PHY 122
Shot Noise

Complete Shot Noise Pre-Lab before starting this experiment

HISTORY

In 1918, experimental physicist Walter Scottky working in the research lab at Siemens was investigating the origins of noise in vacuum tube circuits. He discovered that there was a wideband current noise in vacuum diodes proportional to the square root of the DC current. From its wideband nature he dubbed it "Schrot" noise [Schrot is German for buck shot: factories that make buck shot by dropping cooling molten metal pellets a large vertical distance generate a wideband audio noise which may be heard from afar.]

THEORY OF SHOT NOISE

Shot noise is a result of any random process involving uncorrelated arrival of discrete objects. This is true whatever the nature of the discrete objects, from marbles to charged particles to quanta of light. In the case of electrons, this Poisson process results in current noise. In the case of photons there is a corresponding fluctuation in arrival rate. These statistical fluctuations occur over a broad range of timescales. Other useful references are the pdf files "Shot Noise History" and "MIT Experiment."

The uncorrelated and random nature of the discrete objects is important. For example, in a metal conductor the electrons become correlated because of their mutual electric fields and the shot noise disappears. In a diode the individual electrons are forced to pass a barrier, so that their individual discrete nature is preserved. In that limit they represent random Poisson events.

For such a Poisson process, consider n events (electrons) in time τ. Then the variance in n (the mean square fluctuation of n) is equal to the average n during that time interval,

$$\left\langle (\Delta n)^2 \right\rangle_{time} = \bar{n}$$

For electrons, the current I is given by

$$I = \bar{n} e / \tau$$

Thus, the shot noise current variance is given by

$$\overline{(\Delta I)^2} = \overline{(\Delta n)^2} e^2/\tau^2 = \bar{n} e^2/\tau^2 = eI/\tau$$

In principle, with the right equipment, you could measure these fluctuations on arbitrary timescales τ. However real experiments measure voltages over a range of timescales (or equivalently a range of frequencies) limited by the measurement apparatus. Indeed, it is convenient to define a measurement bandwidth by introducing a bandpass filter which passes voltage fluctuations only over a defined range of frequencies Δf. Integrating for a fixed timescale of τ, in the frequency domain corresponds to a filter with "square" bandpass $\Delta f = 1/\ 2\tau$. Thus, the root mean square (RMS) current shot noise in such a passband Δf is given by

$$I_{noise,RMS} = [\overline{(\Delta I)^2}]^{1/2} = (2eI_{DC}\Delta f)^{1/2}$$

If a DC current of I_{DC} is sent through a barrier such as a diode so that individual electrons randomly cross the barrier then the resulting current noise is given by the above relation. For example, a DC current of 1 mA in such a circuit results in a RMS current noise of 1.8 nA measured in a 10 KHz passband. If this current is passed through a 100 Ω resistor, the resulting RMS voltage fluctuation across the resistor is 180 nV RMS. You could measure this with a low noise preamplifier, RMS voltmeter, and spectrum analyzer.

EXPERIMENT GUIDE

This experiment consists of two parts. You should be able to do both parts in a day. In the first part you will gain familiarity with your equipment, including a noise generator, oscilloscope, and spectrum analyzer. In the second experiment you will measure photon shot noise using a photomultiplier tube (PMT) to count individual photons. Be sure to write down and discuss all your results in your lab book.

EXPERIMENT 1.

This is designed to familiarize you with your measuring equipment. The General Radio 1390B noise generator is a wide-band shot noise source followed by selectable low-pass filters. (See instruction manual on this web page). Use the noise generator on the 20KHz or 500KHz settings, and observe the noise output on your oscilloscope. You can use *either* the HIGH and "MULT BY 0.1" setting or the LOW and "MULT BY 1" setting on the noise generator. These noise generator labels are misleading: they refer to the frequency range over which the output spectrum is guaranteed to be white. In fact, the "20Khz" setting actually has a 40KHz low pass filter, for example. So on that setting the output power at 40KHz is down by half (-3dB power) compared with lower frequencies.

[Before you go too much farther you probably ought to check if there is any contamination of your signal (noise in this case!) by power line 60Hz pickup and its low harmonics. You can do this simply by triggering your scope on the power line (a scope trigger option). If there is such interference it will have spikes that appear stable on the time axis of your scope! Change the scale to 5ms/dev and see if you have a problem. To see an example of this pickup, induce some by instead hooking up a BNC to banana cable to the input and touch the center conductor with your hand (you are now an antenna)].

Adjust the shot noise generator output to about 0.1 volt AC RMS on the scope and look at the noise using a wide range of timescales by changing the scope time base. Observe the amplitude of this noise over a wide range of time bases. Try both 20KHz and 500KHz filtered noise. What does this imply regarding the shape of the noise power spectrum vs frequency? Is there a short timescale on which the noise amplitude decreases? What is its origin?

Let's look directly at the noise spectrum. Now in place of the Tektronix oscilloscope, use the PicoScope which digitizes the input voltage to a full 16 bits. After turning on power, start the PicoScope program (look for icon on bottom of screen). It comes up in the default oscilloscope mode. Choose 50microsec/div and +/- 1V AC. The PicoScope software has some "features" if you measure wideband noise. As shown below you should use either 500mV or 1V [not Auto] for your mode, and y scale dB power. The PicoScope FFT has a limited range of frequencies where is won't alias (insufficient samples per cycle). So choose the 80KHz range (top banner). Note that with the noise generator setting on 20KHz low pass filter there is a drop in the noise power spectral density above ~40KHz. You can get better results by adjusting the spectral resolution and by integrating. Under Settings/Options/ chose 1024 bands, and also chose "Average". Observe the increased accuracy of the spectrum.

Now for the only actual measurements you will make in this experiment. Using the "500KHz" [white spectrum over the 80 KHz range of the PicoScope FFT] adjust the voltage knob on the noise generator for -40dB on the power spectrum display. Start the PicoScope RMS voltmeter running and measure the RMS voltage [it is being calculated over the full displayed spectral range, in this case 80KHz]. Now switch in the "20KHz" low pass filter on the noise generator, and adjust its voltage knob again to maintain -40dB power spectral density at the low frequency limit. Measure the RMS voltage again. You will find that it is less, because there is less power spectral density at frequencies above ~40KHz. Let's try to be quantitative. You could approximate the effective bandwith Δf of the noise by a square bandpass extending from 0 Hz to where the power spectral density drops by half (3dB below your baseline of -40dB. Effectively you now have only half of the white noise spectrum contributing to your measured RMS voltage. Remembering that power goes like voltage squared, do your measurements agree with this?

Finally send the noise output of the filtered shot noise generator to a precision RMS voltmeter such as the Agilent 34410A. Observe this average RMS noise voltage as a function of noise generator amplitude and as a function of filter effective bandpass Δf. The Agilent 34410A has a statistics menu which allows RMS average and standard deviation measurements. Again, what are the functional relations for the dependence of the RMS noise amplitude on the filter passband Δf and the input noise generator amplitude?

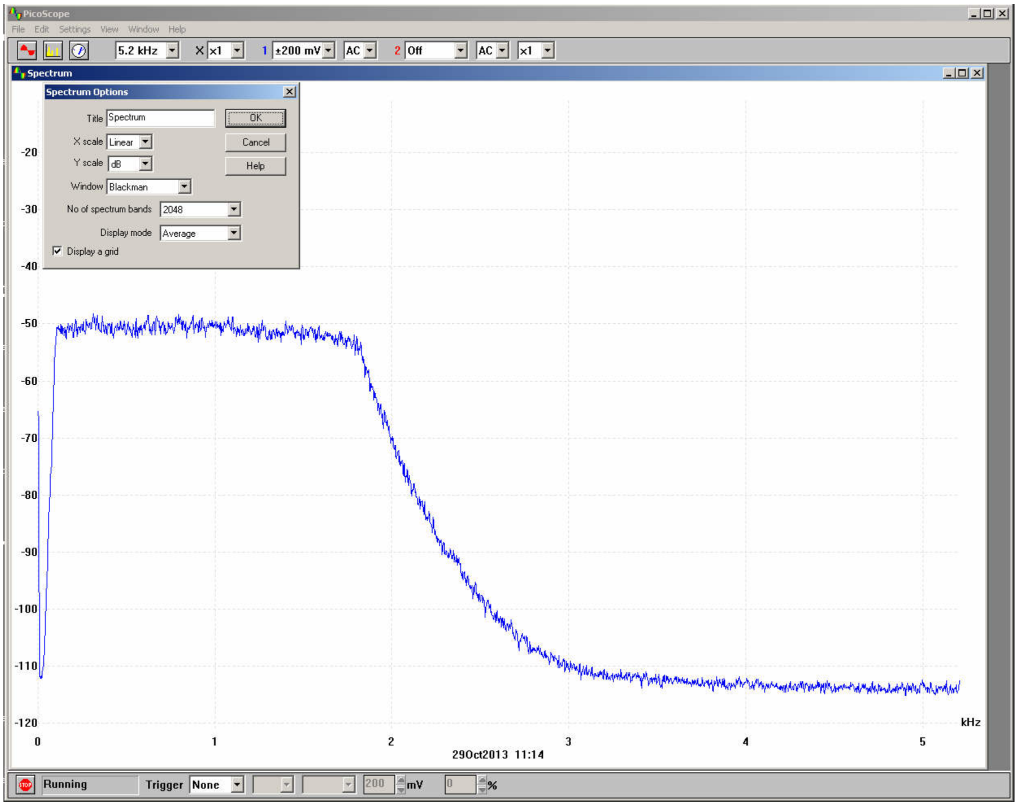

Figure: An example of a filtered power spectrum (from the Johnson Noise experiment) as measured on the 16-bit PicoScope FFT.

EXTRA CREDIT AND GOOD TRAINING FOR JOHNSON NOISE EXPERIMENT: To make a more realistic low-level noise, use a resistive divider (front panel of GR1390B) to divide down the noise generator output to 100 microvolts or less. Note that you will not be able to measure this directly on your scope or voltmeter because this test equipment has effective input noise of several mV. Thus you will have to send this microvolt level signal to an amplifier with gain of around 1000. Use the Signal Recovery 5113 and then observe the output spectrum on the PicoScope. Depending on the amplitude of your noise input you may have to use a gain of 1000 or more on the SR 5113. Do you see the high frequency roll-off of the noise generator's "20KHz" filter? Is there some reason you might want to avoid 60 Hz and 120 Hz in your experiment? You are using the PicoScope as a spectrum exploration tool, but the RMS voltmeter on the PicoScope has limited functionality. So once you are satisfied that there is no pickup or interference, you may want to use the Agilent RMS voltmeter in its STAT and AVERAGE mode, for accurate measurements.

EXPERIMENT 2.

In this experiment you will measure the shot noise in a stream of random uncorrelated photons coming from a Sylvania 7377 light bulb with a small adjustable DC current. To count individual photons you need a very sensitive low noise detector: a PMT. *Use extreme care: this PMT uses high voltage and it can also be damaged if you put too much light on it with the HV on.* The setup is shown in the following figure.

Begin with a contest to see how few photons you can count with your eye. There is an identical Sylvania 7377 light bulb set up at the end of a black tube. Hook this to your 0-10V DC power supply with 100 Ω series resistor. Route this through an ammeter so you can measure the bulb current in the mA range. In a darkened room have your partner tell you when they can see your random secret brief (approx. 5 sec) circuit closures. Ask your partner to say YES when they see a flash. Start at 0 V and gradually increase the voltage (thus current) until your partner begins getting the right answer about 70% of the time. Of course you will have to go to higher currents to define this 70% point. You will be able to convert this current to number of photons per second after you do the PMT counting measurement.

COUNTING PHOTONS:

You have a Burle 8575 PMT in a light tight housing with a Sylvania 7377 light bulb mounted at the far end about 5 inches from the 2 inch diameter PMT photocathode. Read the file on the PMT, paying particular attention to its sensitivity and noise vs HV. Now set up to put very small currents through the light bulb mounted inside the PMT housing. Do not take it apart! The PMT HV is maximum 1900V and you should turn up the (negative polarity HV) slowly from zero. Observe the PMT output on a Tektronix MSO 4054 scope, triggering on the negative pulses in the 40 nsec per division range. Be sure to terminate the input of the scope with the 50 Ohm impedance of your coax (using the internal 50 Ohm and and DC coupled settings). Before putting any current through the light bulb observe the PMT noise by adjusting the (negative) threshold down in the -50 mV range. Be sure the scope is running in "normal" trigger mode rather than "auto". [To get started you may need to put the scope trigger on FIND]. The ~10-50 mV 10nsec pulses you see at PMT HV 1900V are coming from the thermal emission of the PMT photocathode. Change your scope threshold to -100mV or more to avoid most of these background pulses. Now you need to count your pulses which are above your adjustable threshold. In order to count your pulses hook the "Trigger Out" BNC connector on the back of the scope to the rate meter in the NIM BIN.

With no current to the bulb you should see background counts less than 1-2 Hz. Measure this background carefully by averaging. Use rate meter settings that average counts for about 1 sec. Now increase the light bulb current slowly from zero. Around 21 mA the filament in the bulb gets hot enough to emit a few photons per second, collected in the solid angle subtended by the PMT photocathode. You can see the individual detected photons on the scope. The light output of the bulb is a **highly non-linear** function of current. Photon count rates around 100 Hz occur at 23 mA, 1 KHz at 23.5 mA, and 5 KHz at 24 mA. At a HV of 1900V count rates above 2 KHz cause a "motorboating" sound you can hear on your audio monitor, due to the scope trace display frequency. Be sure to stay on the 40ns/div scale for all these measurements, since the pulse trigger output can be affected by the scope sample rate, which can change at some time settings.

You can now use these data to calibrate the photon flux sensitivity of your eyes. Remember that the PMT, while it can detect individual photons, it does not detect them all; the photocathode has about 20% quantum efficiency, so your PMT detects about 1 in every 5 photons. Make this correction to calculate the actual photon flux per steradian from the bulb. Then correct for the ratio of steradians of the PMT setup and your eye (pupil). Now you can estimate your visual threshold in photons per second collected by your eye. How did you do? The winner will be awarded a cheap pair of sunglasses. A typical scope display at ~100 Hz photon count rate is shown below.

The Ortek ratemeter (especially if averaging for times ~ 1 sec or longer) gives the average photon rate. In shot noise, RMS fluctuations in this rate are related to the rate [see equation above]. You can see this roughly by turning down the averaging time on your rate meter to its shortest setting and observing by eye the mean rate fluctuations. Of course this is for only one rather narrow bandwidth and at low frequency [where 1/f noise from the PMT might contribute].

You will use these measurement techniques in your next experiment: Johnson noise.

APPARATUS

Agilent 34401A Digital precision volt-amp meter (AC or DC)
Agilent 34410A Digital high precision volt meter with statistics
Tektronix MSO 4054 Oscilloscope
General Radio 1390B Noise Generator
Signal Recovery 5113 bandpass amplifier-filter
Computer with software for PicoScope and data analysis software
PicoScope ADC216 digital scope and spectrum analyzer
BURLE 8575 PMT and Ortec HV Power supply
Ortec 449 ratemeter