A Review on Variable and Programmable Gain Amplifiers and Applications

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Abstract— **Variable and programmable gain amplifiers have been a recurrent subject of study over the last 50 years, and, are increasingly used in different applications today. This work presents an overview of these amplifiers as to serve as an up-to-date source of information for studies and designs. Different architectures and techniques are presented and classified for both radio and intermediate frequencies, since there are major differences in the requirements according to bandwidth. Typical applications where VGAs and PGAs are employed are also presented.**

Index Terms— **PGA, VGA; AGC; Analog Signal Conditioning; Analog Integrated Circuits;**

I. INTRODUCTION

An electronic amplifier is a device that takes a signal as input and outputs a more powerful version of that signal. It can be a distinct equipment or an electronic circuit within another device, and the latter is considered in this work. Since the invention of the first practical electronic amplifier by Lee De Forest in 1906 [1], electronic amplifiers impelled the electronics era and is an essential analog building block for more complex electronic devices.

Amplifiers are used in the great majority of electronic equipment that perform some signal processing, like video and audio equipment, medical and scientific instruments, and wireless communication devices. They are key components in front-end analog conditioning circuits for measurement, since many sensors output voltage or current signals of usually small magnitude, in the range of μV to mV or pA to nA, such as in the measurement of bioelectric signals [2].

Amplifiers can be designed to operate in specific frequency ranges, in open-loop or closed-loop, in continuous or switched modes, or be required to present high accurate specifications. When designing and specifying an amplifier, some parameters, or figures of merit, are considered according to the application requirements. The most important generally considered are the gain, the bandwidth and power, but, depending on the application, other parameters like linearity, noise, input offset voltage, input impedance, slew rate, efficiency, stability, among others, might be critical in the design as well [3].

In many applications, the amplitude ranges of the amplifier input signal and desired output signal are known, allowing the use of a fixed gain value. However, some applications might need to adjust the amplifier input signal range, and, hence the gain, to cope, for instance, with different signal characteristics from different sources, or due to the varying nature of the signal range. Likewise, analog conditioning circuits that have adjustable gain amplifiers can be fine-tuned according to the need and employed in different types of applications, while ensuring the full measurement range [4–6].

Since definitions of Variable Gain Amplifiers (VGA) and Programmable Gain Amplifiers (PGA) can vary among authors, in this paper, we use the term VGA for architectures that provide a continuous gain range, while PGA is used for architectures that provide discrete gain selection. The term Adjustable Gain Amplifier (AGA) is used in a general form, for both PGA and VGA.

VGAs and are often used in an Automatic Gain Control (AGC) loop, to correct or minimize variations in the amplitude range of the output signal when the the input amplitude of the signal varies with time, for example when you sometimes have a strong signal with a large amplitude range, and other times a weak signal with a small amplitude range. PGAs trade off the continuous gain range of a VGA for the simplicity of a digital selection of gain, and often a higher gain accuracy. In summary, VGAs or a PGAs are used due to its ability to set the input dynamic range to match a given signal range on the run, which end up improving the overall performance of applications.

As a wide number of applications uses VGAs or PGAs, the subject is a relevant research topic from late 1960's until today, being used for example, in 5G communications systems [7] and medical ultra-sounding imaging receivers [8]. Fig. 1 illustrates some selected PGA/VGA publications since 1968.

The main purpose of this paper is to provide a review on architectures, techniques, and use of adjustable gain amplifiers, covering both RF and IF applications. While the review cannot be extensive, it is intended to serve as an up-to-date source of information for studies and designs on this subject. After introducing some definitions to normalize terms usage, in Section II, we cover the main radiofrequency adjustable gain amplifiers building blocks in Section III. Intermediate VGAs and PGAs architectures are covered in Section IV. Typical applications where these amplifiers are employed, together with some examples, are presented in Section V. Finally, Section VI presents some concluding remarks.

II. BACKGROUND DEFINITIONS

Some definitions to normalize terms usage and to help understand different concepts regarding VGAs and PGAs are presented in the next.

A. *Operating frequency*

By definition, radio frequencies (RF) comprises radio waves, microwaves, millimeter and centimeter waves, rang-

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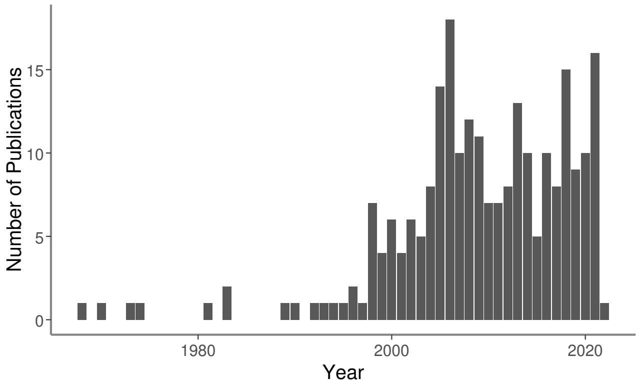

Fig. 1: Number of VGA/PGA publications by year (generated from 240 reviewed publications).

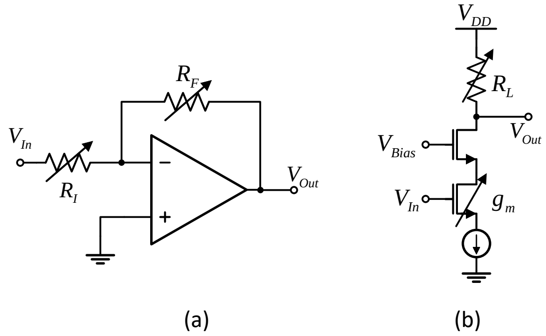

Fig. 2: Basic closed-loop (a) and open-loop (b) based VGA representation [11].

ing from 3 kHz to 300 GHz [9]. On the other hand, intermediate frequency (IF) is not a well defined range and it is often referred to as frequencies around 300 Hz up to 10 MHz [10]. Since there are significant differences in VGA/PGA architectures according to their operating frequencies, this work uses RF and IF frequencies as a form of classifying VGA/PGA, therefore it does not intend to establish a harsh definition of frequency ranges. It is adopted IF to refer to frequencies from DC to a few MHz and RF to refer to all frequencies above.

B. Open-loop versus Closed-loop

Closed-loop based designs offer a simple gain control, usually a good linearity and are very popular in IF applications. A straightforward way of designing a VGA would be to use an operational amplifier with a variable input resistor or negative feedback resistor, as represented in Fig. 2 (a). However, they present severe limitations for high-frequency RF applications due to the large current required by high-frequency operational amplifiers [11].

Designing a high-frequency RF VGA/PGA faces challenges such as gain tuning ability, power consumption, and die area [12]. An open-loop architecture is more popular for these applications, since it has the advantages of demanding low power while presenting low noise, but has the drawback of offering a weak linearity, when compared with closed-loop amplifiers working at the same frequency [7, 11]. The gain in an open-loop based VGA/PGA can be controlled, as an example, by variable transconductance or output-load impedance, as shown in Fig. 2 (b). Nevertheless, open-loop based amplifiers can also be employed to build IF VGA/PGAs when low power consumption is a priority over linearity.

C. Automatic Gain Control

Variable and Programmable Gain Amplifiers provide a way to amplify signals according to the application needs, but in some applications the amplitude of an incoming signal can vary with time over a wide dynamic range. If the signal amplitude changes are much slower than the information rate contained in the signal, then an Automatic Gain AGC circuit can be used to provide a relatively constant output signal amplitude, so that circuits following the AGC can deal with less dynamic range [13]. In summary, an AGC is a closed-loop regulating block, which controls the VGA/PGA gain according to the input signal amplitude to achieve a pre-adjusted output signal amplitude.

III. Radio Frequency VGAs and PGAs Building Blocks

In many applications, including RF designed VGA/PGA, an amplifier with dB-linear (linear relationship in the dB scale) gain characteristic is preferred, since it allows to achieve a constant settling time when used in an AGC loop [13–15]. This relationship is readily available in BJT technologies where gain is exponentially related with the control signal [16–18]. For the MOS devices, even though the exponential relationship exists in the subthreshold region and can provide a wide gain-control range [19], the saturation region is favored to reduce noise and increase bandwidth [20], and, due to the squared relationship of this latter, an exponential V-I conversion circuit is required for achieving an exponential gain-control relationship [21]. Some approaches that implement exponential converters adopt BiCMOS technologies [22–24], parasitic bipolar transistors [20] or use CMOS circuits that provide a pseudo-exponential function approximation [25, 26].

Fig. 3 presents many RF variable gain cells categories and techniques. VGAs can be grouped into three categories: Transconductance (g_m) Tuned, Output-load impedance (R_L) Tuned and Feedback tuned, while PGA can be grouped into g_m Tuned and R_L Tuned categories.

A. Variable Gain Cells and Techniques

The gain of CMOS open-loop based VGA is controlled by a variable g_m or R_L [11], as shown in Fig. 2 (b). Concerning g_m, the main methods to adjust it are tuning the bias current, dividing the output current, tuning the source degeneration resistor, and using a weighted switched MOS array to obtain a tunable *W/L* equivalent ratio.

Tuning Bias Current - The transconductance of a fully saturated MOS transistor can be expressed as

$$g_m = \sqrt{2\mu_{n,p}C_{ox}(W/L)I_D}. \tag{1}$$

Since $\mu_{n,p}C_{ox}$ is a technology constant parameter, the most usual way to modify the transconductance is to control the bias current I_D, although the *W/L* equivalent ratio can be also changed.

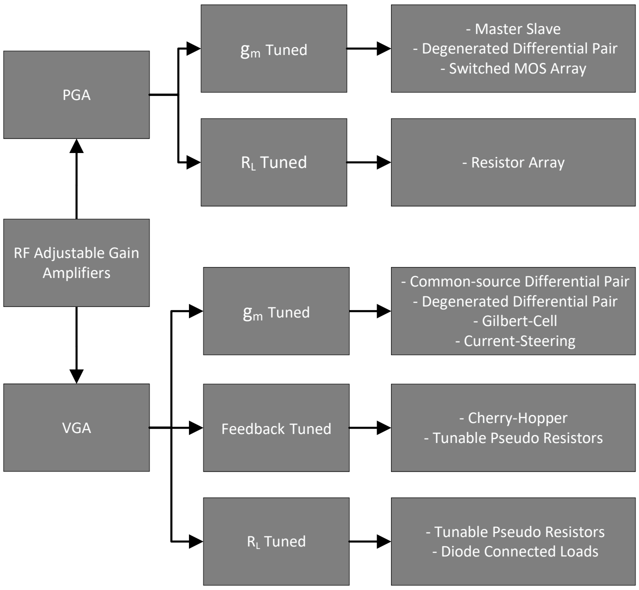

Fig. 3 RF VGA and PGA Categories and Techniques.

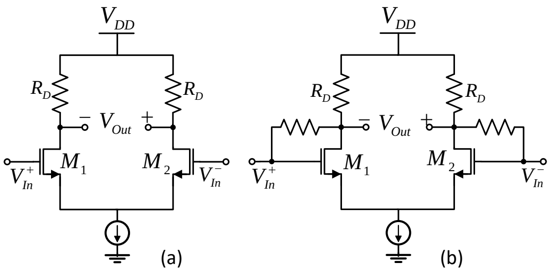

Fig. 4 Differential pair (a) and Resistive feedback differential pair (b).

The g_m of the common-source differential pair in Fig. 4 (a) can be tuned by bias current offering a good linearity, but has a drawback of also changing its output current [27, 28].

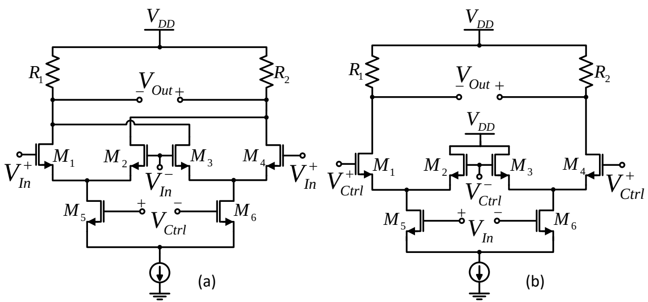

Fig. 5 Gilbert-cell (a) and Current Steering Gilbert-cell (b).

A bias current controlled gain block widely used is the Gilbert-cell [29], shown in Fig. 5 (a), in which a control voltage, applied at $M_{5,6}$, tunes the transconductance by changing the tail current and provides a linear gain-control relationship, as described by

$$g_m = \sqrt{\mu_n C_{ox}(W/L)_{1-4}}\sqrt{\mu_n C_{ox}(W/L)_{5,6}} \cdot V_{Ctrl}. \quad (2)$$

Dividing Output Current - A Current Steering Gilbert-cell [30], shown in Fig. 5 (b), can be also used to tune the amplifier transconductance and is a popular choice due to its simplicity and high speed merits. In this cell, the top differential pair is controlled by V_{Ctrl}, and acts as a current divider, while the bottom pair is used for signal input. As it is still defined by (2), it also provides a linear gain-control relationship [27].

Tuning the Source Degeneration Resistor - The effective transconductance of the differential pair can also be adjusted by a source degeneration resistor [31], which is usually implemented as a MOS device operating in triode region [21], as shown in Fig. 6.

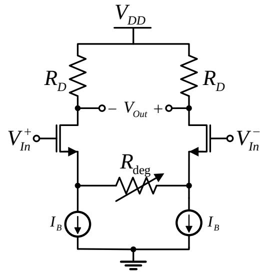

Fig. 6: Degenerated differential pair with variable degeneration resistor [21].

Feedback Tuning - A solution to obtain a variable gain from a common-source differential pair without limiting the output current is to adopt an adjustable feedback resistance, such as a tunable pseudo resistor, shown in Fig. 4 (b). This negative feedback approach has a potential for high linearity, but also reduces the gain range [32]. Another commonly used approach is to use a Cherry-Hopper structure [28, 33, 34], shown in Fig. 7. The gain of this amplifier can be tuned by controlling the feedback pseudo-resistors $M_{7,8}$ and can achieve a broad bandwidth [12].

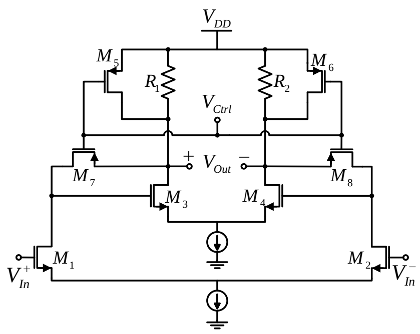

Fig. 7 A Cherry-Hopper variable gain structure [12].

Tuning R_L - A continuous gain adjustment can be obtained also by modifying the output load R_L using tunable pseudo-resistors. However, as the bandwidth is related to the output resistance, the higher the gain the narrower the bandwidth [12].

The topologies presented so far have a gain-control squared relationship. If a dB-Linear relationship is required, while operating in the saturation region, an exponential converter circuit is needed. An alternative way to obtain these converters is to adopt pseudo-exponential variable gain cells. Since quadratic and linear characteristics are obtainable in CMOS processes, an approximate dB-linear VGA can be achieved by circuits implementing first-order or second-order Taylor approximation of the exponential function [27]. Topologies that achieve these approximations, being the most common a VGA with diode connected loads, shown in Fig. 8, are presented in [11, 12, 21, 35].

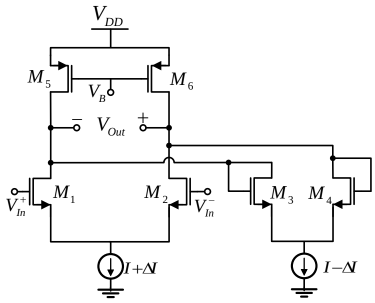

Fig. 8: Variable gain cell for pseudo-exponential approximation with diode connected loads [12].

B. *Programmable Gain Cells and Techniques*

Several works present both advantages and drawbacks in adopting a PGA for high-frequency designs. Song et al. [21], advocate that the control signals of PGAs are usually generated from a digital part, which could induce a latency issue. They also state that to achieve a large number of gain steps, a large resistor array would be required leading to a large die area occupation and Fan et al. [12] say that frequency response of PGAs are usually worse than VGAs. On the other hand, Kang et al. [11], say that PGAs are more suitable for high-frequency applications when considering both chip area and complexity and that a dB-Linear gain relationship is easily achievable with PGAs, but reminds that a closed-loop based design would not be a proper choice due to the large current required by high-frequency operational amplifiers and its sufficient resistive load driving.

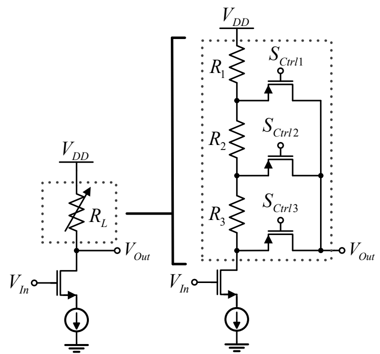

Fig. 9 Resistor array based PGA [36].

The most usual approach to obtain a RF PGA implement the resistor array technique [36], shown in Fig. 9. Resistor arrays are used to obtain discrete gain selection through R_L tuning, or using an array of source degeneration resistors. However, there are several other approaches to obtain a programmable gain cell, such as the Master-Slave based PGA, shown in Fig. 10, which uses two open-loop based VGA to make the gain temperature insensitive and to tune it with high precision over a wide adjustment range [19, 36–38].

Another way to adjust the gain is to tune the *W/L* equivalent ratio, as presented in Fig. 11. This technique is adopted by [11], in which a weighted switched MOS array provides the ratio tuning ability, thus allowing g_m tuning.

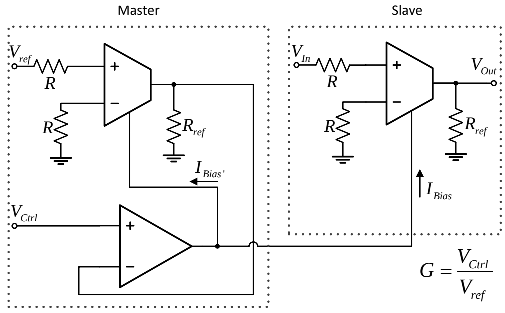

Fig. 10 Master-Slave based PGA [37].

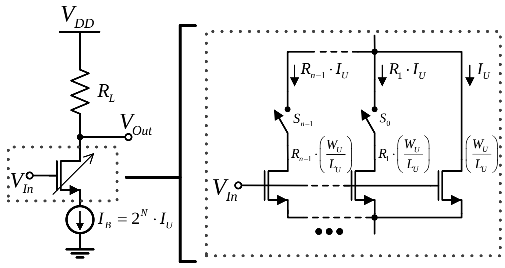

Fig. 11 Switched MOS based PGA [11].

IV. Intermediate Frequency VGAs and PGAs Architectures

IF PGA presented in this work are grouped into five different categories:Variable Impedance; DAC plus a Fixed Gain Amplifier (FGA); Superregenerative; Integrating and Current Division Network, while IF VGA presents a Tunable Pseudo-Resistor Architecture. These are discussed in the following.

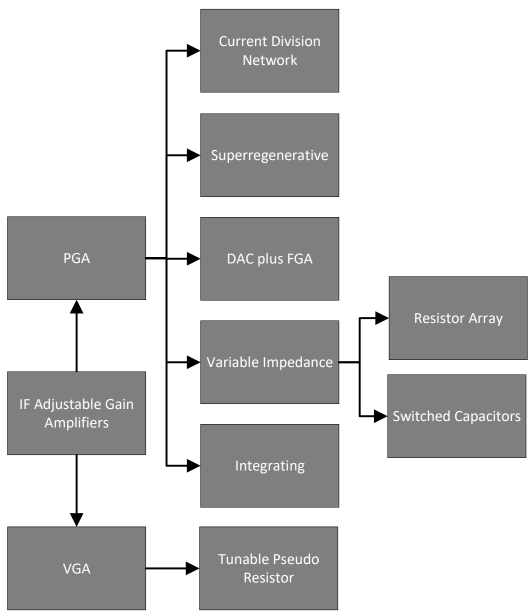

Fig. 12 IF Variable and Programmable Gain Amplifiers.

A. *Variable Impedance PGA*

Many approaches to obtain a IF VGA or PGA uses a closed-loop based amplifier with some sort of variable resistance at the input or in the negative feedback. Two techniques are presented to obtain a variable impedance PGA, in the following.

Resistor Array - One way to design a variable resistor is to use an array with several discrete resistive elements, changing the value of the equivalent resistor by connecting the appropriate combination of these elements. This can be done for the input and/or the feedback resistance, as represented in Fig. 13 (a) [39]. A drawback is that the gain accuracy can be affected by the resistor implementation uncertainties and by the multiple MOS switches On-Resistance R_{ON}. An architecture to eliminate the effect of the switches ON-resistance was proposed by [40] and is shown in Fig. 13 (b). However, these approaches are more effective in obtaining a PGA with a small number of gain steps, otherwise, many resistors might be needed, resulting in a large die area occupation.

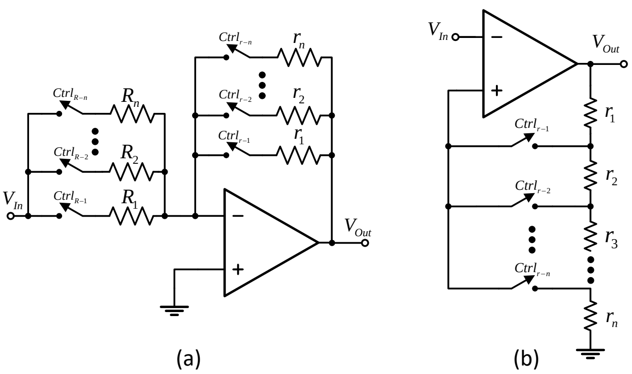

Fig. 13 Resistor Array PGA [40].

Switched Capacitor Array - This approach is similar to the Resistor Array approach, but can reduce the resistor die area issue, since capacitors and switches usually occupy a smaller area than resistors. Besides that, the relative uncertainty between capacitors is smaller than between resistors and than between capacitors and resistors. Thus, this technique allows to achieve a larger number of gain steps using a die area equivalent to that used by the resistor array approach [41–44]. Fig. 14 shows a circuit that implement this idea, where the gain is given by C_1/C_2 [41].

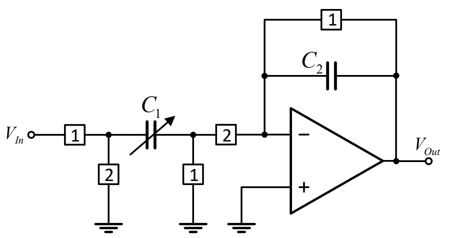

Fig. 14 Switched-Capacitor Array PGA [41].

Some possible drawbacks of the switched capacitor array approach are that charge injection from MOS switches can significantly interfere with the signal and increase the gain uncertainty; it demands switches and control signals that increases the circuit numbers of components and complexity, when compared to the resistance array approach; also, that the output signal is time-sampled, and signal aliasing must be considered.

B. DAC plus Fixed Gain Amplifier

An approach that allows a variable gain without changing the value of the amplifier resistances was presented by [45], which is represented in Fig. 15. It uses a Digital to Analog Converter (DAC) in association with a fixed gain amplifier to obtain a programmable gain.

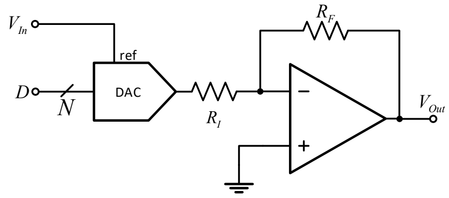

Fig. 15 Obtaining a PGA from a DAC plus a Fixed Gain Amplifier [45].

The DAC is controlled by a digital signal D with N bits and its reference input receives the input signal V_{In} to be amplified. The amplifier has a fixed gain defined by the resistors ratio $K = R_f/R_i$. The fraction of the input signal V_{In} that will reach the fixed gain amplifier input is set by the DAC, resulting in a gain given by $-K \cdot D/2^N$. One possible drawback of this approach is that controlling the gain by fractioning the input signal can degrade the SNR, since the lower the input voltage, the more the noise becomes relevant.

C. Pulse-width PGA

In this class of PGA the gain programming value is defined by the pulse-width of a control signal. It usually presents a lower operating frequency than the previously presented PGAs but provides a large amount of gain steps without the need to increase the number of components. Similarly as for the switched-capacitor array PGA, the output signal is time-sampled and signal aliasing must be considered.

Integrating PGA - This approach uses an integrating amplifier and the gain programming value is normally set by the ratio between the control signal pulse-width and the amplifier integrating constant. The gain is linearly related to the control signal pulse-width. This approach is suitable for biosignals since these require low frequency operation, large number of gain steps and relatively low noise [46–48]. The integrating PGA developed in [47], shown in Fig. 16, provides single-ended with DC level shift and differential signal amplification, possibility of calibration, and the gain defined by $1 + (T_A/(R \cdot C_A))$, where T_A is the control signal pulse-width.

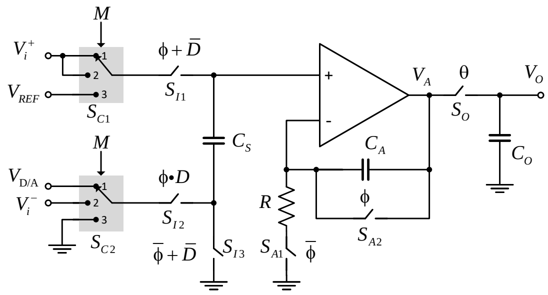

Fig. 16 Programmable Gain Integrating Amplifier [47].

Superregenerative PGA - This approach is derived from the superregenerative receiver and presents an exponential gain-control signal relationship [49–51]. In the superregenerative PGA developed by [50], presented in Fig. 17, The gain value is defined by $e^{T_A/(R \cdot C_A)}$, where which T_A is the pulse-width of the control signal.

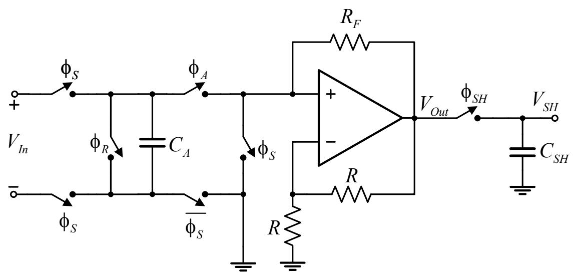

Fig. 17 Programmable Gain Superregenerative Amplifier [50].

D. *Current Division PGA*

The operation of this PGA architecture is based on the inherently linear current division principle. An approach combining good linearity and small area consumption is presented in [52] and is shown in Fig. 18, which uses OTAs and banks of MOS transistors. Programmable current division is achieved using the two identical transistor banks with binary-weighted transistor sizes, which are controlled by complementary n-bit words, with gain defined by $(R_2 \cdot K_2)/(R_1 \cdot K_1)$, where $K_{1,2} = W_{1,2}/L_{1,2}$. Some other works adopting a current division scheme to provide gain control are presented in [53–56].

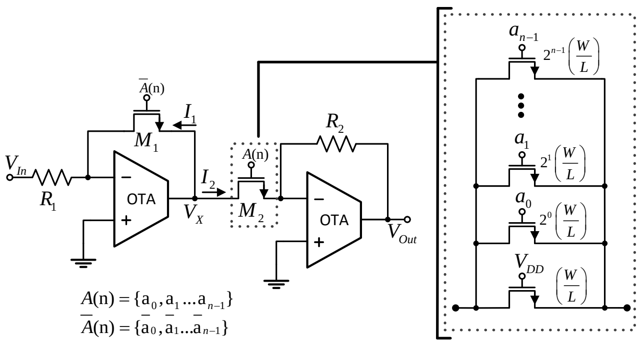

Fig. 18 Current-Splitting PGA [52].

E. *Tunable Pseudo-Resistor based VGA*

An alternative way to implement a variable resistor is use the MOSFET drain-source resistance controlled by its gate-source voltage. Although there are several MOSFET configurations that allows to explore this characteristic, some of them may present a relevant nonlinearity, even in ohmic region. It is possible to exploit this nonlinearity to obtain a pseudo-exponential relationship between control voltage and gain [27]. However, if a linear relationship is desired, there are some techniques to improve it, like the floating gate CMOS common-mode linearization [57].

A tunable pseudo-resistor based VGA achieves continuous gain values, and can be used in applications where the control voltage-gain non-linearity is not critical. This approach was adopted by [14, 58, 59], and is presented in Fig. 19, where $M_{1,2,3,4}$ act as tunable pseudo-resistors. Since the gain tuning is based on the variation of the gate voltage of transistors, usually operating in the triode region, a drawback of this approach for low-voltage systems is that the tuning capability is limited. Furthermore, MOS resistive circuits show distortion levels higher than allowed by some applications [52].

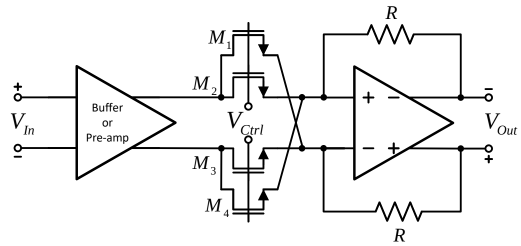

Fig. 19 Tunable Pseudo-Resistor based VGA [58].

V. Applications of VGAs and PGAs

As, in this work, it is impossible to list all the applications of VGAs and PGAs, some relevant ones were selected to bring an overview of how the presented structures are usually employed. A summary of the applications with the adjustable variable gain techniques and architectures is shown in Table I.

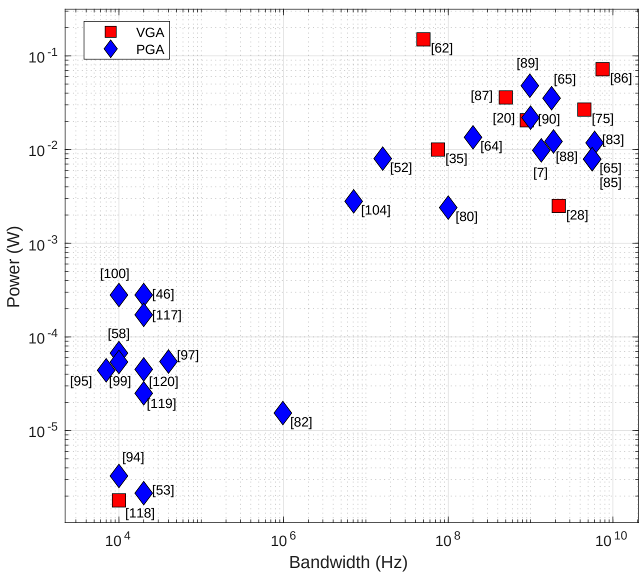

Fig. 20: Referenced VGAs and PGAs scattering over Bandwidth and Power.

VGAs and PGAs requirements of gain range and bandwidth are application specific, and the latter has a great relevance in the dissipated power, as presented in Fig. 20. It can be observed that, differently from PGAs, VGAs are more used for high bandwidth applications. Nevertheless, both VGAs and PGAs are employed in IF and RF, as shown in the applications presented hereafter.

A. *Magnetic Data Storage Systems*

Although a Solid State Drive (SSD) outperforms a Hard Drive Disk (HDD) in data transfer rate, HDDs have some advantages in cost per bit and durability, which makes it nowadays the primary type of storage device in data centers [60].

In a HDD, the signal read from the disk is pre-amplified and then inputted into an Analog Front End (AFE) reading channel. In the AFE, the signal is amplified, equalized, and its asymmetry is corrected, as better explained in [61]. The signal amplification is usually done by a VGA inside an AGC loop [35,62], but a combined PGA and VGA architecture can also be used [63].

B. Wireless Communication

Wireless communication networks are experiencing a rapid development through the last decades [64] and it is known that VGAs and PGAs are recurrent structures in RF front-ends, as reported in [65]. Wireless transceivers can handle signals adopting a IF stage [66], such as superheterodyne and low-IF, but also can directly handle baseband RF signals, like in direct conversion (zero-IF) receivers [67,68]. Depending on the receiver architecture, VGAs and PGAs could both be placed at IF or base-band frequencies [69]. When used in direct-conversion receivers, due to the higher operating frequency (RF) required for wireless communication, VGA and PGA designs for such use are open-loop based amplifiers, often using AGC, that is one of the essential blocks for wireless communication [70]. In the case of using a superheterodyne or low-IF receiver, it is usually adopted a closed-loop based amplifier resulting in better linearity when compared with open-loop amplifiers.

In wireless communication, VGA and PGA are found in technologies like Bluetooth Low Energy (BLE) [70–73], 5G [7, 74–76] and Wireless Local Area Network (WLAN) receivers [77–81], among other applications [64, 65, 82–90].

Bluetooth - BLE 5.0 is the most efficient wireless standard for Internet of Things (IoT) applications [73]. A BLE receiver usually adopts a Low Noise Amplifier (LNA), and a VGA inside an AGC loop to adjust the gain of the LNA output signal, since the under or over amplification may lead to the saturation of the Analog to Digital Converter (ADC) at the end of a demodulation chain [70, 72].

5G - The 2G technology already employed VGAs and AGC loops in mobile networks transceivers designs with Code Division Multiple Access (CDMA) [91]. Nowadays, 5G communications can support multiple data streams, improve the spectral efficiency of multi-user systems, and compensate for the millimeter wave (mm-wave) short communication range with a technique called phased-array [74, 76]. In a phased-array design, gain control is needed to calibrate gain error and to reduce the side-lobe level [75], which is achieved by employing a VGA/PGA inside an AGC loop.

WLAN receivers - Among WLAN technologies, many standards offer different coverage and capacity, existing different demands and architectures [80]. A Direct-Conversion Receiver (DCR), is by far the most common architecture used in low-power applications due to its simplicity and scalability [69], and, thus, WLAN receivers often use this architecture to reduce radio size, power, number of components and consequently, cost. As mentioned before, in these scenarios, the incoming signal is normally handled in baseband using a VGA together with an AGC, yet many WLAN receivers adopt signal handling in IF or low-IF [92, 93]. In summary, the main use of VGA/PGA in WLAN receivers rely on adjusting a previously unknown input signal amplitude to the required specific levels.

C. Biosignals measurement and other biomedical applications

Biosignals usually have low frequency and low voltage characteristics, as shown in Fig. 21, and need to be conditioned beforehand. For this reason, it is common to find a VGA/PGA in the AFE of medical test devices such as a Brain Machine Interface (BMI) [94–97], Photoplethysmography (PPG) [98, 99], Electrocardiography (ECG) [50, 100–103] and others applications [104, 105].

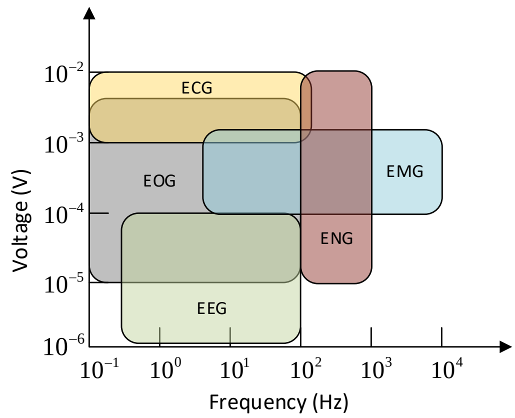

Fig. 21 Frequencies and voltages of different biomedical signals.

BMI - BMI are a class of promising devices that allows the control of computers, robotic limbs and other devices by monitoring and decoding neuron's signals, helping in the diagnosis and treatment of neurological disorders and the restoration of sensory and motor function [94]. The electrical activities of the brain can be recorded from the scalp by an Electroencephalogram (EEG), from the surface of the brain by an Electrocorticography (ECoG) or by an intracranial Electroencephalography (iEEG) and from within the brain, which captures the extracellular activities of neurons. The signals acquired from these methods have a frequency range of a few mHz to 10 kHz and their amplitude is at the range of 20 μV to 10 mV [106]. Usually the signal amplification in the AFE is done using an VGA/PGA [94–97, 107].

PPG - PPG is a technique often used to non-invasively detect blood volume changes in the microvascular bed of tissue. A PPG waveform comprises multiple signals attributed to cardiac synchronous changes in the blood volume with each heart beat ranging from 0.7Hz to 7.2Hz, and is superimposed with various lower frequency components attributed to respiration, sympathetic nervous system activity and thermoregulation, ranging from 0.01Hz to 0.69 Hz [99, 108]. In the COVID-19 pandemic it played a vital role since it allows monitoring heart rate and the arterial blood oxygen saturation (S_pO_2) in real time [109, 110]. A typical PPG readout circuit includes photo-detector, a pre-amplifier, a band-pass filter, a PGA and a Microcontroller Unit (MCU) [98, 99].

ECG and other low frequency tests - ECG is a vital sign monitoring method that provides valuable diagnostic information about the cardiovascular system [111]. It is of great importance since Cardiovascular Diseases (CVDs) are a major health concern in most countries and the chances of a total and fast recovery of the patient diminishes with the late detection of the symptoms [102]. Traditionally performed by

Table I. Summary of techniques and architectures used in VGAs and PGAs applications.

	Tunable Pseudo-Resistor	Integrating	Resistor Array	Switched Capacitor Array	DAC plus FGA	Superregenerative	Current Division	gm tuning	RL tuning	Feedback tuning (Cherry-Hopper)
Magnetic Data Storage	-	-	-	-	-	-	-	[35,61]	-	-
Bluetooth	-	-	[71]	-	-	-	-	[73]	-	-
WLAN receivers	-	-	-	-	-	-	-	[79,80]	-	-
Other RF Transceivers	-	-	[82]	-	-	-	-	[20,65,85,86,88,89]	[83]	[28,90]
BMI	[94-96]	-	-	[96]	-	-	-	-	-	-
ECG	[103]	-	-	-	-	[50]	-	-	-	-
EMG	[103]	-	-	-	-	-	-	-	-	-
ENG	-	[46]	-	-	-	-	-	-	-	-
Hearing-Aid	[58,59]	-	[58,119]	[116,120]	-	-	[53]	[117,118]	-	-
Other Referenced Works	-	[47,48]	-	-	[45]	[49,51]	[52,54,55]	[11]	-	-

bulky stations at health centers, ECG equipment are turning into wearable devices [100]. Therefore, there is a growing demand for low-power, small sized, bio-signal acquisition systems [112]. ECG systems can use fixed gain amplifiers [113], but the use of VGA/PGA [50, 100, 102] usually improves readings, since it optimizes the ADC performance.

Biomedical applications deal with similar (but still different) low bandwidth and voltage range signals, as presented in Fig. 21. Applications like ECG and Electromyogram (EMG) have a relaxed noise requirements, allowing focusing on low power devices, while others, like Electroneurogram (ENG) [46], have strict noise requirement and would require a more power demanding device. Even if there are different requirements concerning bandwidth, signal range, noise performance and power consumption, a way to have a single mobile equipment for multiple applications, reducing the overall costs, is to use a programmable AFE that can also provide an adjustable noise-power trade-off [105].

D. Hearing Aid Devices

Hearing loss is one of the most common human impairments [58]. According to the World Health Organization (WHO) by 2050 nearly 2.5 billion people are projected to have some degree of hearing loss and at least 700 million will require hearing rehabilitation [114, 115].

Hearing aid devices basically comprises a microphone, an AFE with a VGA/PGA and a speaker [58]. However, there are several ways to develop this type of system and may include components such as ADC, Digital to Analog Converters (DAC), Digital Signal Processor (DSP), filters and pre-amplifiers [2, 53, 59, 116–119].

First generation hearing aid devices were full-analog and used a VGA in an AGC to maintain a normalized output level to the speaker. They had some issues with power dissipation and flat frequency response, which made the device uncomfortable to use, since hearing aid needed frequencies vary from one individual to another. Second generation devices adopted band pass filters, but were still bulky and power hungry. A development leap occurred when many hearing aid devices began converting the microphone analog signal to digital and using digital signal processing, favoring programmability and customization for each individual hearing need [58]. Along with this, the VGA/PGA use changed from providing a constant, suitable amplitude signal to the speaker to adjusting the analog signal to the ADC input signal range, improving the device performance [120].

VI. Concluding Remarks

A review of variable and programmable gain amplifiers was presented in this paper, grouping the variable gain cells, techniques, and architectures into the radio frequency and intermediate frequency amplifiers categories. Furthermore, four application classes were presented in which these amplifiers are usually used. A summary of the applications versus the variable gain techniques and architectures is also presented.

VGAs provide continuously adjustable gain, are often used in an Automatic Gain Control circuit, and find more applications for RF frequencies. PGAs exchanges the continuously adjustable gain of VGAs for a discrete programmable gain, but generally achieving more accuracy. Although, PGAs and VGAs have been recurrently studied over the last 50 years, they find increasingly applications today, and new architectures and techniques have been proposed recently, making them an important object of research.

VII. References (Organized by Topics)

The references presented at the end of this paper can be classified into the following groups, according to the topics they cover:

- *General references:* [1-6], [114].
- *Background definitions:* [9-13].
- *Radio frequency VGA/PGA:* [13-26]; g_m tuning [27-31]; feedback tuning [32-34]; diode connected loads [11, 12, 21, 35]; resistor array [36]; master-slave [19, 36-38]; switched MOS [11].
- *Intermediate frequency VGA/PGA*: resistor array: [39, 40]; switched capacitor: [41-44]; DAC plus FGA: [45]; pulse width PGA:[46-51]; current division: [52-56]; tunable pseudo resistor: [14, 58, 59].
- *Applications*: magnetic data storage systems: [35, 61-63]; wireless communication: [66-70]; BLE: [70-73]; 5G: [7,74-76,91]; WLAN: [77-81,92,93]; other wireless applications: [64,65.82-90]; BMI: [94-97,106,107]; PPG: [98,99,108-110]; ECG: [46,50,100-103,111-113]; other biosignal measurement applications: [104,105]; hearing aid: [53,58,59,114,116-120].

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