Dual Polarized Array Antenna for S/X Band Active Phased Array Radar Application

Minseok Han[1] · Juman Kim[1] · Daesung Park[2] · Hyoungjoo Kim[2] · Jaehoon Choi[1]

Abstract

A dual-band dual-polarized microstrip antenna array for an advanced multi-function radio function concept (AMRFC) radar application operating at S and X-bands is proposed. Two stacked planar arrays with three different thin substrates (RT/Duroid 5880 substrates with ε_r=2.2 and three different thicknesses of 0.253 mm, 0.508 mm and 0.762 mm) are integrated to provide simultaneous operation at S band (3～3.3 GHz) and X band (9～11 GHz). To allow similar scan ranges for both bands, the S-band elements are selected as perforated patches to enable the placement of the X-band elements within them. Square patches are used as the radiating elements for the X-band. Good agreement exists between the simulated and the measured results. The measured impedance bandwidth (VSWR≤2) of the prototype array reaches 9.5 % and 25 % for the S- and X-bands, respectively. The measured isolation between the two orthogonal polarizations for both bands is better than 15 dB. The measured cross-polarization level is ≤－21 dB for the S-band and ≤－20 dB for the X-band.

Key words : Dual Polarized, Array Antenna, Dual Band (S and X Bands), Radar, Active Phased Array.

Ⅰ. Introduction

Embedded in the superstructure of future navy ships will be a variety of antenna arrays that will perform different functions such as radar. The advanced multi-function RF concept (AMRFC) testbed has separate Tx and Rx arrays that were designed for future surface ships in an effort to provide the capability to perform a variety of functions [1]. The performance goal of AMRFC is to provide these functions in a near-concurrent and non-interfering manner [2]. Due to the many advantages of performance improvement for various function systems, the development of modern AMRFC radar systems requires advanced antennas operating in multiband with multi-polarization. In general, a dual-polarized operation can provide more useful information about target features, enhance the isolation between transmitter/receiver, and double the capacity of communication systems by means of frequency reuse [3, 4]. A multiband operation, on the other hand, can provide a finer resolution scanning and better penetration and reflection data from various scatterers.

Recently dual-band and dual polarized antenna arrays have been widely studied for satellite and wireless communication applications, particularly for synthetic aperture radar (SAR) applications [5～9]. Operating frequencies are usually widely separated (typically some combination of L-, C-, S- or X-bands) and, require different array element spacing to avoid grating lobes. This spacing implies that an interleaved arrangement of elements at each band needs to be optimized. In [5], a dual-frequency (S-band and X-band) antenna for airborne applications was proposed, but this array has narrow bandwidth at both S-and X-bands. A dual-band dual-polarized array design consisting of four double dipole radiators for WLAN applications [6] was suggested to provide very low cross-polarization levels. However, these techniques can not be utilized for the AMRFC radar applications due to their complex structures. A compact three-layer shared-aperture dual-band dual-polarized subarray operating in L/C-band was proposed in [7]. However, the bandwidth was narrow. In [8], a dual-polarized X-band array antenna was proposed but its bandwidth was also narrow. A dual-band dual polarized hybrid antenna array with a combination of microstrip antenna and dielectric resonator antenna (DRA) elements was proposed in [9], but it has a narrow bandwidth in the X-band. Although many dual-polarized antennas have been proposed, not all of them are good candidates for array design, due to their complex structures, complex feeding-line networks, and narrow bandwidth. In addition, many of them are bulky and heavy, and therefore not suitable for AMRFC radar applications.

In this paper, a novel dual-band dual-polarized (DBDP)

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microstrip array antenna for AMRFC radar application is proposed. The proposed antenna operates at S- and X-bands with a frequency ratio of about 1:3. For the dual-band operation, a multi-layer structure is adopted. Since the perforated patches are used in S-band and are located at the space between the X-band square patches, their lengths can be adjusted within a relatively larger range, resulting in a flexible frequency ratio. The configuration of the DBDP antenna array is presented in the following sections and the parameters affecting the array characteristic are analyzed.

Ⅱ. Antenna Structure

The performance specifications of the antenna to be designed are shown in Table 1. Since the array should have scan capability at both azimuth and elevation planes, no power combiner is printed in the array layer.

The behavior of an array in radar systems is far more complex than that of a passive, mechanically positioned antenna, because the performance characteristics vary with the scan angle. If the element spacing exceeds a critical dimension, grating lobes occur in the array factor. The grating lobe may be suppressed somewhat by the element pattern zero for a broadside array. However, when the array is scanned, the grating lobe location moves away from the null and can be a substantial source of radiation. A criterion for determining the maximum element spacing for an array scanned to a given scan angle θ_0 at frequency f is to set the spacing so that the nearest grating lobe is at the horizontal plane, which leads to the following condition [10]. To avoid the effects of array blindness, the element spacing d_x has to satisfy this condition

$$\frac{d_x}{\lambda_0} \le \frac{1}{1+\sin\theta_0} \tag{1}$$

where λ_0 is the wavelength at the highest operating frequency f_0, which requires spacing not much greater than one-half wavelength for wide angles of scan and θ_0 is given a scan angle at the at the highest operating frequency f_0.

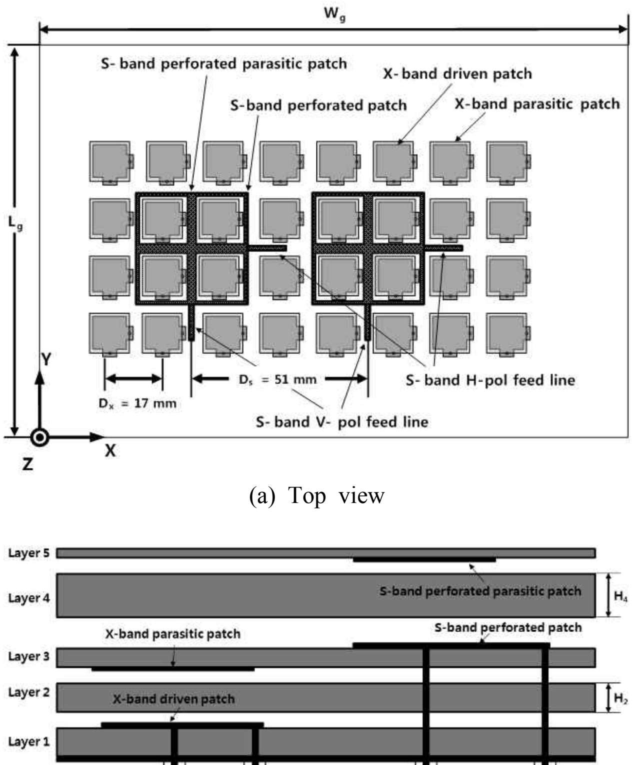
Table 1. Performance specifications for dual-band dual-polarized S- and X-band array antenna.

Parameters	S-band	X-band
Frequency [GHz]	3～3.3 GHz	9～11 GHz
Bandwidth	300 MHz	2 GHz
Polarization	dual-linear	dual-linear
Scan range	±45°	±45°
Cross-polarization	<－20 dB	<－20 dB

To meet the scan range (±45°) requirement, the X-band element spacing is selected to be 17 mm, about 0.56 λ_1, and the S-band element spacing is 51 mm (about 0.54 λ_2) which is three times that selected for the X-band. λ_1 and λ_2 are the wavelengths, calculated in free space at the center frequencies of the S-band and X-band, respectively.

The proposed DBDP array adopts a multi-layer array structure for its multi-function purpose. The array is designed for the operation at the S band (3～3.3 GHz) and X band (9～11 GHz), the geometry of which is shown in Fig. 1. The layer parameters of the multi-layered substrate configuration for the DBDP array are listed in Table 2. The rectangular array was applied to the proposed DBDP array. The structure of the 8×4 array was applied for ease of fabrication and measurement of the T-junction power divider.

Since the bandwidth requirements of both bands are very wide, which is difficult to achieve using a single-layer configuration, parasitic elements are placed above the driven elements to broaden the bandwidth. Every dual polarized antenna element for both bands has two coaxial connectors beneath the substrate of the antenna. Therefore, a dual-polarized S-band 2×1/ X-band 8×4 ar-



(a) Top view

(b) Side view

Fig. 1. Geometry of proposed dual-band dual polarized array antenna.

Table 2. Layer parameters.

Layer	Material	ε_r	Thickness (mm)
Layer 1	RT/Duroid 5880	2.2	0.762
Layer 2	Foam layer	1.07	H_2
Layer 3	RT/Duroid 5880	2.2	0.508
Layer 4	Foam layer	1.07	H_4
Layer 5	RT/Duroid 5880	2.2	0.254

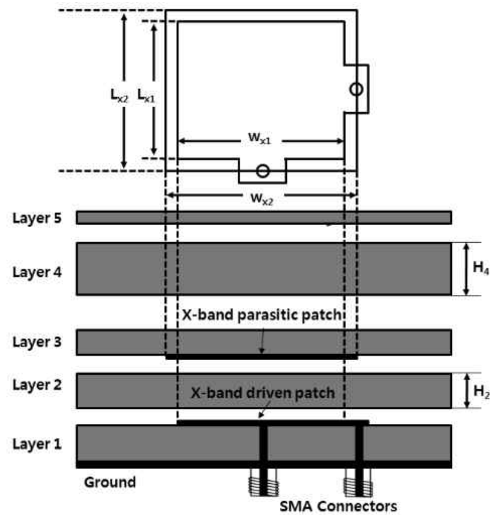


Fig. 2. Top and side views of stacked dual-polarized X-band driven patches and parasitic patches.

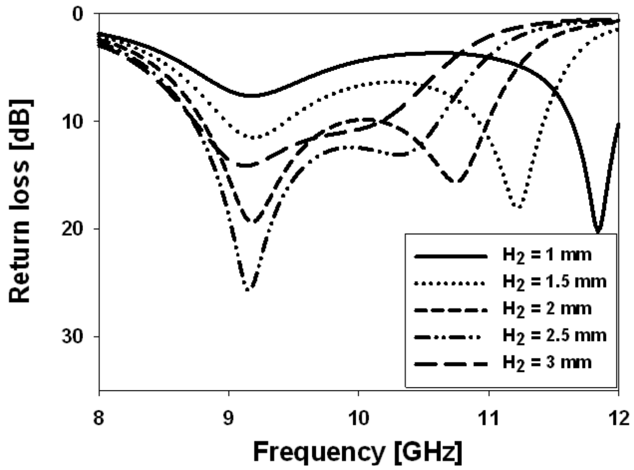


Fig. 3. Simulated return loss characteristics for various values of height (H_2) between layer 1 and layer 3.

ray has sixty eight coaxial connectors. For the X-band array, stacked square patches were selected as its unit element. The driven patch has a length of 9.6 mm and the parasitic patch has a length of 10.6 mm.

It should be noted that the height of the foam layer 2 affects the coupling between the S-band driven square patches and parasitic square patches. Thus, the height of the layer 2 should be adjusted very carefully both to widen the bandwidth and to improve the impedance matching characteristic. Fig. 3 shows the simulated return loss characteristics for various values of height (H_2) between layer 1 and layer 3. As the height (H_2) of foam layer 2 changes from 1 mm to 3 mm, the second resonance frequency varies from 11.8 to 9.98 GHz but the first resonance frequency is hardly changed. The impedance matching characteristics can also be changed by adjusting the height (H_2) of foam layer 2.

An important design consideration for this multilayer dual-band array is that the S-band antenna elements should be nearly transparent to the X-band antenna elements. Otherwise, the S-band elements may degrade the performance of the X-band antenna. Two stacked perforated patches with different polarizations are used for the S-band, as shown in Fig. 4. Four square perforations were placed in the S-band patch surface to allow radiation from the X-band patches located on the lower substrate. The perforations in the S-band element should be large enough so that the radiation from the X-band patches is relatively unimpeded. The loading caused by the perforations has the beneficial effect of making the S-band patch smaller.

It should be noted that the height of foam layer 4 affects the coupling between the S-band driven perforated patches and the perforated parasitic patches. Thus, the height of layer 4 should be adjusted very carefully to

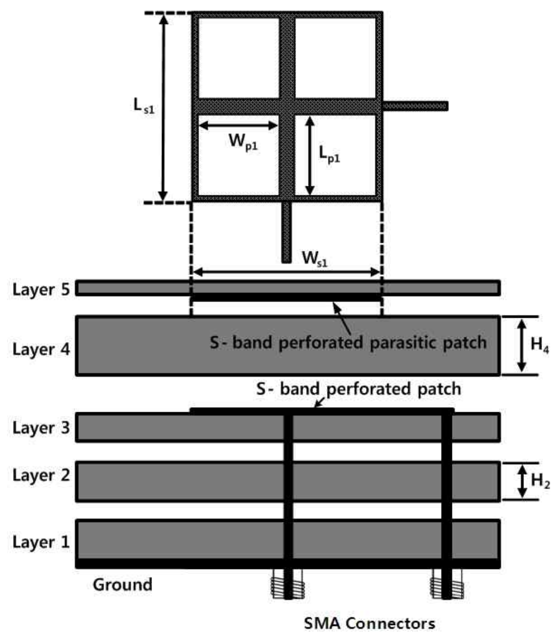


Fig. 4. Top and side views of stacked dual-polarized S-band perforated patches and S-band parasitic perforated patches.

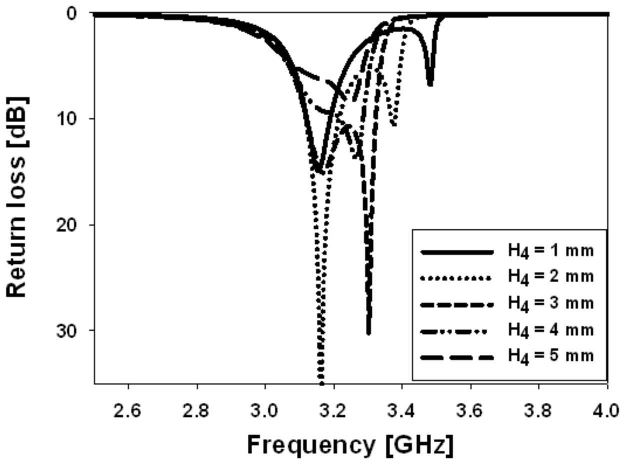


Fig. 5. Simulated return loss characteristics for various values of height (H_4) between layer 3 and layer 5.

Table 3. Final design parameters for the proposed DBDP array antenna.

Parameter	Value (mm)	Parameter	Value (mm)
L_g	128	L_{s1}	32
W_g	196	W_{s1}	32
L_{x1}	9.6	L_{x2}	10.6
W_{x1}	9.6	W_{x2}	10.6
H_2	2	H_4	3

widen the bandwidth and improve the impedance matching characteristic. Fig. 5 shows the simulated return loss characteristics for various values of height (H_4) of the foam layer 4 between layer 3 and layer 5. As the height (H_4) of the foam layer 4 changes from 1 mm to 5 mm, the second resonance frequency varies from 3.48 to 3.21 GHz, however, the first resonance frequency is hardly changed. The impedance matching characteristics can also be controlled by adjusting the height (H_4) of the foam layer 4.

The proposed dual-polarized array antenna has been simulated and designed with the aid of the commercially available simulation software MWS [11] in order to optimize the geometrical parameters of the array antenna. The final design parameters for the proposed DBDP array antenna are listed in Table 3.

Ⅲ. Simulated and Measured Results

The fabrication of the antenna array is quite complex due to its multilayered configuration and external feed network. Fig. 6 shows a photograph of the S-band 2×1/X-band 8×4 prototype array with an external feed network. Unlike references [5～9], an external feed network is chosen in this paper in order to implement the complete feed network for an active phased array which will be delivered in the near future. The external feed network consists of four 1×8 T-junction power dividers for the X-band, one 1×4 T-junction power divider for the X-band, and two 1×2 T-junction power dividers for S-band. The T-junction power dividers were fabricated for testing active phased array. In this paper, a linear array that is made up of elements having equal amplitudes and a constant-phase difference between adjacent ones was used.

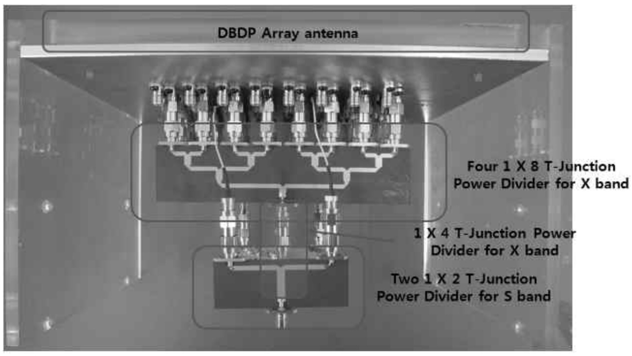
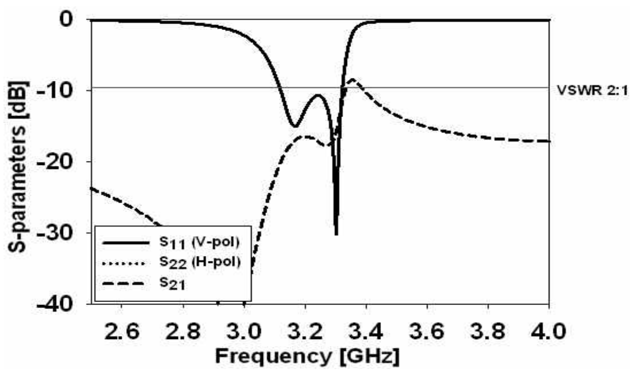


Fig. 6. Photograph of prototype DBDP antenna array for active phased array system.

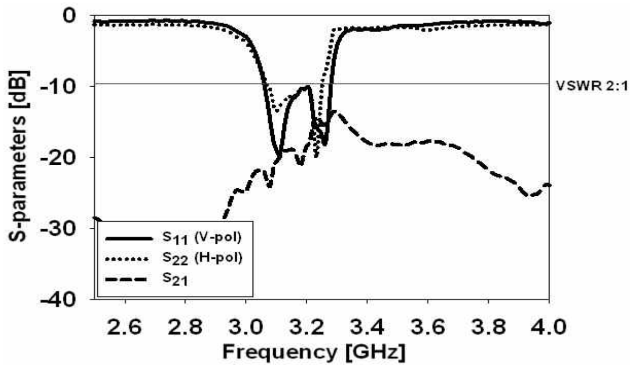
The simulated and measured S-parameter characteristics of the S-band stacked perforated patch array are shown in Figs. 7a and b, respectively. The measured resonance frequencies of the S-band are slightly lower (about 30 MHz) than the simulated ones. The measured bandwidth of VSWR≤2 is 9.5 % from 3.0 GHz to 3.3 GHz. On the other hand, the bandwidths of the S-band arrays introduced in references [5] and [9] are 0.65 % (from 2.95 GHz to 2.97 GHz) and 6.2 % (from 3.1 GHz to 3.3 GHz), respectively. The isolation between the two orthogonal polarizations is ≥15 dB within the operating band.

The simulated and measured S-parameter characteristics of the X-band stacked rectangular patch element are shown in Figs. 8(a) and (b), respectively. For the X-band array, the measured bandwidth of VSWR≤2 reaches 25 %, from 8.5 GHz to 11 GHz. Since the X-band rectangular patch antenna is probe-fed, the measured isolation between the V-port ant the H-port (S_{21}=S_{12}) is better than 15 dB.

It was found in the experiment that the overlaying S-band perforated patch had little effect on the resonant frequency or input impedance of the X-band array, which is apparent because the perforation openings are large enough relative to the thickness of the L-band patch substrate so that the X-band elements could radiate relatively unimpaired by the surrounding metallization of the perforated element. This result greatly both simplifies

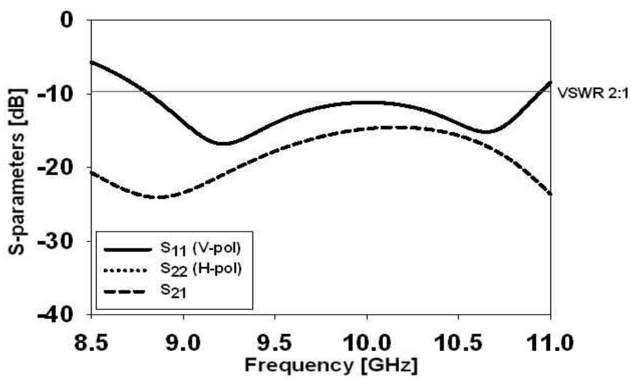


(a) Simulated S-parameter characteristics

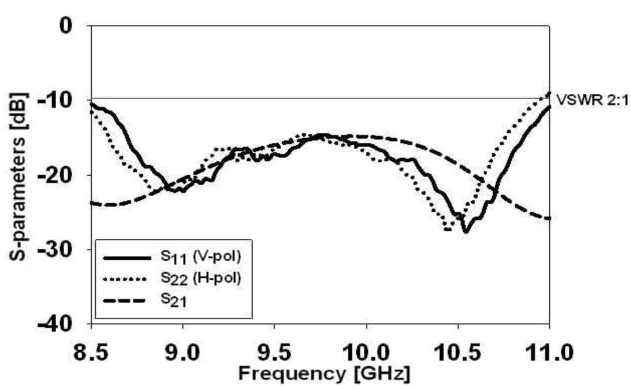


(b) Measured S-parameter characteristics

Fig. 7. S-parameter characteristics of the S-band array.



(a) Simulated S-parameter characteristics



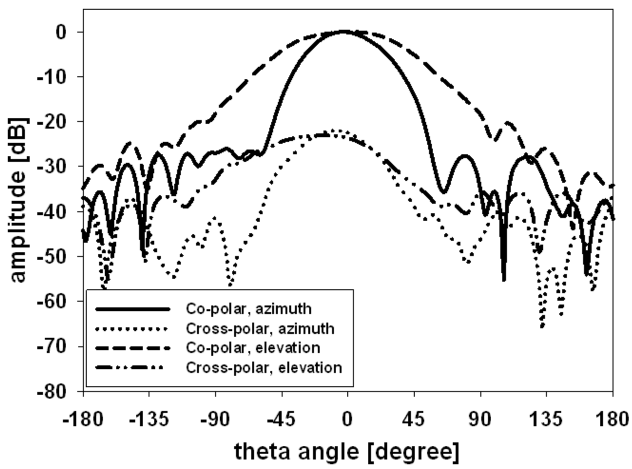
(b) Measured S-parameter characteristics

Fig. 8. S-parameter characteristics of the X-band array.

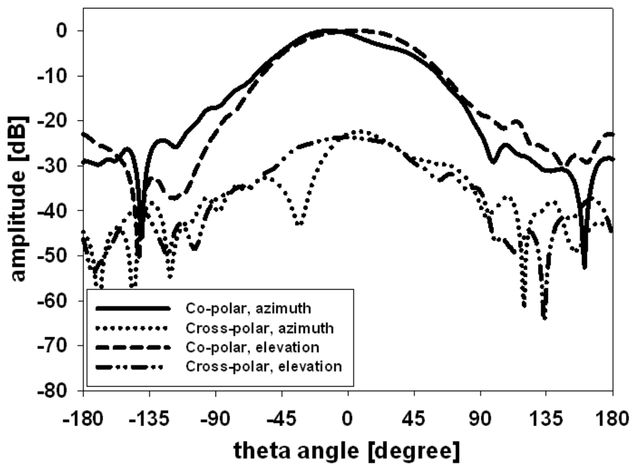
the design of the array and allows the same X-band elements to be used both directly below the S-band patches and in the spaces between these elements. It is speculated that the loading effect of the S-band patches may be more significant for a scanned array, in which case it may be helpful to place parasitic X-band patches in the perforation openings to form a stacked structure.

The measured co-polar and cross-polar radiation patterns of the S-band array, at the center frequency (3.1 GHz) of the S-band, are shown in Figs. 9(a) and (b), respectively. The cross-polarization levels in both the E-plane and the H-plane are lower than −21 dB and the side lobe levels are lower than −19 dB. The maximum measured array antenna gain is 10 dBi.

For the X-band array, the measured co-polar and cross-polar radiation patterns of the horizontal and vertical polarizations, at the center frequency (10 GHz) of X-band, are plotted in Figs. 10(a) and (b), respectively. In both the E-plane and the H-plane, the cross-polarization

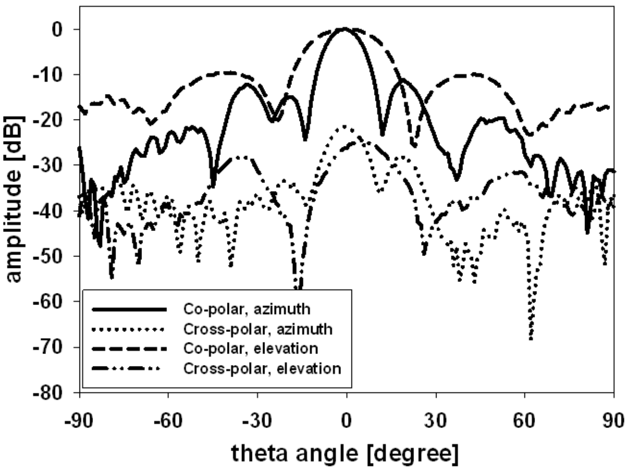


(a) H-port is excited

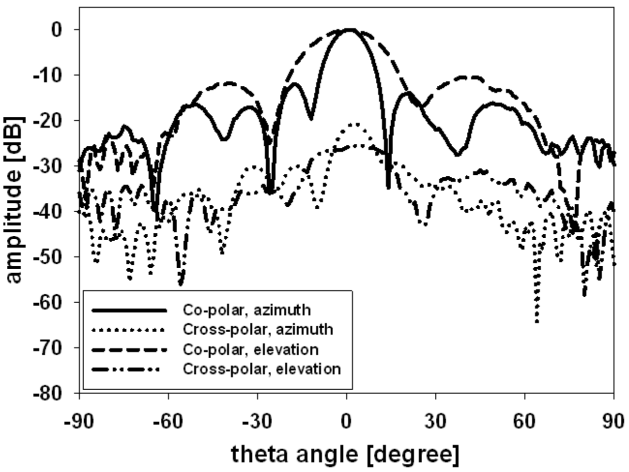


(b) V-port is excited

Fig. 9. Measured radiation patterns of the S-band 2×1 array antenna at 3.1 GHz.



(a) H-port is excited



(b) V-port is excited

Fig. 10. Measured radiation patterns of the X-band 8×4 array antenna at 10 GHz.

levels are lower than −20 dB and the side lobe levels are lower than −10 dB. The maximum measured array antenna gain is 20.3 dBi.

Ⅳ. Conclusions

In this paper, a dual-band dual-polarized array antenna for an AMRFC radar application operating at S- and X-bands was proposed. By using a combination of stacked perforated patches and stacked square patches, a DBDP array with a frequency ratio of about 1:3 was developed. The configuration of the multilayered array was introduced. The simulated and measured S-parameter characteristics as well as the measured radiation patterns for both bands were presented. The measured impedance bandwidth (VSWR≤2) of the prototype array reached 9.5 % and 25 % for the S- and X-bands, respectively, and the measured isolation between the two orthogonal polarizations for both bands was better than 15 dB. The measured cross-polarization level was ≤−21 dB for the S-band and ≤−20 dB for the X-band. The experimental results confirm the practicability of the DBDP antenna array with a flexible frequency ratio, which is an attractive advantage for future active phased array antenna such as AMRFC radar application systems. Further research on the performance improvement applied to future active phased array antenna and the analysis of the change of antenna characteristic based on various scan angles will be carried out. In addition, array size expansion (S-band 2×2 array and X-band 8×8 array) will be conducted.

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