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Retrodirective Array Immune to Incident Waves With Arbitrary Polarizations

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***Abstract*—A retrodirective array (RDA) capable of retransmitting predictable polarization with respect to any received polarization state is presented. RDAs have the unique ability to scatter the received signal back to the interrogator without prior knowledge of the source location. In addition to this unique feature, the proposed system can receive any polarization and always retransmits the signal that is orthogonally polarized with respect to the received polarization state. This added feature helps to maintain a more stable communication link between the RDA and the interrogator by mitigating the polarization mismatch loss. The proposed system shows excellent retrodirectivity for various received linear and circular polarizations.**

***Index Terms*—Orthogonal polarization, phase conjugation, phased array, polarization friendly, retrodirective array.**

I. INTRODUCTION

RETRODIRECTIVE arrays (RDA) have the unique ability to transmit a received signal back toward the interrogator without prior knowledge of the interrogator's location. Under a dynamic communication link where either the interrogator or the responder is in motion, the responder equipped with the RDA can track the interrogator, thereby maintaining a more stable communication link. This concept may be applied to remote sensor, identification tags, unmanned space crafts, etc. There are different techniques to achieve this functionality of rescattering the signal back to the interrogator. However, when high link gain and high-speed target tracking is desired, analog self-phasing method has been the candidate of the choice [1]. The invention of the Van Atta array in 1955 paved the notion of creating analog RDA systems in the form of an array [2]. In addition, unlike the traditional corner reflector, Van Atta arrays enabled the devices to be built entirely on planar substrates with a wider retrodirective angle [3]. Novel techniques and devices based on the Van Atta concept are actively being studied [4]–[6].

A different approach is designing a retrodirective antenna array based on the heterodyne technique, originally introduced by C. Y. Pon in 1963 [7]. The working mechanism is essentially similar to that of the Van Atta array where the effective phase gradient across the array is reversed, thereby directing the signal back to the source location. However, instead of pairing the antennas with respect to the symmetric plane of the array using equi-length interconnects; the heterodyne technique retrodirects the signal by conjugating the received phase at each antenna elements [8]. This technique has stirred much interest among researches by allowing devices to be built on a conformal surface. The method also allows simpler integration of standard electronic devices, modulation, and amplification of the signals. Endeavors toward building yet more robust RDAs has produced interesting design schemes and techniques. For example, a frequency autonomous RDA has been developed to retrodirect the signal without prior knowledge of source location and source frequency [9], a dual-frequency RDA was proposed where two sets of array are used to receive high frequency signal and retrodirect low frequency signal back to the source or vice versa [10], and a RDA system based on phase-conjugating technique has been implemented using not only through local oscillator (LO) at twice the RF frequency but also using sub-harmonic mixing [7], [11]–[13].

To further improve the system performance, this paper emphasizes on the polarization properties of the RDA to build a device immune to arbitrary polarizations of the incident waves. Polarization characteristics have been previously studied in conjunction with RDAs. Polarization duplexing has been utilized, where a set of orthogonal polarizations are used for receiving and transmitting operation with high isolation [14], [15]. However, they operate for linearly polarized case only and require the RDA to be pointing the interrogator with a particular orientation to minimize polarization mismatch loss. Dual-polarized antennas that can receive any type of polarizations have been utilized in the previous RDAs [16]. Nevertheless, with an ideal dual-polarized square patch, incident waves polarized along the patch diagonal axis returns the same polarization; but all other polarization ellipses flips around this axis. Since the retransmitted polarization state from the RDA is highly dependent on the received polarization state and unpredictable, it is difficult to maintain low polarization mismatch loss unless the orientation of the RDA with respect to the interrogator can be tracked at all times.

The proposed RDA is capable of retransmitting the retrodirective signals polarized orthogonal to any received polarization states. Therefore, as long as the interrogator is equipped with a polarization duplexing antenna or a set of separate Tx and Rx antennas that are orthogonally polarized with respect to each

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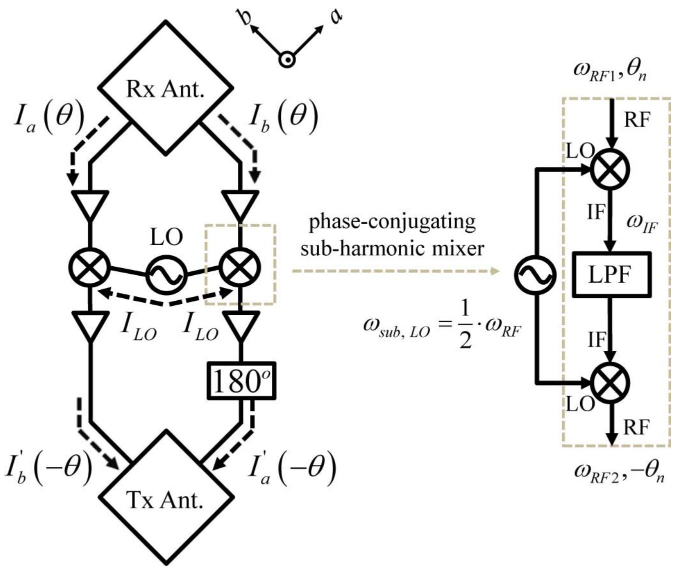


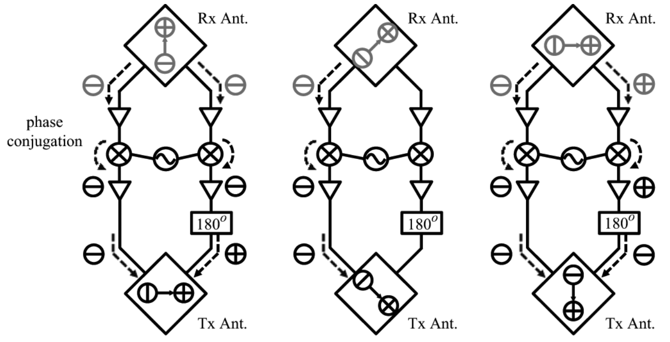
Fig. 1. Schematic diagram of a single element Rx and Tx antenna pair with zoomed view of phase-conjugating sub-harmonic mixer.

other, the loss due to polarization mismatch can always be minimized. Using the new retrodirective array architecture, the array is able to respond to the interrogator without prior knowledge of the source location as well as the state of the incoming polarization, while providing a more desirably polarized retrodirective signal.

The present paper is an expansion of [18] with detailed explanation of the operational mechanism. In addition, circular polarization cases are discussed along with the measured results. The paper is organized as follows. A brief overview of the proposed system configuration is described in Section II. Section III provides the theory of the proposed system. In the last two sections, a fabricated system is used to verify the proposed method with the experimental results.

II. SYSTEM CONFIGURATION

The proposed RDA is realized with a set of dual-polarized Rx and Tx antennas linked by non-radiating phase-conjugating circuits as shown in Fig. 1. Each pair of Rx and Tx dual-polarized antennas are linked by two interconnecting arms. Phase-conjugation needed to direct the signal back to the interrogators is attained through two-stage sub-harmonic mixing. Amplifiers are added before and after the phase-conjugating mixer to compensate the conversion loss of the mixers and provide the signal amplification. Prior to reaching the input ports of the Tx dual-polarized antenna, the signal traveling in one of the linking arms travels through the delay line to flip the phase of the signal by 180 degrees. As will be shown in Section III, this delay line, in addition to the two interconnecting arms arranged in this particular fashion, are required to provide the orthogonally polarized Tx-signal with respect to any received polarization states. The proposed system is a 1-D RDA that can track the interrogator parallel to the array scanning direction.



(a) (b) (c)

Fig. 2. Single element pair illustrating even and odd mode analysis for different incident polarization cases: (a) vertically-pol., (b) diagonally-pol., (c) horizontally-pol. incident E-fields.

III. THEORY

In order to alleviate the high LO frequency, phase-conjugation through sub-harmonic mixing is widely used [12], [13], [20]. Sub-harmonic mixing is advantageous for the proposed RDA not only to reduce the overall system cost and provide higher port-to-port isolation, but also to minimize potential phase errors along the LO path. In order to provide proper polarization rotation, it is critical to minimize any phase errors within the system.

The proposed system is equipped with dual-polarized receiving patch antennas that orthogonalizes the excited currents with magnitude proportional to the incident E-field projected onto each orthogonal spatial coordinate axis a and b (Fig. 1). The subscripts a and b represents the direction of the currents flowing along the respective orthogonal spatial coordinates. To ensure that the retransmitted signals are always orthogonally polarized with respect to the incident polarization, a simple vector transformation needs to be performed. The vector rotation is carried out in analog fashion by arranging the interconnecting arms such that the spatial coordinates of the decomposed currents leaving the system is reversed relative to the spatial coordinates of the currents incident in the system.

The working mechanism of the proposed system can also be analyzed with even and odd mode analysis (Fig. 2). If the linearly polarized E-filed is incident along the symmetric plane of the receiving dual-polarized antenna (vertically-pol), the two linking arms experience even-mode (in-phase) excitation. After the phases are conjugated through sub-harmonic mixers, the signal along one of the branches travels through the delay line, creating odd-mode (out-of-phase) excitation to the transmitting dual-polarized antenna. On the other hand, if the field is incident perpendicular to the symmetric plane of the dual-polarized receiving antenna (horizontally-pol), odd-mode excitation is generated at the output of the receiving dual-polarized patch antenna. Similar to the previous case, the delay line in one of the branches provides even-mode excitation to the transmitting antenna. If the incident field is received at a ± 45 degrees (diagonally-pol) from the symmetric plane of the dual-polarized antenna, the signals only flow through one of the linking arms. In this case, the retransmitted field will also be orthogonally polarized with respect to the incident polarization as shown in

Fig. 2(b). These three linearly-polarized cases along with the circularly-polarized case are verified with measurements.

For circularly or elliptically polarized fields, the proposed RDA will reverse the sense of rotation. Rotational direction of the electric fields incident on the receiving antenna and reradiated from the transmitting antennas will be the same. This can be easily seen by treating Fig. 2 as a sequential time frame. However, received and transmitted fields propagate toward the opposite directions with respect to each other, so the propagation constant will have opposite signs. Therefore, RHCP will become LHCP and vice versa. In summary, the polarization of the retransmitted signal of the proposed architecture will always be orthogonal to any received polarization states. Therefore, as long as the interrogator is equipped with two separate orthogonally polarized antennas, the proposed system is less susceptible to polarization mismatch caused by the motion, rotation, or vibration of the interrogator and can much alleviate the communication link loss.

IV. FABRICATED SYSTEM AND ITS PERFORMANCE

A two element one-dimensional RDA based on the proposed architecture operating around 2.4 GHz is fabricated on a low loss, 50 mil thick Rogers RT/duroid 6010 substrate with $\varepsilon_{\mathrm{r}} = 10.2$. Prior to fabricating the entire system, each component was fabricated and performances were verified. The return loss and isolation of the dual-polarized antenna are 17 dB and 27 dB respectively. Measured cross-pol level is 10 dB below the co-pol for a single antenna element. To compensate the conversion loss of the mixers, amplifiers with 24 dB gain are added at both receiving and transmitting paths. GaAs monolithic-microwave integrated-circuit (MMIC) amplifiers (HP MGA-86576) biased at 5 V, 100 mA are used to provide the gain around the operating frequency region. Phase-conjugation is realized using a pair of sub-harmonic mixer based on antiparallel diode pairs (APDPs). Agilent beam lead Schottky diode pairs (HSCH-5531) are used for the mixers.

In the first mixing stage, the received RF signal $(f_{\mathrm{RF}} = 2.395\ \mathrm{GHz})$ is down-converted to the IF band with an LO frequency slightly higher than half the RF frequency. The phase conjugation is achieved in this process. The IF signal is then up-converted back to the RF frequency band $(f_{\mathrm{response}} = 2.405\ \mathrm{GHz})$ prior to being retransmitted. The optimized conversion loss of each mixer operating at $f_{\mathrm{LO}} = 1.2$ GHz is 11 dB with LO power of 0 dBm. The total LO power of 9 dBm is needed to feed all the mixers in the final fabricated system. Bandpass filters are added at each RF and LO ports of the mixers. Open loop resonator bandpass filters are used in the LO path to reduce the overall size of the system (Fig. 3).

V. MEASURED RCS RESULTS

To validate the retrodirective capability of the proposed system for any incident polarization states, bistatic and monostatic radar cross section (RCS) measurements are conducted for different incident polarizations. The measurement setups for co-pol and cross-pol cases are shown in Figs. 4 and 5 respectively. For the bistatic RCS measurement, an interrogating Tx antenna transmitting a single tone signal (f_{RF}) is placed at fixed positions (0 degrees and 20 degrees) while the reradiated response (f_{response}) pattern of the RDA is measured by sweeping Rx horn antenna along the elevation angle parallel to the array scanning plane. For the monostatic RCS, reradiated patterns of the array are measured while simultaneously sweeping the interrogating Tx and Rx antennas. The interrogator antennas and the RDA are maintained at the far-field distance of $\mathrm{d} \approx 1.5\ \mathrm{m}$.

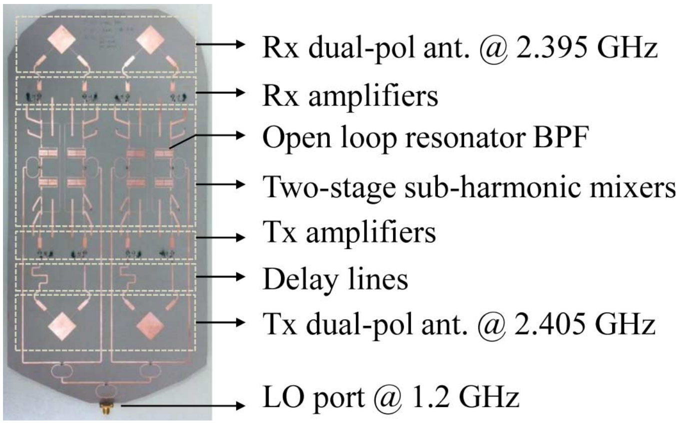


Fig. 3. Picture of the proposed RDA system (two element array).

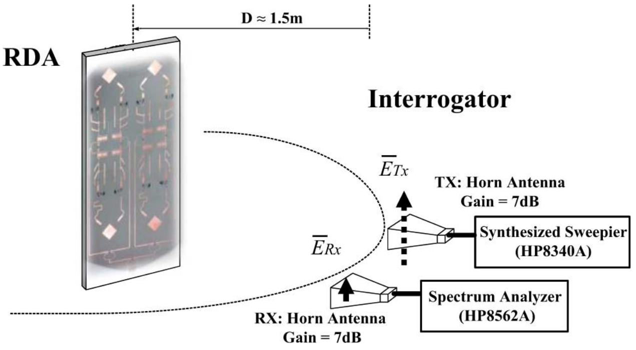


Fig. 4. Measurement setup for the undesired co-pol RCS measurement.

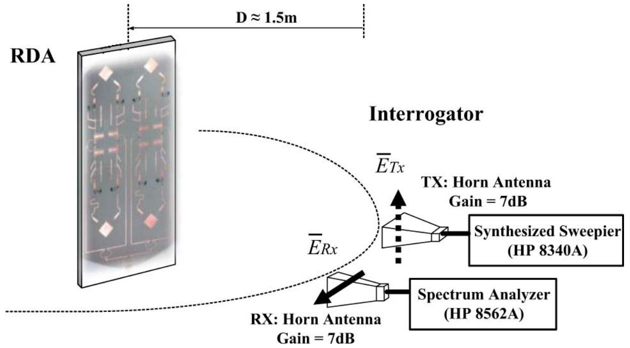


Fig. 5. Measurement setup for the desired cross-pol RCS measurement.

A. Linear Polarization

In the linear-pol measurements, the interrogator is composed of two standard gain horn antennas with the gain of 7 dBi. One

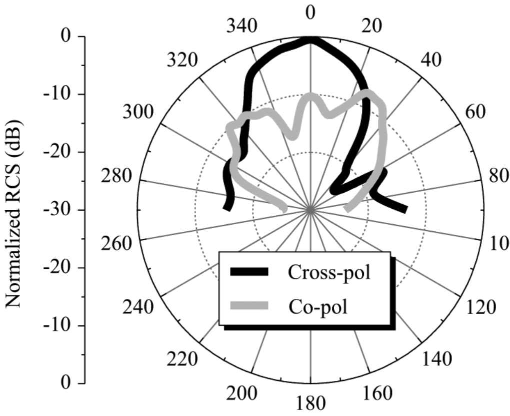


Fig. 6. Measured bistatic RCS for vertically-pol with source at 0 deg.

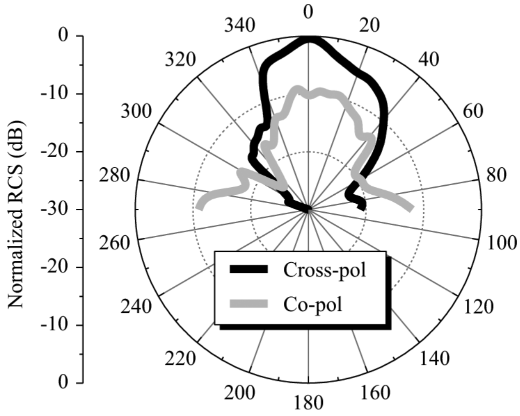


Fig. 7. Measured bistatic RCS for horizontally-pol with source at 0 deg.

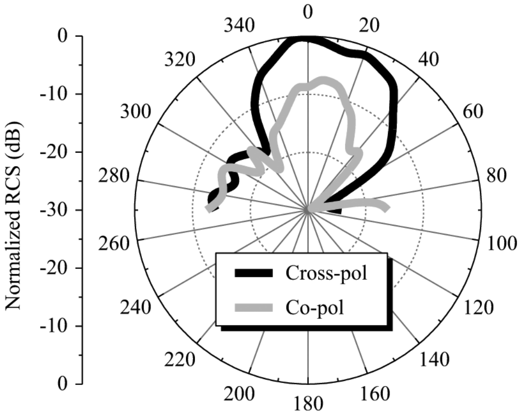


Fig. 8. Measured bistatic RCS for diagonally-pol with source at 0 deg.

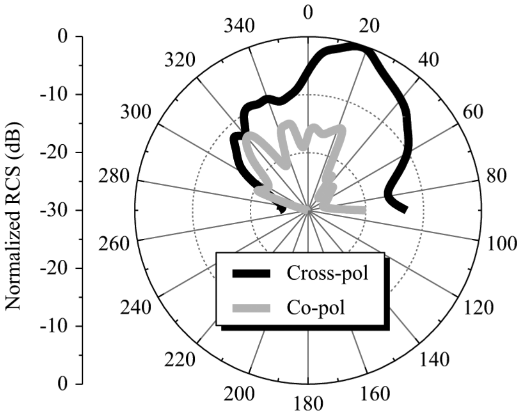


Fig. 9. Measured bistatic RCS for vertically-pol with source at 20 deg.

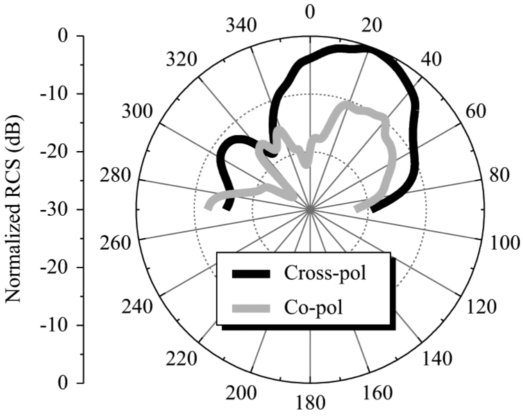


Fig. 10. Measured bistatic RCS for horizontally-pol with source at 20 deg.

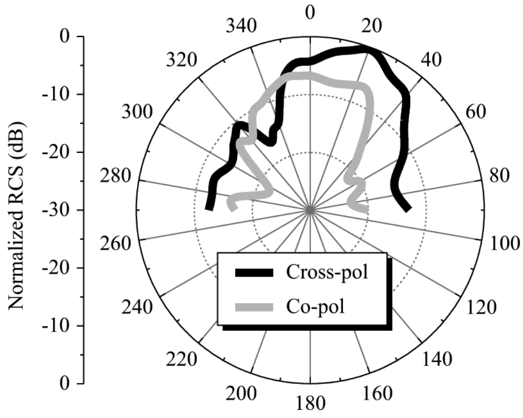


Fig. 11. Measured bistatic RCS for diagonally-pol with source at 20 deg.

of the horn antennas is attached to the signal generator and used as the Tx antenna of the interrogator. The other horn antenna attached to the spectrum analyzer to measure the rescattered power from the RDA, thereby acting as the Rx antenna of the interrogator. For each source locations, three sets of linearly polarized RCS measurements were carried out: transmitting horn positioned to illuminate the RDA with 1) vertically-polarized, 2) horizontally-polarized, and 3) diagonally-polarized signals. For each cases, both desired cross-pol and undesired co-pol RCS levels were measured to verify whether the retrodirected signals are properly (orthogonally) polarized with respect to its received polarization state. Retrodirectivity is clearly confirmed in both source angles and for all three linearly-polarized cases (Figs. 6–11). The measured results show the desired cross-pol levels around 10 dB above the co-pol level for all three polarizations and both source locations. Higher than expected co-pol levels in the measurement results may be due to the interference produced by leakage radiation from the phase-conjugation circuits, fabrication errors, and imperfect measurement setup. Measured monostatic RCS patterns for linearly-pol case are shown in Fig. 12.

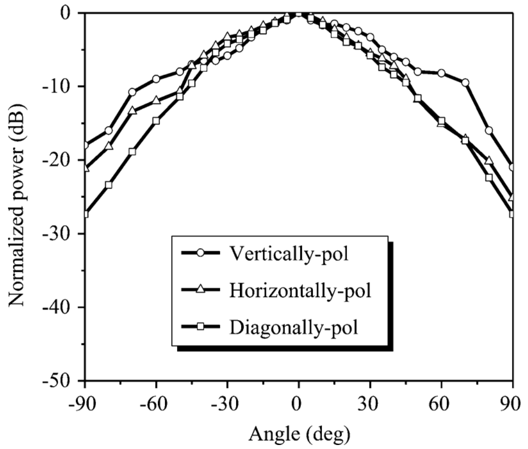


Fig. 12. Measured monostatic RCS patters for different linearly-pol incident fields.

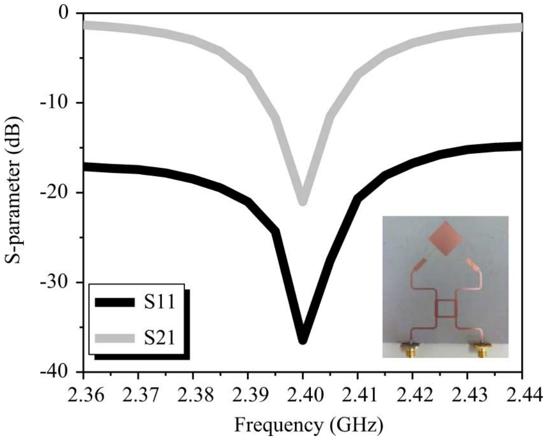


Fig. 13. Measured s-parameter for circularly-pol patch antenna.

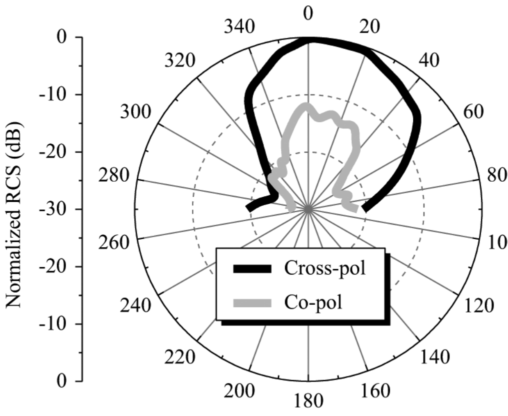


Fig. 14. Measured bistatic RCS for circularly-pol with source at 0 deg.

B. Circular Polarization

RCS measurements for circularly-pol cases are also conducted using a set of circularly-polarized interrogating patch antennas instead of the linearly-polarized horn antennas. Circularly-polarized patch antennas are fabricated using quadrature hybrids as shown in the inset of Fig. 13. Measured bistatic RCS shows the cross-pol level around 15 dB above the co-pol level for the source located at the broadside (Fig. 14) and around 8 dB higher when the interrogator is placed at 20 degrees from the broadside (Fig. 15). Similar to that of the linearly-polcase, the measurement results show good retrodirectivity and the desired cross-pol level is higher than the undesired co-pol level. Measured monostatic RCS pattern for circularly-pol case is shown in Fig. 16.

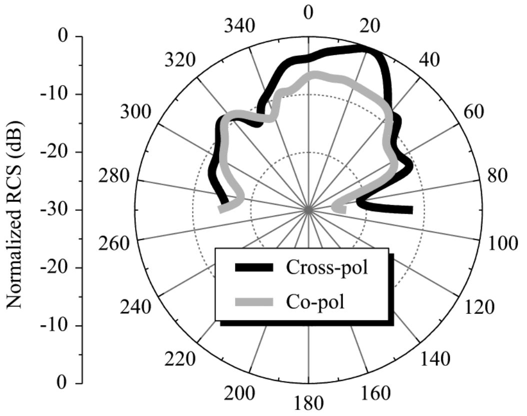


Fig. 15. Measured bistatic RCS for circularly-pol with source at 20 deg.

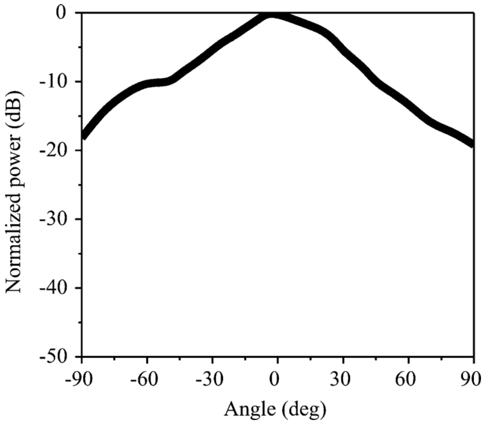


Fig. 16. Measured monostatic RCS patters for different circularly-pol incident fields.

VI. CONCLUSION

We have demonstrated a RDA that is more robust to the polarization of the communication signal. It can receive any polarization and retransmit a predictable orthogonally polarized signal back to the interrogator. Therefore, as long as the interrogator is equipped with orthogonally polarized receiving antennas, the polarization mismatch loss between the interrogator and the RDA will always be minimized. This device may be especially advantageous for unmanned vehicles, spacecrafts or remote sensors under constant motion or rotation. For the linearly polarized case, the orthogonally polarized backscattered signal also helps to steer away from undesired specular reflection. Lastly, since the system enables the interrogator to use two separate antennas, one for Rx and one for Tx, it allows better isolation and higher Tx power at the interrogator side.

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Dr. Itoh received a number of awards including IEEE Third Millennium Medal in 2000, and IEEE MTT Distinguished Educator Award in 2000. He was elected to a member of National Academy of Engineering in 2003. In 2011, he received Microwave Career Award from IEEE MTT Society. Dr. Itoh is a Fellow of the IEEE, a member of the Institute of Electronics and Communication Engineers of Japan, and Commissions B and D of USNC/URSI. He served as the Editor of IEEE Transactions on Microwave Theory and Techniques for 1983–1985. He was President of the Microwave Theory and Techniques Society in 1990. He was the Editor-in-Chief of IEEE Microwave and Guided Wave Letters from 1991 through 1994. He was elected as an Honorary Life Member of MTT Society in 1994. He was the Chairman of Commission D of International URSI for 1993–1996. the Chairman of Commission D of International URSI for 1993–1996. He serves on advisory boards and committees of a number of organizations. He served as Distinguished Microwave Lecturer on Microwave Applications of Metamaterial Structures of IEEE MTT-S for 2004–2006.