The RFAL Technique for Cancellation of Distortion in Power Amplifiers

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This patented linearization technique uses the information present in the reflected input signal to create a correction signal that significantly reduces the distortion of a power amplifier

Reflected signals have always been considered a curse by circuit designers, wasting energy, reducing gain and adversely affecting system performance. This article describes a new technique that uses this normally troublesome reflected signal to cancel output distortion, significantly increase linearity, and double the usable output power of single stage amplifiers.

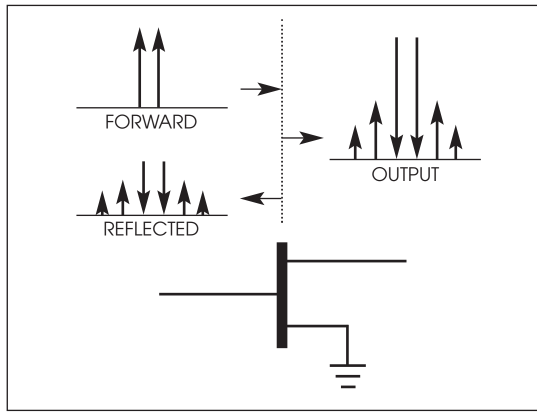

Figure 1 · A transistor's nonlinear frequency spectrum.

The RFAL Technique

The basis for this technique is the behavior of a transistor amplifier operating under nonlinear conditions. At the input, the reflected signal contains both the reflected input signals and the distortion products that are found at its output, as illustrated in Figure 1.

In the Reflect Forward Adaptive Linearizer (RFAL) amplifier, the forward signals and the reflected signals are sampled at the input using a directional coupler. These signals are then attenuated and phased properly before combining them at a summing coupler. The "correcting signal" formed at the output of the summing coupler C3 is amplified and injected into the amplifier's output using another coupler. The injected signal cancels the distortion products at the amplifier output, while simultaneously doubling the power output (see Figure 2).

The RFAL is ideal for systems requiring gain levels of less than 20 dB. It offers high linearity, high efficiency and lower costs than other configurations such as feedforward or predistortion techniques. The RFAL can also improve the performance of feedforward systems when used in nested loop configuration.

Summary of the RFAL features:

- Efficient low intermodulation distortion configuration that doubles the output power of the Main Amplifier over wide input power and frequency ranges.
- Provides distortion cancellation up to the 1 dB compression point of the main amplifier. This is important for operation under multitone signals or complex modulation waveforms that have high peak-to-average power ratios.
- Allows use of more economical and readily available transistors to achieve the high level of linearity required by signal formats such as Multi-tone, CDMA, WCDMA, EDGE, and Wi-Fi.
- Compatible with different transistor types such as GaAs or silicon; FET or bipolar; any

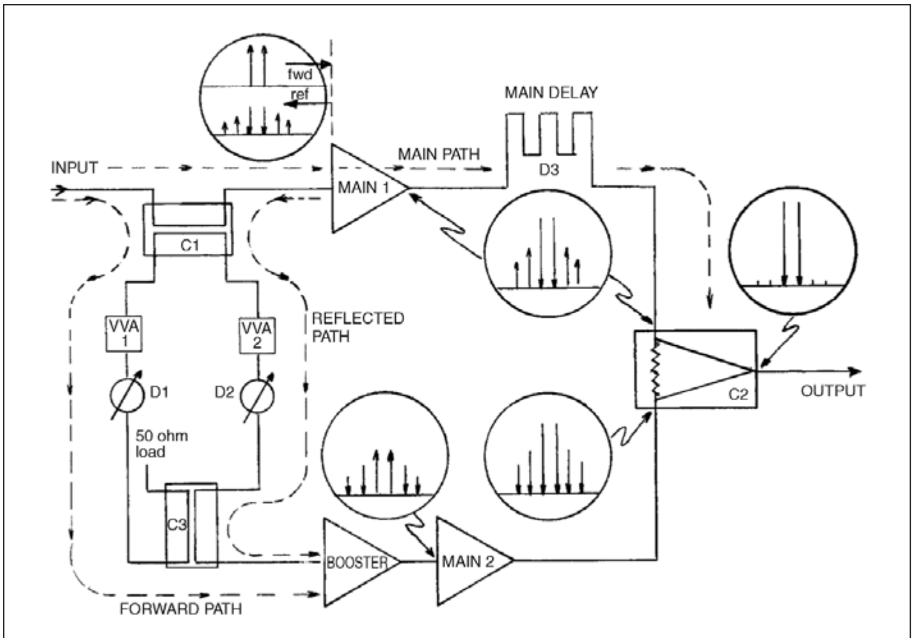

Figure 2 · Block diagram of an RFAL amplifier.

type of single stage, parallel and cascode configurations; and different biasing such as Class A and Class AB.

- Uses no error signal or feedback. All signals move in a forward direction to reach the same time of arrival at the output combiner C2 for maximum fundamental power and real-time cancellation of the distortion products.

Circuit Description

Figure 2 is a block diagram showing RFAL operation. To provide a high performance level, both Main amplifiers should be of the same construction and performance characteristics. The Booster amplifier should have low distortion over the drive range of the Main 2 amplifier with sufficient gain to overcome the forward and reflected path losses. Coupling values for the directional coupler affect the amount of gain required by the Booster amplifier. C1 and C3 coupling values should be selected carefully to achieve the proper fundamental drive and signal level cancellation to the Main 2 amplifier. Output coupler C2 can be an in-phase type Wilkinson or a 3 dB quadrature hybrid. If a 3 dB quadrature is used for C2, the DC or thru port should be connected to the Main 1 amplifier's path to reduce the overall Main Delay line length by 90 degrees and thus reduce the output losses. Table 1 lists the power level relationship for the various signal paths.

Amplitude and Phasing Characteristics for RFAL Amplifier

(Refer to Figures 1 and 2) The fre-

(Calculations are for one of the two-tone signals. Except were noted, use power ratios and watts in all equations. Losses refer to attenuator, delay lines, couplers, and connection losses)

Path 1 (Main 1 Path)

Fundamental Signal:

Pout1 = (Pin-Pref)*(Sum of losses in input path)*(Main 1 Gain)*(Sum of Output Losses)

3rd Order IMD Power:

IMPout1 = (Sum of Output Losses)*(Main 1 Pout) /(10^(2*(IP3dBm-PoutdBm)/10))

Path 2 (Reflected Path)

Fundamental Signal:

Pout2 = (Reflected Power)*(C1 Coupled Port)*(Sum of Losses)*(Booster Gain)*(Main 2 Gain)

3rd order IMD power:

IMPout2 = (Input IM3)*(C1 Coupled Port)*(C3Thru Path Loss)*(Sum of Losses)*(Booster Gain)*(Main 2 Gain)

Path 3 (Forward Path)

Fundamental Signal:

Pout 3 = (Pin*C1 Coupled Port)*(Sum of Losses)*(C3 Coupled Port)*(Booster Gain)*(Main 2 Gain)

3rd order IMD power:

[There are no 3rd Order IMDs in this path]

Output Signal

Fundamental signal:

Pout Final = Pout1+Pout2+Pout 3 [Single tone output power]

3rd order IMD Power:

IMPout final = IMPout1–IMPout2=0 [Assumes perfect amplitude and phase match for optimum cancellation]

Table 1 · Power level relationships for the various signal paths in the RFAL amplifier.

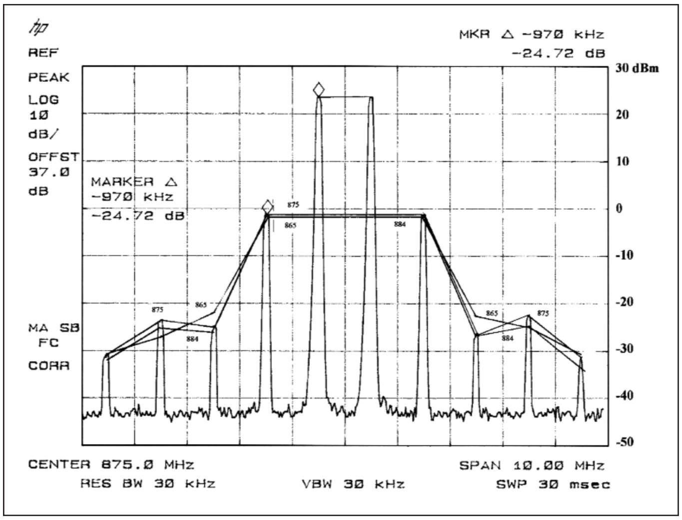

Figure 3 · Two-tone IMD performance of the GaAs FET Main 1 amplifier.

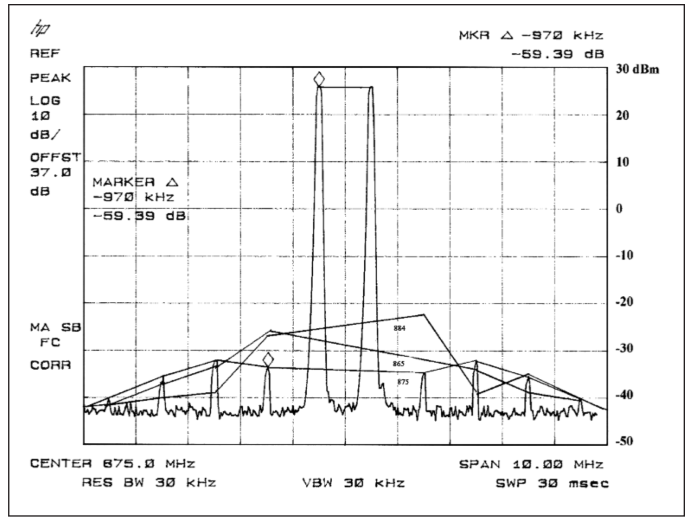

Figure 4 · IMD Performance of the GaAs FET RFAL amplifier under the same test conditions as Figure 3.

quency spectrum drawn in the referenced figures show vector signals with arrows to denote the relative phasing of signals, "0 degree" (arrow-up) or "180 degree" (arrow-down). To simplify the analysis of the phasing characteristics assume operating frequencies <<f_T of the transistor. However, the concept will work at higher frequencies by proper management of the delays at the input and output of the main amplifiers.

The reflected signal at the input of Main 1 has fundamental and intermodulation components with a phasing characteristic that is advantageous for the proper operation of the RFAL concept.

When the forward fundamental signals are reflected from the transistor gate or base in the Main 1 amplifier, the resulting reflected fundamental signals are out-of-phase relative to the forward input signal and in-phase with the output signal. The intermods generated at the transistor's input are in-phase relative to the output intermods.

The fundamental and intermod signals in the composite input reflected signal can be used as a "correcting-signal" to the input of the Main 2 amplifier. This correcting-signal, when properly amplified and phased, cancels the Main 2 output intermods and has an additional anti-phase intermod signal level that can be used to cancel the Main 1 amplifier intermods at combiner C2. The correcting signal's fundamental components from the Main 2 amplifier are in-phase relative to the fundamental signals from Main 1 amplifier and add to increase the output power at the combiner C2.

A lower input VSWR will reflect a lower fundamental signal level. Depending on the input match of the Main 1 amplifier, the reflected fundamental signals from Main 1 amplifier may not have sufficient power level to drive-up the Main 2 amplifier to the same output level of the Main 1 amplifier. The missing level of the fundamental drive can be achieved by using the forward signal path. With the proper selection of the directional coupler C1, attenuator VVA1, summing coupler C3, and Booster amplifier gain, the proper drive can be provided to the Main 2 amplifier for the same output as Main 1 amplifier.

The delays D1 and D2 set the proper phasing required for the signals to be synchronized, achieving the proper time of arrival at the output coupler C2 for optimum cancellation and summing of the signals. The main delay in Main 1 amplifier is set up to compensate for the overall delay of the C1 coupler, VVA2, Delay D2, Summing coupler C3, and Booster amplifier to obtain the optimum cancellation with maximum fundamental signal combining at the output coupler C2.

Prototype Amplifiers

Two types of RFAL amplifiers were built to demonstrate the concept: a lower power Class-A bias GaAs FET linear amplifier and a high power Class-AB biased LDMOS amplifier.

GaAs FET Linear Amplifier

Two Main linear amplifiers were built, each using a single stage Mitsubishi MGF-2445 GaAs FET transistor. Each amplifier provided 16.5 dB of flat gain with IM3 of 25 dBc at a P_{out} of 26 dBm over the frequency range of 850 to 890 MHz. Figure 3 shows the two-tone output frequency spectrum performance of both Main 1 and 2 amplifiers. Three different sets of frequencies were used: 864/866, 874/876, 883/885 MHz.

The two main amplifiers were connected in the RFAL configuration with Anaren's Xinger couplers using values

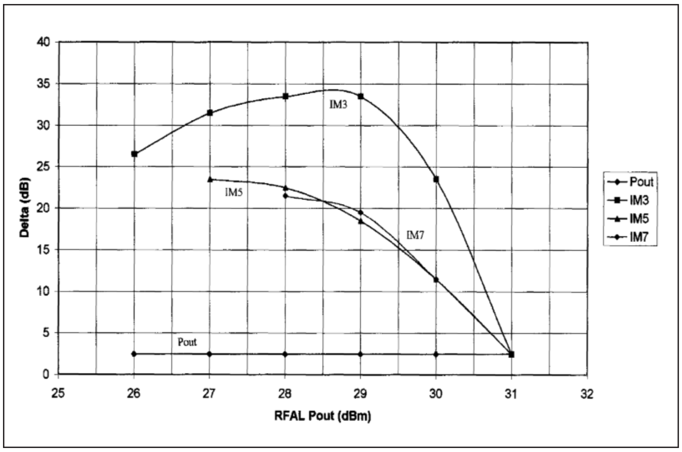

Figure 5 · P_{out} and IMD delta improvement for the GaAs FET RFAL amplifier vs. the Main 1 amplifier.

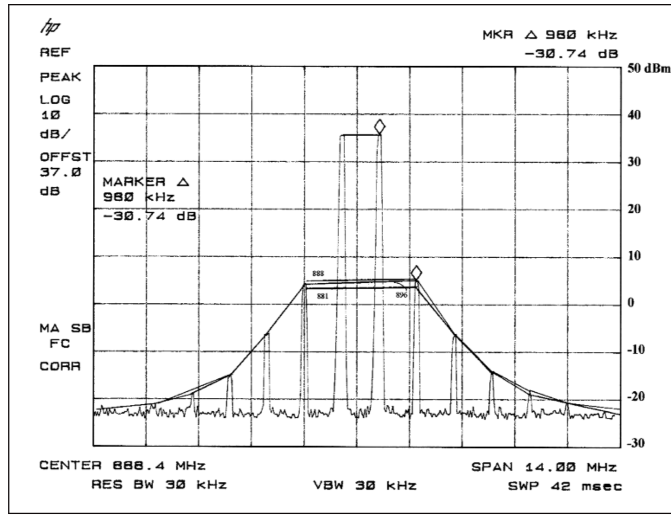

Figure 6 · Two-tone IMD performance of the LDMOS FET Main 1 amplifier.

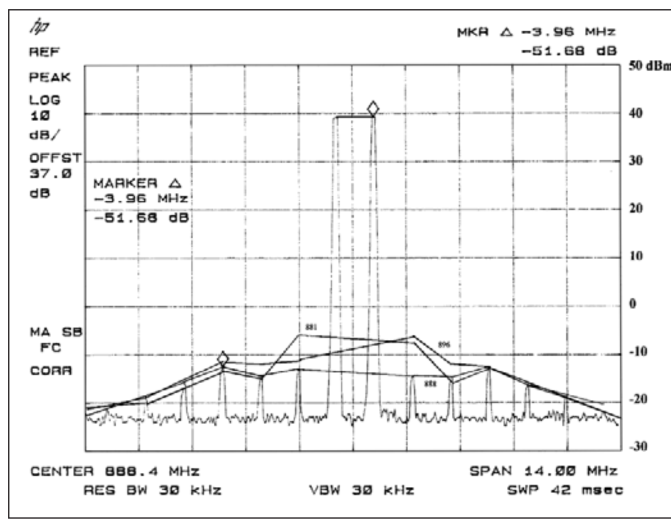

Figure 7 · IMD Performance of the LDMOS FET RFAL amplifier under the same test conditions as Figure 6.

of 10 dB for C1 and C3, and a Wilkinson Xinger combiner for C2 using an effective Booster gain level of 21 dB. The resulting RFAL amplifier assembly provided a flat gain of 15.5 dB with a >20 dB return loss over the 850 to 890 MHz frequency range.

Comparison of the spectrum output performance of the RFAL in Figure 4 to the Main 1 amplifier in Figure 3 shows that the RFAL has +2.5 dB higher level at the fundamental frequency with an IMD improvement of >34 dBc at 875 MHz at 28.5 dBm composite output power. Over the band edges at 865 to 884 MHz the IMD improvement was >22 dBc.

Figure 5 shows the RFAL vs. Main 1 amplifier's P_{out} and IMD performance over the RFAL output power range from +26 dBm to +31 dBm. The fundamental power of the RFAL is approximately 2.5 dB higher than the Main amplifiers. At +28.5 dBm P_{out} the RFAL has an IMD3 cancellation improvement of >34 dB. The IM3 cancellation improvement degrades to 23 dB at +30 dBm P_{out} and goes down to 2.5 dB as the Main amplifiers approach the 1 dB compression point. The RFAL also achieves significant IMD cancellation improvement for the IM5 and IM7 distortion products.

Class-AB LDMOS Amplifier

Two Class-AB Main amplifiers were built using Motorola MRF9030 (30 watts PEP) LDMOS transistors. Each amplifier has 19 dB of gain with a 31 dBc IMD at a P_{out} of 16 watts PEP (8 watts average) over the frequency range of 881 to 896 MHz. The two-tone frequency spectrum performance of each amplifier is shown in Figure 6.

The two main amplifiers were connected in the RFAL configuration with Anaren Xinger couplers using values of 10 dB for C1 and C3, and a 3 dB Quad Hybrid for C2 with an effective Booster gain level of 23 dB.

The Class-AB LDMOS RFAL amplifier provided a flat gain of 19 dB (±0.3 dB) and an input return loss of >17 dB from 881 to 896 MHz. Comparing the performance of the RFAL in Fig. 7 to the Main 1 output in Figure 6, the RFAL increases the fundamental frequencies output level by approximately 3 dB, with an intermod reduction of >21 dBc at the center frequency of 888 MHz at an average P_{out} composite level of 15 watts.

Over the entire band of 881 to 896 MHz at an average P_{out} = 15 watts, there was a >13 dBc IMD improvement over the Main 1 amplifier's IMD. The reason for the lower level of improvement is attributed to the circuit used for the Motorola MRF9030 transistors. The PCB used is a basic narrowband tuned circuit with a bandwidth slightly better than 10 MHz. A better broadband Main amplifi-

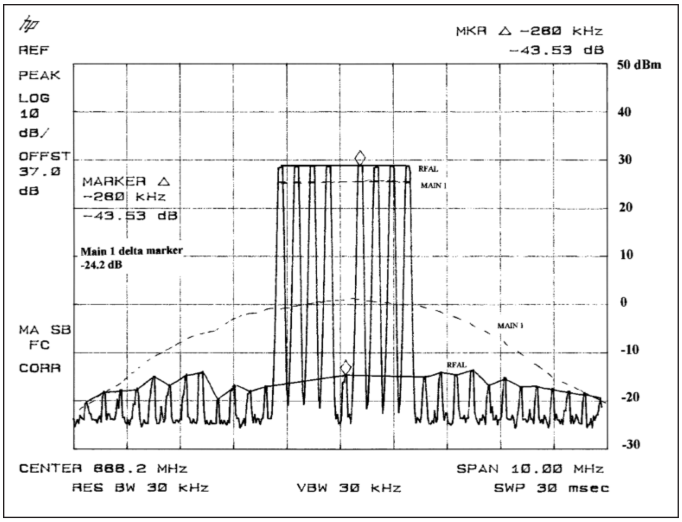

Figure 8 · RFAL amplifier performance with 8 carrier signals spaced 300 kHz apart.

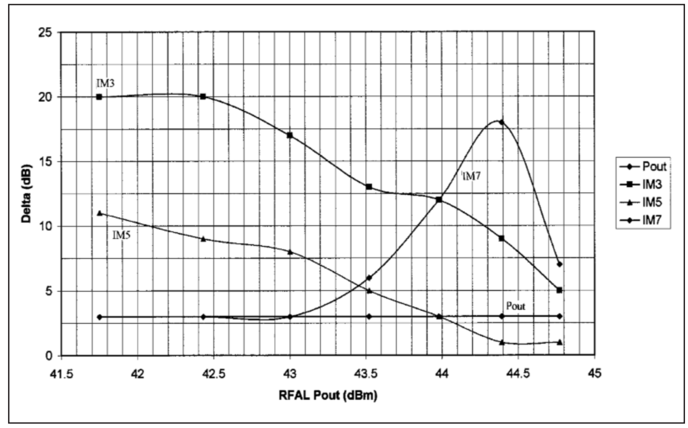

Figure 9 · P_{out} and IMD delta improvement for the LDMOS RFAL amplifier vs. Main 1 amplifier.

er circuit would have provided better cancellation across the full frequency band.

Figure 8 shows the RFAL performance improvement (19 dBc) relative to the Main 1 amplifier with 8 carrier signals 300 kHz apart (input signals from RDL MTG-2000 multitone generator were peaked phase, spectrum analyzer display on max hold) at a composite average output power level of 5 watts.

Figure 9 shows the two-tone P_{out} and intermod delta improvement of the RFAL vs. Main1 amplifiers over a range of RFAL average output power from 15 watts to 30 watts. The IMD3 cancellation improvement is >21 dBc at a P_{out} of 15 watts, while the IM3 cancellation improvement degrades to 13 dBc at an output of 22.5 watts and to >5 dBc as the Main amplifiers approaches the 1 dB compression point. Fundamental output of the RFAL is approximately 3 dB higher than Main1 throughout the full power range. The RFAL also achieves significant IMD cancellation improvement for the IM5 and IM7 distortion products.

Electrical Alignment

The Main 1 amplifier is driven up to its highest normal operating power level and tuned for optimum flatness and return loss. Next the forward path is adjusted in amplitude and phase to drive the Main 2 amplifier to the same output level as the Main 1 amplifier. The reflected path is then adjusted for optimum cancellation at center frequency. The forward path level is backed-off to maintain the same output level while the reflected path is increased to achieve IMD cancellation. Phase and amplitude are adjusted incrementally for optimum performance over a frequency range on each of the three signal paths while trying to achieve the optimum intermodulation cancellation. The goal is to use the minimum delay in the reflected path (D2) to achieve good cancellation over the desired bandwidth. The Main 1 path and path 2 forward path are adjusted to match the overall reflected path delay to achieve the same time of arrival at the output coupler C2. At the end of the alignment sequence the values of attenuation and delays are fixed and do not require further adjustment.

The alignment is somewhat more difficult for RFAL using Class AB amplifier types that require a tight range of RF signal drive to reach the desired bias, output power, and impedance conditions for optimum intermod cancellation and output power.

Advantages of the RFAL Amplifier

The RFAL configuration when used in applications requiring high linearity, with gain levels under 20 dB, offers a higher level of performance and numerous economical advantages when compared to available techniques such as parallel combining, predistortion, and feedforward configurations.

Amplifiers that are used in parallel configurations provide double the output power of a single stage (minus the combining losses), with intermodulation products improving by 6 dBc over the single stage amplifier. With the RFAL technique the RF power combining efficiency of the two main amplifiers approaches that of the parallel amplifiers while the intermodulation products improve from 20 to 30 dBc at the center band. The cancellation characteristics over wider bandwidths is determined by the amplifiers and couplers used and how well the amplitude and phase response of the three signal paths can be controlled over the full bandwidth of the RFAL. The overall efficiency of the RFAL is less than the parallel combining approach by the amount of DC power that the Booster amplifier requires.

Prior art cancellation techniques like predistortion use independently created distortion products ahead of the amplifier to provide cancellation. Because of the difficulty in creating the right transfer characteristics over all input conditions, a typical predistorter normally provides efficient cancellation of 3rd order products and reduces the gain of the overall amplifier by the amount of loss caused by the predistorter. In contrast, the RFAL uses its own transistor's input distortion for cancellation, including higher order products, and thus adapts to different signal conditions to provide a higher level of cancellation for all distortion products. Gain losses are minimized because the Booster amplifier makes up for any circuit losses.

In the feedforward configuration, significant IMD performance degradation occurs when the Main amplifier is used above the start point of gain compression. At this point the first loop becomes unbalanced. The loop imbalance causes the level of error signal to increase significantly, driving the error amplifier to become non-linear and feed new distortion products back into the output. To prevent these undesirable conditions a very high linearity, power-hungry error amplifier needs to be used with complex controlling circuitry to maintain a high level of performance. This is not the case for the RFAL since it continues to provide significant cancellation of IMDs up to the compression point of the Main amplifiers using simpler circuitry.

The simplicity of the RFAL configuration allows fixed values of components and delays. Over the same limited operating conditions the RFAL can provide a higher level of performance without the need of complicated circuitry as required with classical feedforward or predistorter techniques. The configuration can be manufactured economically and has the potential for dense packaging using microcircuit hybrid assembly.

The use of two identical single stage main amplifiers provides good tracking over the operating environment of the system. The Booster amplifier should be selected and temperature compensated correctly to provide linear stable operation over the temperature range and input power levels of the RFAL. For very high cancellation requirements over wide temperature and drive conditions an adaptive feedback network can be used to monitor the relative phase and amplitude of the Main amplifier's outputs and drive the voltage variable attenuators and phase shifters to keep the optimum conditions.

The RFAL Amplifier concept is protected under US Patent 6,573,793 B1 issue date June 3, 2003. The invention is now available for demonstration and licensing.

Acknowledgment

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