Digital Control of Duty Factor for Optically-Chopped Beams

ABSTRACT

An optical chopper blade generally modulates a beam with 50% duty factor. It is possible to achieve <50% duty factor by stacking two identical blades, or by using specialty blades, which exist in both fixed and variable duty factor designs. In all of these cases, duty factor adjustments require stopping the chopper. The most flexible way to vary the duty factor is to synchronize two SR542 Precision Optical Choppers. This allows digital tuning of the duty factor continuously from 0% to 50% without stopping your experiment, and opens the door to remote, automated tests.

Introduction

Most optical chopper blades are manufactured to produce an optical waveform with 50% duty factor: alternately passing and blocking the beam for 50% of each optical period. However, a sample often exhibits interesting or non-trivial dependence on input power (e.g. nonlinear effects, photobleaching, thermal effects, etc.)[1–4]. In other cases, you may need to gate an excitation pulse for time-resolved or pump-probe imaging[5, 6]. For these experiments, the ability to easily vary the duty factor of the chopped optical beam can be valuable.

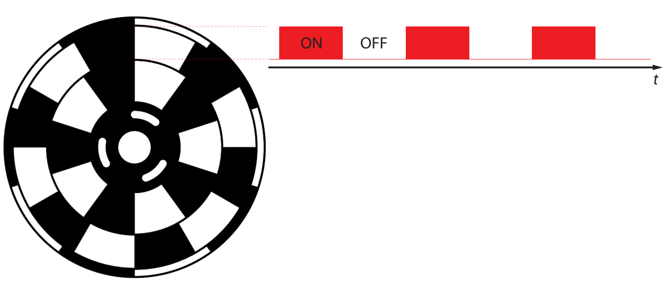


Figure 1: The O54256 5/6 dual-slot blade modulates an optical beam with 50% duty factor: $T_{\mathrm{on}} = T_{\mathrm{off}}$.

There are a few ways to change the duty factor of an optically-chopped beam:

1. Choose or manufacture a blade with unequal "spoke" and "aperture" widths.
2. Mount two chopper blades on the same motor, with a relative rotation between them.
3. Use a variable duty factor blade.
4. Synchronize two optical choppers, and adjust the phase of one relative to another.

If you only need a fixed duty cycle, for example 10%, then selecting or manufacturing a blade with appropriate "spoke" and "aperature" widths is sufficient. We provide design guidelines in the SR542 Operation Manual if you wish to design a custom blade.

Stacked Blades

Perhaps the simplest way to achieve adjustable duty factor is to stack two identical chopper blades, mounting them on the same chopper motor with a rotational offset between the two. That offset reduces the open aperture width, i.e. the duty factor. To change the duty factor, you must stop the motor, loosen the mounting screws, and rotate the additional blade. Achieving a desired duty factor with precision may be difficult.

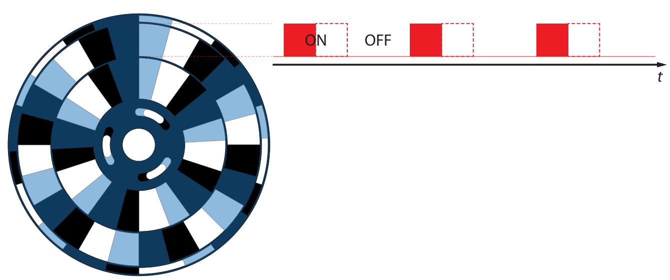


Figure 2: A 25% duty factor on the outer track can be achieved by stacking a second blade (shown in transparent blue), with a relative rotation of 90°opt (15°mech). Original 50% duty factor is shown with red dashed line for reference.

Variable Duty Factor Blade

With the SR542 we offer the O542DF variable duty factor blade. This lithographically-defined and chemically-etched blade provides apertures with precision duty factors between 10% and 90%, in steps of 10%. The duty factor is selected by choosing where along the blade radius you position the beam path. Therefore, a change in duty factor does require beam re-alignment.

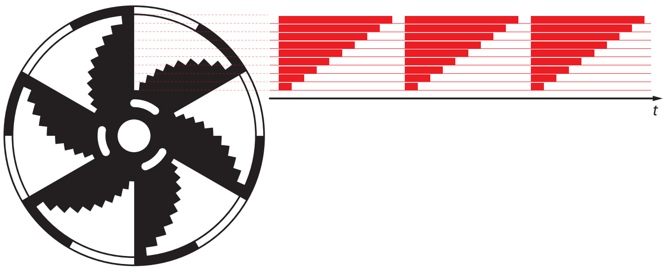


Figure 3: O542DF variable duty factor blade. Depending on the beam position along the blade radius, the duty factor can be set to $n\times$(10%) (for $n = 1, 2, 3 \ldots 9$).

Synchronized Choppers

The most flexible way to control the duty factor is to synchronize two SR542 optical choppers via the Source Out of the first chopper and Ext Sync Input of the second. This is effectively the same as stacking two blades on a single motor, but once synchronized, phase adjustments of the second chopper provide digital and high-precision duty factor control, without the need to stop the chopper motor (or your data collection) to adjust the duty cycle.

Phase alignment using an oscilloscope

To get started, place both optical chopper heads in the beam path, with the beam passing through the desired blade apertures. For concreteness, we will assume installation of standard O54256 5/6 dual track blades on both chopper heads, and alignment of the beam path to the Outer track of slots. Configure the first chopper (hereafter considered chopper 1) as desired. For example:

- Source = Internal Freq
- Multiplier = ×1
- Control = Outer
- Int Freq = $165\,\mathrm{Hz}$

Configure the second chopper (chopper 2) similarly, but with the Source = Ext Sync. On the rear panel, connect the Source Out of chopper 1 to the Ext Sync Input of chopper 2 as shown in Fig. 4. This makes chopper 1 the primary timekeeper, followed by chopper 2's internal phase-locked loop. Connect chopper 1's Outer Slots Reference Output to oscilloscope Channel 1, and chopper 2's Outer Slots Reference Output to Channel 2. Connect the photo-detector's output to Channel 4 of the oscilloscope. Turn on both chopper motors by pressing the Run / Stop button.

Set the oscilloscope to trigger on Channel 1, and set the timebase appropriately to see a few periods of the signals on the display. Many oscilloscopes include a duty factor measurement feature. It can be helpful to activate this for the photo-detector signal. You will likely see waveforms similar to those in Fig. 5a. Note the following features:

1. A phase shift $\Delta\phi_{1-2}$ between the chopper 1 and chopper 2 reference signals
2. A phase shift $\Delta\phi_{\mathrm{s}}$ between the chopper 1 and photo-detector signal
3. A photo-detector signal with less than 50% duty factor ($T_{\mathrm{on}}/T_{\mathrm{off}} < 0.5$)

The phase shift $\Delta\phi_{1-2}$ is due to a difference in the mounted blade orientation on each chopper head. The phase shift $\Delta\phi_{\mathrm{s}}$ is due to the difference in position *around the blade track* where the signals are generated. The reference outputs are produced by photo-interrupters located on the base of each chopper motor (6 o'clock position as shown in Fig. 4), while the laser beam path passes somewhere else (for example, the 11 o'clock position).

By monitoring the photo-detector signal on the scope and adjusting the Phase of chopper 2,[1] we can recover a 50% duty cycle waveform, as in Fig. 5b. We will refer to this arrangement as phase-aligned.[2] Once the two choppers are phase-aligned, it is convenient to press Rel Phase on chopper 2. This turns on the Rel indicator, and displays the current phase setting as 0°. All future adjustments will be relative to this Rel point.

You now have digital control of the duty factor via the phase setting of chopper 2, which is easily controllable via the front panel knob, keypad, or USB remote interface. This makes it easy to optimize your signal, or perform a duty factor sweep. There is no need to stop the motor to adjust stacked blades, or to re-align the beam path. (There will be some small wait time for chopper 2 to settle and re-acquire "Chopper Locked" status after each phase adjustment. For small phase adjustments, this time is quite brief, usually $\ll 1\,\mathrm{s}$).

Note that as you adjust chopper 2's phase about 0° by either $+\Delta\phi$ or $-\Delta\phi$, the duty factor will decrease from a maximum of 50%. The duty factor $D = T_{\mathrm{on}}/T_{\mathrm{off}}$ can be calculated as follows:

[1] Equivalently, the phase of chopper 1 can be adjusted, since both motors are being controlled to chopper 1's internal Source Clock, and the Phase setpoint is relative to that internal reference.

[2] However, "phase-aligned" does not necessarily equate with edge-coincidence of the Reference Output signals. This is only the case when the angular distance between the photo-interrupter and the beam spot is identical for the two motors. See discussion below.

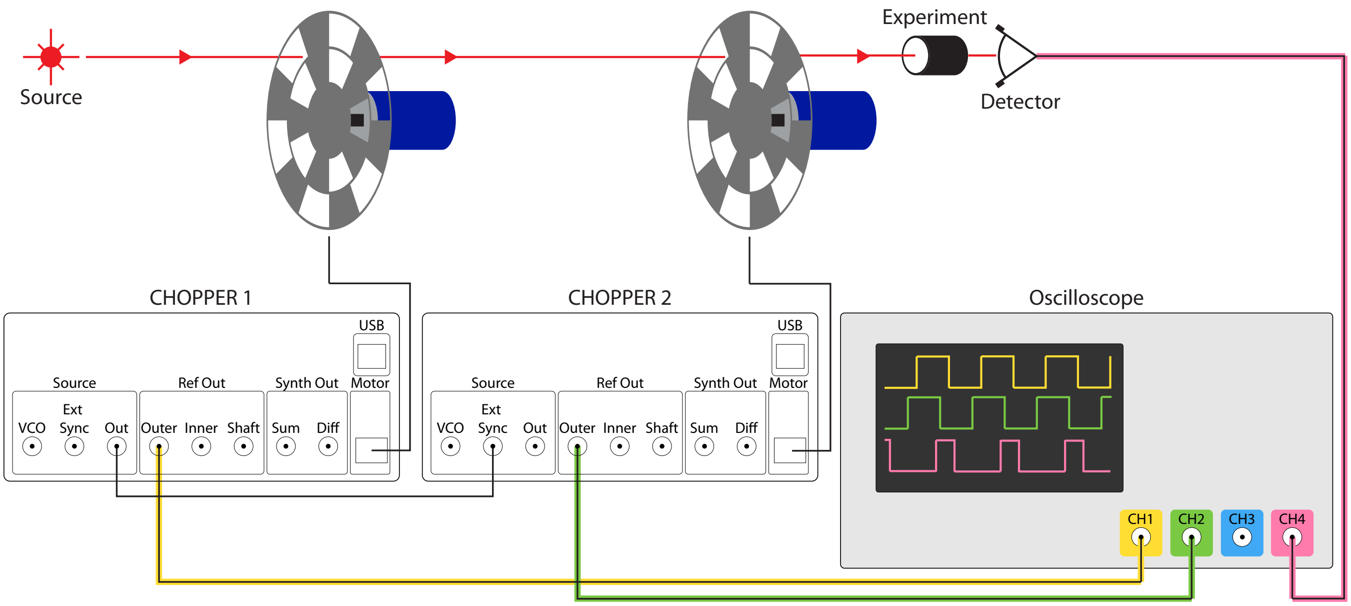


Figure 4: Block diagram for synchronization and phase alignment of two SR542 Optical Choppers using an oscilloscope. Chopper 1 is the primary timekeeper, so it's Source Output is connected to Chopper 2's Ext Sync Input. Outer Slots Reference Outputs from both choppers are connected to an oscilloscope, as is the dual-chopped beam signal, which is output from a photo-detector.

$$D(\phi^\circ) = \left| 0.5 - \frac{(\phi^\circ \bmod 360^\circ)}{360^\circ} \right| \tag{1}$$

where ϕ° is the phase setpoint of chopper 2 (relative to the "zero" that we set above via the phase alignment procedure).

Since both blades are designed with a 50% duty factor, it is not possible to achieve a dual-chopped beam with duty factor $>$50% using this method. For two chopper blades with duty factors D_1 and D_2, the maximum achievable duty factor with this method is the smaller of D_1 and D_2, while the minimum achievable duty factor is $D_1 + D_2 - 1$ (or 0, if the formula is negative).

Perhaps surprisingly, the dual-chopped beam does not suffer from additional phase jitter compared to a single-chopper experiment. For duty factors <50%, one chopper is responsible for gating the beam ON (rising edges of the photo-detector output), while the other gates the beam OFF (falling edges). Therefore, the jitter of the dual-chopped arrangement is approximately the average of the phase jitter from each chopper separately.

As the duty cycle is reduced, if the beam size becomes larger than the effective aperture width, then the effective beam intensity is also reduced. Therefore, care should be taken when interpreting data sets that are acquired as function of duty factor, as both duty factor and (perhaps inadvertently) beam size may be modulated.

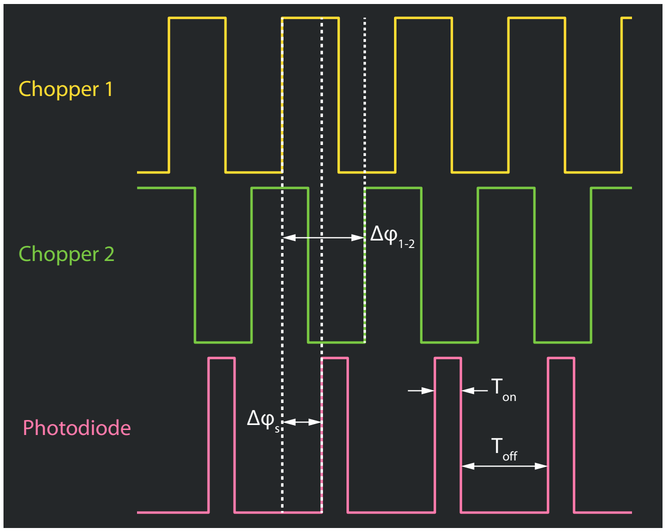
In the representative waveforms of Fig. 5b, you may have noticed edge-coincidence between the Reference Outputs of chopper 1 and chopper 2 when the dual-chopped beam reaches 50% duty factor. Therefore, the dual-chopped beam appears to be the logical "AND" of the Reference Outputs. However, this is only true when the beam passes through each chopper blade at *exactly* the same location (e.g. 11 o'clock), *and* the photo-interrupters are installed identically on each motor.[3] Therefore, the photo-detector signal itself is the only direct and reliable way to establish the dual-chopped duty factor.

If the signal-to-noise ratio (SNR) of the photo-detector output is poor, then you may not be able to detect the rectangular waveform directly on an oscilloscope, much less measure its duty factor. In that case, the phase alignment procedure is performed while monitoring the photo-detector signal with a lock-in amplifier.

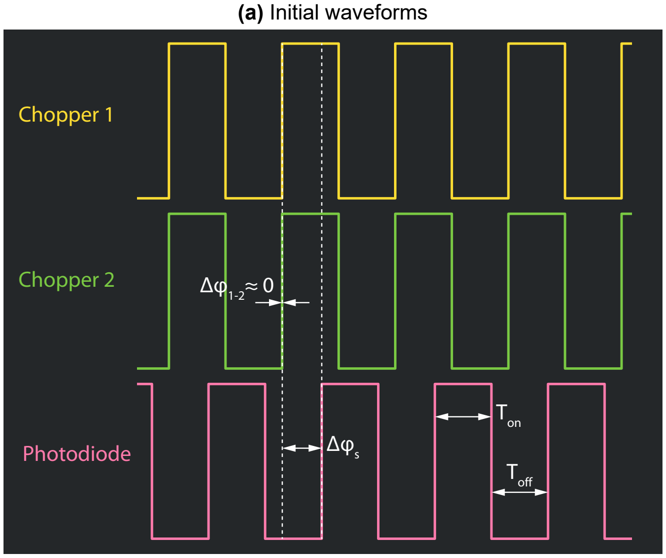
Phase alignment using a lock-in amplifier

To establish phase alignment between the two choppers, we first need to record a baseline lock-in signal for

[3] For high slot count blades, lateral and vertical displacements of the photointerrupters on the motor base will impart a larger phase shift to the Reference Output signal.



(a) Initial waveforms



(b) Phase-aligned waveforms

Figure 5: Simulated oscilloscope traces for a beam passing through a series of two optical choppers. (a) Before phase alignment, a phase shift $\Delta\phi_{1-2}$ exists between the chopper 1 and chopper 2 signals, and the photo-detector signal duty factor ($T_{\mathrm{on}}/T_{\mathrm{off}}$) will likely be <50%. (b) After phase alignment, the photo-detector output waveform has a 50% duty factor. The phase shift $\Delta\phi_{\mathrm{s}}$ of the photo-detector signal persists.

a singly-chopped 50% duty cycle beam. Keep the connection from chopper 1's Source Out to chopper 2's Ext Sync Input unchanged (as in Fig. 4). Connect chopper 1's Outer Slots Reference Output to the lock-in Reference Input, and configure the lock-in Reference to External and Pos TTL.[4] Connect the photo-detector output to the lock-in signal Input, and configure the Sensitivity, Time Constant, Input Range, Input Coupling, and Filter Slope as appropriate for your signal. Once chopper 1's motor has started and indicates "Chopper Locked," the lock-in should also indicate a Reference lock at the chop frequency.

At this point, it may be useful to configure chopper 2 for Shutter Mode.[5] This allows you to use its Phase setting to adjust the static orientation of the chopper blade. While monitoring the signal magnitude R on the lock-in, adjust the phase of chopper 2 until the signal is maximized. Chopper 2 is now oriented as a "beam pass." Record the magnitude (and phase θ) of the signal, as this represents a singly-chopped beam with 50% duty factor.

Turn on the chopper 2 motor. In general, the signal magnitude R will be reduced and the signal phase θ relative to the reference will also have shifted. Adjust the phase of chopper 2 until you have recovered the original signal magnitude and phase. At that point, the choppers are phase-aligned: you have recovered a 50% duty factor waveform. Press Rel Phase on chopper 2 to "zero" the current phase, and enable phase adjustments *relative* to this zero. Eq. (1) can now be used to calculate the duty factor from chopper 2's phase.

Lock-in signal analysis

It's useful to derive the lock-in signal dependence on duty factor. We can describe the time-domain rectangular waveform of the dual-chopped beam as follows.

$$\begin{aligned} x(t) &= A \text{ for } 0 \leq (t \bmod T) < DT \\ &= 0 \text{ otherwise} \end{aligned} \tag{2}$$

where T is the signal period, and $DT = T_{\mathrm{on}}$ is the time spent in the "high" or "ON" state, such that D represents the duty factor ($0 \leq D < 1$). See Fig. 7.

This signal can be represented by a Fourier series of the form:

$$x(t) = a_0 + \sum_{n=1}^{n=\infty} a_n \cos\left(\frac{2\pi tn}{T}\right) + \sum_{n=1}^{n=\infty} b_n \sin\left(\frac{2\pi tn}{T}\right) \tag{3}$$

For comparison, in a lock-in amplifier, the reference oscillators for the X and Y channels are defined by:

$$r_X(t) = \sin\left(n\left(\frac{2\pi t}{T} + \theta_{\mathrm{ref}}\right)\right) \tag{4}$$

$$\begin{aligned} r_Y(t) &= \sin\left(n\left(\frac{2\pi t}{T} + \theta_{\mathrm{ref}}\right) + \pi/2\right) \\ &= \cos\left(n\left(\frac{2\pi t}{T} + \theta_{\mathrm{ref}}\right)\right) \end{aligned} \tag{5}$$

[4] Alternatively, you could use the lock-in as the primary timekeeper, providing its Reference Output to the Ext Sync Inputs of *both* choppers. However, it is beneficial to provide the Slots Reference Output from chopper 1 to the lock-in, as the lock-in's own PLL can then track the actual blade motion.

[5] Set Source = Internal Freq and Int Freq = $0\,\mathrm{Hz}$.

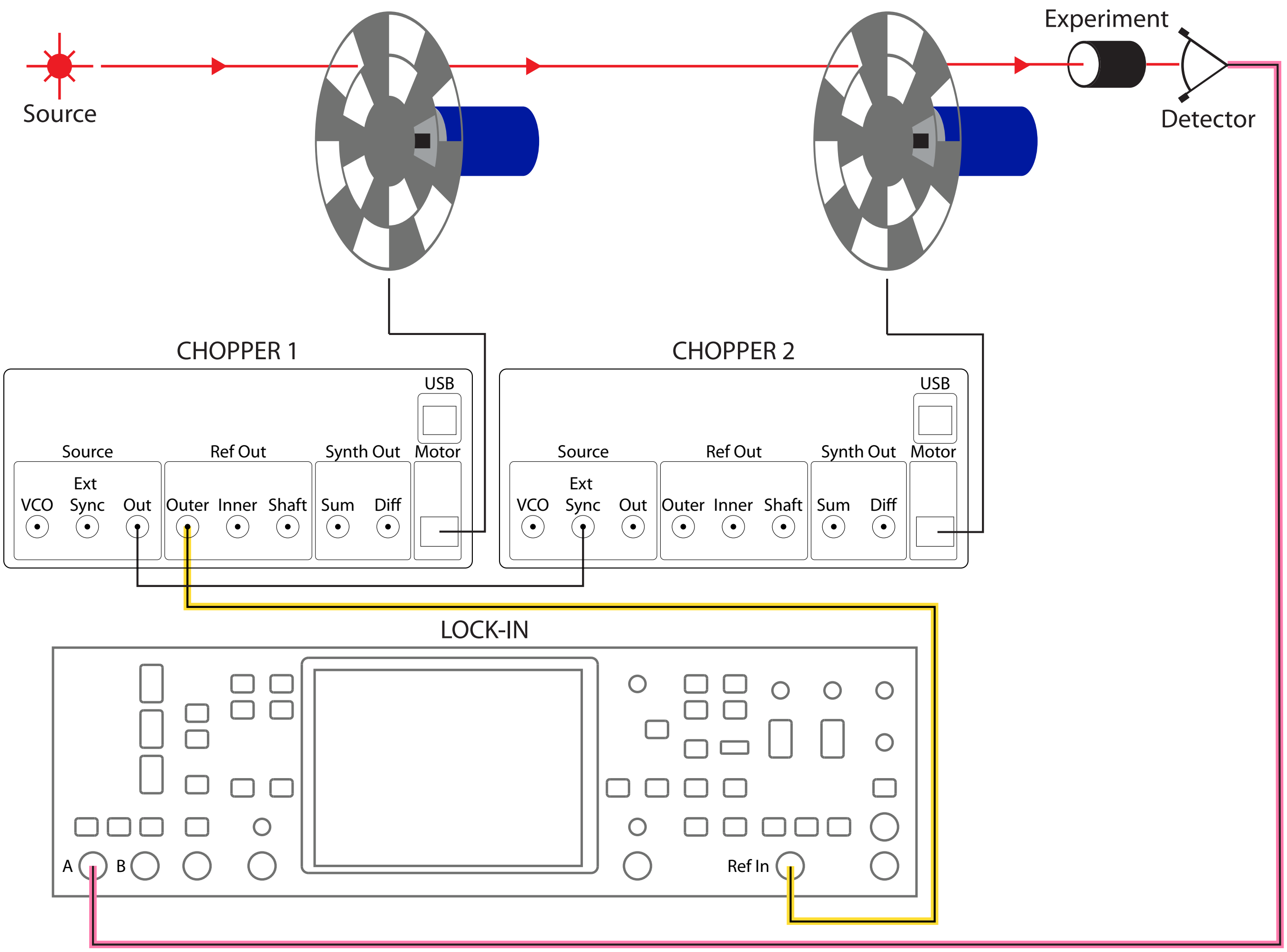


Figure 6: Block diagram for synchronization and phase alignment of two SR542 Optical Choppers using a lock-in amplifier.

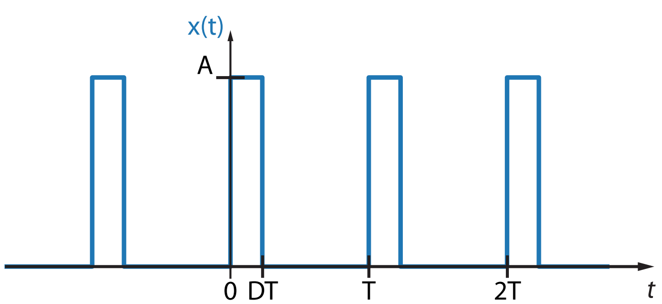


Figure 7: A rectangular waveform with peak-to-peak amplitude A, duty factor D, and period T.

such that the a_n's of Eq. (3) will correspond to Y-channel outputs, and the b_n's to X-channel outputs.

The DC term of Eq. (3) is calculated as

$$\begin{aligned} a_0 &= \frac{1}{T}\int_0^T x(t)dt \\ &= \frac{1}{T}\int_0^{DT} A dt \\ &= AD \end{aligned} \tag{6}$$

The remaining a_n coefficients are calculated as:

$$\begin{aligned} a_n &= \frac{2}{T}\int_0^T x(t)\cos\left(\frac{2\pi tn}{T}\right)dt \\ &= \frac{2}{T}\int_0^{DT} A\cos\left(\frac{2\pi tn}{T}\right)dt \\ &= \frac{A}{\pi n}\sin(2\pi nD) \end{aligned} \tag{7}$$

The b_n coefficients are calculated similarly:

$$\begin{aligned} b_n &= -\frac{A}{\pi n}\left[\cos(2\pi nD) - 1\right] \\ &= \frac{2A}{\pi n}\sin^2(\pi nD) \end{aligned} \tag{8}$$

Using the a_n's and b_n's, we can calculate the magnitude and phase (lock-in R and θ outputs) for a given harmonic, duty factor, and peak-to-peak amplitude.

$$\begin{aligned} \theta &= \arctan\left(\frac{a_n}{b_n}\right) \\ &= \arctan\left(\frac{1}{2}\frac{\sin(2\pi nD)}{\sin^2(\pi nD)}\right) \end{aligned} \tag{9}$$

$$\begin{aligned} R &= \frac{1}{\sqrt{2}}\sqrt{a_n^2 + b_n^2} \\ &= \frac{1}{\sqrt{2}}\left(\frac{2A}{\pi n}\right)\sin(\pi nD) \end{aligned} \tag{10}$$

where the pre-factor of $1/\sqrt{2}$ comes from the lock-in's RMS calculation. The results of these calculations for $0 \le D < 0.5$ are shown in Fig. 8, where the independent variable ϕ_2 is the phase of chopper 2, which is used to adjust the duty factor.

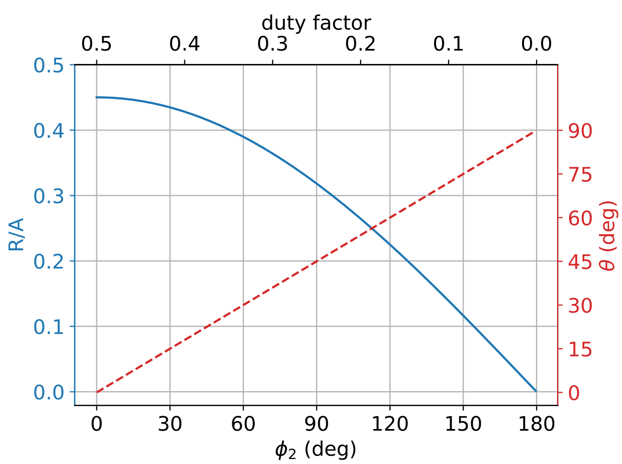


Figure 8: R (normalized to square wave peak-to-peak amplitude A, and including the factor of $1/\sqrt{2}$ for RMS) and θ vs. ϕ_2 (chopper 2 phase) and duty factor, for lock-in harmonic $n = 1$.

In the case that $D = 0.5$, the peak-to-peak rectangular waveform amplitude and the lock-in measurement are related simply by

$$R(D = 0.5) = \frac{1}{\sqrt{2}}\left(\frac{2A}{\pi n}\right) \tag{11}$$

In this case, only $n = 1, 3, 5, 7\ldots$ are non-zero (i.e. the familiar case that a square wave consists of only odd harmonics). As a simple rule-of-thumb, when measuring the the first harmonic (fundamental) of a 50% duty square wave, the lock-in measures an amplitude $R \approx 0.45\times$ the peak-to-peak amplitude, A.

Conclusion

By synchronizing two SR542 Optical Choppers, you can achieve precision digital control of the duty factor of a chopped beam. This greatly simplifies setting and sweeping of the duty factor as compared to other methods for duty factor control. In particular, by using the SR542's remote USB interface and a simple data collection loop, automated studies involving variable duty factor become possible.

Phase alignment of the two choppers does require a bit of manual tuning before chopper 2's phase can be used as a proxy for duty factor. However, this process is straightforward. Even if the signal produced by the chopped beam and photo-detector is too weak for direct visualization on an oscilloscope, synchronization and phase-alignment of the two choppers is possible by monitoring the detector's output with a lock-in amplifier.

The technique can be used with any of available blade designs for the SR542 in order to optimize for your experiment's beam size and ideal chop frequency.

References

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