# An Analog Canceller for Improved COTS Circulator Isolation

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***Abstract*—An analog canceller circuit is added to a commercial off the shelf (COTS) magnetic circulator. Barium-strontium-Titanate (BST) tunable capacitors adjust the return loss at the antenna port to reflect signal back into the circulator with the proper amplitude and phase to cancel transmit leakage at the receive port. The circuit increases the isolation by 20-22dB over a 37.5MHz bandwidth with 0.4dB of additional insertion loss. The 950MHz center frequency can be scaled to other frequencies.**

***Keywords—full duplex; simultaneous transmit and receive (STAR); surface acoustic wave (SAW); correlator; orthogonal frequency code (OFC); radio frequency (RF), communication; BST***

## I. Introduction

Military tactical communications demand has dramatically increased in throughput, number of users, and ad-hoc networking behavior. The recent DoD frequency spectrum auction raised over $44B, placing extraordinary pressure on the limited RF spectrum resource [1]. Signal Processing at RF (SPAR) is developing technology that allows for 2X more efficient use of the spectrum due to full duplex operation. Flexible full duplex operation is the key to a revolution in ad-hoc media access. SPAR will improve jammer rejection by 100x to 10,000x, and provide components small enough for handheld, man pack, and small UAV applications.

## II. Operating Principle of Isolation Canceller

The fundamental idea behind this cancellation approach is to use an antenna port tuner to reflect Tx power back into the circulator with the correct amplitude and phase to cancel the Tx power that leaks from port 1 to Rx port 3 due to nonzero circulator isolation. This scenario is shown in Fig 1 and the tuner can also be used to compensate for antenna match.

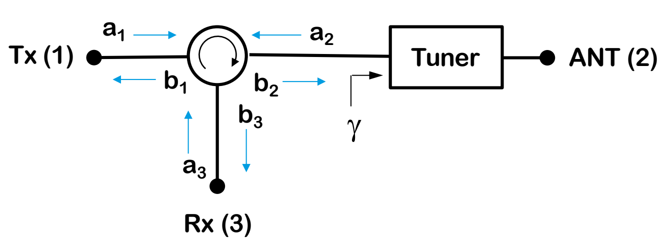


Fig. 1. Circulator with antenna port tuner.

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If the circulator can be considered symmetric it will have an s-parameter matrix of the following form [2].

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} = \begin{bmatrix} \Gamma & \beta & \alpha \\ \alpha & \Gamma & \beta \\ \beta & \alpha & \Gamma \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} \quad (1)$$

Assuming Tx port excitation and a matched Rx port the s-parameter matrix reduces to two simultaneous equations (2).

$$b_2 = \alpha a_1 + \Gamma a_2 \quad (2a)$$

$$b_3 = \beta a_1 + \alpha a_2 \quad (2a)$$

As shown in Fig. 1 the tuner is set to produce non-zero complex reflection coefficient γ and $a_2 = \gamma b_2$. The antenna need not be matched as long the tuner can transform the antenna impedance to reflection coefficient γ. Substituting this into (2) and simultaneously solving produces an expression for the Tx to Rx port isolation.

$$Tx\ to\ Rx\ Iso = \frac{b_3}{a_1} = \beta + \frac{\gamma\alpha^2}{1-\gamma\Gamma} \quad (3)$$

For perfect cancellation of the Tx to Rx port leakage signal (3) would be equal to zero. Setting (3) equal to zero and solving for complex reflection coefficient γ produces the required tuner setting for perfect isolation cancellation (4).

$$\gamma = \frac{\beta}{\beta\Gamma - \alpha^2} \quad (4)$$

## III. Proof of Concept

To verify the technique a tuner circuit was designed using two commercially available Barium Strontium Titanate (BST) varactors as variable capacitors [3]. These devices have a 5:1 capacitance tuning range when the bias is varied from 1V to 24V The bias current draw is the leakage current for the capacitor and can be considered negligible. BST 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. 2. Two BST varactors were required to accommodate an antenna with up to 1.5:1 VSWR at an arbitrary angle. The tuner circuit was designed using measured 3-port s-parameter data to represent the COTs circulator. A realization of the isolation canceller using commercially available 0402 surface mount components and a COTs circulator is shown in Fig. 3. This evaluation board (EVB) was configured to accommodate additional detection and control circuitry to investigate closed loop control of the BST varactor bias voltages. The results presented in this paper however are for manually applied BST bias voltages.

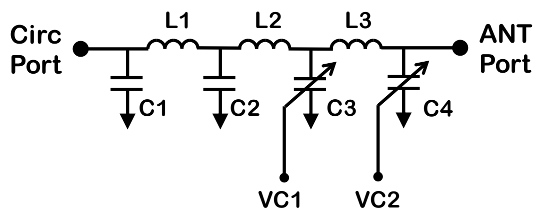


Fig. 2. Antenna port tuner topology with two BST varactors.

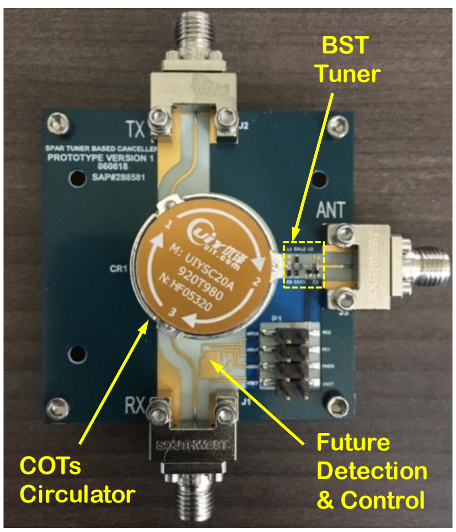


Fig. 3. Analog Tx to Rx port isolation canceller evaulation board.

## IV. Measured Results

To experimentally evaluate the effectiveness of this approach assembled EVBs were tested with a 4-port vector network analyzer at room temperature. The varactor bias voltages VC1 and VC2 were manually adjusted to achieve high Tx to Rx isolation over the frequency range of interest. The bias current draw for the BST varactors was negligible. Measured results for 4 manually biased units are plotted in Fig. 4. A 20-22dB increase in isolation was observed over that of standalone the COTS circulator. The tuner does introduce a small amount of additional loss to the antenna path as shown in Fig. 5. The loss increase was measured to 0.3-0.4dB depending on the unit. Note, this circuit has the ability to install on existing radio designs.

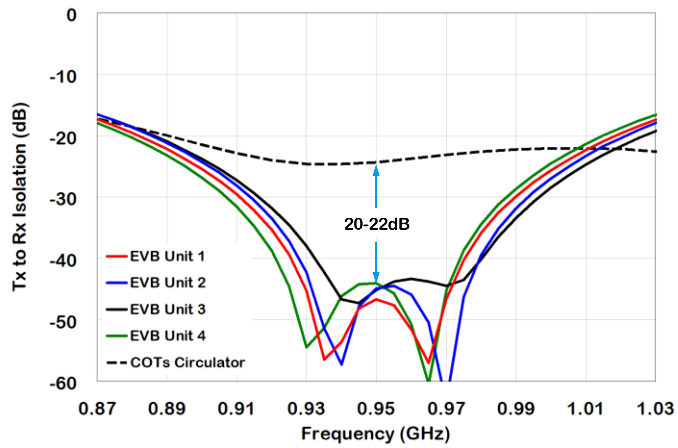


Fig. 4. Measured Tx to Rx port isolation for the evaluation board.

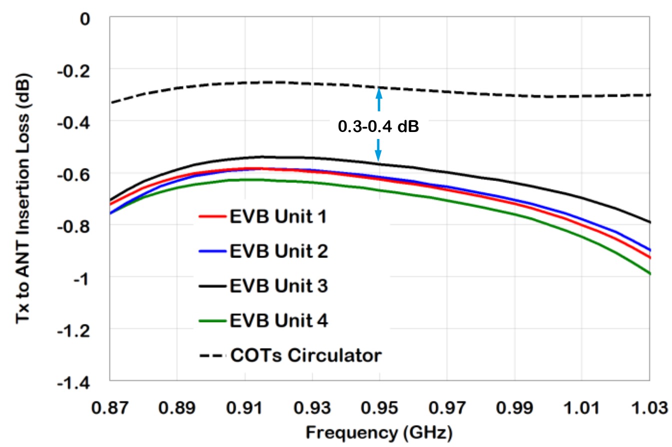


Fig. 5. Measured Tx to ANT port insertion loss for the evaulation board.

## V. Future Work

The manually biased canceller system presented here is useful for evaluating the performance and feasibility of the basic approach. There are many factors however that will influence the varactor bias voltage settings including but not limited to component variation, temperature, antenna VSWR and phase. The use of a manually biased canceller in a real system is likely not practical. Additional development work is under way to investigate automating the biasing of one or more of the varactor voltages with feedback control loops. A basic form of control is the proposed single loop system shown in Fig. 6. The Tx to Rx leakage signal is coupled to a logarithmic detector which is connected to the inverting input of an operational amplifier (op-amp) integrator. A reference voltage Vset is applied to the non-inverting input which corresponds to the detector output for a given level of Tx to Rx leakage. The error signal between the two inputs is integrated and connected to a BST driver circuit. The BST driver converts the relatively small op amp output to the 1V to 24V range required to operate the BST varactors. This closes a feedback loop that drives the tuner produce the target level of Tx to Rx leakage signal. Of course if VC1 is not correctly set the tuner will not be able to force this level of isolation. The VC1 voltage will have to be manually adjusted until it is within the range where the op-amp can lock the two inputs together. More sophisticated systems are possible utilizing dual control loops and automated Vset generation that tracks with Tx power level. Circuitry required to implement closed loop control for the isolation canceller system is under development.

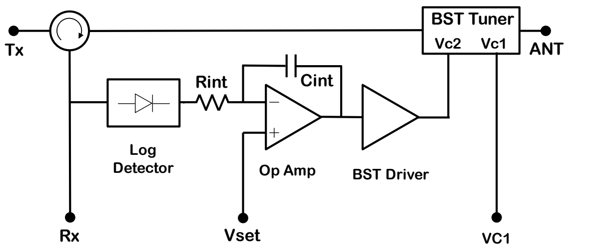


Fig. 6. Proposed closed loop control circuit to automatically bias VC2.

So what keeps the system shown in Fig. 6 from also cancelling the desired received signal? Even if the canceller acheives 50dB or more Tx to Rx isolation the Tx signal leaking to the RF port will still likely be at a much higher level than the expected received Rx port signal picked up by the antenna. The minimum detectable signal level of the logarithmic detector would to need to be well above the expected received signal level such that the tuner bias control loop does not react to it.

## VI. Conclusion

The theory, design and measured results for a circulator Tx to Rx isolation enhancement technique has been presented. The approach utilizes a BST varactor based tuner circuit between the antenna and the circulator that reflects energy at the correct magnitude and phase to cancel the Tx to Rx signal that leaks through the circulator. Measured results on a manually biased two varactor tuner demonstrate 20-22dB of isolation enhancement over a 37.5MHz band centered at 950MHz. When tuned for isolation enhancement the tuner introduces 0.3dB to 0.4dB of additional insertion loss to the antenna path. Future work will include detection circuitry and closed loop control of the varactor bias voltages to automate the tuning of the analog canceller system.

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## References


[1] B. Greeley, "Cell Phone Companies Give the Government an Unexpected Gift: $44 Billion," www.Bloomberg.com, Dec. 18, 2014.

[2] D. Pozar, Microwave Engineering. Reading, MA: Addison Wesley, 1990.

[3] ST Datasheet STPIC-68G2, www.st.com.