Short Papers

An Active Integrated Retrodirective Transponder for Remote Information Retrieval-on-Demand

Ryan Y. Miyamoto, Yongxi Qian, and Tatsuo Itoh

***Abstract*—A retrodirective transponder based on a novel compact phase-conjugating mixer with conversion gain has been developed. The active circuit uses one port for both incoming and outgoing signals, enabling a reduction of circuit size, and the balanced structure provides suppression of undesired signals. By using a modulated local oscillator, the circuit can modulate the received signal in order to retransmit local information to the remote site. A microstrip antenna is integrated with the phase conjugator and the whole system was fabricated on a single substrate, enabling a one-card system. A four-element prototype array with $0.5\lambda_0$ array spacing demonstrated excellent measured retrodirectivity. Additionally, a simplified binary-phase-shift-keying signal transmitted by the array is recovered successfully at the source location, demonstrating great potential for remote tagging and wireless sensor applications.**

***Index Terms*—Active integrated antenna, mobile communications, phase conjugator, retrodirective array, transponder.**

I. Introduction

Ease of deployment, low cost, and high efficiency are highly desired characteristics for next-generation wireless communication systems. The active integrated antenna approach is of great promise for providing some of these traits. Using this approach, transmitting and receiving systems are improved by using high-efficiency amplifiers or mixers [1], [2]. At the same time, the communication link between these systems can be improved by adapting phased-array systems such as the retrodirective array [3]–[14] for communication purposes.

Retrodirective arrays have the unique characteristic that they reradiate an incoming signal back toward the source with no *a priori* knowledge of the arrival direction or reliance on sophisticated digital-signal-processing algorithms. These unique features make the retrodirective array an attractive candidate for advanced digital mobile communication systems where high link gain and self-beam-tracking are desired. A retrodirective array can efficiently be used in a mobile communication system such as from a ground station to moving vehicles, aircrafts, or satellites.

There are two major approaches to perform this retrodirectivity. The first is the Van Atta array. The Van Atta array consists of one set of antennas with connections between pairs of antennas that are equidistant from the center of the array. The signals received by an array are transmitted by the other array, but with the order of elements flipped to achieve proper phasing [3]. Unilateral active devices are typically used in order to retransmit amplified or modulated signals. The second technique for achieving a retrodirective array is by using phase-conjugating mixers [4]. Phase conjugation with heterodyne mixing is a simple and effective technique for achieving retrodirectivity using a local-oscillator (LO) signal at twice the RF frequency [5], [6]. 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 reradiated toward the source direction, as shown in Fig. 1. The phase-conjugation technique has several advantages. First, phase conjugators can provide conversion gain by using active devices for the mixer circuitry. Secondly, it is simple to apply modulation to the retransmitted signals, allowing the transmission of information. In this method, it is important to eliminate undesired signals, i.e., nonphase-conjugated signals [5]–[8] since they are transmitted to the direction that follows Snell's law. 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, hybrids are usually used to eliminate undesired signals.

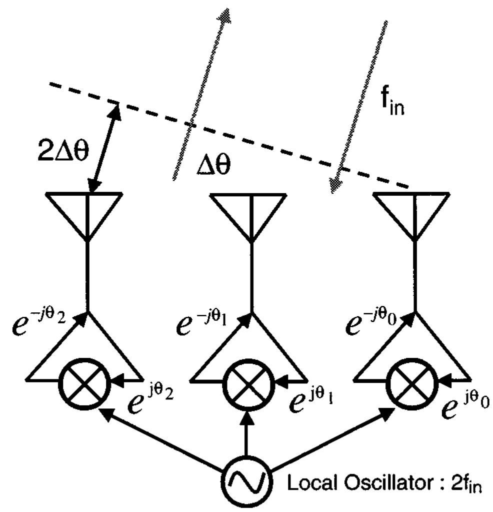

Fig. 1. Phase conjugation using heterodyne mixing.

This paper presents our recent advance in retrodirective arrays, which are particularly advantageous for RF tag applications and remote information retrieval-on-demand. Adopting active devices, the circuitry provides conversion gain in addition to phase conjugation. The circuit also functions as a modulator. Applying a modulated LO signal, the data is transferred to the IF signal through the mixing process, which can then be retransmitted. In our design, the RF and IF signals share one port, resulting in reduced system size. The novel active circuitry architecture is simple and extremely compact, enabling the array spacing small enough to avoid grating lobes. The entire circuitry was fabricated on the same substrate as the antennas, enabling a one-card transponder. A prototype four-element array shows excellent retrodirectivity. Further, a modulated signal transmitted by the array was successfully recovered at the source location. At microwave frequencies, the pointing error caused by frequency shift of the IF signal is small enough. These characteristics make the retrodirective array a good candidate for future remote tagging and wireless sensor applications.

II. Proposed Wireless Sensor System

It is known that a microwave mixer can serve as a phase conjugator when the LO frequency is twice that of the RF signal. This phase conjugation using a microwave mixer is described in (1). When the LO fre-

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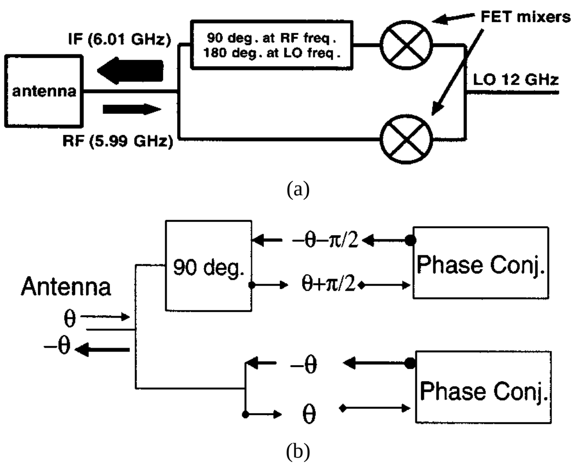

Fig. 2. Schematic of the newly proposed phase conjugator. (a) Circuit schematic. (b) Phaser diagram.

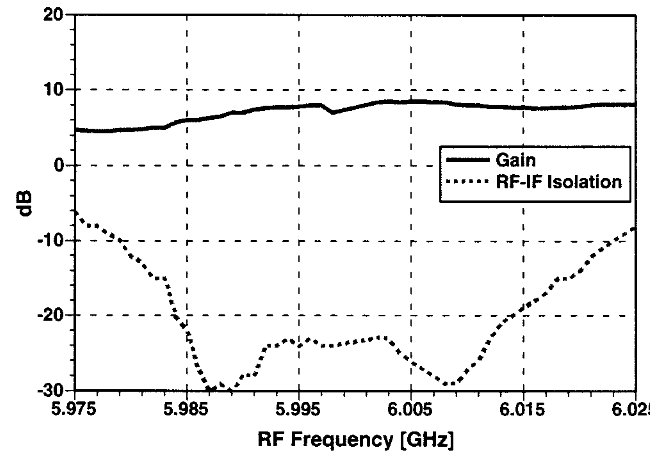

Fig. 3. Measurement results.

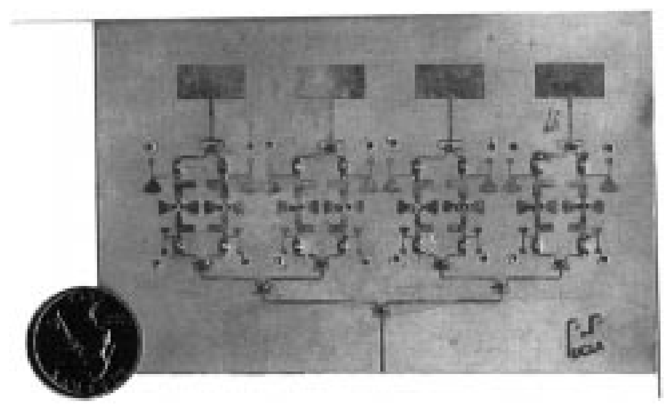

Fig. 4. Photo of the prototype four-element array.

quency is twice the RF frequency, the lower sideband signal is merely the phase conjugation of the received signal

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

The higher sideband signal and LO leakage can easily be removed since the frequency is far apart from the phase-conjugated signal. However, since the RF and lower sideband signals have the same frequency, it is impossible to filter out the RF leakage. In our design, the use of balanced structures provides effective cancellation of undesired signals. Another advantage of this approach is that, by employing active devices for mixing, conversion gain can be obtained in addition to phase conjugation, reducing the number of components.

The schematic of the new balanced quasi-optical phase conjugator is shown in Fig. 2. The circuit has two ports, one for the LO signal that is applied in-phase to the two channels 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. Since the LO and RF signals, whose frequencies are far apart, are applied from the different sides of the FETs, no couplers are needed. This fact significantly reduces the circuit size and complexity. 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, therefore, also canceling the LO to provide good LO isolation. The RF signal is applied into the mixers quadrature out-of-phase. Therefore, the returned RF (nonphase-conjugated) signals from the two channels end up canceling each other at the RF/IF port. At the same time, the IF signals are phase conjugated and combined in-phase with conversion gain. This improves the RF/IF isolation, reducing undesired radiation from the array.

A prototype mixer circuit was fabricated on a Rogers RT/Duroid 6010 substrate (25-mil thickness, $\epsilon_r = 10.2$). The heterodyne mixers used NEC NE76038 GaAs MESFETs. The circuit performance was first tested by using a subminiature A (SMA) connector at the RF/IF port instead of an antenna. Two synthesizers were used to provide the RF (5.99 GHz, −30 dBm) and LO (12 GHz, 10 dBm) signals. By using slightly different frequencies for the RF and IF signals, the IF signal can be readily distinguished from the returned RF signal. The signals going toward the output port are tapped off through a directional coupler to a spectrum analyzer. In this scheme, it is important to reduce RF leakage since the RF and IF are at the operating frequency of the patch antenna and the RF leakage can be retransmitted. The circuit achieves measured RF/IF isolation of 28 dB and conversion gain of 7 dB at the output port. 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.

III. Circuit Overview

The phase conjugator introduced in the previous section will function as a transponder when it is integrated with an antenna. Additionally, an array can be established by combining phase conjugators in order to enhance the directivity. Since each element has a phase-conjugating circuit, the array will serve as a retrodirective array when the LO signal provided to each element is properly synchronized. A prototype four-element retrodirective antenna array based on the proposed phase conjugator has been fabricated and is shown in Fig. 4. The array uses 6-GHz microstrip patch antennas with approximately 2.5-cm spacing corresponding to approximately 1/2 free-space wavelength. The antennas use inset feeds to obtain a input impedance. Each antenna uses only one feed shared by both the receiving and transmitting signals. Active circuitry is integrated for phase conjugation and amplification. The 12-GHz LO signal is applied to each element in-phase through the corporate feeding network. The total size of the array card is approximately 7.5 cm × 11.5 cm. The array serves as a retrodirective array in the azimuth plane. Since the array has four elements, this system will

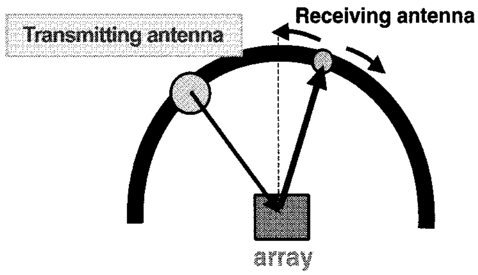

Fig. 5. *RCS* measurement setup.

receive four times as much power as a single element receives. Note that, in the receiving process, it is not an array, but merely four antennas since the signal received by each element is separately processed without being combined. Additionally, due to the retrodirectivity, the peak of the array factor should be in the direction of the source location. The directivity can be written as follows [15]:

$$D_0 = \frac{1}{U_0} = \left[\frac{1}{2} \int_0^{\pi} \left[\frac{\sin\left(\frac{N}{2} kd(\cos\theta - \cos\theta_{\rm in})\right)}{\frac{N}{2} kd(\cos\theta - \cos\theta_{\rm in})} \right] \sin\theta d\theta \right]^{-1} \tag{2}$$

where $\theta_{\rm in}$ is the incoming angle. In our case, the number of elements is four and the array spacing d is approximately $\lambda_0/2$. The directivity is approximately 4.2 (dimensionless) around the broadside and higher at sharp angles (far from broadside). Thus, the reinforcement of the communication link is a factor of more than 16 at any incoming angle compared to the single-element transponder. The radar cross-sectional measurement setup is shown in Fig. 5. In monostatic measurement, the transmitting and receiving antennas are co-located. In bistatic measurement, the transmitting antenna is fixed at one angle and only the receiving antenna is moved. The array was illuminated with a 5.99-GHz wave by a pyramidal horn antenna fed by a signal source located approximately 2.5 m away from the array. The array is driven by a 12-GHz LO signal, resulting in an IF signal of 6.01 GHz. By using slightly different frequencies for RF and IF signals, the system may use the same polarization for uplink and downlink. A second horn antenna located at varying angles for the radar cross-sectional measurement receives the retrodirected signals in H-plane. The received signal is sent to an HP 8562A-spectrum analyzer in order to measure the power.

Due to the retrodirective nature of the array, the peak of the array factor will always be in the direction of the source. The received signal power at the source point depends on the element directivity and the array directivity in the main peak direction. Therefore, the monostatic radar cross-sectional pattern of a retrodirective array is merely given by the square of its element directivity multiplied by the array directivity in the source direction. The monostatic radar cross section is given by

$$\sigma_{\rm monostatic}(\theta_{\rm in}) = D_0(\theta_{\rm in}) G_c D_e^2(\theta_{\rm in}) \tag{3}$$

where

- D_0 directivity of the array;
- G_c conversion gain of the mixer;
- D_e antenna element gain.

Since the source point always "sees" the peak of the radiation pattern, the array should not give any null in the monostatic radar cross-sectional pattern. This is one of the fundamental advantages of retrodirective arrays. Since the monostatic radar cross section strongly depends on the element pattern, the choice of antenna is important. For maximum coverage, the antennas in the array should have as low directivity as possible in order to reduce the angular dependency of the monostatic radar cross section and the beam-pointing error. The beam-pointing error is the deviation of the main beam from that of the array factor pattern. The total array radiation pattern is given by the product of the element and array factor directivities. The product of the two directivity has a peak off the peak of the array factor when a nonisotropic element is used [9]. Using omnidirectional antennas, increasing the number of elements or enlarging the array aperture size can reduce this error. A patch antenna normally has a broad beam and is good for beam-steering arrays. The monostatic radar cross section of the array is shown in Fig. 6. The measured results agree reasonably well with the theoretical predictions based on the measured element pattern.

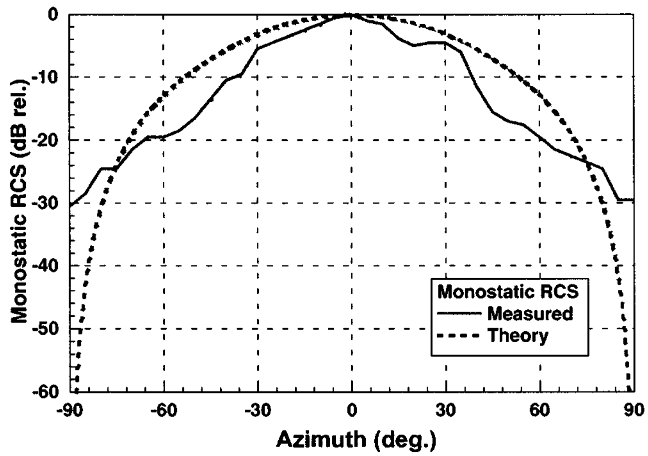

Fig. 6. Monostatic radar cross section of the array.

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

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

The array has an element spacing of 2.5 cm, which is approximately a half-wavelength at the RF frequency. The small array spacing allows the array to avoid scan angle limitations due to grating lobes, which become visible in arrays with array spacing $d > \lambda_0/(1 + |\sin\theta_{\rm in}|)$, where $\theta_{\rm in}$ is the incident angle of the incoming signal. At the same time, the array factor pattern has low sidelobes (< -10 dB). Radiation patterns of the array were measured at different source directions. Fig. 7 shows the bistatic radar cross section with the source at broadside (0°, $-30°$, and $+45°$). They are comparable with the theoretical results, which is obtained by multiplying the array pattern with the measured patch antenna radiation pattern. Retrodirectivity of the array is clearly observed. Note that no grating lobe is observed in all three cases. This is due to the small array spacing.

IV. Information Retrieval From the Array

Using a modulated LO signal allows the retrodirective array to send a unique identification (ID) code or other information back to the source location. Note that the LO signal can be modulated and it should not affect the phase-conjugating process since it is applied to each element in-phase. In this case, the information on the LO signal will be passed to the IF product through the mixing operation. One important factor is the bandwidth of the modulated signal. Since the carrier is at microwave frequency, a small frequency shift due to modulation should not affect the retrodirective performance of the array. The shift of the main beam due to a frequency change in the array is given by (5) [6] as follows:

$$\frac{\sin\theta_{\rm in}}{\sin\theta_{\rm s}} = \frac{f_{\rm LO} - f_{\rm in}}{f_{\rm in}} \tag{5}$$

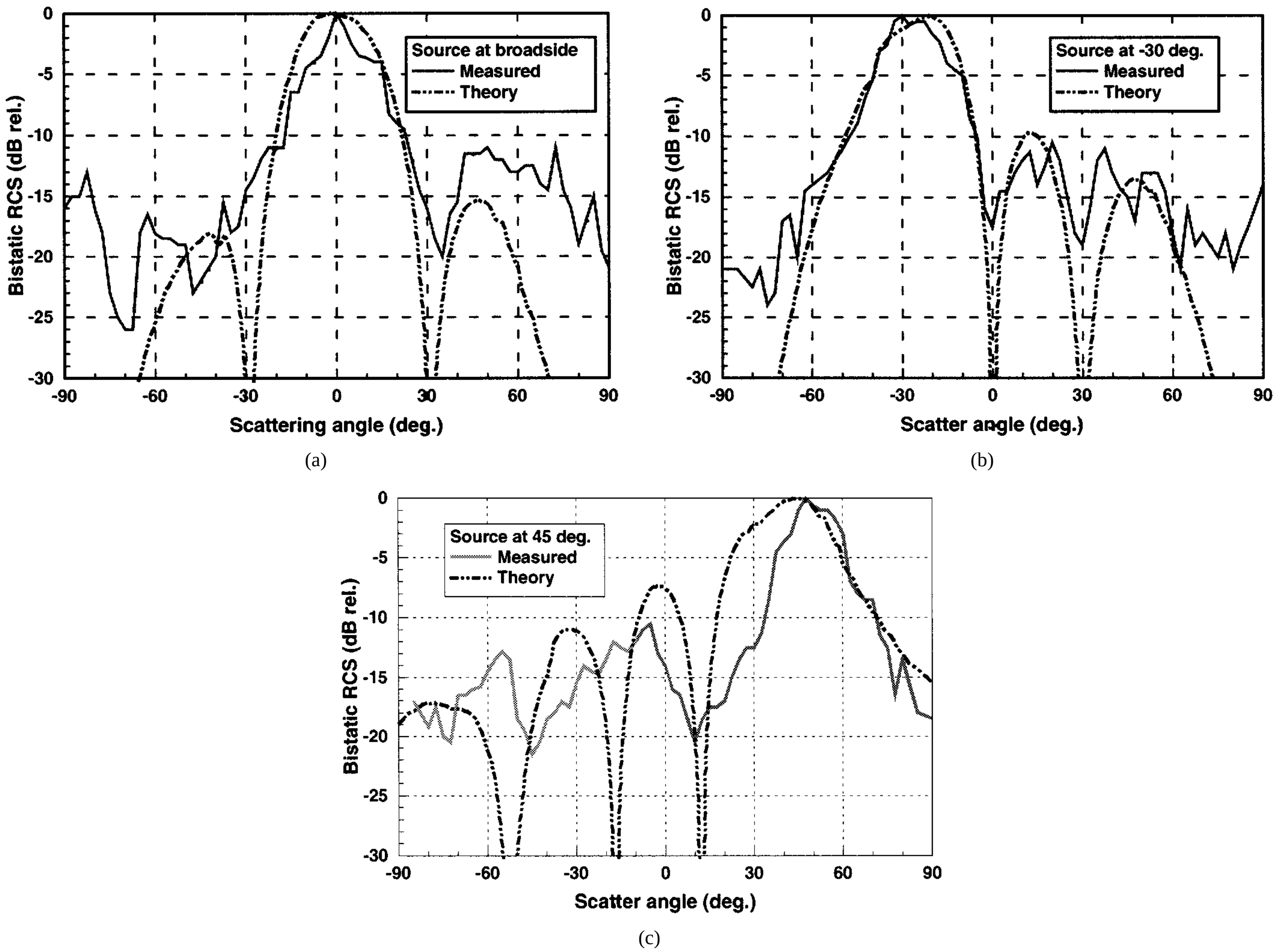

Fig. 7. Bistatic radar cross section. (a) Source at broadside. (b) Source at -30°. (c) Source at 45°.

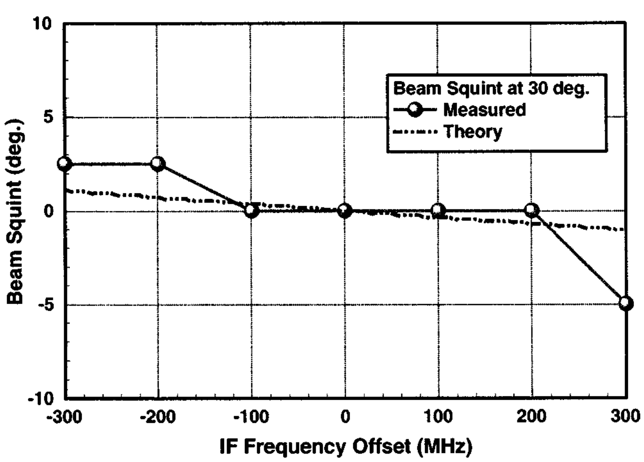

Fig. 8. Beam squint versus IF frequency offset.

where

$\theta_{\rm in}$ incoming angle;
$\theta_{\rm s}$ scattering angle;
$f_{\rm LO}$ LO frequency;
$f_{\rm in}$ frequency of the incoming signal.

For a typical modulation bandwidth, the beam squint due to the frequency offset should be negligible. Fig. 8 shows a beam squint with the source located at $+30^{\circ}$. Angular errors are sufficiently small even when the bandwidth of the signal is as wide as 100 MHz. For simplicity, the LO signal is modulated with a 1-kHz binary-phase-shift-keying (BPSK) signal in this demonstration. The returned signal from the array was demodulated at the source point by using a synchronized 6.01-GHz source. The baseband signal is then successfully recovered at the source location. By further improvement in modulation schemes, the system should also be useful in advanced applications requiring higher data rates, such as remote information retrieval-on-demand.

V. Conclusion

In this paper, an active retrodirective transponder based on a novel compact phase conjugator has been introduced. The four-element prototype array fabricated on a single card demonstrates excellent retrodirective performance. By sharing one port for both transmitting and receiving, the circuit size has been significantly reduced in order to keep the array spacing less than one-half the free-space wavelength. The balanced structure of the circuit provides good RF/IF isolation at the output port. Employing active devices as the mixers, the circuit provides conversion gain in addition to phase conjugation. With an LO signal carrying data, the data is transferred to the IF signal and the transponder may then be used to put local information on the carrier signal. This type of self-tracking system should find uses in advanced wireless applications such as RF ID tags and remote information retrieval.

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