Article

Design of a Polarization-Selective EM Transparent Mesh-Type E-Shaped Antenna for Shared-Aperture Radar Applications

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Abstract: In this paper, we propose a polarization-selective electromagnetic (EM) transparent mesh-type E-shaped antenna unit-cell in a shared aperture. The proposed antenna unit-cell, which can be expanded to a larger array in a modular way, has one S-band antenna on the upper layer and nine X-band antennas on the lower layers. The simple E-shaped structure, which has a low profile with a good bandwidth, is used for the antenna elements. However, due to the limited aperture size of the stacked configuration, the lower-layer elements can be physically blocked by the upper-layer element. To reduce this blockage effect, the S-band element is rotated 90 degrees with respect to X-band elements so that the polarizations between the S- and X-band elements are perpendicular to each other. Moreover, to minimize performance degradation due to the blockage effect, a mesh structure is applied for S-band elements for EM transparent characteristics, thereby improving EM transparency from $-30\, \text{dB}$ to $-1.5\, \text{dB}$. The extended via cavity wall is also employed outside the nine X-band elements to minimize the mutual coupling and to reduce antenna size. To confirm the effectiveness of the proposed design, the proposed antenna unit-cell is fabricated, and the radiation characteristics are measured, in a full anechoic chamber. The average bore-sight gains in the S- and X-band are 5 dBi and 4.5 dBi, respectively. The results confirm that the proposed design is suitable for shared-aperture radar applications.

Keywords: polarization-selective structure; electromagnetically transparent structure; S-band antenna; X-band antenna; E-shaped antenna; shared aperture

1. Introduction

Dramatic advances in the latest active electronically scanned array (AESA) technologies have resulted in the development of high-performance multi-function radars (MFRs) for military ship radar systems [1–5]. Modern advanced MFRs can simultaneously handle surveillance, tracking, electronic warfare, and missile guidance in addition to a single classical mission [6–9]. Although various frequency bands are applicable to military ship radar systems, the S-band and X-band are particularly important and are widely adopted [10]. In such system configurations, the S-band radar is often employed for the surveillance of targets, whereas the X-band radar is used for the accurate tracking of targets [11,12]. In previous studies, various element types for the S-band and X-band radar systems have been reported, such as patch antennas [13–18], dipole antennas [13,14], and Vivaldi antennas [19]. In particular, patch-type antennas with a low profile and reduced radar cross section (RCS) characteristics are considered to be more suitable for military ship MFRs.

However, since the S-band and X-band antennas are mounted in different spaces on the ship mast, the aperture area of the system is increased, resulting in a high RCS. In addition, since the antenna elements are not generally in the form of expandable modules, whenever the array antenna is applied to a differently sized platform, the full array antennas for a
new platform must be re-developed [20]. Even in the case of failure of individual antenna elements, the entire system must be repaired or replaced if not modularized. In order to lower the RCS, it is necessary to reduce the array aperture size by stacking the antennas in the same aperture space, and to increase the efficiency of maintenance, modularization is required. Therefore, one candidate solution to this challenge is to efficiently stack the modularized S-band and X-band antennas on a shared aperture. However, as the space efficiency increases, the elements on the lower layer are inevitably blocked by the elements on the upper layer due to the decreased distance between elements. This physical blockage leads to a deterioration of the electromagnetic radiation characteristics of the antenna [21].

For the multi-layer shared-aperture array, perforated elements were applied to the upper elements to avoid the blockage of the upper-layer elements [22–24]. Nonetheless, it is difficult to apply this solution for space-efficient shared-aperture arrays, since there are many restrictions on the antenna shape and configuration of the upper and lower layers, which lead to the degradation of the array characteristics. In order to compensate for the performance degradation of the elements, complicated feed structures, such as a feeding network with a stub-loaded resonator (SLR), or a differential feeding method, have also been tried [22,23]. Even so, these complicated feed structures make the modularization of array elements difficult.

In this paper, we propose the electromagnetic (EM) transparent E-shaped antenna, which consists of one S-band element stacked on top of $3 \times 3$ X-band elements in a shared aperture. These ten antenna elements form a basic unit-cell, which can be expanded to a larger array in a modular way. The proposed modular configuration has the advantage of easy maintenance at a low cost, since damaged unit-cells can easily be replaced with an identical module product. The simple E-shaped structure, which has a low profile with a good bandwidth, is employed for the antenna elements.

However, due to the limited aperture size of the stacked configuration, the elements on the lower layer can be physically blocked by the upper-layer elements. To reduce this blockage effect, the S-band element is mounted to rotate 90 degrees with respect to X-band elements so that the polarizations between the S- and X-band elements are perpendicular to each other. Moreover, to minimize performance degradation due to the blockage effect, a mesh structure is applied to the S-band elements to ensure better EM transparent characteristics due to the polarization-selective characteristics of the mesh structure. The extended via cavity wall, which is advantageous for stable manufacturing, is applied outside the nine X-band elements to minimize the mutual coupling and to reduce the antenna size [25]. The proposed antenna is fabricated, and the radiation characteristics such as reflection coefficient, bore-sight gain, and radiation patterns are measured in a full anechoic chamber. The results demonstrate that the proposed mesh structure of the E-shape antenna can minimize the blockage effect of the upper layer and the extended via cavity wall can improve the mutual coupling effect with a simple via hole manufacturing process.

2. Proposed Antenna Design

2.1. Proposed Unit-Cell Structure

Figure 1 depicts the geometry of the proposed antenna unit-cell. The proposed antenna unit-cell has one S-band antenna on the upper layer and nine X-band antennas on the lower layers, as shown in Figure 1a. To achieve broadband matching characteristics with a low-profile structure, the simple E-shaped geometry is employed for both the X- and S-band array elements. Since the X-band and S-band elements must share a limited size aperture in the stacked configuration, lower-layer elements, especially those in the center, are inevitably blocked by upper-layer elements. To reduce this blockage effect, the S-band element is arranged to rotate 90 degrees with respect to X-band elements so that the polarizations between the S- and X-band elements are perpendicular to each other. Moreover, to minimize performance degradation due to the blockage effect, a mesh structure is also applied to the S-band element for EM transparent characteristics, as depicted in Figure 1b. Then, the thin mesh line structure of the upper-layer S-band element is optimized so that the
S-band element has polarization-selective EM transparent characteristics in the X-band. The top view of the X-band element is illustrated in Figure 1c. To block the mutual coupling effect among X-band elements, an extended cavity structure is added outside the nine X-band elements. We propose using a via cavity structure instead of a normal cavity wall, for a more stable manufacturing process. The red dot presents the feed pin location of the antenna, where the ports of the S-band and X-band antennas are optimized to minimize the reflection coefficient characteristics of the antenna. The heights of the lower (X-band) and upper (S-band) layers are \( h_1 \) and \( h_2 \), respectively, as indicated in Figure 1d. The thickness of the E-shaped antenna on the top layer is \( h_3 = 0.035 \) mm. The radiating patch of the antenna is made of copper with a conductivity of \( 5.87 \times 10^7 \) S/m and is printed on the substrate, RF-35 (\( \varepsilon_r = 3.5, \tan \delta = 0.0018 \)), using an etching process. The optimal parameters are derived from parametric studies using the FEKO electromagnetic simulator [26] and the detailed geometrical parameters are listed in Table 1.

In this configuration, as the S-band element with a larger size radiator is stacked on top, the performance of the X-band element deteriorates due to the blockage effect. The blockage of the E-shaped antenna, which is related to optical transparency (OT), can be defined as the ratio between its open area to the total area. Herein, the OT has a value between zero and one, and the value of one means the total transmission. The OT of the S-band E-shaped antenna without the mesh structure can be calculated as follows [27]:

\[
\text{OT} = \frac{2 \times (w_2 \times l_5)}{w_1 \times l_1}
\]  

(1)

Table 1. Geometrical parameters of the proposed antenna.

| Parameters | Values (mm) | Parameters | Values (mm) |
|------------|-------------|------------|-------------|
| \( h_1 \)  | 1.52        | \( l_0 \)  | 51          |
| \( h_2 \)  | 4.56        | \( l_1 \)  | 48          |
| \( h_3 \)  | 0.035       | \( l_2 \)  | 7.5         |
| \( w_0 \)  | 51          | \( l_3 \)  | 10          |
| \( w_1 \)  | 20          | \( l_4 \)  | 0.5         |
| \( w_2 \)  | 18          | \( l_5 \)  | 0.5         |
| \( w_3 \)  | 13          | \( l_6 \)  | 8.5         |
| \( w_4 \)  | 6.5         | \( l_7 \)  | 7           |
| \( w_5 \)  | 4.55        | \( l_8 \)  | 0.2         |
| \( fpx \)  | 8.9         | \( l_9 \)  | 2.8         |
| \( fpx \)  | 2.9         | \( d \)    | 17          |

Figure 1. Cont.
Figure 1. Geometry of the proposed antenna unit-cell: (a) isometric view; (b) top view of S-band layer; (c) top view of X-band layer; (d) side view.

Through this equation, the OT of the S-band E-shaped antenna is 0.019, which is significantly low, and may therefore lead to the performance degradation of the center X-band element. In order to lower the OT and improve the performance of the X-band element, the physical area of the S-band element must be minimized. However, since the area of the S-band element is related to various radiation characteristics, it is important
to reduce the blockage effect while maintaining the performance. Therefore, the mesh structure with polarization-selective EM transmission characteristics is employed, which effectively increases the electromagnetic (EM) transparency of the upper E-shaped element.

Figure 2 shows a conceptual diagram of driving the EM transparency according to wave polarization for a periodic E-shaped element with the mesh structure. When the mesh direction is in the same direction as the polarization of the incident wave, the traveling wave is mostly reflected, as shown in Figure 2a. The simulated EM transparency for this case at 10 GHz is $-30.0$ dB, whereas, when the mesh direction is perpendicular to the polarization of the incident wave, as shown in Figure 2b, the EM transparency increases up to $-1.5$ dB.

Figure 2. EM transparent characteristics for a periodic mesh structure: (a) for parallel polarization incident wave; (b) for perpendicular polarization incident wave.

Figure 3 shows the average gain (averaged from 9 GHz to 11 GHz) of the X-band element (solid line) and the bandwidth of the S-band element (dashed line) according to the mesh length ($w_3$) in the S-band antenna of the unit-cell. The average gain increases as the mesh length increases, due to the reduced blockage effect. The bandwidth of the S-band remains almost the same until the mesh length is approximately 13 mm, as shown in Figure 3. With the optimum length of the mesh structure, a maximum average gain of 7.43 dBi and a bandwidth of 756 MHz are achieved.

Figure 4a,b show the electric field distribution of the X-band antennas with and without the extended via cavity at the resonance frequency of 10 GHz. The total electric field is observed in the same reference plane as the radiating patch when 1 W of the input power is supplied at each X-band element. The average leakage field between the radiating elements in Figure 4a,b is examined. The averaged leakage field of 52.04 dB V/m is observed with the extended via cavity, while 55.24 dB V/m is observed without the extended via cavity. The electric field of the E-shaped patch antenna with the extended cavity is more confined around the radiator than without the extended via cavity structure.
The mutual coupling characteristics among neighboring elements can be reduced by adding the extended via cavity.

Figure 3. Optimization of mesh length considering the bore-sight gain (X-band) and the bandwidth (S-band).

Figure 4. E-field distribution according to the cavity: (a) with cavity; (b) without cavity.
2.2. Verification of the Proposed Antenna

To verify the feasibility of the proposed antenna, a unit-cell is fabricated and measured in a full anechoic chamber. Figure 5a,b present the top views of the fabricated S-band and X-band layers. The S-band element has a mesh structure, as shown in Figure 5a, and the E-shaped antenna in the X-band has extended via cavities, as shown in Figure 5b. The S-band and X-band layers are tightly attached using a glue-type adhesive. The measurement setup in the full anechoic chamber is shown in Figure 5c, where the antenna under test (AUT) in the yellow rectangle is fixed with a zig and taping. The reflection and active element patterns for the 10 elements are fully measured in the S-band and X-band.

Figure 6 presents the reflection coefficient and bore-sight gain of the fabricated S-band element and the central X-band element. For the reflection coefficient measurement, 800 sample points are used. For the bore-sight gain measurement, 11 sample points (S-band) and 7 sample points (X-band) are used. The ‘x’ mark, solid line, dashed line, and dotted line indicate the measured bore-sight gain, the measured reflection coefficient, the simulated bore-sight gain, and the simulated reflection coefficient, respectively. The average gains (from 2.5 GHz to 3.5 GHz) of the S-band antenna are 5 dBi by simulation and 5.5 dBi by measurement. The simulated reflection coefficient of the S-band element is under $-10\,\text{dB}$ from 2.70 GHz to 3.456 GHz (a bandwidth of 756 MHz), which is in good agreement with the measurement. The average gains (from 9 GHz to 12 GHz) of the X-band center element are 4.5 dBi by simulation and 4.7 dBi by measurement. The reflection coefficient of the X-band center element is under $-10\,\text{dB}$ from 8.76 GHz and 10.72 GHz (a bandwidth of 1.96 GHz).

Figure 7a,b show the simulated and measured two-dimensional (2D) radiation patterns of the S-band antenna at 3 GHz. A half-power beam width (HPBW) of around 80° is examined for the co-polarization.

Figure 8a,b show the 2D radiation patterns of the center X-band antenna at 10 GHz. The co-polarization pattern shows a bore-sight gain of 6 dBi, while exhibiting a low level of cross polarization. A measured half-power beam width (HPBW) of 44.1° is observed for the co-polarization beam pattern.
Figure 5. Photographs of the fabricated antenna and measurement setup: (a) top view of the S-band layer; (b) top view of the X-band layer; (c) measurement setup.

Figure 6. Cont.
Figure 6. Simulated and measured reflection coefficients and bore-sight gains of the antenna: (a) S-band; (b) X-band.

Figure 7. Simulated and measured 2D radiation patterns of the S-band antenna: (a) co-polarization; (b) cross-polarization.

Figure 8. Simulated and measured 2D radiation patterns of the X-band antenna: (a) co-polarization; (b) cross-polarization.
In order to verify the beam forming characteristics, the active element patterns of all nine elements of the X-band antenna are measured, and then the array pattern is achieved using the following equation [28,29]:

\[
G_{array}(\theta, \phi) = \frac{\sum_{i=1}^{N} w_i g_i(\theta, \phi)}{\sqrt{\sum_{i=1}^{N} |w_i|^2}},
\]

where \(g_i\) and \(w_i\) are the active element pattern and weight vector of the \(i\)-th element, respectively. Figure 9 shows the simulated and measured 2D array patterns of the nine X-band elements at 10 GHz. The bore-sight gains at 10 GHz for the simulated and measured beam patterns are 13.6 dBi and 13.2 dBi, respectively.

![Simulated and measured 2D array patterns of the nine X-band elements at 10 GHz.](image)

**Figure 9.** Simulated and measured 2D array patterns of the nine X-band elements at 10 GHz.

3. Conclusions

We investigated the polarization-selective electromagnetic (EM) transparent mesh-type E-shaped antenna unit-cell, which consisted of one S-band element being stacked on top of \(3 \times 3\) X-band elements in a shared aperture. To reduce the blockage effect, the S-band element was arranged to rotate 90 degrees with respect to X-band elements so that the polarizations between the S- and X-band elements were perpendicular to each other. In addition, to minimize performance degradation due to the blockage effect, a mesh structure was used for the S-band element, which improved EM transparency from \(-30\) dB to \(-1.5\) dB. The extended via cavity wall was also employed outside the nine X-band elements to minimize the mutual coupling and to reduce the antenna size. The simulated average bore-sight gain and bandwidth of the S-band antenna were 5 dBi and 756 MHz, respectively. The simulated average bore-sight gain and bandwidth of the X-band center element were 4.5 dBi and 1.96 GHz, respectively. Finally, array patterns were achieved using active element patterns of all nine X-band elements. The maximum array gains at 10 GHz by simulation and measurement were 13.6 dBi and 13.2 dBi, respectively. The results demonstrated that the proposed antenna was suitable for shared-aperture radar applications.
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