CHOPPER STABILIZATION TECHNIQUES.
PART I: CHOPPER AMPLIFIER TOPOLOGIES OVERVIEW

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Rezumat. *Lucrarea prezintă proiectarea optimală, bazată pe analiza manuală susținută de simularea SPICE a unui amplificator cu modulare-demodulare (chopper). În prima parte a lucrării sunt trecute în revistă metodele de reducere a tensiunii de ofset și a zgomotului unui amplificator prin folosirea tehnicii de modulare-demodulare punându-se în evidență rezultatele importante pentru proiectarea amplificatorului de bază. Sunt comparate performanțele care se pot obține folosirea unui amplificator de bandă largă și respectiv a unuia selectiv în frecvență analizându-se cauzele ofsetului rezidual și performanțele de zgomot.*

Abstract. *This paper presents the chopper amplifier optimal design flow, based on manual analysis and backed up by SPICE simulation. The first part is a tutorial like overview of chopper technique effects on offset voltage and noise reduction, highlighting the significant results for the base amplifier design. The performances of a wide band amplifier and respectively a frequency selective base amplifier are compared. The residual offset and noise performances are analyzed.*

Keywords: chopper amplifier, offset voltage, frequency selective amplifier.

Introduction

For precision amplifier design, the noise and offset become critical issues, especially for MOS technologies. For MOS transistor both mismatch and flicker noise level are generally higher than that of similar area bipolar transistor. Taking into account only process and layout induced mismatching, the typical value of a MOS amplifier offset voltage is limited to a few milivolts. To further reduce the offset voltage, special techniques have been implemented, namely *chopper stabilization* and *autozero.*

The *chopper stabilization technique* uses modulation to shift the signal spectrum to a frequency domain where it is not affected by the amplifier's offset and low frequency noise. This way, the useful signal is separated from offset and low frequency noise which now can be filtered out while the signal is amplified.

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In the *autozero technique* the offset is firstly sampled and then subtracted from the input signal (either at the input, at the output or at an intermediary point on the signal path). The offset performances are greatly improved, but some residual offset still remains, due to sample and hold errors and offset drift. The autozero technique also improves the low frequency noise performances but degrades the wide band noise due to undersampling. Also, the autozero is a sampling technique and is best suited for sampled data systems.

Many papers have been written on this subject. An important reference in precision amplifier literature is the Enz and Temes paper, [1], which presents most of the up to date noise and offset reduction techniques. The present paper, which is largely based on Enz and Temes paper, select and highlight the important results concerning chopper stabilization technique and g_mC filtering. Our goal was to provide a general overview of the chopper stabilization technique, focused on the base amplifier optimal design (Part I). A frequency selective g_mC implementation has been chosen for the base amplifier and its performances are discussed for a 0.6 μm CMOS process implementation (Part II).

Chopper Stabilization Technique

The Chopper Stabilized Amplifier Basic Schematic

This section describes the chopper stabilization technique and analyzes its performances. Even if there are many different chopper amplifier implementations, all of them share the same basic principle of using modulation to separate the input signal from noise and offset.

The *chopper stabilized amplifier* bloc level schematic is presented in Fig. 1. From this figure the three main phases of the chopper stabilization technique and the corresponding functional blocks becomes apparent: (1) the modulation phase, respectively the *modulator*, (2) the amplification phase, respectively the *base amplifier*, and (3) the demodulation phase, respectively the *demodulator*, [1].
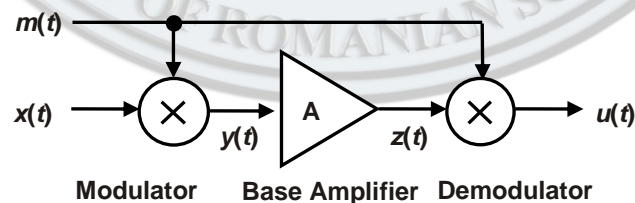

Fig. 1. The chopper stabilized amplifier block level schematic.
$m(t)$ is the modulation signal, $x(t)$ – input signal, $y(t)$ – modulated signal,
$z(t)$ – amplified modulated signal, and $u(t)$ – output signal.

The *modulation phase* role is to transfer the signal spectrum from its base-band to a higher frequency domain. Any kind of modulation can be used, but, for practical reasons, most chopper amplifiers use a rectangular signal.

The *amplification phase* represents the actual signal amplification. The modulation and demodulation phases contribute to the offset and noise reduction, but do not provide signal gain. During the amplification phase, the amplifier's noise and offset are added to the useful signal. However, after modulation, signal is centered on the modulation frequency so it is separated from offset and low frequency noise. The white noise is still overlapped on the signal and cannot be reduced by means of chopper stabilization technique.

During the *demodulation phase*, the amplified signal is brought back to its base-band while the offset and noise are scattered to higher frequencies.

We note that the chopper stabilized process presented in this section does not eliminate the offset or noise but scatters them to higher frequency. A forth, filtering phase, is needed to eliminate offset and low frequency noise.

The Modulation Phase

The most commonly used modulating signals in chopper stabilization technique are the rectangular signals, as they are easily implemented and provide the desired frequency shift. Let us consider the rectangular signal given by:

$$m(t) = \begin{cases} 1 & \text{for} \quad t \in (kT; kT + T/2) \\ -1 & \text{for} \quad t \in (kT + T/2; kT + T) \end{cases} \tag{1}$$

where T is the modulation signal period and $\omega_0 = 2\pi/T$ is the modulation signal frequency. The modulating signal Fourier transform, $M(\omega)$, is given by

$$M(\omega) = \sum_{n=-\infty}^{\infty} 2 \frac{1 - (-1)^n}{jn} \delta(\omega - n\omega_0) \tag{2}$$

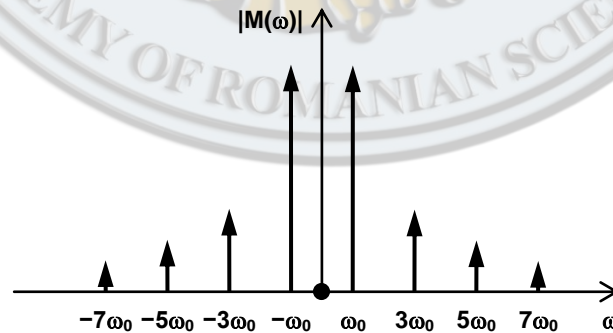and the modulating signal spectrum is presented in **Fig. 2**.

Fig. 2. Modulating signal frequency spectrum.

The first step of the chopper stabilization technique consists of input signal modulation, by multiplying it with the modulating signal, as shown in Fig. 1. The modulated signal, $y(t)$, is given by, [2],

$$y(t) = m(t)\, x(t)$$

$$Y(\omega) = \frac{1}{2\pi} M(\omega) * X(\omega) \tag{3}$$

The modulating signal spectrum is given by equation (2), so we have

$$Y(\omega) = \frac{1}{\pi} \sum_{n=-\infty}^{\infty} \frac{1-(-1)^n}{jn} X(\omega - n\omega_0) \tag{4}$$

This equation shows that the input signal spectrum has been shifted around the modulating signal odd harmonics. This is a very important aspect of the chopper technique, as this frequency shift allows the signal separation from the amplifier's offset and low frequency noise.

The Amplification Phase

The modulating signal is applied to the base amplifier. We shall first consider the general case of arbitrary transfer function, $A(\omega)$, of the amplifier. In this case, the amplified signal spectrum is given by

$$Z(\omega) = A(\omega)\, Y(\omega) \tag{5}$$

Replacing the modulated signal expression [equation (4)], we get

$$Z(\omega) = A(\omega)\, \frac{1}{\pi} \sum_{n=-\infty}^{\infty} \frac{1-(-1)^n}{jn} X(\omega - n\omega_0) \tag{6}$$

We shall analyze in more detail two of the most important amplifier possible transfer functions:
- − the *wide band amplifier* and
- − the *band pass amplifier*.

Wide band amplifier

This amplifier has a *constant, frequency independent, gain*, $A(\omega)=A_0$. Of course, *no any amplifier has infinite bandwidth. However, the modulated signal* harmonics decrease rapidly with the harmonic order (as they are multiplied by $1/n$). For this reason, any amplifier having for the modulated signal first few harmonics a constant gain can be considered a "wide band amplifier". In this case, the amplified signal spectrum is given by

$$Z(\omega) = \frac{A_0}{\pi} \sum_{n=-\infty}^{\infty} \frac{1-(-1)^n}{jn} X(\omega - n\omega_0) \tag{7}$$

It is worth to note that for wide band amplifier (i.e. constant gain) case the amplified signal and the modulated signal spectrum have the same shape, for both frequency and time domains:

$$Z(\omega) = A_0 Y(\omega) \qquad\qquad z(t) = A_0\, y(t) \qquad\qquad (8)$$

Band pass amplifier

Another base amplifier transfer function widely used in chopper stabilization technique is the *band pass amplifier*. The wide band amplifier has the same gain for the useful signal and for the input referred noise and offset. This is not a major disadvantage, as the chopper stabilization technique separates the noise and offset from the useful signal. However, the *frequency selective amplifier* use is an efficient approach in order to amplify significantly only the useful signal.

The basic idea of using a frequency selective amplifier is to keep only the first useful signal harmonic. This way, two goals are met: (*a*) all the input signal's information is kept and (*b*) the amplifier has a minimal pass-band, resulting in minimal noise amplification.

In this case, the amplified signal spectrum is given by

$$Z(\omega) = \frac{2A_0}{j\pi}\left[X(\omega - \omega_0) - X(\omega + \omega_0)\right] \qquad\qquad (9)$$

The Demodulation Phase

In standard chopper stabilized amplifiers, the same signal is used for both modulation and demodulation. The input signal is modulated [multiplied by $m(t)$], amplified by a constant gain A_0, and finally demodulated [second time multiplied by $m(t)$].

Based on modulating signal definition [see equation (1)] we note that

$$m^2(t) = 1 \qquad\qquad (10)$$

because $m(t)$ can take only $+1$ and -1 values.

This means that any signal multiplied twice by $m(t)$ is left unchanged:

$$u(t) = A_0\, x(t) \qquad\qquad (11)$$

This is a very important result for the chopper stabilization technique. It shows that after demodulation, the input signal is completely recovered (ideally no parasitic harmonics remain) and only the base amplifier gain remains. From the input signal point of view, the entire chopper amplifier has the same effect as the base amplifier.

Now we shall determine the output signal spectrum, $U(\omega)$, for the case of frequency selective amplifier having an ideal pass-band transfer function use.

During the demodulation phase, the amplified signal, $z(t)$, is second time multiplied by the modulating signal, $m(t)$.

The output signal spectrum is given by [see equation (2)]:

$$U(\omega) = \frac{1}{2\pi} M(\omega) * Z(\omega) = \frac{1}{\pi} \sum_{n=-\infty}^{\infty} \frac{1-(-1)^n}{jn} Z(\omega - n\omega_0) \qquad (12)$$

Replacing $Z(\omega)$, as given by equation (9), we get the output signal frequency spectrum for a chopper stabilized amplifier that uses a frequency selective base amplifier:

$$U(\omega) = \frac{2A_0}{\pi} \sum_{n=-\infty}^{\infty} \frac{1-(-1)^n}{n} \{X[\omega - (n-1)\omega_0] - X[\omega - (n+1)\omega_0]\} \qquad (13)$$
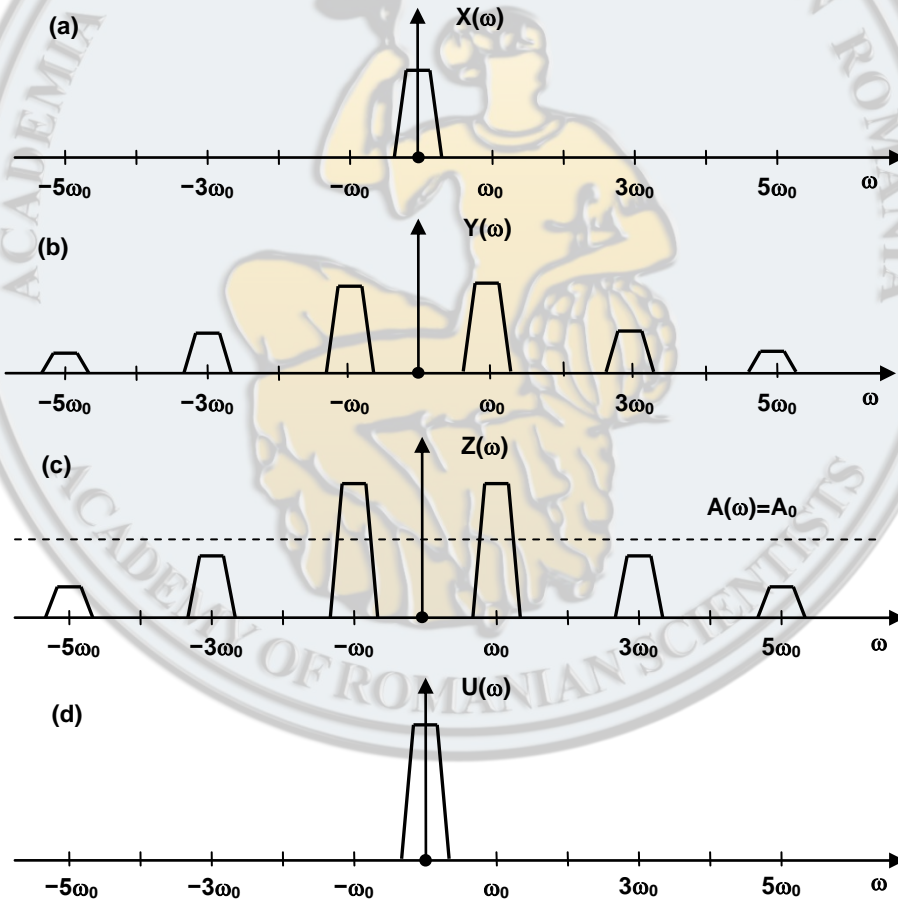

Fig. 3. Chopper amplifier signal evolution, *wide band base amplifier*:
(a) input signal, (b) modulated signal, (c) amplified signal, and (d) output signal.

Signal Spectrum Evolution in Chopper Stabilized Amplifier

The Wide Band Base Amplifier Topology.

In this section, all previous results are put together and the signal evolution is described from the amplifier's input to output, [1].

Let us consider a finite bandwidth input signal, with the frequency spectrum presented in **Fig. 3**.a and b. The input signal bandwidth must be smaller than half the modulating frequency, $\omega_0/2$.

During the modulation phase, the signal is multiplied by $m(t)$. As a result, the input signal spectrum is shifted around the modulating frequency odd harmonics. The modulated signal spectrum, $Y(\omega)$ is presented in **Fig. 3**.b and described by equation (4).

This signal is further amplified by the base amplifier. In this section we consider a wide band amplifier, with a constant gain, A_0, for the entire frequency range. In this case, all modulated signal's spectral components are simply increased by A_0, without any change of the spectrum shape. The amplified signal, $Z(\omega)$ [see equation (7)] and the base amplifier transfer function are presented in **Fig. 4**.c. During the next phase – the demodulation – the amplified signal is multiplied once again by $m(t)$. This results in bringing the signal back to its baseband. The output (demodulated) signal is presented in **Fig. 4**.d.

The Frequency Selective Base Amplifier Topology.

This section is devoted to the selective amplifier topology effects on the chopper technique analysis. We consider the same input signal as in the previous case applied this time to a chopper amplifier having a frequency selective base amplifier. The selective amplifier design, [3], is treated in the second part of this paper. The modulation phase is similar to the previous discussed case. The modulated signal is presented in **Fig. 4**.b and is given by equation (4).

This signal is further amplified by the base amplifier. In this section we consider an ideal frequency amplifier, with a pass-band constant gain, A_0, and zero gain for all other frequencies.

Also, we consider that the base amplifier's pass-band is centered on the modulating frequency and is wide enough to let passing the useful signal. In this case, only the modulated signal component centered on the modulation frequency is amplified, and all other components are rejected. The amplified signal, $Z(\omega)$ [see equation (9)] and the base amplifier transfer function are presented in **Fig. 4**.c.

During the demodulation phase, the signal is multiplied once again by *m*(*t*) and the amplified signal is shifted to the modulating signal odd harmonics. This results in bringing the useful signal back to its baseband, but also results in parasitic harmonic components centered on the even multiples of the modulating frequency. The output (demodulated) signal spectrum is presented in **Fig. 4**.d and is given by equation (13).
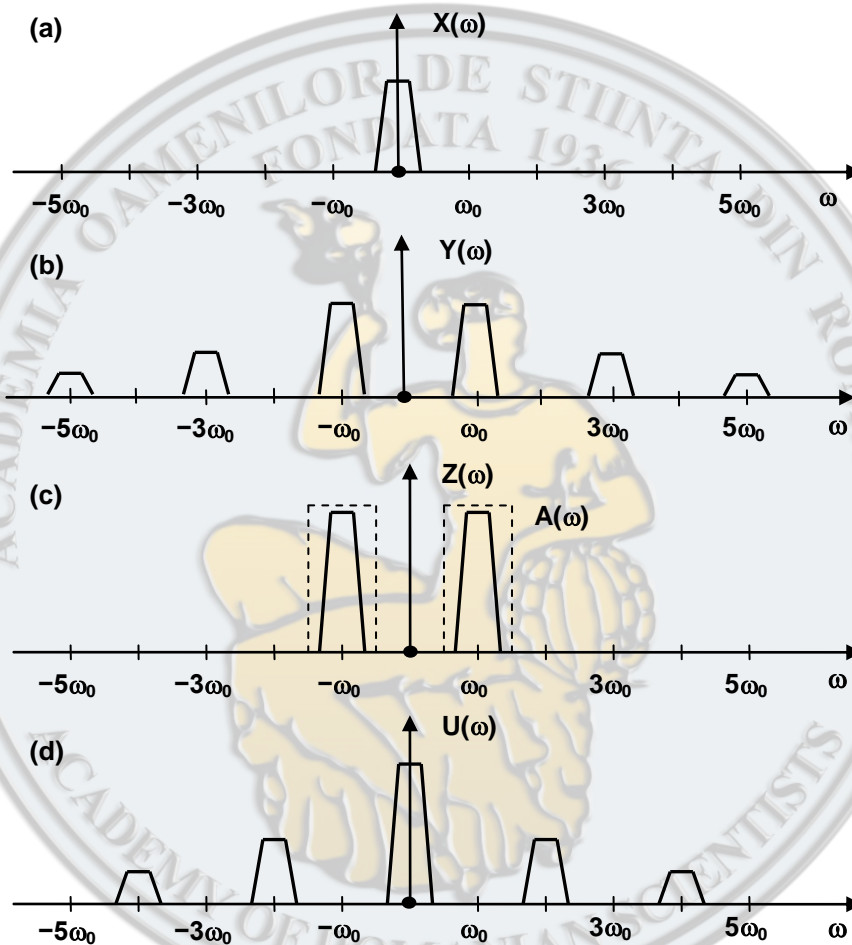

Fig. 4. Chopper amplifier signal evolution, *frequency selective base amplifier*:
(a) input signal, (b) modulated signal, (c) amplified signal, and (d) the output signal.

This result shows that, unlike the wide band base amplifier case, the selective amplifier use results in unwanted harmonic components centered on the even multiples of the modulating signal. However, this is not an important disadvantage of the frequency selective topology, as the output signal is generally filtered for noise and offset performance reasons.

Residual Offset and Noise Performances

Residual Offset

Ideally, the chopper technique completely eliminates the offset voltage. In practical applications however, chopper amplifiers present a finite offset voltage. The main contribution to this offset is given by the spikes introduced by the input modulator during switching, [1]. To evaluate the input modulator spike contribution to the residual offset we consider a zero input signal, $x(t)=0$.

Fig. 5. Spikes introduced by the modulator.   Fig. 6. The demodulated spike signal.

The real modulated signal will not be zero (as in the ideal case), but will present spikes at the modulating signal commutations. This effect is mainly due to capacitive coupling and charge injection, [7]. The spikes are in the same direction as the $m(t)$ value change. [For example, a rising $m(t)$ will introduce a positive spike (the positive input increases and the negative input decreases from their d.c. values)]. We also consider that the spikes shape is characterized by a negligible rise time followed by an exponential settling to the normal d.c. value. The real modulated signal for a zero input signal is presented in **Fig. 5**.

The modulated signal is then amplified and demodulated resulting in demodulated signal, $u(t)$, shape presented in Fig. 6. All spikes are now positive, because during the demodulation phase, the positive $y(t)$ spikes are multiplied by 1 (as the positive spikes appeared when $m(t)$ changed to "1") and similarly, the negative spikes are multiplied by -1. The output signal, $u(t)$, has a non zero d.c. component that represents the output residual offset.

For the wide band base amplifier topology the input equivalent residual offset can be evaluated, [1], to:

$$V_{OS,\text{rez}} = \frac{2\tau}{T}V_s \qquad (14)$$

The residual offset can be significantly reduced by using a frequency selective base amplifier.

The modulated signal spikes are narrow, fast variation signals, so they have a large band spectrum, much larger than the bandwidth needed for the useful signal. Using a frequency selective base amplifier we can get a significant rejection of the spikes frequency spectrum components outside the useful signal band. This rejection results in the output signal d.c. component and thus the residual offset voltage reduction.

It can be shown that, for a selective amplifier that rejects all components larger than double of modulating frequency, $2\omega_0$, the total input residual offset is given by, [1]:

$$V_{OS,rez} = \left(\frac{2\tau}{T}\right)^2 V_S \qquad (15)$$

Noise Performances

This section focuses on the chopper stabilization technique effects on the base amplifier's noise performances. Noise is a random signal and, for this reason, statistical methods must be applied in order to get accurate results on the chopper stabilized amplifier noise performances. [5], [6]

The base amplifier's noise is added to the useful signal during the *amplification phase* and then is affected by the *demodulation phase*, [4].

To describe the chopper amplifier noise performances comes to determining the effects of multiplying a random, noise signal, to the deterministic modulating signal, $m(t)$. By first evaluating the noise repartition and distribution functions, we can get the output noise autocorrelation function. Finally, integrating the autocorrelation function we get the output noise power spectral density, g_Y, [8]:

$$g_Y = \frac{2}{\pi^2} \sum_{n=-\infty}^{\infty} \frac{1-(-1)^n}{n^2} g_N(\omega - n\omega_0) \qquad (16)$$

where g_N is the base amplifier output noise power spectral density.

This result describes the *demodulation phase* effect on the base amplifier noise. Equation (16) gives only the relationship between the demodulator input and output noise and cannot predict the output noise by itself, we must first know the base amplifier noise. What equation (16) tells us is that, after demodulation, the base amplifier's noise is scattered at the odd multiples of the modulation frequency and that the noise power corresponding to the n order harmonic is reduced proportionally to $1/n^2$. The total noise power is not affected by demodulation, as ideally the switching process has no power losses.

Another important conclusion is that the chopper stabilization technique affects the base amplifier noise in the same manner, regardless if a wide band or frequency selective amplifier is used. However, the wide band amplifier and the frequency selective amplifier have different output noise power spectral distributions, so the total output noise will be different in the two cases.

Conclusions

The Part I of this paper gave a tutorial like overview on the chopper stabilization technique. The chopper technique uses modulation to shift the input signal spectrum to a higher frequency domain getting the signal separation from the amplifier's offset and low frequency noise. A standard chopper amplifier consists of a modulator, a base amplifier and a demodulator. The modulator moves the signal spectrum from the base-band to a higher frequency domain.

The base amplifier is the actual gain block. Two approaches are discussed: the use of a wide band amplifier and the use of a frequency selective amplifier. The wide band base amplifier is the simplest solution but the frequency selective amplifier has the advantage that only the useful signal is amplified while the offset and low frequency noise are rejected offering lower residual offset due to the spikes introduces during the modulation phase filtering. The demodulator brings the signal back to its base-band and scatter the offset and noise to higher frequencies.

One of the main advantages of the chopper stabilization technique is the low frequency noise reduction. The general chopper stabilization amplifier output noise PSD model presented in this paper was also used to analyze the chopper technique effect on two very common noise distributions: the white noise and the $1/f$ noise. The $1/f$ noise is successfully scattered around the modulation signal's odd harmonics, separating it from the signal and making it easy to filter. For this reason, chopper stabilization is an efficient technique in reducing the low frequency noise in precision amplifiers.

The chopper stabilization technique effectively reduces the input offset voltage to the microvolt level due mainly to the spikes introduced by the modulator during switching process.

R E F E R E N C E S

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