DESIGN OF A MINIATURE SOLID STATE FEED-THRU NULLER

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ABSTRACT

One major disadvantage of high power CW radars is finite transmitter to receiver isolation. Transmitter feed-thru can cause receiver sensitivity degradation or compress the receiver front end if the feed-thru power level is high. A new solid state component solution for active feedback nulling of transmitter feed-thru is discussed and experimental results are presented.

INTRODUCTION

Due to the finite isolation between the transmit antenna and the receive antenna in a CW radar, some of the power at the transmit frequency (feed-thru) enters the receiver. Transmitter feed-thru can cause degradation of the receiver noise floor and may cause the receiver to compress.[1]

Noise floor degradation can be brought about by two distinct mechanisms, with each having the potential to severely limit radar performance. The first mechanism involves the transfer of uncorrelated local oscillator noise onto the microwave feed-thru signal. Although the transmitter feed-thru signal may be notch filtered at the IF processing frequency, the uncorrelated local oscillator noise remains, increasing the receiver noise floor.

The second manner in which the noise floor can be degraded is by the transmitter AM noise sidebands on the feed-thru. The correlation of FM noise in the mixing process generally eliminates the adverse effects of transmitter FM noise, although it can become a problem if system time delay mismatches are large.[2] However, the feed-thru carries the transmitter's AM noise sidebands, and it is not possible to remove the AM sidebands through frequency mixing.[3]

At certain positions of the transmit and receive antennas, the feed-thru signal strength is often beyond the dynamic range of the receiver front end. Unless the signal level is reduced before entering the receiver's active components, the receiver is desensitized and begins to distort the incoming doppler signals.

Many CW systems space the transmitting and receiving antennas as far apart as possible to obtain sufficient feed-thru isolation. This technique is not practical when space constraints are a factor and large objects exist near the antennas that cause reflections. A notch filter is needed to reduce the feed-thru signal as it enters the receiver. At microwave radar frequencies a passive filter is impractical, since it is necessary to notch the feed-thru at zero doppler without interfering with the desired doppler return signals which may be only a few kilohertz offset.[4]

One solution is to use active signal cancellation, or feed-thru nulling (FTN), to reduce the feed-thru signal. With this technique, a portion of the transmit signal is combined with the feed-thru at the receiver input. The transmits sample is amplitude and phase adjusted with a feedback system to be equal in magnitude and opposite in phase to the feed-thru. This results in up to 60 dB of reduction in the feed-thru signal level before it reaches the receiver's active front end components. FTN cancels AM and FM noise sidebands on the feed-thru by the same amount that the carrier is cancelled, allowing CW radars to operate with reasonable transmitter output purity.

FEED-THRU NULLER THEORY OF OPERATION

A solid state X-band FTN was developed for a high power CW radar. The implementation chosen for the FTN involves two separate feedback loops. Figure 1 presents a conceptual block diagram of the FTN.

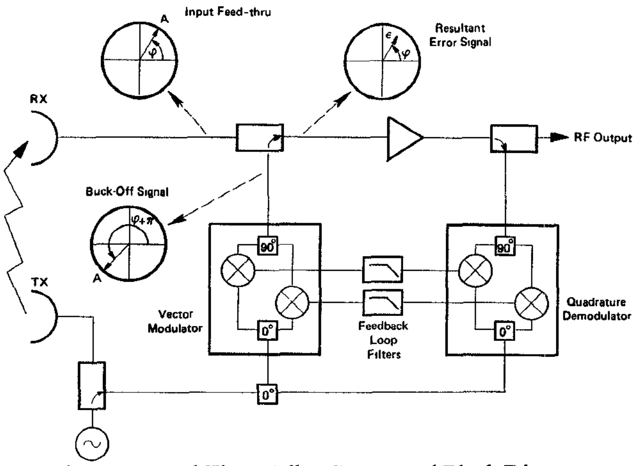
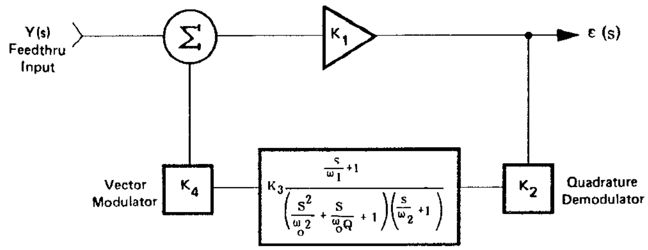


Figure 1. Feed-Thru Nuller Conceptual Block Diagram

The feed-thru signal is demodulated into two quadrature vector components with a coherent quadrature demodulator. The outputs of the demodulator drive two separate feedback loop filters. Each feedback loop filter drives one quadrature component of a vector modulator. The output of the vector modulator (the buck-off signal) is then injected into the receiver front end through a directional coupler to cancel the input feed-thru signal. By resolving the feed-thru into in-phase (I) and quadrature (Q) components, the feedback system may be accomplished with two amplitude and sign servo loops.[2],[5] If the assumption is made that there are no phase errors in the RF components in the FTN loop, then the system may be treated as two completely independent standard linear feedback networks. This assumption proves to be an acceptable starting point in developing the design of the FTN feedback response as long, as the quadrature phase errors are controlled to less than

20 degrees. Using the above assumption, the feedback network is illustrated by Figure 2 and described by equation 1.



$$\frac{\varepsilon(s)}{Y(s)} = \frac{G(s)}{1+G(s)H(s)} = \left[\frac{K_1}{1+K_1K_2K_3K_4\left[\dfrac{\frac{s}{\omega_1}+1}{\left(\frac{s^2}{\omega_o^2}+\frac{s}{\omega_o Q}+1\right)\left(\frac{s}{\omega_2}+1\right)}\right]}\right] \quad \text{[EQ.1]}$$

where
$Y(s)$ = The amplitude envelope of the I (Q) feedthru vector component
K_1 = Receiver front end gain
K_2 = Quadrature demodulator amplitude const
K_3 = Loop filter DC gain
K_4 = Vector modulator amplitude const

Figure 2. Feedback Diagram Assuming No RF Phase Errors

The feedback loop frequency response determines the effective notch filter bandwidth and the stability of the nulling system. The unity gain bandwidth is chosen to be several hundred hertz wide so that the feed-thru signal may be cancelled without interfering with the doppler band of interest.

RADAR SYSTEM CONSIDERATIONS

In addition to the RF feedback network design, attention must be paid to several FTN performance parameters which play a critical role in determining the dynamic range and clutter performance of the radar system. Subtle differences in FTN circuit realization can have serious impact on radar system maximum range and clutter handling capabilities. A brief discussion is given below for several of the key requirements for the FTN system.

If there is perfect RF phase quadrature in the FTN loop, then the feedback loop stability and time domain step response can be determined using standard linear control theory. However as quadrature errors are introduced, the I and Q control circuits in the feedback network begin to interact and the feedback loop stability decreases. It can be shown that the FTN feedback control system becomes unstable if the quadrature phase errors reach 60 degrees. However, in a practical FTN system the time domain step response and the control loop stability become unacceptable for phase quadrature errors in excess of 20 degrees. Figure 3 shows the effect of increasing phase quadrature errors on the time domain step response of the control loop.

The FTN cancellation signal is injected into the receiver front end preceding the low noise amplifier. To prevent degradation of the receiver noise floor, the added noise from the FTN must be well below the receiver noise figure. If the FTN must null large feed-thru signal levels, this requirement equates to extremely low AM and FM noise sideband levels at the output of the vector modulator. The noise generated in the loop filter network, the vector modulator, and the voltage regulator system must be minimized to obtain reasonable noise performance. The maximum level of single sideband noise allowed at the output of the vector modulator is presented in equation 2.

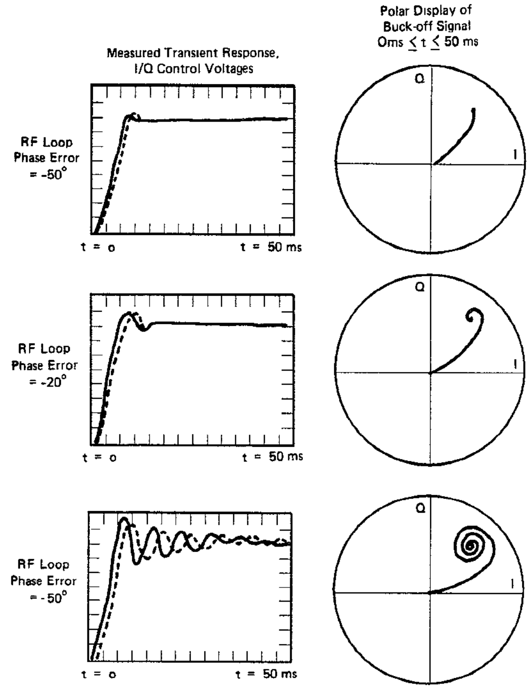


Figure 3. FTN Transient Response to a Pulsed Feed-thru

$$SSB_{max}\,(\text{dBc/Hz}) = [kT + NF - NM] - P_{max} \quad \text{(EQ.2)}$$

where, P_{max} = maximum feed-thru signal power at the receiver input (dBm)
kT = thermal noise in a 1 Hz bandwidth (dBm)
NF = receiver noise figure (dB)
NM = min. ratio of receiver noise to added noise (dB)

It is often a requirement to track radar targets while the radar receive antenna is sweeping past obstructions that cause large return signals. The geometry of certain obstructions can cause a small doppler frequency shift, relative to the transmit frequency, of the feed-thru return signal as the antenna beam travels past the obstruction. This offset is often on the order of 20 Hz for an X-band radar. The FTN system must be able to cancel this signal just as it cancels signals at zero doppler. All nonlinearities in the FTN loop must be minimized to ensure that the magnitude of the higher order doppler harmonics are well below the receiver noise floor.

Just as with doppler shifted feed-thru signals, any nonlinearities in the FTN loop will cause high order inter-modulation products when high level clutter signals are present. Clutter signal parameters play a key role in determining vector modulator linearity requirements and the design of the servo frequency response in the FTN feedback system.

SOLID STATE FEED-THRU NULLER IMPLEMENTATION

In the past, high power feed-thru nullers have often been constructed utilizing split-milled waveguide assemblies and ferrite modulators. The disadvantages associated with this type of construction are large size and high DC power consumption. These drawbacks make this device unsuitable for many applications, creating the need for a smaller solid-state high power feed-thru nuller.(2)

A solid-state feed-thru nuller has been developed which offers significant improvement in size, weight, and DC power consumption. The solid-state feed-thru nuller employs a Schottky diode quadrature demodulator, a PIN diode vector modulator, and microstrip construction techniques. A block diagram of the radar receiver, which includes the solid-state feed-thru nulling loop, is shown in Figure 4. Notice that the FTN loop includes a downconversion and that a sample of the IF frequency is the input to the quadrature demodulator. Demodulating the error signals at the IF frequency provides two primary advantages: a demodulator operating at the (fixed frequency) IF can be built with superior performance, and undesired input signals, which can interfere with FTN loop performance, may be filtered prior to reaching the demodulator.

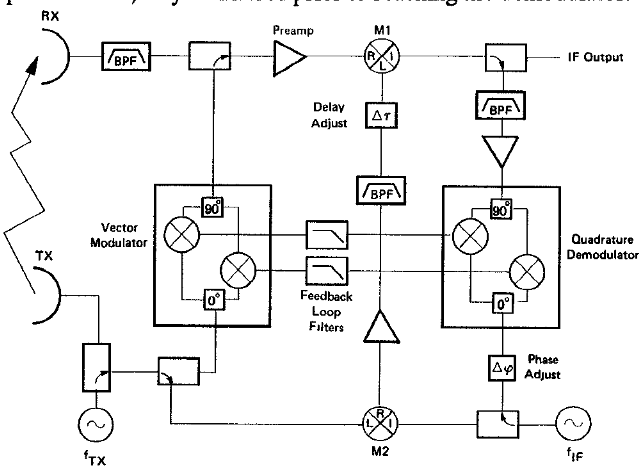


Figure 4. Feed-Thru Nulling with Downconversion

Two key components depicted in the loop block diagram include a coaxial delay line and an adjustable microstrip phase-shifter. The delay line matches the electrical delays ($\delta\phi/\delta f$) of the RF and LO inputs to mixer M1, thereby eliminating any dependance of RF loop phase shift on the transmitter frequency. The adjustable phase-shifter is used to set the overall RF loop phase shift by aligning the phase of the fixed frequency demodulator reference.

Vector Modulator Realization

The PIN diode vector modulator design was formulated by blending microwave circuit design, a unique DC biasing scheme and special MIC construction techniques in order to meet the phase vs. attenuation, amplitude control linearity, and power handling requirements placed on this component. A conceptual block diagram of the vector modulator is presented in Figure 5, and shows two independently-controlled bi-phase attenuators positioned between 0° and 90° 3 dB hybrids.

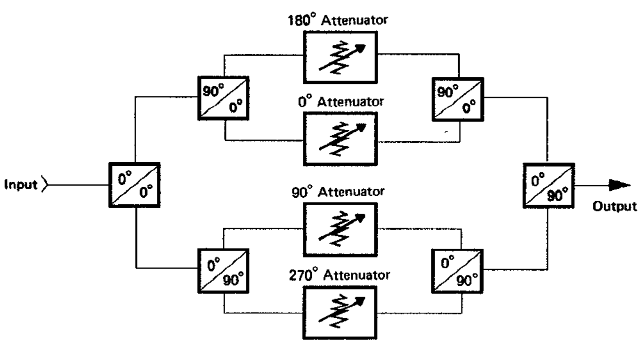


Figure 5. Vector Modulator Block Diagram

The bi-phase attenuators are made up of two variable attenuators positioned between 0° and 180° 3 dB hybrids. The diodes in each variable attenuator are arranged in balanced series configurations as shown in Figure 6. Figure 6 also shows the unique self-cancelling bias scheme that was developed for the bi-phase attenuators that imparts a large dynamic range with very good amplitude control linearity (see Figure 7). Analog linearizing circuits were thus avoided, minimizing the generation of high order intermodulation products which interfere with the doppler band noise floor in the presence of high clutter levels.

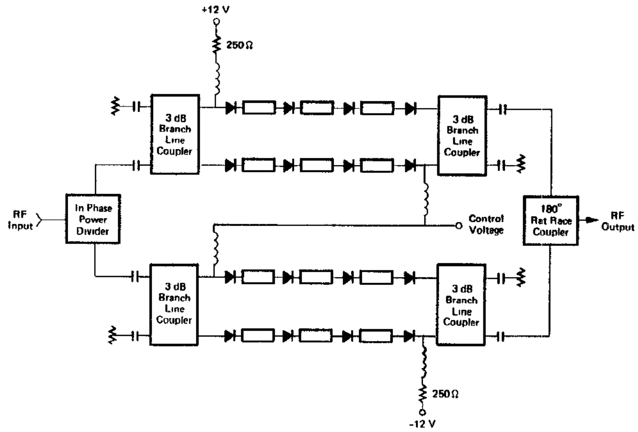


Figure 6. Bi-Phase Attenuator Schematic

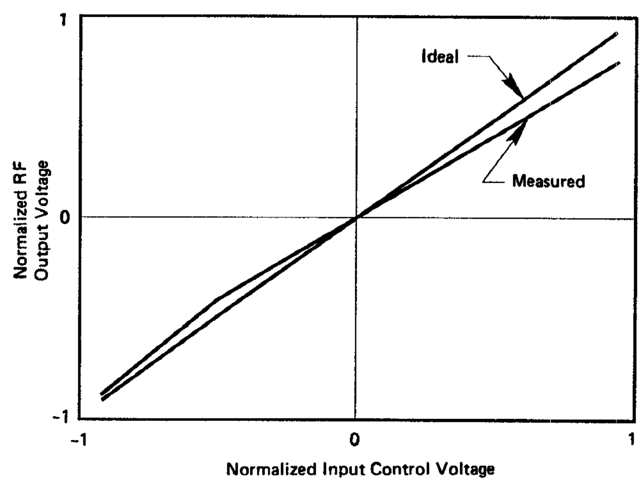


Figure 7. Measured Vector Modulator Control Linearity I or Q Component

It is critical that the phase variation versus amplitude of each bi-phase modulator output be minimized, since any RF phase variation adds to the overall loop phase error. The RF phase shifts in the bi-phase attenuators are minimized in the design by adjusting the impedance and length of the transmission lines between the PIN diodes. This, combined with inherently forgiving balanced configuration of the bi-phase attenuators, results in very little phase variation as a function of amplitude (see Figure 8.)

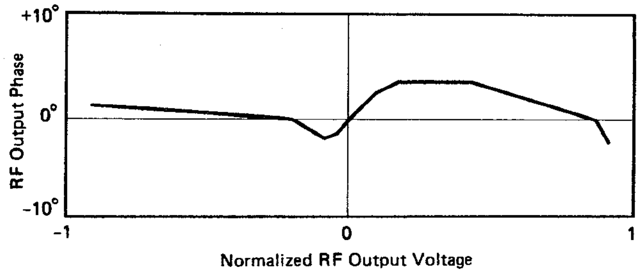


Figure 8. Measured Phase vs. Amplitude Response, Vector Modulator I (or Q) Channel

The fabrication techniques employed to handle the power dissipation in the PIN diodes included selecting diodes with low θ_{JC}, brazing diode chips to a 15 mil alumina substrate, and attaching the substrate directly to the aluminum housing. A photograph of a solid-state vector modulator RF circuit is presented in Figure 9.

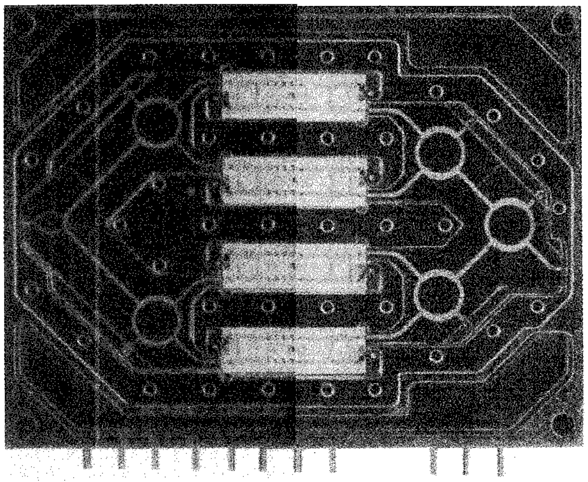


Figure 9. Vector Modulator RF Circuit Photograph

Loop Filter Realization

The loop filter circuitry feeds the outputs of the quadrature detector back to the vector modulator, closing the feedback loop. The loop filter determines the frequency response of the loop, limiting the unity gain crossover frequency to roughly 500 Hz in this case. A fourth-order filter response, utilizing lead-lag compensation, provides a loop phase margin of 45° at unity gain. The loop filter network also includes temperature compensation circuitry to null the demodulator's DC offset voltages as they vary over temperature.

Any noise generated in the audio circuits ultimately modulates the transmitter sample in the vector modulator, creating uncorrelated noise on the buck-off signal, thereby degrading receiver sensitivity. In addition, constraints imposed by the RF design of the receiver required that most of the loop gain (≥60 dB) be located in the loop filter circuits. Care is required to design a network which provides the desired frequency response and transfer gain and prevents the active components in the loop filter from saturating during operation with clutter.

The eventual solution involved minimizing op-amp and voltage regulator noise and interspersing the frequency poles with gain stages throughout the loop filter chain. The resultant network provides the frequency response necessary for stable loop performance, suppresses noise generated in the loop filter, and rejects clutter signals exiting the demodulator.

SOLID STATE FTN MEASURED PERFORMANCE

The feed-thru nuller was implemented as part of a Doppler radar receiver operating over a three percent bandwidth at X-band. Use of the delay adjustment reduced the frequency dependent RF phase errors over the operating bandwidth to less than 5°, allowing the feed-thru nulling loop to maintain excellent stability. By temperature compensating the quadrature demodulator offset voltages, greater than 50 dB of feed-thru nulling was maintained over the operating frequency and temperature ranges as shown in Figure 10.

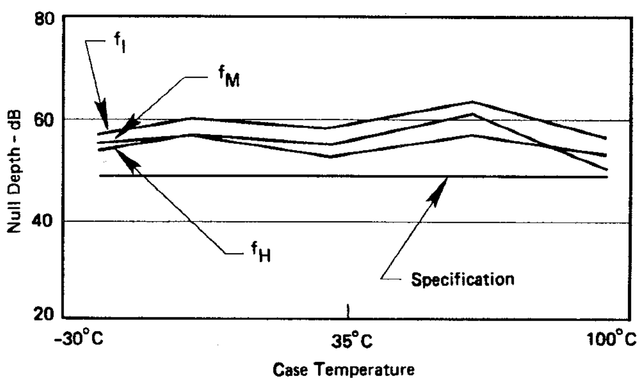


Figure 10. Null Depth vs. Temperature

Despite efforts to reduce noise in the loop filter, uncorrelated noise sidebands on the buck-off signal were found to be increasing the receiver noise figure by several dB. The source of the uncorrelated noise was traced to the PIN diodes used in the vector modulator. Work is now in progress to reduce the impact of the PIN diode noise in the vector modulator on the receiver noise figure degradation.

SUMMARY

A CW radar receiver utilizing a solid-state feed-thru-nulling system has been developed which provides 50 dB of signal cancellation over a 3 percent frequency band centered in X-band. The noise performance of the feed-thru nuller proved to be the most difficult problem to solve, and the performance of the present design slightly degrades the noise figure of the radar receiver. Work is currently underway to improve this noise performance.

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