High Linearity HBT Amplifiers for CATV Systems

Abstract

Monolithic Amplifiers using GaAs HBT technology have been developed. HBT based amplifiers offer extremely flat frequency response with high dynamic range and use less DC power than Silicon or GaAs MESFET based circuits. These inexpensive amplifiers are packaged in a standard SOIC plastic packages and feature very flat frequency response to beyond 1GHz with OIP_3 numbers in excess of +40dBm. They are capable of amplifying multicarrier CATV signals with very high fidelity.

Introduction

The need for high linearity amplifiers arises from stress placed on communications channels by the addition of more data and the requirement to handle digitally modulated signals with high fidelity. As the amount of data increases and the necessity to reduce spurious interference increases, the channel linearity must be improved over current implementations. A particularly difficult problem is obtaining the linearity and bandwidth needed for the amplification of multicarrier signals such as those found in the TV distribution industry. Cable TV, for example, is expanding rapidly in terms of both the number of channels and additional subscribers. Hence, more bandwidth and power output capacity (without degrading linearity) are necessary. These systems are also incorporating more technology into their systems including two-way channels for voice and data, and digital video modulation. As this additional capacity is added, the bandwidth and signal handling capability of the various links in the distribution chain must be improved. In addition to the need for more capacity, the linearity of the channel must further improve because digital modulation schemes are less tolerant of IM distortion products than the analog systems currently in use. The infrastructure needed to accommodate these technology innovations must be in place throughout the distribution chain before it can become available to the consumer. Hence, there is considerable pressure to improve channel linearity, bandwidth, and power handling capability in the many links of the various distribution channels.

RF Micro Devices is developing a line of high linearity, wide bandwidth products to address these requirements. The first in the series is the RF2312 amplifier which has been released as a standard product by RFMD. Other higher power units are the RF2317 (a higher power version of the RF2312) and the RF2316, which is a balanced device having improved second order distortion over the unbalanced designs. The latter two devices will be in full production in January 1997.

The RF2312 and RF2317 are essentially a low cost, traditional Darlington “Gain Block” circuits with the exception that performance far outstrips previously available units. The gain is essentially flat over the bandwidth from 1MHz to well over 1GHz and has an IP3 of over +40dBm. The secret to the performance of the unit (as in all the units mentioned) is in the use of GaAs Heterojunction technology in the fabrication of the device. The unit will replace more expensive and less reliable discrete amplifiers and permit much better distortion levels for a given amount of DC power consumption.

Characteristics of Multicarrier Channels

A multicarrier channel consists of many independent RF carriers each with its own frequency and modulation. It is important that each of these signals remain “uncontaminated” by all of the other signals in the channel. For simplicity, consider that if n CW carriers are present, have the same amplitude, and are coherent with each other, the resulting frequency spectrum is a “picket fence” as shown in figure 1. The time waveform resembles an impulse function as shown in figure 2. (Note that because the frequency spectrum does not start at zero and because some phase distortion is introduced by filters and amplifiers in the chain, the time function is generally not, strictly speaking, an impulse.) The amplitude of the voltage peak is $20\log(n)$dB above the amplitude peak of a single tone. This occurs when all of the signals have a peak amplitude occurring at the same point in time. If, however, each carrier is independent and has a random phase with respect the other carriers, the time waveform is similar to that shown in figure 3 while the frequency spectrum remains the same as in figure 1. In some newer systems, this spectrum can extend from a few MHz to about 1GHz. The result is a noise like signal which has the same average power as in the coherent case, but has much smaller peak excursions. This is an important fact, since the amplifier has to be designed to handle peak excursions in a linear fashion and designing the part for voltage excursions of $20\log(n)$ dB above the single tone amplitude would be very difficult and be an “overkill”.

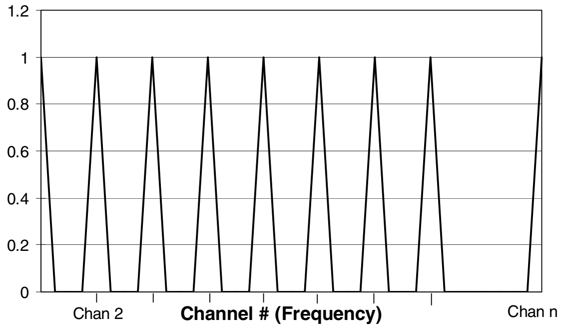

Figure 1. CATV Spectrum

Figure 2. Time waveform of signal with zero phase

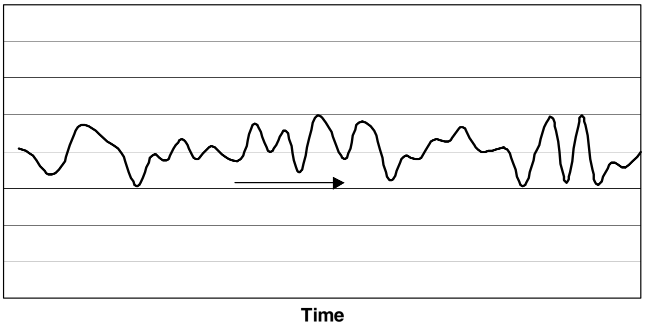

Figure 3. Time waveform with random carrier phases

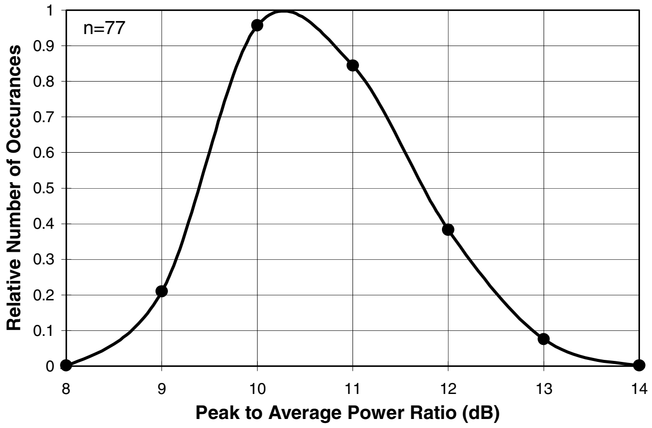

Figure 4. Peak to average power ratio for CATV signal

Because the signal is noise like, the peak excursions of the voltage waveform are a statistical function and therefore the maximum level is indeterminate except to say that it is smaller than A*20 log(n), where A is the amplitude of each carrier and n is the number of signals. In fact, successive measurements may yield different answers. Because of the nature and quantity of the signals present, however, it is possible to estimate the maximum likely excursion of the waveforms. Many measurements have shown that as the number of signals increase, the actual peak excursion is always reduced markedly from the theoretical maximum given above. The curve of figure 4 shows the probability of measuring a number of peak to average power ratios with a typical CATV composite signal. Note that, in general, 14dB is the practical (but not theoretical) maximum ratio of peak to average power in the composite signal. Therefore, the design of an amplifier which is to handle such a signal must have a linear signal handling ability which is 14dB above the average power and 14+10*Log(n)dB power handling ability over the power in a single channel.

As an example, consider a 110 channel system where each carrier is at a level of 50dBmV (0.316V_{RMS}).

Channel Power=$(0.316)^2/75$=1.33mW=+1.24dBm.

Composite Average Power=110*1.33mW =146mW=+21.6dBm

Peak Power if each carrier phase is 0° =+43.8dBm

Expected Nominal Peak Power=10.5+21.6=+32.1dBm

Maximum Peak Power = 14 + 21.6 = 35.6dBm (3.6W)

Maximum Output Voltage Peak = 16.4V (or 32.8V_{PP})

Therefore, an amplifier designed to handle this signal should have the ability to produce +35.6dBm in a linear fashion - i.e. be able to swing 32.8V_{PP} without clipping.

Causes of Distortion

Four different sources of distortion in an amplifier are listed below. These issues must be addressed either in the design of the amplifier or in the choice of technology used to implement the circuit.

- **Voltage compliance:** As noted above, an amplifier which has to handle 110 signals must be capable of an output peak to peak voltage swing of about 31dB higher than the peak to peak voltage of each carrier signal and 40dB higher than the RMS voltage of each carrier signal. So, if the output is set to

+35dBmV (the RMS voltage of a single signal is 35dB above 1mV=56.2mV$_{RMS}$), the output swing must be at least 66dBmV which is a 5.64V$_{PP}$ voltage swing (+/- 2.82V). If the amplifier clips during this voltage swing, severe distortion results. In practical circuits, there is an emitter degeneration resistor which raises emitter voltage causing early saturation. It is also necessary to guard band the saturation of the output device since approaching V_{SAT} will cause distortion as well. So the DC V_{CE} (or V_{DS} for FETs) used for the design must be at least 6.5V for this application (or about 3.8V if the collector feed is a choke instead of a resistor). In general, high transistor breakdown voltages are needed for these applications in order to prevent voltage compliance distortion.

- **Drive Current:** Although the exponential I-V characteristic of bipolar devices is thought to make the device nonlinear, experimental results and analysis prove otherwise. The use of emitter degeneration, feedback and ample DC collector current permit the designed to obtain arbitrarily good linearity of G_M (Transconductance). It is necessary to bias the device at a high enough current level to achieve suitably linear operation. In general, devices used in this application have more current drive than would theoretically be necessary to drive the load at the required power level. This excess current is used to provide superior linearity over amplifiers designed for single carrier applications.
- **Distortion due to non-linearity of base-collector capacitance:** Because devices used for multicarrier systems are, of necessity, fairly large devices (because of power density), the base-collector capacitance may be larger than other amplifiers of the same power level. Ideally, the transistor’s capacitance is constant, and therefore may cause roll off in frequency response, but not contribute distortion. Real world devices, however, exhibit a nonlinear capacitance vs. voltage curve which contributes significantly to distortion in the output signal, particularly when the voltage swing is quite large.
- **Non-linear R_{OUT} of the transistor:** Non-linear loading of the output by the amplifying device itself also causes considerable distortion in the output waveform. Ideally, R_{out} is high and constant. If it is not, the loading of the output changes with signal voltage level, in effect modulating the output signal and causing distortion.

Advantages of HBT

The subject amplifiers are fabricated with a GaAs HBT technology. It is a proven technology which uses a GaAs/AlGaAs heterostructure for producing bipolar devices which have very high f_T, very high Early Voltage, high BV_{CEO} and a capacitance vs. Voltage curve that is nearly flat. This HBT process is the most reliable commercially available HBT process in the world and has been qualified for class S space applications. The level of ruggedness is absolutely needed for space applications, but it is also demanded by commercial applications such as TV distribution systems and cellular base stations which have to be extremely rugged and reliable.

RF Micro Devices has supplied high volumes of Power Amplifiers utilizing this process with excellent results. The HBT process and products built with this process have been tested to determine that failure rates are at least 10^7 hours at 125 degrees C.

The main reason that this technology was selected for this product was that it provides superior linearity and bandwidth compared to other technology choices. The desired performance requires amplifying devices which have a very high transition frequency (f_T). The minimum f_T is about 15GHz and 20GHz or more is desirable in order to obtain a really flat response with good return loss through 1GHz. Silicon devices could not be used for this application because, as the f_T of Silicon Bipolar monolithic transistors increases, a heavy price is paid in terms of breakdown voltage. The best Si BJT devices (for ICs) which have an f_T in excess of 15GHz, have a breakdown voltage of 12V (BV_{CBO}) and higher f_T devices result in even less BV_{CBO}. So, there is a limit to the voltage swing on the output which is too low for any multicarrier applications. GaAs devices (both HBT and MESFET) can have Breakdown voltages which are much higher (18V for MESFET and over 22V for the HBT) even though they have transition frequencies well over 20GHz.

For the HBT, whose f_T is over 25GHz, the DC collector voltage can be as high as 10V and the resultant voltage swing is then 20V$_{PP}$. With a push pull arrangement, the voltage swing doubles to 40V$_{PP}$ which covers most CATV distribution requirements. This makes the HBT the best candidate to provide the best voltage compliance for a wideband amplifier. The second very real advantage of the HBT is the fact that base - collector capacitance is small and much more constant than either the Si BJT or the MESFET. Figure 5 shows the capacitance variation vs. voltage for a Si BJT and an HBT. Note that the HBT capacitance is nearly constant with collector voltage. This has a significant effect on linearity as will be shown later.

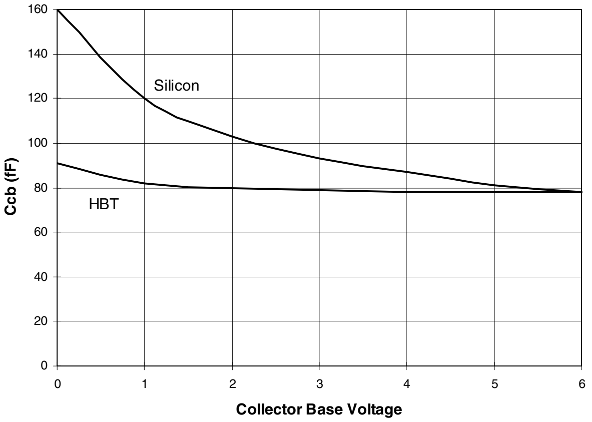

Figure 5. Ccb for HBT and Silicon Bipolar

RF Micro Devices has approached the marketplace for RF products using a philosophy of Optimum Technology Matching (OTM) which uses the best technology at our disposal (GaAs MESFET, Silicon Bipolar, CMOS, and GaAs HBT) to address the needs of the market. In other words, we don't restrict the selection of the technology utilized, a priori, but instead, seek that which will yield the most effective solution for our customers. In this case, the overriding concern is to maximize the linearity of the amplifier with minimum power consumption, and of course, do so at a reasonable price. Over the years, our experience is that the most linear amplifiers we can build are invariably GaAs HBT devices. In order to illustrate the performance differences and show why we selected HBT for ultra linear amplifier products, three different parts have been simulated for comparison - two HBT parts, a Si BJT part, and a GaAs MESFET part. The modeling used to simulate these devices is very accurate and has been tested in practice for many types of circuit. One of the HBT parts is the RF2312, and the other is the RF2317. We have laboratory confirmation of the accuracy of the simulation since each of these parts have been tested

Figure 6 shows distortion in the RF2312 and RF2317 which use HBT devices. The test tones are those used for DIN4500B testing which is a standard test used for European TV systems. The large tone is at a frequency of 736MHz. The smaller tones are each 6dB below the large tone, and the frequency offsets are 18 and 24MHz, respectively. Normally, the DIN rating is the highest level for the large signal which produces distortion products which are -60dBc. As seen in figure 6, the RF2312 distortion is -53dBc for the +60.5dBmV level used for the test. In order to obtain -60dBc, the level of the large signal must be decreased to about 57dBmV. Since we are only interested in comparative data, the signal is left at +60.5dBmV for the comparisons even though all but the RF2317 will not have good enough performance at the +60.5dBmV level. The RF2317 obviously has the capability to produce significantly more than +60.5dBmV per channel since its IM products are down about 65dB. In fact, it should meet DIN requirements up to a level of +63dBmV.

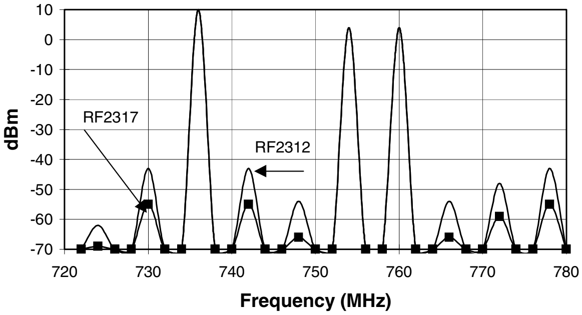

Figure 6. IM distortion with Three-Tone Input

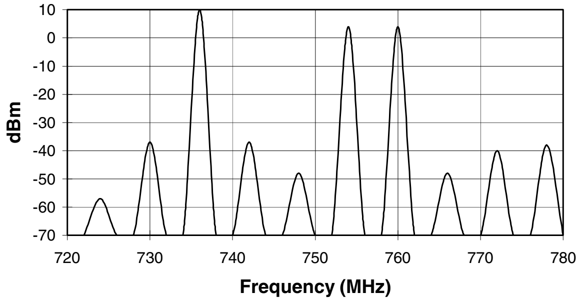

Figure 7. IM Distortion with Three-Tone Input, Silicon device

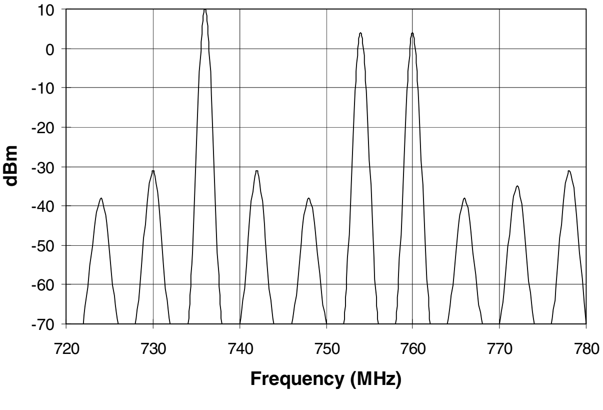

Figure 8. IM Distortion with Three-Tone Input, GaAs MESFET device

The spectrum of figure 7 is the output of the same circuit as the HBT parts except that Silicon Bipolar transistors are used. The transistors are actually hypothetical transistors, in that they have identical properties as the HBT circuit except for the base - collector capacitance which is set to have Capacitance vs. Voltage variations like the Silicon transistor shown in figure 5. The bias conditions, both current and voltage are identical to those used for the RF2312 simulation. This Silicon circuit is a very optimistic case since no Silicon BJT IC process exists which has the combination of Early Voltage, f_T, and BVCEO which is associated with the HBT device. But, if one could find a Silicon process with these attributes the result would be as shown. Note that the distortion products increase by approximately 6dB, because, and only because, the base - collector capacitance varies with voltage. The degradation in performance shows clearly the advantages of the HBT over any process which has a significant variation in Capacitance vs. Voltage.

Figure 8 shows the same circuit using GaAs MESFET devices for the active elements of the design. Again, the bias conditions are identical. In addition, the sizing (Gate width) and pinch off voltage for these FETs were optimized for best performance. This circuit is not hypothetical in the sense used above, because it is possible to physically realize the circuit. The linearity of this circuit suffers because of varying capacitance like the Silicon device, and also because of the strongly non-linear output conductance of MESFETs. In addition, because of the lower GM for the MESFET, no source degeneration is possible. In fact, it proved impossible to obtain the same gain as is possible with the HBT and Si BJT implementations, so the input signals had to be increased to get the same output power. The results are clearly very inferior to both the Si Bipolar design and the HBT. So, while it is possible to obtain MESFET devices which have sufficient breakdown and f_T, they are not a good choice for high linearity amplifiers because gain is lower and distortion is higher.

Chip Design

The RF2312 and RF2317 are a simple Darlington “Cascadable Gain Block” circuit design as shown in figure 9. This is a broadband feedback amplifier which has its inputs and outputs matched to 75Ohms by virtue of the feedback resistor. Gain is determined by the feedback resistor (RFB) and the emitter resistor (RE2). These resistors along with resistor RB also set the DC bias conditions on the part. The output is connected to the power supply through an inductor (to provide an RF open circuit) and a series resistor which sets the current through the device. The value of the resistor is determined by calculating the necessary voltage drop at the desired current level. The voltage drop is the difference between the power supply voltage and the device voltage as given in figure 10. For example, if the power supply voltage is to be 10V and the device current is desired to be 100mA, consulting figure 10, we see that the device voltage is 5.4V and the drop across the external resistor must be 10-5.4=4.6V. The current is 100mA, so R=4.6/.1 = 46Ohms. In this manner, the desired bias conditions may be set up for any power supply voltage from about 7V to 12V. Voltages outside of that range are not recommended.

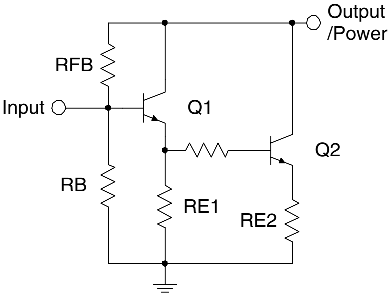

Figure 9. Darlington gain block

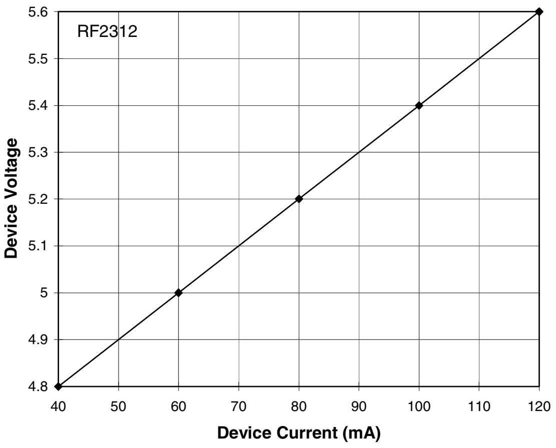

Figure 10. Device voltage versus device current

The inductor value is set such that the reactance at the lowest frequency of operation is at least 200 Ohms. The input and output coupling capacitors are set such that their reactance at the lowest frequency of operation is less than 10Ohms.

Chip Performance

A summary of the measured performance of the RF2312 and RF2317 is shown in table 1. Note that the table reflects measurements done in a 50Ohm system. This is because we were equipped for only 50 Ohm measurements for some of the parameters. So for consistency, all of the performance measures are listed as 50 Ohm measurements. To perform all of the measurements with laboratory test equipment, a 50 to 75Ohm transformer must be connected to both the input and output ports. Unfortunately, the transformers have some loss and don't do a good job over the full bandwidth of the part - hence the 50Ohm measurements. Because the imaginary parts of Z_{IN} and Z_{OUT} are very low, the VSWR is pretty good in both 50Ohm and 75Ohm systems, so 50Ohm measurements were performed for the table.

Typical Performance	**RF2312**	**RF2317 (expected)**
Gain	15.5dB	14.5dB
Gain Flatness	±0.3dB	±0.5dB
Bandwidth (3dB)	2.5GHz	1.8GHz
Noise Figure	3.8dB	5dB
P_{MAX} @ 500MHz	+21dBm	+26dBm
OIP_3 @ 500MHz	+38dBm	+44dBm
OIP_2	+57dBm	+63dBm
Input VSWR	1.4:1	1.2:1
Output VSWR	1.6:1	1.3:1
I_{CC}	100mA	200mA
V_D	5.4V	8.0V

Table 1. Chip performance

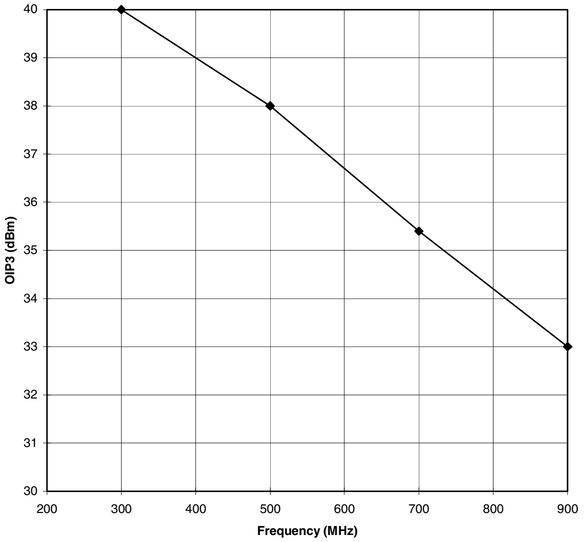

Figure 11. OIP3 versus frequency

A concern with any wideband amplifier of this sort is its stability - particularly when driving filters and severely unmatched loads. The HBT parts have been tested under a variety of conditions using various bandpass and lowpass filters without evidence of any oscillations. The parts has also been driven and loaded simultaneously with 10:1 tuners and showed no unstable properties.

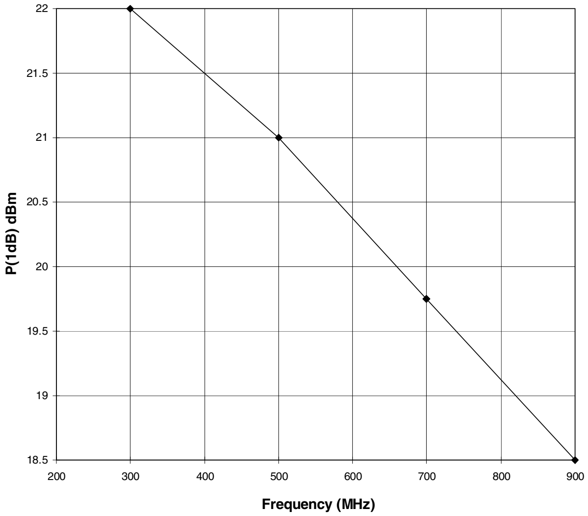

Figure 12. P1dB versus frequency

Figures 11 and 12 show the Output Third Order Intercept Point (OIP3) and Power Output at the 1 dB gain compression point (P_{1dB}) of the RF2312 vs. Frequency. Note that power handling ability does decrease as frequency increases. This is inherent in the Darlington configuration. It is the result of Beta decreasing in the second transistor (Q2) which forces the emitter follower stage (Q1) to provide more current at higher frequencies. A lower f_T, as may be found in a Si device, aggravates that situation - i.e. the higher the f_T of the devices, the better. Distortion resulting from this effect can be decreased by increasing the collector current of the first stage (lower the value of RE1). This, of course, increases overall power consumption. The current level set in the RF2312 is set to achieve the performance goals for the part, and yield good multi-carrier performance up to 1 GHz.

Figure 15 shows the frequency response of the RF2312 mounted on a PCB with approximately 3 inch microstrip traces. Note that while the amplifier has a very flat frequency response, parasitic elements associated with the construction of the circuit board roll the response off slightly at the higher frequencies. Generally, this roll off is of the order of a few tenths of a dB if care is taken in the layout of the PCB. One frequently overlooked aspect of the layout is the ground traces. To obtain a flat frequency response, a ground plane should be placed directly under the amplifier and the ground pins soldered directly to it. If the opposite side of the PCB is used for ground plane, multiple vias should be placed beneath each ground pin. Input and output traces should be 50 or 75Ohm microstrip and high quality, high frequency coupling capacitors and inductors should be used.

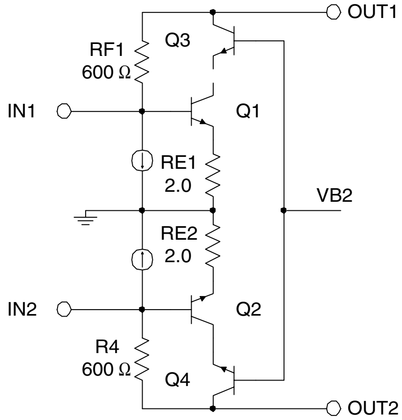

Figure 13. Cascade push-pull

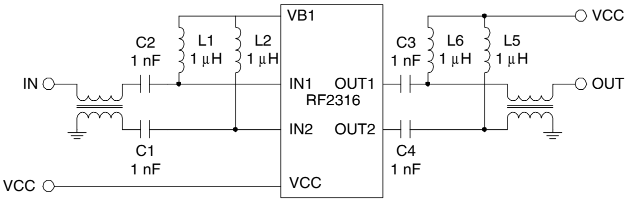

Figure 14. External connections for the RF2316

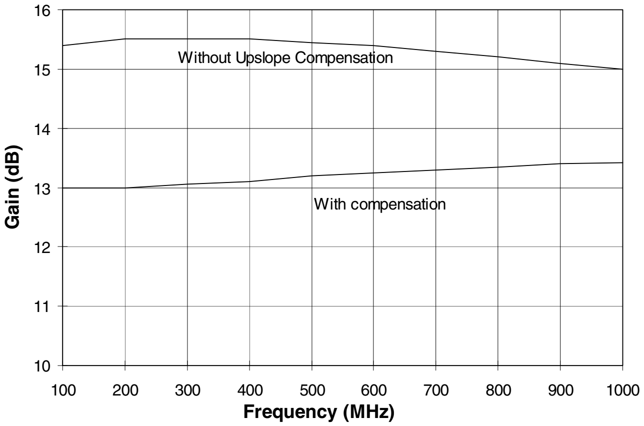

Figure 15. Gain versus frequency

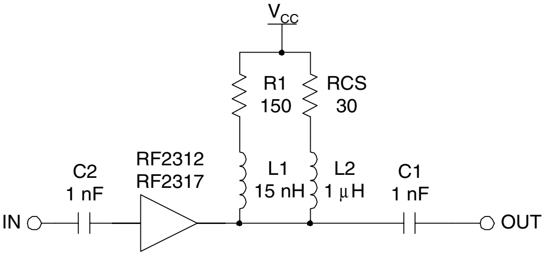

Figure 16. Circuit for high frequency up-slope compensation

In some applications, however, even a few tenths of a dB can be a problem. In that case, the circuit of figure 16 can be used to provide a positive “upslope” to the frequency response. Essentially, a series L-R is added to the output circuit in parallel with the VCC feed L-R network. This loads the output at the lower frequencies hence reducing the gain. As frequency goes up, however, the loading is reduced because the reactance of the inductor goes up with frequency. This circuit may be used with any Darlington amplifier which has adequate bandwidth, including the RF2317 and the RF2316. The output return loss is also improved with the addition of this circuit.

Push Pull Configuration

Figure 13 shows a partial schematic of a Push Pull Cascode circuit using HBT devices. This architecture is typically used for high power distribution amplifiers which produce high output voltages. It has an inherent advantage over singe ended designs in that the output voltage swing can be double that of the single ended design (providing 4 times the power) and, importantly, the even order distortion products are reduced from a single ended design. That is, for a given collector current and voltage, the balanced design produces the same odd order results (same IP3), but even order distortion is reduced typically 10 dB (better IP2) - depending on the balance achieved. The disadvantage of this circuit configuration is that it requires transformers or baluns in order to convert the single ended input and output signals to differential balanced signals at the ports of the active device. These passive devices have power loss which must be made up by the amplifier. The frequency response is also adversely affected.

The RF2316 is a balanced amplifier. It uses external baluns which are easy to wind and have a minimal impact on frequency response and power. The connections external to the chip are shown in figure 14. The unit will produce an output of +44dBmV per channel with acceptable distortion products.

Conclusion

The HBT amplifiers offer the best frequency response and the highest linearity (for a given DC power consumption) of any commercially available integrated circuit. They offer the small size and the inherent reliability and repeatability of a monolithic design. OIP3 numbers up to +48dBm have been achieved and the frequency response is extremely flat across a full Gigahertz of bandwidth for all the mentioned parts. They operate from a single power supply, which can range from 7V to 12V. Pricing is less than $4.00 for the RF2312 and RF2317.