# Chirp-Partition based Pre-Distortion for Reduced Carrier Leakage in Circulator-based Wide-band FMCW Radar Systems

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***Abstract* — This paper presents a digital pre-distortion scheme to reduce carrier-leakage in wideband FMCW radars that use a circulator to provide isolation between the transmitter and receiver. The proposed digital pre-distortion technique first power combines the leakage signal with a second pre-distorting signal prior to entering the radar receiver. The Phase & amplitude of this pre-distorting signal are adjusted for partitions of the FMCW chirp to provide cancellation. Transitions between sections are pulse shaped to eliminate broadband frequency content.**

**Index Terms — Pre Distorter, FMCW, Circulator**

## I. INTRODUCTION

One of the major challenges in wideband radar systems (radar systems where the fractional bandwidth is greater than 50%) is the issue of carrier leakage where high power signals from the radar transmitter (TX) leak into the receiver (RX) and saturate or desensitize the receiver. Saturation of the receiver reduces the ability to dectect dim or weak targets, targets at close ranges, and may even cause damage to the receiver's front-end.

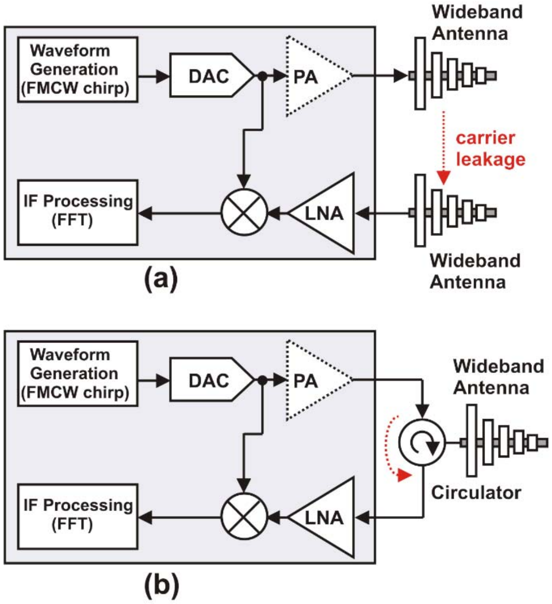

Fig 1. The two basic options to achieve isolation between radar TX and RX: (a) separate TX and RX antennas, (b) use of a circulator to provide TX-to-RX isolation while both TX and RX are coupled to the same antenna.

Of these wideband radars, penetrating radar [1,2,3] (systems where frequencies below a few GHz are used in order to allow penetration into a lossy material) are particularly difficult as the operating wavelengths are long, meaning that the antennas need to be placed in close proximity (a few wavelengths) to maintain a compact form factor. For a wideband radar systems, the radar designer has essentially two architecture options to manage the carrier leakage from Tx to Rx:

**Separated Tx/Rx Antennas-** The most common approach for wideband radar is to use separate TX and RX antennas, however this requires twice the mass/volume, and in most cases the antennas are large (due to their long wavelengths) meaning they can only be separated a few wavelengths, limiting isolation to the range of 20-30dB at best (based on 3 wavelengths of separation [3]). In the case of small vehicles (cars, UAVs, …) this approach is poor as the form factor of two large antennas separated by many wavelengths is not feasible. The separated antenna approach is depicted in Fig. 1a.

**Circulator Based-** The second approach is to use a circulator as shown in Fig. 1b. Circulators are devices which allows RF energy to flow in only one direction in order to co-couple the TX to a single antenna, and RX to the same antenna, while providing isolation between the TX and RX ports. While this approach is compact, circulators suffer from poor isolation across wide-bandwidths. A survey of recent circulator products from top vendors, showed no better than 25 dB of isolation for circulators that can operate in a wideband configuration (considers our system requirement of 1.0 to 2.0 GHz BW).

## II. DIGITAL PRE-DISTORTED RADAR TO IMPROVE CARRIER LEAKAGE SUPPRESSION

For most emerging commercial wideband radar applications related to self-driving cars, sensing of precipitation, or underground sensing for construction, 20-30 dB of isolation is simply not enough to prevent a receiver from compressing to the point where the ability to detect dim targets becomes diminished. For example a typical ground penetrating radar system for construction surveying transmits over 30dBm, and with this modest isolation provided by commercial circulators, still allows for 5-10mW to be present at the receiver input (well over what most commercially available receivers can accept without saturating). In order to overcome the limited isolation available from either the dual-antenna approach with long

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wavelengths or limited isolation available from using a wideband circulator we propose the radar architecture in Fig. 2.

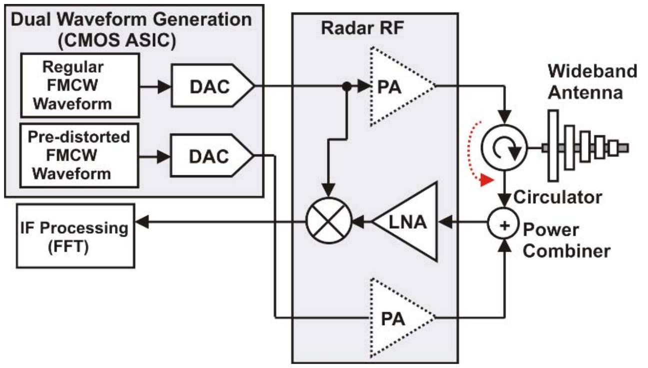

Fig 2. Block diagram of the digitally-pre-distorted circulator radar where a pre-distort waveform is added in front of the receiver to suppress carrier leakage.

In this approach the waveform is generated and transmitted to an antenna via a circulator similar to the traditional radar architecture, however a second waveform generator is added which provides a signal that is power combined at the circulator output prior to entering the receiver. This second waveform is specifically designed to cancel the carrier leakage that results from the circulator leakage path. This method of cancellation falls under the category of digital pre-distortion. In all cases both the regular frequency-modulated-continuous wave (FMCW) waveform generator that generates the radar signal, and the second waveform generator generating the pre-distorted signal are synchronized so that the cancellation waveform is aligned in time with the transmit waveform that leaks through the circulator and comprises the carrier leakage signal.

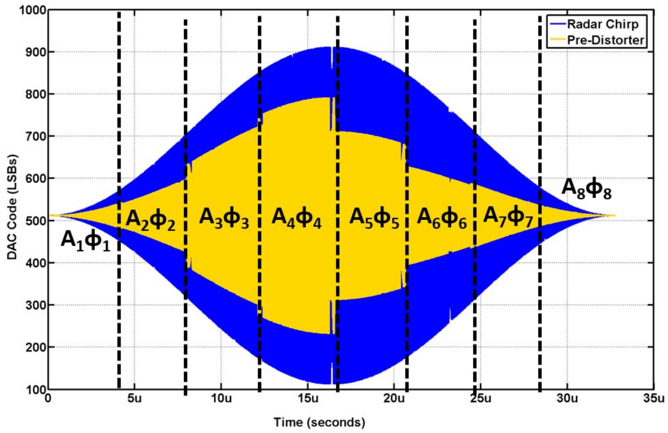

Fig 3. Waveform diagram showing the transmit FMCW waveform chirp (with a hanning applied) in blue, and the pre-distortion waveform in yellow. Marked in the figure are each pre-distortion partition where a unique amplitude/phase pair is applied.

Key to the success of this approach is that the design of the cancellation waveform produced by the second waveform generator. As the carrier leakage signal which passes from the TX through the circulator and to the RX input is a wideband signal, it will experience a non-unity frequency response from the circulator, and therefore cannot be represented by a single fixed amplitude and phase quantity, but instead both amplitude and phase become dependent on frequency. Exploiting the unique property of FMCW radar modulation where the frequency is swept linearly with time, we can then represent the leakage path as a pair of amplitude and phase functions which depend only on time and not frequency (assuming a fixed set of FMCW radar signal parameters in terms of chirp time, bandwidth and center frequency). As radar waveforms are typically very long in sample count (in our case 64K points), deriving 64K pairs of amplitude/phase correction coefficients for the pre-distorter is neither efficient nor practical as each would have to be measured independently. Instead we simply divide the radar chirp time into n partitions (in this example 8 partitions) and apply a phase/amplitude correction on a partition basis. This process is illustrated in Fig. 3., where the transmit signal is shown in blue and the pre-distortion signal is shown in yellow along with dotted lines indicating the barrier between each pre-distortion partition where a set of amplitude/phase corrections unique to each section is applied. The number of partitions used in the pre-distortion waveform can be varied depending on how much distortion is present in the carrier leakage pathway. Note that in our radar system a Hanning window is applied to the chirp signal to reduce FFT bin spill-over in the demodulator.

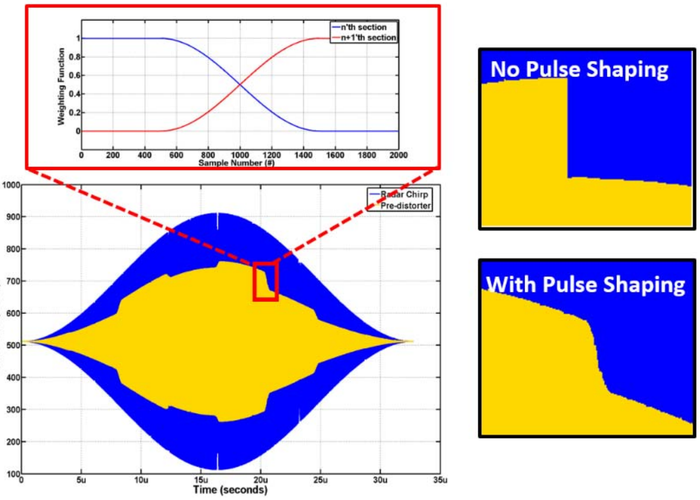

Fig 4. Application of pulse shaping at pre-distortion partition boundaries to eliminate sharp transitions and phase discontinuities and reduce generation of broadband spectral content.

One immediate problem from this approach is that the partition boundaries will create phase discontinuities and sharp amplitude transitions if the coefficients from adjacent sections are not similar. These discontinuities and transitions will create broadband content that artificially increases the noise floor of the radar system, causing reduced sensitivity to weak targets. To solve this we use a two input pulse-shape windowing filter applied to the regions around the partition boundaries. In our prototype case the shaping is applied from the 90% point of each partition to 10% into the next partition (this can be adjusted depending on the carrier leakage observed). The pulse shape filter is implemented as a root-raised-cosine function in the time domain in our prototype. Other filter types are also applicable (Elliptical/Butterworth, Chebychev). In the boundary region the two shaped waveforms (from each side of the boundary) are superimposed to produce the final output as shown in Fig. 4.

## III. TESTING SETUP AND MEASUREMENT RESULTS

In order to evaluate the proposed pre-distortion technique we implemented a simple radar as shown in Fig. 5 which uses a custom arbitrary waveform generator (AWG) CMOS chip containing two channels of 64K waveform memory and two 10b 2GS/s output DAC channels.

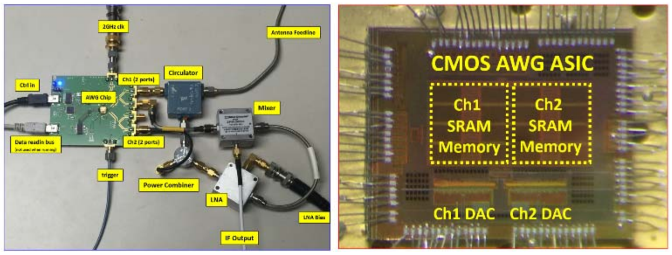

Fig 5. Testing setup of the radar front-end with circulator between TX and RX and CMOS AWG chip to generate the FMCW chirp and pre-distortion signals.

To demonstrate the cancellation capability of the proposed carrier leakage pre-distorter we first capture the time domain waveform at the receiver input with no pre-distortion signal applied. We then repeat the time domain capture with the pre-distortion both with and without pulse shaping applied to the waveform and plot the resulting time-domain trace from each condition in Fig. 6.

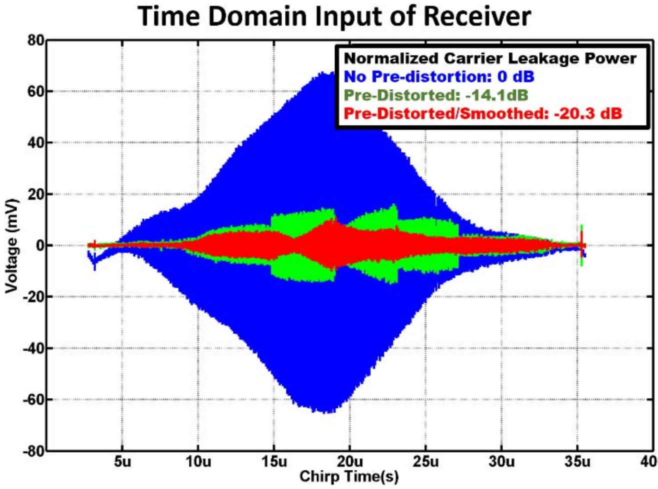

Fig 6. Captured waveforms at the LNA input of the receiver in our prototype pre-distorted FMCW radar showing the time-domain waveforms and total power of the carrier leakage signal for 1 radar pulse when: the circulator is operated without pre-distortion, pre-distortion is applied without shaping between partitions, and when shaping is applied between pre-distortion waveform partitions.

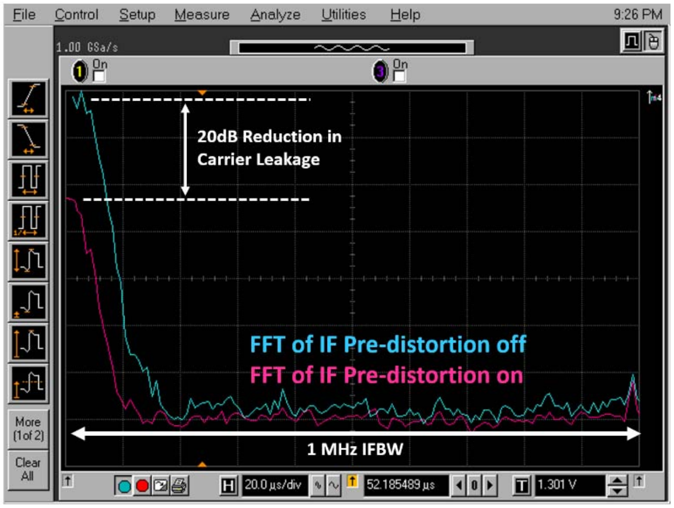

Fig 7. Captured IF spectra from the pre-distorted radar when the pre-distortion is signal is applied and removed.

Fig 7. Plots the resulting FMCW radar output spectrum at the receiver IF for close in ranges when no target is present in the radar beam, both with the pre-distortion waveform applied and removed from the receiver input. As seen from both the time domain and frequency domain measurements, a suppression of more than 20dB is possible (limited by our estimates of $A_n$,$\Phi_n$ for each pre-distortion section and the resolution of the DAC that generates the TX and pre-distorting waveforms).

## IV. CONCLUSIONS

The demonstrated ~20 dB of carrier leakage suppression achievable by the pre-distortion approach presented here is in addition to the 20-25 dB isolation already provided by the circulator itself providing a total isolation in the range of 40-45dB, suitable for many wideband radar applications, providing an elegant solution to suppressing carrier leakage in low-frequency but wideband radar systems.

## ACKNOWLEDGEMENT

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