THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

DEPARTMENT OF ENGINEERING SCIENCE AND MECHANICS

Stochastic resonance in Silicon photodetector

Yujing Wang
SPRING 2021

A thesis
submitted in partial fulfillment
of the requirements
for a baccalaureate degree Engineering Science
and Mathematics
with honors in Engineering Science

Reviewed and approved* by the following:

Saptarshi Das
Professor of Engineering Science and Mechanics
Thesis Supervisor

Xiantao Li
Professor of Mathematics
Honors Adviser

* Electronic approvals are on file.

ABSTRACT

Weak signal detection method under strong noise background has a very wide range of applications in many disciplines. Conventional weak signal detection methods are mainly based on time domain and frequency domain, for example, self-correlation in time domain and power spectrum density in frequency domain. However, these methods have some limitations, mainly for the high signal-to-noise ratio (SNR) threshold of the input signal. Therefore, there is an urgent demand for a new method to make up for the above deficiencies.

In recent years, with the burgeoning development of nonlinear science and stochastic resonance theory, a cutting-edge idea for weak signal detection is created. The uniqueness of stochastic resonance theory depends on its different utilization of noise. The traditional signal detection methods are sparing all effort to suppress noise considering it harmful while stochastic resonance theory is just using the energy of noise signal, which is a new method to turn waste into treasure.

This thesis aims at discussing a Silicon (Si) photodetector which is a highly sensitive photodetector with fast response. It can detect the weak photoelectric signal from the long-distance light-emitting diode. Through multiple sets of experiments, we try to find out the optimum standard deviation required in detecting the low intensity optical signal for different wavelength of light.

TABLE OF CONTENTS

LIST OF FIGURES

ACKNOWLEDGEMENTS

I would first like to thank Dr Das for advising me. I would like to thank the graduate student, Akhill Dodda, who helped me often throughout this process. I would like to acknowledge the other undergraduate in the laboratory, Michael Felins, for his continuous support. Finally, I would like to thank the Schreyer Honors College for their help throughout my undergraduate studies.

Chapter 1

Introduction

Academic background

In contrast with the conventional view on noise, stochastic resonance is a remarkable phenomenon revealing that noise can play a constructive role as well. Scientific studies have shown that an appropriate level of noise, rather than an excessive amount, can actually enhance information processing by increasing the signal-to-noise ratio (SNR).

In history, the concept of stochastic resonance was firstly put forward by Italian scholars and others when they were studying the paleo-meteorological problems of the earth. The earth takes about ten thousand years as a cycle to alternate between a warm climate period and an ice age, and the period of the eccentricity change of the earth's rotation around the sun is also about 100,000 years. This overlapping in the period implies that the sun imposes periodic signals on the earth. But only a small periodic signal such as eccentricity is insufficient to cause such a large change in the earth's climate. So Benzi et al. proposed a bistable non-linear climate model. In this model, they regarded the warm climate of the earth and the ice age respectively corresponding to the two steady states of the system. The change of the earth's eccentricity is considered as an external periodic drive; and the interference of random forces is regarded as Gaussian white noise. In this way, the earth's climate alternates between the heating period and the glacial period under the combined action of small-cycle driving and noise. Benzi et al. call this phenomenon of weak periodic driving and random force under the action of a nonlinear system, which causes strong periodic output to appear as stochastic resonance, which well explains the large periodic changes in the earth’ s paleoclimate phenomenon. Since then, the stochastic resonance concept was created.

While stochastic resonance has seen its application of diverse fields, in the device community, the stochastic resonance is hardly recognized. In this community, traditional but well-established methods like low-noise amplifier for improving detection limit of sensors continues to be successful such that not too much room is left for the novel approaches based on stochastic resonance. However, the conventional approaches have their own shortcomings in energy efficiency, which involves more challenges especially in the era of internet of things. Under comparison, using the noise, signal-enhancing approaches can achieve the same effect with the least energy. So, it is envisioned that stochastic resonance would be applied to enhance signals of sensors very soon and initiates a shift in paradigm of the device community.

The traditional weak light signal detection is based on the photoelectric effect, which mainly uses the organic combination of detection equipment and detection technology. The first step of the whole process is to convert the signal collected by the detector into an analog electrical signal through a photoelectric converter. The analog electrical signal contains important parameters such as peak value, phase, and periods, and then the electrical signal is amplified or its signal noise is improved. Different degrees of noise will be generated in the detection process, and the source of noise is complex, such as multiplicative noise scattered by signal light, additive noise from non-target light sources, and multiplicative noise generated by distortion when signal light passes through the system. For the processing methods of these noises, generally adopt methods such as adjusting the system structure, reducing background light interference, adding filtering devices to the system, etc., these methods can play a certain role in the noise from non-homologous sources. When the signal itself and the noise intensity is very strong, its effect is very limited. Therefore, in order to be able to extract the signal annihilated by strong co-frequency noise, a new and effective detection method needs to be studied.

Considering the brilliant future of stochastic resonance for devices mentioned above, we investigate the application of stochastic resonance for detecting the ultra-low-density optical signals by Silicon based photodetector from light-emitting diode (LED). It is expected the stochastic resonance effect can be measured and studied with LED of different wavelength at distance distances from the photodetector.

As illustrated above, the sensors enhanced by the stochastic resonance can have great edges over conventional ones. However, promising as the future of stochastic resonance is, the accurate impact on factors affecting stochastic resonance is seldom studied, which certainly should be addressed for the precise control of stochastic resonance. For example, there is a lack of knowledge in the impact of LED wavelength on the stochastic resonance effect. For different wavelength of LED, we cannot know how stochastic resonance changes. A knowledge gap also exists in the impact of LED distance on stochastic resonance. As the distance of LED to the photodetector varies, the current knowledge can hardly answer what would happen to stochastic resonance.

To answer the questions and fill the knowledge gaps above, in this thesis, we delve into the factors affecting the stochastic resonance, including wavelength of LED, distance of LED, and the voltage of LED to figure out the quantitative and qualitative effects of factors on stochastic resonance. Except for the investigation of a single factor, we also combine different levels of two or more factors to figure out the compound effects of these factors on stochastic resonance. It is intended that our experiments and results can uncover the effects of various factors to stochastic resonance and speed the widespread applications of this remarkable phenomenon.

Basic structure

In section 2, it provides the basic principle and application of stochastic resonance in detail. Part 3 shows the basic information of photodetector, also, the characteristics and parameter of Silicon photodetector. The fourth part explains how to implement this experiment and its results and discussion. The last part is conclusion and further work.

Chapter 2

Theory of Stochastic Resonance

This section provides detailed principle and applications of stochastic resonance.

Mechanism of Stochastic Resonance

The mechanism of stochastic resonance can be simply explained by the model of a symmetric double well as shown in Figure 1(Hänggi). There is a weak modulating signal imposed on the particle such that the potential well of the right and life sides can be titled. While the modulating signal is so weak that the particle cannot transit from one well to another, a white noise enables to enhance the signal and then induce the transitions of the particle under certain conditions (McDonnell and Abbott). By this process, the stochastic resonance occurs.

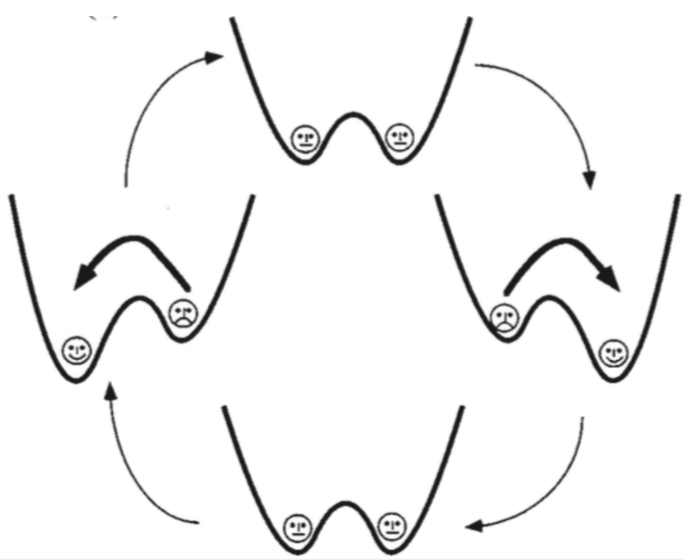


Figure 1. An illustration of the mechanism of stochastic resonance (Hänggi).

Principle of Stochastic Resonance

From the perspective of signal processing, stochastic resonance is a signal transmission in a nonlinear system. The input is a weak signal in a strong noise background. By adjusting the input noise intensity or system parameters, the system output reaches an optimal value, such as the maximum output signal to noise ratio. This kind of synergy caused by signal, noise and nonlinear system is called stochastic resonance.

Since the amplitude of the output signal is greater than the amplitude of the input signal, it has an effective amplification effect. At the same time, because the output state of the system changes regularly, the amount of noise in the output state of the system is effectively suppressed, and part of the noise energy is converted into the signal. In this way, the output signal-to-noise ratio of the entire system is greatly improved. At this time, the weak signal, noise and bistable system constitute a stochastic resonance signal processor. In traditional communication systems, we always try to reduce the interference of noise. However, from the above analysis, it can be seen that noise is sometimes beneficial to signal transmission and detection. Therefore, the emergence of stochastic resonance provides a new idea for the detection of weak signals, which is of great significance to the development of information science.

The pure non-periodic stochastic resonance system cannot be widely used. One of the reasons is due to the characteristics of the traditional stochastic resonance system. For example, the bistable periodic stochastic resonance system mentioned above achieves the resonance between the weak noise signal and the bistable system by adjusting the intensity of the input noise so that it can achieve the maximum output signal-to-noise ratio. That is to say that the signal-to-noise ratio at the output firstly increases with the increasing noise intensity, and then decreases. However, the intensity of noise in an actual communication system is not controlled by the receiving end, but it makes contributions to the channel. Bulsara et al. believe that stochastic resonance can also be achieved by adjusting system parameters, especially the Parameter-induced Stochastic Resonance (PSR) proposed by Xu et al., which makes the application of stochastic resonance more practical.

Three basic conditions are required to produce stochastic resonance, namely, nonlinear system, input signal and noise. In the presence of noise and periodic signal excitation, we may first consider the over-damped motion of the Brownian particle in the bistable potential which is shown in the equation below.

$$\frac{dx}{dt} = -\frac{dU(x)}{dx} + Asin(2\pi ft + \varphi) + n(t) \quad (1)$$

In this function, U(x) represents the image symmetry square potential and can be calculated through equation 2. When the phase in equation 1 is zero, it can be regenerated as equation 3.

$$U(x) = -\frac{a}{2}x^2 + \frac{b}{4}x^4 \quad (2)$$

$$\frac{dx}{dt} = ax(t) - bx^3(t) + Asin(2\pi ft + \varphi) + n(t) \quad (3)$$

In the non-linear system, signal and noise jointly produce the synergistic effect. The way that the non-linear system presents is the potential barrier of the system. The higher the potential barrier is, the greater the energy is required for signal and noise to produce a synergistic effect. Otherwise, the energy required for signal and noise is smaller. Knowing from the equation, the variances of value a and b can control the system barrier value. As the value of a becomes smaller, the distance between the two potential wells of the system is shortened, and the potential barrier of the system is reduced. In this system, the damping force of the system is reduced, which reduces the energy required when the system enters the stochastic resonance state. This quality is beneficial for the system to extract useful signal characteristics. As the value of b becomes larger, the changing situation is the same as when changing the value of a.

Because the voltage difference between the bistable state is far greater than the input signal amplitude, it makes the output signal amplitude greater than the input signal amplitude. At the same time, since the state of the system output has regular change, it can effectively restrain the noise intensity in the output state of the system so that the system can improve the output SNR, which means the output signal has been enhanced. This kind of phenomenon is essentially synergy between signal and noise and nonlinear systems, called stochastic resonance.

Applications of Stochastic Resonance

To begin with, the hypothesis of stochastic resonance proposed by Benzi et al. did not arouse much interest until a series of physical experiments verified the existence of stochastic resonance. In 1983, Fauve and Heslot implemented a stochastic resonance system in a Schmitt trigger circuit system for the first time; Mcnamrar confirmed the existence of stochastic resonance in a bistable laser ring in 1988. In 1989, Fox.RF first applied the eigenfunction perturbation expansion method to study the theory of stochastic resonance, and obtained an approximate analytical formula for the power spectrum of a one-dimensional double potential well system; especially in the early 1990s, Collins proposed non-periodic stochastic resonance theory, which combines stochastic resonance with information theory. Standing on the shoulders of so many giants, scientists started observing stochastic resonance in the fields of electromagnetism, oscillatory circuits, optics and chemical reactions. And the phenomenon of stochastic resonance began to attract the attention of many scholars, which advance the development of the theory and application of stochastic resonance in various fields substantially.

For example, in biology, biologists have discovered that stochastic resonance exists widely in life phenomena. They believe that the various neural sensory tissues of the organism can use the noise inside the organism and the external environmental noise to detect and perceive the external stimulus signal submerged in the noise. And they even use the stochastic resonance theory to explain how the muscles are dispersed in the body. What's more interesting is that in biomedicine, a cochlear hearing aid has been developed based on stochastic resonance. It uses a set of band-pass filters to simulate different parts of the cochlear nerve and then adds noise to the cochlear vowel signal through the nerve stimulation structure. Attributed to stochastic resonance, the performance of the cochlear hearing aid channel is improved.

People traditionally consider noise as harmful signals and the chief culprit of reducing the transmission performance of the system. Therefore, reducing noise intensity is an effective way to improve the efficiency of the system. However, in some nonlinear systems with specific parameters, noise plays a more important role than what we conventionally think. The increase of noise intensity will inevitably affect the nonlinear system. When noise gets superimposed on subthreshold input signal, the input signal occasionally crosses the threshold of activation and results in an increases SNR value. Under optimum noise, a better SNR value will be obtained.

This phenomenon provides us with new ideas for extracting signals that are annihilated by strong co-frequency noise.

Chapter 3

Photodetector

The principle of the photodetector has great connection with the changing conductivity of the irradiated material due to radiation. Photodetectors are widely used in various fields of military and national economy. This paper utilizes Silicon photodetector to be the main equipment and its characteristics will be illustrated in this section.

Basic information of Photodetector

The working principle of the photodetector is based on the photoelectric effect. The thermal detector is based on the material that absorbs the light radiation energy, which can make the temperature rise, thereby changing its electrical performance. The main feature of which is different from the photon detector is that the wavelength of light radiation is not selective. Selective. In order to improve the transmission efficiency and transform the photoelectric signal without distortion, the selections of the photodetector in different situations have various requirements, so that each interconnected device is in the best working condition. The photodetector must match the spectral characteristics of the radiation signal source and the optical system, and the photoelectric conversion characteristics must be according to the incident radiation energy. At the same time, the photodetector must satisfy the modulation form, signal frequency and waveform of the optical signal to ensure a good time response and an output waveform without frequency distortion.

Photodetectors based on semiconductor materials have been widely used and become one of the core technologies of modern industry and science. In practical applications, ultraviolet or near-infrared semiconductor photodetector technology is becoming mature. In order to broaden the response range and realize more practical applications, more research set out to develop some new materials or use physical and chemical methods to change the energy of the original material, which can make it respond in a longer wavelength band. However, most of the existing semiconductor detectors often need extreme temperatures to improve their long-wavelength detection performance.

Mechanism of Photodetector with different material

In contrast with the widespread attention gained by stochastic resonance in some areas of science above, there is a scarce number of researches applying stochastic resonance to improve the detection limit of various solid-state sensors perhaps because the conventional improvement methods like lock-in amplifiers, oscillators, low noise amplifiers, are so successful that no one would consider such a radical idea (Dodda et al.). The turning point occurs as the internet of things technologies emerges. Although the conventional improvement methods work well in enhancing signal-to-noise ratio of sensors, they are inefficient in terms of energy use, especially in internet of things facilities requiring a high amount of energy to support billion of sensors. Against this backdrop, stochastic resonance stands out with an edge over conventional methods in energy efficiency. And as recently as last year, the first research in the application of stochastic resonance was published in nature communication. In this research, Dodda et al. used a monolayer MoS_2 based photodetector coupled with stochastic resonance to detect an otherwise undetectable light signal from a light-emitting diode far away. Specifically, they synthesized MoS_2 monolayer from the reaction between Molybdenum hexacarbonyl, Mo $(CO)_6$, and hydrogen sulfide, H_2S. Then a weak signal emitted by the LED light along with a white noise was input into the monolayer MoS_2 photodetector.

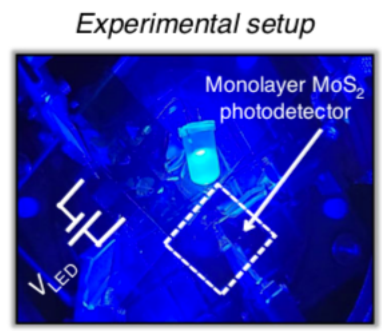


Figure 2. The experimental setup for stochastic resonance on MoS_2 photodetector (Dodda et al.).

The signal-to-noise ratio of MoS_2 decreases monotonically with LED intensity. However, the experimental result given in Figure 3 below shows that, at a given LED intensity, the signal-to-noise ratio of MoS_2 device has non-monotonically effect with noise intensity.

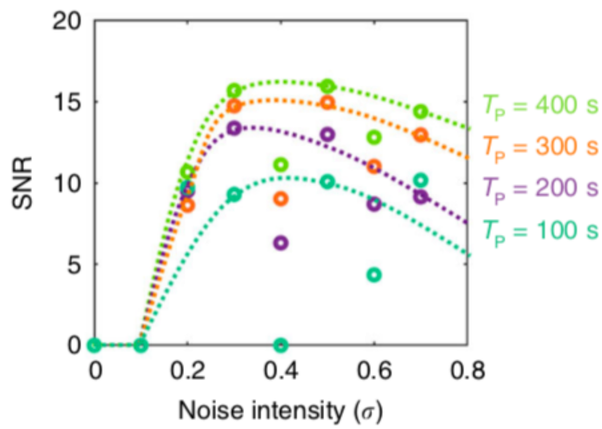


Figure 3. The signal-to-noise ratio of MoS_2 under a series of noise intensity (Dodda et al.).

This non-monotonical trend can be exactly explained by stochastic resonance as shown in Figure 4 below. When the variance of Gaussian noise is lower than 0.2, none of the signal centered at V_{BG}= -2.5V crosses over the detection threshold at -1.5V. Appropriate amount of signal goes above the detection threshold when the variance of Gaussian noise is well between a range. However, as the variance of Gaussian noise becomes extremely large, too many signal crosses the detection threshold and the periodic feature of the signal will be suppressed.

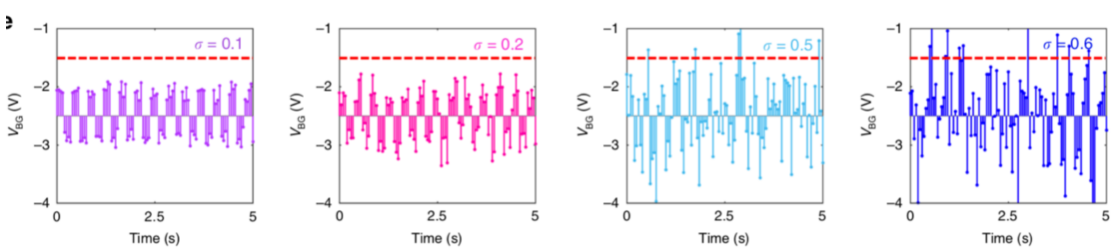


Figure 4. The back-gate voltage under different variances of Gaussian noise (Dodda et al.).

More than the self-synthesized monolayer MoS2 photodetector, stochastic resonance can also be exploited to extend the detection limit of a commercial Silicon photodiode. Figure 5 below illustrates the experimental results of the MoS_2 photodiode and results from the same experiments performed on a commercial Si photodiode. Similar to MoS_2 photodetector, stochastic resonance can also be exploited to extend the detection limit of a Silicon photodiode. The photodiode detection limit can be enhanced by the Gaussian noise under medium levels while the noise has no benefits as its intensity is extremely low or high.

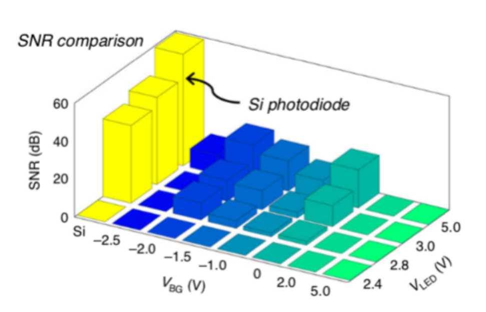


Figure 5. The signal-noise-ratio under different V_{LED} and V_{BG} for MoS_2 and Si photodiode (Dodda et al.).

In this thesis, I adopted Silicon photodetector which has the advantages of small size, sturdiness, reliability, and low power consumption. Its response wavelength ranges from 0.35 μm to 1.1 μm, which makes it the most commonly used photodetector in the visible to near-infrared spectrum. It is an indispensable detection element in many applications such as laser measurement and optical fiber communication. The internal photoelectric effect is the main principle of Si photodetector. The electron-hole pairs in Si photodetector excited by incident photons are called photo-generated electron-hole pairs. Although the photo-generated electron-hole pairs are still in the material, they change the conductivity of the semiconductor photo-electronic materials. By detecting this change of performance, the change of the optical signal can be easily detected. The Si photodetector is essentially a reverse-biased diode. The reverse working current of the Si photodiode is modulated by incident light because it absorbs light waves of various wavelengths selectively. The response speed of silicon photodiodes is limited by three factors: the time for carriers to diffuse into the depletion region, the drift time in the depletion region, and the RC time constant determined by the capacitance of the depletion region. In order to obtain high-sensitivity, low-noise and fast-response devices, there are still some problems worthies of studying in structural design, process manufacturing and other aspects.

Chapter 4

Analysis and Discussion

The signal received may be impacted in diverse ways, for instance, the distance between the receiver and the generator, latency effect and signal wavelength, which are the variables in this paper. These experiments demonstrate these effects in histograms and try to find out the best variance of the stochastic resonance of Gaussian noise for each signal.

Methodology

Dark current refers to the reverse DC current generated by the device when there is no incident light under the condition of reverse bias, which exists in each photo-electronic component. When photodiode runs in reverse bias there is also a dark current, though there is no signal. In order to offset the effect of dark current and create a stable noise floor, an additional background LED will be added. In Figure 6, the fluctuation around -1nA is the dark current when there is no light, while the waveform below represents the noise floor after applying the background LED.

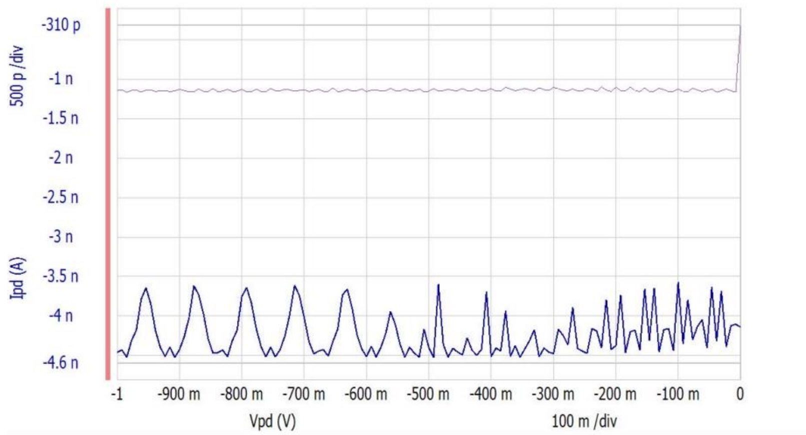


Figure 3. The dark current and noise floor with background voltage

The specific voltage of the background LED is obtained by testing and its location is fixed throughout the experiment. Also, different background voltages are for different wavelength of LEDs, which are the sum of the specific voltage and a random standard derivation. The wavelength of background LED must be identical with the signal LED.

In this experiment, I choose red LED and blue LED to be the signals due to their evident difference of their wavelengths. To make the results more convincing, I respectively set the signal LED 2cm and 10cm away from the Silicon photodiode, which can prove the distance effect to the receiving signal. Utilizing this setup can assist to detect the detection threshold of this photodiode and find out this limit with Fast Fourier Transform (FFT) plot using MATLAB. During the test, the input signal includes 512 periodic data points, consisting of 128 cycles. The last data point in a cycle has the largest amplitude, while other three are smaller and below detection threshold. This periodic signal gives a 0.25Hz input signal if the last data point in a cycle is above the detection threshold.

Except for the detection threshold, the latency of the input signal is also a big deal. In this test, I changed the number of data points from 512 to 2048 because higher duration of time can make the receiving signals more integrated. Each data point lasts 10ms. For each different signal led voltage, this 5.12s test will be performed four times.

In the end, perform Stochastic resonance measurement by adding various amount of noise and try to find out whether signals which are originally below the detection limit are detected by stochastic resonance.

Results and Discussion

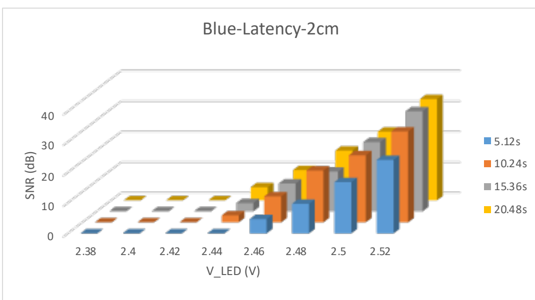
After testing, the voltage of background LED for the blue one is about 2.5V while the one for red LED is about 1.75V. These testing voltages will not be changed during the following test, however, with a random derivation added.

In the test of latency, I considered time and input density as variables and implemented four groups of experiments. Fig.7(a) and (b) shows the latency when the input signal is generated from a blue LED and a red one, respectively, which are 2cm away from the target. Then, Fig.7(c) and (d) are the results of these two LEDs which are 10cm away from the receiver. The detailed data in the experiments are recorded in Table 1-4 of the Appendix.

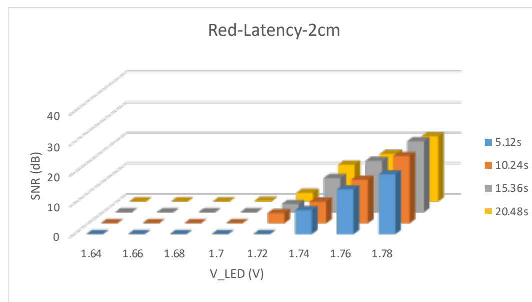
This is the traditional method does enhance the signal. As time and the number of data point increase, the signal strength is improved. However, as shown in the graphs, this method cannot effectively help to detect signals below the threshold.

Comparing (a) and (c) or (b) and (d), we can find out that the receiving SNR is greater if the signal source is closer to the target.

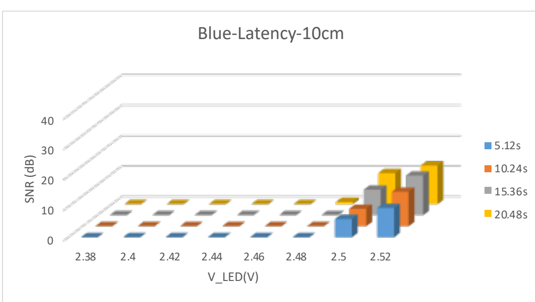
Also, comparing the performance of blue LED and red LED, we can recognize that the blue light can transmit more energy than the red one. This is because, for the same medium, the sensitivity of the detector is wavelength dependent. Frequency is the reciprocal of the period, which represents the number of vibrations per unit time. The wavelength is the distance that light travels in a period, which is equal to the wave speed multiplied by the period. The energy and momentum of a photon is only related to the frequency or the wavelength of the photon. From the relationship between energy and momentum, we know that the wavelength and energy of light are inversely proportional.



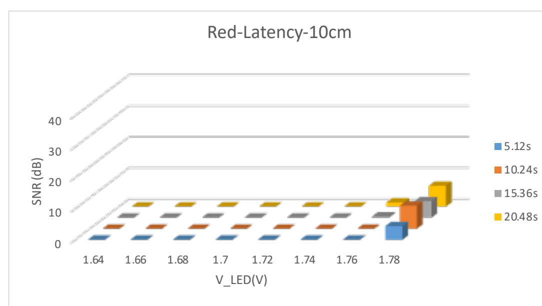
(a)



(b)



(c)

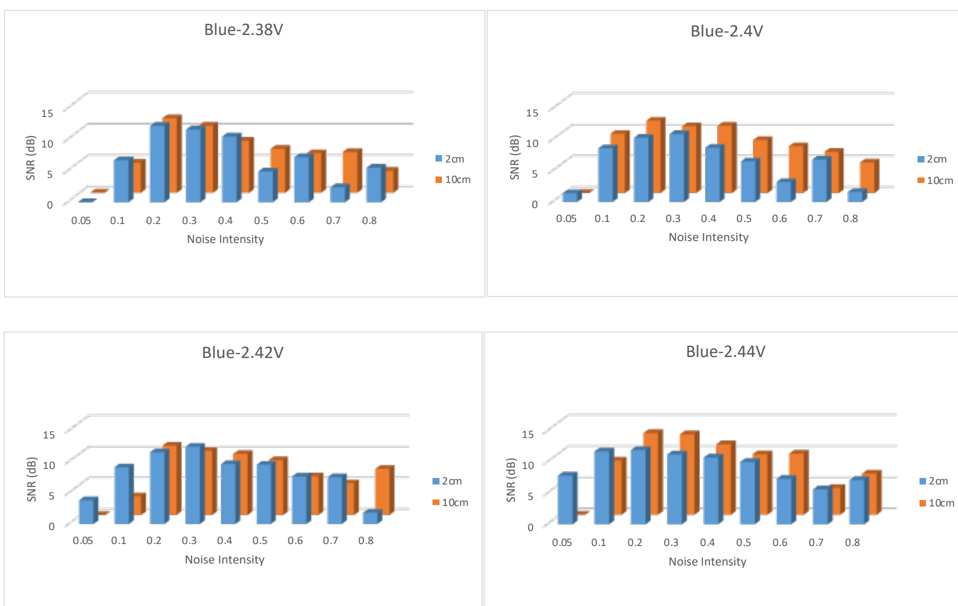


(d)

Figure 4. Latency in different experimental groups

Then, I added different noises to different input signal. The receiving strengths with various additional noise are our key studying objects. In each group, I used nine kinds of standard derivation, 0.05, 0.1, 0.2, ..., 0.8, respectively. The detailed data in the experiments are recorded in Table 5-20 of the Appendix.

Theoretically and practically, the signal under threshold can be detected with additional noise due to the effect of stochastic resonance. As the noise increases, the signal strength will increase before reaching the peak. As shown in the graphs, it is not that the stronger the noise is, the better the output it may be. There is an optimally critical point. Crossing over that point, such strong noise will interfere with the signal strength. Fig.8 and 9 illustrate each signal strength with different experimental conditions when the source is blue LED and red LED respectively.



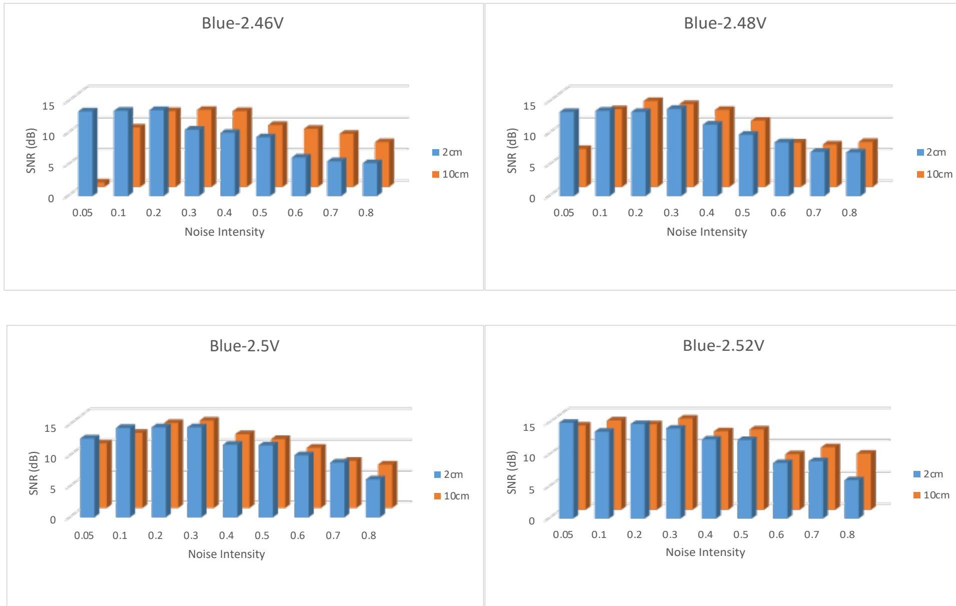
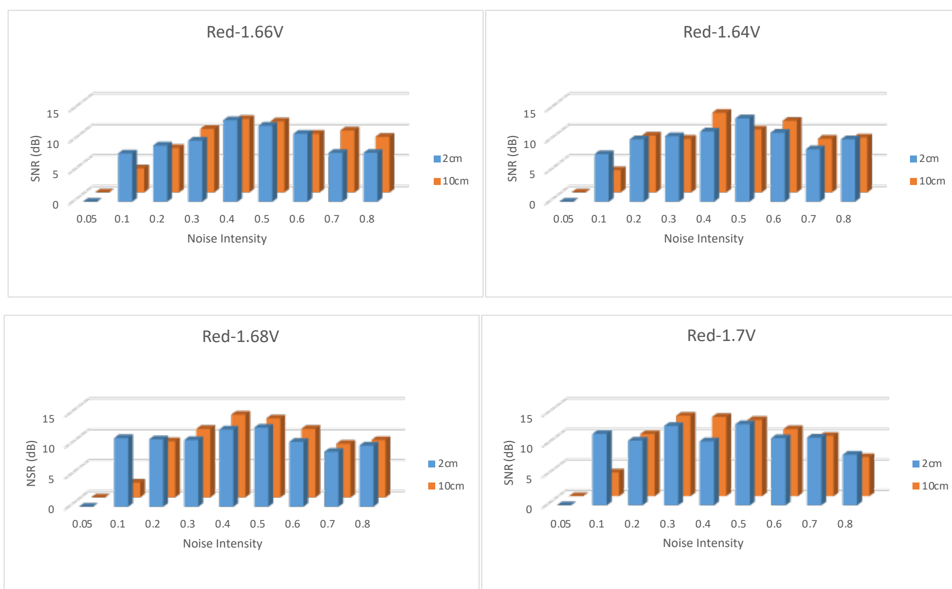


Figure 5. Stochastic resonance in different experimental groups with blue LED



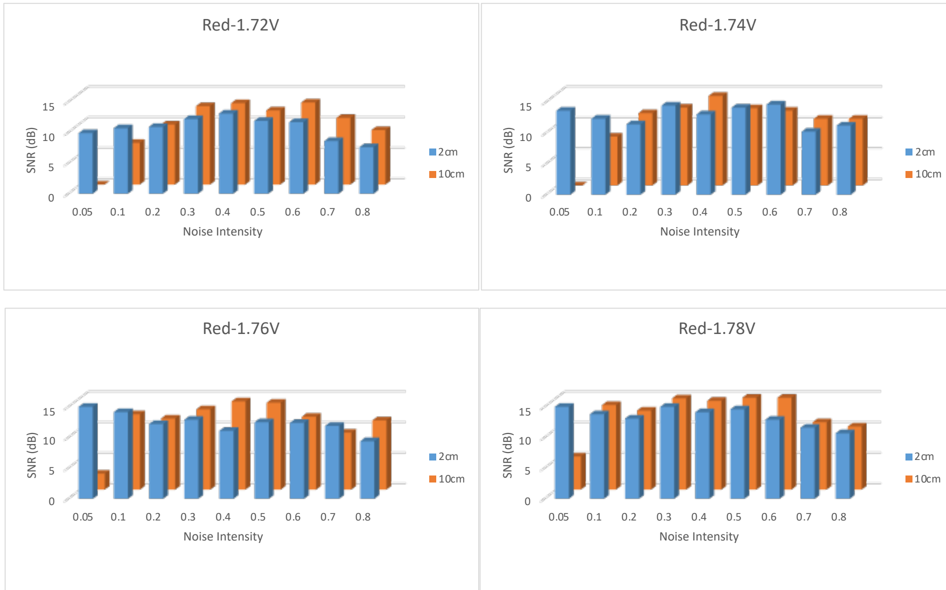


Figure 6. Stochastic resonance in different experimental groups with red LED

Making comparison between eight experimental groups in Fig.8, the impact from the distance between the generator and receiver on the extinction of optimal point is not observed. Further investigation is needed to make sure why is that the case.

Comparing Fig.8 and 9, we can find that the best variance has a lot differences between blue LED and red LED due to their wavelength diversity.

The input signal voltage also influences the best variance of Gaussian noise for the signal. As shown in Fig.8, when input voltage is 2.38V, the best variance is 0.2 while it changes to 0.3 when the voltage is 2.52V. This is because, when the signal is below the detection threshold, the input signal of larger amplitude is enhanced by stochastic resonance and crosses the detection limit. When the signal is above the detection threshold, both levels of the input signal cross the detection threshold, and thus shows no periodic feature. So, the stochastic resonance effect will only enhance the signal when it’s under the detection threshold and destroys the signal if above.

Chapter 5

Conclusions and further work

Conclusions

The utilization of noise offers us a brand-new possibility of strengthening the signals owning to stochastic resonance. This effect depends a lot on the characteristics of the source, for example, the wavelength, voltage and distance to the target, which have varying degrees of impact of finding out the best variance of the stochastic resonance of Gaussian noise for each signal. Further research is necessary to implement to make the better use of the noise.

Suggestions for further work

The widespread attention drawn from science to stochastic resonance as mentioned above has been extended to the industry. The industrial use of stochastic in troops in battle is being considered. Since soldiers in the battle field have carried a lot heavy devices, a light weighted sensor enhanced by stochastic resonance would relieve their bulky burdens and increase their mobilities. In addition, the stochastic resonance is applicable in some remote energy deficient areas such as mountainous or undersea regions such that the weak signals created by earthquakes or volcano eruptions can be detected with the highest energy efficiency.

More innovatively, scientists even consider how to apply stochastic resonance to increase the sensitivity of our brains. As we can imagine, our brains are analogical to sensors in some aspects. Perhaps, by using stochastic resonance, our vision or hearing can be sharpened in some noisy or dark environment. Actually, some researchers have done some pioneering work in this field, in which they explore the potential of stochastic resonance to prevent the falling of elderly people(White et al.). And the balance of those people does see an increase attributed to the stochastic resonance.

In conclusion, stochastic resonance is a really promising concept, which extends both our imagination and techniques. No one would even imagine noise can play a constructive role before the discovery of stochastic resonance but it does exist. With this technique, the signal processing and sensing would expect a revolution or at least a shift in paradigm. The conventional methods would be superseded by brand-new and energy efficient methods enabled by stochastic resonance. Doors would be open to an ignored and unexplored world of noise-enhanced signal detection. And more work is required in the scale-up of stochastic resonance techniques to really industrial and commercial applications. Also, it is hoped that internet of things can be integrated with stochastic resonance techniques for a well-detected world.

Appendix

2cm

		5.12s	10.24s	15.36s	20.48s
1	2.38	0	0	0	0
2	2.4	0	0	0	0
3	2.42	0	0	0	0
4	2.44	0	2.3	2.7	4.3
5	2.46	4.7	8.5	9.1	9.9
6	2.48	9.7	17	13	16.3
7	2.5	16.8	22	22.7	22.5
8	2.52	24.1	29.8	32.8	33.2

Tab.1 Latency test for blue LED 2cm away from receiver

2cm

		5.12s	10.24s	15.36s	20.48s
1	1.64	0	0	0	0
2	1.66	0	0	0	0
3	1.68	0	0	0	0
4	1.7	0	0	0	0.2
5	1.72	0	3.3	2.7	2.8

6	1.74	7.8	7	11.2	12
7	1.76	14.6	14.2	16.8	15.5
8	1.78	19.5	21.9	23.2	21.3

Tab.2 Latency test for red LED 2cm away from receiver

10cm					
		5.12s	10.24s	15.36s	20.48s
1	2.38	0	0	0	0
2	2.4	0	0	0	0
3	2.42	0	0	0	0
4	2.44	0	0	0	0
5	2.46	0	0	0	0
6	2.48	0	0	0	0.7
7	2.5	6	5.7	8.4	10.2
8	2.52	9.6	11.3	13	12.7

Tab.3 Latency test for blue LED 10cm away from receiver

10CM					
		5.12s	10.24s	15.36s	20.48s
	1.64	0	0	0	0

1.66	0	0	0	0
1.68	0	0	0	0
1.7	0	0	0	0
1.72	0	0	0	0
1.74	0	0	0	0
1.76	0	0	0.3	1.3
1.78	4.4	7.4	5.3	6.7

Tab.4 Latency test for red LED 10cm away from receiver

1- 2.38V		2cm	10cm
1	0.05	0	0
2	0.1	6.7	4.8
3	0.2	12.2	11.9
4	0.3	11.6	10.7
5	0.4	10.5	8.3
6	0.5	4.9	7
7	0.6	7.2	6.3
8	0.7	2.4	6.5
9	0.8	5.5	3.5

Tab.5 Stochastic resonance test for blue LED with 2.38V input voltage

2- 2.4V		2cm	10cm
1	0.05	1.4	0
2	0.1	8.6	9.5
3	0.2	10.3	11.6
4	0.3	10.9	10.7
5	0.4	8.7	10.8
6	0.5	6.5	8.5
7	0.6	3.2	7.5
8	0.7	6.8	6.6
9	0.8	1.6	4.9

Tab.6 Stochastic resonance test for blue LED with 2.40V input voltage

3- 2.42V		2cm	10cm
1	0.05	3.8	0
2	0.1	9.1	3
3	0.2	11.5	11.1
4	0.3	12.4	10.3

5	0.4	9.6	9.8
6	0.5	9.5	8.8
7	0.6	7.6	6.2
8	0.7	7.5	5.1
9	0.8	1.8	7.4

Tab.7 Stochastic resonance test for blue LED with 2.42V input voltage

4-			
2.44V		2cm	10cm
1	0.05	7.8	0
2	0.1	11.7	8.7
3	0.2	11.9	13.1
4	0.3	11.2	12.9
5	0.4	10.7	11.3
6	0.5	10	9.7
7	0.6	7.3	9.8
8	0.7	5.6	4.3
9	0.8	7.1	6.6

Tab.8 Stochastic resonance test for blue LED with 2.44V input voltage

5-2.46V		2cm	10cm
1	0.05	13.4	0.7
2	0.1	13.5	9.4
3	0.2	13.6	12
4	0.3	10.5	12.2
5	0.4	10	12
6	0.5	9.3	9.8
7	0.6	6.1	9.2
8	0.7	5.5	8.4
9	0.8	5.2	7.1

Tab.9 Stochastic resonance test for blue LED with 2.46V input voltage

6-2.48V		2cm	10cm
1	0.05	13.3	6
2	0.1	13.5	12.3
3	0.2	13.3	13.6
4	0.3	13.8	13.1
5	0.4	11.3	12.2

6	0.5	9.7	10.5
7	0.6	8.5	7
8	0.7	7	6.7
9	0.8	6.9	7.1

Tab.10 Stochastic resonance test for blue LED with 2.48V input voltage

7-			
2.5V		2cm	10cm
1	0.05	12.7	10.4
2	0.1	14.4	12.1
3	0.2	14.5	13.7
4	0.3	14.5	14.1
5	0.4	11.7	11.9
6	0.5	11.6	11.1
7	0.6	10	9.7
8	0.7	8.8	7.6
9	0.8	6.1	7

Tab.11 Stochastic resonance test for blue LED with 2.50V input voltage

8-			
2.52V		2cm	10cm
1	0.05	18.6	13.2
2	0.1	13.6	14
3	0.2	14.8	13.4
4	0.3	14.1	14.3
5	0.4	12.4	12.3
6	0.5	12.3	12.6
7	0.6	8.7	8.7
8	0.7	9	9.8
9	0.8	6	8.8

Tab.12 Stochastic resonance test for blue LED with 2.52V input voltage

1-			
1.64		2cm	10cm
1	0.05	0	0
2	0.1	7.7	3.6
3	0.2	10.1	9.2
4	0.3	10.6	8.7
5	0.4	11.37	12.9
6	0.5	13.5	10.2

7	0.6	11.17	11.6
8	0.7	8.5	8.7
9	0.8	10.1	8.9

Tab.13 Stochastic resonance test for red LED with 1.64V input voltage

2		2cm	10cm
1	0.05	0	0
2	0.1	7.8	3.9
3	0.2	9.1	7.2
4	0.3	9.9	10.3
5	0.4	13.2	11.9
6	0.5	12.3	11.5
7	0.6	11	9.5
8	0.7	7.9	10.03
9	0.8	7.9	9

Tab.14 Stochastic resonance test for red LED with 1.66V input voltage

3		2cm	10cm
1	0.05	0	0

2	0.1	11.1	2.4
3	0.2	10.9	9.1
4	0.3	10.8	11.1
5	0.4	12.5	13.4
6	0.5	12.8	12.8
7	0.6	10.5	11.1
8	0.7	8.9	8.7
9	0.8	9.9	9.3

Tab.15 Stochastic resonance test for red LED with 1.68V input voltage

4-			
1.7V		2cm	10cm
1	0.05	0	0
2	0.1	11.7	3.9
3	0.2	10.6	10.2
4	0.3	13	13.2
5	0.4	10.5	13
6	0.5	13.3	12.5
7	0.6	11	11
8	0.7	11.1	9.9
9	0.8	8.3	6.4

Tab.16 Stochastic resonance test for red LED with 1.70V input voltage

5		2cm	10cm
1	0.05	9.9	0
2	0.1	10.7	6.8
3	0.2	10.9	9.8
4	0.3	12.2	12.8
5	0.4	13.1	13.3
6	0.5	11.9	12.1
7	0.6	11.7	13.4
8	0.7	8.6	10.9
9	0.8	7.6	8.9

Tab.17 Stochastic resonance test for red LED with 1.72V input voltage

6		2cm	10cm
1	0.05	13.6	0
2	0.1	12.3	7.9
3	0.2	11.4	11.7
4	0.3	14.43	12.6
5	0.4	13	14.5

6	0.5	14.1	12.5
7	0.6	14.6	12.1
8	0.7	10.2	10.8
9	0.8	11.2	10.8

Tab.18 Stochastic resonance test for red LED with 1.74V input voltage

7		2cm	10cm
1	0.05	15.2	2.6
2	0.1	14.15	12.3
3	0.2	12.2	11.6
4	0.3	12.9	13.1
5	0.4	11.1	14.4
6	0.5	12.5	14.2
7	0.6	12.4	11.9
8	0.7	11.9	9.3
9	0.8	9.4	11.3

Tab.19 Stochastic resonance test for red LED with 1.76V input voltage

8		2cm	10cm
1	0.05	16.8	5.4

2	0.1	13.8	13.8
3	0.2	13.1	12.9
4	0.3	15.2	14.9
5	0.4	14.13	14.5
6	0.5	14.6	15
7	0.6	12.9	15.6
8	0.7	11.6	11
9	0.8	10.7	10.3

Tab.20 Stochastic resonance test for red LED with 1.78V input voltage

Reference

Benzi, R., et al. “The Mechanism of Stochastic Resonance.” *Journal of Physics A: Mathematical and General*, vol. 14, no. 11, 1981, doi:10.1088/0305-4470/14/11/006.

Casado-Pascual, Jesús, et al. “Stochastic Resonance: Theory and Numerics.” *Chaos*, vol. 15, no. 2, 2005, doi:10.1063/1.1858671.

Dodda, Akhil, et al. “Stochastic Resonance in MoS2 Photodetector.” *Nature Communications*, vol. 11, no. 1, 2020, pp. 1–11, doi:10.1038/s41467-020-18195-0.

Duan, Fabing, and Bohou XU. “PARAMETER-INDUCED STOCHASTIC RESONANCE AND BASEBAND BINARY PAM SIGNALS TRANSMISSION OVER AN AWGN CHANNEL.” International Journal of Bifurcation and Chaos, vol. 13, no. 02, 2003, pp. 411–425., doi:10.1142/s0218127403006601.

Hänggi, Peter. “Stochastic Resonance in Biology.” *ChemPhysChem*, vol. 3, 2002, pp. 285–90.

Huang, Yu, et al. “Van Der Waals COUPLED Organic Molecules WITH Monolayer MoS2 for Fast Response Photodetectors With Gate-Tunable Responsivity.” ACS Nano, vol. 12, no. 4, 2018, pp. 4062–4073., doi:10.1021/acsnano.8b02380.

McDonnell, M. D., et al. *Stochastic Resonance: From Suprathreshold Stochastic Resonance to Stochastic Signal Quantization Cambridge*. University Press, New York, 2008.

McDonnell, Mark D., and Derek Abbott. "What Is Stochastic Resonance? Definitions, Misconceptions, Debates, and Its Relevance to Biology." *PLoS Computational Biology*, vol. 5, no. 5, 2009, doi:10.1371/journal.pcbi.1000348.

McDonnell, Mark D., et al. "The Future of Stochastic Resonance and Suprathreshold Stochastic Resonance." Stochastic Resonance, pp. 358–361., doi:10.1017/cbo9780511535239.013.

Moss, Frank, and Kurt Wiesenfeld. "The Benefits of Background Noise." *Scientific American*, vol. 273, no. 2, 1995, pp. 66–69, doi:10.1038/scientificamerican0895-66.

Nicolis, C. "Stochastic Resonance in Multistable Systems: The Role of Intermediate States." *Physical Review E - Statistical, Nonlinear, and Soft Matter Physics*, vol. 82, no. 1, 2010, pp. 223–87, doi:10.1103/PhysRevE.82.011139.

SUN, SHUIFA, and SAM KWONG. "STOCHASTIC RESONANCE SIGNAL PROCESSOR: PRINCIPLE, CAPACITY ANALYSIS AND METHOD." International Journal of Bifurcation and Chaos, vol. 17, no. 02, 2007, pp. 631–639., doi:10.1142/s0218127407017495.

White, Olivier, et al. “The Promise of Stochastic Resonance in Falls Prevention.” *Frontiers in Physiology*, vol. 10, no. JAN, 2019, pp. 1–12, doi:10.3389/fphys.2018.01865.

ACADEMIC VITA

Yujing (Eugene) Wang

814-699-0376; yfw5169@psu.edu; 130 Northbrook Ln, 203, State College, PA, USA 16803

EDUCATION BACKGROUND

The Pennsylvania State University, Schreyer Honor College
Sept.2017-Dec. 2021

- BSc in Engineering Science & BSc in Mathematics

Awards: ***The Dean's List*** (for six consecutive terms); ***Outstanding Student in Chemistry*** in 2017

ACADEMIC RESEARCHES

Stochastic Resonance (SR) Enhanced Photodetection, Penn State University
Nov.2020- Now

- Designed photodetection circuit and performed an experiment to determine value of the subthreshold signal to be SR-Enhanced; analyzed data obtained using MATLAB.

Intelligent Automated Visual Inspection System, Penn State University *May 2018-Aug.2018*
Individual Research Project, instructed by Prof Elangovan

- Assembled a robotic arm and designed a control system interfaced with a computer to control it;
- Write an image processing function to detect and classify the surface defects.

Jun Wang's Lab, South China University of Technology
Jul.2018-Aug.2018
Research Assistant

- Synthesized RNA in vitro, DNA by RT-PCR, and constructed plasmids;
- Cultured cells and analyzed them with FCM; analyzed protein by Western Blot;
- Made Cationic Lipid Assisted Nanoparticles by PEG-PLA and PEG-PLGA emulsion.

Muscle Activation during Passive Leg Drop, Penn State University
Sept.2017-May2018
Core Member

- Co-designed and manufactured the device that allowed subjects' legs to bend to 90 degrees in the experimental chair;
- Tested human subjects' muscle activity test through EMG (electromyography);
- Collected and analyzed research data; prepared PPT to release the result to the public.

INTERNSHIPS

Penn State Learning Center, Abington, PA, USA
Sept.2018-Dec.2018
Peer Tutor

- Tutored and communicated with over 100 students during the internship.

Huahai Pharmaceuticals Co., Ltd, Guangzhou, China *May 2018-Jun.2018*
Physical & Chemical Inspector
- Inspected corporate products and materials under the standard of Good Manufacturing Practice (GMP).
- Prepared the test solution according to Chinese pharmacopoeia; operated the instruments such as balance, precise PH device, ultraviolet spectrophotometer, and liquid chromatography, etc.
- Recorded the process and result of the inspection and kept the instruments and lab clean.

EXTRACURRICULAR ACTIVITIES

Charity Event, India
Dec.2016
Financial Director
- Collected donations for a primary school in India, checked the expenses, and reported it to every donor.

ADDITIONAL

- **Language:** Chinese (native), English (fluent), Cantonese (basic)
- **Skills:** Python, MATLAB, Arduino, AutoCAD, SolidWorks, and laboratory skills.