

Review Article

Overview on the Phase Conjugation Techniques of the Retrodirective Array

Lei Chen,¹ Yu Chun Guo,^{2,3} Xiao Wei Shi,¹ and Tian Ling Zhang¹

¹National Key Laboratory of Science and Technology on Antennas and Microwaves, Xidian University, No. 2 South Taibai Road, Xi'an, Shaanxi 710071, China

²National Laboratory of Information Control Technology for Communication System, Jiaxing, Zhejiang 314033, China

³Antenna Research Department, Jiangnan Electronic Communication Research Institute, Jiaxing, Zhejiang 314033, China

Correspondence should be addressed to Lei Chen, leichen@mail.xidian.edu.cn

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This paper presents an overview on the phase conjugation techniques of the retrodirective antenna array. The concepts, advantages, and disadvantages of phase conjugation techniques are introduced. The self-phasing characteristic and technical difficulties of the array are presented as well as their structures and applications. Further researches in this area are presented finally.

1. Introduction

Retrodirective antenna [1–3] has the ability of retransmitting a wave to the direction it is arriving without the prior knowledge of the incoming signals. It has the characteristics of high link gain and low cost which make the retrodirective antenna array useful in many fields, including automatic pointing and tracking [4], phase aberration correction [5], and phase conjugate resonators [6].

The key technique of retrodirective antenna is phase conjugation technique which can be realized in many methods such as the heterodyne technique [7], phase detection [8] and digital technique [9]. The phase conjugation technique performs retrodirectivity by conjugating mixer which is used to “reverse” the incoming wavefront received by the array. The phase detection technique can achieve full-duplex communication but more complex and expensive than the heterodyne technique. The digital technique uses the digital receiver which is easily to realize various modulation methods, however the use of digital circuit increases the cost of the system.

This paper summarizes the phase conjugation techniques of the retrodirective antenna array. The concepts and self-phasing characteristics of some retrodirective arrays will be presented.

2. Heterodyne Technique Using Mixers

The retrodirective array using phase conjugation mixer is called PON array for simple. This array has the advantages as follows. (1) Active mixers [10] can be used to provide conversion gain which reduce the burden of the power amplifier. (2) The incident wave needs not to be restricted to a plane wave. This feature makes the abnormality and a nonplane to be used in the retrodirective array which is very useful in conformal antenna [11]. (3) The use of an intermediate frequency (IF) mixing makes the full-duplex communication to be possible. There are two major ways of phase conjugation by using mixers: heterodyne technique using an local oscillator (LO) at twice the radio frequency (RF) and heterodyne technique using an IF [12].

2.1. Heterodyne Technique Using an LO at Twice the RF Frequency

2.1.1. Concept. Phase conjugation with heterodyne mixer is a simple and effective technique to achieve retrodirectivity. It does not need any phase shifters or complex digital signal processing that appears in phased array antennas and smart antennas. In this scheme, the incoming RF signal is mixed

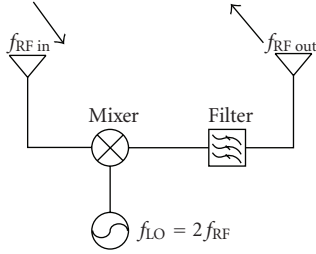


FIGURE 1: Schematic of the heterodyne technique using an LO at twice the RF frequency.

with a LO signal at twice the RF, thus the lower sideband product has the same frequency as the RF signal with conjugated phase [13]. The schematic of this technique is shown in Figure 1.

The expression is

$$\begin{aligned} V_{IF} &= V_{RF} \cos(\omega_{RF}t + \phi) V_{LO} \cos(\omega_{LO}t) \\ &= \frac{1}{2} V_{RF} V_{LO} \left(\cos((\omega_{LO} - \omega_{RF})t - \phi) \right. \\ &\quad \left. + \cos((\omega_{LO} + \omega_{RF})t + \phi) \right). \end{aligned} \quad (1)$$

Since the retransmitted IF signal has the same frequency with the incoming signals, the isolation between the interrogating and answering signals is very difficult which cannot be achieved by filters. Usual solutions to differentiate the RF and IF signals are orthogonal polarizations [14], low frequency offset [15], directional couplers [11], and balanced mixers [16].

2.1.2. Isolation Techniques

(a) *Dual-Polarized Antenna and Low Frequency Offset.* Polarization diversity can separate receiving and transmitting paths [14, 17]. The interrogating signal is received by one port, and the retransmitting signal is radiated with an orthogonal polarization by the other port. This may also reduce the array size.

A low frequency offset may compensate for the beam pointing error induced by the polar pattern directivity of the retrodirective array elements [15] and help in reducing the mutual interference between the receiving and retransmitting signals.

(b) *Balanced Structures.* Figure 2 shows a C-band retrodirective array using rat-race diode mixer which was developed at the university of California, Los Angeles (UCLA) [11]. The RF-IF isolation is achieved by a rat-race coupler. The incoming signal is fed 180° out of phase, and the LO signal is applied to the diodes with equal power and in phase. The resulting IF signals from the two diodes will be combined at the in phase port of the rat-race coupler. However, the RF leakage signal will be rejected at the same port. The measured conversion loss is 5–7 dB from 5.5–6.5 GHz; the RF-IF isolation exceeds conversion loss by 10 dB.

TABLE 1: Comparison of the phase conjugation mixers using balanced structures.

	RF fed	LO fed	Characteristics
rat-race coupler	180° out of phase	in phase	simple structure, poor isolation degree, and broadband use
balanced mixer 1	180° out of phase	180° out of phase	good isolation degree
balanced mixer 2	90° out of phase	in phase	combined RF/IF port
delay line	in phase	in phase	combined RF/IF port, delay line in one channel, and used in narrow band or point frequency

Figure 3 shows the schematic of an active phase-conjugating element using a balanced FET gate mixer [16]. The RF signal and LO signal applied to the mixers are out of phase, thus the leakage is canceled at the Wilkinson power combiner. The IF signals from each channel are combined in phase. This phase conjugation element provides 20 dB RF-IF isolation and 6 dB conversion gain at 6 GHz.

A 90° hybrid coupler [18] is used to achieve RF-IF isolation shown in Figure 4. The incoming RF signal is fed 90° out of phase to each mixer through the hybrid coupler. The generated phase conjugated signal combines in phase at the shared port, while the RF leakage appears out of phase at the opposite port of the coupler which is connected with a matched load.

Another type of balanced active phase conjugator is designed by the researchers at UCLA [19]. Figure 5 shows the schematic of the phase-conjugating element. The circuit contains two ports, one for the LO signal which is applied in phase to the two channels, and the other is a combined RF/IF port. A 90° phase delay line which is used for cancellation of the returned RF signal at the RF/IF port for isolation is introduced in one channel. Since the LO frequency is twice the RF frequency, the LO signal from two channels will experience a 180° delay when combined at the RF/IF port, thus canceling the LO leakage. The IF signals are phase conjugated and combined in phase. The conversion gain is above 5 dB from 5.975–6.025 GHz and the RF-IF isolation is below 20 dB within a 30 MHz bandwidth.

The orthogonal polarizations and low frequency offset techniques separate the incoming and retransmitting signals by signaling themselves such as different polarizations and frequencies. The rat-race coupler, balanced mixers, and delay line realize good isolation by balanced structures. Table 1 shows the comparison of these balanced structures. These techniques improve the RF-IF and LO-IF isolations, reduce undesired radiation from the array. The actual methods to achieve heterodyne technique using an LO at twice the RF frequency are often the combination of some of them.

2.2. *Heterodyne Technique Using an IF.* All the above arrays and other reported retrodirective arrays [20, 21] are only

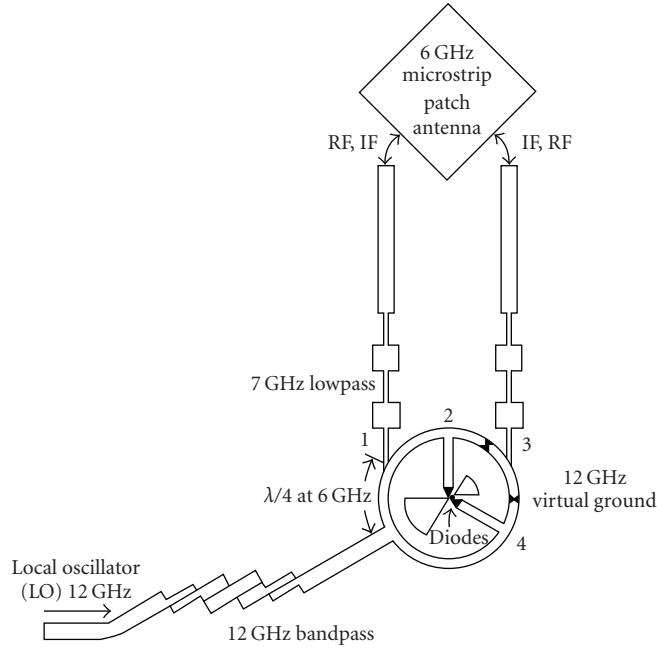


FIGURE 2: Phase-conjugating element using rat-race coupler.

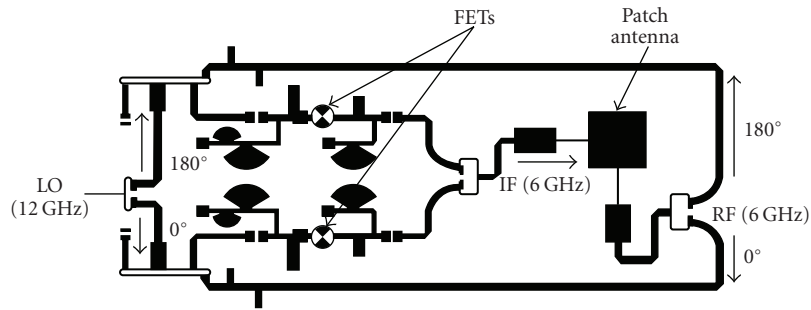


FIGURE 3: Schematic diagram of active phase-conjugating element.

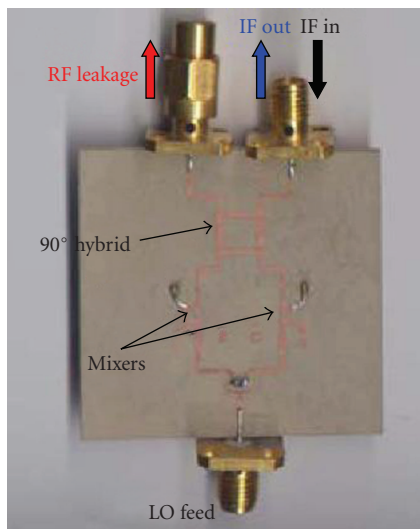


FIGURE 4: Phase conjugating mixer using 90° hybrid coupler.

capable of simplex communication. However, the full-duplex communication can be achieved by the heterodyne technique using an IF. The receiving signal is down-converted to the IF using a high or low LO signal, and then the IF is up-converted to the RF using a low or high LO signal. The special characteristic of this technique is that it is simple to apply modulation to the retransmitted signals, allowing the transmission of information. The schematic of this technique is shown in Figure 6.

The expressions are

$$\begin{aligned}
 V_{IF} &= V_{RF} \cos(\omega_{RF}t + \phi) V_{LO1} \cos(\omega_{LO1}t) \\
 &= \frac{1}{2} V_{RF} V_{LO1} \{ \cos((2\omega_{RF} + \omega_{IF})t + \phi) + \underline{\cos(\omega_{IF}t - \phi)} \}, \\
 V_{RF} &= V_{IF} \cos(\omega_{IF}t - \phi) V_{LO2} \cos(\omega_{LO2}t) \\
 &= \frac{1}{2} V_{IF} V_{LO2} \{ \cos((\omega_{RF} - 2\omega_{IF})t + \phi) + \underline{\cos(\omega_{RF}t - \phi)} \}.
 \end{aligned}
 \tag{2}$$

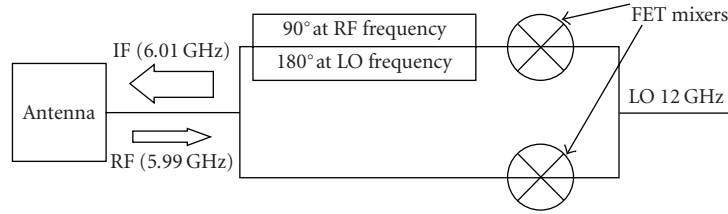


FIGURE 5: Schematic diagram of an active phase-conjugating element.

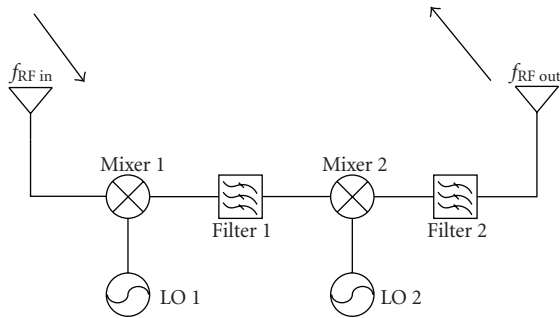


FIGURE 6: The schematic of heterodyne technique using an IF.

Considering the uninterrupted carrier and the requirement of the communication, a multichannel structure is used. A power divider is introduced in the RF or IF path to separate the incoming signals that the retrodirectivity and the modulation can be achieved at the same time. This is the common form of the retrodirective array for full-duplex communication application.

2.2.1. A Reconfigurable Array. In [22, 23], a reconfigurable array is proposed which can serve as both a retrodirective array and a direct conversion receiver by changing the LO frequency. The switching is initiated by the header code contained in the signal from the interrogator. The schematic of the reconfigurable phase-conjugating circuit is shown in Figure 7.

The LO signal is divided into two channels with a delay line which is 180° at $2f_{RF}$ and 45° at $f_{RF}/2$ in one channel. When the LO frequency is $2f_{RF}$, the circuit works as a phase conjugator and the isolation of the RF-IF and LO port is achieved by the delay line which is described previously in Section 2.1.2. When the LO frequency is $f_{RF}/2$, the circuit works as a direct down-converter; the delay line may cause the 45° phase difference of LO and 90° of the received signal. The mixer performs modulation as well as phase-conjugation. This system provides 20 dB RF-IF isolation in the retrodirective array mode. The 10 Mbps BPSK baseband signal is successfully recovered in the direct down-converter mode.

2.2.2. A Full-Duplex Communication System. The reconfigurable array provides a semi-full-duplex communication

actually. A full-duplex system presented in [24] utilizes an AM diode detector and clipper circuit to separately recover the data and generate a carrier which can then be phase conjugated. New data can be remodulated by the mixers. The circuit shown in Figure 8(a) is an AM detector receiver, and the circuit in Figure 8(b) is a digital beam-former receiver. These two circuits have the same principle and structure but different modulate mode.

2.2.3. Interference Suppression. The retrodirective array has the ability of tracking each individual source simultaneously when multitargets exist [25]. This introduces a disadvantage to the system that a signal with vital information could be retransmitted to the interfere source. Thus interfere suppression should be discussed before the retrodirective array widely used in communications. Considering the uninterrupted carrier phase, the common interference suppression technique such as array weighting method does not fit for the retrodirective array. Therefore subarray synthetic technique is introduced.

In [26, 27], a phase-conjugating retrodirective array capable of semiadaptive interference rejection is described. The basic concept is to employ a two-element subarray in each channel with phase shifters which can be controlled to multiply with the array factors so that the automatic beam tracking can be achieved with interference rejection. Then the IF path is separated to achieved retrodirectivity and DOA estimation at the same time. The schematic of the interference rejection system is shown in Figure 9.

In [28], the interleaved subarray has the same interference rejection concept with the method described in [27] but more efficient and convenient. Two identical subarrays are contained in the architecture. By feeding each subarray with a different LO phase, a single null can be steered for interference suppression at an appropriate location. The DOA estimation is realized by butler matrix.

The retrodirective array using an IF can achieve semi-full-duplex or full-duplex communication. All these systems separate the receiving signals to realize the retrodirectivity and modulation simultaneously. The feature of tracking every individual source when multi-targets exist makes the retrodirective array has to solve the interference suppression problem before it is widely used in practice. The idea of subarray synthetic technique is the best choice by far to realize interference suppression and has no harm on the carrier phase.

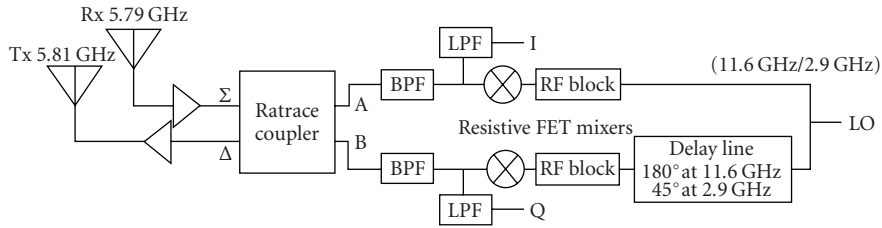


FIGURE 7: The schematic of the reconfigurable array element.

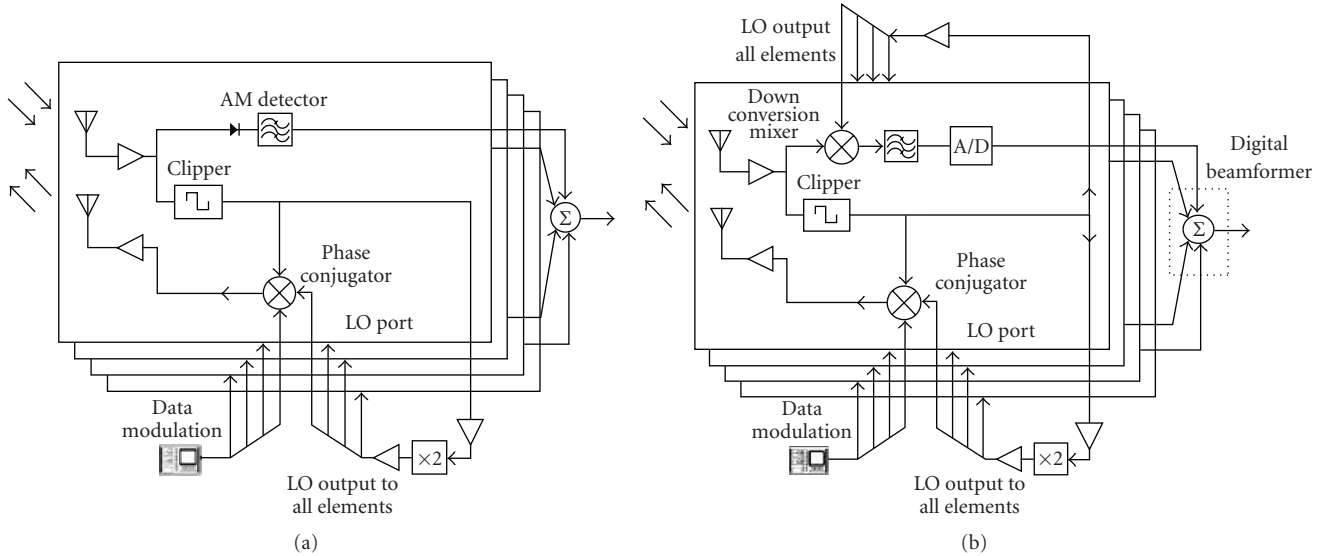


FIGURE 8: Schematic diagram of a multielement retrodirective transceiver. (a) AM diode detector receiver, (b) DBF receiver.

3. Phase Detection and PLL Technique

The heterodyne phase-conjugating architectures are the conventional methods for realizing a retrodirective array. However, the phase conjugation could also be achieved by phase detection and PLL technique [8, 29].

A full-duplex dual-frequency self-steering array using phase detection and phase shifting is presented in [8] shown in Figure 11. By RF decoupling the transmitter and receiver arrays, the system can ensure a constant transmitting power. The power of the received signal is improved by up to 12 dB for $-60^\circ \leq \theta \leq 60^\circ$ when compared to a conventional two-element array.

In [29], a phase-conjugating locked loop (PCLL) is introduced which can support a programmable frequency offset between receiving and retransmitting signals, this feature is necessary for full-duplex communication.

4. Digital Retrodirective Array

The corner reflector, the Van Atta array, and the PON array are based purely on analog circuit. A full-duplex communication was achieved by digital receiver [9] which is shown in Figure 12. The received signal is first mixed down to a lower frequency. Then all other processes including carrier

recovering, demodulation, modulation, and up-converting are realized by digital signal process. Amplification and demodulation are all done at a low frequency, reducing the complexity and cost of the system. The BER of the realized system is better than 10^{-6} for signal-to-noise ratios around 10 dB.

Like other digital receivers, the signal enters an A/D converter by down-converter, and then all the process is completed by DSP. However, a phase conjugation principle is used in the digital retrodirective array to achieve autobeam tracking. This is the combination of the digital receiver technique and the concept of the phase conjugation.

It is shown in Table 2 that the heterodyne technique has the advantages of flexible structure and easily realized, but it may face the problems of high LO frequency and interference suppression. However, it is still the most popular phase conjugation technique. The phase detection and PLL technique avoid using a high LO frequency and also exhibit other advantages such as excellent conversion gain and efficiency, but this technique increases the complexity of the circuit. The digital retrodirective array has many advantages such as flexible structure and multifunction but the system is more expensive by using the digital circuit and is restricted to the performance of the digital element.

TABLE 2: Comparison of the major phase conjugation techniques.

Phase conjugation technique	Advantages	Disadvantages	Applications
heterodyne technique using LO at $2f_{RF}$	flexible structure, easily realized	high LO frequency, poor RF-IF isolation	simplex communication, RFID
using IF		existing interference	full-duplex communication, wireless sonar, and radar
phase detection and PLL	better conversion gain and efficiency, high power carrier	more complex and expensive	full-duplex communication, point to point wireless application
digital technique	high link gain, flexible structure, and multifunction	more expensive	duplex digital communication

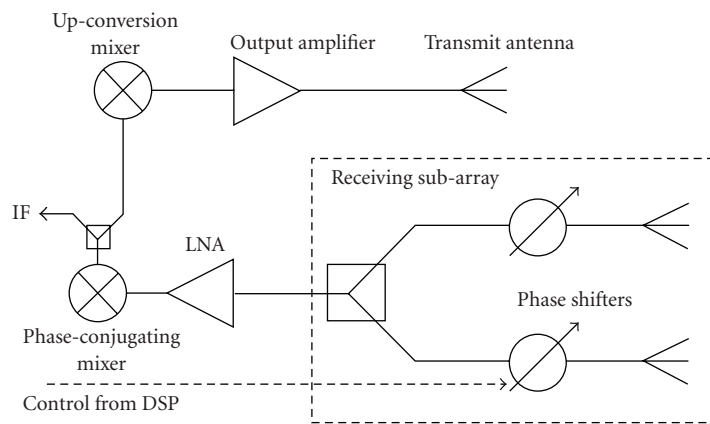


FIGURE 9: Schematic of one channel in a retrodirective array with subarray interference rejection.

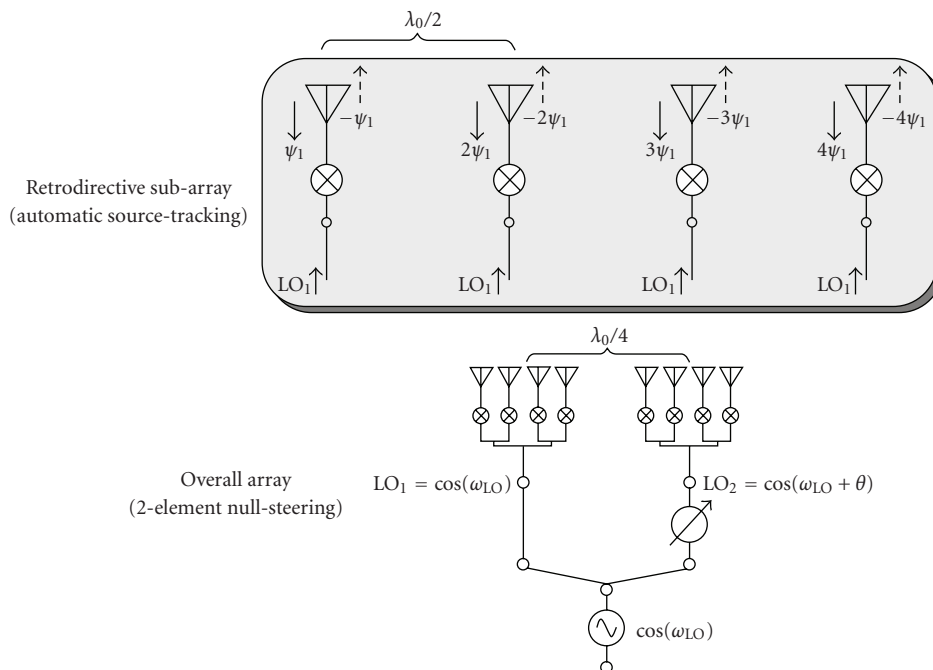


FIGURE 10: Schematic of interleaved retrodirective subarray system.

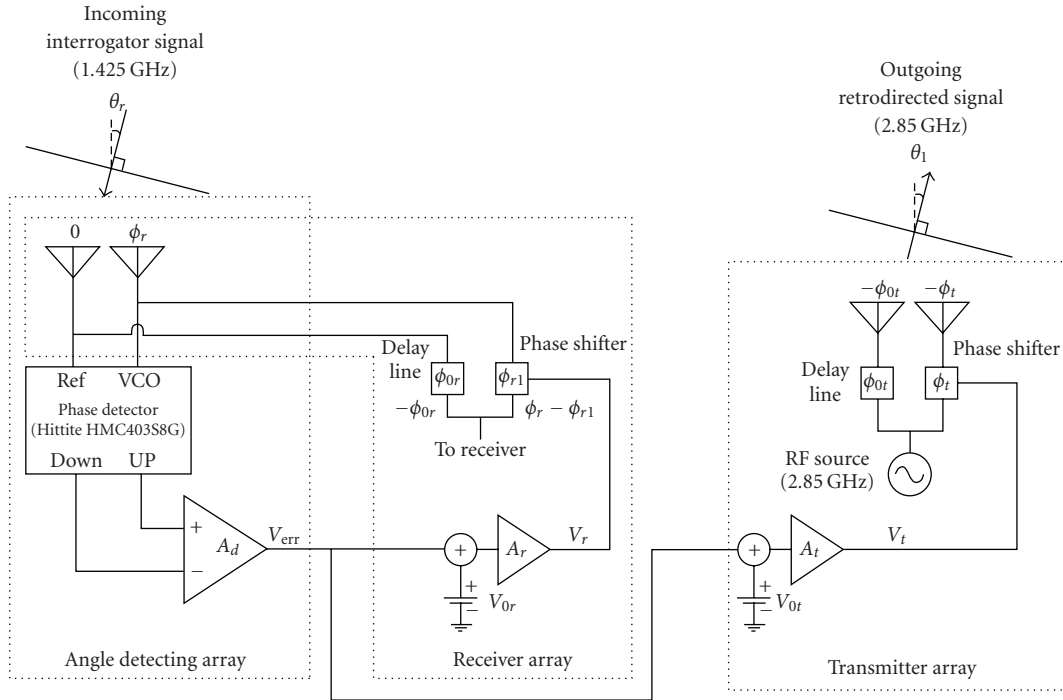


FIGURE 11: Schematic of a retrodirective array using phase detection and phase shifting.

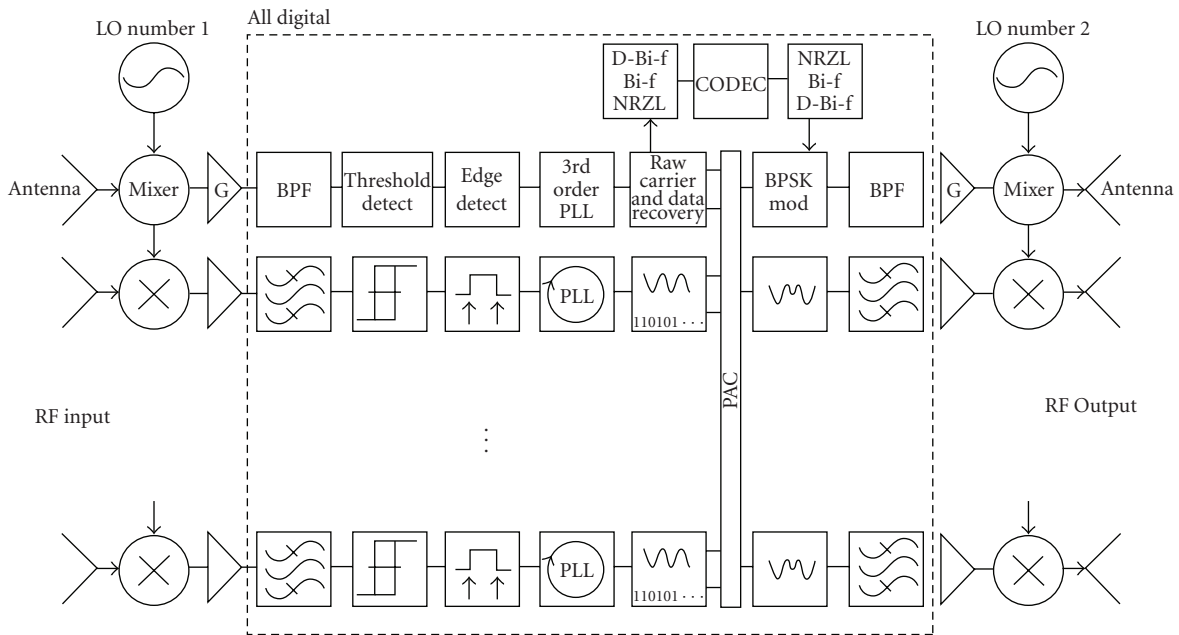


FIGURE 12: Schematic of a digital retrodirective array.

5. Some Recent Works

Researches of the theory analysis and experimental validation of the retrodirective array are carried on. In [30], it is shown experimentally that retrodirective array operating in a multipath environment can be utilized in order to spatially encrypt digital data. In [31], a more extensive

experimental is presented to show that the performance of the phase-conjugating array may be influenced by the changes in the phase difference, incident angle, and amplitude imbalance of multi-interrogating sources. In [32], the investigation of the situation where obstructing elements presented in the near field of a retrodirective array shows that the array is able to provide compensation for

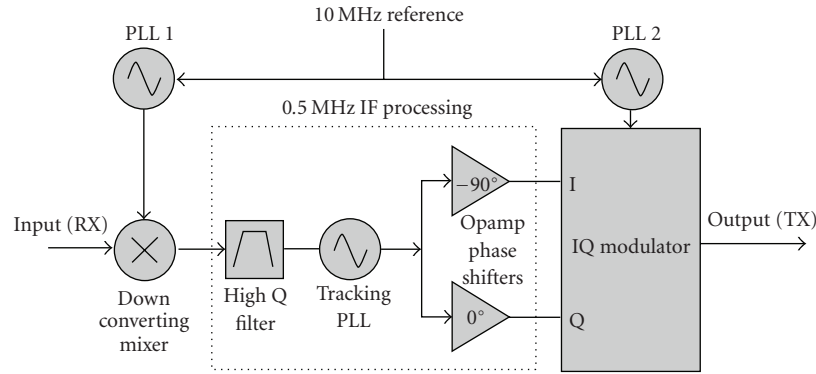


FIGURE 13: Schematic of the IQ modulator-based phase conjugator.

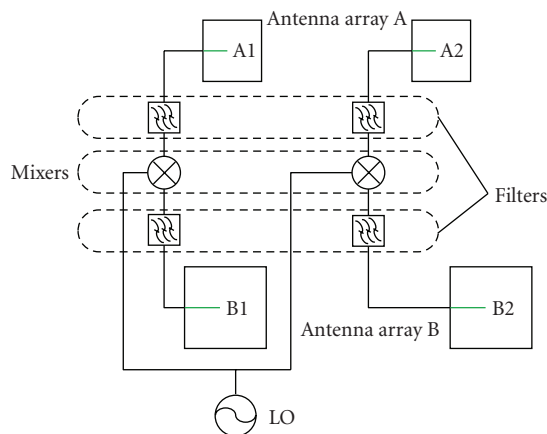


FIGURE 14: Schematic of the dual-frequency retrodirective array using heterodyne technique.

the presence of obstructions by delivering gain increase over a range of azimuthal angular positions. The work shows that there is practical advantage to use retrodirective arrays in difficult propagation environments for the first time.

All the researchers have been working for finding more functions of the retrodirective array since it was proposed. The frequency autonomous retrodirective array [33] is able to respond to a query without knowing the exact frequency and the direction of the source. The LO signal can be provided by using self-oscillating mixers [34, 35] and spatially fed local oscillator [36]. Active mixers are used to provide conversion gain. Adaptive power controllable retrodirective array is achieved in [37, 38]. These techniques can make the retrodirective array more flexible and easier to implement in practice.

A new phase conjugating architecture shown in Figure 13 is proposed in [39]. The schema is based on a modified IQ modulator architecture; it has the advantages of removing the need of LO signal, maintaining a constant transmit power, high suppression of unwanted retransmitting signals, and good RF-IF leakage than the conventional mixer-based approach and high conjugation accuracy.

Dual-frequency retrodirective array shows prominent performance in the full-duplex communication system which is few reported so far in the published literatures. In [8], a dual-frequency self-steering array is proposed using phase detection and phase shifting. The dual-frequency retrodirective array also can be achieved using heterodyne technique shown in Figure 14. By using two separated antenna arrays and double-balanced passive mixers, this array has the characteristic of dual-frequency retrodirectivity in a bidirectional way. This novel architecture may be useful in the two-way communication.

6. Further Research

Proper application of the retrodirective array is always the most important part of the research. The application areas by far are satellite communications [40], wireless communication, multiple targets tracking, multipath suppression [41], smart antenna system [42], RFID [43], microwave power transmission [44], and so on. All these should be discussed more consummate until the retrodirective array finds its position for commercial and military applications.

Further research is required to establish a full radio link consisting of two retrodirective transceivers, realize interference suppression, reduce the cost and hardware requirements of the system, and discuss the proper application of the retrodirective antenna.

7. Conclusion

Retrodirective antenna has the ability of retransmitting a wave to the source without any prior knowledge of the incoming signals. The key technique of the retrodirective antenna array is the phase conjugation technique. This paper presents an overview on the phase conjugation techniques including the heterodyne technique, phase detection and digital technique. The concepts and characteristics of all these phase conjugation techniques are introduced. The self-phasing attributes technical difficulties of different arrays, and further researches in this area are presented. As the development of the phase conjugation technique the retrodirective array may find widely military and commercial applications.

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