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Selecting an Analog Front End for Imaging Applications

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INTRODUCTION

Every imaging system starts with an image sensor. The signal from the sensor must be processed in the analog domain, converted to digital, and further processed in the digital domain. This allows the image to be analyzed, manipulated and enhanced, prior to storage, display, transmission, and/or further processing. Imaging applications typically involve three chips—an image sensor, an analog front-end (AFE), and a digital ASIC. The AFE conditions the analog signal received from the image sensor and performs the analog-to-digital (A/D) conversion. The digital ASIC contains image-processing and timing-generation circuitry. Figure 1 shows a block diagram of a typical imaging system. Additional application-specific circuitry following the digital image-processing ASIC depends upon whether the imaging system is a camera, scanner or copier.

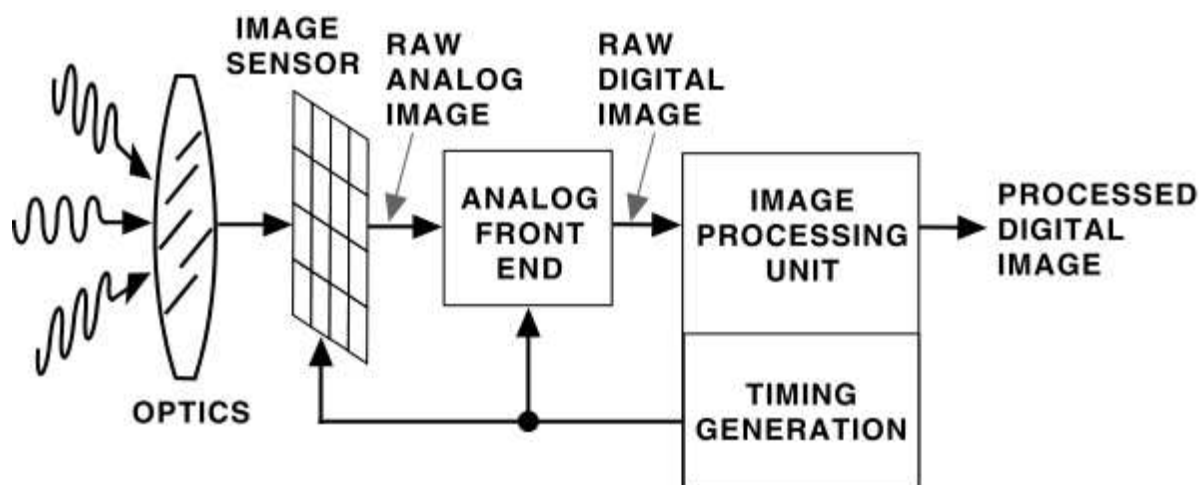


Figure 1: Block diagram of a typical imaging application

Analog front-ends A typical AFE starts with an input clamp. The common-mode level of the image sensor's output signal could range from 0 V to more than 9 V, so the signal must be ac-coupled to the AFE. The input clamp restores the dc level of the signal to an optimum point within the supply range of the AFE.

A sampling function follows the input clamp. AFEs designed to work with charge-coupled devices (CCDs) use a correlated double sampler (CDS). The CDS takes two samples of each pixel, one at the reset level and one at the video level, and performs a differential measurement between the two. The CDS improves the signal to noise ratio (SNR) by eliminating the correlated kT/C noise associated with the output stage of the CCD, and by attenuating low frequency drift. Contact image-sensors (CIS) and focal-plane arrays (FPA) used in commercial infrared (IR)-imaging applications typically output a single-ended, ground-referenced signal, and do not require a differential measurement. AFEs designed to work with these sensors use a sample-hold amplifier (SHA) in place of the CDS. A coarse black-level offset-correction stage is integrated with the CDS or SHA.

A programmable- (or variable-) gain amplifier (PGA or VGA) follows the CDS to amplify the signal and better utilize the full dynamic range of the A/D converter (ADC). If black-level offset correction is not performed ahead of the PGA, the dynamic range of the imaging system will suffer. A high-speed ADC converts the conditioned analog image signal to the digital domain, allowing for additional processing by a digital ASIC.

The AFE is programmed via a standard serial port that easily interfaces with most off-the-shelf microcontrollers or the digital ASIC. The PGA-gain registers, offset-correction registers, and sampling modes are all programmed through this interface. The choice of an AFE for an imaging application depends on many factors, including: the type of sensor being used, dynamic range, resolution, speed, noise, and power requirements. This article is

intended to provide a guide to making appropriate AFE choices for imaging applications.

DIGITAL VIDEO AND STILL CAMERA APPLICATIONS

Digital video and still cameras are among the fastest growing segments in consumer electronics today. Camera manufacturers continually need to create higher-performance cameras at lower cost in order to remain competitive. This need has driven IC manufacturers to higher levels of circuit integration in order to reduce the size and cost of camera components.

The first step in this process was to integrate all of the analog circuitry into a single chip. Figure 2 shows a simplified block diagram of a digital camera. Although each application will have different requirements for sampling rate, noise performance, power consumption, image resolution, and operating modes, the AFE is a crucial link in establishing and maintaining system performance.

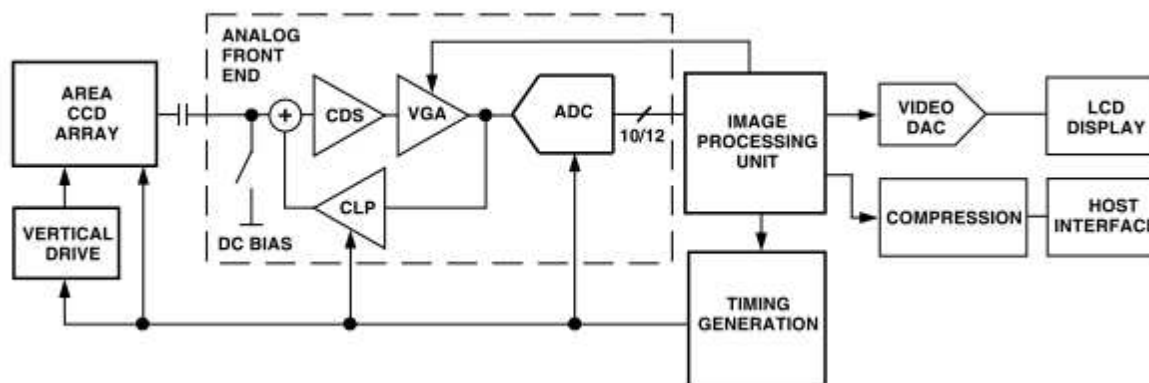


Figure 2: Simplified block diagram of a digital camera

Need for speed In standard analog video applications, VGA (640×480) resolution is common, so 300 kpixel CCDs are used. With an NTSC-standard transmission rate of 30 frames per second (fps) and interlaced CCD arrays, an AFE would have to process pixels at a rate of almost 10 MHz. For higher-definition applications, such as digital TV (DTV), progressive scanning is used. Using a progressive-scan CCD with 300 kpixels, the analog front-end needs to run at speeds approaching 20 MHz ($300,000 \times 30 \times 2 = 18$ MHz).

Applications such as security and high-speed analysis require even higher speeds. An AFE running at 36 MHz can process 100 fps of a 360-kpixel CCD. Multi-function digital cameras and camcorders, such as camcorders with still-shot capability and digital still cameras with video capability, require high-resolution CCDs (one megapixel or greater) to combine the still-shot capability with the high-speed video capability. A one-megapixel video camera that has still shot capability and operates at the standard 30 fps will need a progressive scan CCD in order to transfer a full frame at a time while taking still pictures, and an AFE that can operate at speeds of at least 30 MSPS.

High resolution Historically, camcorders and digital cameras for the consumer market have required 10-bit intensity-signal resolution. Recent advancements in image processing technology have created a need for higher resolution to allow for additional image editing and manipulation, and to ensure minimal loss of image integrity. In addition to the existing high-speed 10-bit AFEs for the camera market, Analog Devices has recently developed the AD9842 and AD9844 12-bit AFEs to satisfy higher-resolution requirements.

Noise and nonlinearity Noise generated within the AFE must be minimized because it directly affects the *dynamic range* of the imaging system. The dynamic range of a system is determined by comparing the maximum signal that can be processed to the minimum resolvable signal. The AFE noise consists of wideband noise from the analog signal processing circuitry plus the quantization noise of the A/D converter.

Because imaging signals are rarely pure sine waves, classical converter specifications such as SNR and signal-to-noise-and-distortion (SINAD) are not directly applicable to an imaging system. Instead, SNR can be defined in a somewhat different manner, based on wideband noise. The wideband noise of an AFE can be measured by using a

"fixed-input histogram" test. In an ideal system, a fixed input should produce a single output code. Noise in the system will produce a range of codes; from their distribution, the rms noise value can be statistically calculated. The rms wideband noise can then be compared with imager noise, and the overall system SNR can be calculated.

The linearity of the AFE is also important to the performance of an imaging system. *Differential nonlinearity* (DNL) is the difference of the actual code width and the ideal code width (quantum step) between adjacent digital levels. If the converter has large DNL errors it could transform smooth changes in luminosity to "steps" or lines visible to the human eye. Acceptable DNL performance is typically of the order of 0.5 least-significant bits (LSBs). *Integral nonlinearity* (INL) is also important. Abrupt transitions in the INL, concentrated around a small number of codes, can contribute to noticeable image artifacts. But if the transfer function of the INL is smooth, the nonlinearity will be gradually spread out over the entire range of the converter, and moderate errors will be less objectionable to the human eye. However, large "smooth" INL errors can sometimes cause errors in the digital image processing, leading to color artifacts in the final picture.

Automatic black-level offset correction Ideally the reset and video levels of the CCD would be identical when there is no light being applied to the CCD. However, the inherent CCD *dark current* causes a black-level offset that can exceed 100 mV. This offset must be corrected before any gain is applied to the signal in order to utilize maximum dynamic range of the ADC. The AFE includes an automatic black-level correction loop that samples the black level, determines the black-level offset, and applies the proper offset correction to the signal prior to the gain stage.

With an area-CCD array, the dark current will vary from line to line, so this process must be done for each line in the array. The AFE does this automatically, so the calibration coefficients for the entire area do not need to be stored. CCD arrays provide optical black pixels at the beginning of each line to allow the automatic black-level correction loop to determine the correction needed on a line by line basis.

Pixel-rate gain adjustment A pixel in a CCD is not inherently able to distinguish between colors. In order to separate incoming light into a series of colors, color filters are placed individually over each pixel of a CCD array in a mosaic pattern. The specific pattern and selection of colors depends on the manufacturer.

CCD arrays typically output data in a serial fashion from a single channel. The sequence in which the color information comes out of the CCD depends on the filter pattern and scanning technique. For example, a progressive-scan CCD that uses a Bayer filter will output data in the following order:

R	G	R	G	Line 0
G	B	G	B	Line 1
R	G	R	G	Line 2
G	B	G	B	Line 3

The responsivity to each color in this array will be different. With white light, the green pixels, for example, may be much stronger than the red or blue pixels. In order for each pixel to be able to utilize the full dynamic range of the ADC, a variable-gain amplifier (VGA) is required before the ADC. This VGA must be able to switch gain settings to the appropriate value for each color at the pixel rate. If the VGA were not capable of changing gain at the pixel rate, the gain would have to be fixed such that the "strongest" color would utilize the full dynamic range

of the ADC. At this gain setting, the "weaker" colors would have a smaller dynamic range and SNR relative to the "stronger" color.

Analog Devices has addressed this issue by developing a pixel-rate-gain amplifier ($PxGA^{TM}$). The AD9841 and AD9842 are 10- and 12-bit 20-MHz AFEs that use $PxGA$ technology to switch gain-coefficients into the VGA individually at the pixel rate. Using the example of the progressive-scan CCD with the Bayer filter, each R, G, and B pixel would have its own gain coefficient applied, allowing each color to utilize the full dynamic range of the ADC, maximizing SNR. Furthermore, the effect of any nonlinearity in the analog domain will be reduced, because all colors are being processed at similar amplitudes.

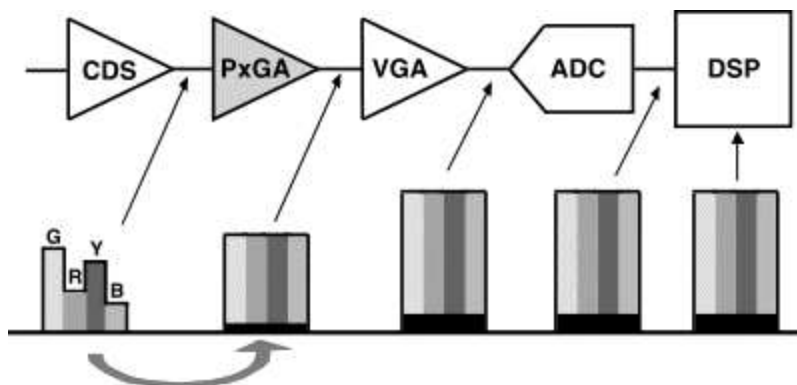


Figure 3: Signal path with $PxGA^{TM}$

Figure 3 is an example of $PxGA$ employed with a CCD array having 4-color filtering.

AD984x Family of analog front-ends

The AD984x family is a group of high-speed, low-power CMOS analog front-ends for imaging applications that use area-CCD arrays. They feature industry-leading lows in noise, nonlinearity, and power consumption at speeds of up to 36 MHz. The AD984x family is ideal for low-voltage, high speed, portable imaging applications, such as digital still cameras and digital video camcorders—as well as any other imaging system using interlaced or progressive-scan area-CCD arrays (including machine vision, security cameras, scientific spectroscopy, video conferencing, and digital copiers).

The signal chain consists of an input clamp, correlated double sampler (CDS), pixel-rate gain amplifier ($PxGA$ —on AD9841 and AD9842), digitally controlled variable-gain amplifier (VGA), automatic or programmable black-level offset calibration, and A/D Converter. Figure 4 shows a block diagram of the AD9841/9842 products, which contain a $PxGA$. The AD9845A, a 12-bit, 30-MSPS AFE with $PxGA$ technology, is scheduled for release in December, 2000.

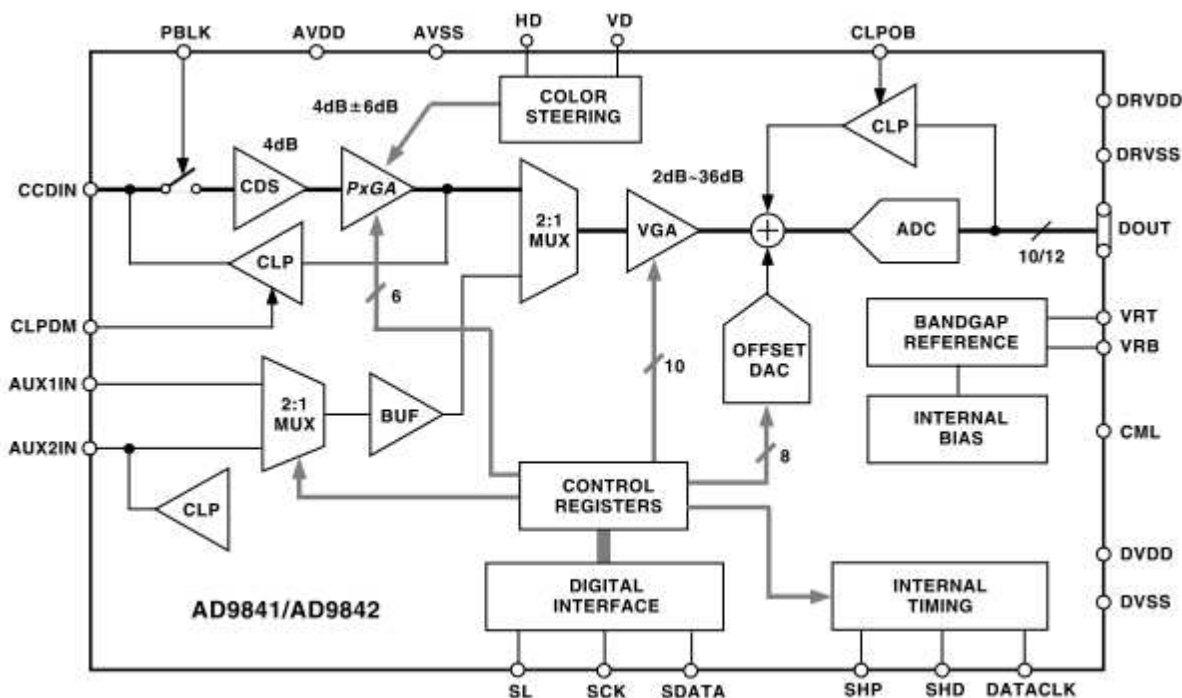


Figure 4: Block diagram of the AD9841/9842

The 10-bit AD9840, AD9841, and AD9843 have exceptionally low noise, (~0.2 LSB rms of output noise, 74-dB SNR), operate at speeds of up to 36 MHz, and are ideal for progressive-scan CCD and high frame-rate video applications. The 12-bit AD9842 and AD9844 have 77-dB SNR and are ideal for high-end, high-resolution applications. For battery-powered applications, the AD9840 offers the lowest power consumption available, 75 mW at 20 MHz and 140 mW at 36 MHz. Although the AD984x AFEs are single channel products, their digital output bus has three-state outputs—so several AFEs can be used in multi-channel high-speed applications. Table 1 lists the critical specifications.

Auxiliary modes The AD984x series AFEs offer 2 auxiliary inputs for applications that require other functions besides the standard CCD input. AUX1 samples, biases, amplifies (0 to 36-dB variable gain) and converts ac coupled continuous waveforms to digital in applications for purposes such as diagnostics of the imaging system. AUX2 samples analog video-type waveforms, such as NTSC or PAL signals, providing black-level clamping, 0 to 18-dB variable gain, and A/D conversion.

Table 1: Critical specs of the AD984X family of analog front-ends.
(Click here for a selection guide to all AFE products for imaging applications.)

Generic type	Resolution (bits)	Fs max (MSPS)	DNL typ (LSB)	SNR typ (dB) ¹	Power (mW)	Input range (Vp-p)	PGA gain range (dB)	PxGA™	PGA control type	Black Level Adj. (LSB)	Aux video inputs
AD9840	10	36	±0.5	74	140	1.0	0 - 34	no	digital	0 - 64	2
AD9841	10	20	±0.4	74	75	1.0	0 - 34	yes	digital	0 - 64	2
AD9843	10	20	±0.4	74	75	1.0	0 - 34	no	digital	0 - 64	2
AD9842	12	20	±0.5	77	75	1.0	0 - 34	yes	digital	0 - 255	2
AD9844	12	20	±0.5	77	75	1.0	0 - 34	no	digital	0 - 255	2
AD9845	12	30	±0.5	77	140	1.0	0 - 34	yes	digital	0 - 255	2

1. SNR is calculated as $20\log_{10}(\text{full-scale output/rms output noise})$

SCANNING, COLOR COPYING & VERY HIGH-END IMAGING APPLICATIONS

There are many imaging applications with AFE needs that, though similar, are different from those of the camera market. Scanners, color copiers, fax machines, bar-code readers and professional imaging applications—such as graphic arts scanners and scientific imaging systems—each have their own sets of requirements. The major differences are the image sensor being used and the interface that connects to the back end of the AFE. The analog front-end for each of these systems may have different input requirements, offset correction techniques, dynamic-range requirements, and speed requirements—and are best served by a different type of AFE than is used by the digital still-camera and camcorder market.

Multi-channel requirement In an area-CCD array, color images are created by placing filters over each pixel, with the pixel values fed out from a single channel serially. In a linear CCD array or CIS module, three linear arrays are used to create color images; one line is used for each color (R, G, or B). The outputs of these three arrays are transferred simultaneously from three output channels. Color scanning applications such as document scanners, multi-function peripherals (MFP) and digital color copiers use this type of imager. The ideal AFE for these types of applications will have three sampling channels operating simultaneously.

Black-level offset correction for a linear CCD array Unlike camera applications that use area-CCD arrays, an AFE that interfaces with a linear CCD array does not need an automatic black-level correction loop. Since there is only one line of up to a few thousand pixels, a single black-line calibration can be performed to determine the black-level offset once at the start of every scan. A black-level offset-correction factor can then be programmed into the AFE as an input word to the DAC, which will apply the coarse black level offset correction to each pixel for the entire scan. This circuitry is much simpler to implement than the automatic black-level calibration loop used in a camera AFE.

High-end scanning Professional scanning applications use the best CCDs available today. Graphic-arts scanners and film scanners may also use cooling mechanisms to control the temperature of the CCD, maximizing the SNR. Integration times will be as long as reasonable to maximize the dynamic range of the CCD output signal and increase the SNR. With CCD signals of up to 4 V commonly available in these applications, true 13- or 14-bit performance is achievable. In any imaging system, the AFE should not be the limiting factor in performance, so for these high-end applications a true 14-bit AFE is necessary. The AD9814 provides a true 14-bit no-missing-codes solution with 0.55-LSB rms noise at the 14-bit level (89 dB SNR) and a 4-V input range.

Low-to-mid-range scanning Low-end scanners have progressed from 30-bit color systems (10 bits/channel) a few years ago to 36- and even 42-bit color (12 and 14 bits/channel). While the CCDs in these low-end scanners can't achieve the 14-bit performance of the high-end scanners, the digital post-processing algorithms still require 14-bit resolution from the ADC. The AD9822, a lower-cost version of the AD9814, is ideal for these applications; it provides 1.5-LSB rms noise performance at the 14-bit level (80-dB SNR).

Speed requirements The scan-speed for a stand-alone scanner has historically been limited by the host interface, whether it's EPP, USB, or even SCSI. With the scanner's ability to transmit a maximum of only a few megabytes per second to the host, the image sensor and AFE only need to operate at several megapixels per second or less. Most AFEs for scanner applications offer sample rates of 6 MHz, corresponding to 2-MHz/color. In a digital copier, the host interface is not needed. The maximum sample rate of the scan will be limited by the digital image processing and the speed of the print engine, both of which can currently operate much faster than host interfaces. Looking ahead, IEEE-1394 (Firewire, iLink) is starting to gain market acceptance and a spec for USB 2.0 is taking shape. The host interface could potentially operate at up to 800 MHz and would no longer be the bottleneck that it is now.

To look more closely at the speed requirements for the AFE, consider typical copying specifications. For standard copying, a 300-dots-per-inch (dpi) scan is adequate. For a letter-sized document, color scanning at 300 dpi yields roughly 30 million pixels. Allowing for some processing overhead, scanning at a sample rate of 6 MHz (2 MHz/color) takes about 6 seconds, for a page rate of 10 pages per minute (ppm). To achieve 20 ppm, a sample rate of 12 MHz is needed—double the sample rate of most currently available scanner AFEs.

A multi-function peripheral (MFP), which integrates the scanner/fax/copier functions in a single unit, typically requires a higher-speed AFE than a flatbed document scanner, but it still needs to function as a good-quality scanner (600 dpi or more). For this case, the resolution needed for a letter-sized document is approximately 120 million color pixels. For this resolution, a 6-MHz AFE can produce only about 2.5 ppm, and a 12-MHz AFE increases the throughput to about 5 ppm. Many newer MFPs on the market can support 8-10 ppm in color-copy mode, at 600 dpi resolution; this requires an AFE sampling rate of around 20 to 22 MHz. With its 14-bit performance at 15 MSPS and 10-bit performance at up to 30 MSPS, the AD9822 is ideal for these applications. Figure 5 shows a block diagram of the AD9814/9822.

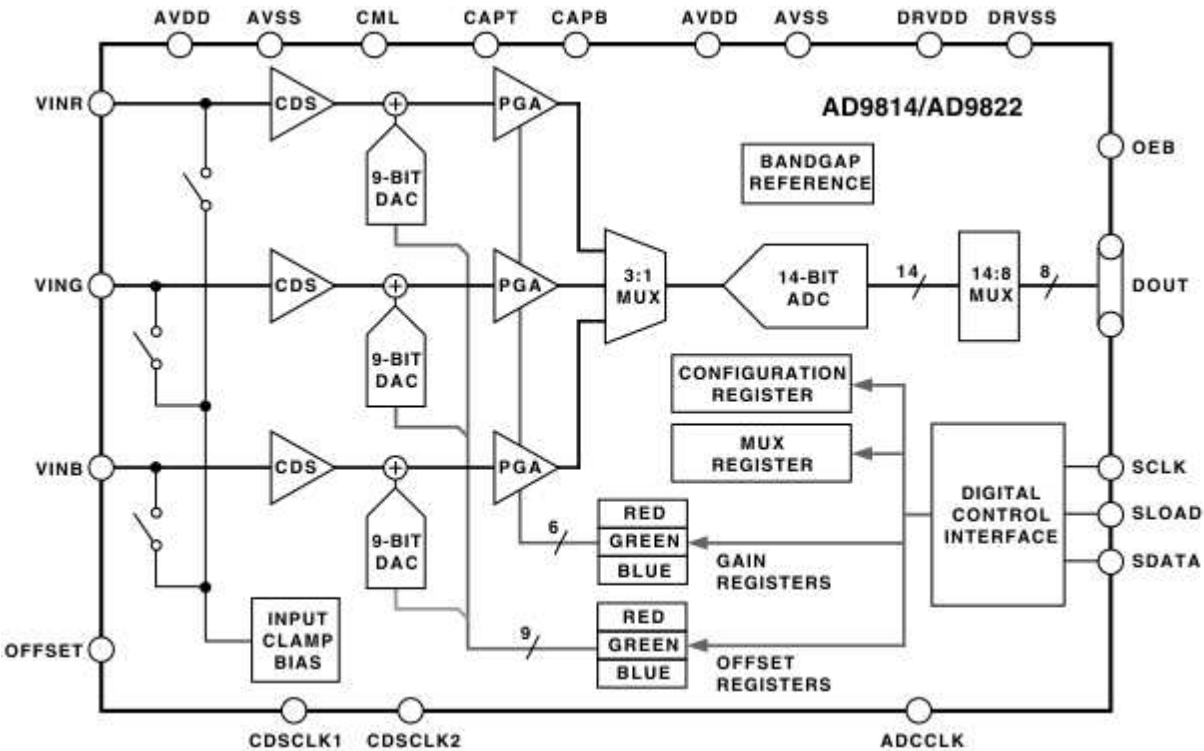


Figure 5: Block diagram of the AD9814/9822

The 14-bit AD9814 and AD9822 , operating at 6 and 30 MSPS, are at the high end of an Analog Devices family of three-channel AFEs with 10- to 14-bit resolution and sampling rates from 6 MSPS to 30 MSPS.

The AD9814 provides true 14-bit performance with high dynamic range for high end imaging applications such as film scanners and graphic arts scanners. The AD9822 can operate at up to 30 MSPS with 10-bit performance for high-speed scanning applications. It is ideally suited for imaging applications that use tri-linear color CCDs or CIS modules. At 15 MSPS, it provides high speed 14-bit no missing codes performance, suitable for low- to mid-range document scanners, digital color copiers, and MFPs

In 2001, scanners that boast 48-bit color scanning will hit the shelves; they require a 16-bit AFE. To meet this need, the AD9826, to be released in November, 2000, is a 16-bit, 15 MSPS AFE that will operate at speeds up to 30 MSPS with 10-bit performance.

The family of 3-channel AFEs, tabulated below (Table 2), has the low noise and high dynamic range necessary for graphic-arts scanners and spectroscopy systems. It has the speed necessary to work in digital color copiers and MFPs. It also has a programmable single-channel mode that would be useful in machine vision systems, bar code readers, and infrared (IR) imaging systems. The input voltage range of these products is as high as 4 V p-p, which is ideal for many document- and transparency scanning applications

Table 2: Critical specs of the family of 3-channel analog front-ends.
(Click here for a selection guide to all AFE products for imaging applications.)

						Input-		Input	PGA	Offset	Digital
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generic	Resolution (bits)	# of channels	Fs max (MSPS)	DNL typ (LSB)	INL typ (LSB)	referred noise (LSBrms)	Power (mW)	range (Vp- p)	gain range (V/V)	correction range (mv)	shading and offset correction
AD9805	10	3	6	±0.25	±0.75	0.1	450	2/4	4	-80/+20	yes
AD9807	12	3	6	±0.4	±1.5	0.3	450	2/4	4	-80/+20	yes
AD9816	12	3	6	±0.4	±1.5	0.5	420	1.5/3	6	±100	no
AD9814	14	3	10	±0.5	±4.0	0.55	350	2/4	6	±300	no
AD9822	14	3	15	±0.65	-10/+2	1.5	380	2	6	±350	no
AD9826	16	3	15	±0.75	±16	3	380	2/4	6	±300	no