Title: New High Efficiency Intermodulation Cancellation Technique for Single Stage Amplifiers.

By: Ray Gutierrez
Micronda LLC email: ray@micronda.com February 12, 2008.

Introduction: This article provides a new circuit configuration that uses the basic concept of the **RFAL (Reflect Forward Adaptive Linearizer**) distortion cancellation technique. Previous published configurations using the RFAL uses two main amplifiers. The new technique requires a single stage main amplifier and low level MMIC amplifiers in the Intermodulation Cancellation Loop.

The basic RFAL technique uses the behavior of a transistor when driven into its non-linear operating region. At the high drive levels the input reflects not only the fundamental components of the input signal but also the non-linear distortion components that appear at the output of the transistor. The level of the distortion products at the input are sufficiently proportional to the output such that it can be used and processed as a correction or error signal to cancel the output distortion of the main transistor amplifier. The technique provides excellent cancellation of the IM3 products and significant cancellation of the IM5 products.

Description of the main circuit blocks of the Single Stage RFAL (SS-RFAL).

The basic block diagram of the SS-RFAL is shown on **Figure 1**.

Signal Sampler.
A 10 dB directional coupler samples the forward and reflected signal at the input of single stage Main Amplifier. The reflected signal contains the fundamental input components and when operating at high signal levels it also contains the distortion components that appear at the output. (Output fundamental composite average levels of 2 to10 dB back-off from 1 dB Pout compression)

Ideally the error signal that cancels all the distortion at the output of the main amplifier should contain only the distortion products (no fundamental signal components). If the matching network from the main amplifier has a very low input VSWR then the fundamental signal components will be very low, however, the reflected distortion energy is not affected appreciably by the input reactive matching network. Normally well matched amplifiers have input VSWR less or equal to 1.5:1. However, even these low levels of fundamental input signals are not acceptable for the final error cancellation. This problem is addressed with a unique circuit named the “Input Signal Cancellation Network”.

Input Signal Cancellation Network
A dedicated circuit network is used to significantly cancel the fundamental components from the reflected signal. The “input signal cancellation network” uses the sampled input

signal at the forward port of the input coupler. The input signals go into the network and are sent back through the coupled line to the reflected port of the coupler at just the proper amplitude and phase to cancel the fundamental signals that are reflected from the input of the main amplifier and ideally leaving only the distortion products.
The input signal cancellation network consists of a fixed delay line connected to the forward port , followed by an I/Q vector modulator and an RF short at its output to reflect a portion of the input signal all the way back to the reflected port of the coupler to cause significant input signal cancellation over the operating frequency band. It is desirable to have sufficient broadband input signal cancellation so that when the error signal is combined with the main output signal the final output level does not change more than ±0.5 dB with IM Cancellation Loop from On to Off condition.
A simpler input signal cancellation network can be made using a fixed delay line with a fixed attenuator and a short.

IM Loop Cancellation Network.
The composite error signal created at the coupler reflect-port is amplified by linear amplifiers to overcome the circuit losses such as coupling values, variable attenuator, and circuit losses. The error signal is then boosted to the correct level to cancel the main amplifier distortion at the output of the SS-RFAL. A variable attenuator and a phase shifter are used to adjust the precise level and phase of the error signal. The linear amplifiers must have good flatness and flat phase over the operating frequency band. To provide a high level of efficiency the amplifiers should be selected to have just the necessary level of IP3 capability to be linear up to the highest level of error correction desired and includes any residual fundamental components. The correctly sized booster amplifiers will reduce the DC power dissipation to the minimum and increase the overall efficiency of the SS-RFAL. It is recommended to use MMIC amplifiers to reduce the phase shift, size and cost of the SS-RFAL. A good temperature compensation network will be required for operating the SS-RFAL over a wide temperature range

It is also very important to have sufficient isolation between the Main Amplifier and the IM Loop Cancellation Network to prevent stability problems. The use of high isolation amplifiers is desirable, otherwise isolators should be used.

Main Amplifier.
The SS-RFAL technique can be used with FET and LDMOS transistors, class A and AB. The amplifier should have a low input VSWR and must be very stable. Excellent phase linearity and good output to input isolation is important. Negative feedback can be used as long as loop isolation is not appreciably degraded. The amplifier can be a low noise or power amplifier type.

Main Delay Line.
The output signal and the error cancellation signals must have the same time of arrival with opposite phase to cancel the intermodulation distortion. The IM Loop Cancellation Network will normally have a longer delay than the Main Amplifier. A 50 ohm line with the proper electrical length is added to the output of the Main Amplifier to provide the

correct signal phase at the loop's summing point. It is possible to operate with various full wavelengths of mismatch but this will reduce the operating bandwidth of the SS-RFAL.

Summing Coupler.
The output signal of the main amplifier/delay line feeds a 10 dB directional coupler. The forward port is terminated in 50 ohms and the reflect port connects to the IM Loop Cancellation Network's output to provide a summing function. At the output of the coupler the signal should provide a high level of IM cancellation. (10 dB to 25 dB of cancellation of the IM3 products and 5 to 17 dB of the IM5 products)

Prototype Performance.

The prototype SS-RFAL was designed to operate over the 855 to 905 MHz frequency band. The 800 to 960 MHz frequency band was selected only because of equipment and materials availability. The basic design when scaled properly should work at any other frequencies See circuit in **Figure 2.**
The main amplifier uses an old Avantek/Agilent GaAs FET type ATF-25735 with a typical in-circuit Gain of 10 dB, 1dB CP of +19 dBm and IP3 of +28.5dBm at the +5volt 50 ma DC bias point.

- **Review of the Input Distortion Characteristic of the ATF-25735 GaAs FET transistor used for the Main Amplifier.**

  When a transistor is driven into is non-linear region (2 to 10dB back-off from the 1dB compression point) significant intermodulation products are generated. The intermod products that appear at the gate are roughly 20 dB lower than the output. (This value is transistor and bias dependent)

  The selection of the DC operating point is important to achieve the best IM3 and IM5 cancellation over a 10 dB input and frequency band operating range.

  The main transistor amplifier was evaluated at various gate voltages and plotted over the 10 to 16 dBm average output power range. The Input and Output IM3 and IM5 distortion product characteristics versus Pout and Vgs were plotted in **Figures 3a** and **3b.**

  The IM Loop cancellation has a fixed gain level and phase to provide the best IM3 cancellation. The input reflected IM3 is amplified and phased in the IM Cancellation Loop to cancel the Output IM3 products. The gain needed to cancel the IM5 products is about 4 dB lower than the gain needed to cancel the IM3 at the +13 dBm Pout level. The gain setting used provides only a 6 dB improvement in IM5 cancellation as compared to 27 dB improvement for the IM3 products at 880 MHz (See Figures 6 and 7). The IM5 cancellation improves as the power level increases to the +16 dBm level. Since the IM5 distortion levels are much lower than the IM3 it is more important to cancel the IM3 than the IM5 to maintain the distortion at a level low enough to meet the acceptable distortion limits of the final system.

Note: Vd=5v is kept fixed by the DC regulator. Vgs was set with RF off condition and changes slightly with RF drive-on conditions.

Prototype Description
The prototype circuit uses isolators at both the output of the main amplifier and also at the output of the IM Loop amplifier to prevent interaction of the two circuits while performing the circuit alignment. When the isolators were removed there was some reduction of the operational bandwidth although the circuit appeared to be stable in the 855 to 915 MHz band.
The IM Cancellation Loop Amplifiers were selected to have a high enough IP3 to never become non-linear so as not to interfere with the out-of-band frequency tests. This is not necessary or desirable in the final circuit design to improve the overall circuit power efficiency.
The maximum composite output average error signal required to be handled within the 855 to 905 MHz is around 6 dBm for SS-RFAL linearized output of +15 dBm. This makes necessary for the final MMIC of the IM correction Loop to have a 1dB compression of about +16 dBm. If the operating bandwidth is slightly narrower this level can be dropped to a 1dB compression of +13 dBm.

Figure 4. A set of figures **4a** and **4b** shows the gain versus frequency and input return loss for "IM Loop Gain" **Off** and **On** conditions, and also the fundamental levels that feed through in the IM Cancellation Loop on figure **4c**. Maximum input signal rejection occurs between 850 to 910 MHz (**Figure 4c**). Below and above the 850 to 910 MHz frequency band the IM Loop input signal cancellation network fails to provide the proper out-of-band cancellation causing the fundamental signal levels to increase and add to the final output signal of the SS-RFAL. (Shown by the up-shape of the gain curve in **Fig. 4b**) This is not a problem for the prototype unit, except that in a properly efficiently designed SS-RFAL amplifier the high level signals can overload the IM Loop amplifiers causing new intermod products to be feed into SS-RFAL output. Use of a band-pass filter at the input of the SS-RFAL can normally prevent out-of-band input signals from overloading the IM Loop.

Figure 5a shows a picture of the spectrum analyzer screen and the IM Cancellation Loop **On** at a composite Pout average +13 dBm, **Figure 5b** shows a picture with the IM Loop **Off**. Comparison of Figures **5a** and **5b** shows an average IM3 improvement of 20 dB. **Figure 5c** shows the Output of the IM Cancellation Loop before the 10 dB summing coupler port. (The suppression of the input fundamental products can be clearly seen in this figure.)
The intermod levels at the summing port of the coupler must be approximately 10 dB higher than the main amplifier output to overcome the coupler coupling levels and produce distortion product cancellation at the final output port of the SS-RFAL.

Figure 6 shows a plot of the delta IM3 improvement over frequency and output power when the IM Cancellation Loop amplifiers are turned on or off. The cancellation improvement increases up to the +14 dBm average Pout level for all 3 frequencies. Significant IM3 cancellation was possible to within a few dB of the 1 dB compression point of the transistor used in the main amplifier.

Figure 7 shows a plot of the delta IM5 improvement over frequency and output power. IM5 cancellation seems to be much difficult to achieve than IM3 cancellation. It requires very precise alignment of the delay and loop gain and the transistor bias level. At lower drive levels the improvement is zero or negative but since the IM are so low at these output levels it may have no effect on the overall linearity performance.

The set of **Figures 8a** and **Figure 8c** consist of nine tones (860, 865, 870, 875, 885, 890, 895, 900 MHz) with 5 Mhz separation. All the channels are peaked phase for worse case loading and with the 880 MHz center tone missing to allow measurement of the worse case IM product generated. Very clean input signals were generated from a RDL/Aeroflex MTG-2000 Multitone generator. The Pout composite average at the output of the SS-RFAL was measured at +6 dBm. **Figure 8a** is with the IM Cancellation Loop "**Off**", **Figure 8b** is with the IM Cancellation Loop "**On**", and **Figure 8c** is the error signal at the IM Cancellation Loop output.

There is an 18 dB IM improvement at the 880 MHz empty channel and a significant clean-up of the IM products in and out-of band.

Figure 8d shows the reflected input signal at the input of the SS-RFAL. (10 dB needs to be subtracted from the levels shown in the figure to set the reference levels to absolute value in dBm).

Further Circuit Improvements:

A SPST 50 ohm terminated switch can be added is series with the IM Cancellation Loop's input and output to switch off the loop gain when the output power of the Main Amplifier is low. This will maintain the Noise Figure of the Main Amplifier undisturbed. Also the overall efficiency of the SS-RFAL can be improved if the Loop amplifiers can be shut-down or operated at reduced currents at low input levels. (This depends on the reaction time expected from the input signals and amplifier recovery time.)

The forward port of the summing coupler at the output could be used to detect the power level and drive the SPST switches and IM loop amplifiers bias levels.

A Band-Pass filter should be added to the input of the SS-RFAL to narrow the operating bandwidth thereby limiting high level signals from overloading the IM Cancellation Loop amplifiers. This filter could be placed in the IM Cancellation Loop to minimize the input losses as long as the phase and amplitude flatness is well behaved. Also the additional phase shift of the filter within the IM Loop will require additional Main Amplifier Delay line length to compensate and match the overall loop phase.

References:

- US Patent 6,573,793. "Reflect Forward Adaptive Linearizer" June 3, 2003,
- "The RFAL Technique for Cancellation of Distortion in Power Amplifiers". High Frequency Electronics, June 2004.
- "High Frequency Linearized LDMOS Amplifiers Utilize the RFAL Architecture." High Frequency Electronic, February 2006.
- "Criss-Cross RFAL Cancels the IMD Distortion in Amplifiers". December 2007 RFCafe website. Posted on the "Engineering & Science Technical Articles" section. See link and pdf file at: www.rfcafe.com/references/articles/articles.htm

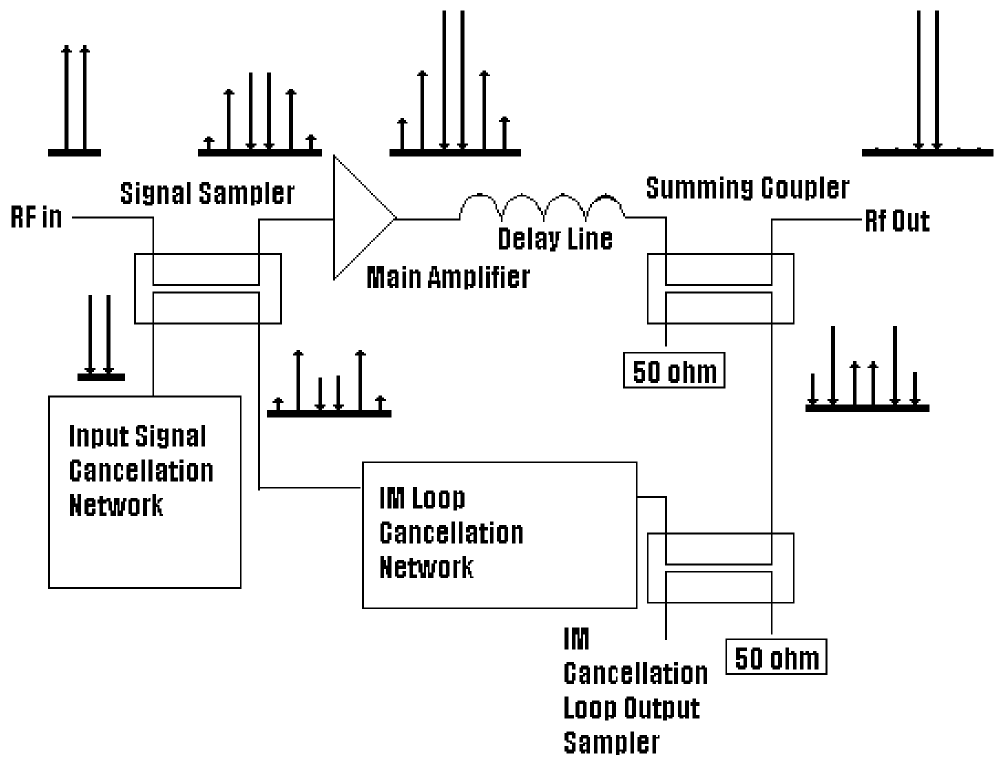

Figure 1 Simplified Block Diagram of SS-RFAL

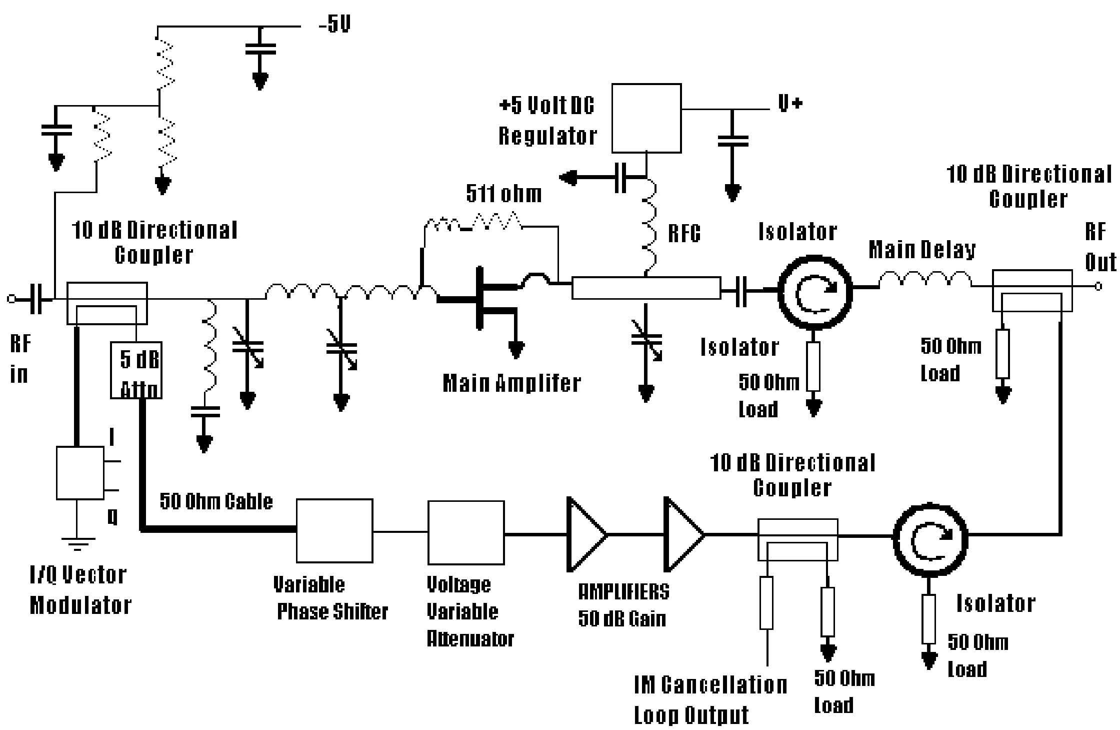

Figure 2 Prototype Block Diagram

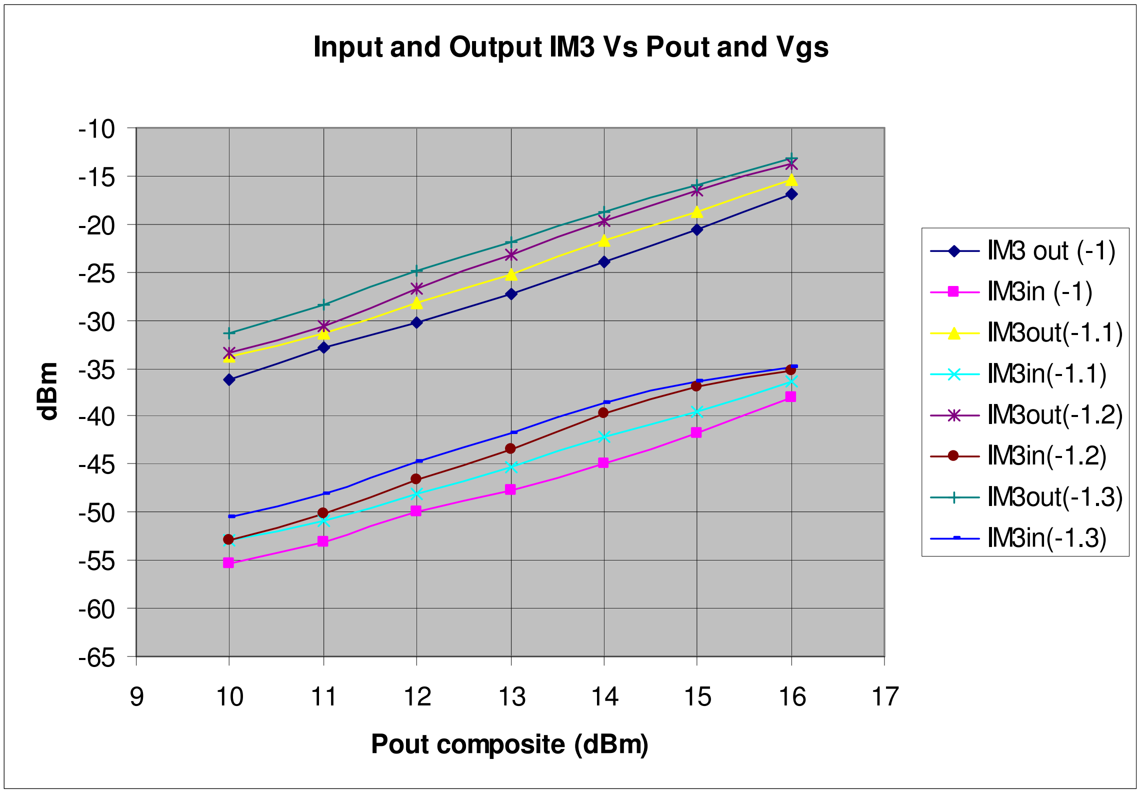

Figure 3a **Transistor IM3 Intermods versus Pout and Vgs**

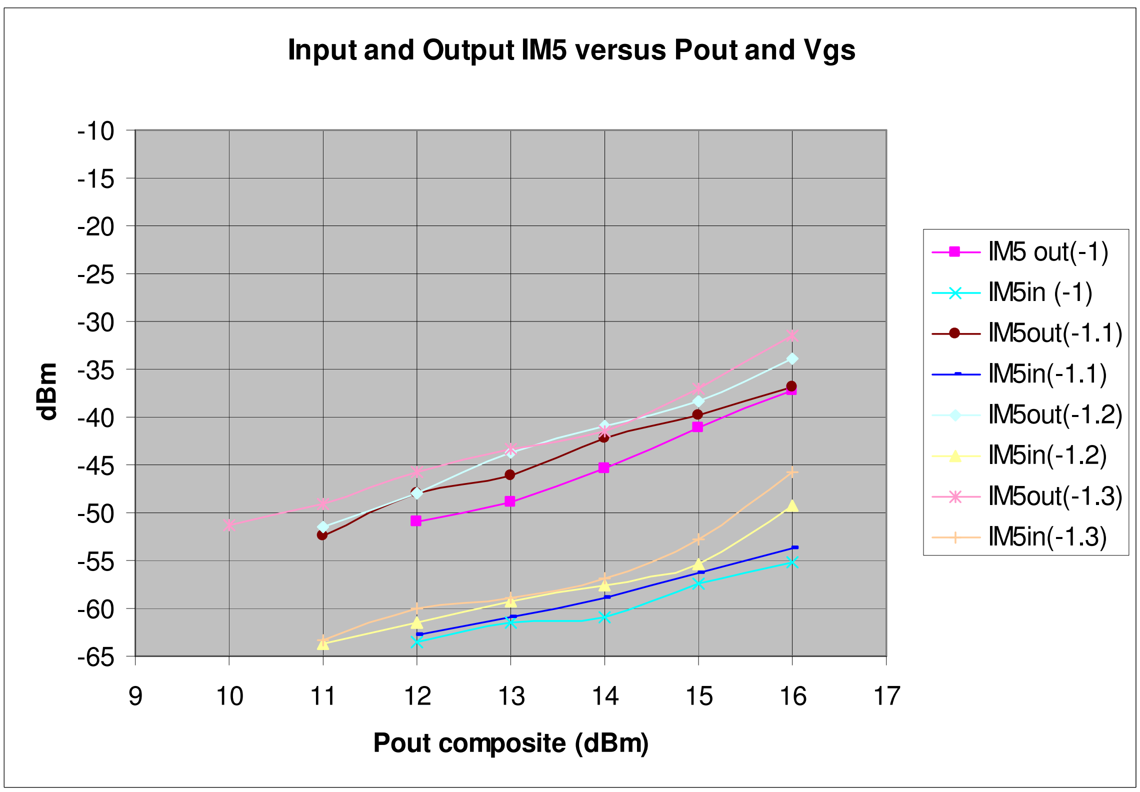

Figure 3b **Transistor IM5 Intermods versus Pout and Vgs**

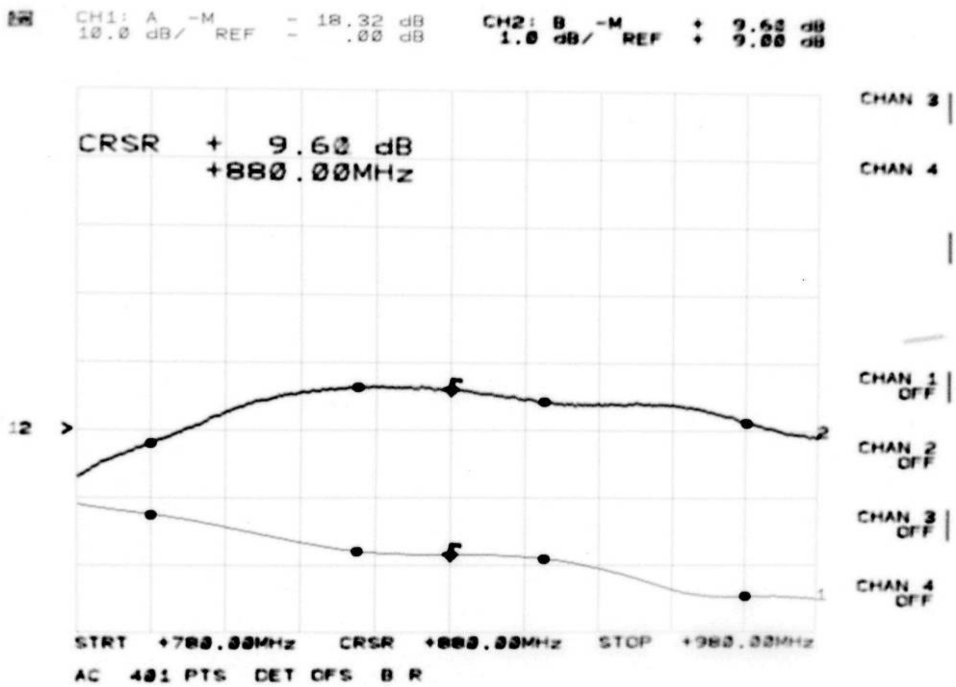

Figure 4a **Gain and Input Return Loss (IM Cancellation Loop Off)**
Markers at 800, 850, 880 flag, 910 and 960 MHz

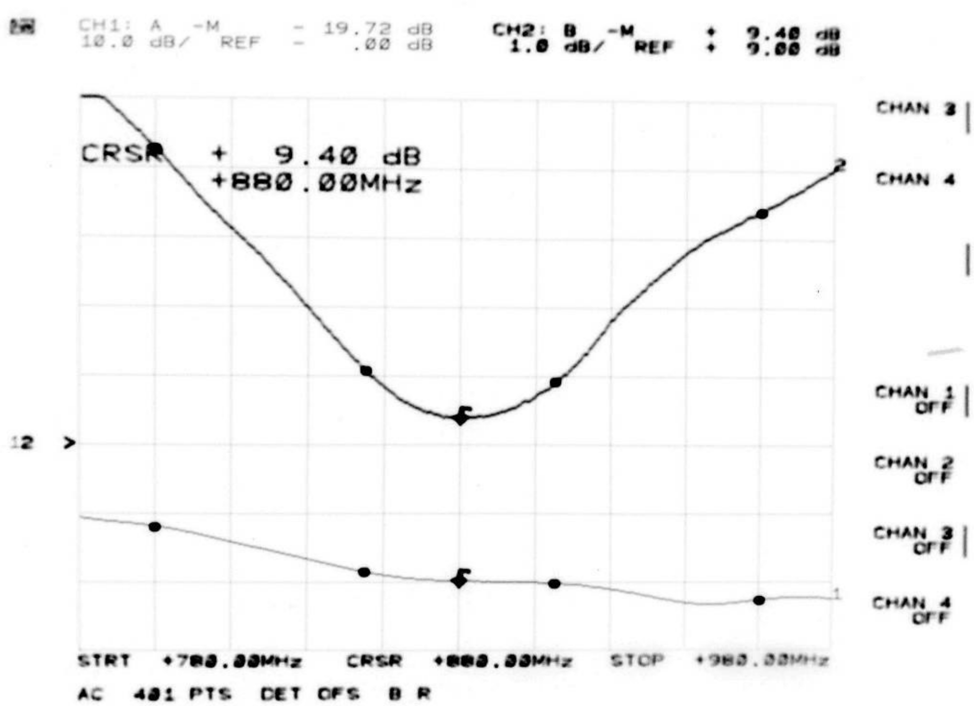

Figure 4b **Gain and Input Return Loss (IM Cancellation Loop On)**
Markers at 800, 850, 880 flag, 910 and 960 MHz.

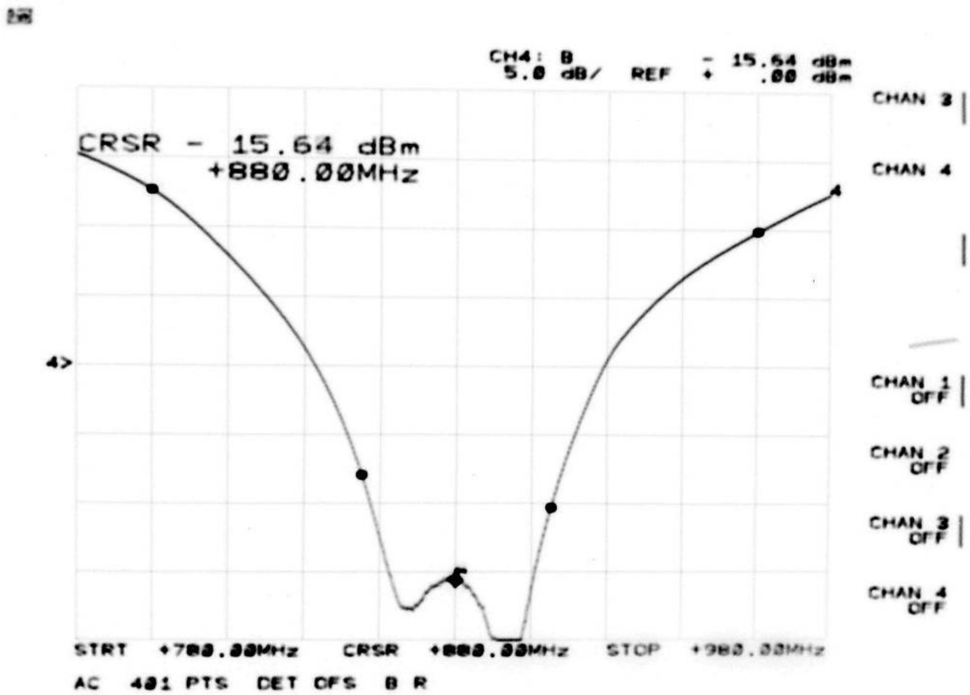

Figure 4c **IM Cancellation Loop Output into Summing Coupler SS-RFAL at +4 dBm. Markers at 800, 850, 880 flag 910, 960 Mhz.**

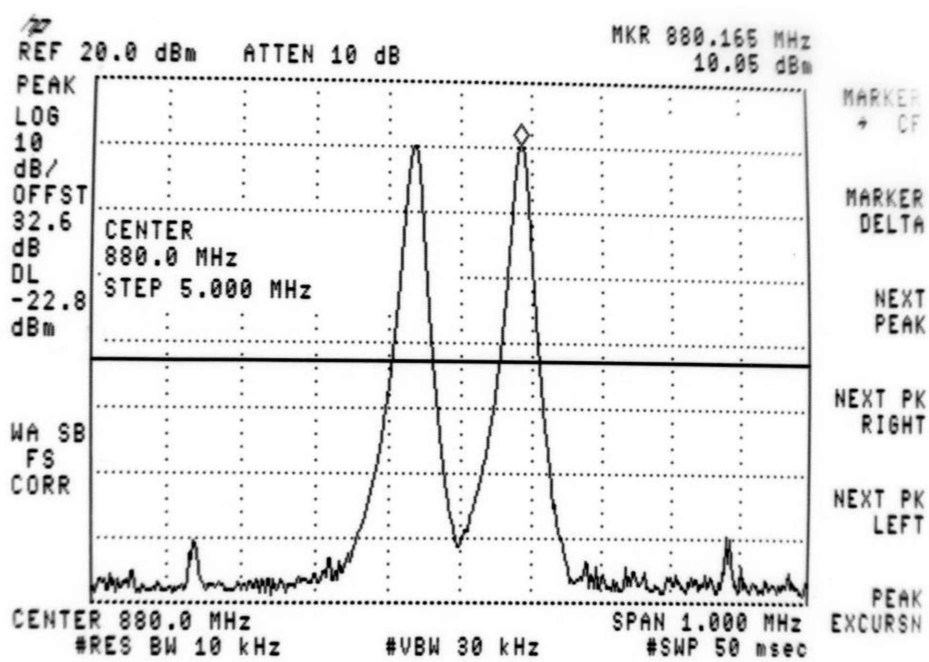

Figure 5a **Output at Pout average +13 dBm (IM Cancellation Loop On)**

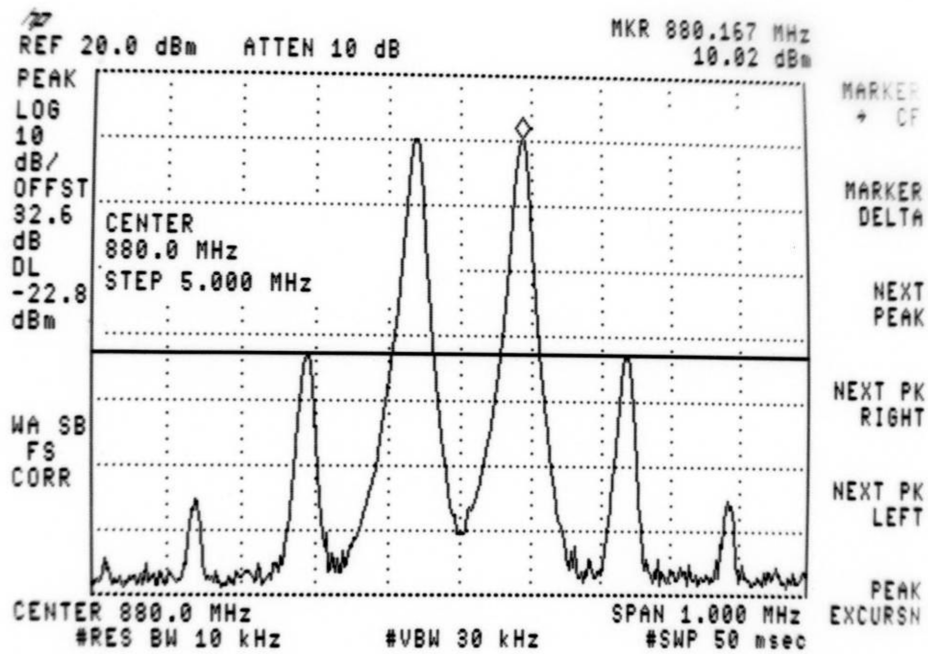

Figure 5b Output at Pout average +13 dBm (IM Cancellation Loop Off)

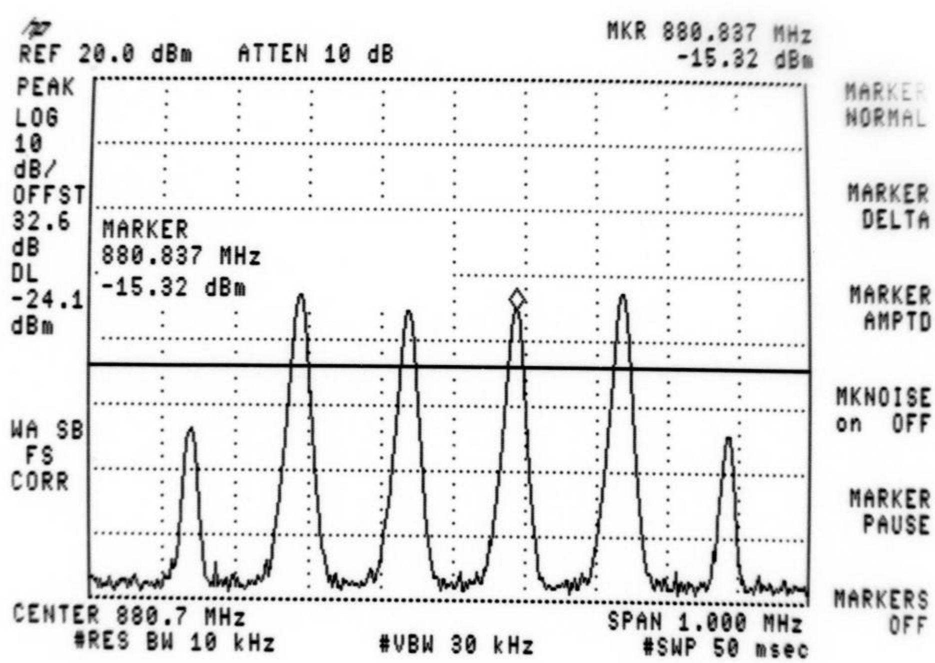

Figure 5c IM Cancellation Loop Output into Summing Coupler SS-RFAL at Pout of +13 dBm ave.

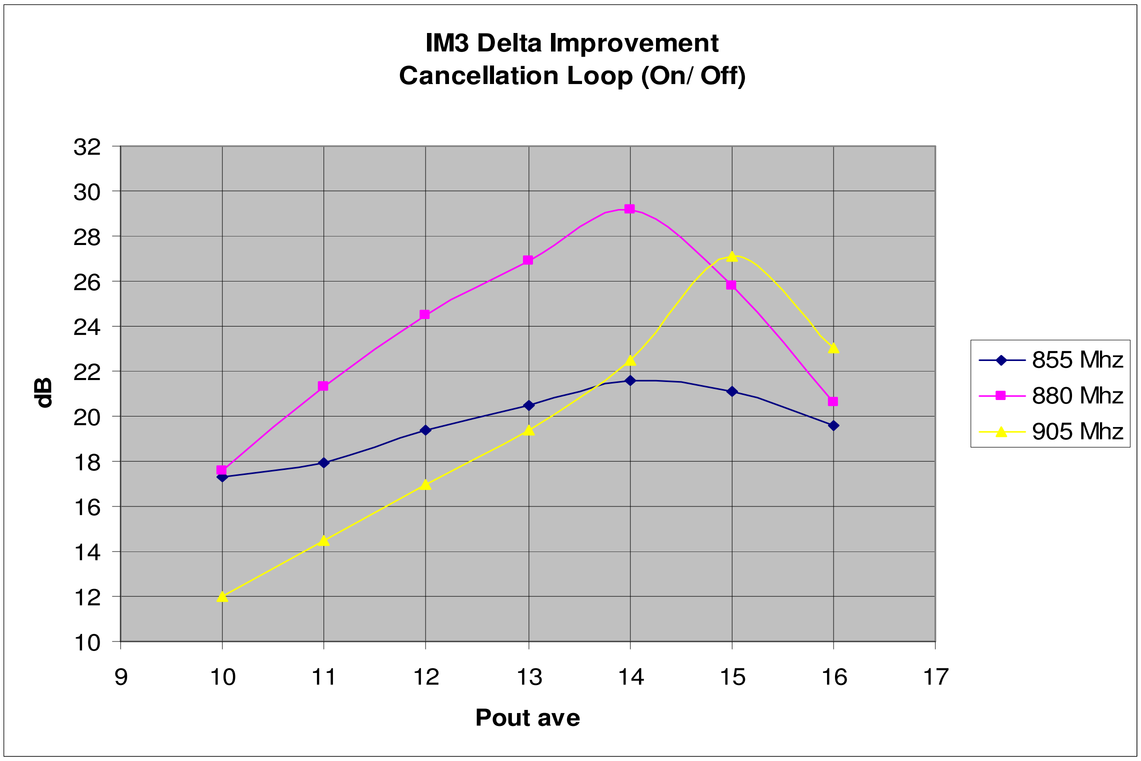

Figure 6 **IM3 Improvement (IM Cancellation Loop On/Off)** (Vgs= -1.25 volt)

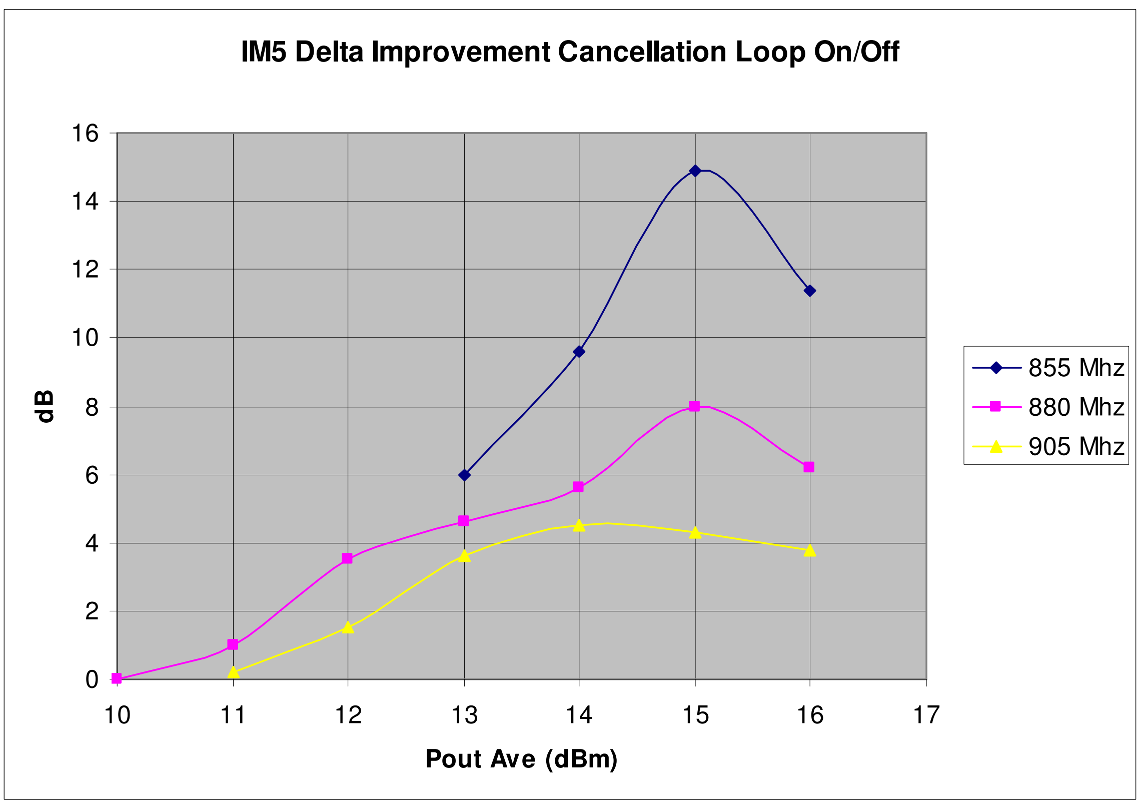

Figure 7 **IM5 Improvement (IM Cancellation Loop On/Off)** (Vgs= -1.25 v)

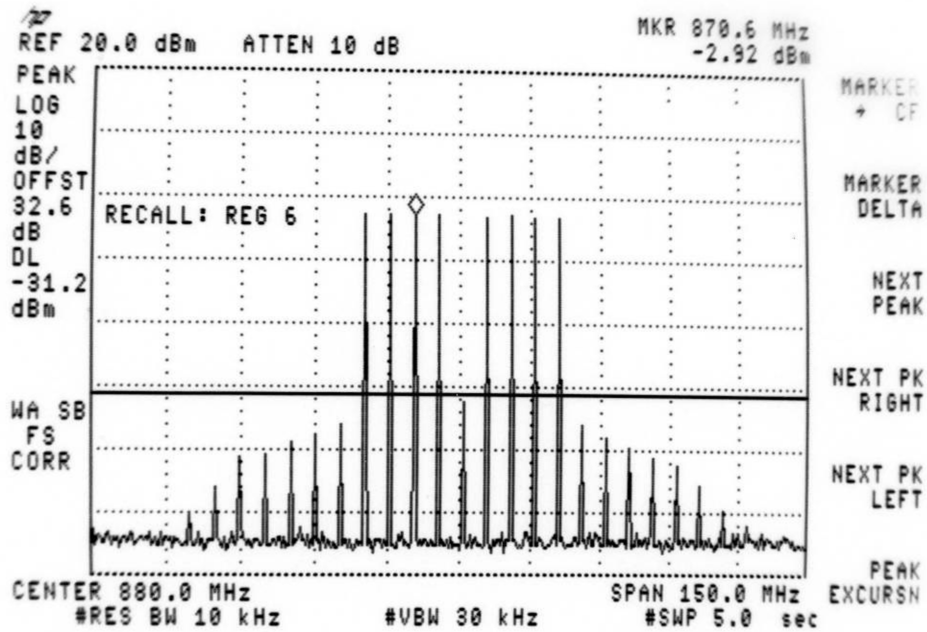

Figure 8a **Output (IM Cancellation Loop Off)** (8 Tones Peaked Phase, Spectrum Analyzer at Peak Hold Pout +6 dBm average composite)

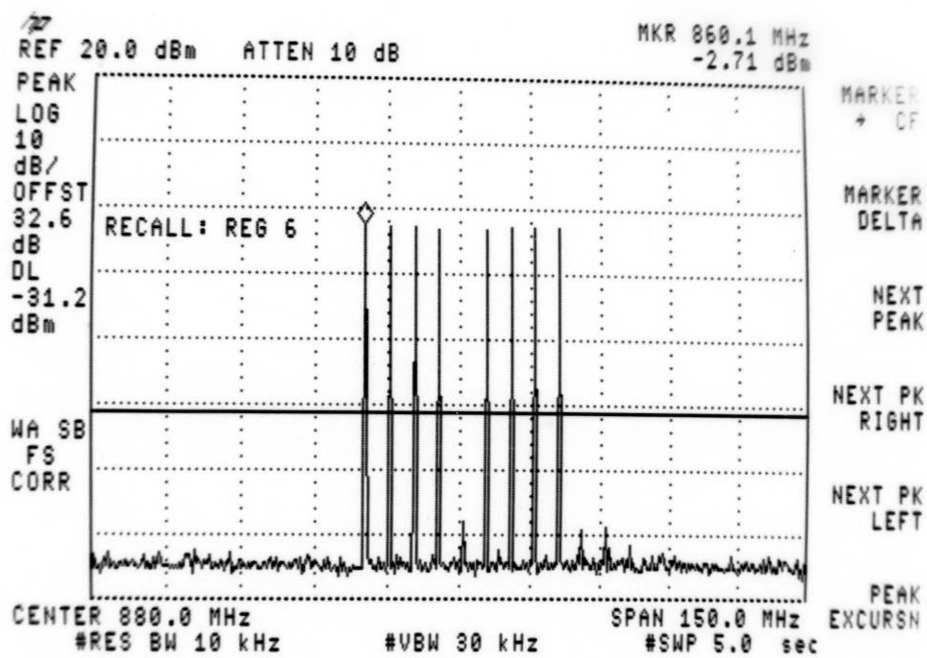

Figure 8b **Output (IM Cancellation Loop On),**
(8 Tones Peaked Phase Output at Peak Hold, Pout 6dBm)

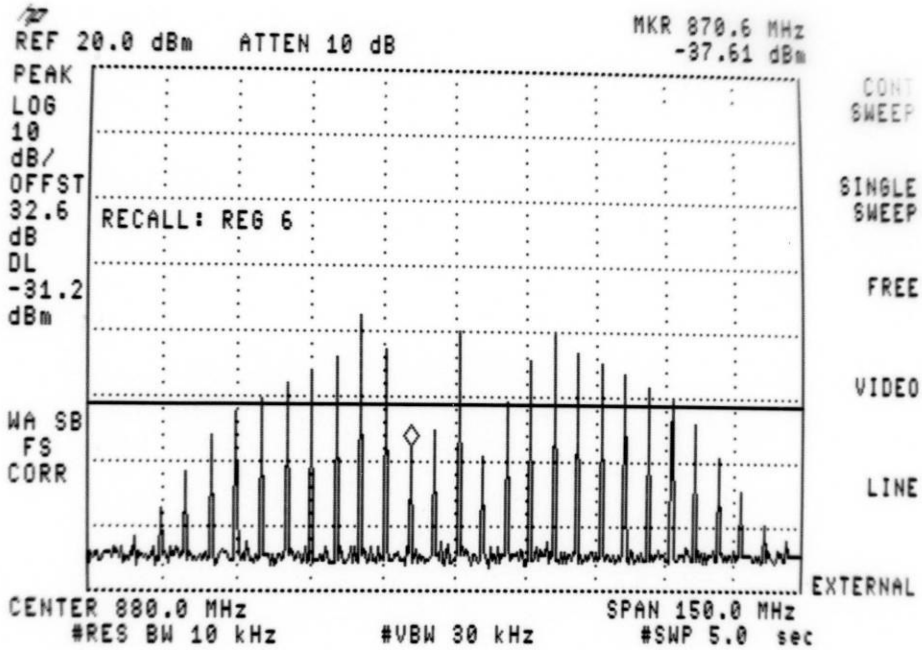

Figure 8c IM Cancellation Loop Output into Summing Coupler
(8 Tones Peaked Phase, Output at Peak Hold, Pout 6dBm)

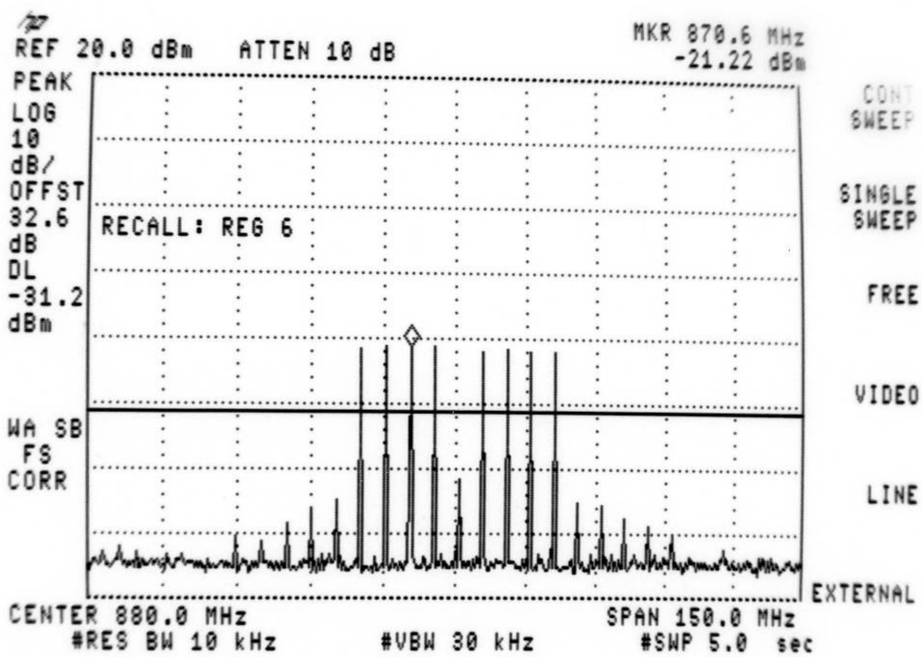

Figure 8d Reflected Input Signal (Subtract 10 dB from Levels).
(8 Tones Peaked Phase, Spectrum ANA Output at Peak Hold, Pout +6dBm average composite)