Measuring Fundamental Charge by Observing Photon Shot Noise of a Photodetector

Franklin Liou[1]
[1] Department of Physics, Stanford University, Stanford CA

E-mail: fliou@stanford.edu

Abstract. We observe the photon shot noise spectrum of an incandescent light on a photodetector. By averaging the noise level over a flat region in the spectrum, we obtain a measurement of the spectral density for varying optical power. We found that the spectral density varies linearly with the optical power, confirming observation of photon shot noise. From the constant of proportionality, we calculate the fundamental charge to be $(1.76 \pm 0.52) \times 10^{-19}$C.

I. Introduction

At sufficiently high optical power, photon shot noise becomes the dominant source of statistical error. This noise is stochastic, thus its noise spectrum is independent of frequency. In addition, the power level of photon shot noise is proportional to the optical power of the incident light. The constant of proportionality is related to fundamental quantities such as electron charge and photon energy. In this paper, we calculate the electron charge using the ratio between the photon shot noise power and the voltage output of a photodetector.

The formulas we use to calculate the electron charge are described as follows. In a photodetector with a certain bandwidth B, the relation between its average voltage output in the bandwidth V_{psn} and average optical power $\langle P_{opt} \rangle$ is given by

$$\frac{V_{psn}^2}{B} = 2 r_v q R_L \langle P_{opt} \rangle \equiv S_{psn} \tag{1}$$

where S_{psn} is the spectral density, B is the bandwidth of the detector, r_v is the responsivity, q is the electron charge and R_L is the resistance of the circuit. The power of the incident light is determined by the voltage output of the photodetector $\langle V_{out} \rangle$ and its responsivity r_v.

$$< P_{opt} >= \frac{\langle V_{out} \rangle}{r_v} \tag{2}$$

Using equations (1) and (2), we can eliminate r_v and solve for the electron charge.

$$q = \frac{1}{2B} \frac{V_{psn}^2}{R_L} \frac{1}{\langle V_{out} \rangle} = \frac{S_{psn}}{2R_L \langle V_{out} \rangle} \tag{3}$$

We can measure $\frac{V_{psn}^2}{R_L}$ using a spectrum analyzer, and $\langle V_{out} \rangle$ using a voltmeter.

II. Experimental Methods

In order to measure $\frac{V_{psn}^2}{R_L}$ and $\langle V_{out} \rangle$, we connect a photodetector to a digital voltmeter and spectrum analyzer in parallel. The photodetector is reverse biased to increase sensitivity. First, we illuminate the photodetector with an incandescent light and and observe the power spectrum P of the photodetector from 0 to 10 MHz. We observe the noise level for various light intensities. We also record the spectrum when the photodetector is on but dark P_{dark}, which excludes photon shot noise, leaving us with other noise sources. We subtract this noise from our power spectrum P, thus obtaining

$$\frac{V_{psn}^2}{R_L} = P - P_{dark} \tag{4}$$

Since at MHz frequencies, we match the input impedance of the spectrum analyzer to the output impedance of the photodiode circuit, the voltage level measured by the spectrum analyzer V_{in} actually half the actual value, thus

$$\frac{4V_{in}^2}{R_L} = P - P_{dark} \tag{5}$$

We plot this power with photodetector voltage $\langle V_{out} \rangle$ and fit a linear equation to it, which will yield q, using equation (3). We substitute 10 MHz for the bandwidth B of the photodetector, 50 Ohms for the resistive load R_L.

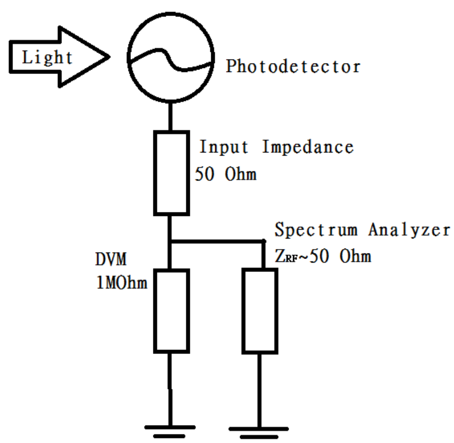

Figure 1: Experimental Setup
We connect a photodetector to a digital voltmeter in parallel with a spectrum analyzer. We vary the light intensity and record the spectrum. At radio frequencies, the output impedance of the photodiode matches the input impedance of the spectrum analyzer, halving the observed voltage.

We average each spectrum from 3.4 to 10 MHz to get the noise level. Then we plot and fit a line to the noise level versus photodetector voltage, which are respectively proportional to spectral density and optical power.

III. Results

In the spectral profile, we found that 1/f noise dominates below 1 MHz. There is a flat region between 1 and 8 MHz, and the spectrum gradually falls off at frequencies greater than 8 MHz. We also observe that the noise level rises with increasing light intensity.

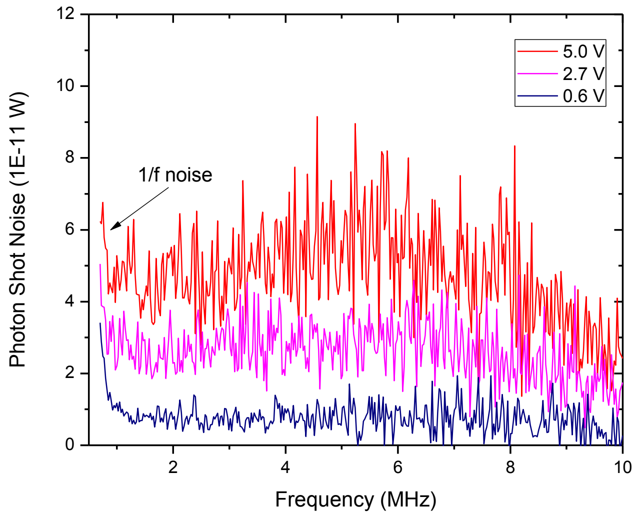

Figure 2: Noise Spectrum of Incandescent Light with Varying Intensities

The linear fit to noise level versus photodetector voltage had a R-square value of 0.995, indicating this model fits well. The slope of this line is $(3.56 \pm 1.04) \times 10^{-12}$. This translates to a value for q of $(1.76 \pm 0.52) \times 10^{-19}$ C.

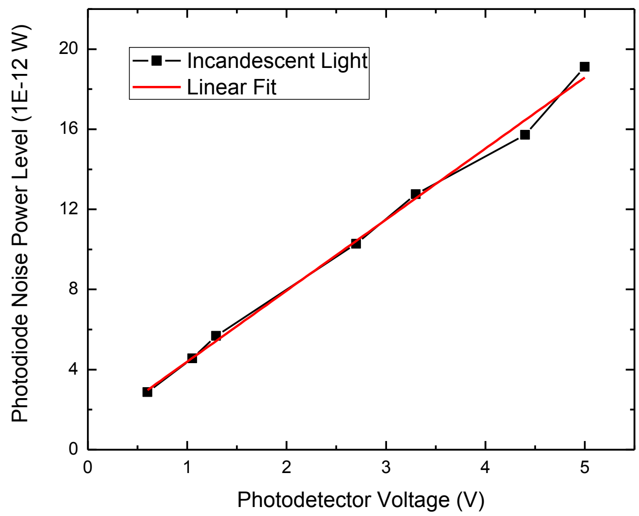

Figure 3: Linear Fit to Noise Level versus Photodetector Voltage

IV. Discussion

We have verified the linear relation between the spectral density and the optical power, as shown in equation (3). This confirms that we observed photon shot noise, as opposed to Johnson noise, which does not scale with optical power. The constant of proportionality indicates the fundamental charge. Our experiment agrees with the known value, which is within the range of our experimental error. Systematic errors may include unknown resistance in the circuit or electronic noise introduced by the incandescent light. The former possibility will change the impedance of the load and thus the power measured by the spectrum analyzer, which will cause the slope between spectral density and the optical power to be higher or lower than the actual value. The latter introduces uneven spectral features in the noise spectrum, which can distort the average noise level. As seen in figure 2, the spectrum becomes more uneven at higher optical power.

V. Conclusion

We found that in our photodetector, the spectral density varies linearly with the optical power, which is characteristic of photon shot noise. The slope of this dependence was used to determine the fundamental charge, $(1.76 \pm 0.52) \times 10^{-19}$ C. The spectral features in the MHz range are mostly flat for an incandescent light source. However, high optical power can distort the spectrum, making it harder to obtain a noise level over a wide frequency range. Nevertheless, we were able to measure a noise level by averaging over a range of frequencies, which yielded predicted linear relation of spectral density versus optical power. We might account for systematic error due to this averaging method by performing measurements at lower optical power.

References

[1] Schleier-Smith, Monika and Pam, Rick. Stanford Physics 107 Lab3 Handout. (2014)