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Chopper Amplifier

Welcome to the ninth article in this column series. As the title suggests, each article provides insights and intuitions into circuit design and analysis. These articles are aimed at undergraduate students but may serve the interests of other readers as well. If you read this article, I would appreciate your comments and feedback, as well as your requests and suggestions for future articles in this series. Please e-mail your comments to me at ali@ece.utoronto.ca.

The previous article in this series presented two techniques for offset cancellation. These techniques rely on storing the dc offset voltage of the amplifier on a capacitor that is placed in series with the amplifier so as to cancel the offset. However, in doing so, the capacitors will end up in the signal path, blocking the dc content of the input signal and attenuating its content at low frequencies. Obviously, this would be OK if the signal is at higher frequencies, but there are many applications in which the signal being amplified is indeed at low frequencies (in the order of a few hertz). For example, temperature sensors and light sensors may produce signals that are in sub-1-Hz frequencies. Yet, we need to amplify these signals with amplifiers that inherently include offset. How can we do this? In this article, we explore a powerful technique known as chopper stabilization.

The principle of operation of a chopper amplifier is described using the block diagram shown in Figure 1. A chopper amplifier consists of a regular voltage amplifier with a gain of A and an (unwanted) offset voltage of V_{OS}, flanked on both sides by a modulator or *chopper*. The input voltage to a chopper amplifier is multiplied (*or chopped*) by a square wave periodic signal $p(t)$, which assumes $+1$ and -1 values. The chopped input signal is then *effectively* added to V_{OS} before being amplified by A. The output of the amplifier will be multiplied by $p(t)$ again to form the final output of the chopper amplifier. In this process, the input waveform is chopped twice, reproducing the input voltage at the output node with a gain of A. The offset voltage, V_{OS}, however, is chopped only once, hence appearing chopped at the final output of the chopper amplifier. In other words,

$$v_{out}(t) = Ap^2(t)\,v_{in}(t) + AV_{OS}\,p(t).$$

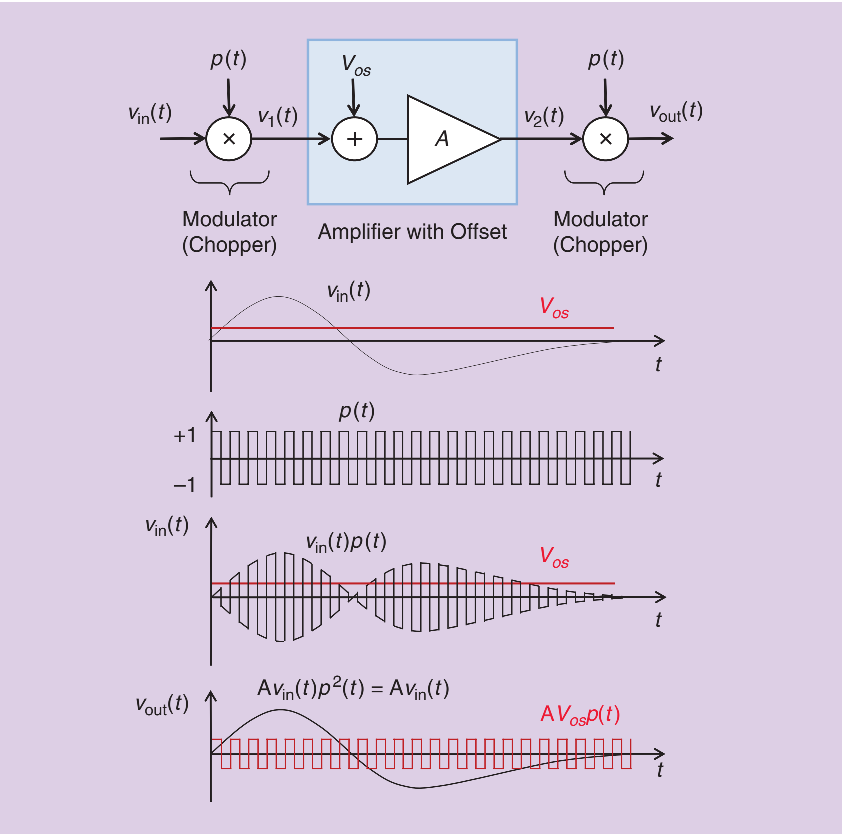

FIGURE 1: A chopper amplifier and its sample waveforms. While the input signal $v_{in}(t)$ preserves its waveform at the output, the offset voltage, V_{os}, appears as chopped at the output.

Digital Object Identifier 10.1109/MSSC.2016.2548821
Date of publication: 21 June 2016

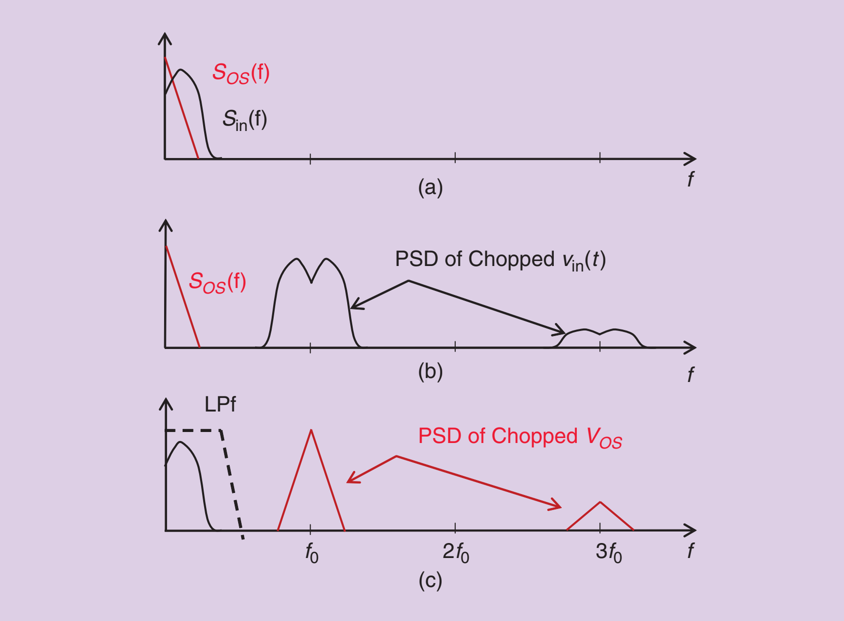

FIGURE 2: The PSD of signals in the chopper amplifier. (a) Both the input signal and the offset voltage occupy the same frequency band around dc. (b) After the first chopping operation, the signal spectrum is shifted to odd multiples of f_0 while the offset voltage remains centered around dc. (c) At the output node, the signal spectrum is down-converted to around dc while the offset voltage is shifted up in frequency. A low-pass filter can easily separate the two.

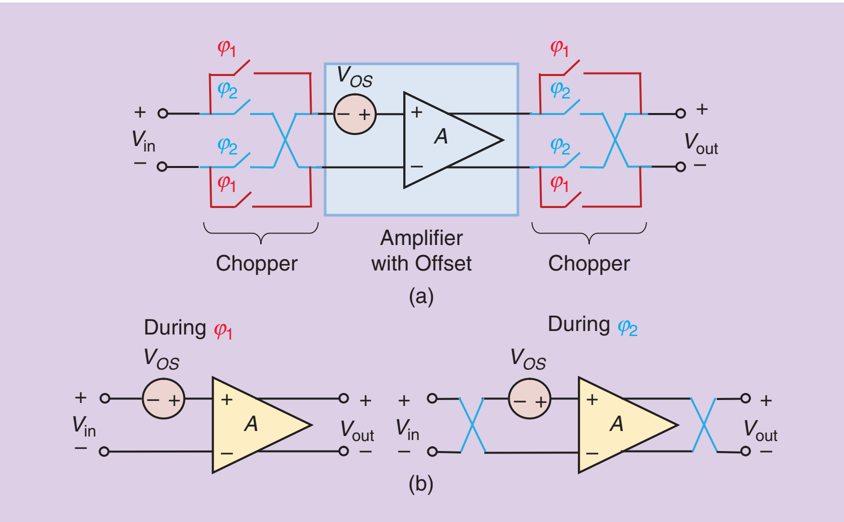

FIGURE 3: A differential implementation of chopper amplifier. (a) Multiplication by +1 is achieved during φ_1 and by −1 during φ_2 and (b) equivalent chopper amplifier circuit during φ_1 and φ_2.

Since $p^2(t) = 1$, we can write

$$v_{out}(t) = A(v_{in}(t) + V_{OS}\,p(t)).$$

Note that the output voltage $V_{out}(t)$ is the sum of two signals: the input waveform and the chopped offset voltage, both amplified by A.

To see how we can separate the desired output signal ($Av_{in}(t)$) from the undesired output signal ($AV_{os}\,p(t)$), let us examine these signals in the frequency domain.

Figure 2(a) shows the power spectral density (PSD) of the input signal $S_{in}(f)$ in black and the PSD of the offset voltage $S_{OS}(f)$ in red. Even though the offset voltage is considered a dc quantity, we have assumed an offset that may vary slowly with time and, hence, considered a nonzero bandwidth for the offset. This also includes the effect of flicker noise, a type of low-frequency noise whose PSD exhibits $1/f$ behavior. In this case, $V_{in}(t)$ and V_{os} overlap in their frequency content as shown and need to be separated.

The first chopping operation can be considered as an up-conversion (modulation) of the input signal to odd multiples of f_0, where f_0 is the fundamental frequency of $p(t)$. This is because $p(t)$, which is a square wave, is an odd function of time and, when expanded into its Fourier series, will only have components at odd multiples of f_0. Therefore, as shown in Figure 2(b), the up-conversion creates scaled copies of the spectrum centered around odd multiples of f_0, with the scaling factors being the Fourier coefficients of $p(t)$.

Upon a second chopping operation, the scaled up-converted copies of the input spectrum will all add up at around dc to reproduce the original input spectrum as shown in Figure 2(c). However, the offset voltage now experiences an up-conversion, and hence its frequency content will be shifted to around odd multiples of f_0, with no frequency content around dc. If f_0 is chosen to be sufficiently larger than the sum of the signal bandwidth and the offset bandwidth (actually, the flicker noise corner frequency), one can see that the chopper amplifier fully separates the signal from the chopped offset voltage. A simple low-pass filter can then easily preserve the input signal but eliminate the chopped offset voltage (and flicker noise).

Now let us see how we can implement a chopper amplifier. The multiplication by $p(t)$ is really simple if we opt for a fully differential implementation. As shown in Figure 3, the multiplication by −1 is simply implemented by swapping the two wires whereas the multiplication by one is implemented by *not* swapping the wires. In this figure, the multiplication by one is accomplished during phase 1 of the clock (φ_1: red switches) whereas the multiplication by −1 is accomplished during phase 2 of the clock (φ_2: blue switches), where the two phases are assumed nonoverlapping. To see this better, Figure 3(b) depicts an equivalent circuit during each of the two phases. This clearly shows that, in both phases of the clock, the input is essentially multiplied by A, as either there is no swap of wires (as in φ_1) or there are two swaps (as in φ_2), which is equivalent to no swapping. The offset voltage, however, is amplified by A during φ_1 and by $-A$ during φ_2; that is, the offset is chopped once.

A transistor-level implementation of a chopper simply replaces the ideal switches with transmission gates. These transmission gates add extra parasitic capacitances to the input and output nodes of the core amplifier, in addition to possible parasitic capacitances across the switches, causing charge sharing between nodes as the switches are turned on and off. Furthermore, the chopping operation puts extra constraints on bandwidth and power consumption of the core amplifier. A detailed discussion of these effects goes beyond the scope of this article. Interested readers are referred to a recent tutorial [1] and two key papers on this topic [2], [3].

In summary, the chopper stabilization technique chops the input voltage twice but chops the input offset voltage only once. This results in the input voltage preserving its waveform as it reaches the output while delivering a chopped (up-converted) version of the offset voltage to the output. A simple low-pass filter can then attenuate (or ideally eliminate) the chopped offset voltage.

References

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ASSOCIATE EDITOR’S VIEW

(continued from p. 6)

the magnetic field. What will happen? Here engineers with physics insight are separated from the MATLAB cowboys.

This candidate needs a technical follow-up question. How much energy is stored on an uncharged capacitor C? (Answer: no energy is stored.) And how much on a second capacitor of the same size C, charged to V? [Answer: $(1/2)CV^2$.] If the capacitors are shorted together and as charge must be conserved, the final voltage over both capacitors is V/2. The total energy has dropped to $(1/4) CV^2$. So, knowing a capacitor doesn’t dissipate power, why is the energy stored by the capacitors before connecting the capacitors together not equal to the energy stored by the parallel combination after the capacitors are shorted? Where is power lost in the system?

Actually, I missed that last one during my interview and still got the job. These questions do not check whether the candidate remembers the right answer but how he approaches a problem.

It is always a challenge to get a candidate to the point where he asks a question on a topic relevant to my company.

The technical part of the interview is over. The conversation moves to the candidate’s plans and ideas for his future. Although one cannot expect a five-year road map, it is always useful to know what is certainly excluded. Some interviewers appreciate a broad scope of interests: three sports, two societal engagements, and backpacking around the entire world. For me, it is more important that people make some reasonable choices and that there are no signs of erratic behavior.

It is always a challenge to get a candidate to the point where he asks a question on a topic relevant to my company. Sometimes that happens when we move on to the next interviewer. I tend to drop into a laboratory. Technically driven people want to know what is happening there, and the interaction with the researchers reveals more aspects of his personality. In the office of the next interviewer, I say goodbye to that gangly guy. One day he will work here and has to make sure I get my pension. Good education and sharp selection is, for me, a matter of self-interest!