Ongoing Retrodirective Array Research at UCLA

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I. Introduction

When receiving a signal from an unspecified direction, retrodirective arrays [1] are able to transmit a signal response to that same direction without any previous knowledge of the source direction. This function is performed automatically, without the use of phase-shifters or digital circuitry. The capability to perform high gain antenna pointing automatically, makes the retrodirective array an attractive candidate for advanced digital mobile communication systems.

This paper discusses ongoing research efforts towards developing new retrodirective array architectures at the University of California, Los Angeles (UCLA). The arrays presented here have other features in addition to the self-phasing aspects such that they can be applied to practical communication systems.

II. General Considerations

Retrodirective behavior can be induced using a number of different techniques. The most basic is the corner reflector. Corner reflectors consist of perpendicular metal sheets, which meet at an apex. Incoming signals are reflected back in the direction of arrival through multiple reflections off the walls of the reflector. These reflectors must be large in terms of wavelengths and they are not readily conducive for use in wireless communication systems.

Van Atta arrays also exhibit retrodirectivity [2]. This array is made up of pairs of antennas spaced equidistant from the center of the array, and connected with equal length transmission lines. The signal received by an antenna is re-radiated by its pair, thus the order of re-radiating elements are flipped with respect to the center of the array, achieving the proper phasing for retrodirectivity. Van Atta arrays perform retrodirectivity over a wide bandwidth, which simply is limited by the bandwidth of the antenna element.

The technique for achieving retrodirectivity which has been the focus of research at UCLA is using phase conjugating mixers [3]. Phase conjugation with heterodyne mixing uses an LO signal at twice the RF frequency (Fig. 1). In this scheme, the lower sideband product has the same frequency as the RF, but with conjugated phase. When combined with an antenna and placed in an array, the phase-conjugated signal from each antenna element will be re-radiated towards the source direction. Phase conjugation is described in eq. (1). When the LO frequency is twice the RF frequency, the lower sideband signal is merely the phase conjugation of the received signal.

eq. (1)

$$V_{IF} = V_{RF}\cos(\omega_{RF}t+\theta_n)\cdot V_{LO}\cos(\omega_{LO}t)$$
$$= \frac{1}{2}V_{RF}V_{LO}\begin{bmatrix}\cos((\omega_{LO}-\omega_{RF})t-\theta_n)+\\ \cos((\omega_{LO}+\omega_{RF})t+\theta_n)\end{bmatrix}$$

The upper sideband signal and LO leakage can easily be removed since the frequency is far apart from the phase conjugated signal. In this method, it is important to eliminate undesired signals, i.e. non-phase-conjugated signals since they are transmitted to the direction that follows Snell's law. Therefore, the RF leakage suppression is one of the key factors of phase conjugating circuitry. Especially burdensome in the phase conjugation approach is that the IF frequency is the same as that of the RF signal, making it impossible to separate the two signals with a filter. For this reason, balanced structures are usually used to eliminate undesired signals.

The major advantage of this approach is that by employing active devices for mixing, conversion gain can be obtained in addition to phase conjugation. Another design concern is the

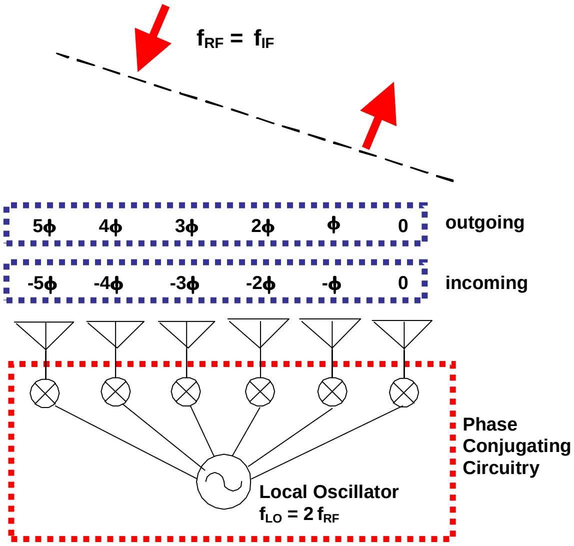


Fig. 1 Schematic of phase conjugating retrodirective array.

array spacing. The array spacing should satisfy the condition given by eq. (2) in order to avoid scan angle limitations due to grating lobes:

eq. (2)

$$d > \lambda_0 /(1+|\sin\theta_{in}|)$$

where θ_{in} is the incident angle of the incoming signal. For a full scan range -90° to 90°, the array spacing should be smaller than a half wavelength of the RF signal. The small array spacing allows the array to avoid scan angle limitations due to grating lobes, which become visible when the array spacing is large.

III. Active Retrodirective Arrays

In order to observe retrodirective radiation behavior we need only to conjugate the incoming wave's phase. However, to make this technology more practical we would also like to amplify the outgoing wave. To this end, active devices such as MESFETs are attractive since they can provide conversion gain as well as mixing operation. This allows the array to send amplified signals towards the source location without including additional amplifiers, which will increase circuit size and cost.

A compact active phase conjugator circuit is presented in [4]. The circuit (Fig. 2) has two ports, one for the LO signal which is applied in phase to the two mixers and the other port which is shared by the incoming RF and outgoing IF signals. The LO signal is applied to the drains of the FETs while the RF signal is applied into the gates and the IF (phase-conjugated) signal is extracted from the same port.

One challenge in the design of phase conjugator circuits is to provide isolation between RF and IF. This cannot be done using filters, since the frequencies are often very close in frequency, or even the same frequency.

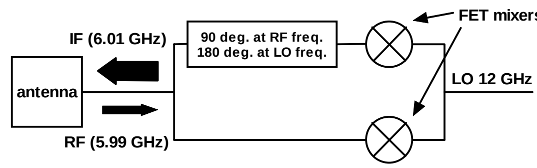


Fig. 2 Compact active phase conjugator.

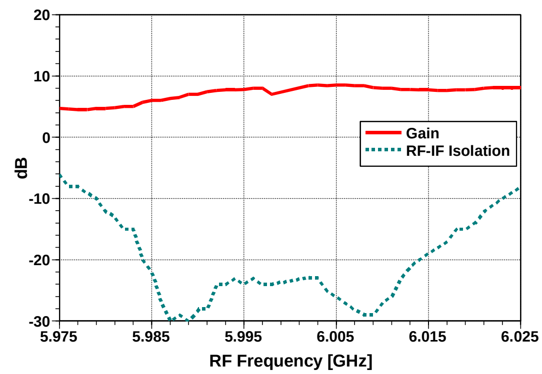


Fig. 3 Conversion gain and RF-IF isolation.

Instead, a balanced mixer design is used to provide isolation. The channels are identical except for a 90° phase delay line at the RF frequency. This delay line is used for cancellation of the returned RF signal at the RF/IF port for isolation. Since the LO frequency is twice that of the RF frequency, the LO from the two channels will experience a 180° delay when combined at the RF/IF port, thereby canceling the LO leakage to provide good LO isolation. The IF signals are phase-conjugated and combined in phase with conversion gain.

Because the circuit input and output port are shared, a 10 dB directional coupler was used to separate the incoming RF and outgoing IF phase-conjugated signal. The measurement of the circuit was done by applying LO power at a frequency twice that of the RF frequency with a 1 MHz offset, so that the IF and RF leakage frequencies can be distinguished. Fig. 3 shows the circuit performance over the frequency range from 5.975 to 6.025 GHz. The conversion gain is above 5 dB over the range and the RF/IF isolation stays below 20 dB within a 30 MHz bandwidth.

Fig. 4 shows a prototype C-band four-element retrodirective array based on the UCLA compact active phase conjugator. The array spacing is approximately 2.5 cm corresponding to approximately ½ free space wavelength. Each antenna has only one feed shared by both the receiving and transmitting signals. The 12 GHz LO signal is applied to each element in phase through a corporate feeding network.

Due to the retrodirective nature of the array, the peak of the array factor will always be in the direction of the source. Therefore, the monostatic radar cross-section pattern of a retrodirective array is merely given by the square of its element directivity multiplied by the array

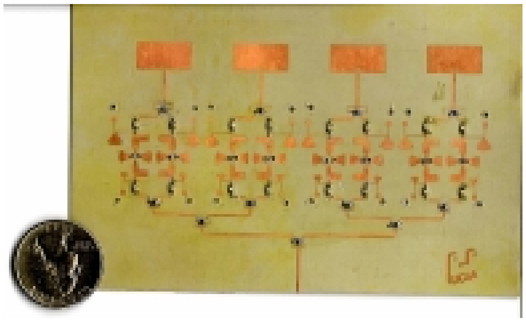


Fig. 4 Photo of the prototype 4-element active retrodirective array.

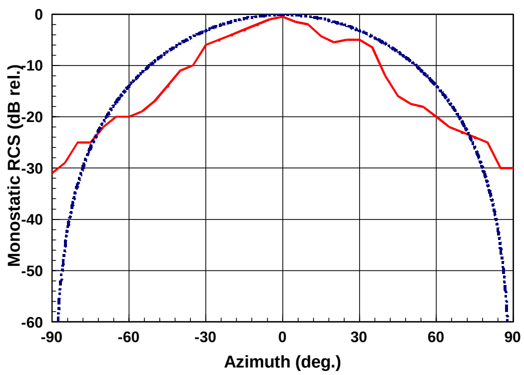


Fig. 5 Monostatic RCS pattern.

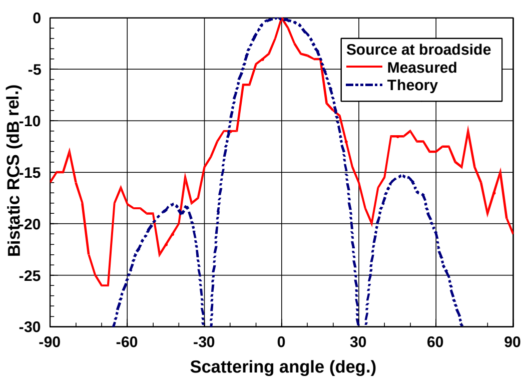


Fig. 6 Bistatic RCS, source at broadside (0°).

directivity in the source direction. Note that the directivity of the array is multiplied only once because the received signal is processed at each element separately without being combined. The array factor is involved only when the phase-conjugated signal from each element is spatially combined when it is transmitted. Since the source point is always tracked by the peak of the radiation pattern, the monostatic radar cross section pattern should have no nulls. The monostatic radar cross section of the prototype array is shown in Fig. 5. The measured results agree reasonably well with the theoretical predictions based on the measured element pattern.

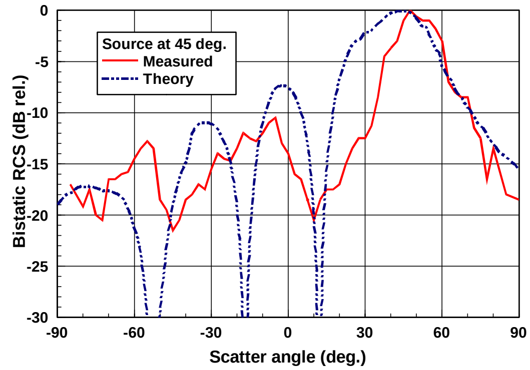


Fig. 7 Bistatic RCS, source at 45°.

The bistatic radar cross section of a retrodirective array is given by

$$\sigma_{bistatic}(\theta,\theta_{in}) = \frac{\lambda^2}{4\pi} G_c D_0(\theta,\theta_{in}) D_e(\theta_{in}) D_e(\theta) \tag{3}$$

where

G_c : Circuit gain

D_0 : Array directivity

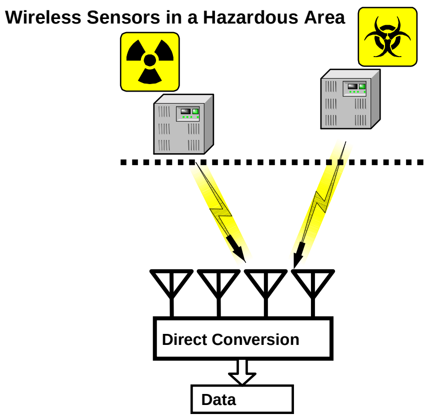
D_e : Element directivity

Radiation patterns of the array were measured with sources in different angles. Fig. 6 and Fig. 7 shows the bistatic radar cross-section with the source at 0° and +45°. They are comparable with the theoretical results. Retrodirectivity of the array is clearly observed. Note that no grating lobe is observed in all cases. This is due to the small array spacing.

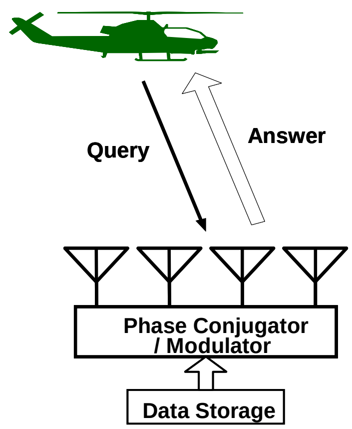
IV. Reconfigurable Arrays

RF front-end multi-functionality and reconfigurablity presents significant advantages in wireless system design. Such circuits would have the ability to accommodate multiple wireless standards, operate in multiple frequency bands, and potentially have the innate ability to adapt to its local environment to improve signal reception, reject interference, and compensate for multipath effects. In short, such reconfigurable front-ends would be able to perform several functions while using the same circuit hardware. This fact, directly translates to lower costs and overall less hardware that needs to be deployed.

This design ideology was applied to develop a reconfigurable retrodirective/direct down conversion receiver array [5]. Both types of arrays generally rely on front-end mixers to perform phase-conjugation and down conversion, respectively. The two functions have been combined into a single mixer which is dynamically reconfigured by simply changing the LO frequency.



(a) Direct Conversion Receiver Mode



(b) Retrodirective Transponder Mode

Fig. 8 Wireless sensor system using a reconfigurable array.

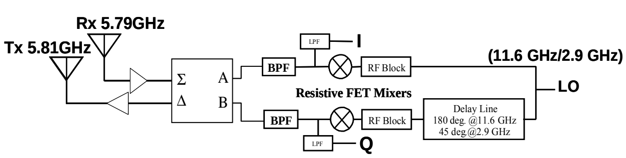


Fig. 9 Schematic of reconfigurable circuit.

A. Proposed Wireless Sensor

A proposed wireless sensor system using a reconfigurable active retrodirective/direct conversion receiver array is shown in Fig. 8. In the receiving mode (a), the array system works as a direct conversion receiver and stores data received from remote sensors. Next, upon receiving an instruction signal from an interrogator, the system starts working as a retrodirective transponder (b), and sends the stored data to the interrogator. This switching can be initiated by the header code contained in the signal from the interrogator. Then after a prescribed time limit the retrodirective array reverts back to receiver mode.

The retrodirective function of the array enhances the link gain between interrogator and array without requiring the interrogator to identify its exact location.

B. Circuit Overview

The schematic of the multi-function circuit is shown in Fig. 9. The signal received by the receiving antenna is amplified by a LNA and applied into the resistive FET mixers in phase. The LO signal feeds the two FETs with a set phase delay. At 11.6 GHz LO is fed 180° out of phase while at 2.9 GHz the phase deviation is 45°.

The differing LO frequencies are used to switch the mixer between its dual modes of operation. When an 11.6 GHz LO is applied, the circuit works as a phase conjugator. At the same time, when a 2.9 GHz LO is applied, the circuit functions as a subharmonic direct downconverter.

In the phase conjugating mode, we again face the task of ensuring RF and IF isolation. This issue can be resolved by using the phase relationship between the four ports of a ratrace coupler. Using a conventional ratrace coupler the RF signal is applied into the mixers in phase, the rejected RF returns in phase while the phase-conjugated signal is 180° out of phase due to the phase delay in the LO feeding. Thus, at the Δ port, the rejected RF should cancel out and only the phase-conjugated signal passes on to the next stage. This scheme provides decent isolation between the phase-conjugated signal and RF leakage. This architecture also allows both receiving and transmitting amplifiers to be inserted in to the circuit.

In the direct downconverting mode, a LO (2.895 GHz) is applied to the mixers with a 45° phase difference. This translates into a 90° shift at the carrier frequency of the received signal which is twice that of the LO frequency. I and Q channels are obtained through lowpass filters from the drains of the FETs. Since resistive FET mixers are used, there is no biasing at the drain, therefore DC separation problems are eliminated.

i. Phase Conjugator Mode

The phase conjugating mode of the circuit was tested by using two synthesizers connected to the RF and LO input ports in order to provide the RF (-50 dBm, 5.79 GHz) and LO (10dBm, 11.6GHz) signals. The circuit achieved RF-IF isolation of 20 dB and gain of 20 dB. By cascading amplifiers, the signal can be amplified more depending on the communication distance while maintaining the isolation. The circuit performance over the RF frequency range 5.7 GHz – 5.9 GHz. The conversion gain is fairly flat and the RF-IF isolation stays below –10 dB over the range. The mixers serve as modulators as well, when baseband signals are applied into the I and Q ports.

ii. Direct Downconverter Mode

The measurement of the direct downconverter was done by using a LO at 2.895 GHz, which is half the frequency of the incoming signal. I and Q channels are obtained through the lowpass filters at the drains of the devices. A unmodulated RF at 5.79 GHz and a LO at 2.8975 GHz are applied so that the IF offset is 5 MHz. The phase imbalance is approximately 10 deg. A 10 Mbps BPSK signal was successfully recovered.

C. System Measurements

To confirm the retrodirectivity, the monostatic RCS measurement was done. In this measurement, the array was illuminated with a 5.79 GHz wave generated by a signal source, and was driven by an 11.6 GHz LO signal. The IF (phase-conjugated) power was measured at the source location. Since the interrogator always 'sees' the peak of the array radiation, the monostatic pattern should not exhibit any nulls. The monostatic RCS pattern should be the square of the antenna directivity in the direction of the interrogator. This is one advantage of using a retrodirective array.

V. Frequency Autonomous Array

A retrodirective array operates automatically; they are able to retransmit a response immediately after being interrogated by a specific angle. We have developed an array with another useful autonomous feature. The new retrodirective array architecture, allows the array to respond to a query without knowing the source direction as in conventional retrodirective arrays, but the added feature allows it to respond without knowing the exact source frequency as well [6]. This adds another dimension in system flexibility and increases the covert nature of the retrodirective array. This feature is obviously inherent in passive retrodirective arrays, such as Van Atta arrays, but we demonstrate this using phase conjugation mixers. Frequency automatism is accomplished by using the received RF frequency power to generate LO power used by the phase-conjugating mixers.

A. Circuit Overview

A schematic of the proposed retrodirective array is shown in Fig. 10. It is comprised of two main sub-circuits, namely an array of phase-conjugating mixers and the LO generator circuit. The signal received by the phase-conjugating mixers first passes through the circulator placed closest to the antenna, then is fed to one of the ports of a 3-dB branch line coupler via a second circulator. The signal is then spilt equally, feeding each Schottky diode mixer in quadrature phase. The RF signal is then phase-conjugated using heterodyne mixing. Because the LO frequency is exactly twice the RF frequency, the IF frequency will be the same

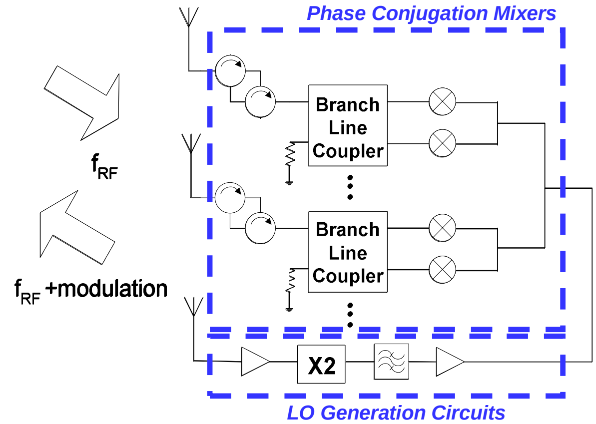


Fig. 10 Schematic of frequency autonomous retrodirective array.

as the RF frequency, making it impossible to provide IF-RF isolation using a filter. IF-RF isolation is achieved by using the relative phase relationship of the IF and RF leakage signals at each individual diode mixer. The phase-conjugated IF signals from the mixers combine at the same port where it entered while the non phase-conjugated RF leakage is dumped into the 50 Ω load terminating the opposite port of the branch line coupler. The phase conjugated IF signal passes back to the antenna through the circulators and is retransmitted. Note that the circulators are present just to demonstrate that receive and transmit amplifiers may be incorporated.

The performance of a single Schottky diode phase-conjugating mixer was evaluated using two frequency synthesizers acting as the RF and LO signal sources. The maximum IF-RF isolation of 43 dB at 5. 3 GHz. The isolation remains better than 20 dB from 5.15 GHz – 5.35 GHz. By adjusting LO power the minimum mixer conversion loss was measured to be 5.1 – 9.1 dB over a 5 -5.9 GHz frequency range. The optimum LO power was typically 3 dBm per diode mixer. For this reason diode mixers are better suited for this system architecture than FET mixers because of the limited LO power.

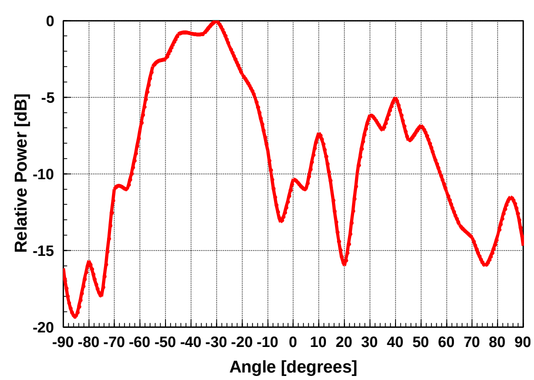


Fig. 11 Bistatic RCS, source at -30°, RF= 5.2 GHz.

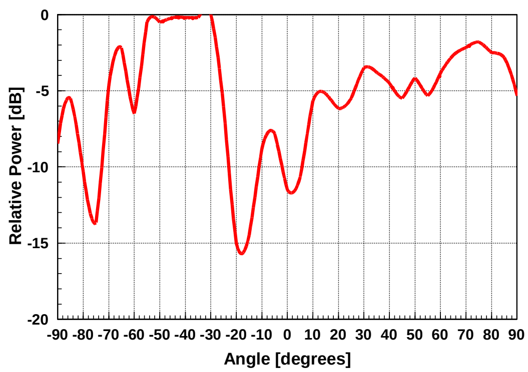


Fig. 12 Bistatic RCS, source at -30°, RF= 5.8 GHz.

LO signal is created by first amplifying the RF power and doubling its frequency using a passive doubler. The doubled signal is further amplified and used to feed the phase-conjugating mixer array.

B. Retrodirective Antenna Array

A prototype 4-element retrodirective antenna array based on the proposed phase-conjugating mixer was built on RT/Duroid 25 mil $\varepsilon_r = 10.2$. To facilitate the relatively wide bandwidth of this system, the quasi-Yagi antenna, which is reported to have a wide operational bandwidth, 3.74 – 6.22 GHz (50%) was used. The array spacing was chosen to be half-wavelength at 5.2 GHz. Retrodirectivity was measured by transmitting a single tone interrogation signal at a fixed position and measuring the radiated response of the retrodirective array. Because of the system architecture, the return signal must be at exactly the same frequency of the interrogator signal. In order to allow the receiver to distinguish between the array response and the interrogator signal, a 25 KHz sinusoidal modulation signal was mixed with the response signal transmitted by the retrodirective array. This demonstrates the arrays' functionality as an information transponder.

As with all mixers, the phase-conjugating mixers' conversion loss is greatly dependent on the amount of LO power used to pump the mixers, therefore overall circuit performance relies on the LO generator sub-circuit. In this proof-of-concept array, the LO power level was manually controlled by adjusting the gain of the amplifier used to amplify the LO signal generated from doubling of the RF signal.

Fig. 11 shows the measured bistatic RCS of the retrodirective array with the interrogator source at -30° at 5.2 GHz. Retrodirectivity is clearly observed for other angles of test as well. In order to qualify that this newly proposed array is frequency autonomous, bistatic RCS was measured using an interrogation frequency of 5.8 GHz (Fig. 12). Again, we see that the array is able to track the position of the interrogator quite well, with no grating lobes. For this measurement only the interrogator frequency was changed.

VI. Conclusions

Retrodirective arrays have the unique ability to retransmit signals back to its origination point without a priori knowledge. The self-beam-steering feature potentially offers the improvement of communication link gain between an interrogator and a retrodirective array, reducing the burden on transmitting and receiving amplifiers. This paper has introduced some of the research done at UCLA on this topic, including an active retrodirective array, a reconfigurable retrodirective/direct downconverter receiver array for wireless sensor systems, and a frequency indiscriminate retrodirective array.

References

[1] R. Y. Miyamoto and T. Itoh, "Retrodirective arrays for wireless communications," *IEEE Microwave Magazine*, vol. 3 is. 1, March 2002, pp. 71 -79.

[2] L. G. Van Atta, "Electromagnetic Reflector," U. S. Patent No. 2,908,002; October 6, 1959.

[3] C. Y. Pon, "Retrodirective array using the heterodyne technique," *IEEE Trans. Antennas and Propagation*, Vol. 12, pp. 176-180, Mar. 1964.

[4] R. Y. Miyamoto, Y. Qian, and T. Itoh, "An Active Integrated Retrodirective Transponder for Remote Information Retrieval-on-Demand," *IEEE Trans. Microwave Theory and Techniques*, Vol. 49, No. 9, September 2001.

[5] R. Y. Miyamoto, Y. Qian, and T. Itoh, "A Reconfigurable Active Retrodirective/Direct Conversion Receiver Array for Wireless Sensor Systems," in *IEEE MTT-S Intl. Microwave Symposium Digest*, Phoenix, AZ, May 2001, pp. 1119-1122.

[6] K. M. K. H. Leong, R. Y. Miyamoto, S.-S. Jeon, Y. Wang, and T. Itoh, "A Frequency Autonomous Retrodirective Array Transponder," *IEEE MTT-S 2002*, pp. 1349 -1352.