Analog VGA Simplifies Design and Outperforms Competing Gain Control Methods

by Walter Strifler

Introduction

Variable gain amplifiers (VGAs) are widely used in communications and imaging applications such as cellular radio, satellite receivers, global positioning, radar, and ultrasound applications. Most of these applications involve transmit and receive signals of varying amplitude that need to be managed within the constraints of the overall system design. On the transmit side, the signal amplitude is usually adjusted near a maximum limit imposed by the transmit power amplifier or below a power limit imposed by the receivers or reflectors of the signal. On the receive side, the signal amplitude is usually amplified and tailored to take optimum advantage of the demodulator or ADC that decodes the signal. In both the transmit and receive case, the optimum signal gain targets change over time and temperature, so most systems share a common requirement of controlling signal amplitude through the use of adjustable gain stages commonly known as variable gain amplifiers.

This article introduces the LTC6412, Linear Technology's first high frequency, analog-controlled VGA—now added to Linear Technology's existing portfolio of digitally controlled VGAs. The design considerations for analog vs digital control are also discussed. This is followed by a brief introduction to the important design and performance features of the LTC6412 along with a discussion of a few application examples.

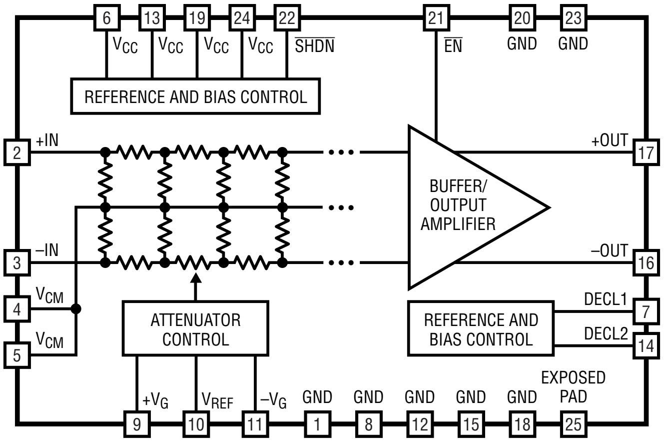

Figure 1. Block diagram of the LTC6412

Analog vs Digital Control of VGAs

The vast majority of modern communication and imaging equipment contains significant digital hardware in the form of microprocessors, controllers, memory, data busses and the like, so the choice of analog vs digital system control would seem to be a forgone conclusion in favor of the digitally controlled VGA. While this trend statement is largely true, it overlooks important distinctions between the two types of VGA control.

The digitally controlled VGA is a natural choice when the system parameters that determine optimum gain are known to the digital control system and are readily available across a data bus. This information is piped to the data inputs of the VGA, and the desired gain is step-adjusted during noncritical periods in the time-slotted signal.

The digital control scenario is the goal of most system designs, but it leaves many application gaps for

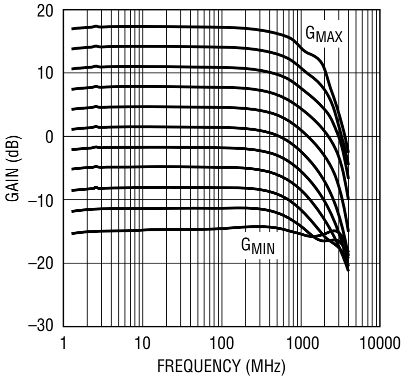

Figure 2. LTC6412 gain vs frequency over gain control range

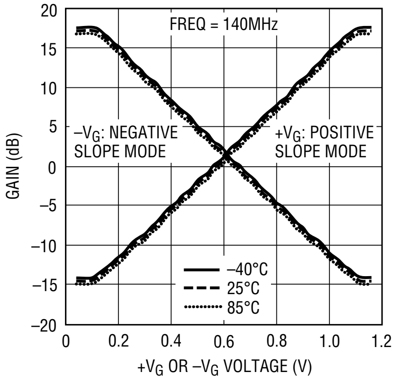

Figure 3. Differential gain vs control voltage over temperature for the LTC6412

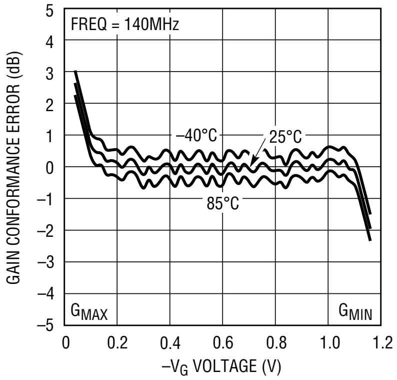

Figure 4. LTC6412 gain conformance error vs control voltage over temperature

clever analog solutions. For example, what if the information needed to control the amplifier gain is not known to the digital control system or no practical data bus is available? What if the RF signal through the amplifier chain cannot tolerate any step disturbance in amplitude or phase? These kinds of situations arise often enough to sustain a healthy market for analog-controlled VGAs. A few such applications are discussed later in this article.

Design Features

The LTC6412 is an 800MHz analog-controlled VGA manufactured on an advanced silicon-germanium (SiGe) BiCMOS process that offers the speed and performance of a complementary SiGe bipolar process along with the flexibility and compactness of a CMOS process. The term SiGe refers to the material composition of the bipolar base layers whereby a SiGe semiconductor alloy is used to create critical bandgap discontinuities and drift fields within the bipolar devices to improve high speed performance.

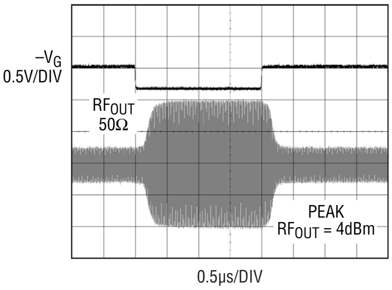

Figure 5. LTC6412 gain control 10dB step response at IF = 70MHz

Figure 1 shows a block diagram of the LTC6412. The design employs an interpolated, tapped attenuator circuit architecture to generate the variable gain characteristic of the amplifier. The tapped attenuator is fed to a buffer and output amplifier to complete the differential signal path. The circuit architecture provides good RF input handling capability along with a constant output noise and output IP3 characteristic that are desirable for most IF signal chain applications.

The internal circuitry takes the gain control signal from the ±V_G terminals and converts this to an appropriate set of control signals to the attenuator ladder. The attenuator control preserves OIP3 through the interpolated transitions and ensures that the linear-in-dB gain response is continuous and monotonic over the 31dB gain range for both slow and fast moving input control signals, all while maintaining a fixed input and output terminal impedance. The control terminal inputs can be configured for positive or negative gain slope mode by connecting the unused control terminal to the V_{REF} pin provided.

The output amplifier employs an open-collector topology and linearizing techniques similar to the LT5554. Enhanced clamping circuits provide fast overdrive recovery up to 15dB signal compression. The entire circuit runs off a 3.3V supply at a nominal total supply current of 110mA.

Electrical Performance

The LTC6412 is a fully differential VGA designed for AC-coupled operation in signal chains from 1MHz–500MHz and provides a typical maximum gain of 17dB and minimum noise figure (NF) of 10dB over this frequency range.

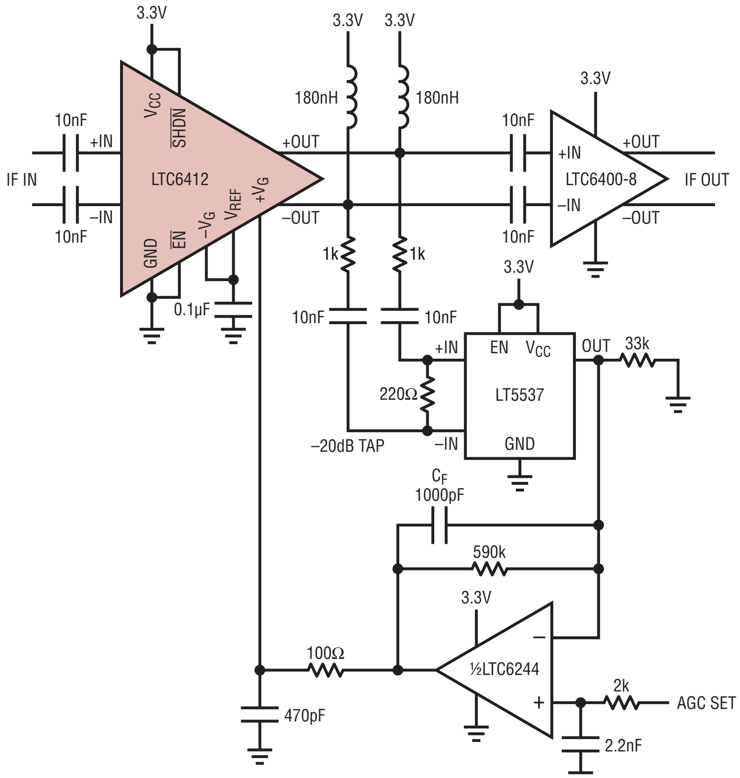

Figure 6. Analog control loop application circuit at IF = 240MHz. LTC6412 bypass capacitors to ground omitted for clarity.

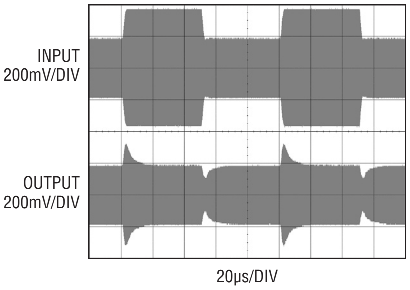

Figure 7. Measured analog control loop circuit response to 6dB step changes in input signal amplitude for C_F = 1000pF

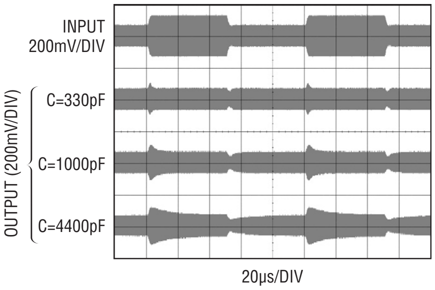

Figure 8. Measured analog control loop response to 6dB step changes in input signal amplitude over a range of C_F values

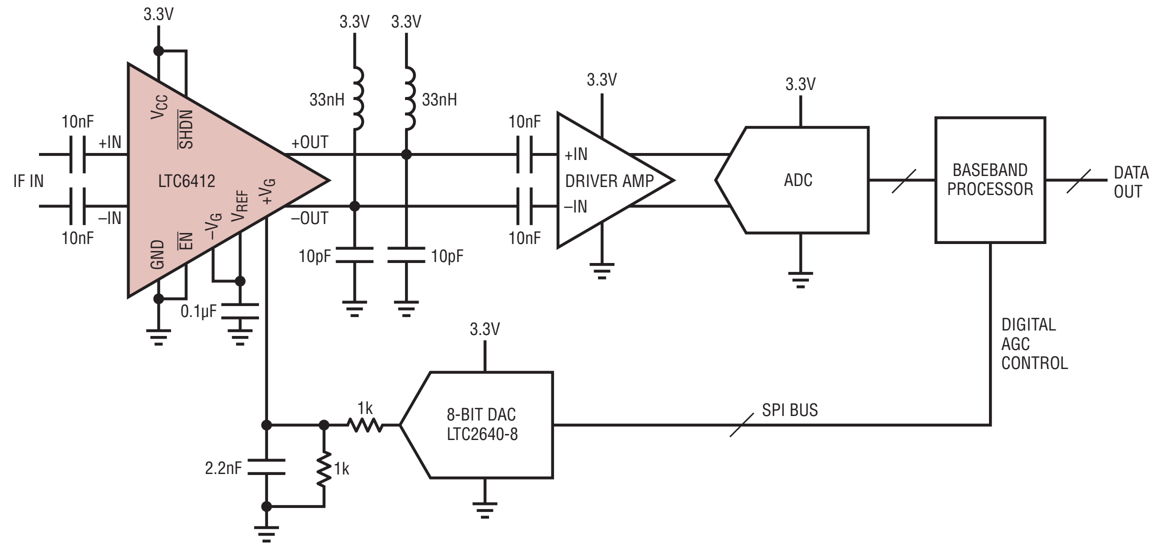

Figure 9. Digital control loop application circuit at IF = 240MHz. LTC6412 bypass capacitors to ground omitted for clarity.

At a typical operating intermediate frequency (IF) of 240MHz, the part delivers a constant OIP3 = 35dBm and constant (IIP-NF) = 8dBm over the −14dB to +17dB gain range. The flat output noise (NF + Gain) and flat OIP3 combination produces a uniform spurious-free dynamic range (SRDR) > 120dB over the full gain control range at 240MHz. The data sheet describes the operating performance in more detail, but a few excerpts are worth noting here.

Figure 2 illustrates the gain vs frequency performance of the LTC6412. Uniform gain slope and spacing are maintained throughout the gain control range and across the recommended operating frequency range.

Figure 3 illustrates the gain control response to the $\pm V_G$ inputs. The linear-in-dB response is accurately maintained throughout the gain control range with an RMS error ripple of approximately 0.1dB as depicted in Figure 4.

Figure 5 illustrates a typical gain step response. The settling time of 400ns is smooth and roughly independent of the step size. The phase change is also continuous through any step and typically less than 5° for signals of 240MHz or lower.

Typical Applications

Analog AGC

Automatic gain control (AGC) is usually the first application that comes to mind for an analog-controlled VGA. The idea is to use the linear-in-dB VGA together with a linear-in-dB detector to form a servo control loop that automatically adjusts the signal amplitude to a set level. An example of such a control loop is shown in Figure 6. The loop gain of 100 provides an AGC accuracy of a few tenths of a dB, and the dominant pole compensation from C_F = 1000pF provides a well-damped response time of 15µs shown in Figure 7. Adjusting C_F over a 13:1 range produces a similar proportional range in settling time (see Figure 8).

The analog gain control loop is an attractive solution for simple signals. The linear-in-dB nature of both the VGA and detector produces control dynamics that are constant and linear throughout the control range. The detector shown in the example is a peak detector, but an RMS detector can also be used.

Digital AGC

The analog gain control loop is less attractive for 3G and 4G communication signals with a high crest factor

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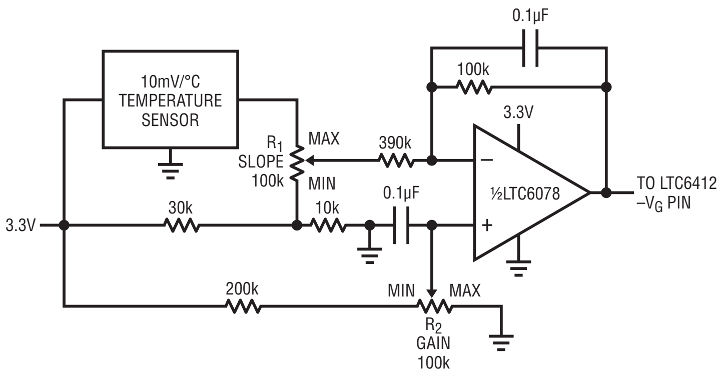

Figure 10. Application circuit for static gain adjust and temperature gain slope compensation using a PTAT temperature sensing IC. Adjust R1 and R2 as needed and route output to $-V_G$ control terminal of the LTC6412.

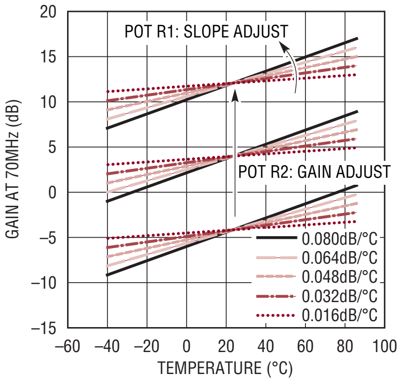

Figure 11. Gain vs temperature performance characteristics of the PTAT sensor based circuit shown in Figure 10

also be adjusted by applying a single resistor from ADJ to ground, as shown in Figure 3.

The PWM control pin allows high dimming ratios. With an external MOSFET in series with the LED string as shown in Figure 4, the LTM8040 can achieve dimming ratios in excess of 250:1. As seen in Figure 5, there is little distortion of the PWM LED current, even at frequencies as low as 10Hz. The 10Hz performance is shown to illustrate the capabilities of the LTM8040—this frequency is too low for practical pulse width modulation, being well within the discrimination range of the human eye.

The LTM8040 also features a low power shutdown state. When the $\overline{\text{SHDN}}$ pin is active low, the input quiescent current is less than 1µA.

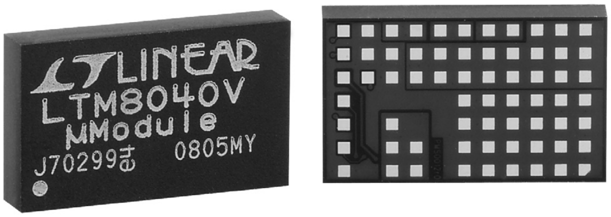

Figure 6. Only 9mm × 15mm × 4.32mm, the LTM8040 LED Driver is a complete system in an LGA package

Conclusion

The LTM8040 µModule LED driver makes it easy to drive LEDs. Its high level of integration and rich feature set, including open LED protection, analog and PWM dimming, save significant design time and board space.

LTC6412, continued from page 21

because the control target is often more complicated than a simple peak or RMS amplitude, and the amplitude noise introduced by the analog control loop may be unacceptable. A common solution for these systems is an analog VGA driven by a DAC as depicted in Figure 9.

The contradiction of a DAC controlling an analog-controlled VGA may appear at first as unusual and unecessary, but the arrangement provides key benefits. The gain step resolution is not determined by the VGA, and 8–12 bit DAC's are relatively inexpensive. More importantly, the signal gain can be adjusted with arbitrary smoothness, so the baseband processor can continue its demodulation/decoding operation without interruption. Most digital VGAs produce unacceptable signal discontinuities. The DAC does have a glitch of its own, but it is a baseband glitch that can be smoothed with filters. The glitch in many digital VGAs has no such remedy.

Gain and Temperature Compensation

Many communication receivers require frequent gain optimization, but others are designed with over-performing ADCs that can tolerate moderate signal amplitude variation and avoid much of the AGC hardware problem. However, even these "fixed gain" system blocks often require a gain adjustment to compensate gain drift overtemperature and any cumulative gain tolerance of the other components. Several system components are cascaded to form a chain that usually includes a VGA to perform a one-time adjustment of gain and temperature slope to compensate the tolerances and slopes of the other components. In this scenario, the required temperature and compensation information is not known to the baseband processor or it is impractical to send this data to a suitably located VGA.

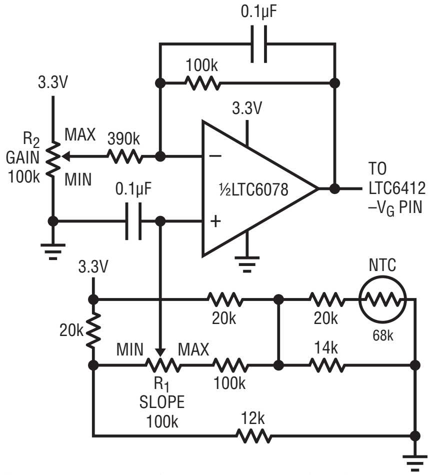

Figure 12. Thermistor-based application circuit for static gain adjust and temperature gain slope compensation. Adjust R1 and R2 as needed and route output to $-V_G$ control terminal of the LTC6412.

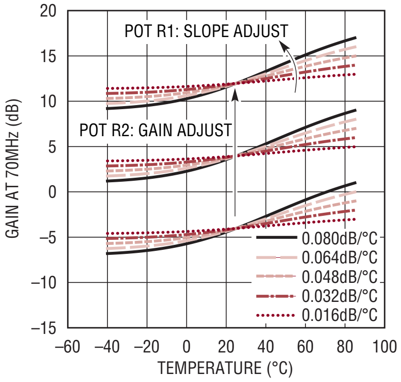

Figure 13. Gain vs temperature performance characteristics of the thermistor-based circuit shown in Figure 12

An analog-controlled VGA is a natural solution for this application because it can easily interpret the output of most temperature transducers without digitization. Figure 10 shows a simple application circuit using a common PTAT temperature sensor and an op amp to create the required $-V_G$ signal to adjust room temperature gain and temperature slope as shown in Figure 11. If temperature slope accuracy is only important for T > 0°C, then the same function can be performed with an inexpensive NTC thermistor as shown in Figures 12 and 13. Trying doing that with a digitally controlled VGA!

Conclusion

By combining the advanced SiGe process with an innovative design, the LTC6412 offers unparalleled analog VGA performance at 3.3V. The tiny 16mm^2 leadless package and minimal external components produce a cost effective, fully differential VGA solution in less than 1cm^2 of PCB area.