A BST Varactor Based Circulator Self Interference Canceller for Full Duplex Transmit Receive Systems

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Abstract—An analog closed loop feedback system for improving the transmit to receive isolation of a generic circulator is described. The RF section of the circuit utilizes barium strontium titanate (BST) varactors to realize an antenna port tuner that reflects transmit power back into the circulator at the correct amplitude and phase to cancel the transmit signal leaking into the receiver port. Closed loop operation of the tuner is demonstrated using an Op Amp controller and a logarithmic detector at the receiver port. More than 33dB of additional self-interference cancellation was observed over that of the circulator for a 30MHz bandwidth QPSK transmit signal centered at 930MHz.

Keywords— Full Duplex, Barium Strontium Titanate, BST, Varactor, Circulator, Canceller.

I. INTRODUCTION

Full duplex transmit and receive systems require a very high level of transmit (TX) to receive (RX) isolation to prevent the TX signal from interfering with the operation of the receiver. Recently, research activity in this area has dramatically increased. While not possible to cite all of the work here several selected references are included in this paper [1-6]. Some of the approaches utilize a circuit between the TX and RX ports that recombines a precisely adjusted sample of the TX signal in order to cancel the leakage at the RX port. Digital signal processor (DSP) based controllers are generally used to track TX signal changes to maintain cancellation over time and signal bandwidth [2-5]. Other approaches use couplers connected to reflection tuners to form a high isolation circulator like function [6]. Both methods have been successfully demonstrated to work, however the first approach can be complex to implement and the latter suffers from high insertion loss due to the couplers.

In this paper a completely analog closed loop system is described for significantly increasing the TX to RX isolation of a circulator based front end. The approach works with a generic circulator, does not require DSP or computer based control and incurs a 0.7dB insertion loss penalty.

II. PRINCIPLE OF OPERATION

The cancellation approach investigated in this work uses an antenna port tuner to reflect TX power back into the circulator with the correct amplitude and phase to cancel the TX power leakage at the RX port due to nonzero circulator isolation [7]. This scenario is illustrated in Fig 1. Though not investigated here, the tuner can also be used to compensate for non-unity antenna VSWR.

As shown in Fig. 1, the tuner is set to produce non-zero complex reflection coefficient $\gamma$ such that $a_2 = \gamma b_2$. The antenna need not be matched as long the tuner can transform the antenna impedance to reflection coefficient $\gamma$. Assuming a matched RX port, the matrix shown in Fig. 1 can be expanded and solved for the TX to RX port isolation,

$$\begin{bmatrix} a_1 \\ b_1 \\ b_2 \\ b_3 \end{bmatrix} = \begin{bmatrix} \Gamma & \beta & \alpha \\ \alpha & \Gamma & \beta \\ \beta & \alpha & \Gamma^* \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix}$$

where $\alpha$, $\beta$, and $\Gamma$ are the insertion loss, isolation and reflection coefficient for a symmetric circulator. Setting Eq. (1) equal to zero and solving for complex reflection coefficient $\gamma$ produces the required tuner setting for perfect cancellation (2).

$$\gamma = \frac{\beta}{\beta \Gamma - \alpha^2} \approx -\frac{\beta}{\alpha^2}$$

To confirm the circuit shown in Fig. 1 was simulated with a lossless tuner and measured 3-port s-parameter data for a commercially available L-band circulator. A lossless tuner was used to terminate port 2 of the circulator with reflection coefficient $\gamma$ as calculated with Eq. (2). Simulated results for the circulator/tuner system are plotted in Fig. 2. The TX to RX port isolation improves about 20dB over the entire simulation range. Perfect cancellation does not occur because the measured s-parameters for the circulator are not perfectly symmetric. What is interesting is that the insertion loss decreases, with the largest improvements occurring where the isolation is poorest. This is not unexpected, as the amount of TX power being lost to RX port is greatly reduced.
III. CIRCUIT DESIGN

To verify experimentally a tuner circuit was designed for a 930MHz center frequency using two commercially available Barium Strontium Titanate (BST) varactors as variable capacitors. These devices have a 5:1 capacitance tuning range when the bias is varied from 1V to 24V. The bias current draw is specified to be less than 100nA. These varactors are rated for 10W series CW power handling and have a 3rd order intercept points in the 60-70dBm range. The circuit topology for the tuner design is shown in Fig. 3. Two BST varactors were required to accommodate an antenna with up to 1.2:1 VSWR at an arbitrary angle. This type of varactor was selected because available digital capacitor banks did not have enough resolution. The circuit was designed using measured 3-port s-parameter data to represent the circulator. The tuner can be operated manually by applying fixed voltages $V_{C1}$ and $V_{C2}$ to the varactor bias pins. Simulations however indicated that the TX signal rejection is extremely sensitive to varactor bias. This is not unexpected given that cancellation in the -40dB to -50dB range would require a very precise setting.

![Fig. 3. Antenna port tuner with two BST varactors.](image)

A practical implementation of this circuit would likely require some sort of automated control of the bias voltages. A logarithmic detector was connected to the RX port to sense TX leakage and serve as the input to a controller. The BST varactors are not particularly fast with respect to capacitance adjustment requiring 20-40μs to settle. To design a stable controller, the frequency response of the feedback loop would need to be characterized. This was done experimentally with the arrangement shown in Fig. 4. Varactor biases $V_{C1}$ and $V_{C2}$ were set manually for minimum TX leakage at the tuner center frequency and a small AC signal was superimposed on $V_{C1}$. The AC signal was then swept over frequency while recording amplitude and phase of the modulation at the detector output.

The measured frequency response was then fit to a lowpass $RC$ circuit from which poles at 4.1kHz and 11.1kHz were extracted. Using this equivalent circuit to represent the control loop, a PID controller was designed for a commercially available high voltage operational amplifier (op amp) to have a stable step response. The single bias implementation of the self-interference canceller with controller is shown in Fig. 5. Voltage $V_{SET}$ determines the rejection goal for the controller, as the op amp will attempt to adjust $V_{C1}$ until the detector output voltage is equal to $V_{SET}$. For a given TX rejection goal, a range for $V_{C1}$ and $V_{C2}$ exists for which the tuner can achieve said goal, the so called “solution space” of the tuner. The tuner is not capable of achieving an arbitrary level of TX rejection over a non-zero bandwidth, and if $V_{SET}$ is set too low the op amp will not be able to maintain lock. For the work presented here, tuner bias voltage $V_{C2}$ is set manually and must be within the solution space of the tuner. A two bias single input multiple output (SIMO) controller is certainly possible but was not investigated.

![Fig. 4. Circuit to characterize the control loop.](image)

![Fig. 5. Self-interference canceller, single bias controller.](image)

IV. MEASURED RESULTS

An evaluation board (EVB) was designed using commercially available surface mount components. A photograph of the EVB is shown in Fig. 6. The EVB has a second detector coupled to the TX port for input independent $V_{SET}$ generation along with an op amp reset circuit. A second EVB with just the circulator and similarly configured 50Ω traces was also assembled. The circulator only EVB was useful for performance comparisons with the canceller EVB.
To verify functionality, the canceller EVB was manually biased such that small signal s-parameters could be measured. Results for the canceller EVB and circulator EVB are plotted in Fig. 7 and Fig. 8 for TX to RX port isolation, TX to ANT port insertion loss and ANT port return loss.

The antenna port tuner improved the TX to RX port isolation by more than 25dB over a 30MHz bandwidth, and some level of isolation increase was observed for a 160MHz bandwidth. Tuning for high isolation also improved the antenna port return loss by about 10dB, return loss for the other ports was similar to that of the circulator. Inclusion of the canceller system increases the insertion loss by about 0.7dB.

To evaluate large signal performance with closed loop control, a 30MHz bandwidth QPSK signal with 2W average power was applied to the TX port. Measured results are plotted in Fig. 9 for the EVB with the canceller and the EVB with just the circulator. Tuner bias $V_{C2}$ was manually set with a fixed power supply while $V_{C1}$ is determined by the control loop. The TX to RX port leakage was reduced more than 33dB when integrated over the bandwidth of the QPSK signal. The total DC power consumption for the canceller EVB was 35mW.

The canceller was operated in full duplex mode to verify that the incoming antenna port signal is not adversely degraded by the operation of the canceller. A low level 30MHz QPSK waveform was applied to ANT port to represent a received signal and a 2W CW tone was simultaneously applied to the TX port. The RX port spectrum for EVBs with and without the canceller are plotted in Fig. 10. A greater than 50dB reduction of the TX leakage signal was observed over that of the standalone circulator. The received QPSK signal is altered only by the additional insertion loss of the tuner circuit.
Next, a 2W CW TX port signal and a CW ANT port signal offset by 5MHz were applied simultaneously. The power level of the ANT port signal was swept for different $V_{SET}$ voltages from a low level up to a level high enough to unlock the control loop. Both the TX leakage and the received signal were recorded at the RX port. There were no observable intermodulation products. The objective of the test was to characterize the impact on the leakage and received signals when they became nearly equal in strength. The results are plotted in Fig. 11.

![Fig. 11. Full Duplex operation: Offset TX and ANT signals.](image)

Note that the ANT to RX port insertion loss is a near constant 1dB, independent of ANT port signal level. This strongly suggests that closed loop self-interference cancellation process is not significantly distorting the received signal entering the ANT port. As expected, the TX signal leakage present at the RX port decreases as $V_{SET}$ is decreased. The TX leakage signal level is independent of ANT port input power until the sum of the two signals is enough to increase the output voltage of the detector. The control loop reacts to this by attempting to further reduce the TX leakage to restore the condition $V_{DET} = V_{SET}$. This effect is clearly visible for the isolation curves shown in Fig. 11. The ANT to RX loss is unaltered because bias voltages variations within the solution space of the tuner have a negligible impact on tuner loss and match. Eventually the detected sum of these two signals becomes large enough that the system departs the solution space of the tuner and the control loop then becomes unlocked. Manually biasing both $V_{C1}$ and $V_{C2}$ would result in a near constant TX leakage level over the entire ANT port power range.

The circuit shown in Fig. 5 will hold TX leakage power constant at a level determined by the value of $V_{SET}$. Therefore, if the TX power is changed, the TX to RX isolation will vary along with it. The circuit can be altered for constant isolation by adding a second detector coupled to the TX port with a coupling factor approximately equal to the target level of isolation. The TX coupled detector will generate the appropriate $V_{SET}$ voltage as the TX power level is varied. To investigate automatic $V_{SET}$ generation and TX power independent isolation, a second detector was coupled to the TX port. The coupling factor turned out to be about 37dB, which is somewhat stronger coupling than anticipated. Nonetheless, CW TX power was swept from 17dBm to about 37dBm with the TX port detector output connected to the $V_{SET}$ pin of the controller. The resulting isolation and generated $V_{SET}$ are plotted in Fig. 12. The measured TX to RX isolation is 37.5dB ±1dB and the generated $V_{SET}$ varies 0.50V to 0.82V. The cause of the deviation from constant isolation is suspected to be the result of log-linear error of the detector and process variation.

![V. CONCLUSION](image)

A tuner-based self-interference canceller with an analog closed loop feedback system for improving the transmit to receive isolation of a generic circulator has been presented. Closed loop operation of the tuner was demonstrated using a logarithmic detector at the RX port connected to an op amp controller. A 33dB increase in self-interference cancellation was observed over that of the circulator for a 30MHz bandwidth QPSK TX signal centered at 930MHz. Full duplex operation of the system demonstrated significant TX leakage reduction with minimal impact to the received signals incident at the antenna port.

**ACKNOWLEDGMENT**

Sponsored by the Defense Advanced Research Project Agency, contract HR0011-17-C-0017. The views, opinions and/or findings expressed are those of the author and should not be interpreted as representing the official views or policies of the Department of Defense or the U.S. Government.

**REFERENCES**