Abstract—The scattering characteristics of a phased array depends on its feed network. The variation of scattered fields within the feed network affects the antenna mode scattering. In this paper, an attempt is made to determine the radar cross section (RCS) of a planar array with parallel-feed network. The scattered field of the array is obtained by following the path of the signals through the antenna system. This yields the scattered field in terms of reflection and transmission coefficients at each stage of the feed network. The simulation results are presented to emphasize the effect of design parameters like number of antenna elements, inter-element spacing, beam scan angle and the level of couplers on the RCS pattern. The analysis presented can be used for designing the phased arrays with reduced RCS, suitable for stealth applications.

Keywords—Radar cross section (RCS); parallel feed network; reflection coefficient; transmission coefficient

I. INTRODUCTION

The scattering of the signals by an antenna array depends on the geometry of the array, its frequency of operation and the employed feed network. For a phased array operating with a frequency equal to that of the radar, the effect of array geometry and the feed network become prominent [1]. In general, the feed network comprises of orderly arranged radiators, phase shifters and couplers. As all these devices will not possess identical terminal impedances, significant mismatches might exist at each level of the feed network. This results in the reflection of the incident signal which propagates from the radiators (array aperture) towards the receive port. These individual scattered fields might add-up coherently under certain scenarios to yield a significant value of radar cross section (RCS).

Several techniques have been reported in open domain to estimate and optimize the RCS of the phased array [2]-[4]. However these approaches do not explain the contribution of each individual level of the feed network towards the total scattering cross section of array. In [5], RCS of a series-fed phased array is estimated using an approximate method. Similar method was extended to an array with parallel-feed network [1]. However neither of these presents analysis on the variation of RCS pattern due to the changes in the array parameters. The formulation used to arrive at the RCS of the phased array is presented in Section 2. In Section 3, simulation results showing a detailed parametric study are discussed for both linear and planar phased arrays. Finally the analysis is summarized in Section 4.

II. RCS OF PHASED ARRAY WITH PARALLEL FEED

A typical 8-element parallel-fed phased array, consisting of radiating elements ($A_i$), phase shifters ($P_i$), and three levels of couplers, is shown in Fig. 1. All the elements in the array are considered to be identical. Moreover the radiators are considered to be isotropic and the couplers are assumed to be hybrid couplers to simplify the analysis. The reflection and transmission coefficients associated with the feed network components are ($r_r$, $r_p$, $r_c$, $r_d$) and ($t_r$, $t_p$, $t_c$) respectively. Here $r$, $p$ and $c$ indicate radiators, phase-shifters and couplers respectively. In addition, the reflection coefficients at the sum and difference ports of the couplers are represented as $r_c$ and $r_d$ respectively.

The scattered field at $(m,n)$ element is given by

$$E_m^s(\theta, \phi) = \frac{j}{\lambda} A_m e^{-j\beta R} e^{j[(m-1)\alpha n - (n-1)\beta]} E_m^r(\theta, \phi)$$  \hspace{1cm} (1)$$

where $\lambda$ is the wavelength, $R$ is the distance between the target and the observation point, $E_m^r$ is the total reflected
signal, \( \tilde{k} = k(\hat{x}\sin\theta\cos\beta + \hat{y}\sin\theta\sin\phi + \hat{z}\cos\theta) \) is the wave vector, \( \alpha = k_d d\sin\theta\cos\phi \), \( \beta = k_d d\sin\theta\sin\phi \). \( A_i = d_i d\cos\theta \), with \( d_i \) and \( d \) being the inter-element spacing along \( x \)- and \( y \)-directions, respectively.

The dependence of scattered field on the feed network is indicated by the factor \( E_{m}^{3}(\theta, \phi) \) of (1). This total field is obtained by tracing the path of the signals assuming the array to be operating in receive mode. The first source of scattering for an incident plane wave is the junction of radiating element and the phase-shifter. This yields the scattered field and the RCS due to radiators as

\[
E_{mn}^{\text{sc}} = e^{j[(m-1)2\pi x + (n-1)\beta]} r_m e^{j[(m-1)2\pi x + (n-1)\beta]}
\]

(2)

\[
\sigma_{\text{r}} = \frac{4\pi^{2}}{\lambda_{0}^{2}} \sum_{m=1}^{N_x} \sum_{n=1}^{N_y} r^2_m e^{j[2\pi x ((m-1)\beta)]} \left( \frac{\sin\left(N_x\alpha\right)}{\sin\alpha} \right)^2 \left( \frac{\sin\left(N_y\beta\right)}{\sin\beta} \right)^2
\]

(3)

Thus the RCS due to scattered fields at phase shifters is

\[
\sigma_{\text{p}} = \frac{4\pi^{2}}{\lambda_{0}^{2}} t^2 p e^{j[2\pi x ((m-1)\beta)]} \left( \frac{\sin\left(N_x\alpha\right)}{\sin\alpha} \right)^2 \left( \frac{\sin\left(N_y\beta\right)}{\sin\beta} \right)^2
\]

(4)

The signal, which survives the reflections at both radiators and the phase-shifters, undergoes a phase shift as determined by the beam scan angle. This signal which arrives at the input port of the couplers give rise to the scattered field and hence the RCS given by

\[
E_{mn}^{\text{sc}} = r^2_m e^{j[2\pi x ((m-1)\beta)]}
\]

(6)

\[
\sigma_{\text{c}} = \frac{4\pi^{2}}{\lambda_{0}^{2}} t^4 c e^{j[2\pi x ((m-1)\beta)]} \left( \frac{\sin\left(N_x\alpha\right)}{\sin\alpha} \right)^2 \left( \frac{\sin\left(N_y\beta\right)}{\sin\beta} \right)^2
\]

(7)

where, \( \zeta = \alpha + \alpha_s \), \( \eta = \beta + \beta_s \), \( \alpha_s = k_d \sin\theta\cos\phi \) and \( \beta_s = k_d \sin\theta\sin\phi \). The signal transmitted from the input port of couplers may move either towards the sum or the difference arm of the hybrid tees (couplers). Further the signal suffers the reflection at each level of the coupler in the network. If the reflections at all the stages of feed network except for the first stage are neglected, then the expressions for the RCS due the reflections from sum and difference arms of the couplers will be

\[
\sigma_{\text{c}} = \frac{4\pi^{2}}{\lambda_{0}^{2}} t^4 c e^{j[2\pi x ((m-1)\beta)]} \left( \frac{\sin\left(N_x\alpha\right)}{\sin\alpha} \right)^2 \left( \frac{\sin\left(N_y\beta\right)}{\sin\beta} \right)^2
\]

(8)

Thus the total RCS for a parallel-fed planar array will be

\[
\sigma(\theta, \phi) = \sigma_{\text{r}} + \sigma_{\text{p}} + \sigma_{\text{c}} + \sigma_{\text{h}}
\]

(10)

Although the formulations presented consider the array geometry to be planar, they are applicable even for linear arrays.

III. SIMULATION RESULTS

The effect on the RCS pattern due to the increase in the number of antenna elements from 20 to 40 for a linear array is shown in Fig. 2. Other parameters are taken to be \( d = d_s = 0.5\lambda \), \( \theta = \phi = 0^\circ \) and \( r = 0.3 \). The highest lobe at \( \theta = 0^\circ \) can be attributed to specular scattering from the aperture. The lobes near \( \theta = \pm 85^\circ \) arise due to Bragg diffraction. Spikes at the position of \( \theta = \pm 30^\circ \) correspond to the mismatches between the first level couplers. It is seen that the lobes in the pattern become narrower, sharper and hence more pronounced, as the array size increases. This is because of the increase in the physical (and hence effective) area of phased array with the increase in number of array elements. However the location of the lobes in the pattern remains almost unchanged.

Next the effect of varying the inter-element spacing from 0.4\( \lambda \) to 0.5\( \lambda \) along the axis of the couplers is analyzed in Fig. 3. It is observed that the pattern exhibits the presence of Bragg diffraction lobes only if the spacing is equal to or greater than half wavelength. Although the location of the specular lobe remains unchanged, the location of the lobes due to the coupler mismatches varies. Moreover all the lobes in the pattern exhibit rise in their levels with an increase in the inter-element spacing due to the increase in effective area of the array.

Figure 2. Dependence of RCS of a parallel-fed linear array on the number of antenna elements. \( d_s = d_r = 0.5\lambda \), \( \theta = \phi = 0^\circ \) and \( r = 0.3 \).
Fig. 4 shows the dependence of the RCS pattern on the beam scan angle. It is seen that the scanning of the beam from 0° to 45° changes the RCS pattern drastically as the (i) Position of the lobes due to coupler mismatches changes, (ii) Additional lobes appear in the pattern, and (iii) Level of all the lobes changes. However the location of the specular lobe remains independent of scan angle although its level alters.

The equations for the scattered fields show that the amount of scattering is dependent on the magnitude of reflection coefficients. The effect of varying the reflection coefficients of the feed network components on the RCS is shown in Fig. 5. It is seen that the increase in the value of reflection coefficients increases the level of all the lobes in the RCS pattern. A similar effect is exhibited by an array which is scanned to an angle of 60°, as shown in Fig. 6.

Further the effect of varying different parameters on the RCS pattern incase of planar array is analyzed. A typical RCS pattern of a 8×8 planar array is shown as a contour plot in Fig. 7. Other parameters are taken to be \( d_x=d_y=0.4\lambda, \theta_s=\phi_s=0°, q=1 \) and \( r=0.3 \). It is apparent that the field level drops as one moves away from the principal planes \((u=0,v=0)\). The contour at \((u,v)=(0,0)\) can be attributed to specular scattering; those at \((-0.65,0)\) are due to the mismatches between the couplers at the first level.

The effect of varying the number of antenna elements from 32×32 to 32×24 on the RCS pattern is shown in the Fig. 8. It is observed that the location of the specular contour and the scattering due to first level couplers remains unaltered. However, the increase in number of elements makes the contours narrower and more pronounced. This is due to the change in effective area of the array.
Further, the effect of changing the interelement spacing along the axis of couplers from 0.5λ to 1.0λ is shown in Fig 9. It is seen that the increase in the spacing between the array elements increases the number of the contours in the pattern of RCS. This is because; greater the interelement spacing, larger will be the array aperture. This leads to the increase in the magnitude of scattered fields, which inturn increases the RCS. However the location of the contours in the pattern is shown to remain the same of either case.

Next, the role of beam scan angles is shown in Fig. 10. It is observed that six additional contours at (u,v)=±(0.5,±0.5); (0,±0.5) appear in the RCS pattern. These contours correspond to the antenna beam location and the scattering due to the mismatches at the first level couplers. This change in the pattern is due to the dependence of ζx and ζy on the scan angles. However, the RCS components arising from the reflections due to the radiating elements and the components before phase shifters remain unaffected. This is apparent from the unchanged position of the specular contour.

As the RCS of the array is the power reflected from the target towards the transmitter, it is largely governed by the reflection coefficients of the components in the feed network.

Fig. 11 presents the broadside RCS pattern for reflection coefficients of 0.1 and 0.3. It is observed that the increase in the value of reflection coefficient makes the contour to look more pronounced as it increases the level of RCS. This is indicated by the increased level of RCS in the pattern. However the location of the contours remains unchanged. The effect observed is shown to be independent of beam scan angle as shown by Fig. 12. A similar phenomenon was observed in case of linear array (Fig. 6). This indicates that it is possible to reduce the RCS by reducing the scattering due to the mismatches in the feed network. Thus the design of a low scattering platform requires the design of a feed network with well matched devices.
IV. SUMMARY

In this paper, the RCS of a parallel-fed phased array is computed as the coherent sum of individual scattered fields from each level of the antenna system. The simulation results analyze the effect on the RCS pattern of a parallel-fed phased array due to the variation of different design parameters. The analysis of parametric variation for both linear and planar array show the effect observed is similar in either case. However the changes in the linear array manifests in the form of lobes whereas in planar array they are in the form of contours.

The increase in the number of antenna elements, and hence the effective aperture is shown to narrow the lobes or contours by making them sharper. This causes an enhanced visibility of the lobes or contours due to the increasing aperture area. Although a rise in their level is evident, their location remains unchanged. The variation of interelement spacing along the axis of couplers is shown to increase the number of lobes or contours appearing in the RCS pattern. The scanning of beam is shown to affect the RCS pattern by changing both the location and the levels of lobes or contours. Moreover additional contours are found to appear in the RCS pattern due to the change in the inter-element phase delay. However, the RCS contributions due to the radiating elements and the components before the phase shifters remain fixed, as evident from the specular contour.

The study of RCS pattern for a variation in the reflection coefficients is presented to show that the scattering is majorly affected by the reflection coefficients. The value of reflection coefficient and the RCS are shown to be directly proportional. This indicates that the minimization of individual scattering sources by an efficient design of the feed network would lead to a significant reduction in the RCS of the phased array.

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