Synchronous Detection of Signals in Noise

PC Robinson

Introduction

A useful technique for extracting small signals embedded in noise.

Amplifiers are required to increase the amplitude of small signals in order to allow them to be processed. However, semiconductors exhibit several well known noise characteristics: shot, thermal, 1/f (flicker), burst and avalanche, and are associated with random recombination of charge carriers, thermal effects and defects contained within the semiconductor materials. This is particularly true of the ubiquitous high gain operational amplifier.

Early bi-polar op-amps were particularly susceptible to these problems until improved types were developed with low noise FET input stages and noise figures of around 15 $nV/(Hz)^{0.5}$ (e.g. LF356). These days devices with noise figures of 0.9 $nV/(Hz)^{0.5}$ (e.g. AD797) are common.

Nevertheless the basic problem still remains: signals have to be amplified but the signal to noise ratio remains the same.

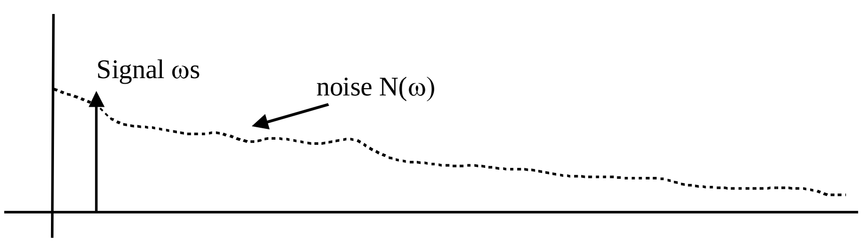


Fig 1: Noise problem

Techniques exist to get round this problem. For example recalling the convolution theorem, the output of an estimator (filter) is given by convolving the impulse response of the estimator with its input. Hence by matching the impulse response with a known input signal, a good estimate can be retrieved at the output. A so called matched filter. Another technique is to use a correlator.

The technique to be described here uses a synchronous detector. I used this technique some years ago now on a laser alignment system used in a semiconductor wafer stepper.

Basic Alignment System

Consider the problem of a laser alignment system (simplified) Fig 2, as follows.

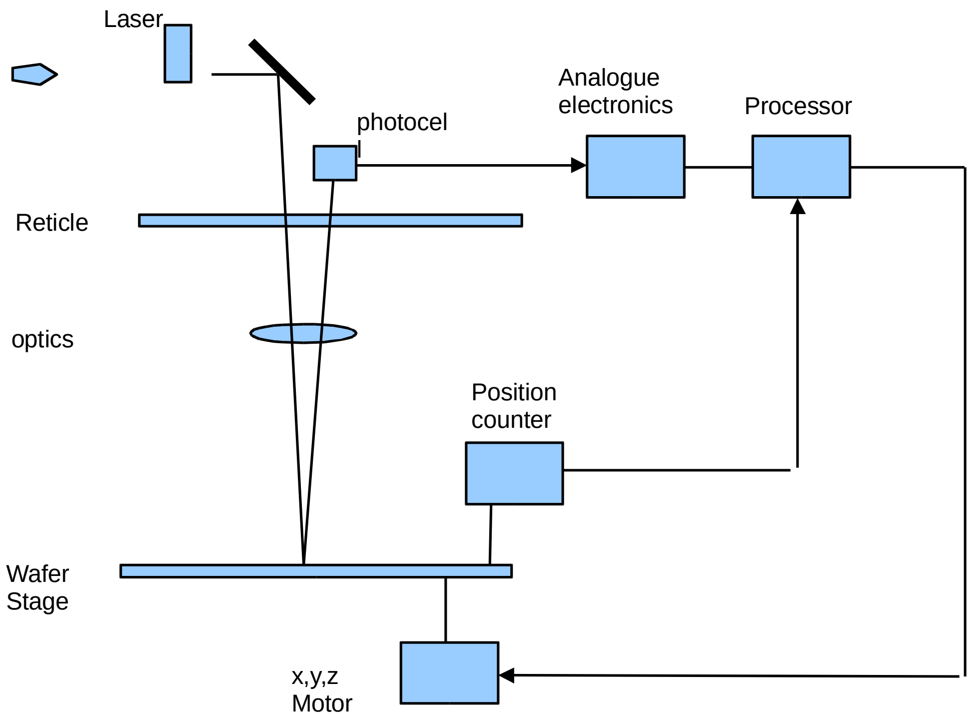


Fig 2 Alignment System

A basic description (Fig 2): the reticle containing the the chip mask contains fiducial markers identical to those etched on the wafer stage. The laser illuminates the alignment markers and the processor commands the stage motor to scan, such that the reflected alignment laser radiation is amplitude modulated by the marker spatial frequency and detected by the photocell. The signal is amplified and zero crossing interrupts cause the processor to read the stage position counters. When the two alignment signals are in phase, then the aligned position has been found and the position counts stored. This is the aligned position.

There are two problems: 1) as each photolith process layer is applied to the wafer, the signals become much smaller giving a dynamic range problem 2) The signals generated are corrupted with optical and electrical noise, thus the interrupt threshold detector is subject to errors causing errors in the stored counter data.

These problems were solved by 1) incorporating an effective 60 db agc loop in the front end electronics and 2) optically phase modulating the laser signal (30 kHz) and then synchronously detecting the scan modulation using the 30 kHz reference signal. See Fig 3.

Fig 4 shows the spectra of the modulation process of the alignment signal. The electrical signal from the photcell is a double side band suppressed carrier signal plus system noise.

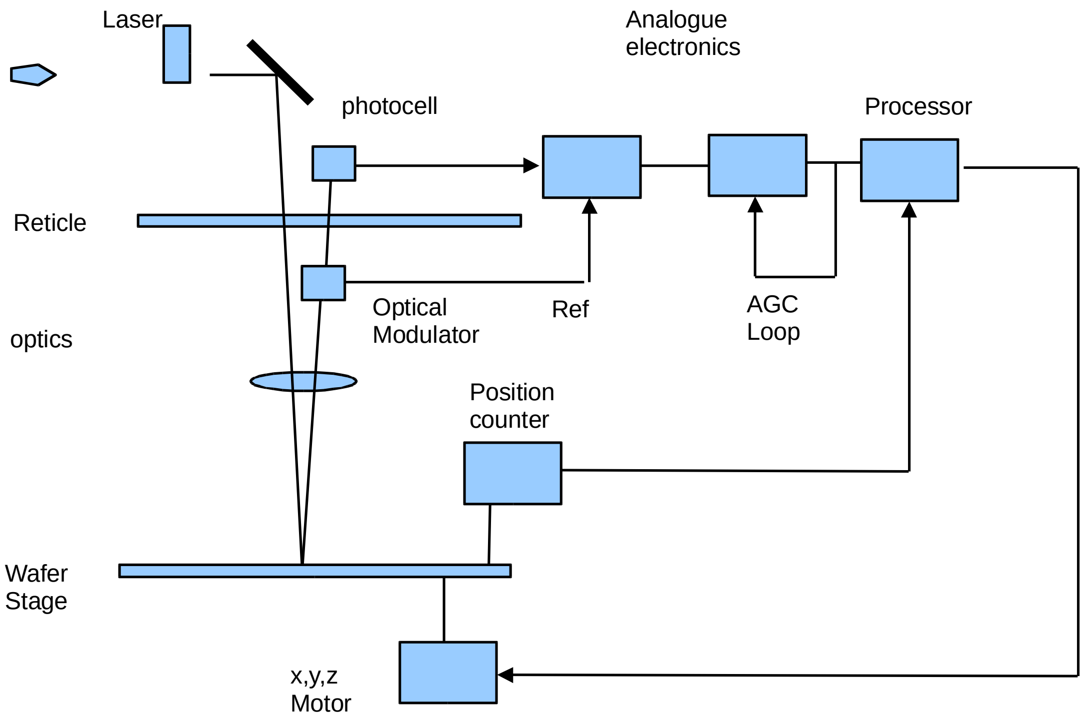


Fig 3: Alignment System with AGC and Synchronous Detection

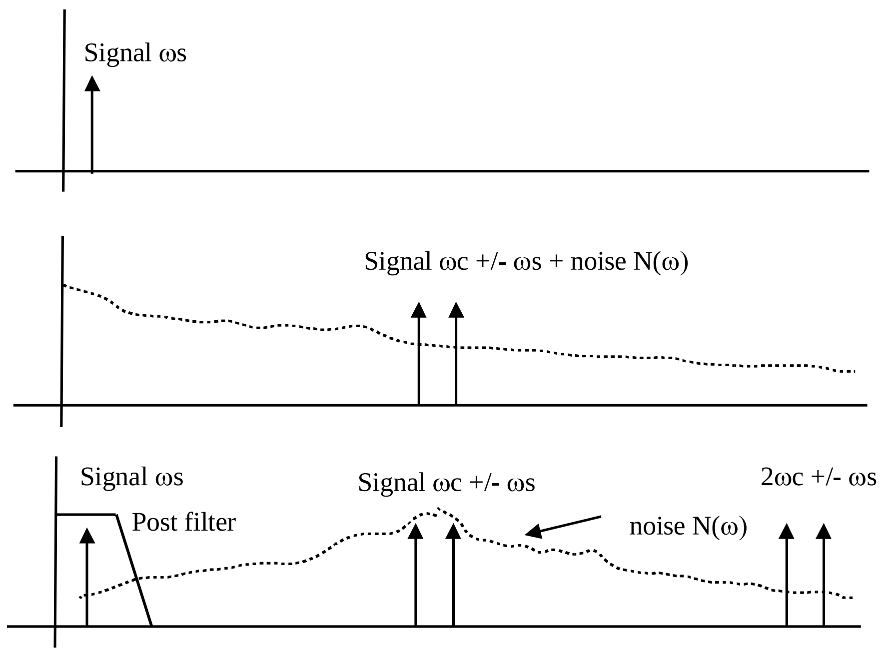


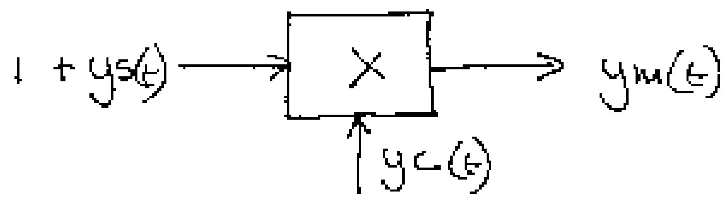
Fig 4: a) Scan signal b) Received modulated signal plus noise c) Detected Signal

The synchronously detected signal frequency translates the noise spectra to the carrier (optical modulation) frequency, plus a twice frequency component and the synchronously detected scan modulation is returned to base band and can be filtered with a simple post detection filter. The signal to noise ratio is greatly improved. The following analysis includes a DC term and thus the carrier is retained and is therefore more general.

Synchronous detection analysis

P C ROBINSON 11/11/11

Consider a balanced modulator (multiplier)



This produces an AM signal as follows

$ys(t) = \sin \omega s t$ ---(1) base band signal

$yc(t) = \sin \omega c t$ ---(2) Carrier

$ym(t) = \sin \omega c t \,(1 + \sin \omega s t)$

the '1' is a DC... term that ensures the carrier is present.

$\therefore \quad ym(t) = \sin \omega c t + \sin \omega c t . \sin \omega s t$ ---(3)

using $\quad 2 \sin A \sin B. = \cos(A-B) - \cos(A+B)$

We get $\quad ym(t) = \sin \omega c t + \frac{1}{2} \cos(\omega c t - \omega s t)$

$\qquad + \frac{1}{2} \cos(\omega c t + \omega s t - \pi)$ --(4)

Which is the carrier + upper and lower side bands

Now pass signal through a noisy channel, recieved signal is

$$y_R(t) = \sin\omega_c t + \sin\omega_c t.\sin\omega_s t + N(t) \quad \text{---} (5)$$

We detect with a locally produced oscillator signal tuned to the carrier frequency ω_c, and with some random phase ϕ with respect to the incoming carrier, in a multiplier

$$y_D(t) = \sin(\omega_c t + \phi).\ y_R(t)$$

$$= \sin\omega_c t.\sin(\omega_c t + \phi) + \sin(\omega_c t + \phi).\sin\omega_s t.\sin\omega_c t + \sin\omega_c t.N(t)$$

Using $\sin(A+B) = \sin A\cos B + \cos A\sin B$

$$y_D(t) = \cos\phi.\sin\omega_c t.\sin\omega_c t$$
$$+ \sin\phi.\cos\omega_c t.\sin\omega_c t$$
$$+ \sin\omega_s t.\sin\omega_c t\left[\sin\omega_c t.\cos\phi + \cos\omega_c t\sin\phi\right]$$
$$+ \sin\omega_c t.N(t)$$

$$\therefore y_D(t) = \cos\phi.\sin^2\omega_c t + \sin\phi\left[\cos\omega_c t.\sin\omega_c t\right]$$
$$+ \cos\phi.\sin^2\omega_c t.\sin\omega_s t$$
$$+ \sin\phi.\cos\omega_c t.\sin\omega_c t.\sin\omega_s t + \sin\omega_c t N(t)$$

$$\therefore y_D(t) = \cos\phi.\sin^2\omega_c t + \frac{\sin\phi}{2}.\sin(\omega_c t + \omega_c t) - \frac{\sin\phi}{2}.\sin(\underbrace{\omega_c t - \omega_c t}_{=0})$$
$$+ \cos\phi.\sin^2\omega_c t.\sin\omega_s t + \quad \text{Cont...}$$

Cont ...

$$+ \sin\phi \cdot \cos\omega_c t . \sin\omega_c t . \sin\omega_s t + \sin\omega_c t . N(t)$$

the 3rd term is zero

$$\therefore \; y_D(t) = \cos\phi . \sin^2\omega_c t + 0.5 \sin\phi . \sin 2\omega_c t$$
$$+ \cos\phi . \sin^2\omega_c t . \sin\omega_s t$$
$$+ \sin\phi . \sin\omega_s t \left[\cos\omega_c t . \sin\omega_c t \right] + \sin\omega_c t . N(t)$$

$$\therefore \; y_D(t) = \cos\phi . \sin^2\omega_c t + 0.5 \sin\phi . \sin 2\omega_c t$$
$$+ \cos\phi . \sin^2\omega_c t . \sin\omega_s t$$
$$+ \sin\phi . \sin\omega_s t \left[\frac{1}{2} \sin(2\omega_s t) - \frac{1}{2} \sin(0) \right]$$
$$+ \sin\omega_c t . N(t)$$

$$\therefore \; y_D(t) = \cos\phi . \sin^2\omega_c t + 0.5 \sin\phi . \sin 2\omega_c t$$
$$+ \cos\phi . \sin^2\omega_c t . \sin\omega_s t$$
$$+ 0.5 \sin\phi . \sin\omega_s t . \sin 2\omega_c t + \sin\omega_c t . N(t)$$

Collecting terms

$$y_D(t) = \cos\phi \left[\sin^2\omega_c t + \sin^2\omega_c t . \sin\omega_s t \right]$$
$$+ 0.5 \sin\phi \left[\sin 2\omega_c t . \sin\omega_s t + \sin 2\omega_c t \right]$$
$$+ \sin\omega_c t . N(t) \quad --- \quad (6)$$

(4)

Now if ϕ is zero, $\cos\phi = 1$, $\sin\phi = 0$ ie the local oscillator is synchronous to the carrier, then (6) becomes

$$y_D(t) = \cancel{\cos}\ \sin^2\omega_c t + \sin^2\omega_c t . \sin\omega_s t$$
$$+ 0 + \sin\omega_c t . N(t)$$

$$y_D(t) = \sin^2\omega_c t\left[1 + \sin\omega_s t\right]$$
$$+ \sin\omega_c t . N(t)$$

$$\therefore y_D(t) = \sin\omega_c t\left[\sin\omega_c t + \sin\omega_c t . \sin\omega_s t + N(t)\right]$$

$$= \sin\omega_c t\left[\sin\omega_c t + \frac{1}{2}\cos(\omega_c t - \omega_s t) - \frac{1}{2}\cos(\omega_c t + \omega_s t)\right.$$
$$\left. + N(t)\right]$$

$$y_D(t) = \sin^2\omega_c t + 0.5\sin\omega_c t . \cos(\omega_c t - \omega_s t)$$
$$- 0.5\sin\omega_c t . \cos(\omega_c t + \omega_s t) + \sin\omega_c t . N(t)$$

$$y_D(t) = \sin^2\omega_c t + 0.5\sin(\omega_c t + \omega_c t - \omega_s t)$$
$$+ 0.5\sin(\cancel{\omega_c t} - \cancel{\omega_c t} + \omega_s t)$$
$$- 0.5\sin(\omega_c t + \omega_c t + \omega_s t)$$
$$- 0.5\sin(\cancel{\omega_c t} - \cancel{\omega_c t} - \omega_s t)$$
$$+ \sin\omega_c t . N(t)$$

$$y_D(t) = \sin^2\omega_c t + 0.5\sin(2\omega_c t - \omega_s t) + 0.5\sin\omega_s t$$
$$- 0.5\sin(2\omega_c t + \omega_s t) + 0.5\sin\omega_s t$$
$$+ \sin\omega_c t . N(t)$$

collecting terms

$$
\begin{aligned}
y_o(t) = \; & \sin \omega_s t \quad \text{--- (A)} \\
& + \sin^2 \omega_c t \quad \text{--- (B)} \\
& + 0.5 \sin(2\omega_c t - \omega_s t) + 0.5 \sin(2\omega_c t + \omega_s t + \pi) \quad \text{(C)} \\
& + \sin \omega_c t . N(t) \quad \text{--- (D)}
\end{aligned}
\quad \text{--- (7)}
$$

(A) is the detected base band

(B) is carrier^2 component (ie DC + $2\omega_c$)

(C) is upper & lower side bands at twice carrier

(D) is noise shifted to carrier freq.

Now if ϕ is non-zero, and worse case 90°, then $\cos\phi = 0$, $\sin\phi = 1$ then (6) becomes

$$
y_o(t) = 0 + 0.5 \sin 2\omega_c t . \sin \omega_s t + 0.5 \sin 2\omega_c t + \sin \omega_c t . N(t)
$$

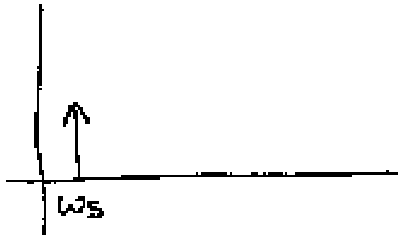
$$
\therefore y_o(t) = 0.5 [\sin \omega_s t . \sin 2\omega_c t + \sin 2\omega_c t] + \sin \omega_c t . N(t)
$$

$$
\therefore y_o(t) = 0.5 \sin 2\omega_c t + \sin \omega_c t . N(t) + \frac{0.5}{2} \cos(2\omega_c t - \omega_s t) - \frac{0.5}{2} \cos(2\omega_c t + \omega_s t)
$$

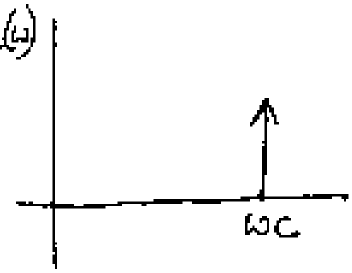
this is thus a twice carrier component plus two upper and lower side bands plus noise shifted up to the carrier.

Spectra

$y_S(\omega)$

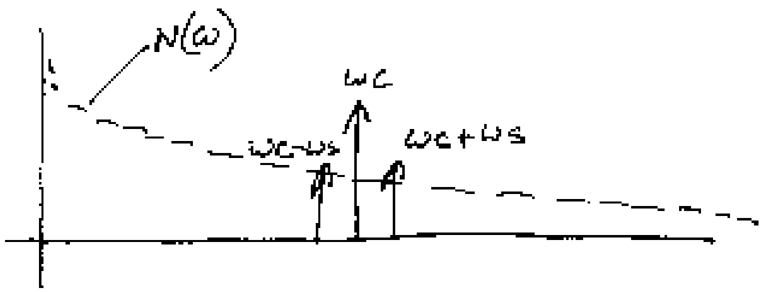


$y_C(\omega)$

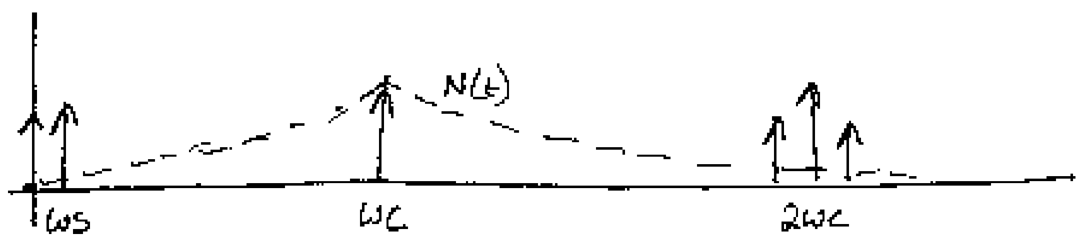


$y_M(\omega)$

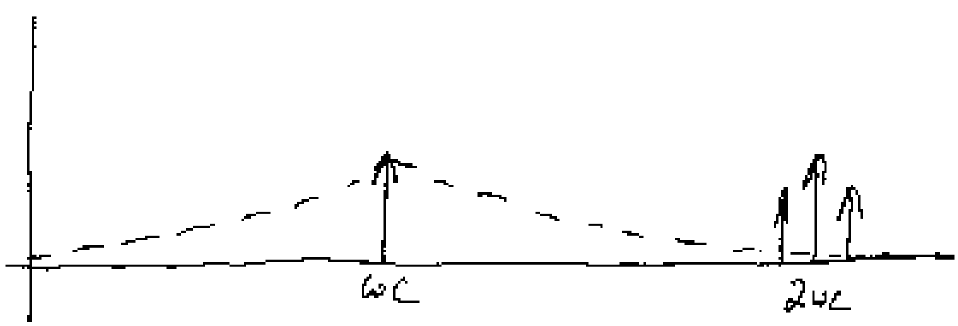
$y_R(\omega)$



$y_D(\omega)$
$\phi = 0$



$y_D(\omega)$
$\phi = 90$



Note from the above analysis, we get equation (6) :

$$yD(t) := \cos(\phi)\cdot\left[\sin^2(\omega c\cdot t) + \sin^2(\omega c\cdot t)\cdot\sin(\omega s\cdot t)\right] + 0.5\cdot\sin(\phi)\cdot[\sin(2\omega c\cdot t)\cdot\sin(\omega s\cdot t) + \sin(2\omega c\cdot t)] + \sin(\omega c\cdot t)\cdot N(t)$$

and if $\phi = 0$, then the carrier is in phase with received signal, $\cos(\phi) = 1$, $\sin(\phi) = 0$ and we recover the base band signal.

However if $\phi = 90$, then the carrier is not in phase (not synchronous) with received signal, $\cos(\phi) = 0$, $\sin(\phi) = 1$ and we get zero base band signal.

The detection process is therefore phase sensitive and the other name for a synchronous detector is a “phase sensitive detector”, or “Lock In Amplifier”

It is therefore important to maintain the carrier in phase with the received signal. In the above system, this is maintained by using the reference signal from the optical modulator and operating the photocell non-amplifier at mid-band with low phase shift.

The same technique can also be used for radio reception and is referred to as a Homodyne or Synchrodyne receiver.

The system as described has been used for many years for the alignment system of a well known European manufacturer of Wafer Steppers noted for their high performance alignment system.