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RESEARCH ARTICLE

# Design and analysis of an 8-element dipole array for passive coherent location systems

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**Abstract**
This article deals with a design and analysis of an 8-element dipole array for passive coherent location (PCL) systems. The array is composed of eight identical dipole elements that are arranged at a radius of $0.5\lambda_0$ from the center to the elements. To verify the performance for the PCL system, the array is fabricated and measured in an outdoor test site. Array performances such as the antenna gain, peak to side lobe ratio (PSLR), half-power beam width (HPBW), null width, and null depth are then analyzed. The results demonstrate that the proposed array has beam pattern characteristics suitable for PCL systems.

**KEYWORDS**
8-element circular array, passive coherent location system, reference beam, surveillance beam

## 1 | INTRODUCTION

Passive coherent location (PCL) systems that use commercial broadcasts, such as FM radio, television broadcasts, and mobile networks, have been proposed and extensively studied in recent years.[1-3] The main purpose of the PCL system is to detect and track targets by examining the correlation between the reference and surveillance channels. Such systems have the advantages of low manufacturing and operation costs along with less exposure to enemy radars, since the system utilizes commercial broadcasts as illuminating radio sources. In particular, it also has potential ability to detect stealth aircraft and long-range targets using a bistatic system with a low operating frequency. Many studies have been conducted to increase the detectability of the targets, such as direction-of-arrival (DOA) estimation techniques through multichannel configurations and canceling sequential zero-Doppler signal components that minimize interference signals.[4,5] To further enhance detection efficiency, a Doppler-sensitive cross-correlation method has also been proposed.[6] In addition, antenna elements with multiband and dual polarization characteristics have been proposed to obtain higher target detection probability by expanding the operating frequency and available polarization.[7,8] Antenna arrays are generally required for steering and nulling beam patterns toward multiple transmitters. Therefore, it is necessary to design the optimum array configuration since the detection performance of the PCL system can be further improved by generating proper array beam patterns.

In this article, we design and analyze an 8-element dipole array for PCL systems. The array consists of eight dipole elements, and the antennas are arranged at a radius of $0.5\lambda_0$ from the center to the elements. To ensure their proper performance for PCL systems, each array element is designed and manufactured to operate in the FM frequency band. The dipole antenna elements are then extended into an 8-element uniform circular array (UCA), and the beam-forming performances such as the antenna gain, peak to side lobe ratio (PSLR), half-power beam width (HPBW), null width, and null depth are analyzed. The results demonstrate that the proposed 8-element dipole array has beam pattern characteristics that are suitable for PCL systems.

## 2 | DESIGN AND MEASUREMENT OF THEDIPOLE ANTENNA ELEMENT

Figure 1 shows the geometry of the dipole element consisting of the upper and lower radiating poles with a housing structure. The dipole element is designed to operate at the FM frequency band, and the antenna has a length and diameter of $l_d$ and $D_d$, respectively. The operating frequency bandwidth of the antenna increases as the diameter of the dipole is raised. The diameter is limited to less than 40 mm taking into account weight and structural stability. The feed housing structure with dimensions of $h_w \times h_l \times h_h$ mm$^3$ tightly holds the lower and upper conducting poles, and a circuit board is inserted inside the feed housing. The two conducting poles are connected to the broadband balun (ADT1.5-1+ from Mini-circuits embedded into the board) through the transition parts. This balun operates from 1 to300 MHz and has an inserting loss of less than 1 dB. In order to maximize the average gain of the dipole element in the range of FM band, the design parameters of $D_d$, $l_d$, and $d_f$ are optimized by a genetic algorithm (GA) in conjunction with the FEKO EM simulator.[9,10] The detail optimized parameters are shown in Table 1. To ensure proper performance of the dipole element for PCL systems, the dipole element is fabricated and measured at the outdoor test site, as presented in Figure 1B,C.

Figure 2 presents a comparison between the measured and simulated gains ($\theta = 90°$) and reflection coefficient of the dipole antenna element. The measured and simulated results are indicated by solid and dashed lines, respectively, and are in good agreement with each other. The bore-sight gain of more than 1 dB and a reflection coefficient of less than −7 dB are observed in the FM frequency band. These results verify that the designed dipole element is suitable for PCL systems. Figure 3 shows the gain according to the diameter of the dipole antenna. The gains for the thin wire dipole and the cylinder dipole with $D_d = 20$ mm, which are indicated solid and dashed lines, have similar tendency. However, the bandwidth with a gain of ≥1 dB greatly increases when the $D_d$ is more than 30 mm. We determined the cylinder dipole of optimized $D_d$ for the PCL element, taking into account the structural stability and efficient performance enhancement of the system.

## 3 | 8-ELEMENT ARRAY ANTENNA FOR THE PCL SYSTEM

The dipole antenna element is then extended to 8-element UCA as illustrated in Figure 4. The array radius from the center to the antenna element is $0.5\lambda_0$. Each element is connected to an arm with a length of about $0.5\lambda_0$ that fits into the antenna housing. Eight arms are then again connected to

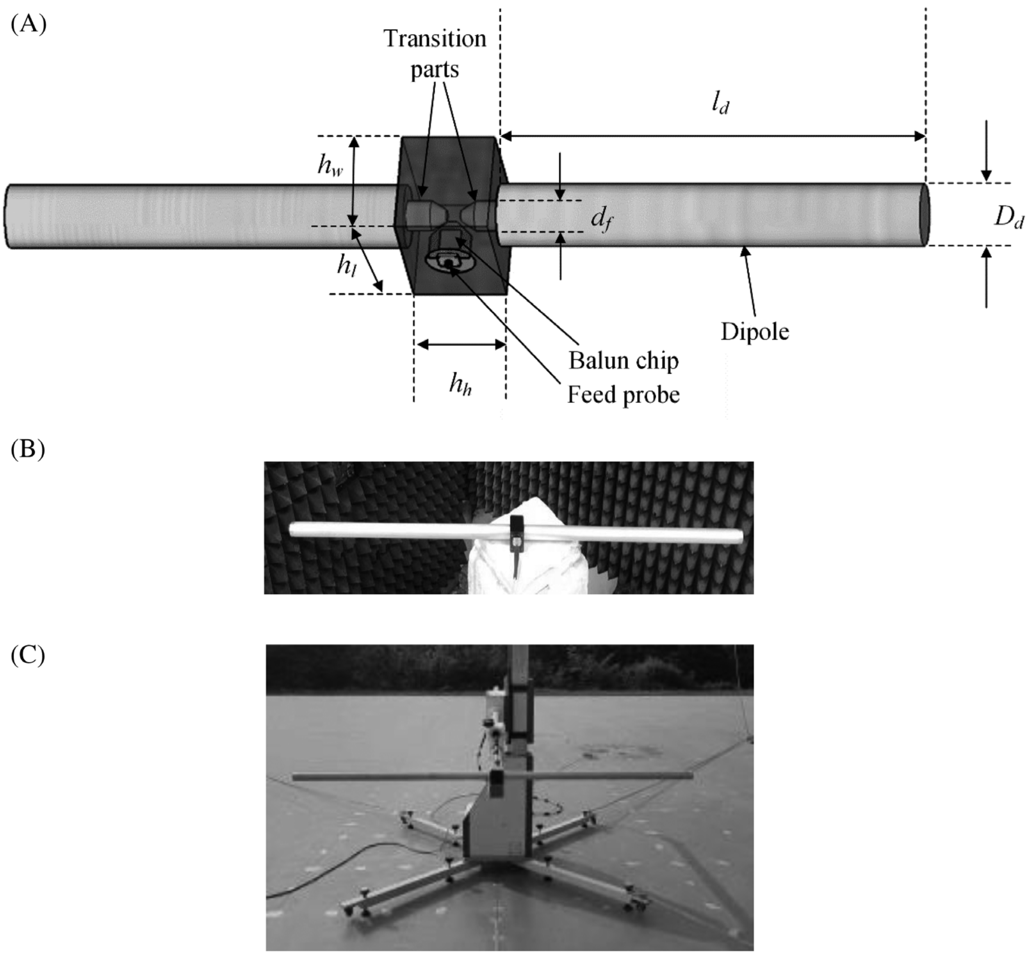


**FIGURE 1** Geometry and measurement of the dipole element. A, Geometry of the antenna. B, Photograph of the fabricated antenna. C, Outdoor test site supporting the CIS16-1-5 standard

**TABLE 1** Design parameters of the dipole element

| Parameter | $D_d$ | $l_d$ | $h_h$ | $h_l$ | $h_w$ | $d_f$ | $\varepsilon_f$ |
|---|---|---|---|---|---|---|---|
| Valure | 30 mm | 670 mm | 45 mm | 68 mm | 49 mm | 14 mm | 3.8 |

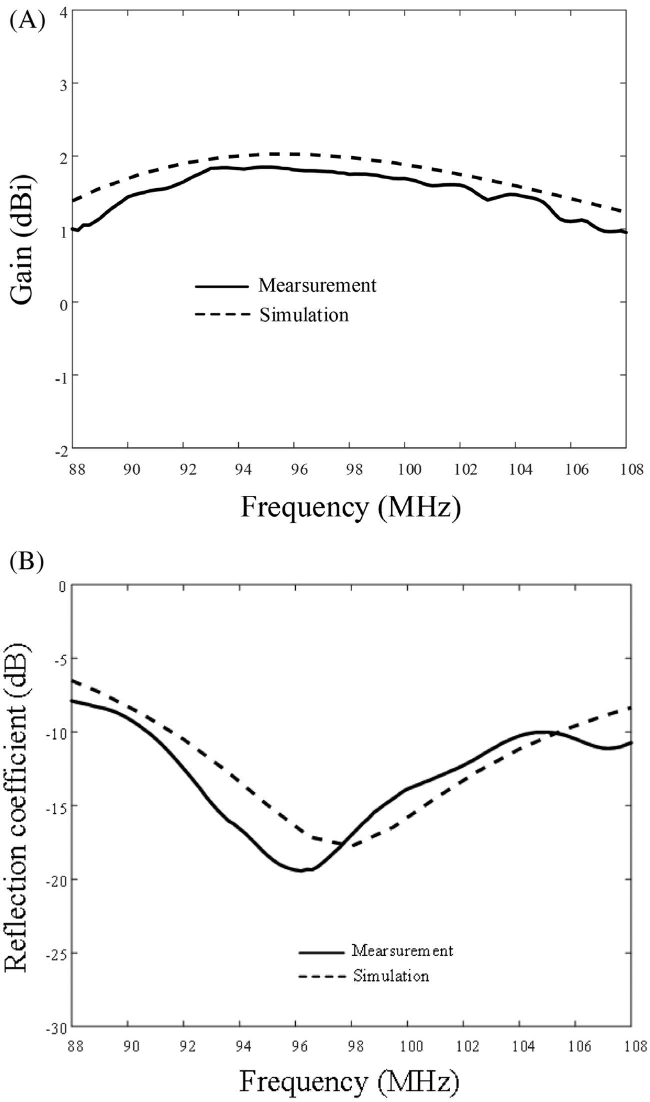


**FIGURE 2** Comparison of the measured and simulated antenna performance. A, Bore-sight gain. B, Reflection coefficient

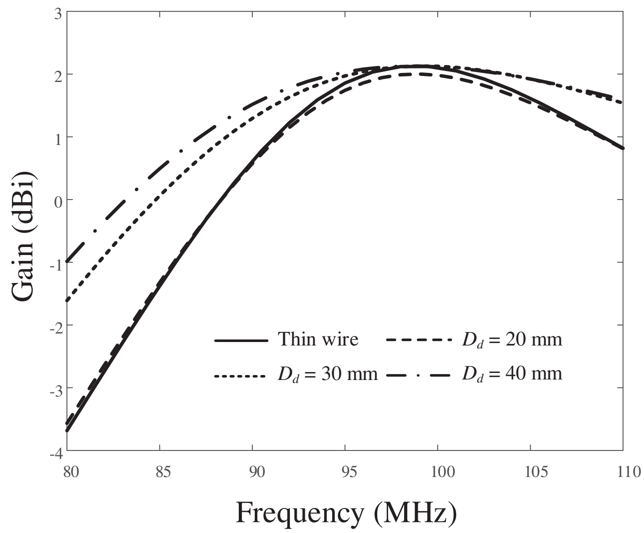


**FIGURE 3** Gain according to the diameter of the dipole antenna

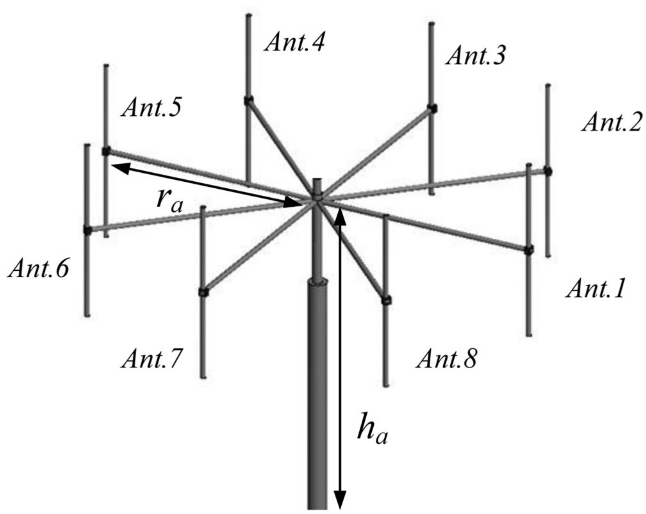


**FIGURE 4** Geometry of the 8-element dipole array for PCL systems. PCL, passive coherent location

an expandable mast to hold them at an elevated position of 8 m. This array is fabricated and measured to verify the beam forming performance of the PCL system. Figures 5A, B shows the measured and simulated couplings between the elements, which are represented by S-parameters. The S-parameter values decrease as the distance between the elements increases, except for $S_{15}$ due to the high pattern correlation between Ant.1 and Ant. 5.

In general, PCL systems have two different channels that are the reference and the surveillance channels. In the case of reference beam, it is necessary to have a high PSLR and a narrow HPBW, since PCL systems often use commercial broadcast signals from FM base stations as the reference signal for detecting a target. On the other hand, the beam pattern of the surveillance channel should have a deep null in the direction of the base station to obtain the scattered signals from targets without any strong reference signal. The least-mean-square (LMS) algorithm is used for obtaining proper reference and surveillance beam patterns considering the PSLR, HPBW, null width, and null depth. First, we make the array manifold from each active element pattern (AEP) of the array element under the 8-element UCA configuration, where the AEP includes all the coupling factors. Then, we set the desired ideal array beam pattern, which is

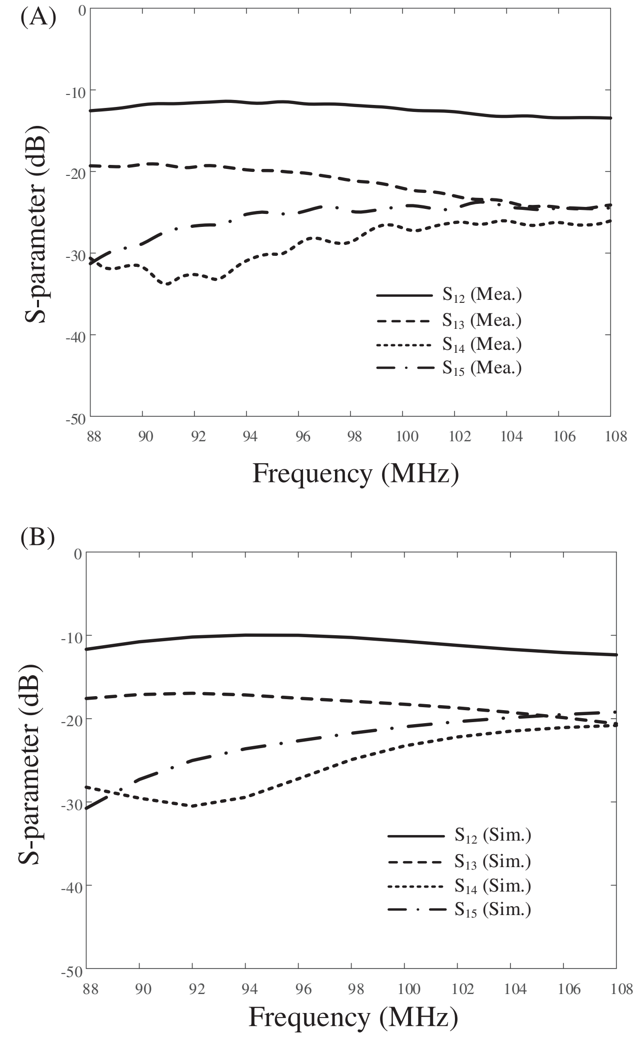


**FIGURE 5** S-parameter of the 8-element array antenna. A; Measurement. B, Simulation

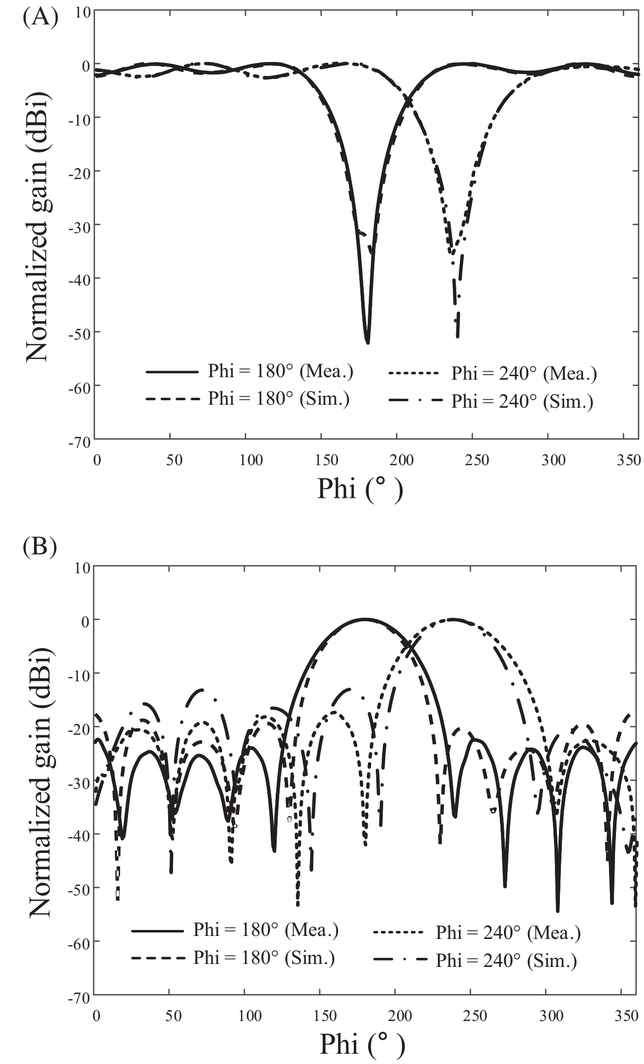


**FIGURE 6** Beamforming performance of the 8-element array at 100 MHz A, Surveillance beam. B, Reference beam

called as the mask function.[11] The mask function $F$ can be written as:

$$A \cdot \omega = F, \tag{1}$$

where $A$ and $\omega$ are the array manifold and weightings to calculate the beam pattern of the proposed array, respectively. The weightings for the beam pattern are extracted by using the following equation:

$$\omega = \left(A^{\mathrm{H}} \cdot A\right)^{-1} \cdot A^{\mathrm{H}} \cdot F. \tag{2}$$

From Equation (2), we can obtain the weightings $\omega$ that can minimize the square error between the pattern and the mask function. For the reference beam, we achieve weightings for the maximum PSLR, while for the surveillance beam, we obtain weightings for the maximum null depth and null width.

Figure 6 shows the beam patterns of the reference and surveillance beams at 100 MHz. The beam patterns are obtained using each AEP of the antenna element. For the required beam and null steering, the feed weight of each element is achieved using the LMS algorithm that takes into account the PSLR, HPBW, null width, and null depth. As can be seen, the array exhibits a HPBW of less than 50° with PSLRs of 18 dB at $\phi = 180°$ and 14 dB at $\phi = 240°$. However, the beam pattern of the surveillance channel should have deeper null depth toward the base station to remove the strong reference signal. A null depth of 32.5 dB and a null width of 25°are observed at $\phi = 180°$for the proposed array. In our study, not only the PSLR but also the important parameter of the null depth is comprehensively considered. Table 2 shows comparisons between the prosed array and some previous studies.[11,12]

Figure 7 shows the relationship between the null width and null depth for the surveillance beam. For the proposed array, the narrower the null width, the deeper the null pattern can be observed. When the null width is 25°, the null depth is 32.5 dB, but if the null width is changed to 45°, the null depth decreases to 14.9 dB. Since the null width and null depth are interdependent, the proper null width for the

**TABLE 2** Comparison of the performance with previous work (at the direction of $\phi = 180^{\circ}$)

| Referencee | Number of elements | Array type | PSLR | Null depth |
|---|---|---|---|---|
| 11 | 8 | UCA | 23 dB | — |
| 12 | 8 | UCA | 20 dB | — |
| 12 | 8 | UCA w/ cetral element | 13 dB | — |
| Proposed | 8 | UCA | 18 dB | 32.5 dB |

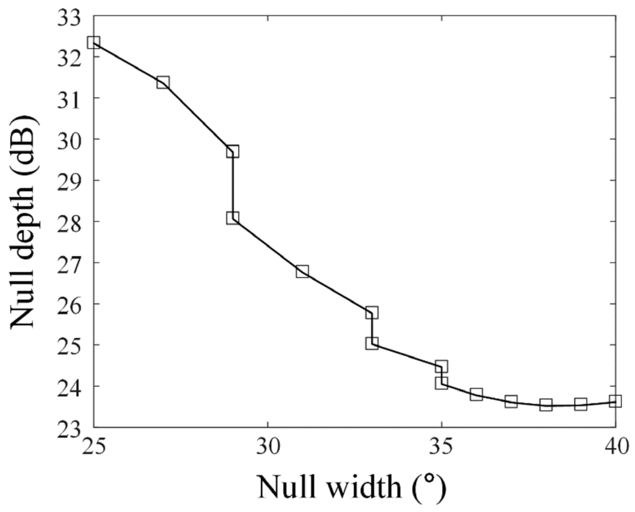


**FIGURE 7** The relationship between the null width and null depth for the surveillance beam

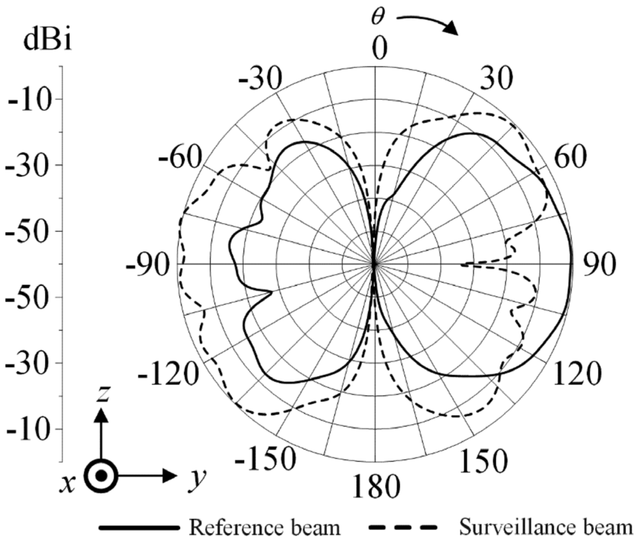


**FIGURE 8** The elevation patterns at $\phi = 180^{\circ}$ for the reference and surveillance beams

surveillance beam pattern could be selected along with the null depth.

Figure 8 shows elevation patterns at $\phi = 180^{\circ}$ for the reference and surveillance beams. The solid line represents the reference beam pattern, and the maximum gain is observed at near $\theta = 90^{\circ}$. The dashed line illustrates the surveillance beam pattern, and the null is placed near $\theta = 90^{\circ}$.

## 4 | CONCLUSION

We have investigated the design and analysis of an 8-element dipole UCA for PCL systems. The array consists of eight dipole elements with a radius of $0.5\lambda_0$ from the center to the elements. To ensure proper performance for PCL systems, an antenna element was fabricated and measured. The fabricated element showed a measured reflection coefficientof −13.8 dB with a gain of 1.6 dBi at 100 MHz. The dipole antennas were then extended into an 8-element UCA, and the beam-forming performances of PSLR, HPBW, null width, and null depth were analyzed. The results demonstrated that the designed 8-element dipole array has suitable beam patterns for PCL systems.

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