Balanced Subharmonic Mixers for Retrodirective-Array Applications

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***Abstract*—The drawback of conventional Pon retrodirective antenna systems is the requirement of a local oscillator (LO) working at approximately twice the receive frequency. This limits the use of these systems to rather moderate frequencies where such an oscillator can be obtained. To overcome this problem, a new phase conjugate mixer topology is proposed, whereby the use of a harmonic mixer instead of the conventional fundamental type effectively halves the LO frequency requirement. Another significant problem of conventional Pon phase conjugate mixers is the small spacing in frequency, typically only a few 0.1% of the carrier frequency, between RF, IF, and LO frequency. In this paper, we have overcome this problem by introducing a double balanced structure with a novel phasing strategy. The phasing circuit automatically cancels the RF and LO signal at the system's output port, giving 36-dB RF/IF, and 34-dB LO/IF isolation for a 970-MHz IF and 990-MHz RF signal. The new mixer structure proposed here is an attractive proposition for use in retrodirective antenna arrays significantly enhancing their potential for application in the millimeter-wave frequency range.**

***Index Terms*—Pon retrodirective antenna systems, self phasing, self tracking, subharmonic mixing.**

I. Introduction

In 1964, Pon suggested an antenna structure that would achieve retrodirective operation, i.e., automatically retransmit a signal toward an incoming signal without prior knowledge of its spatial position [1]. To achieve this function, the received signal wavefront sampled at each of the elements in an array has to be phase conjugated before retransmission.

The Pon method of phase conjugation, unchanged to the present time, uses a heterodyne technique; here, the incident RF signal is mixed with a local oscillator (LO) operating at approximately twice the incident signal frequency. The difference product from the mixer bears the necessary phase conjugate relationship with respect to the incident signal. The use of this method results in the potential for realization of general retrodirective arrays that are conformal [1], unlike the earlier Van Atta retrodirective array [2] which must be planar in nature.

Fig. 1(a) shows a two-element representation of the classical retrodirective array using Pon's phase-conjugation concept, while Fig. 1(b) shows a simplified variant, which exploits the isolation properties of a dual-port microstrip patch antenna in order to replace the circulators required in Fig. 1(a). To further facilitate isolation, the retransmitted signal f_t is approximately equal to the received signal f_r and polarization diversity on transmit and receive is used [3], [4].

To see how phase conjugation by mixing occurs, let the signal received at the ith array element in a retrodirective array be $A_i e^{(j\omega_r t+\varphi)}$, where φ is the angle of arrival measured relative to array boresight. The incident signal at each element, after mixing with an LO signal running at $2\omega t$, generates sum and difference products $A_i e^{j(2\omega t+\omega_r t+\varphi)}$ and $A_i e^{j(2\omega t-\omega_r t-\varphi)}$; if $\omega \approx \omega_r$, then dominant mixing products $A_i e^{j(3\omega t+\varphi)}$ and $A_i e^{j(\omega t-\varphi)}$ occur.

Here, the difference product $A_i e^{j(\omega t-\varphi)}$ bears the wanted phase conjugate relationship with respect to the incident signal. An unwanted nonphase conjugated leakage signal $A_i e^{(j\omega t+\varphi)}$ also exists, which will lead to a perturbation of the returned signal [5]. A bandpass filter, normally the narrow-band response of the antenna, is used to filter out all other unwanted mixer products. When these phase conjugated signals, suitably amplified are fed back to the antenna elements, a reradiated wavefront will be created, which propagates back along the path of the incident signal, i.e., retrodirective action occurs.

II. Balanced Harmonic Mixer

A balanced version of the subharmonic mixer was created in order to provide LO suppression (Fig. 2). Here, the LO signal is applied to the DIFFERENCE port of a 180° rat-race hybrid [6], whereas the RF signal is applied to the SUM port. Two pairs of diodes in a back-to-back antiparallel configuration [7] are connected to the remaining arms of the hybrid, denoted as $M1$ and $M2$ in Fig. 2. Hence, the LO signal is canceled since the LO signals from both mixers are 180° out-of-phase, thus providing high LO/IF isolation at the output port. The RF leakage signal through $M1$ and $M2$, however, being in-phase, add at the output, consequently, RF/IF isolation is poor. This deficiency will be addressed in Section III.

The use of harmonic mixers in Fig. 2 allows a phase conjugate signal at the RF frequency to be generated using a fundamental oscillator. This considerably eases the LO drive frequency requirement, which, until now, had to be at twice the RF frequency. The preservation of phase-conjugation action through a balanced harmonic mixer of the type shown in Fig. 2 is now described.

In its conventional mode of operation, a harmonic mixer is driven with a signal at one-half of the frequency of the required LO frequency, thereby reducing complexity of the required oscillator [7]. If only even-order harmonics are of interest (as it

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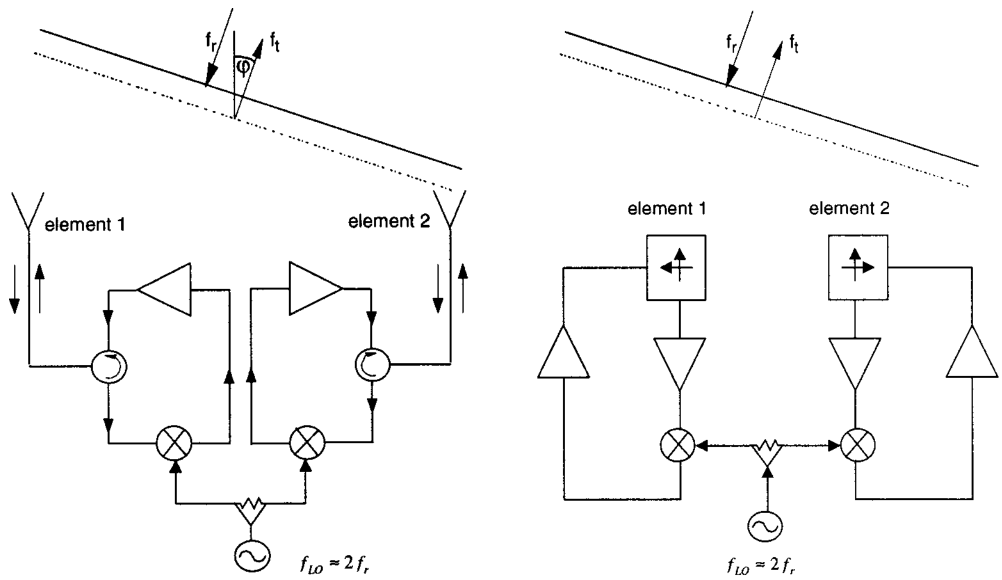
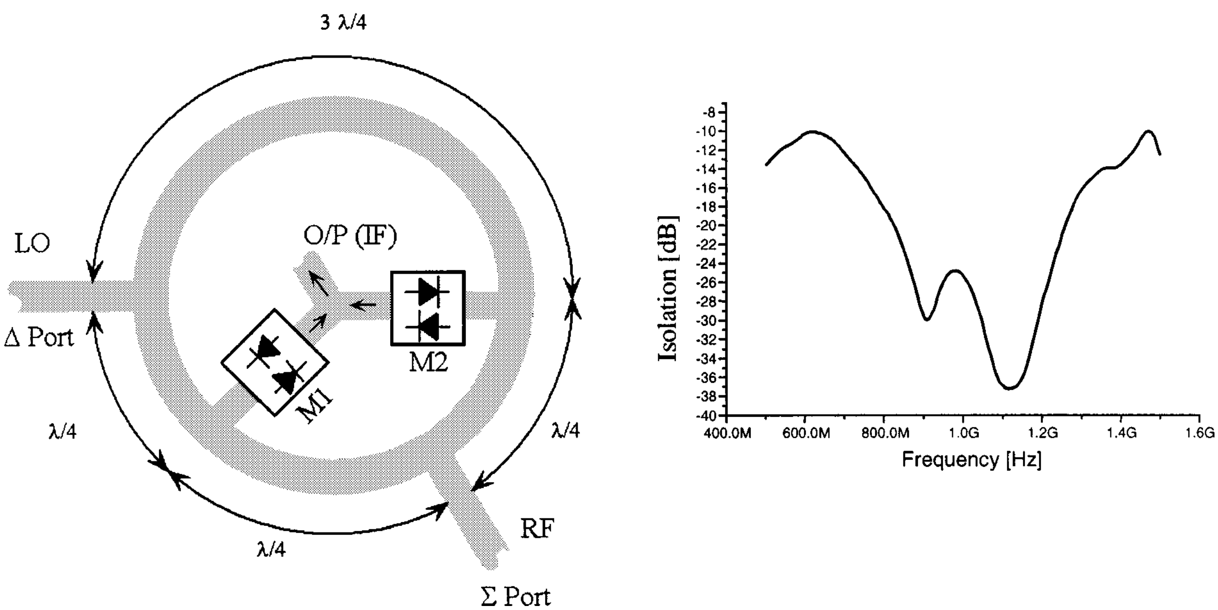


(a) (b)

Fig. 1. Two-element retrodirective Pon array. (a) Classical. (b) Simplified.



(a) (b)

Fig. 2. Balanced harmonic mixer. (a) Layout. (b) LO/IF isolation versus frequency.

is the case here), then the configuration in Fig. 2 is of use. For phase-conjugation action, the RF and LO frequencies are made approximately equal and are applied to antiparallel mixer pairs $M1$, $M2$ via the 180° hybrid. Analysis of the system shows that if the LO signal is much stronger than the RF signal, an approximate expression for the current through the antiparallel diode pair can be derived as follows.

With the LO voltage denoted by $V = V_1 \cos(\omega_1 t + \vartheta)$, the small-signal conductance of each diode in the antiparallel pair g_1, g_2 can be written as

$$g_{1,2} = \alpha I_s e^{\pm \alpha V} \tag{1}$$

where $\alpha = e/kT\eta$, and η is the ideality factor.

On expansion of the exponential term, the total conductance for the pair is

$$g = 2\alpha I_s \left[I_0(\alpha V_l) + 2I_2(\alpha V_l) \cos 2\omega_l t + \dots \right] \tag{2}$$

where $I_{2k}(x)$ are modified Bessel functions of the second kind. Since the IF output current I_{IF} can be written as $I_{IF} = V_{RF} \cdot g$, then we can obtain the lower sideband mixing product, which for an RF signal voltage $V_{RF} \cos(\omega_r t + \varphi)$ and $\omega_l \approx \omega_r$ is given as

$$I_{IF} = 2\alpha I_s I_2 (\alpha V_l) \cos(\omega_l t - \varphi + 2\vartheta). \tag{3}$$

Thus, phase conjugation the $+\varphi$ phase shift due to the angle of arrival of the RF signal has become $-\varphi$ automatically ob-

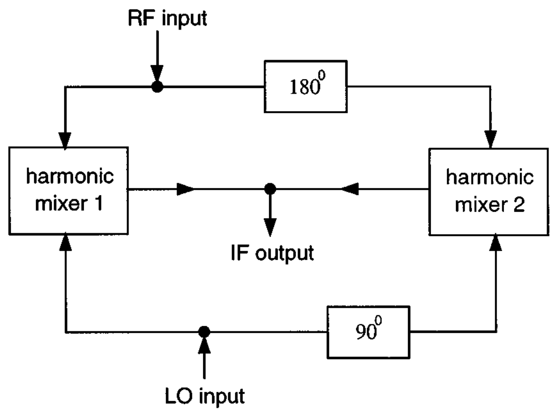


Fig. 3. RF/IF suppression configuration.

tained without recourse to a harmonic oscillator, which, up until, now has always been required.

The circuit shown in Fig. 2 was constructed in microstrip using FR4 ($\varepsilon_r = 4.4$, $h = 1.6$ mm) substrate, diodes of type HSMS-2822 [8] (L networked matched to 50 Ω at input and output) and a power combiner of type LRPS-2-11 [9]. The circuit was tested with $\mathrm{LO} = 980$ MHz and $\mathrm{RF} = 990$ MHz, yielding an IF frequency of 970 MHz. The performance of the circuit is summarized as LO/IF suppression of 29 dB, RF/IF suppression of 6 dB, and conversion loss of 12 dB. The circuit is reasonably broad band, maintaining more than 25-dB LO/IF suppression over more than 300 MHz, i.e., it exhibits approximately 25% bandwidth. The sum and difference port return losses were better than -13 dB. From these results, it can be seen that since the IF frequency is very close to both the LO and RF drive frequencies, the RF/IF suppression level must be improved in order to make the circuit useful for retrodirective applications.

III. Improved System with RF Suppression

The poor RF/IF isolation at the output port of the subharmonic mixer can be improved by using two balanced subharmonic mixers arranged as shown schematically in Fig. 3. Here, the RF signals to the two harmonic mixers are applied by means of transmission lines such that they are 180° out of phase. In addition, a phase difference of 90° is applied to the LO signal fed to the two mixers. This arrangement results in self-cancellation of the RF and LO signal. The RF/IF isolation phasing strategy given here when combined with the lack of requirement for an LO running at twice the RF frequency offers fundamental advantages over the references above. Techniques for RF cancellation were reported in [10]–[12], but with different phasing relationships to that adopted here in order to accommodate insertion of the balanced harmonic mixers in Fig. 2. For example, in [11], two rat races and two combiner splitter circuits, as well as a $\times 2$ RF LO, are required. Although offering conversion gain, the most critical parameter, the RF/IF isolation obtained was 20 dB compared to 36 dB obtained here (see Table I).

The operation of the RF/IF suppression configuration [13] can be understood with the help of Fig. 3. The LO and RF signals, applied at the sum and difference ports of the balanced harmonic mixers (shown in Fig. 2) and defined as harmonic mixer 1 and 2 (shown in Fig. 3) are f_L and $f_R + \varphi$ (where φ is the phase term to be conjugated). Using the notation in Fig. 2, the signals at the output of mixer $M1$ will be

$$\text{LO:}\quad f_L + 90^\circ \quad \text{RF:}\quad f_R + \varphi + 90^\circ$$

and, similarly, the signals at the output of mixer $M2$ will be

$$\text{LO:}\quad f_L + 270^\circ \quad \text{RF:}\quad f_R + \varphi + 90^\circ.$$

Using (3), the output sum product f_S of mixer $M1$ will have the following frequency and phase relationships:

$$2\left(f_L + 90^\circ\right) + \left(f_R + \varphi + 90^\circ\right) = f_S + \varphi + 270^\circ$$

and the difference product f_D will be

$$2\left(f_L + 90^\circ\right) - \left(f_R + \varphi + 90^\circ\right) = f_D - \varphi + 90^\circ \tag{4}$$

where

$$f_S = 2f_L + f_R \quad f_D = 2f_L - f_R.$$

Using the same considerations for the output of mixer $M2$ gives the frequency and phase of the sum product to be

$$2\left(f_L + 270^\circ\right) + \left(f_R + \varphi + 90^\circ\right) = f_S + \varphi + 630^\circ \Rightarrow f_S + \varphi + 270^\circ$$

and for the difference product

$$2\left(f_L + 270^\circ\right) - \left(f_R + \varphi + 90^\circ\right) = f_D - \varphi + 360^\circ \Rightarrow f_D - \varphi + 90^\circ. \tag{5}$$

The mixer difference outputs from $M1$ and $M2$, i.e., (4) and (5), add in phase, giving the composite output from mixer 1 in Fig. 3 as

$$f_D - \varphi + 90^\circ \tag{6}$$

i.e., phase conjugation is preserved, but a 90° phase shift has been added.

Using the same considerations for the harmonic mixer 2 (see Fig. 3) leads to the following results. The LO and RF signal's frequency and phase will be $f_L + 90^\circ$ and $f_R + \varphi + 180^\circ$, respectively.

Hence, the difference product for $M1$ in mixer 2 will be

$$2\left(f_L + 180^\circ\right) - \left(f_R + \varphi + 270^\circ\right) \Rightarrow f_D - \varphi + 90^\circ \tag{7}$$

and for the difference product for $M2$ in mixer 2 will be

$$2\left(f_L + 360^\circ\right) - \left(f_R + \varphi + 270^\circ\right) = f_D + \varphi + 450^\circ \Rightarrow f_D - \varphi + 90^\circ. \tag{8}$$

As before, the difference outputs from $M1$ and $M2$, i.e., (7) and (8), add in phase. Therefore, the output from harmonic mixer 2 in Fig. 3 will be

$$f_D - \varphi + 90^\circ. \tag{9}$$

Finally, the IF outputs from the harmonic mixers 1 and 2 in Fig. 3, i.e., (6) and (9), are added in phase using a power combiner in order to give maximum signal strength for the conjugated IF signals at the output port. Here, the difference product (f_D) bears

TABLE I
SUPPRESSION COMPARISON BETWEEN THE CIRCUIT GIVEN IN FIG. 2 AND IMPROVED CIRCUIT OF FIG. 3 ($f_{\mathrm{LO}} = 980$ MHz, $f_{\mathrm{RF}} = 990$ MHz)

Suppression	Figure 2	Figure 3
LO/IF	29 dB	34 dB
RF/IF	6 dB	36 dB
Conversion Loss	12 dB	16 dB

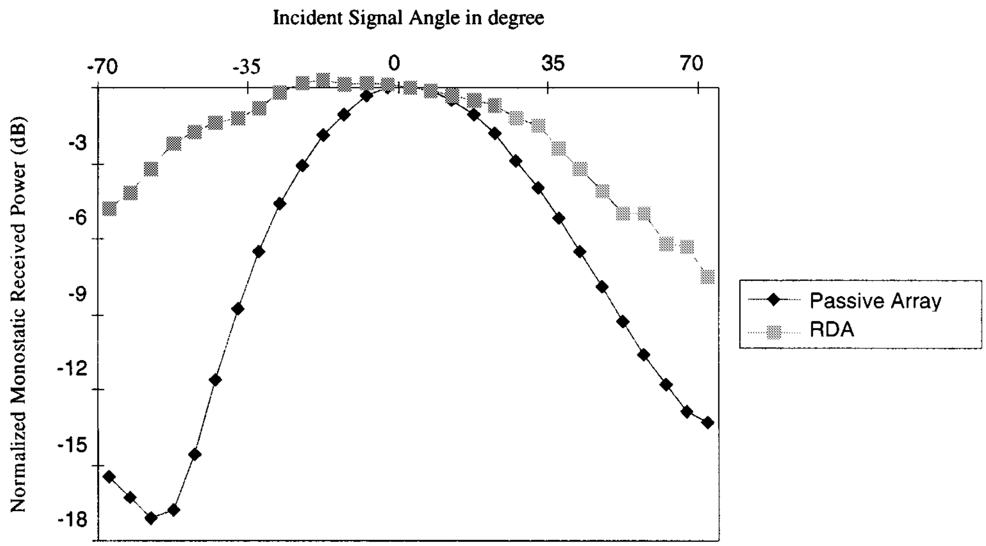


Fig. 4. Two-element retrodirective-array response.

the phase conjugate relationship with the incident RF signal. The sum product from the mixers (f_S) that does not contain a phase conjugate component is filtered out by the high-Q antenna response. In the balanced harmonic mixers 1 and 2 (see Fig. 3), the LO signal is self-canceled at outputs of the rat race mixers.

The RF leakage signal from harmonic in Fig. 3 mixer 1 is $f_R + \varphi + 90°$ and from harmonic mixer 2 is $f_R + \varphi + 270°$; hence, the RF signal is canceled during the combining process, thereby leading to improved RF/IF suppression. Fig. 3 when constructed on an FR4 board exhibited return losses of -14 dB at the RF port and -13 dB at the LO and IF ports. Its port-to-port suppression characteristics are summarized in Table I. The degraded conversion loss with respect to the case shown in Fig. 2 is probably due to intrinsic line losses and mismatches.

The system shows the typical high conversion loss of a passive harmonic diode mixer arrangement [7]. In our study, a passive antiparallel diode mixer was chosen in order to keep the initial demonstrator simple, e.g., it does not need any dc biasing. However, the conversion losses (considered justified due to the significant simplification in LO requirements) could be reduced by using active antiparallel balanced mixers or compensated by the use of an IF amplifier.

IV. RETRODIRECTIVE-ARRAY PERFORMANCE

To demonstrate that the circuitry is viable for use in a retrodirective-array application, a two-element array with 0.5-λ_0 element spacing was constructed using the topology given in Fig. 1(b). Here, microstrip-patch dual-polarized antennas exhibiting better than -35-dB port isolation were constructed on an FR4 material. The patches operated in TM_{10} mode on receive at 990 MHz and in TM_{01} mode on retransmit at 970 MHz, the return loss of each of the antenna ports was better than -17 dB. Reference [14] provides detail on the design and radiation patterns of the resulting antenna elements. This arrangement of orthogonal polarization diversity on receive and retransmit combined with slightly frequency offset receive and retransmit frequencies ensures minimum interference between received and retransmitted signals, and allows enhanced discrimination between them at the signal source location.

The measured monostatic response is shown in Fig. 4. This plots the locus of the E-field maximum of the retrodirected signal as a co-located transmitter and receiver are moved around the retrodirective array and a monostatic measurement made [14]. The measured monostatic response of the retrodirective array thus constructed has a flatter azimuthial response (96° to the -3-dB points) than its passive array counterpart (50° to the -3-dB points) indicating that the novel mixing technique proposed here does function as predicted, as defined by the ability to self-track an incoming signal over azimuth in a one-dimensional (1-D) array.

V. CONCLUSIONS

A novel harmonic-mixer phase-conjugation circuit has been developed. This mixer permits that the critical requirement for an LO running at twice the receive frequency is eliminated while retaining the phase-conjugation properties needed for a self-tracking conformal retrodirective array. For example, this means that, for a millimeter-wave mobile broad-band system application operating at 42 GHz, the LO can be at 42 GHz instead of 84 GHz, as would have been required otherwise. This restriction would probably have excluded the application of a retrodirective array at this frequency. In this paper, the reduction in

LO frequency requirement compensates for the fact that passive harmonic mixers have inherent conversion loss, which can be recovered by the use of IF amplification. In fact, IF amplification is deployed as a matter of course in retrodirective arrays in order to boost retransmitted signal levels and thereby enhance return signal range.

In addition, the final structure reported here exhibits very high RF to IF and LO to IF suppression (36 and 34 dB, respectively). In self-tracking antenna applications where the RF and IF frequencies are identical or nearly identical, this is a highly desirable feature, as it removes the requirements for the virtually impossible design of high-Q filters that would otherwise be necessary to achieve the same levels of suppression. The enhancements given in this paper to conventional phase conjugate mixer design (i.e., removal of the need for a $\times 2$ RF oscillator and high RF/IF and LO/IF suppression), suggest Pon-type retrodirective arrays could now be used at very high microwave frequencies for a variety of applications, e.g., vehicular telemetry at 62 GHz and missile tracking at 94 GHz.

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