LIMITATIONS AND CHARACTERISTICS OF BROADBAND FEEDFORWARD AMPLIFIERS

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Abstract

The nature of critical multi-channel broadband system design parameters using Feedforward technology is strikingly different from previously existing technologies. Several system design procedures taken for granted prior to using Feedforward circuits must be re-evaluated. The unique characteristics and limitations of Feedforward circuits regarding output capability, gain compression, temperature stability, noise figure, flatness, cross modulation and delay line technology are presented. The effects of these on system design considerations are discussed.

1.0 Introduction

The distortion reduction provided by the Feedforward circuit configuration makes this circuit very attractive for use in broadband distribution equipment.[1] However, several unique characteristics of the Feedforward circuit are strikingly different from existing technologies. The system designer must then become familiar with the nature of the Feedforward circuit in order to understand the limitations of these devices.

This paper presents an analysis of the characteristics of the Feedforward circuit and defines limitations to be used by the system designer. Analytical means are emphasized rather than empirical methods commonly used prior to widespread Feedforward circuit use. Output capability, gain compression, temperature stability, noise figure, flatness, cross modulation and delay line technology are discussed.

2.0 What is Feedforward?

Feedforward is a distortion reduction technique. Since cancellation circuits are used twice in the Feedforward circuit, understanding the characteristics and limitations of cancellation provides the basis for analyzing the characteristics and limitations of a Feedforward circuit. The internal operation of the Feedforward circuit is discussed in this section.

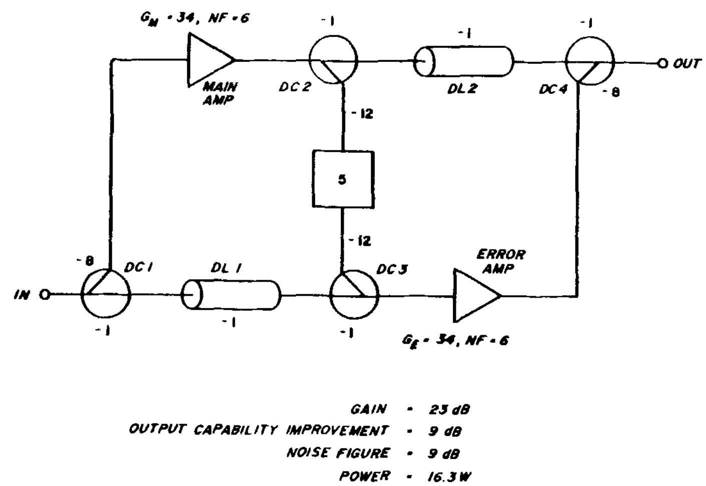

FIGURE 1
FEEDFORWARD FUNCTIONAL BLOCK DIAGRAM

Figure 1 is a functional block diagram of a Feedforward amplifier. Two push-pull cascode hybrid integrated RF amplifiers are required, the first is the main amplifier, the second is the error amplifier. There are two cancellation loops, the first isolates noise and distortion generated by the main amplifier and the second produces the distortion cancellation phenomena.

2.1 First Loop Cancellation

The first loop isolates the noise and distortion created by the main amplifier. This technique is shown in Figure 2 with the signal flow indicated by the dotted lines. A signal (S) is applied to the input of the circuit and is sent in two directions by DC1. At the output of the main amplifier not only is the original signal (S) present, but also the errors involved in the amplification process; namely, noise and distortion (indicated by N and D respectively).

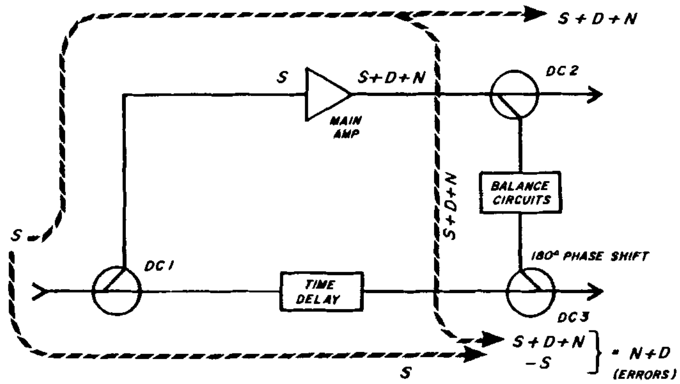

FIGURE 2

FIRST LOOP CANCELATION

Most of the output signal of the main amplifier is directed towards the output of the Feedforward circuit through DC2, however, some of that signal is siphoned off and brought down to DC3 where it is combined out of phase with the original input signal. Equation 1 indicates the cancellation process if the cancellation were ideal.

$$\underbrace{S + D + N}_{\text{main amp output}} - \underbrace{S}_{\text{input signal}} = \underbrace{D + N}_{\text{errors in the amplification process}} \qquad (1)$$

2.2 Second Loop Cancellation

The cancellation of the second loop reduces noise and distortion. This second loop is shown in Figure 3. In this figure the N plus D term isolated by the first loop cancellation is amplified by the error amplifier and reinjected out of phase with the signal coming from the main amplifier at DC4. The end result is shown in Equation 2. If the cancellation process were ideal, then the output signal would be an exact replica of the input signal without the noise and distortion created by the main amplifier.

$$\underbrace{S + D + N}_{\text{main amp output}} - \underbrace{(D + N)}_{\text{distortion and noise}} = \underbrace{S}_{\text{clean output signal}} \qquad (2)$$

3.0 Cancellation

Ideally, the Feedforward circuit would provide a perfect replica of the input signal without any distortion. In fact, the Feedforward circuit relies on cancellation to provide distortion reduction and the limitations of cancellation define several of the limitations of the Feedforward amplifier; output capability, flatness, temperature stability, and long term stability.

Cancellation involves the combination of two signals which are of equal amplitude and opposite phase. The state of the art for broadband circuits over the temperature range -40° C to +60°C is on the order of 22 to 26 dB cancellation. We will use 24 dB cancellation as a basis for the rest of the analysis presented in this paper. Improvements in second order distortion of push-pull hybrid IC's and typical passive and tap output-to-output isolation specifications can be cited as good examples of this 24 dB cancellation figure.

4.0 A New Phenomenon; Third Order Nonuniformity

Modern multichannel broadband systems are being specified with third order distortions being the main output limiting factor. This is still the case with Feedforward amplifiers. However, the nature of this parameter has changed dramatically. RF hybrid IC's with a push-pull cascode circuit were the main gain blocks used in broadband distribution amplifiers prior to the use of Feedforward. The third order performance of these circuits did not rely on cancellation, but rather depended on the performance of the transistor die. Because of this, the third order performance of the individual transistors, the hybrids; and therefore, the distribution amplifiers themselves was a relatively fixed value. Unit-to-unit and lot-to-lot variations in third order performance were very small. The amplifier performance was then very predictable and orderly. System performance calculations based on individual amplifier tests were also predictable, orderly and practical.

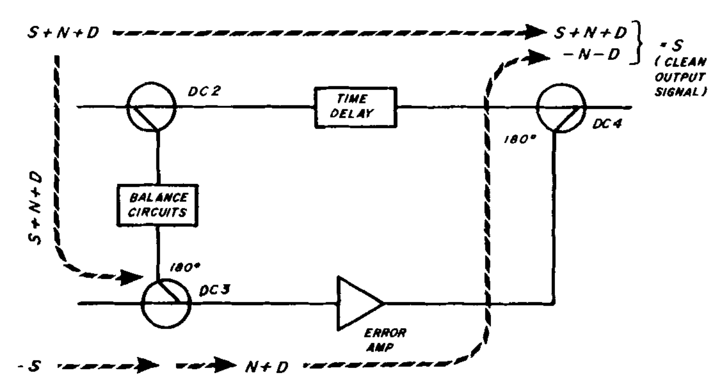

FIGURE 3

SECOND LOOP CANCELATION

System designers relied on this uniform product to predict system performance by using empirical techniques. That is, one could measure the performance of the single trunk amplifier and then predict the performance of a cascade of these amplifiers or predict system performance based on data accumulated from amplifier performance. With Feedforward circuits, this is no longer the case. A discussion of the specification of the output capability of the Feedforward amplifier follows.

4.1 Cancellation And Distortion Reduction

The distortion of the Feedforward circuit compared with the distortion performance of the main amplifier will be considered. The second loop (Figure 3) produces 24 dB cancellation. We are concerned with third order distortions being the limiting system design factor and these, if the main amplifier is operating in a well behaved mode, will derate on a two for one basis. That is, if the output signal level is increased by 1 dB, the carrier to composite triple beat ratio will be degraded by 2 dB. A 24 dB cancellation would then result in a basic 24 dB reduction in distortion. However, a 3 dB loss exists between the main amplifier output and the Feedforward circuit output (see Figure 1). This loss reduces the output capability, so we should subtract 6 dB from the 24 dB reduction in distortion. The result is an 18 dB reduction in distortion with this Feedforward circuit.

4.2 Cancellation Measurements

As was stated earlier, third order distortion performance of non-Feedforward type amplifiers was uniform from unit to unit. Examine Figure 4 which is a photograph of a swept display of the cancellation of the second loop of a Feedforward gain block versus frequency. This photo was taken at room temperature. Notice that the cancellation is generally better than 24 to 26 dB with the high frequency cancellation having two nulls where the distortion is substantially better than 30 dB. Also note that the cancellation is not uniform across the entire bandwidth. These cancellation characteristics will not be uniform from unit to unit. The nulls will be displaced in frequency from one unit to the next. In a typical production run, some units will align to better than 28 or 30 dB across the band while others may have no nulls at all and will be relatively uniform in the 24 to 26 dB range.

The result is that the third order distortion performance of several Feedforward amplifiers will naturally be remarkably different from one another. Empirical tests on individual amplifiers must then be basically unreliable in and of themselves as an evaluation and specification process.

5.0 Temperature Stability

The cancellation shown in Figure 4 involves a delicate balance of amplitude and time delay along two different signal paths. When the temperature changes, the gain and delay of the main amplifier as well as the insertion loss and delay characteristics of the directional couplers and delay lines will change slightly with temperature. It is impractical to assume that the precise balance needed to maintain 30 or 35 dB cancellation can be maintained over the temperature range. Figure 5 shows the cancellation of the circuit in Figure 4 at +60° C temperature. Figure 6 shows the cancellation at -40° C.

The key point here is that the equipment manufacturer and system designer must deal with specifications based on the analysis of the limitations of the cancellation process and not rely upon empirical data taken on one or even several units. Generally speaking, 16 to 18 dB cancellation would be a poorly designed circuit, while 22 to 26 dB cancellation is a well designed state of the art circuit. However, 26 to 30 dB cancellation is impractical to achieve over the temperature range and across the entire spectrum.

6.0 Cascade Test Results

Cascade tests of 20 Feedforward trunk stations were conducted. The amplifiers had 26 dB spacing and were operated at 36 dBmV output signal level at the highest channel with a 7 dB linear tilt between the highest and lowest channel. Without providing the details,[1] the assumption of 24 dB cancellation on the Feedforward circuit plus the minimum performance specifications of the hybrids used in these amplifiers indicated an individual amplifier carrier-to-composite triple beat ratio (CCTB) performance of 89 dB. Assuming in-phase addition of CCTB, the cascade of 20 trunks would produce 20 Log N or 26 dB worse CCTB than an individual amplifier. This results in an expected CCTB of 63 dB for the cascade.

The CCTB of each amplifier was measrued individually. The minimum CCTB was 92 dB, while the mean value was 95.2 dB. Cascade test results are shown in Table 1. Clearly, the minimum performance of an individual amplifier should not be used to predict cascade performance. This results in an overly pessimistic performance prediction of 63 dB for the cascade. The mean value of 95.2 dB could be used to make cascade preditions, with a calculated performance being 69.2 dB.

TABLE 1

	Calc	25° C	-20° C	55° C
Carrier-to-Composite Triple Beat	63	72	70	69

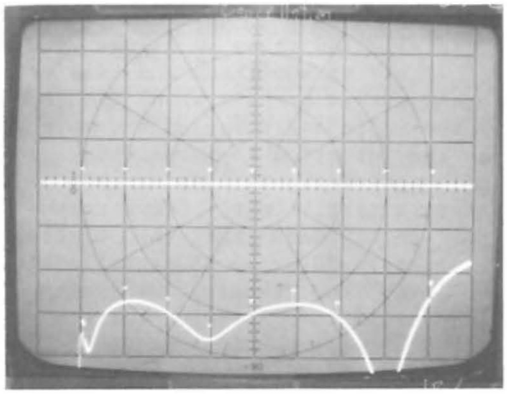

FIGURE 4

CANCELLATION AT
ROOM TEMPERATURE

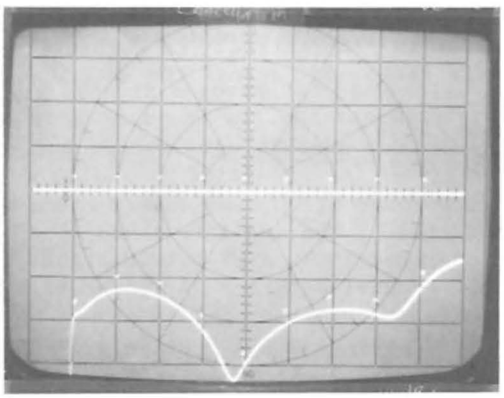

FIGURE 5

CANCELLATION AT 60° C

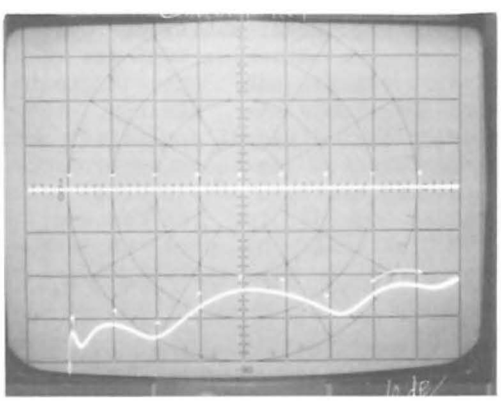

FIGURE 6

CANCELLATION AT -40° C

Two points should be considered. First, individual minimum amplifier performance should be specified along with typical amplifier performance in a Feedforward circuit if meaningful cascade performance calculations are to be attempted. Secondly, will the typical performance of the system, which clearly depends upon better than 24 dB cancellation, be maintained with time? This author believes that some consideration to an ultimate softening of the cancellation characteristics with time and temperature ought to be considered in system designs with Feedforward circuits.

7.0 Gain Flatness

There are two parameters which affect the basic flatness of the Feedforward gain block. One is relatively straight forward, understandable, and controllable. The other is more subtle, insidious, and out of control. The more controllable parameter is the fact that 34 dB gain hybrid IC's are used in the Feedforward amplifier instead of the commonly used 18 dB gain blocks. The higher gain combined with basic limitations of the packaging technology result in reduced gain flatness in amplifiers utilizing 34 dB gain blocks. This, however, is controllable by a slight increase in the complexity of the flatness circuits provided with the trunk-line equipment.

The new and unusual phenomenon associated with a Feedforward circuit is understood by looking at Figure 7. This figure shows that the output signal is in reality a combination of the desired output signal derived from the main amplifier plus an undesired output signal provided by the error amplifier. The undesired signal is below the desired signal by an amount equal to the cancellation achieved in DC3, the coupler before the error amplifier. This phenomenon does not exist in trunk stations of the non-Feedforward type. This phenomenon has two effects, one concerns the equipment designer and the other concerns the system designer. The equipment designer must add further complexity to his interstage flatness circuits in a trunk station to overcome the results of the flatness degradation caused by the undesired output signal at room temperature.

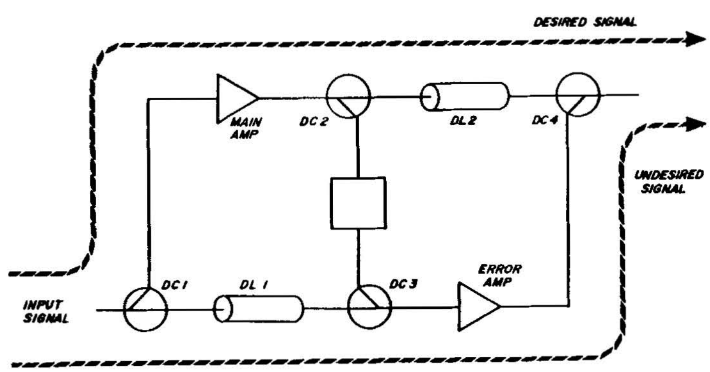

FIGURE 7

UNDESIRED OUTPUT SIGNAL WITH A FEEDFORWARD CIRCUIT

The system designer must realize that the flatness of the Feedforward circuit is dependent on the cancellation of the first loop and that the cancellation profile will change with temperature, thus producing a small gain change. For example, a null might exist at room temperature so that essentially no undesired signal is present at the output. At the temperature extremes, the null may disappear and the undesired signal at the output could be 24 dB below the original signal. This is still well within expected performance for cancellation. However, the change in cancellation from 35 dB to 24 dB at that particular frequency will cause a gain change of approximately 0.1 dB.

The net result is that trunk-line cascade flatness will change more with temperature with Feedforward equipment than it will with non-Feedforward equipment. This flatness change is due primarily to changes in cancellation of the first loop of the Feedforward circuit. In a 20 amplifier cascade, a gain change caused by this phenomenon of 0.1 dB per amplifier could result in 2 dB flatness degradation different from and not normally seen on previous equipment. Very long supertrunk cascades may require seasonal balancing if these gain changes cause significant changes in cascade flatness.

8.0 Noise Figure

Although the Feedforward circuit has excellent properties for using it as an output amplifier on a trunk station, its use on the input or preamplifier stage of a trunk station is restricted.

The noise figure of the Feedforward amplifier can be analyzed by considering the fact that the noise generated in the main amplifier is cancelled by the first loop so that the noise at the output of the Feedforward amplifier is primarily due to the noise created by the error amplifier. Noise is not usually considered to be a cancellable phenomenon, however, in this case the noise being cancelled is correlated. That is, the noise output of the main amp is contained in both signal paths and, therefore, is correlated and cancellable. The noise generated by the error amplifier is not in both signal paths, is not correlated and not cancelled.

Where does the noise come from? In Figure 1 it can be seen that the gain of the Feedforward amplifier is equal to the gain of the main amplifier minus those losses incurred through DC1, DC2, DL2, and DC4 (Equation 3). A general characteristic of the Feedforward circuit is that if we neglect the effect of the cancellation of the first loop, the gain from input to output through DC1, DL1, DC3, the error amplifier, and DC4 is also equal to 23 dB (Equation 4). The noise at the output is due to error amplifier noise. Therefore, the noise figure of the Feedforward amplifier is equal to the noise figure of the error amplifier plus those losses incurred between the Feedforward circuit input and the error amplifier input. In this case the noise figure would be equal to 9 dB.

$$-DC1 + G_M - DC2 - DL2 - DC4 = \text{Gain}$$

$$-8 + 34 - 1 - 1 - 1 = 23 \text{ dB} \quad \text{main path gain} \quad (3)$$

$$-DC1 - DL1 - DC3 + G_E - DC4 = \text{Gain}$$

$$-1 - 1 - 1 + 34 - 8 = 23 \text{ dB} \quad \text{error path gain} \quad (4)$$

Generally, this Feedforward circuit will always have a worse noise figure than an equivalent RF Hybrid amplifier. It follows then that the use of a more complex Feedforward circuit on the input or preamp of a trunk station would have to improve the distortion of the trunk station enough to overcome the deleterious effect of reducing the dynamic range by increasing the noise figure.

9.0 Gain Compression

Feedforward circuitry does not improve the power handling capability of the amplifier, rather it simply reduces the distortions created by the main amplifier. Figure 8 presents the CCTB ratio versus output levels for a 450 MHz 60 channel system operating with output levels having a 6 dB linear tilt between the highest and lowest channel on the system.

Note the performance of the single hybrid. At levels below 45 dBmV, the third order distortions behave in a well-mannered fashion and follow the two for one slope lines indicated on the chart. Above this, higher order terms such as 5th, 7th, and 9th order terms, start coming into play and the distortion performance departs from the well behaved performance.

The other two performances indicated on the chart, the parallel hybrid and Feedforward performance, are determined by using the single hybrid performance as a reference and then constructing the other two charts according to the following rules.

The parallel hybrid performance is obtained by shifting the single hybrid performance to the right 3 dB at each point.

The Feedforward curve is constructed by taking any point on the single hybrid line, shifting to the left 3 dB to allow for Feedforward circuit output losses, and then shifting downwards 24 dB to allow for cancellation of the second loop.

Figure 8 presents an analytical approach to determining the expected performance of the Feedforward feeder amplifier at the higher output levels required for bridger and line extender functions in the distribution system. Empirical data taken on individual units can and will vary considerably. Note that at 51.5 dBmV out the Feedforward amplifier performance is identical to the parallel hybrid performance. Also note that if the lines were extended further, that at 54 dBmV out, the single hybrid performance would be better than the Feedforward circuit performance.

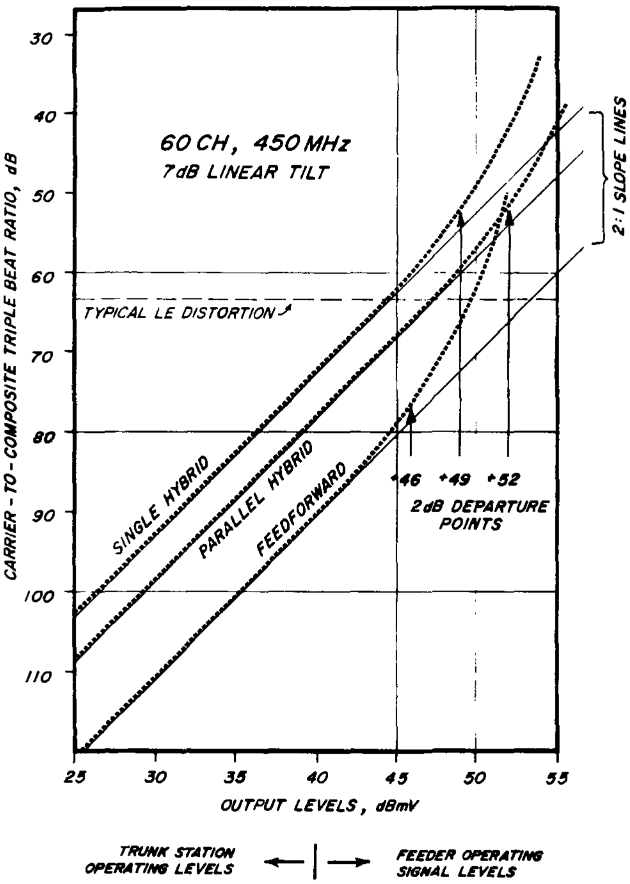

FIGURE 8

OUTPUT CAPABILITY COMPARISON

This unique behavior, that is, poor derating at elevated signal levels complicates the task of the system designer when selecting and specifying the output signal level for Feedforward distribution amplifiers in bridger and line extender applications.

This analysis indicates that if a 3 dB safety margin were required in the system design that equivalent performance between parallel hybrids and Feedforward circuits would be achieved at 48.5 dBmV output levels. At this point, a parallel hybrid device would have 60 dB CCTB while a Feedforward device would have 67 dB CCTB. However, if the output levels of each were increased by 3 dB, each would have a 55 dB CCTB.

There is some question then as to whether a parallel hybrid circuit would be preferrable to a Feedforward circuit in bridgers and line extenders. The Feedforward circuit is substantially more complex and consumes more power than a parallel hybrid circuit.

11.0 Delay Line Selection

The selection of the proper delay line approach affects the ability to maintain, repair, and upgrade equipment. Two types of delay lines are presently being used in feedforward circuits. The first is a lumped element delay line utilizing a low pass filter circuit. These delay lines are generally 10 branch circuits with 20 or more components.

The lumped element delay lines have several drawbacks. They are costly, requiring many components and requiring time-consuming alignment. Furthermore, a unique delay line must be used for each type of hybrid. When changing hybrids from one vendor to another or if a hybrid vendor changes his manufacturing process in such a way as to change the delay of the circuit, a redesign of delay lines might be required. The history of the broadband amplifier business has been such that this type of change occurs every 18 months to two years. Repair of existing equipment using future hybrids can require redesign of the delay lines. Changing the hybrid vendor can require redesign of the delay lines.

Furthermore, technician training related to alignment and balance procedures for equipment using Feedforward circuits with lumped element delay lines is complex.

Another type of delay line is useable in these circuits, that is a fixed delay line utilizing microstrip technology. It has several distinct advantanges over its lumped element counterpart. The use of a plug-in fixed delay line allows a change in the time delay without redesign. A series of several time delay values can be configured in a common package which can plug into a Feedforward circuit. Thus, if the hybrid vendor or hybrid process is changed, the delay line can be easily changed.

The microstrip delay line has a constant impedance with an inherently broad bandpass, generally greater than 1.2 GHz. The lumped element counterpart is inherently a low pass filter with band limiting characteristics. Also, the fixed impedance of the microstrip delay line requires no alignment, therefore, no training for maintenance purposes.

The cost differences for these delay lines are near an order of magnitude, the micrcostrip delay line being dramatically lower in cost than its lumped element counterpart.

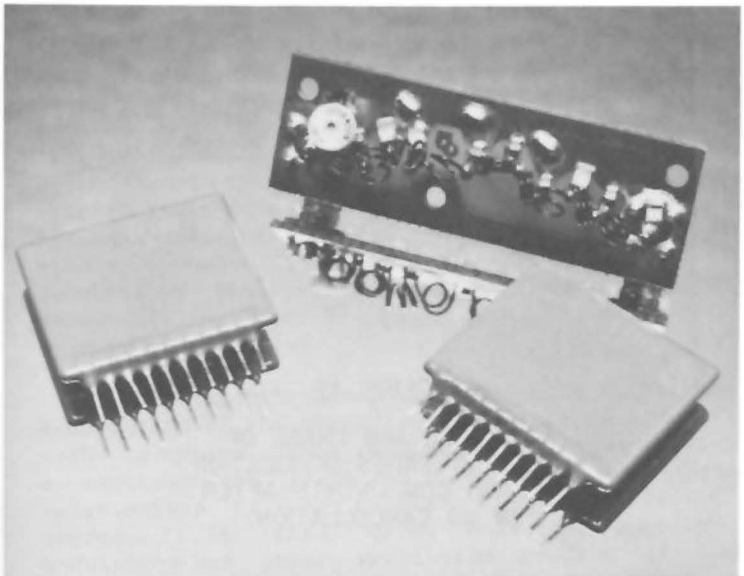

FIGURE 9

PHOTO SHOWING MICROSTRIP AND LUMPED-CONSTANT DELAY LINES

12.0 Power Consumption and Heat

A disadvantage of the Feedforward circuit over the RF hybrid counterpart is the increased power consumption and heat generated within the package. This increased power consumption requires the use of an efficient switching regulator power supply, and attention to the thermal characteristics of the amplifier package. In many instances, repackaging of standard broadband product lines will be necessary to allow for switching power supplies and lower thermal resistance packages in order to maintain reliability and avoid excessive overheating of critical amplifier components.

13.0 Cross Modulation in Broadband Feedforward Circuits

The feedforward circuit configuration provides significant improvement in the intermodulation distortion performance of a broadband amplifier. However, amplitude cross modulation reduction at high frequencies does not necessarily occur to the same extent in a feedforward circuit. This will be shown after first discussing cross modulation in push-pull cascode amplifiers.

The nature and behavior of cross modulation at high frequencies in multichannel broadband amplifiers is well known and documented. Gumm[7] and Luettgenau[5] have described, documented and characterized phase cross modulation at high frequencies. Simply stated, the predominant energy of the cross modulation sidebands occurs as phase modulation instead of amplitude modulation of the carrier at higher frequencies.

Furthermore, the visual effect of the phase cross modulation occurs at levels which make composite triple beat noise the limiting factor in broadband systems which carry 50 or more channels. Even in systems which use harmonically related or phase-lock carrier techniques, the triple beat mechanism is of prime importance, while cross modulation was deemed incidental.[3,6]

The cancellation phenomenon of the Feedforward circuit introduces yet another degree of complexity in analyzing high frequency cross modulation. The following analysis shows the effect of cancellation on cross modulation sidebands and predicts the resultant effect on amplitude cross modulation.

Jeffers used the classical rotating vector representation of narrowband FM to describe the phase cross modulation phenomenon at low levels of nonlinearity. This approach will be used to describe the effect of Feedforward circuit cancellation on the cross modulation sidebands.

Figure 10 shows a carrier vector with the double sideband cross modulation vectors having a resultant vector whose phase is 90 degrees out of phase with the carrier vector. This represents pure narrowband FM or phase modulation. Detection of the envelope of this signal would result in no amplitude modulation.

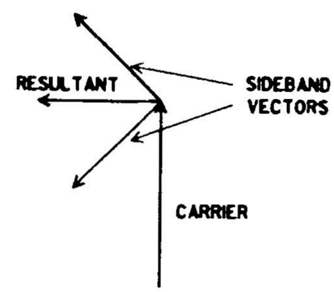

FIGURE 10

NARROW BAND FM MODULATION VECTOR REPRESENTATION

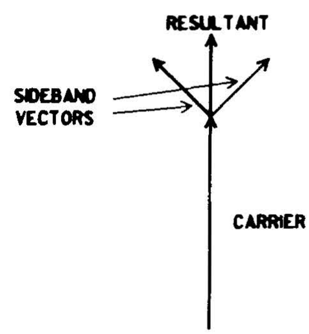

FIGURE 11

AM MODULATION VECTOR REPRESENTATION

Figure 11 shows a similar representation for the case of pure amplitude modulation. In this case the resultant vector of the sideband components is shown in phase with the carrier vector and therefore provides pure amplitude modulation, with no phase modulation.

Experiments were conducted to define the extent of this effect on push-pull cascode RF hybrids. The magnitude of the phase difference between the carrier and cross-mod sideband components can be calculated by first measuring the magnitude of the cross modulation sidebands on a spectrum analyzer and then comparing the results to the measurement of amplitude cross modulation by standard NCTA techniques.

Experiments on 450 MHz, 60 channel RF hybrids indicate a typical phase angle of 80 degrees for the resultant of the sidebands at the high frequencies. This is very close to pure phase modulation as shown in Figure 10.

Figure 12 shows the general tendency of the phase modulation to produce a discrepancy between the amplitude of cross modulation sidebands as measured on a spectrum analyzer and cross modulation measured by NCTA methods.

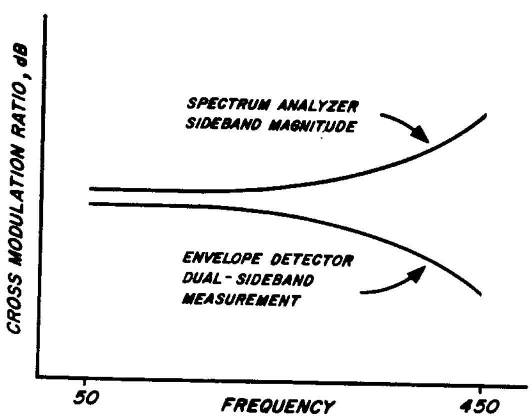

FIGURE 12

CROSS MODULATION OF RF HYBRID IC USING TWO MEASUREMENT TECHNIQUES

This beneficial phase relationship can be destroyed by the cancellation process in a feedforward circuit. For instance, the high frequency cross mod component generated by the main amplifier will have a phase characteristic similar to that shown in Figure 10 with characteristicaly low amplitude cross mod. The cancellation process of the error loop involves the combination of the sideband with another signal of nearly equal amplitude and nearly opposite phase to provide an output signal with substantially reduced sideband magnitude. However the phase of the resultant sideband can take on any value between 0 and 360 degrees. This is shown in Figure 13.

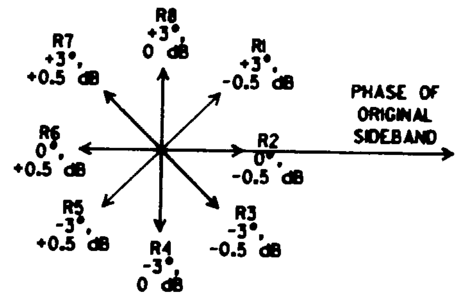

FIGURE 13

MAGNITUDE AND PHASE OF RESULTANT CROSS MODULATION SIDEBAND COMPONENTS AFTER 26 dB CANCELLATION

There are several resultant vectors R1 through R8, plotted in Figure 13. Each of the possible resultant components has a magnitude 26 dB below the original distortion sideband, corresponding to a cancellation signal having a magnitude within 0.5 dB and a phase within 3 degrees of 180 degrees with respect to the original sideband. Clearly, the resultant can take on any phase value.

What then is a reasonable expectation for amplitude cross-modulation performance for feedforward circuits? The answer to this question involves first recognizing the magnitude of the original cross modulation sideband and then analyzing the results of the cancellation process.

Hybrid vendors now specify both composite triple beat and amplitude cross modulation on their 450 MHz parts. Typical performance numbers for both distortions with 60 channel loading at +46 dBmV output levels at all channels is 60 dB. Yet, these same devices exhibit cross mod sideband magnitudes of typically 45 dB referenced to the sideband of a 100% square wave modulated signal for the same test conditions. That is, the sideband magnitude for cross mod components is 15 dB worse than the composite triple beat. But again, this is predominantly phase modulation and not amplitude modulation. Using this information, the amplitude of the cross mod sidebands of a feedforward circuit can now be calculated.

Refering to Section 4.1, which presumes 24 dB cancellation and 3 dB in output losses for the feedforward circuit, one could expect a reduction in the magnitude of the cross mod sidebands of 18 dB relative to the performance of a single hybrid. So, if we start with a predominatly phase modulated sideband component of 45 dB and improve this by 18 dB, the result is a cross mod sideband component 63 dB below reference. This takes care of the magnitude of the component. Now, we must look at the phase.

Figure 13 shows the phase of the resultant component after cancellation. If the resultant is either R2 or R6, the original beneficial phase relationship will be maintained. If the resultant is either R4 or R8, the opposite is true, with complete PM to AM conversion taking place. Note that this condition occurs at perfect amplitude balance of the Feedforward circuit while the extreme limit of delay balance is being reached. Assuming that all points in this circuit are equally probable, the typical or average phase will intuitively be between these extremes. That is, either R1, R3, R5 or R7 on Figure 13 represents average performance.

Combining this assumption with the amplitude information of the preceding paragraphs we are left with the typical cross modulation sidebands having a magnitude of 63 dB and a resultant whose phase relationship to the carrier of typically 45 degrees. In this case, both the amplitude modulation and phase modulation content of the sidebands are assumed to be equal with a corresponding value 3 dB below the magnitude of the resultant component. This assumption is shown graphically in Figure 14 and results in a prediction of typical amplitude cross modulation of 66 dB for the case being considered.

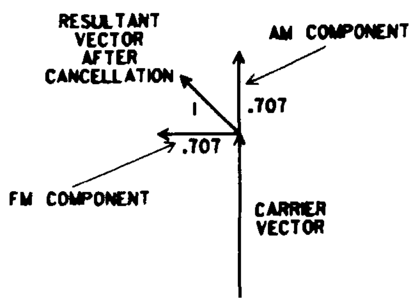

FIGURE 14

ASSUMED TYPICAL PHASE RELATIONSHIP OF THE CROSS MODULATION SIDEBAND RESULTANTS AFTER CANCELLATION

Summarizing and comparing cross modulation and composite triple beat performance predictions for the Feedforward circuit; a hybrid with 46 dBmV output at 60 channels ha 60 dB CTB, 60 dB AM cross modulation, and 45 dB cross modulation sidebands. A Feedforward circuit with the same output level will have 78 dB CTB with 66 dB AM cross modulation. The key point is that this analysis predicts the probability of PM to AM cross modulation conversion by the cancellation process of the Feedforward circuit. Therefore, AM cross modulation should not be specified at levels equal to CTB in a Feedforward amplifier.

Experiments on individual circuits confirm the existence of this process.[4] Room temperature performance of Feedforward circuits can be aligned to minimize this effect, however, the effects of time and temperature can and will produce AM cross modulation in a balanced Feedforward circuit at levels well above the CTB.

14.0 Summary and Conclusions

Feedforward amplifiers have attractive advantages, but specification of equipment performance and system performance must be done on an analytical basis rather than empirical basis. Critical third order distortion performance is not uniform, but is rather dependent on a cancellation phenomena which can change with frequency, temperature, and time.

450 MHz, 60 channel composite triple beat for a Feedforward gain block should be specified at no better than an 18 dB improvement over existing hybrid integrated circuit technology distortion performance.

Use of Feedforward circuits for trunk station pre-amplifiers is not normally advisable due to the decrease in dynamic range associated with higher noise figures of Feedforward circuits.

System designers must expect cascade flatness at temperature extremes to be measureably less than previous non-Feedforward systems.

Poor Feedforward circuit derating should be considered in specifying amplifiers which operate at high output levels, such as bridgers and line extenders.

Cross modulation performance should be specified at levels worse than the composite triple beat.

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