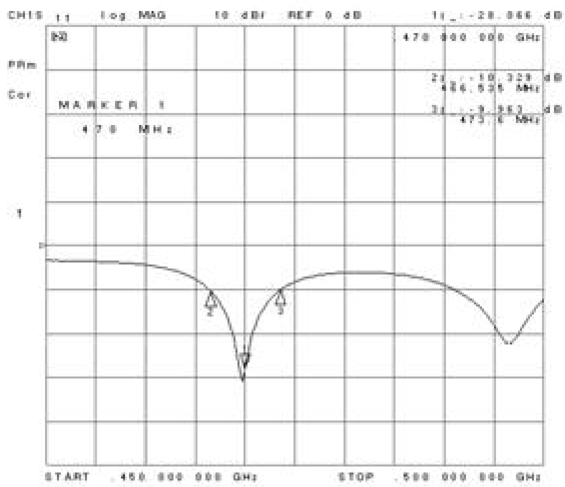
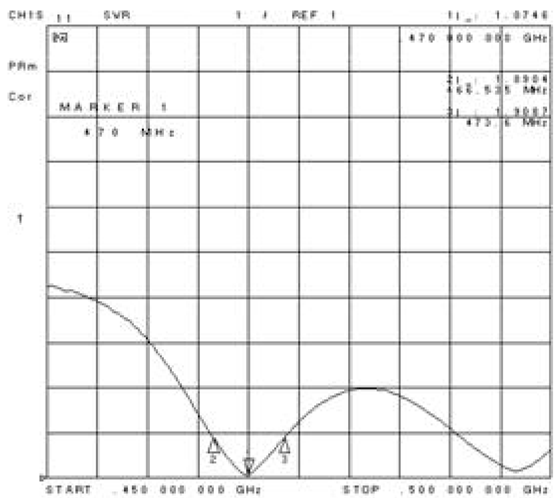


Fig.14 The input impedances of two curved dipoles are measured through the phasing line.



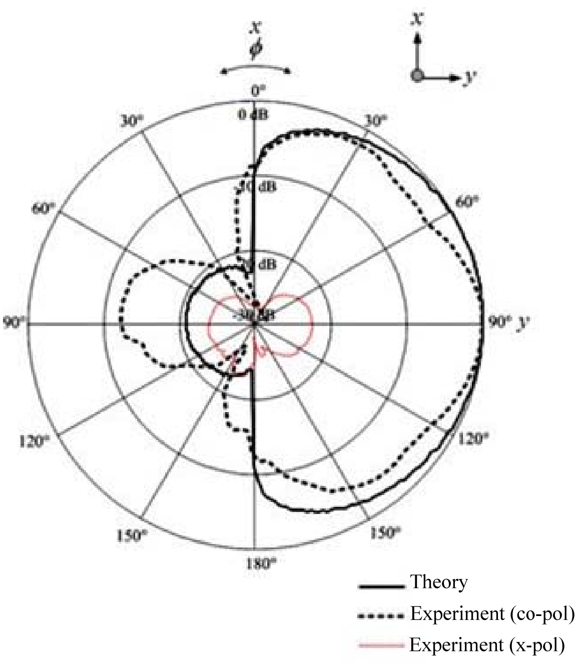
(a) Measured return loss.



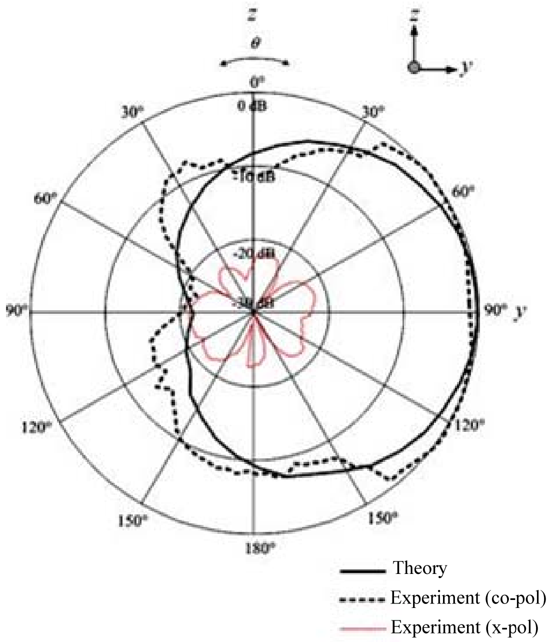
(b) Measured SWR

Fig.15 The impedance characteristics of two curved dipoles are measured through the phasing line.

Fig.16 shows the comparison of the theoretical results with measurements for the total far-field radiation patterns on the center frequency of 470 MHz. In Fig.16 (a) shows the simulated E-plane pattern compared with the measured co-polarization (Co-pol) and cross-polarization (X-pol) patterns, while Fig.16 (b) is the compared results of H-plane. It is noted that the front-to-back (F/B) ratios of theoretical and experimental E-plane patterns are about 21 dB and 13 dB, respectively, and measured cross-polarization pattern is about -24 dB. In this E-plane pattern, it is found that the prototype array antenna will yield F/B ratio lower than the simulated result. For H-plane pattern, the measured cross-polarization is about -22 dB. Therefore, it is summarized that the proposed array antenna is probably-true linear polarization. The measured radiation patterns are superimposed together with the theoretical results as dashed line both in E- and H-plane as shown in Fig.16 (a) and (b) will resemble to the simulated ones. However, the pattern in H-plane will be distorted at some θ-angles, while pattern in E-plane at ϕ-angles at about 60° and 120° will be small concaved. Nevertheless, the measured patterns both in E- and H-plane still maintain the half-power beamwidths (approx. 120°) as the theoretical ones.



(a) E-plane



(b) H-plane

Fig.16 Compared total far-field radiation patterns for array antenna using two curved dipoles on a reflector plane.

Fig.17 shows the measured antenna gains of the array antenna using the two shorted-end curved dipoles on a square reflector versus the frequency variation have been superimposed together with the theoretical gains as solid line. In this figure depicts that the directive gains of simulation are near to that of measurement, which they occur at the operating frequency of 470 MHz are about 8.6 dB and 8.55 dB, respectively.

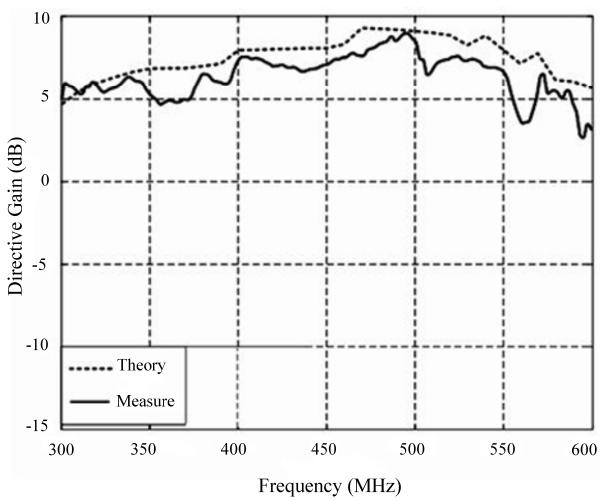


Fig.17 Measured directive gains of array antenna compared to theoretical results

4 Conclusion

In this paper, a compact and low profile array antenna using the two shorted-end curved dipoles on a square reflector for UHF TV broadcasting station has been proposed. The input impedance of each curved dipole is an important characteristic that affects the antenna efficiency. It must be well investigated so that the matched antenna can be designed. While the wider beamwidth in azimuth plane (E-plane) of antenna is the major requirement of broadcasting station. Therefore, this paper focuses on the input impedance characteristics and the radiation characteristics of a so-called array antenna using the two shorted-end curved dipole on a reflector plane. This antenna is developed to be an UHF TV broadcasting antenna due to its simple structure and simple feeding system. In order to investigate the impedance characteristics of this antenna, the straightforward procedure has been applied. Starting from formulations of integral equations of the structure of single curved dipole based on the Pocklington's integral equation. The entire domain basis function is used in the Method of Moments to solve the electric current density on a curved dipole. The input impedance can be found from this current subsequently. From the numerical results, the frequency response of input impedance can be investigated, which is very useful to find the optimum matching conditions by simply adjusting the length of curved dipole. Then, the radiation patterns have been calculated and plotted to determine the beamwidth of antenna. Next, the total field radiated by the two curved dipoles array on a square metallic reflector, assuming no coupling between the elements, is calculated, which equal to the sum of the two and in the y-z plane. Finally, the prototype of an array antenna using two shorted-end curved dipoles was fabricated and measured its performances. The experimental results give good overall agreement with the theoretical results. Therefore, this proposed array antenna can be realized and used for UHF TV broadcasting station, because of its bandwidth can cover the TV broadcasting operation and its beamwidth is wider enough for placing around the tower at least three panels.

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