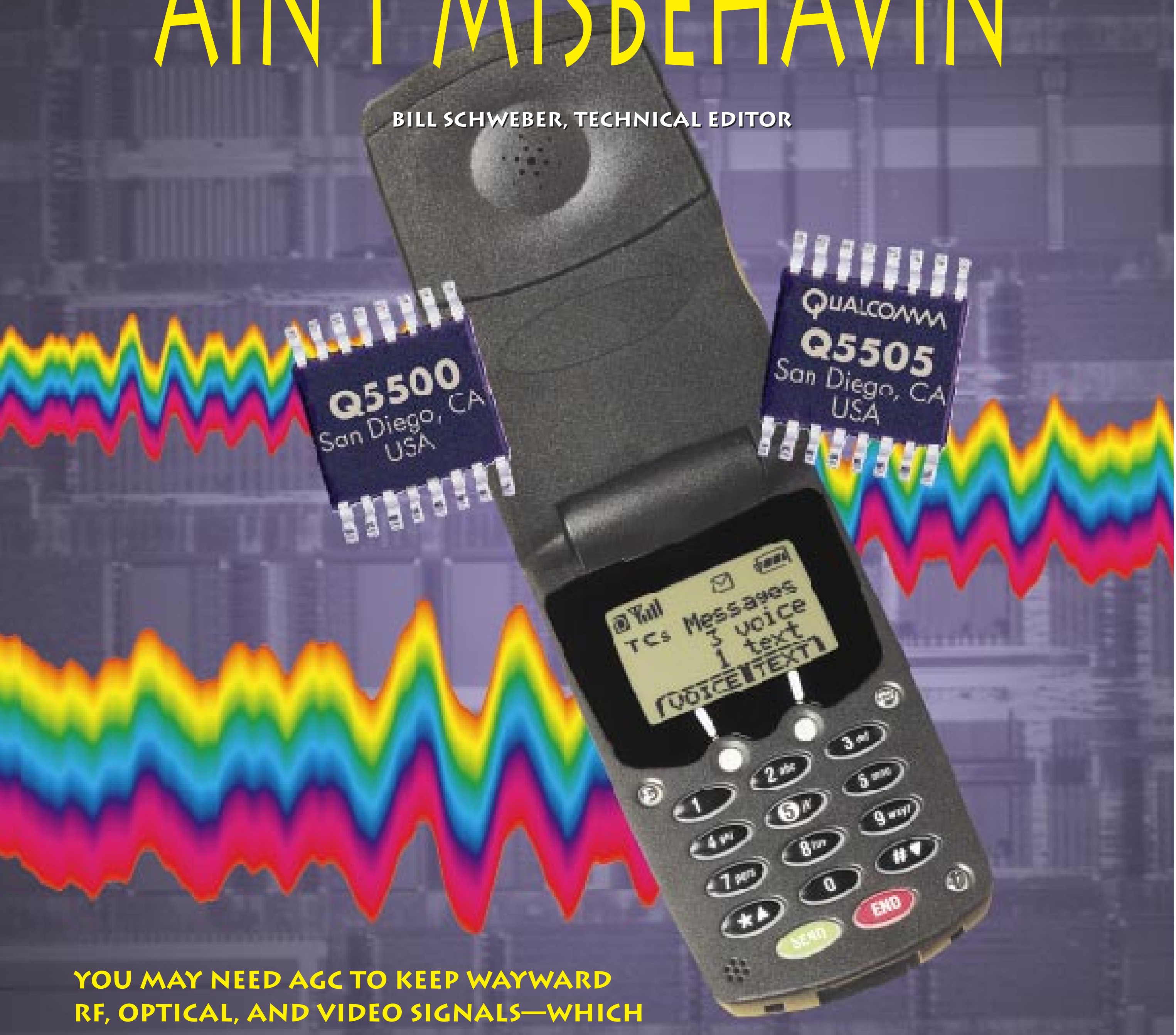
AGC DISCIPLINES RF AND FIBER SIGNALS SO THEY "AIN'T MISBEHAVIN'"

BILL SCHWEBER, TECHNICAL EDITOR



YOU MAY NEED AGC TO KEEP WAYWARD RF, OPTICAL, AND VIDEO SIGNALS—WHICH SWING OVER A WIDE DYNAMIC RANGE—WITHIN ACCEPTABLE BOUNDS. BY CONSIDERING KEY SPECIFICATIONS AND TECHNIQUES, YOU CAN GET OPTIMUM AGC RESULTS.

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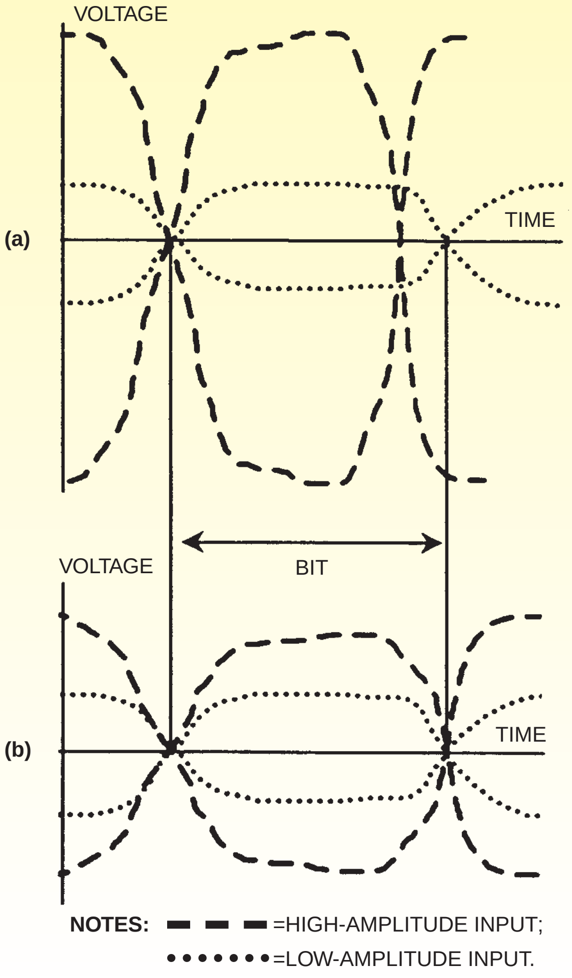
FIGURE 1



An AGC circuit in fiber-optic timing-recovery circuits reduces signal distortion, which decreases jitter at the zero crossings and thus reduces the bit-error rate. The eye pattern without AGC (timebase is exaggerated) shows greater distortion (a) than the eye pattern with the AGC function employed (b) (adapted from Vitesse Semiconductor).

Digital signals were supposed to minimize the nasty problem of information-bearing signals that have undesirably wide dynamic ranges. Sure, digital signals might have some additive noise, but at least they generally stick close to their nominal levels. Although analog signals, such as RF waveforms, would still have varying power levels, the ability of digital circuitry to retrieve and restore pristine signal levels would make dynamic-range problems much less common.

But the real analog world didn't succumb to that forecast. Wireless systems in new and widespread applications have increased the demands on analog circuitry, which must capture the usually minuscule front-end signal and make it viable—an increasing challenge when the signal strength fluctuates because of rainfall attenuation, tree absorption, and walls and openings in buildings. Fiber-optic signals endure loss and variability from weakening emitters, from fiber variations, and through switches. Video-signal sensors must operate under light conditions from near dark to bright sunlight.

The AGC circuit, a classic analog function that engineers have used since the 1930s in basic radio circuitry, has increased in importance. The function of an AGC is simple: to keep the maximum and minimum signal voltages or power levels within desired boundaries despite inherent widespread variations and to do it by automatically controlling gain in a closed-loop control function, based on the input-signal strength.

The more things change…

The underlying problem is this: In many applications, it's the modulated-signal *envelope*, not the absolute received-signal value, that conveys information, and this signal-envelope span is too uncontrolled in your circuit to properly analyze. The wide range either saturates the next stage, or, if you attenuate the signal to provide head room, falls below an acceptable noise level.

For example, 1 bit equals 1.5 μV in a 16-bit ADC with a 0 to 1V input span. If your design's average signal drops below a few least significant bits, it loses most of its ability to characterize the actual signal with high resolution and likely loses the signal in noise. The same situation is true if the signal's average value is near the high end of the span. Either way, your actual resolution is not one part in 2^{16}, but only a few bits. And if the signal drops too low or balloons too high, you lose all potential resolution.

Look at this situation from another perspective. A converter's dynamic range, in decibels, is six times the number of bits, so a 10-bit converter has 60 dB of range, and a 16-bit device has 96-dB resolution. If the carrier average-signal-strength swing is 50 to 80 dB, which is common in many applications, you lose most or all of the head room you need to distinguish the information embedded *within* that carrier.

Even if you don't use an ADC to extract data from a signal, variations in nominal signal strength affect analog-signal processing. In a fiber-optic system, you may see 30 dB of power variation at the photodetector output. When picoseconds are critical, such as in systems with rates of more than 100 Mbps, the timing-extraction circuit is prone to more jitter when the signal's amplitude variations prevent a continuously optimal match between anticipated amplitude and recovery-circuitry design (**Figure 1**). Without gain control, the zero crossing of the full-amplitude signal shifts from that of the lower amplitude signal be-cause of distortion. Using an AGC circuit levels the amplitudes, thus reducing the recovered timing jitter and the system bit-error rate.

The basic AGC circuit neatly solves these problems without active intervention by the rest of your system (**Figure 2**). The circuit uses a measure of the input-signal strength to control the gain of a voltage-controlled amplifier (VCA). This measure of strength can be input-signal voltage amplitude or signal energy or power as derived from the voltage. Although the AGC function has one input and one output, some AGCs also provide access to the control-voltage output of the lowpass filter, which drives the VCA. You can use this gain-control voltage as a received-signal-strength indicator, which some applications need to adjust other circuit parameters.

The lowpass filter is critical to overall AGC dynamics, just as it is in a PLL (**Reference 1**). You must balance any initial attractiveness of fast response against transient response and even loop instability. For example, you can use a peak detector rather than a root-mean-square (rms) detector to adjust the gain when the input crosses a threshold. In making this substitution, however, you allow impulse-noise spikes to cause sudden decreases in gain; these decreases are often undesirable if the actual signal strength is otherwise low and the gain loop takes time to recover.

Note that many engineers often use the terms "AGC" and "VGA" (variable-gain amplifier) interchangeably, because AGCs use VGAs as cores. Although this substitution is not strictly correct, the difference between the two is the addition of the loop-closing path to the VGA. Also, before you assume that the AGC function is the solution to your range-matching problem, look at other functional relationships that may be appropriate (see **box** "Analyze the relationship").

@a glance

- Over a wide dynamic range, AGCs can continuously, automatically, and smoothly match your input signal's amplitude span to the operating range of your circuitry.
- Consider all traditional amplifier specifications, in addition to AGC-specific parameters.
- For some situations, alternative gain-control circuits, such as logarithmic amps, clamping amps, and even programmable-gain amps, can meet your needs.

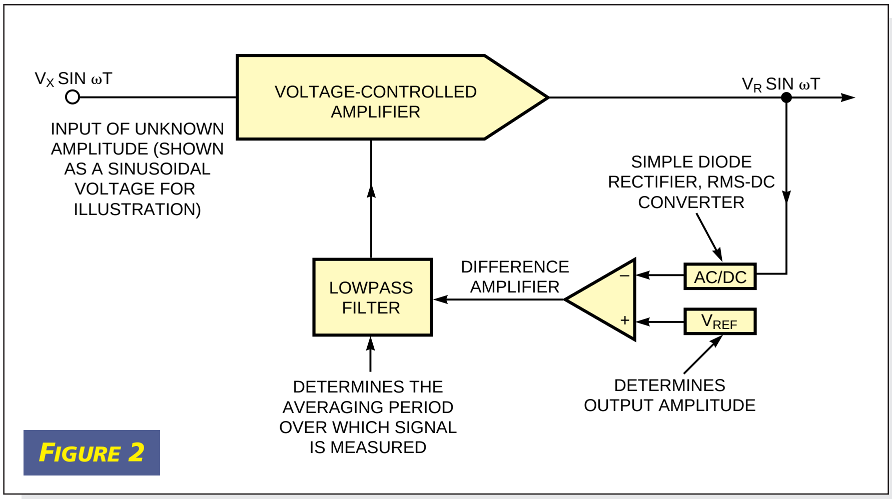


FIGURE 2

A typical AGC function provides closed-loop operation using a voltage-controlled amplifier with gain controlled, in turn, by a signal derived from the voltage-controlled-amplifier output itself (adapted from Analog Devices Inc).

AGC circuits face varying signal conditions. For RF and fiber signals, gain-control adjustment range may be 40 to 100 dB; for analog video signals, the required span is typically just a 4- or 5-to-1 range. Accuracy requirements differ as well: Gain leveling with 5 to 20% accuracy usually satisfies wide-ranging RF and fiber signals, but video signals often need leveling to less than one IRE (Institute of Radio Engineers) unit, or approximately 0.5%.

Loop response is another AGC issue. A short time constant causes gain changes in response to the modulating signals or data bits themselves. Thus, a faster response is often less desirable than a slower one that allows the circuit to assess signal strength over many carrier cycles or bit periods. You should set the initial loop time constant in terms of the expected rate of signal-strength changes and not the embedded data rate or modulating-signal bandwidth. Although the best time constant depends on the application, start with values of approximately 10 μsec for RF and fiber-optic links and 60 to 100 μsec for video (equal to a horizontal-sync frame).

Two other dynamic specifications of an AGC function need your attention. First, the gain-control response time tells you how fast the gain setting of the AGC slews from one value to the next when directed by the gain-control signal. This response time must be compatible with the loop response time you choose. Further, unless you can ensure that your input signal is well-behaved and will stay within a maximum value, check the overload response of the AGC to see how long it takes to recover from a saturated state. During saturation, while the AGC is temporarily immobile, your signal path is no longer linear. Thus, the consequences of overload may affect your system design and signal-processing algorithms.

Don't forget that, at its core, an AGC circuit provides an *amplifier* function. This fact means that you need to look at traditional amplifier considerations, such as bandwidth, linearity, distortion, noise, input conditions, and output drive, but with an added layer of subtlety because of gain changes. The signal in your application determines the needed amplifier bandwidth: about 5 MHz for composite video but 30 MHz for high-definition TV. Note that bandwidth changes with gain settings for voltage-feedback amplifiers, so optimizing gain range vs bandwidth involves careful consideration of the trade-offs in your system.

Be careful with both harmonic and intermodulation distortion, especially at higher frequencies. Typical distortion-value requirements are 30 to 40 dB or more below the input-carrier amplitude. For video applications, keep minimal differential gain and phase errors at 0.1% and 0.01°, respectively; some applications have even tighter tolerance requirements.

Evaluating noise effects in an AGC circuit is more difficult than it is with a conventional fixed-gain amplifier. Although your system design can sometimes compensate for or accommodate a constant rms noise magnitude, an AGC has varying gain, and, thus, its output noise level varies as well. Noise also tends to increase with bandwidth, so minimize bandwidth, commensurate with your dynamic specifications.

Another noise source in wideband AGC applications is high-frequency feedthrough. Even if you set the amplifier for maximum attenuation, some of the signal feeds through because of internal IC capacitance, board layout, and power-supply signal paths. Think of this feedthrough as a noise floor in your error-budget analysis.

The output of an AGC typically has a high-impedance drive and needs a good buffer to drive subsequent stages and to possibly scale the output magnitude. Make sure that the amplifier specifications for bandwidth, distortion, and noise don't defeat the AGC and that you have sufficient current drive and output swing. As with all high-speed amplifier designs, layout is critical. Bypassing, ground planes, and

ANALYZE THE RELATIONSHIP

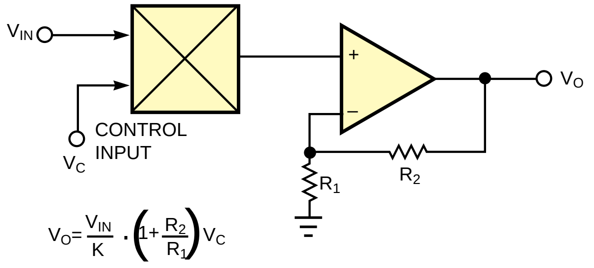
AGC is not the only technique for accommodating signals with wide dynamic range (**Reference A**). Logarithmic amps may be suitable alternatives for compression signals with ranges as high as 100 dB, but only in certain applications. A log amp provides small gain for large signals and logarithmically increases the gain factor as the input signal shrinks. Unlike the AGC, which uses a closed-loop-based operation driven by some measure of signal strength to adjust the gain, the compression that the log amp provides is inherent in its transfer function and is not the result of a signal-derived closed loop. A log amp gives you no control of time constants, either.

Also, although the AGC-amp transfer function is ideally linear and thus produces little distortion, the log amp is clearly not linear, by definition. The harmonic distortion that the log amp produces is acceptable in some applications, but not in others, such as RF front ends for CDMA signals, in which fidelity is critical.

If your objective is minimizing amplifier overload and saturation rather than accommodating and analyzing a wide-dynamic-range signal, a clamping or limiting amplifier may be a good choice. This device acts as a conventional amplifier over the nominal input range. As its input signal approaches the extremes of the allowed range, the amplifier's output begins to smoothly compress in a well-behaved manner and limit the output magnitude in a nonlinear clamping region. The virtues of the clamping amplifier are that it is a fixed-gain, linear device throughout the normal operating range and thus yields low harmonic distortion for that portion of the signal's dynamic range. Clamping amplifiers are available with small-signal bandwidths of several hundred megahertz, and recovery time from the clamping regime to normal linear operation can be on the order of several nanoseconds. Note that a clamping amplifier is a poor choice when you need signal-path linearity throughout a wide dynamic range.

If you need more control over the signal than a standard AGC IC can provide, consider building one using an analog multiplier as the gain-control element for a VCA. The VCA, in turn, is the building block for the AGC (**Figure A**). By using these low-level building blocks, you gain additional freedom, because you can select a multiplier that has bandwidth and performance to match your needs. Stay with a two-quadrant multiplier rather than a four-quadrant device; the latter can cause loop instabilities when the control signal inadvertently drops below the zero boundary because of noise, feedthrough, or other hard-to-control factors.

FIGURE A



Further deconstructing the AGC circuit into building blocks, you can implement the voltage-controlled amplifier and, thus, the AGC function using an analog multiplier and an output amplifier (adapted from Reference A).

You probably want to use a transimpedance or current-feedback amplifier as the multiplier buffer, because the bandwidth of this type of amplifier stays relatively constant over a range of closed-loop gains. Before you build your own AGC from a multiplier, though, consider if a complete and tested AGC may be more cost-effective and fully specified.

Finally, you can use a programmable-gain amplifier with decimal- or binary-gain steps and control the gain via a signal derived from the programmable-gain-amplifier output, similar to the one that adjusts gain in the AGC. The programmable-gain amplifier gives you known gain values, which is useful for applications in which the absolute signal magnitude is critical. This type of architecture also lets you select fixed-gain amplifiers that have the linearity and dynamic specifications you need. However, it is difficult to build a programmable-gain amplifier with gain values greater than ×16 that has good range-to-range tracking. This difficulty limits the dynamic range that you can achieve, and signal-span discontinuities can exist as the amplifier's ranges change. In addition, errors resulting from internal offsets and temperature-related drifts become more severe at high gain ranges.

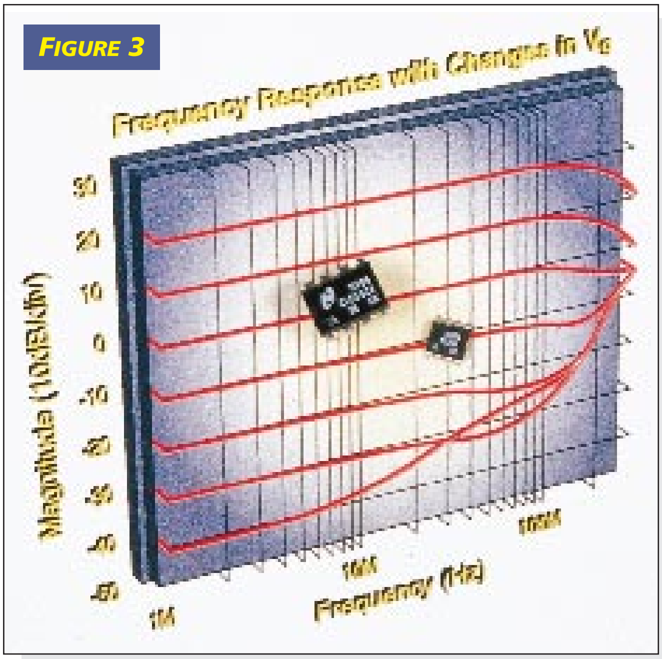
Reference

A. Kester, Walt, editor, Analog Devices Inc, *Linear Design Seminar*, 1995.

input- and output-signal paths all need the attention you would give a conventional amplifier.

Don't expect the AGC to do it all. Taking a microvolt input and making it large enough while handling larger-than-desired signals—and achieving these tasks with low distortion—are a lot to expect. Most AGCs have a nominal output magnitude at which their distortion is at a minimum, such as 100 mV. You may need to use a low-noise preamplifier stage ahead of the AGC circuit to remove some of the gain burden from the AGC and to improve the SNR. The level at which the AGC operation asserts and thus adds gain is also critical, because this level is where you have additional noise on that small, fragile input signal.

FIGURE 3



In addition to the numerous performance graphs that op amps have, AGCs must show factors such as frequency response vs gain-control voltage, as you can see in this graph for the National/Comlinear CL5523.

Look at both the minimum detectable signal, which circuit noise primarily governs, and the overload head room and consequences of amplifier saturation. You may even want to explore ganged AGCs, which can solve a gain-partitioning problem, give more freedom in selecting optimal operating points, and provide two independent time constants.

AGC ICs and functional blocks are available from both broad-line op-amp vendors and sources that specialize in AGCs for specific applications (**Table 1**). Be prepared to spend a lot of time studying their data sheets. These data sheets have many graphs defining performance under various operating conditions, and the AGC data sheets have

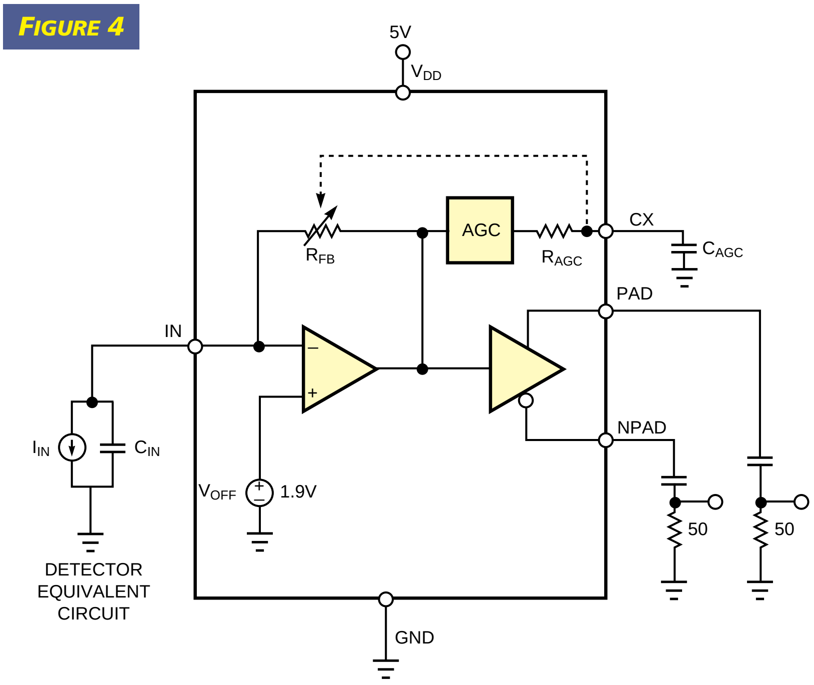
TABLE 1—REPRESENTATIVE AGC-FUNCTION VENDORS

Vendor	Model number	Key specifications
Anadigics **Circle No. 301**	ATA06212	Transimpedance AGC for SONET, SDH, ATM, fiber distributed data interface; up to 622 Mbps; –34-dBm sensitivity; 0-dBm optical overload
Analog Devices **Circle No. 302**	AD603	Linear in decibels (25 mV/dB); –11 to +31 dB (90-MHz bandwidth); 9 to 51 dB (9-MHz bandwidth); 0.5-dB-gain accuracy
Burr-Brown **Circle No. 303**	VCA610	30-MHz voltage-controlled amplifier (linear in decibels); 80-dB control range; 300 dB/μsec gain slew rate
Elantec **Circle No. 304**	EL4451C	Variable-gain amplifier with 70-MHz bandwidth; gain flatness (0.1 dB) to 10 MHz; 400V/μsec slew rate
	EL2082	Two-quadrant current-mode multiplier; 200-MHz bandwidth; 46-dB gain-control range; 0.15% differential gain and 0.05° differential-phase errors
Linear Technology **Circle No. 305**	LT1251/LT1256	Video fader voltage-controlled amplifier; 40-MHz bandwidth; 1% accurate; gain from 0 to 1V/V
Maxim **Circle No. 306**	MAX2102	L-band tuner/downconverter; integral 50-dB variable-gain amplifier
National Semiconductor **Circle No. 307**	CLC5523	250-MHz-bandwidth AGC; 1800V/μsec slew rate; gain flatness (0.2 dB) to 75 MHz; 60-dB gain-attenuation range; 4-dB/nsec gain-change rate
Oki Semiconductor **Circle No. 308**	KGF2441	AGC with 90-dB range; 70- to 250-MHz bandwidth
Qualcomm **Circle No. 309**	Q5500	AGC for dual-mode CDMA/FM receiver; –45- to +45-dB gain-control range; 10- to 300-MHz signals; 5-dB noise figure at 45-dB gain
	Q5505	AGC for dual-mode CDMA/FM transmitter; –45- to +39-dB gain-control range; 10- to 250-MHz signals; 5-dB noise figure at 39-dB gain
RF Micro Devices **Circle No. 310**	RF9957	Dual-mode CDMA/FM receiver AGC plus demodulator; 100-dB gain-control range
Vitesse **Circle No. 311**	VSC7903	155-Mbps optical-signal transimpedance preamp for SONET/SDH with AGC; 2-pA/$\sqrt{Hz}$ typical noise
	VSC7912	622-Mbps optical-signal transimpedance preamp for SONET/SDH with AGC; 2.8-pA/$\sqrt{Hz}$ typical noise

even more graphs because of AGCs' inherent gain variability. The data sheets characterize various aspects of AGC performance at nominal supply, such as 3.6V, as well as at lower voltages—2.4V, for example. The sheets also present temperature-related performance factors, although these factors are often less critical than other parameters because of the closed-loop nature of the AGC action, which tends to compensate for some temperature-induced variations.

Elantec, for example, offers a VGA with maximum gain fixed at +2 and 70-MHz signal bandwidth, targeting input-signal spans of ±2V. The EL4451C has differential inputs and includes an output amplifier, and its output slews at 400V/µsec. If you prefer a multiplier, the EL2082C current-mode multiplier has 150-MHz large- and small-signal bandwidths, with 46 dB of calibrated gain-control range. Specified for video applications, this multiplier has 0.15% differential-gain error and 0.05° differential-phase error under NTSC test conditions.

FIGURE 4



An AGC, such as the Vitesse VSC7903 transimpedance amplifier for SDH/SONET fiber-optic applications, incorporates an amplifier block, an AGC function, and a differential 50 driver.

If you prefer to adjust your gain in decibels using a linear signal, the AD603 from Analog Devices is worth considering (see **box** "When bad things happen to good signals"). This calibrated VGA for use in RF/IF AGCs lets you select gain range of –11 to +31 dB with a 90-MHz bandwidth or 9 to 51 dB with a 9-MHz bandwidth. You can also select intermediate gain ranges. The VGA is scaled at 25 mV/dB and needs a 0 to 1V signal to control gain over the 40-dB range. Gain-control response time is less than 1 µsec for the

WHEN BAD THINGS HAPPEN TO GOOD SIGNALS

Not all AGC applications are a response to random or unforeseeable changes in signal strength, such as those that occur over a communications link. For some applications, the change is predictable and unavoidable. For example, in medical ultrasound instrumentation, a transducer placed against the patient's skin produces a pulsed, 5-MHz acoustic signal. This signal radiates into the body and then is echoed back to the transducer by impedance discontinuities, which result from transitions between various tissues and organs in the signal path. You can determine the distance from the skin to the tissue that reflected the original signal using the echo time and the known velocity of sound waves in the body (nominally, approximately 1500m/sec for most tissue).

Capturing the echo, however, presents a problem. The fluids and tissue in the body severely attenuate the acoustic signal. According to the ultrasound engineers at the Imaging Systems Division of Hewlett-Packard's Medical Products Group (Andover, MA) a representative nominal figure for this attenuation is 0.5 dB/MHz/cm, or 2.5 dB/cm at 5 MHz, although different body tissues and fluids have different numbers. Therefore, the magnitude of the source signal and its reflected echo rapidly decrease with the distance and time to the reflecting tissue.

You could use a conventional AGC to compensate for this decrease in strength, but it would have difficulties because of the wide acoustic-signal dynamic range and the dynamics of the AGC transient response. A more creative option is to use both the known signal velocity and attenuation factors and an AGC with gain that is adjustable in decibels per volts of control. Instead of driving the AGC's gain-control input with a signal derived from the received-signal strength, you use a linearly ramping waveform synchronized with the start of acoustic pulse. This ramp signal increases the preamp gain in decibels per second, compensating for the attenuation of the signal in the patient's body. This "time-gain compensation," smoothly normalizes the received-signal strength, so it stays constant independent of distance, thus keeping the echo signal within desired bounds at the preamp-stage output.

full range; input-noise spectral density is 1.3 nV/$\sqrt{\text{Hz}}$.

The CLC5523 VGA from the Comlinear Group at National Semiconductor provides 250-MHz bandwidth (75 MHz with 0.2-dB gain flatness) and 60-dB gain range, and its gain-control response rate is 4 dB/nsec. You can set the maximum gain from 2 to 100 using two resistors and control the gain level using a 0 to 2V signal. The CLC-5523's data sheet represents a typical AGC and VGA, and provides a graph of frequency response with changes in gain-control voltage (**Figure 3**).

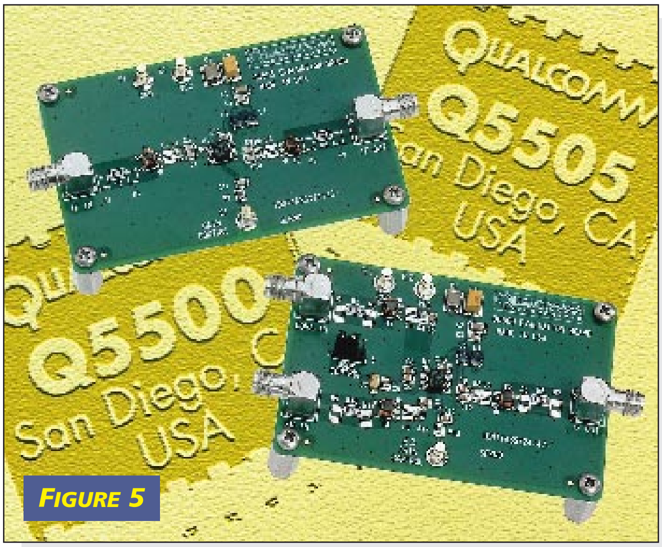


FIGURE 5

Evaluation boards, such as these for the Qualcomm Q5500 and Q5505 CDMA/FM receive and transmit AGC ICs, help you evaluate the ICs' performance and minimize layout iterations when applying high-gain, high-speed devices.

For fiber-optic applications, Vitesse offers two amplifiers with integral AGC. The VSC7902 for 155-Mbps SONET/SDH links and the VSC7911 for 622-Mbps links provide broadband amplification with a single-ended input and output; differential-output versions are also available (**Figure 4**). You set the AGC loop time constant using an external capacitor, with a 470-pF unit yielding a 33-μsec result. Noise is critical in high-speed fiber applications, and the input-noise-current density of the VSC7911 is 2.8 pA/$\sqrt{\text{Hz}}$.

Don't spend your time reinventing the signal path and AGC implementation if you can avoid it. Vendors often offer evaluation boards that have worked out the layout and application subtleties that you'll have trouble rediscovering until it is often late in your project's design cycle. For example, Qualcomm offers a pair of dual-mode CDMA/FM AGCs for cell-phone receiving and transmitting paths. The receiving-channel Q5500 for 10- to 300-MHz operation has a 90-dB gain-control range, and the transmitting-channel Q5505, for 10- to 250-MHz operation, has a control range of 84 dB. In addition, Qualcomm offers a separate evaluation board for each IC that lets you

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assess performance with both single-ended and differential configurations using a jumper that selects signal-path mode (**Figure 5**).

The relentless march of analog integration onto one IC has affected AGCs, too. You may find that an embedded AGC, as part of a larger functional device, is sufficient for an application and thus eliminates the need to provide a separate VGA function. For example, the MAX2102 from Maxim tunes L-band signals from 950 to 2150 MHz and converts them to baseband. In addition to the requisite low-noise amplifier, the IC includes a front end with a 50-dB VGA for carrier signals from –69 dBm to –19 dBm.

By embedding the AGC into the larger, application-specific IC, the vendor can also make trade-offs rather than provide a device that must be superior in all dimensions. Knowing the application, the vendor may, for example, concentrate on minimizing distortion but give up some unnecessary gain-control range. EDN

Reference

1. Schweber, Bill, "PLL synthesizers make channel-hopping swift and sure," *EDN*, March 14, 1997, pg 51.

Acknowledgments

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