Retrodirective Array Augmentation for Electronic *RCS* Modification

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***Abstract*—In this paper, an active Pon type retrodirective array (RDA) is augmented with a passive array in order to provide electronic modification of the transmit function of the combination in response to the influence of an external interrogating signal. By the use of a single phase shifter and level setting control, it will be shown that different types of broadcast mode can be initiated. The first of these is the self-tracking capability normally associated with a Pon heterodyne RDA. Broadside radiation production associated with a conventional in-phase fed passive array operating in transmission mode is also demonstrated. Additionally, new modes of operation which include the use of the configuration are described: 1) as a radiation nulling device; 2) its use as a sidelobe suppressor; and 3) as a beamwidth control device.**

***Index Terms*—Adaptive antenna, radar crosssection, retrodirective array, self-tracking array.**

I. Introduction

IN MANY applications, it is required to desensitize in a particular direction the spatial pattern of a transmit antenna array in order to prevent jamming [1]. In other applications, it is required to make the antenna array transmission have a shaped beam characteristic which permits it to send a signal in a direction which previously may have been directed along a sidelobe null of the antenna array, thereby enabling the transmitter to make a general broadcast announcing its presence. At other times, we may wish that in response to a signal from an interrogating unit that no energy is returned to the interrogator (unfriendly) or conversely that energy is broadcasted only to the interrogator (friendly). With these applications, in mind we propose in this paper, a new active antenna array architecture and analysis formula which demonstrate practically and theoretically that under certain operating conditions all of these modes of operation can be made to occur with the same antenna array under the control of a 1-bit phase shifter and a single variable-gain amplifier.

The purpose of this paper is to show by means of a theoretical and practical assessment that a standard array of identical radiating elements, in this case dual–port microstrip patch elements, with equal phase and magnitude excitation when operated in parallel combination with an active retrodirective antenna array (which shares the same radiating elements as the passive conventional array) can be made to exhibit interesting and useful features which could potentially be exploited for communications and radar cross-section modification applications.

It should be noted that, since phase conjugation in the Pon structure is locally defined on a per radiation element basis at each conjugation mixer, then the array can be deployed in a conformal arrangement assuming that its augmentation is with a passive conformal or volumetric array. In the work described here, we consider only a planar augmented array configuration.

In the past, retrodirective beam formation techniques have been used for pattern modification [2], [3]. However, these approaches, while carrying the same name as the approach to be developed in this paper, operate on different principles that do not exploit the automatic self-tracking array augmentation technique discussed in this paper. To the authors' knowledge, all previous implementations calculate, using conventional adaptive array theory [1], the required magnitudes and phase cancellation weights needed to nullify the beam in a particular direction. This normally requires that the same number of attenuators and phase-shifting elements as radiating elements in the array be used; often, digital control algorithms are also deployed. The example in [3] shows a particularly simple embodiment of this strategy as applied to the specific example of sidelobe nulling.

II. Augmented RDA Architecture

The architecture for the proposed setup is shown in Fig. 1. Here, a Pon [4] type retrodirective, self-tracking antenna array is operated in parallel with a classical passive array; both share the same radiating elements. With reference to Fig. 1, the return loss at the Tee interconnection points marked "x" were measured to be less than -8 dB and all local oscillator (LO) and RF feed cables were phase matched to within three degrees. In this paper, the radiating elements are two-port rectangular microstrip patch antenna elements designed to operate at 1 GHz with a return loss <-12- and >30-dB orthogonal port isolation (see [5] for a detailed description of the antenna elements).

The operation of the Pon self-tracking array is such that, by a mixing process the phase of an incoming signal with a given angle of arrival (AOA) has its phase conjugated. By selecting after mixing the lower sideband of the fundamental mixing product between the RF signal ($\omega_{\rm RF}+\phi$) and the LO signal at ($\approx 2\omega_{\rm RF}$) this phase conjugated signal ($\omega_{\rm RF}+\phi$) is returned to the antenna. Here it is retransmitted in the direction in which it was incident. In this way, the retransmitted signal follows the spatial position of the incoming waveform without the need for additional beam-forming electronics [6], [7]. The phase-conjugate circuits shown shaded in Fig. 1 have a 30-dB conversion gain when operated at 1 GHz with -20- to -40-dBm incident RF signal level, with 0-dBm LO drive.

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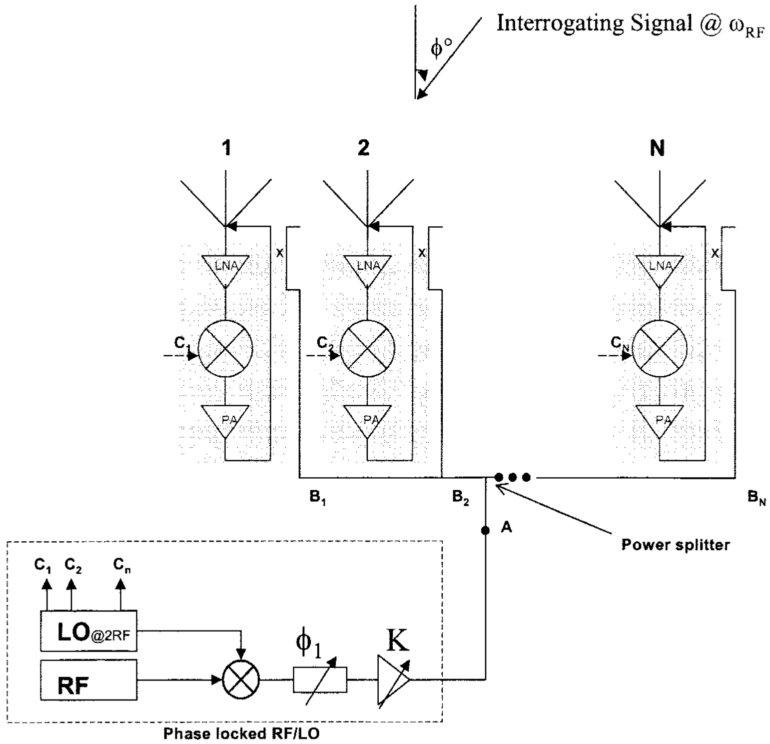


Fig. 1. Augmented RDA.

Next a classical passive array, with feed points B_1 to B_N (see Fig. 1), is overlaid on the Pon retrodirective array. This passive radiating structure operates according to normal antenna array principles, producing far-field reinforcement for equal in-phase excitation at broadside to the antenna array.

To complete the arrangement, an LO running at twice the incoming interrogating RF signal frequency is synchronized to the RF oscillator in order to phase lock the phase-conjugated IF signal at frequency $f_{\rm RF}$ to the passive array transmission frequency, which is also at $f_{\rm RF}$.

Synchronization could be achieved by doubling the RF signal and using this as the LO signal. Alternatively, an offset mixing arrangement can be used to produce an RF signal that is phase locked to the LO signal. This is the preferred method for the work presented in this paper. In the case of our work, the RF interrogation frequency selected is 980 MHz while the LO frequency is 2006 MHz, giving a retransmitted signal at 1026 MHz. This frequency offset was introduced together with orthogonal linear polarization diversity between the interrogation and retransmitted signals in order to expedite a simplified monostatic *RCS* measurement setup [5].

III. Augmented Array Model

For the arrangement in Fig. 1, we can write the composite reradiated electric field strength as

$$E = \exp j\omega t \sum_{i=1}^{N} g_c^i(\phi) \times \left\{ C_i \exp j \left[\frac{2\pi x_i}{\lambda} (\sin\phi_t - \sin\phi_r) - \psi_i' \right] + L_i \exp j \left[\frac{2\pi x_i}{\lambda} (\sin\phi_t) + \delta_i \right] + e^{j\phi 1} \right\} \quad (1)$$

which allows the bi-static radiation pattern for the augmented array to be established since ϕ_r, ϕ_t can both be varied. The parameter definitions used in this equation are as follows:

- $g_c^i(\phi)$ the ith individual element radiation pattern measured *in situ*;
- C_i retrodirective retransmitted conjugate signal;
- L_i direct-feed signal level;
- N the total number of antenna elements in the array;
- λ free-space wavelength of the array's operating frequency;
- ϕ_r angle (from the boresight) of the received signal arriving at the array;
- ϕ_t angle (from the boresight) of the retransmitted signal leaving the array;
- x_i distance of the ith element from the center of the array;
- ω angular frequency of the array;
- ψ' total phase delay introduced in the retrodirective elements;
- δ_I phase delay introduced in the direct-feed signal;
- ϕ_1 switchable phase offset in the RF chain.

The electric field strength associated with the direct signal from the passive array will be called "L," while that from the Pon phase-conjugate circuit will be called "C." By varying the ratio of these two signals, the antenna array shown in Fig. 1 can be made to exhibit five different and potentially useful modes of operation.

IV. Modes of Operation

Using the theoretical assessment of the augmented array's bi-static behavior as provided by (1), we first show here for illustration purposes two basic results [1) and 2)]. We also show more advanced uses for the augmented array [3) and 4)].

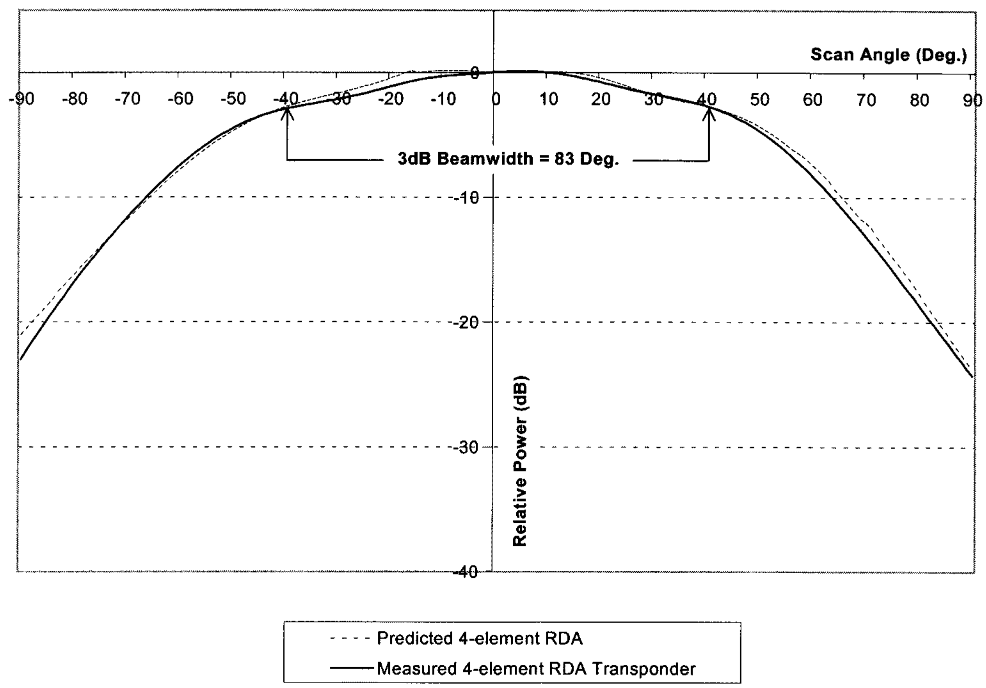


Fig. 2. RDA action; $L/C < -30$ dB.

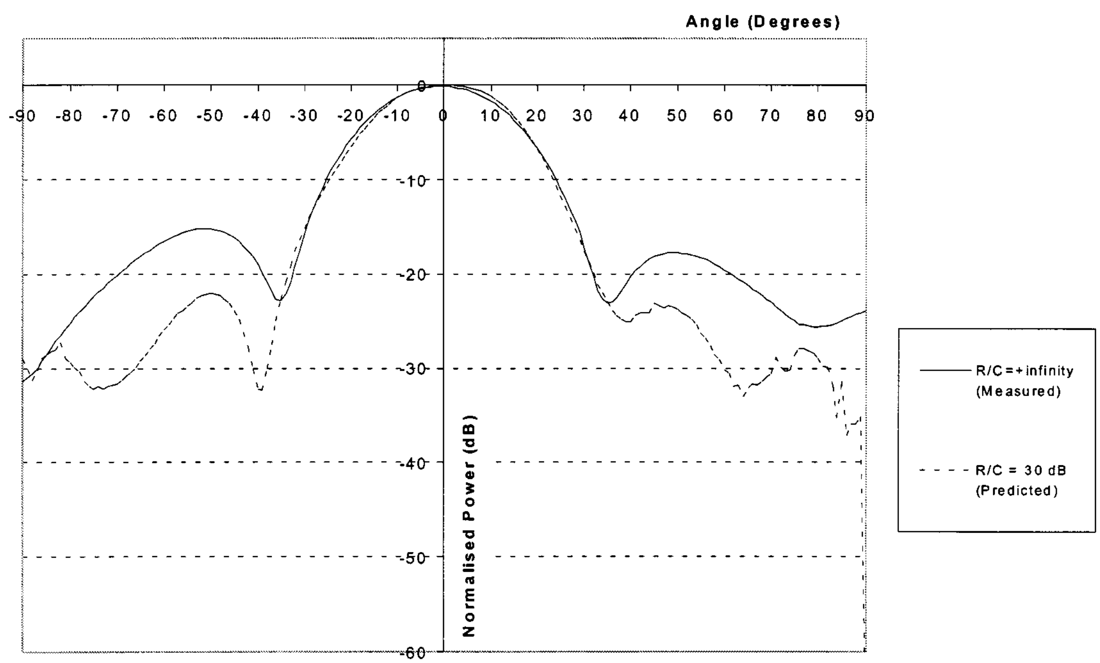


Fig. 3. Passive array action; $L/C > 30$ dB.

1) The array arrangement given in Fig. 1 is excited with a signal coming from boresight angles of $-90°$ to $+90°$, and the signal strength of the transmit power from the boresight passive array is adjusted so that the ratio of the value of the direct transmit signal level "L" to "C" the retrodirective array signal level is made to be <-30 dB. Here "C" represents the signal produced by the phase-conjugation circuit after its gain is taken into account. When operated in this mode, a selective rebroadcast of a friendly interrogating signal is made along a narrow spatial segment, i.e., normal RDA action is achieved [5].

At $L/C = -30$ dB, the signal from the conjugate circuit dominates and retrodirective action occurs with the main beam forming as expected along the AOA of the incoming signal. In this mode, the array in Fig. 1 is sensitized to the signal interrogating the array such that a narrow-beamwidth two-way communication path occurs [5]. Here, the beamwidth of the rebroadcast signal is defined by the size of the array aperture in the normal way. Fig. 2 shows the measured and predicted monostatic response for the arrangement in Fig. 1 when configured as a four-element array. In the work presented here, a four-el-

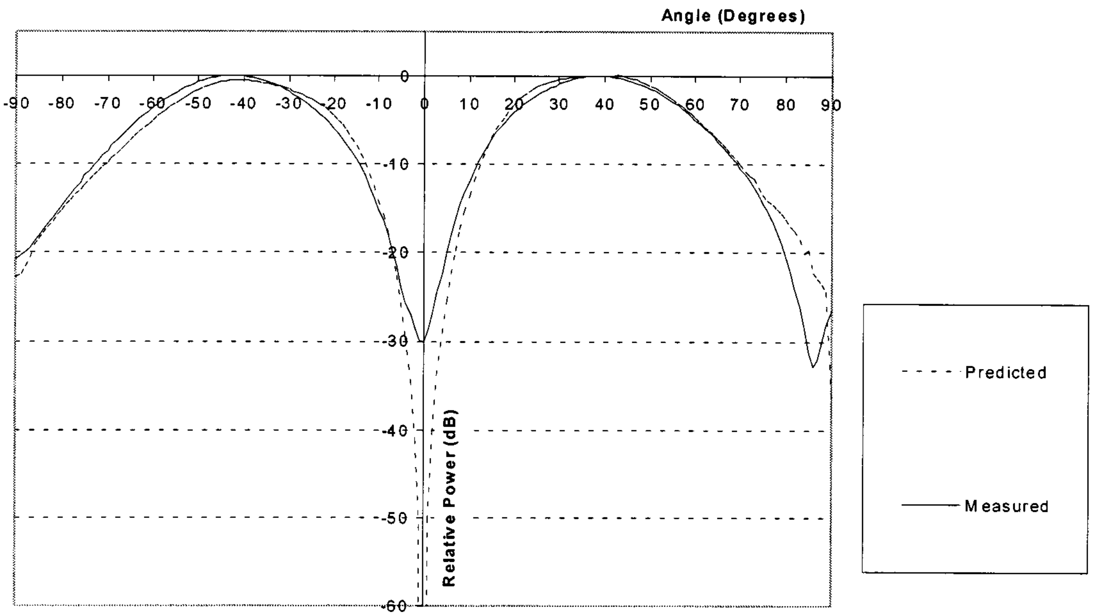


Fig. 4. Beam nulling; $L/C = 0$ dB, $\phi_1 = 180°$.

ement array was selected as a compromise between the inherent beam-pointing error (i.e., the absolute difference in degrees between the actual AOA and the angle of the retransmitted signal) and the size of our anechoic chamber. A four-element array will provide only three degrees of beam-pointing error over the ±40° 3-dB monostatic *RCS* response of the RDA [8], [9].

2) In the next mode of operation, $L/C > 30$ dB, here the direct transmission signal swamps the phase-conjugate leakage signal and normal broadside L far-field radiation patterns are formed (see Fig. 3). The simulation used to create these results [see (1)] uses the actual radiation patterns of the array, $g_c^i(\phi)$, as measured when individually cited *in situ*, i.e., they contain mutual coupling effects [10]. Hence the asymmetry of the pattern and noninfinite depth nulls are embodied.

3) In the next mode of operation, either the gain of the amplifiers in each phase-conjugate circuit in Fig. 1 and/or the gain of RF signal, as controlled by K (see Fig. 1) is used to set the L/C ratio to 0 dB. In addition, ϕ_1 in Fig. 1 is set to 180°. Now when the interrogating signal is allowed to traverse the range +90° to −90°, the monostatic *RCS* pattern shown in Fig. 4 results. This shows that the configuration is capable of providing partial cancellation of the transmit signal from the array, i.e., it is behaving as a pseudoradar absorber with −30-dB response at boresight and −10-dB response out to ±15°.

Fig. 5 illustrates why this effect is occurring. When the AOA is at broadside, the fields radiated by the passive array plus the phase-conjugated response from the RDA sum to zero [see Fig. 5(a)]. As the AOA moves away from broadside, then the length of the resultant vector increases and the augmented array starts to radiate in these directions [see Fig. 5(b)]. Note how the phasor components for each of the radiating elements, E_1 through E_N, in the RDA has the phase of its incoming signal phase conjugated, while those in the passive part of the array are not phase conjugated.

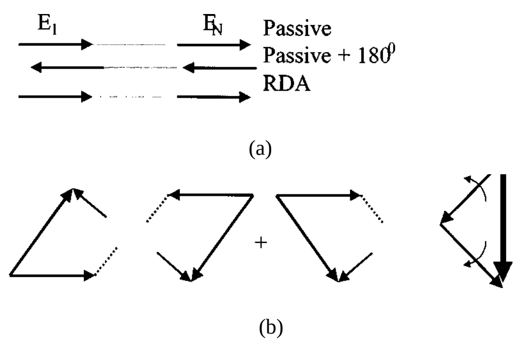


Fig. 5. Phasor representation of beam nulling; $L/C = 0$ dB, $\phi_1 = 180°$. (a) AOA at broadside, $\Sigma = E_{\min} = 0$. (b) AOA away from broadside.

4) In a second variant of this mode, ϕ_1 (see Fig. 1) is set to 0° and L/C is maintained at 0 dB. In this mode, as the interrogating signal reaches the region of operation in azimuth where the passive array response is reduced due to its angular response, the signal from the RDA can be made to broaden the angular coverage of the augmented array beyond that which an individual passive or RDA array could independently provide. Fig. 6 illustrates this point by showing a bistatic pattern for the augmented array operated in this mode.

This mode of operation is potentially useful; for example, when the array was interrogated by a friendly signal and the augmented array wished its presence to be made known to a variety of widely angular spaced observers, compare this to case 1) above, where the augmented array makes itself known only to the interrogator. It is of interest to note that a decrease in gain will accompany this mode of operation. The reason for the gain drop is given in Fig. 7. Here, for an interrogating signal coming in at broadside, the radiation from the passive array and the RDA sum to give maximum possible field

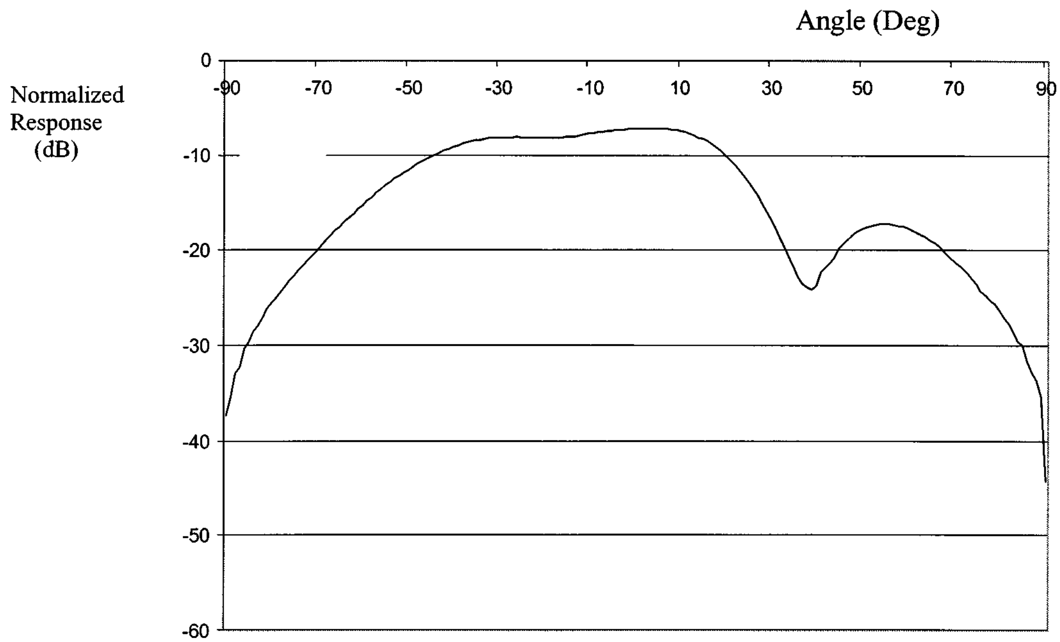


Fig. 6. Beamwidth broadening; $L/C = 0$ dB, $\phi_1 = 0°$, $AOA = -50°$.

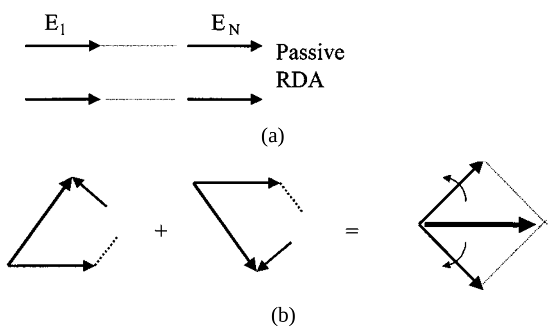


Fig. 7. Phasor representation for gain decrease; $L/C = 0$ dB, $\phi_1 = 0°$. (a) AOA at broadside, $\Sigma = E_{\max}$. (b) AOA away from broadside.

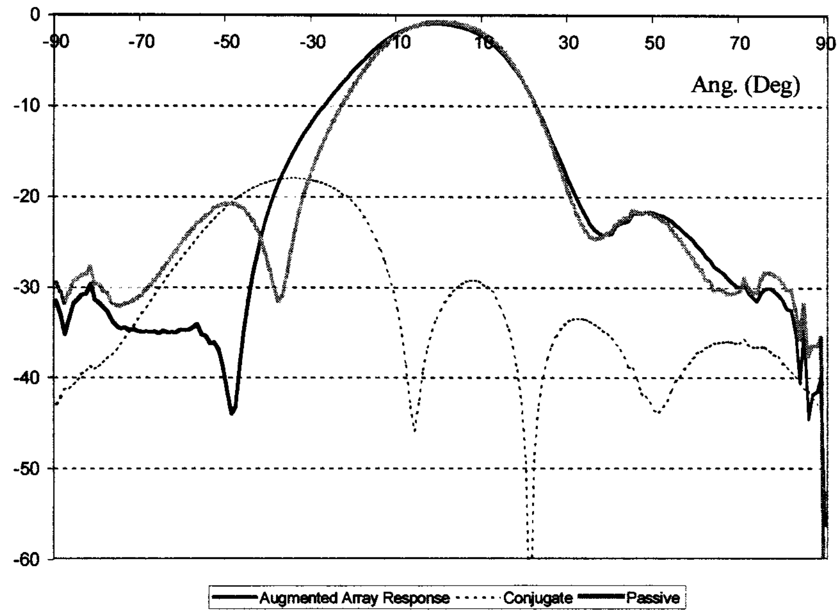
strength [see Fig. 7(a)]. As the AOA arrives further away from broadside, then the resultant field decreases [see Fig. 7(b)].

5) Observation of the passive array response (see Fig. 3) shows that its first sidelobe lies at about −15 dB relative to boresight. Hence, by making the L/C ratio of the order of +15 dB, it should in principle be possible to modify the sidelobe response of the passive array without grossly affecting its main lobe radiating characteristics. Once again, two cases were examined: $\phi_1 = 0°$ and $\phi_1 = 180°$.

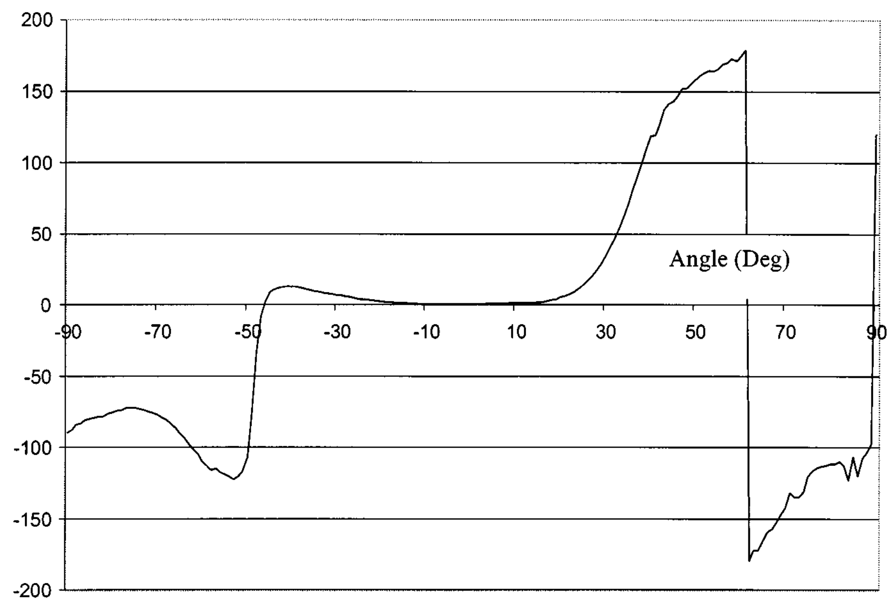
   1) For $\phi_1 = 0°$ and $L/C = 15$ dB for an AOA of less than ±20°, the array pattern of the passive array is unaffected by the RDA operation. However, as AOA approaches ±40°, i.e., the position of the first null of the passive array, the beam of the augmented array broadens and sidelobe levels in the region of the AOA reduce by up to 10 dB due to inherent phase cancellation between the RDA and passive array. For illustration, Fig. 8 shows the predicted bi-static magnitude and phase response for the situation described above at an AOA of −40° (selected to lie close to the first sidelobe of the passive array) as predicted using (1). In the region −10° to +90°, the conjugate signal response is much weaker than the response from the passive array, and consequently both of these are similar in appearance regardless of the composite phase response of the array [see Fig. 8(b)]. On the other hand, in the region covering approximately −70° to −50°, both the passive and Pon arrays have a similar magnitude and out-of-phase components, which lead to a significant reduction in sidelobe energy production in this region. For example, at −50°, the conjugate and passive signals are approximately 110° out of phase and both magnitudes are approximately −20 dB, giving a total signal strength after vector addition of around −42 dB [see Fig. 8(a) and (b)].
   2) For the case when $\phi_1 = 180°$ with $L/C = 15$ dB over a range of AOA of ±80°, the level of the first sidelobe level will be increased to around a maximum of 6 dB while the shape of the main beam remains largely unaltered. This occurs since RDA and passive array radiation phase reinforcement occur.

V. Conclusion

In this paper, we have shown how an antenna array transmitter comprised of a classical passive array operating in parallel with an active Pon type retrodirective array, each sharing the same radiating elements, can be made to exhibit five different and potentially useful modes of operation. It was shown how the initiation of a particular mode depends on the relative strength ratio of the classical array transmit signal strength to the strength of a phase-conjugated signal occurring as a consequence of a wanted, or perhaps unwanted, remote signal interrogating the



(a)



(b)

Fig. 8. Sidelobe nulling; $L/C = -15$ dB, $\phi_1 = 0°$, $AOA = -40°$. (a) and (b) Augmented array bistatic phase response $R/C = -15$ dB, target $= -40$ deg.

array. These modes are summarized briefly here as: mode 1 classical self-tracking ($L/C < -30$ dB), mode 2 classical passive transmitter action ($L/C > 30$ dB), mode 3 transmit beam cancellation ($L/C \cong 0$ dB, $\phi_1 = 180°$), mode 4 beam spreading ($L/C \cong 0$ dB, $\phi_1 = 0°$), mode 5a ($L/C \cong 15$ dB, $\phi_1 = 0°$) sidelobe suppression, and, mode 5b ($L/C \cong 15$ dB, $\phi_1 = 180°$) sidelobe enhancement.

Mode 1 is useful when a vehicle carrying the augmented array wishes to disclose its presence or send a modulated communication to the interrogating source only without having to use conventional beam-steering techniques in order to minimize cost. Mode 2 operation yields a narrow beam-radiation pattern normal to the array, giving a constrained field-of-view (FOV) illumination. Mode 3 allows, upon receipt of an interrogating signal, the array to act as null radiator over a particular FOV without powering down the passive transmitter. Mode 4 operation facilitates the augmented array making its presence known to observers occupying a wider FOV than could be achieved by mode 1 or mode 2 operation alone. Finally mode 5 operation allows the augmented array to enhance or reduce sidelobe levels, albeit in a relatively crude manner.

In future work, the beam from the passive array could be scanned in the conventional manner and the benefits of using the augmented approach described here also accrued to give greater flexibility. The one-dimensional (1-D) augmented array could also be extended to two-dimensional (2-D) for full three-dimensional (3-D) target tracking. The work described in this paper could find application in electronically radar cross-section modification and agile communication scenarios.

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