Power Amplifier Linearization Using IF Feedback

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Abstract- **A narrowband feedback technique for linearizing power amplifiers is presented. The technique uses frequency conversions, thus allowing loop compensation and added loop gain to be implemented at the intermediate frequency (IF). An analysis is presented which allows assessment of the applicability of the technique and which shows the performance advantages of using a two pole loop compensation filter. When applied to a 450MHz power amplifier with a delay of 70nS, the technique suppressed intermodulation products at ±500 KHz by 12dB with the amplifier driven to within 5dB of its 1dB compression point.**

POWER AMPLIFIER LINEARIZATION

Many modern communications systems have been designed to take advantage of the high spectrum efficiency offered by complex modulation schemes such as Quadrature Amplitude Modulation (QAM). However, such schemes are far more susceptible to distortion than were the relatively simple modulation schemes of the past. In addition to causing intersymbol interference which raises bit error rate, distortion can spread the transmitted spectrum making it difficult to comply with FCC regulations. Therefore all components in such a system must be highly linear. Unfortunately the system power amplifier (PA) must be operated close to saturation, a nonlinear region, in order to exhibit power efficiency. This dilemma has led to the development of several PA linearization techniques in an effort to realize a communication system that exhibits both spectrum efficiency and power efficiency.

This paper presents a closed loop PA linearization technique which was developed for use in a narrowband repeater system. It uses narrowband negative feedback to provide temperature and aging stability and to reduce both intersymbol interference and spectrum spreading. The technique has been demonstrated at 450MHz, but is just as applicable at microwave and millimeter-wave frequencies.

Narrowband Negative Feedback

Narrowband negative feedback can be applied to a PA to achieve significant linearization. Rosen et. al. (1) and Hsieh et. al. (2) applied feedback through a cavity filter at RF as shown in figure 1. The IF feedback technique similarly applies feedback through a bandpass filter, but the feedback path includes frequency conversions. The features common to the design of any circuit which uses narrowband negative feedback are considered here.

The loop bandpass filter shapes the loop gain. To ensure stability, it is designed so that this gain is greater than one over only a predetermined frequency band. Within this band, the loop transmission phase is allowed to change by typically ±135 degrees with respect to bandcenter thus resulting in a phase margin of 45 degrees ($\pi/4$). Once the filter design is complete, the allowable loop gain is also established. The loop delay, which is uncompensatable, causes this phase change across the band. The filter must be designed for the best tradeoff between linearization capability and loop stability with the loop delay setting the limits.

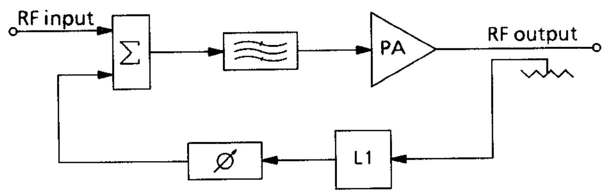


Figure 1. Narrowband RF Feedback

The feedback loop must also include a method of adjusting the phase to ensure negative feedback at bandcenter. Once this is done, the phase shift due to the delay is simply $-(\omega-\omega_{IF})\tau_L$, where ω_{IF} is the center frequency of the IF bandpass filter, and τ_L is the loop delay. This suggests that the POLE/ZERO arrangement be approximated as perfectly symmetric around ω_{IF} so that ω_{IF} can be used as the reference frequency ($\omega=0$) for a lowpass equivalent analysis. This approach is used in the analysis section of this paper.

With a properly designed filter and a phase adjustment capability, the loop can accommodate a delay of many periods of the RF signal.

IF FEEDBACK

The IF feedback configuration evolved from the narrowband RF feedback configuration shown in figure 1. Frequency conversions were added so that the loop compensation filter and the added loop gain could be implemented at the IF, where in general, amplifiers and filters (of a given bandwidth) are easier and less expensive to implement. This also makes it practical to use a more complex compensation filter which offers the potential for greater loop gain, and therefore improved linearization.

A block diagram of the IF feedback circuitry is shown in figure 2. The loop error signal is derived at RF in the input power combiner. This allows the closed loop transmission gain of the circuit to be established by the loss from the PA output to the combiner input. The transmission gain will be equal to this loss as long as the loop gain is adequate. The attenuator, L1, of figure 2 is adjusted in order to achieve the desired closed loop transmission gain for a

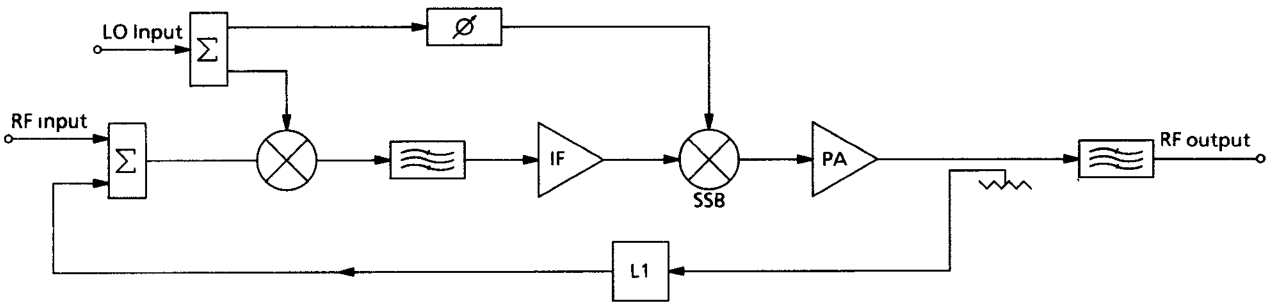
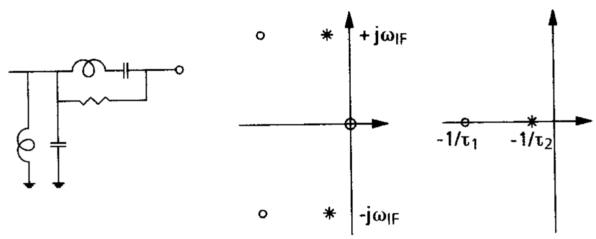


Figure 2. IF Feedback

given application. In general, it is best to set this gain equal to the gain of the standalone PA so that the RF drive requirement will not change.

A good choice for a loop filter is one that includes two POLEs and a ZERO such as that shown in figure 3a. This type of filter offers the potential for a loop with improved performance when compared to loops which use a single resonator filter such as a cavity. The POLE and ZERO locations of this bandpass filter and its lowpass equivalent are shown in figures 3b and 3c.



(3a) Bandpass Circuit (3b) Bandpass S-Plane (3c) Lowpass Equivalent

Figure 3. Loop Compensation Filter

The upconverter must be a single-sideband version, because the unwanted sideband would cause distortion if it were allowed to drive the PA. An additional bandpass filter is shown at the output, because it will usually be necessary to further reduce the already suppressed LO and unwanted sideband.

The phase shifter allows adjustment of the feedback phase so that negative feedback will occur at bandcenter. This phase adjustment could also be accomplished by changing the relative length of the LO paths.

ANALYSIS

In classical form the closed loop response is:

$$G_T = \frac{A}{1 + A\beta}$$

where G_T is the transmission gain and $A\beta$ is the loop gain. The denominator of this expression describes the loop's error correction capability - errors such as intermodulation products are reduced by $1+A\beta$. Therefore the loop performance will improve with increasing loop gain, but loop gain cannot be increased to a point where stability is threatened. A close examination of the loop gain clarifies this tradeoff between performance and stability.

A corresponding expression for the IF feedback configuration can be written. It can be a relatively simple expression if the center of the IF filter is taken as the frequency reference ($\omega=0$ at ω_{IF}) and if it is assumed that the POLE/ZERO locations are symmetrical around bandcenter.

$$G_T(\omega+\omega_{LO}+\omega_{IF}) = \frac{g_d(\omega)F(\omega)G_{IF}(\omega+\omega_{IF})G_p(\omega+\omega_{LO}+\omega_{IF})}{1 + g_d(\omega)g_f(\omega)F(\omega)G_{IF}(\omega+\omega_{IF})G_p(\omega+\omega_{LO}+\omega_{IF})}$$

where:

$g_d(\omega)$ describes the loss and phase shift in the direct path from input to output due to components other than the filter and amplifiers (eg cables). $g_d(\omega)=g_{do}$ at bandcenter

$F(\omega)$ is a lowpass filter response equivalent to the transformed IF bandpass filter with the relative POLE and ZERO locations maintained:

$$F(\omega) = \frac{1+j\omega\tau_1}{(1+j\omega\tau_2)^2}$$

$G_{IF}(\omega)$ is the IF amplifier response with $G_{IF}(\omega)=G_{IFo}$ at bandcenter

$G_p(\omega)$ is the PA response with $G_p(\omega)=G_{po}$ at bandcenter

$g_f(\omega)$ describes the loss and phase shift in the feedback path due to couplers, L1, and cables. $g_f(\omega)=g_{fo}$ at bandcenter

At bandcenter the loop gain is:

$$G_o = g_{do}g_{fo}G_{IFo}G_{po}$$

and the loop phase shift, Φ_o, is a combination of amplifier transmission phase offsets, the phase shift at bandcenter due to total loop delay τ_L, and phase shifts due to cable lengths. If τ_0 is now used to represent τ_L-τ_F (loop delay minus filter delay), the loop gain is:

$A\beta = G_L(\omega)$ where:

$$G_L(\omega) = G_o e^{-j\Phi o} e^{-j\omega\tau 0} \frac{1+j\omega\tau_1}{(1+j\omega\tau_2)^2} \frac{\text{(far ZEROs)}}{\text{(far POLEs)}}$$

which describes the loop's equivalent lowpass response. The phase shifter of figure 2 must be adjusted so that $\Phi_0 = 180+n360$, thus providing negative feedback at bandcenter. With the assumption that the (far POLEs) and (far ZEROs) in the above equation are far enough removed so as to have negligible influence on the loop response, the loop gain expression becomes:

$$G_L(\omega) = G_0 e^{-j\omega\tau 0} \frac{1+j\omega\tau_1}{(1+j\omega\tau_2)^2}$$

The unity gain frequency, ω_c, or the closed loop half-bandwidth is found by setting:

$$|G_L(\omega_c)| = 1$$

The phase angle of the loop gain expression is:

$$<G_L(\omega) = -\omega\tau_0 + \tan^{-1}(\omega\tau_1) - 2\tan^{-1}(\omega\tau_2)$$

The phase margin is:

$$M_\Phi = \pi - |<G_L(\omega_c)|$$

A good stategy for compensating the loop is to set the ZERO location, $1/\tau_1$, equal to the unity gain frequency, ω_c, then choose a phase margin, and locate the POLEs for maximum midband loop gain. Assuming that this will be done for each design, the above expression for phase margin describes the relative positions of the POLEs and the ZERO, τ_2/τ_1, for each choice of $\omega_c\tau_0$ and M_Φ, see figure 4. As an example, the maximum closed loop bandwidth for $M_\Phi = \pi/4$ is achieved when $\omega_c\tau_0$ (half-bandwidth times the delay of a filterless loop) is chosen to be $\pi/2$. Figure 4 shows $\tau_2/\tau_1 = 1$ thus requiring a single resonator filter.

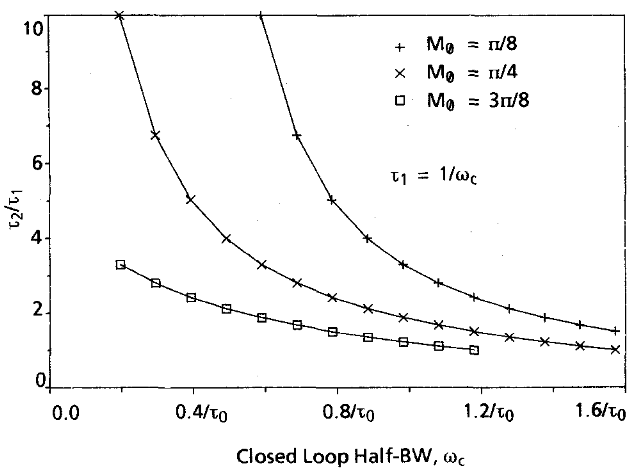


Figure 4. Pole Location as a Function of ω_c

Once τ_2/τ_1 is known, the midband loop gain can be found from the M_Φ equation above:

$$G_0 = \frac{1+(\tau_2/\tau_1)^2}{2^{\frac{1}{2}}}$$

This relationship is plotted in figure 5. Note that for the above example, the midband loop gain is only 3dB. Midband intermodulation products would be reduced by (1+1.414) or 7.6dB.

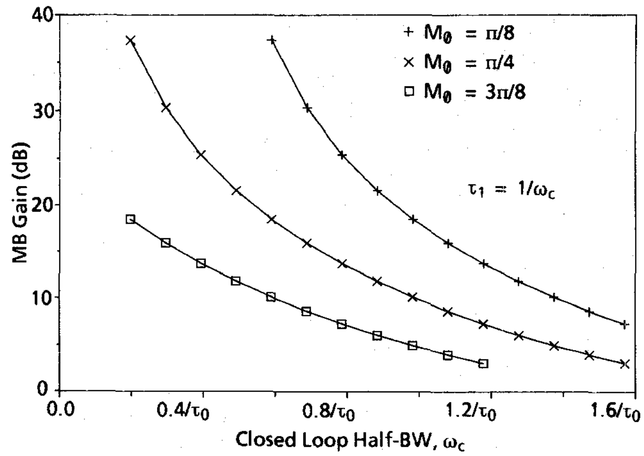


Figure 5. Midband Gain as a Function of ω_c

The loop gain dependence on frequency can be found from:

$$|G_L(\omega)| = G_0 \frac{(1+(\omega\tau_1)^2)^{\frac{1}{2}}}{1+(\omega\tau_2)^2}$$

Using this relationship the loop gain is plotted versus frequency in figure 6 with midband loop gain as the 0dB reference. Note that, as would be expected, the above example yields -3dB at:

$$\omega = 1/\tau_2 = 1/\tau_1$$

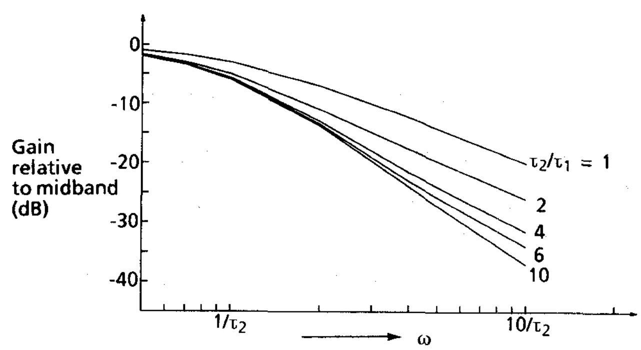


Figure 6. Gain Versus Frequency

DESIGN STRATEGY AND TEST CIRCUIT

To design such a loop, begin by choosing ω_c based on the required linearization bandwidth. Considerable margin must be allowed, because ω_c is the unity gain frequency where very little performance improvement is available. Determine $\omega_c\tau_0$ remembering that a typical IF hybrid will add a delay of approximately $0.25\omega_{IF}$ (τ_0 is the delay of the loop without the compensation filter). Use $\omega_c\tau_0$ in figures 5 and 6 to determine if the loop gain is adequate over the band of interest remembering that improvement in intermodulation will essentially equal the loop gain. Design a loop filter based on τ_2/τ_1 from figure 4, set the loss in the feedback path equal to the PA gain, and add gain in the IF so that the required midband gain is achieved.

The technique was used to linearize a 450MHz PA which exhibited a delay of 70nS. The coupler, 20MHz IF amplifier, and frequency converters added another 10nS which brought τ_0 to 80nS. The unity gain frequency was chosen to be 1.3MHz which leads to $\omega_c\tau_0 = 0.65$. Using this value, the relative POLE/ZERO positions were found from figure 4 for a phase margin of $\pi/4$, $\tau 2/\tau 1 = 2.95$. To satisfy this requirement, the POLES of the loop filter were placed at:

POLE (Hz) = 1.3MHz/2.95 = 440KHz

A 20MHz bandpass filter of the figure 3 configuration was constructed to the above specifications and used to compensate the loop.

The resulting midband loop gain can be found from figure 5, G_0=16.7dB. (Intermodulation products at midband would be reduced by this ammount.) The relative loop gain at 500KHz is found from figure 6 which shows it to be 6.6dB below the midband loop gain or 10.1dB. These relationships are illustrated also in the frequency response plots of figure 7.

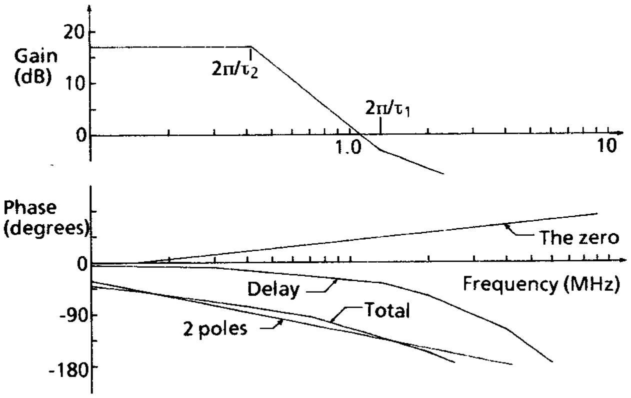


Figure 7. Test Circuit - Gain and Phase Versus Frequency

The loop was tested for linearity using a standard two-tone intermodulation test with the PA driven to within 5dB of its 1dB compression point. Results of the test are shown in the spectrum analyzer plots of figure 8. The intermodulation products at ±500KHz were reduced by 12dB rather than the expected 10dB. The performance is better than predicted probably because the loop gain was set high, resulting in a phase margin of less than $\pi/4$.

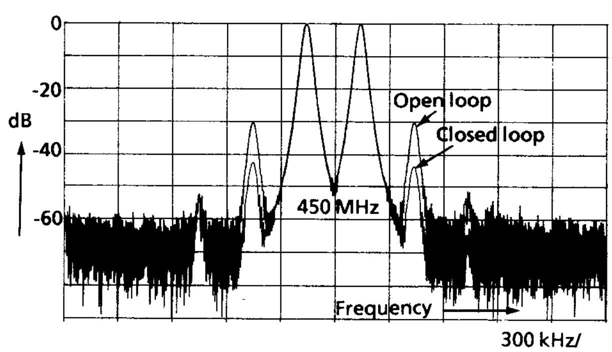


Figure 8. Spectrum Analyzer Data

It is useful to compare this performance to that which would be achieved using simple RF feedback ($M_\Phi=\pi/4$) through a cavity. For a cavity with a loaded Q of 400, a simple loop would yield a midband loop gain of 11dB rather than 16.7dB as shown in Figure 9. For applications where an even narrower bandwidth is allowed, the performance superiority of the IF feedback loop would be even more evident.

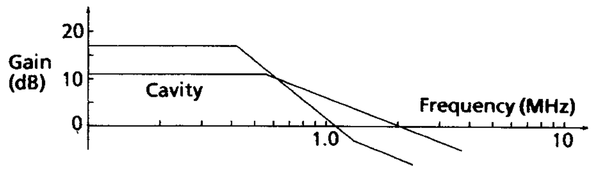


Figure 9. Comparison to Single Resonator Feedback

SUMMARY

The IF feedback technique is a method of linearizing PAs in narrowband systems. The scheme makes it practical to use a loop compensating filter which is more complex than just a simple cavity. In many cases this allows loop gain to be increased, which in turn, results in improved intermodulation performance. The feedback loop is configured so that loop gain can be added as an IF amplifier which, in general, is easier and less costly to implement than an RF amplifier. These advantages, however, must offset the fact that an IF feedback loop is more complex than a simple narrowband RF feedback loop.

REFERENCES

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(2) C. Hsieh and E. Strid, "An S-Band High Power Amplifier," *IEEE 1977 International Microwave Symposium Digest*, pp. 182-4, 1977