USING TRANS-IMPEDANCE AMPLIFIER AND SMOOTHING TECHNIQUES TO IMPROVE SIGNAL-TO-NOISE RATIO IN A 24-BIT SINGLE BEAM VISIBLE SPECTROMETER

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Abstract - Using charge-coupled devices and CMOS sensors in spectrometers increases device cost due to complex circuitry requirements. In this work, a single beam visible spectrometer is designed and built using a single photodiode as a sensor and a simple circuitry hence reducing the cost of the device. Moreover, on the market, most of the spectrometers use 16-bit analog to digital converter to convert analog signal thereby limits the measurement concentration resolution and sensitivity of the spectrometers. To extend its ability, a 24-bit ADC is used in the design for more accurate spectrum measurements. This single beam visible spectrometer works in the spectral range from 400nm to 750nm. The use of the trans-impedance amplifier and smoothing sensor reduces noise and increases accuracy of the measured spectrums.

Keywords - Visible light spectrometer, noise, photodiode, filter.

I. INTRODUCTION

In practice, spectrometer methods in different electromagnetic spectra are extremely useful tools for chemical analysis and structure investigations. The spectrometer methods can be classified via the spectrum regions such as nuclear magnetic resonance spectrometer (NMR SPEC), Raman spectrometer, microwave spectrometer, infrared spectrometer, ultra-violet spectrometer (UV SPEC) and visible spectrometer (VISPEC). Depending on features and structures of the analysed specimen, a certain spectrometer is chosen, as different types of molecule have different electromagnetic spectra. Among these spectrometers, or spectroscopies, “the infra-red spectroscopy is best for structural investigation because of the ideal wave length region it covers in the electromagnetic spectrum” [1], while ultra-violet and visible spectrometer, also so-called electronic spectrometer, provides not much structural information [1]. However, from many different molecule spectra, the structure can be revealed by electronic spectrometer [1].

Moreover, thanks to Beer-Lambert law [2], UV SPEC and VISPEC probably give useful information about the concentration of many substances, such as sodium niobate crystals [3], alkaline copper quaternary [4], or ozone [5], and many other particular applications, for instant, biomolecular ions investigation [6], explosives characterization [7] and “pattern recognition methods for differentiation and classification of wines” [8]. The Beer-Lambert law points out that the higher concentration the molecules have, the higher energy the molecules will absorb. Subsequently, there will be the difference between the input light intensity and the output light intensity of the sample. In practice, researchers investigate the intensity of several reference samples which already have been known the concentrations of certain molecule or substance; then a measurement of the intensity of an unknown concentration of a sample containing the same molecule in the previous measurement step is performed by a photo sensor. The sensor transfers the intensity into electrical signal. Note that each device has its own sensitivity or limit resolution. The light intensity difference, which now becomes electrical strength difference of the known and unknown samples, will reveal the concentration of the molecule in the investigated sample.If the concentration difference between a reference sample, let’ say A, and investigated sample, let’s say B, is so small, then the light intensity difference is small as well. Consequently, the signal strength difference produced by the sensor is probably so small that the device cannot distinguish the difference. At this time, the device will ‘make’ a decision of that the concentration of B is equal to the concentration of A. These days, most spectrometers have an analog-to-digital converter (ADC) to digitize the analog data from sensor.There are several ways to evaluate the ability of an ADC. One simple is basing on ADC’s resolution. According to [9], “an ADC’s resolution is its number of output bit”. Thus, with the above given problem, to be able to recognize the small differencein molecule density, the ADC need to be increased the number of output bit. On the market right now, with a single beam spectrometer, most of the ADCs used is 16 bits [10, 11]. To improve resolution of the device for some especially low concentration or density of analysed substances, spectrometers need to use higher resolution analog-to-digital converter such as 24-bit ADC.

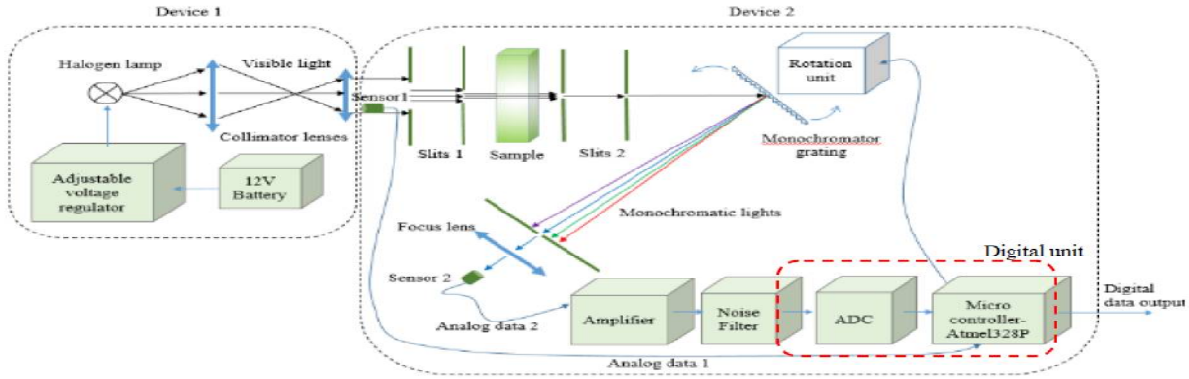
However, to possibly maximize and utilize the ability of spectrometers, several problems, of which data handling techniques takes significant roles, should be paid attention to. Data handling techniques includes

error correction, formatting, signal-to-noise enhancement, quantitative analysis, searching, and difference spectroscopy [12], which should be processed by a computer. In practice, signal-to-noise ratio (SNR) enhancement can be fulfilled by careful design such as taking care of noise reduction or smoothing technique by using hardware and data processing such asdigital filtering. Data fidelity is achieved if both of the descripted SNR enhancement techniques are adequately and sufficiently attended, in other words, reducing data error. Consequently, the benefits of the 24-bit ADC are maximized. In this paper, for SNR enhancement, amplification and filtering are mainly discussed. The digital filter techniques will be expressed in another article.

II. VISPEC DESIGN

FOR CONVENIENCE IN FOLLOWING SECTIONS, A BRIEF REVIEW OF SPECTROSCOPY THEORY IS RECOMMENDED. THE THEORY HAS BEEN WELL DISCUSSED IN LITERATURE [14, 15]. FIG. 1 SHOWS THE BLOCK DIAGRAM OF THE DESIGNED VISPEC. THERE ARE 2 DISTINCT DEVICES IN THE SYSTEM. THE SEPARATION OF THE SYSTEM INTO DEVICE 1 AND DEVICE 2 IS INTENDED FOR THE USE OF THE LIGHT SOURCE FOR OTHER APPLICATIONS.

Fig. 1 VISPEC structure



A. Device 1

Device 1 includes a 12V-50W halogen lamp, an adjustable voltage regulator of three 2N1544 transistors in parallel, 12V battery, and a collimator of lenses of 61.5 ± 0.5mm and 36.0 ± 0.5mm focus. The collimator is important in the light source as it assists in collimating the light. The collimating procedure in this design is time consuming as various parts must be carefully arranged. The distance between the light source and the lenses must be perfectly aligned to produce the best parallel light beams. Without a well collimated light, superposing spectra will happen. In addition, in the regulator circuit, each 2N1544 transistor can tolerate 5A collector current [16], while current goes through the circuit is around $\frac{50W}{12V} = 4.16$A. In the circuit, all three transistors are connected in parallel to withstand the required current. This abundant tolerance helps to maintain the output voltage steady in orderto stabilise the light intensity output.

B. Device 2

Device 2 includes slits, in which the narrowestslit is 0.05mm ± 0.01mm, sample holder, monochromator of 747 ± 11nm, focus lens, silicon photodiode BPW

34, amplifiers, low pass filter, 24-bit ADC ADS1252, and a microcontroller (µC) Atmel328P.In principle, the specimen in the sample absorbs part of the light energy from the halogen lamp light source, then the light going through is narrowed down by the slits before analysed by the grating and transferred into monochromatic lights. The acquired mono lights are scanned on the photodiode sensor, BPW 34. The scanning unit, which the main parts are the stepper motor 5V 28BYJ-48 DCwith 4096 steps/roundand the integrated circuit (IC) ULN2003APG, takes responsibility to control the scanning process. By improvement, the scanning unit can scan 82,944 steps/round. Thus, one step is equal to $\frac{360^o}{82,944} \approx 0.00434^o$. The scanning process, including start position and number of steps, will be set to cover from violet to dark red region. In data acquisition, the unnecessary portions of the data are discardedto provide the data only for the interested region of spectrum from400nm to 750nm. The sensor function is to convert the light intensity into electrical signal. As the signal is very weak, amplification is required to increase its amplitude to a suitable level for the 24-bit ADC. The ADC converts the analog signal into digital values, and at the next stage the µC will read these values, as well as processing the data.

III.SIGNAL-TO-NOISERATIO MPROVEMENT

A. Noise sources

There are several noise sourcesaffecting to the spectrometer data such as unstable light intensity, variance in ambient temperature, drifting in power

supply, atoms vibration and moving electrons in the detector, emitted electromagnetic wave from closed by electronic equipment, and so on [15]. These noisesare, practically, unavoidable. If the noise is so large, it can saturate the real signal. In general, signal fidelity is inversely proportional to noise. Noise reduction is a must in the design. The noisy signal can be considered as a random noise added to the actual signal. To recover the real signal, noise must be eliminated or reduced by different noise reduction techniques. There is a convention to assign a value to the noisysignal and the common rule is the root-mean-square value definition. As defined in Oxford Reference, "A typical value of a number (n) of values of a quantity (x_1,x_2,x_3…) equal to the square root of the sum of the squares of the values divided by n, i.e., RMS value = [$\sqrt{(x_1^2 + x_2^2 + x_3^2 \ldots /n]}$" [17].However, even after applying the convention to evaluate the values from the received data, the real data probably never can be achieved. Thus, the estimated data still contains noise in its. Subsequently, to describe how clean a given signal, the signal-to-noise ratio is defined. According to Attila Felinger [18], the SNR of a stable state signal is defined as

$$SNR = \frac{m}{\sigma} \quad (1)$$

wherem is the mean value and σ is the standard deviation.In reality, when working with very weak signals and 24-bit ADC, one should be aware of any sources of noise, and eliminate or mitigate them much as possible, as long as the signals' information would not be impaired.

B. Photodiode

The sensor choice is somewhat crucial. Choosing the sensor is based on several conditions such ascost, response time, spectral sensitivity, and noise. In general, discrete photodiode is low cost. For response speed, in case the project needs sensor to detect a quick changing quantity, for instant a laser pulse, then a small photodiode, with an intrinsic small capacitor, is more appropriate. However, the current noise caused by the small photodiode should be paid attention to. In counter case, a large photodiode will be more sensitive to the change of the ambient light, but its will response slowly, because it has a large intrinsic capacitor. Otherwise, its voltage noise will cause much difficulty. Fig. 2 depicts the size of each photodiode and their equivalent circuit.

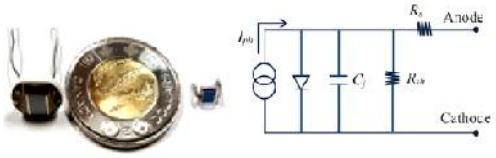


Fig. 2 From left to right, PCB-C140 and BPW 34 photodiodes; photodiode's equivalent circuit

Consider specifications in [19, 20],the active area of PDB-C140 is larger than BPW 34's, so, indeed, the capacitance of PDB-C140, which is 200pF, is also higher than BPW 34's, which is 72pF. In fact, the BPW 34 sensor, with the sensitivity area of 7.5mm^2, is still not small enough to be considered as a small sensor, since a small one's capacitance should be lower than 10pF. Both of the sensors' spectral sensitivity are somewhat similar to each other. The noise equivalent power (NEP) of BPW 34 is much smaller than PDB-C140. In this application, the BPW 34 is chosen, because there is no fast changing quantity studied, and through testing, the photodiode sensitivity is sufficient for the application. Moreover, the key point is that the sensor noise and current signal of this sensor are more easily controlled by a trans-impedance amplifier than the PDB-C140's.

C. Low Pass Filter

1. Ferrite bead

Ferrite bead and ferrite coils can be used as low pass filter to suppress high frequency noise. Applications and use of ferrite can be found in [21]. In this design, with the purpose of eliminate the radio frequency in the megahertz range, several ferrite coils have been chosen and tested. From the experiments, the cut-off frequency of the ferrite coils are around 9.487MHz.

2. Active low pass filter

From Eq. (1), the SNR is possibly increased by lowering standard deviation value or reducing the noise. An easy way is the use of filtering circuit. The active low pass filters are employed. The IC LMC6462's operational amplifiers (OPAMP) are used as shown in Fig. 3. The cut-off frequency of the active filters are the identical and equal to

$$f_{-3dB} = \frac{1}{2\pi.R_1.C_1} = \frac{1}{2\pi.82.10^3.0.039.10^{-6}} \cong 50\ Hz \quad (2)$$

Another function of these active low pass filters is amplification with the gain of:

$$G_1 = 1 + \frac{R_1}{R_3}, \text{ and } G_2 = 1 + \frac{R_2}{R_{V2}} \quad (3)$$

The total gain of both amplifier is G=G1*G2. In practice, the desired gain of the circuit can be achieved by the adjustment of the trimmer R_{V2} and using an oscilloscope for observation.

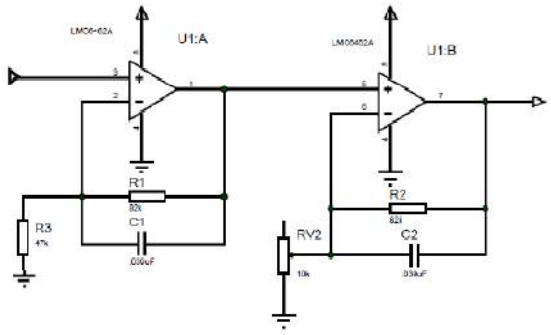


Fig. 3 Active low-pass filter

As seen in Fig. 4, the signal contains some noise, although the analog signal has been filtered ahead. The waveform is from the digitized signal output of the 24-bit ADC ADS1252 [21]. As mention in the

introduction, this paper does not discuss smoothing techniques by digital filters.

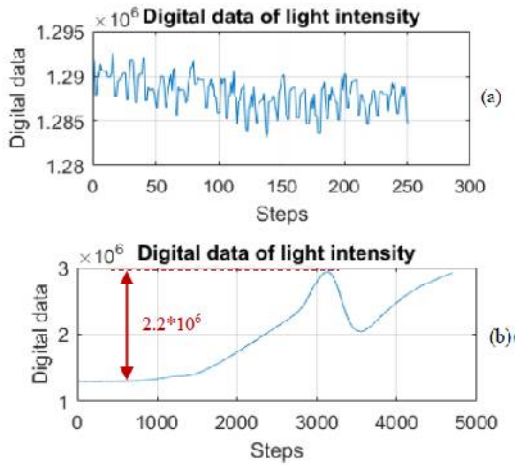


Fig. 4Digital data of light intensity. (a): data values from step 300thto step 600th; (b): data values from step 300th to step 6500th.To simplify the noise evaluation, the digital value from the ADC output is investigated, instead of voltage or power. In the closed view picture, (a), the peak-to-peak deviation value caused by the noise is approximately $1.294*10^6 - 1.288*10^6 = 6000$, and the background values are around $1.3*10^6$. The maximum value, with which the spectrometer can deal, theoretically, should be a value of 24 bits. However, in the device, the maximum value set up to 22 bits only. Consequently, from experiment the max value is $3.5*10^6$. Therefore, it can be said that the measureable range is $3.5*10^6 - 1.3*10^6 = 2.2*10^6$.

D. Transimpedance Amplifier and Results

To improve the SNR of the system, another type of op-amp, OPA314 [24], which issuitable for amplifying small signal such as the one in this spectrometer, is trans-impedance amplifier or current-to-voltage amplifier. Shown in Fig. 5 are two configurations of the trans-impedance amplifier for the photodiode to detect the light intensity. The photodiode is used in photoconductive or photovoltaic mode (PV), i.e., no biasing is required.

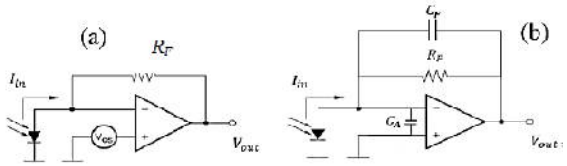


Fig. 5 Trans-impedance amplifier.(a) without feedback capacitor, (b) with a feedback capacitor.

In Fig. 5, R_F is the feedback resistor, and V_{OS} is offset voltage which equals to zero if the positive pole is connected to ground. When the photodiode is in the photoconductive mode, there is no dark current (dark current always occurs in biasing mode), as a result, the background output voltage from the amplifier is low. The output voltage of the trans-impedance amplifier is

$$V_{out} = -(I_{in} \cdot R_F) \quad (4)$$

There is thermal noise generated in the resistor R. This noise is expressed as a current source [22]:

$$I_{jn} = \sqrt{\frac{4k_B T \Delta f}{R}} \quad (5)$$

in which T is the absolute temperature (K), $k_B=1.38*10^{-23}$J/K, is the Boltzmann constant, and Δf is noise bandwidth (Hz). Consequently, the output due to the noise is:

$$V_{in} = I_{in} \cdot (R_s + R_f) = \sqrt{4k_B T \Delta f (R_s + R_f)} \quad (6)$$

As described in Eq. (4), $V_{out}$is proportional to R_F. Subsequently, one can see that:

$$SNR \sim \frac{V_{out}}{V_{in}} \sim \sqrt{R_f} \quad (7)$$

The reason the approximation sign is used but equivalence sign because there are different noises in the system which affect the output voltage. However, in practice the thermal noise mostly dominates other noises. It is obvious that if R_F is increased then the SNR will grow by the square root of the R_F. However, with just the above circuit, in work, the output will be unstable and eventually, oscillates. The reason is that the intrinsic capacitor C_i of photodiode along with R_F form a RC discharging-oscillating circuit. To compensate this effect, according to [22], the circuit will probably be stable when a feedback capacitor, parallel with the R_F, is added in and satisfies the condition:

$$\sqrt{\frac{GBP}{2\pi R_F (C_j + C_F + C_A)}} > \frac{1}{2\pi R_F C_F} \quad (8)$$

whereGBP is the gain bandwidth product, C_F is the feedback capacitor, and $C_A$is the input capacitor as in Fig. 5, (b). From [23, 24], one can find the values which are satisfying Eq. (8). In the design of this VISPEC spectrometer, the chosen C_F and R_F are 90pF and 1GΩ, respectively. C_A is not put in the circuit here, so equal to zero. From the steady condition in Eq. (8), it can be seen:

The condition is properly satisfied. The trans-impedance amplifier is then connected to the previous two amplifiers as a front-end amplifying stage. Some results from experiment are shown in Fig. 6.

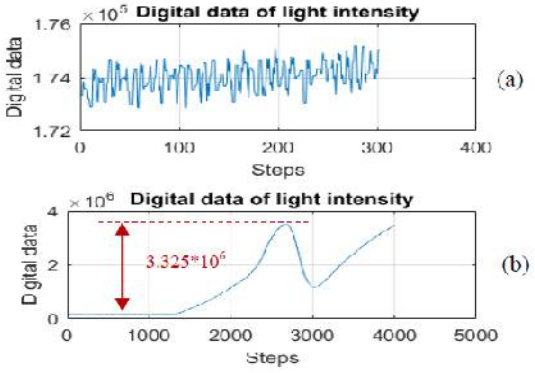


Fig. 6 Digital data of the light intensity. (a): data values from step 50th to step 250th; (b): data values from step 1th to step 4000th

From the measurement results, it can be seen that the noise error, which is, just again, roughly estimated, is

about $1.745*10^5$ – $1.73*10^5$ = 1500, and the background value is around $1.75*10^5$. Thus the range of values is approximately $3.5*10^6$ – $0.175*10^6$ = $3.325*10^6$. In comparison with the results from section Dabove, now, the noise error is smaller than the previous investigated, and the range of measureable values is effectively extended. The noise is decreased by $\frac{6000}{1500}$ = 4 times, consequently, andthe measureable range is increased by $\frac{3.325*10^6}{2.2*10^6}$ = 1.5 times.The plots of standard deviation of the case without trans-impedance amplifier,σ_1, and standard deviation of the case with trans-impedance amplifier,σ_2, are shown in chart (a) of Fig. 7. In chart (b), the plot of log(SNR2/SNR1) is depicted, where:SNR1=$\log \frac{m}{\sigma_1}$, and SNR2=$\log \frac{m}{\sigma_2}$.

From the figures, it can be seen that the data measured by the device with trans-impedance amplifier has higher fidelity than the data measured by the device without the trans-impedance as described in section C. 2.

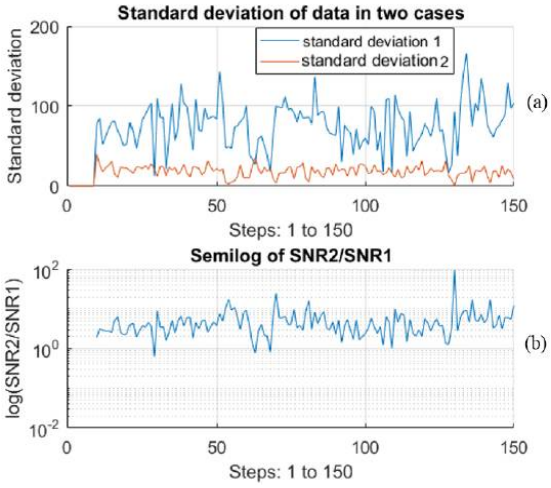


Fig. 7 (a) Plots of standard deviations, (b) Plot of log(SNR2/SNR1)

DISCUSSION

In the design of the VISPEC, SNR improvementis performed by, (a) using ferrite material in the form of beads or coils to suppress the high frequency noise, (b) choosing appropriate photodiode in size, capacitance, resistance to mitigate the noise, (c) using trans-impedance amplifier with appropriate resistors and capacitors. The amplifier circuits which are represented here are congruous with this application. For other measurements, there should be some adjustment to adapt with the application. There are more other different ways to improve the SNR for the device. For example, the bias current of the op-amps has not been dealt with. This bias current is one of the main reasons which results in the background signal is high or low. Using digital filter to embed into the microcontroller is also a very effective method in dealing with noise.

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