Optical Attenuation Sensor for Process Control

Senior Project Final Report

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Executive Summary

The goal of this senior project was to develop an optical attenuation meter for manufacturing process control. This was inspired by a local corporation interested in using the optical attenuation characteristics of materials to monitor the binary chemical components of a glue used by a mechanized sprayer. The end product was to exhibit the following characteristics:

- **Cost –** By replacing an expensive optical spectrum analyzer, there is immense possibility for cost reduction through this project.
- **Dynamic Range** – The device should be able to function over a large range of optical attenuation levels.
- **Correlation –** The device should provide a DC voltage output that linearly varies with the optical attenuation the device is exposed to.
- **Stability –** The measurement should not be susceptible to slight flaws in the material (i.e. bubbles in the fluids) or changes in ambient lighting.

Ideally multiple identical circuits with different center optical wavelengths will be used to measure the infrared attenuation spectra of a specific material.

The circuit that has been designed and built uses a light emitting diode – phototransistor pair to measure the optical transmission using a modulated optical signal. By amplifying this detected signal and measuring the magnitude of the AC portion with a lock-in amplifier circuit the design goals have been successfully met.

Table of Contents

Introduction

This idea for this project originated at a manufacturing company in the greater Cleveland area. (The name of the company has not yet been disclosed to us.) This company uses robotic sprayers to combine two binary components to form an epoxy on an assembly line. Their problem is finding a less expensive means of testing the composition of the glue to ensure that it is correct.

The idea that was presented to us was to design an optical circuit using an LED and a photodiode to measure the attenuation through the glue. Our goals were to keep the design simple while achieving a large dynamic range and a strong correlation between attenuation levels and output values. We designed a circuit that satisfied these goals as well as more complex issues such as amplification and noise reduction.

There has been at least one senior project that has investigated components for this type of circuit. We investigated this prior work, as well as work that Dr. Merat did himself, and then continued the research. We split our group into two teams to get more effectively carry out our research. One team researched the optical components while the other team researched the electronic output circuitry. The two teams both generated basic design concepts. We then came together, compared findings and ideas, and decided on a final circuit design. Through several stages of testing and tweaking we came up with a design that we were happy with and working prototypes on breadboards. After testing and characterizing our circuit on the breadboards, we soldered the components onto a board allowing our creation to be more portable and permanent. After another series of tests to ensure that our soldered board worked as expected, we are ready to present our final product.

Methodology

Our first step toward completing this project was investigation. We looked at past research projects to see what they could contribute to our ideas, and we searched out the components necessary to design the simplest and most effective circuit. We split our project team into two groups. One group designed the optical front end, while the other group designed the electrical back end. We have defined the "front end" of our circuit to be the portion that converts an electrical signal to an optical signal, transmits and receives that signal, and converts it back to an electrical signal. The "back end" contains all of the circuitry that the signal passes through on its way to the output.

The two teams came together with their design ideas and we worked out the basic design as a whole. We then came up with a list of design considerations as well as a list of necessary components which we gave to Dr. Merat to order. The parts took longer than we anticipated (over two weeks) to arrive, but after receiving them, progress increased considerably.

Our next step was to make decisions on most of our major design considerations. These issues are discussed in more detail in the following section. For the front end, we had to decide: what waveform to use, how to generate that waveform, whether to use AC or DC coupling, and amplification of the optical output. We also had several back end decisions to make including whether to use an AD630 Balanced Modulator/Demodulator or an AD536 RMS-to-DC converter to complete the attenuation measurement. Other back end considerations included: what we wanted our output to look like, how we wanted to get that output, and what factors we should consider regarding noise and resolution.

After deciding these issues and agreeing on a final design, we built our circuit on a solderless breadboard. We started with the front end and the AD630 circuitry, and later added the on-board oscillator, the visual output, and control of the voltage offset and amplification. After testing, adjusting and characterizing our prototype to our satisfaction, we soldered the circuit to a breadboard.

Design Considerations

There were many factors to consider during the process of conceiving, designing, and implementing this sensor. Some decisions were easy to make, others required more thought, and still others required considerable forethought as to possible future uses and design changes. Here we will discuss these decisions not in the order they were made, but as a walkthrough tour of our circuit.

Oscillator Design

Given a project with such a nebulous design specification, we were presented with a plethora of design paths to explore. The first step in any AC system is signal generation. Though this may appear on the surface to be a trivial element in the design considerations, the AC-signal is the basis for the entire circuit. We decided early in this process that we would like to generate the signal as part of our circuit, thus eliminating the need for an outside signal source.

We next were faced with the question of what type of signal to generate. Sine waves, while not necessarily easier to generate, ideally contain only a single frequency component. The single frequency component has many attractive attributes including no switching noise in a high gain circuit, and reduced high-frequency noise emanating from the finished product. Additionally, having a single frequency component theoretically improves the efficiency of a lock-in amplifier's interference rejection characteristics. As a final consideration, a sinusoidal input eliminates any concerns with switching times of the optical components and accompanying circuitry.

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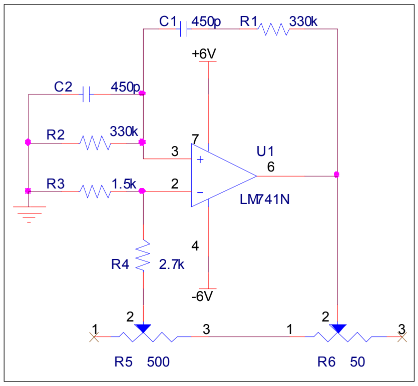

Fig. 1) Wien Bridge Oscillator

A Wien Bridge oscillator (figure 1) is perhaps the simplest method of sine wave generation. Using a single inexpensive op-amp and a few discrete components, this circuit generates a surprisingly clean and stable signal at our arbitrarily chosen frequency of 1kHz. The oscillation frequency of a Wien Bridge circuit is not selected by a resonant (LC) oscillation, but rather through a frequency-selective feedback network consisting of both a high-pass and low-pass filter. One bonus here is that capacitors are much cheaper than inductors. The only difficulty with this oscillator involves the feedback network in that it needs to supply a gain that exactly balances the attenuation through the Wien Bridge. If the feedback resistors define a gain too low, the circuit will not oscillate. If the gain is too high, the circuit will oscillate, but the amplitude will be determined by the op-amp output hitting the supply rails and clipping, thus creating a less than perfect sine wave. We inserted a potentiometer into the feedback path to adjust the gain and then decided to slightly overdrive to ensure that the oscillation never collapsed. The less than perfect sine wave still possessed fewer frequency components than a square wave and was not a major issue for reasons that will be discussed later. We placed a voltage follower after this oscillator to prevent the rest of the circuit from excessively loading the feedback network.

Optical Transmission and Detection

For our optical transmitter, we chose a common high-output infrared light emitting diode (LED). The drive circuitry for this LED contains separate DC and AC drive transistors, allowing the AC magnitude and DC offsets to be varied independently. This provides an AC signal which is free from distortions due to turn-on effects of the LED. The LED circuitry is a current rather than voltage drive as this provides for optimal uniformity should various LEDs be used in the circuit. (Different LEDs, while having will have very similar light-to-current curves, but different light-to-voltage curves.) A phototransistor was chosen to be the optical receiver rather than a photodiode because the phototransistor has a higher gain, and therefore greater output. The phototransistor does have higher dark current than a comparable photodiode, but we send the received signal through a high pass filter to remove any components caused by dark current or ambient lighting, as well as the DC bias of the transmitted signal.

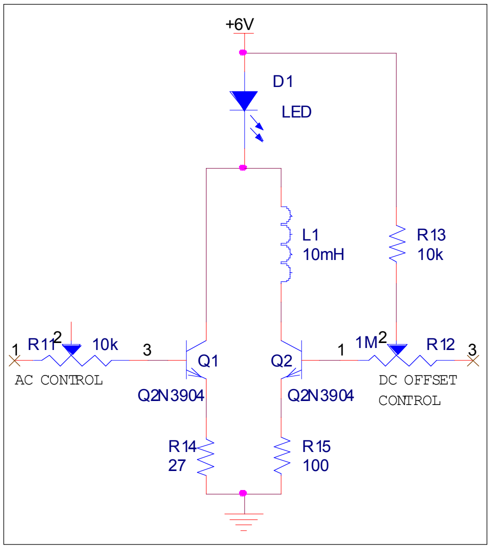

Fig. 2) LED Drive Circuitry

The received signal is then amplified before proceeding to the back end of the circuit. The noise floor is crucial at this stage, so we chose National Semiconductor's CLC425 Ultra-Low-Noise Wide Band Op Amp. We used another voltage follower as a buffer after this amplifier, again to prevent the rest of the circuit from loading the feedback network.

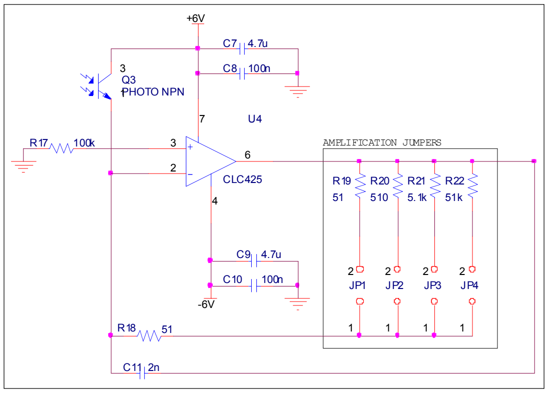

Fig. 3) Photoreceiver / Amplifier

The range of attenuation expected from the epoxy is unknown at this time, so we chose to design our circuit to amplify a wide dynamic range. Our original design accomplished this with potentiometers in the feedback path of the low-noise amplifier for a manually adjustable gain. We later decided that potentiometers were likely to cause additional noise, especially as they age. We decided to use a variable resistance network using four resistors that can be individually selected with a jumper. The four resistor values selected were 51 W, 510 W, 5.1 kW, and 51 kW. These four sufficiently overlap and still offer a greater dynamic range than our previous potentiometers.

With this variable gain it is possible to overload the amplifier network. To warn the user that the amplification is too high for the received signal strength, we added a detection circuit. A diode network in series with an LED is used to detect and warn of an overdrive condition.

Attenuation Measurement Circuitry

The actual attenuation measurement is performed using Analog Devices' AD630 Balanced Modulator/Demodulator chip. This chip is a balanced mixer that will be used as a lock-in amplifier (figure 4) which takes the signal from our amplifier as well as a reference waveform from our oscillator demodulate the signal waveform. This greatly reduces noise and allows for an accurate attenuation measurement. The circuit is supposed to provide up to 100dB of dynamic range. The lock-in amplifier also allows for frequency selection, and should prevent crosstalk if several of these boards are operating in close proximity at different frequencies. We tested for crosstalk and our findings are discussed in the Results section.

The reference waveform is AC coupled, which causes the AD630 to rectify its output signal. This output signal is sent through a low pass filter (on the order of 10Hz) to filter out the AC components. The DC value at this point is the output of our circuit. Our decision to use a DC output is the reason why a perfect sine wave is not necessary at the front end. The DC value at a known good attenuation can be set as a baseline and any variations can be detected.

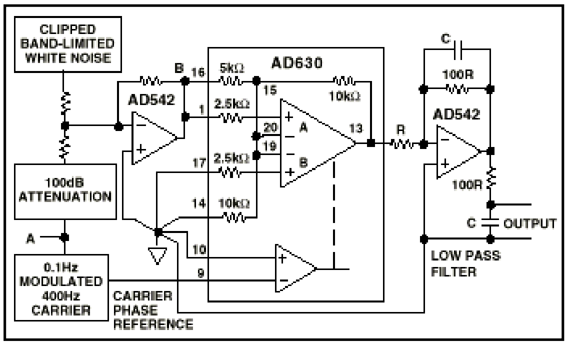

Fig. 4) Sample Lock-In Amplifier Circuit

There are several different methods that can be used to generate an output from our circuit. One method would be to have the output feed to an A/D converter and then into a neural net. This would be beneficial for use with multiple attenuation sensors operating at multiple wavelengths to measure a material's composition, but is beyond the scope of a one-semester project. We are more focused on the attenuation of one signal due to concentration. We chose to use two voltage comparator circuits to define a "good" voltage range which is then fed into a 7400 series logic chip to fire separate LEDs when the voltage is within one of three ranges. A similar output could have implemented without the use of the logic chip with some diodes and resistors, but the logic allowed for an easier-to-read display which would be more beneficial in a factory type setting.

One final design consideration was the operating voltage of our circuit. The AD630 chip requires a minimum of 5V. The CLC425 amplifier has a maximum voltage rating of 7V. All of our other components can operate within that range. We tested our circuit at 5, 6, and 7 volts to determine the optimal point. There was no major difference in operation, so we chose 6V to facilitate on board power in the form of batteries. Our circuit draws a current of 200mA maximum (100mA typical) from the positive power supply and under 100mA from the negative.

Results

The primary results from our project are contained in figures 5 and 6 below. As can be seen in the graph, the DC output voltage from our circuit has a direct linear correlation to the optical attenuation (transmission) to which the optical "front end" is subjected. The deviations from the linear that can be seen in the graph are residues of the fact that the attenuation sources used were calibrated for the visual spectrum and not the infrared. Despite this limitation (which was most evident at very high attenuation levels) the curves still closely follow the ideal linear curves that we hoped to achieve.

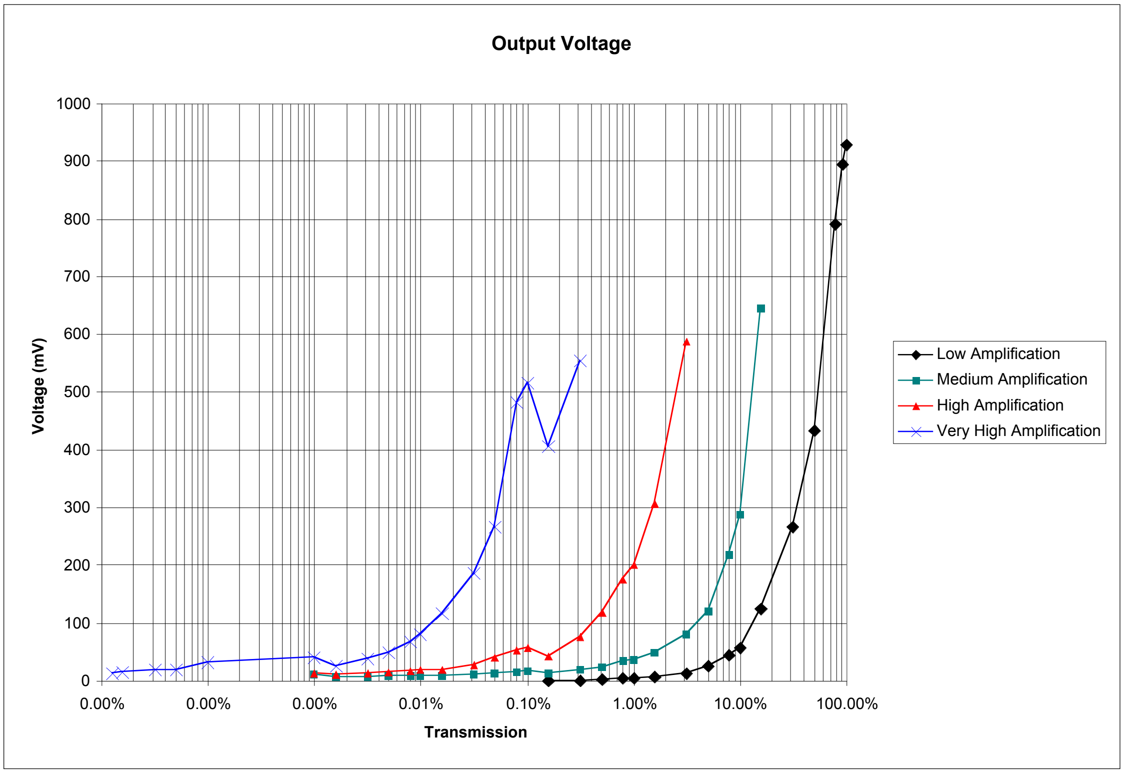

Fig. 5) Output Voltage vs. Optical Transmission

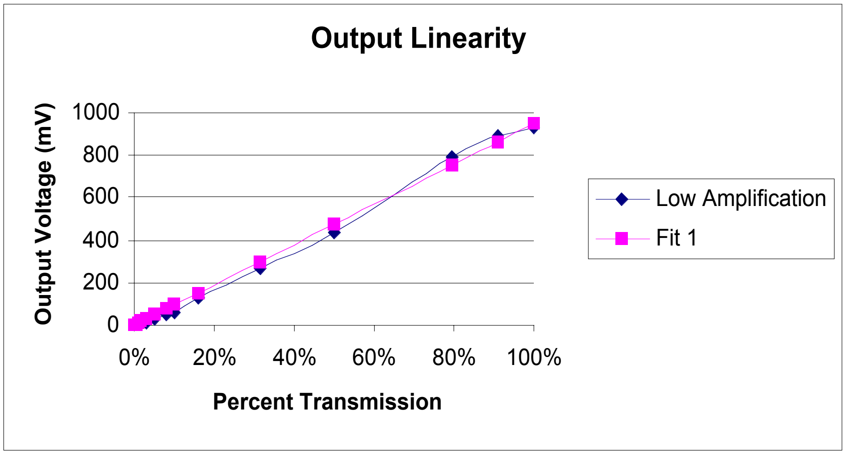

Fig. 6) Output Linearity

Upon building our second prototype board, we were able to further investigate issues concerning crosstalk. We tested two boards side-by-side, each using different signal modulation frequencies. We discovered that there was a significant amount of crosstalk. Because the AD630, given a clean reference signal, *should* be able to pull the each signal from significant noise, we did a Fast Fourier Transform analysis of our sine wave. We discovered that by overdriving the circuit to stabilize the wave (figure 7a), we introduced undesirable frequency components (figure 7b). This opened the door, so to speak, for noise, in this case crosstalk, to invade the output signal. By not operating the oscillator at an overdriven state (figure 7c), we were able to decrease the extra frequency components (figure 7d). While this did not eliminate crosstalk, it did decrease it from around 10 percent to 3-4 percent.

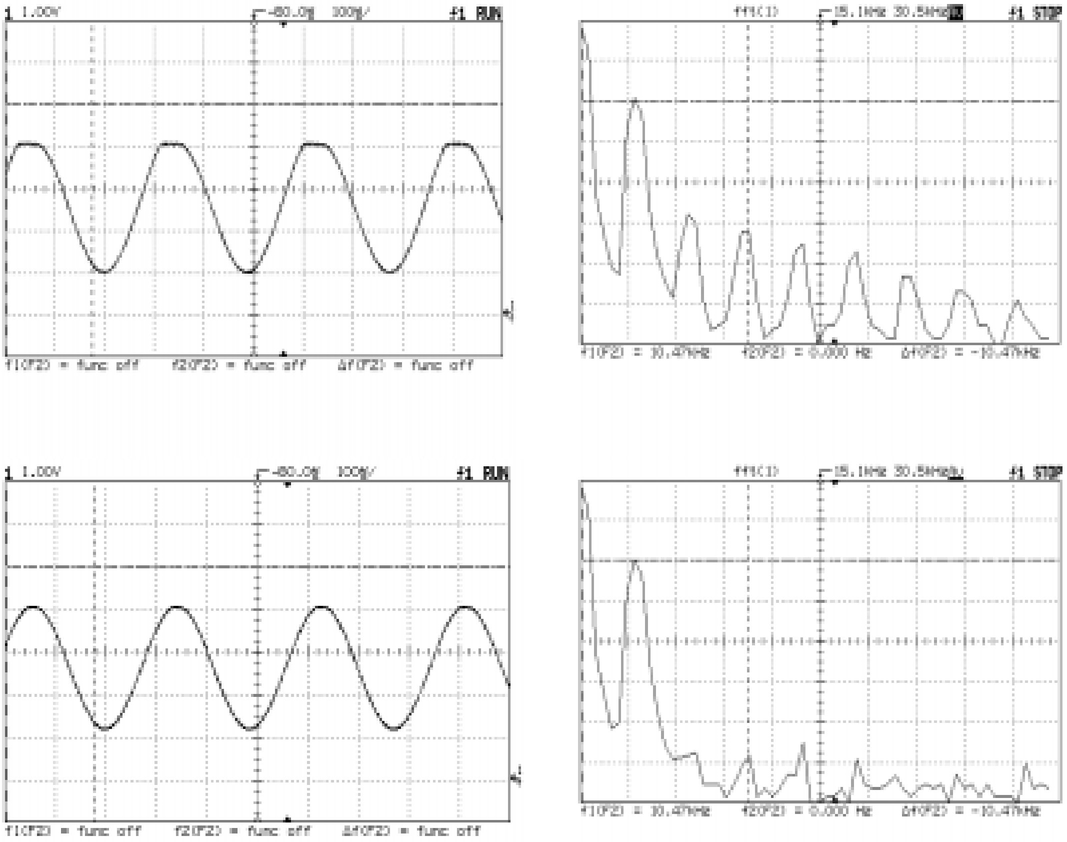

Fig. 7 a,b,c,d) Top: “Imperfect” sine wave and its FFT; Bottom: “Perfect” sine wave and its FFT

Figure 8 illustrates the capabilities of the AD630 as a lock-in amplifier. Channel 1 shows a unfiltered 1 V_{P-P} input, attenuated by more than 60 dB being fed into the AD630 while channel 2 shows the unfiltered output from the lock-in amplifier.

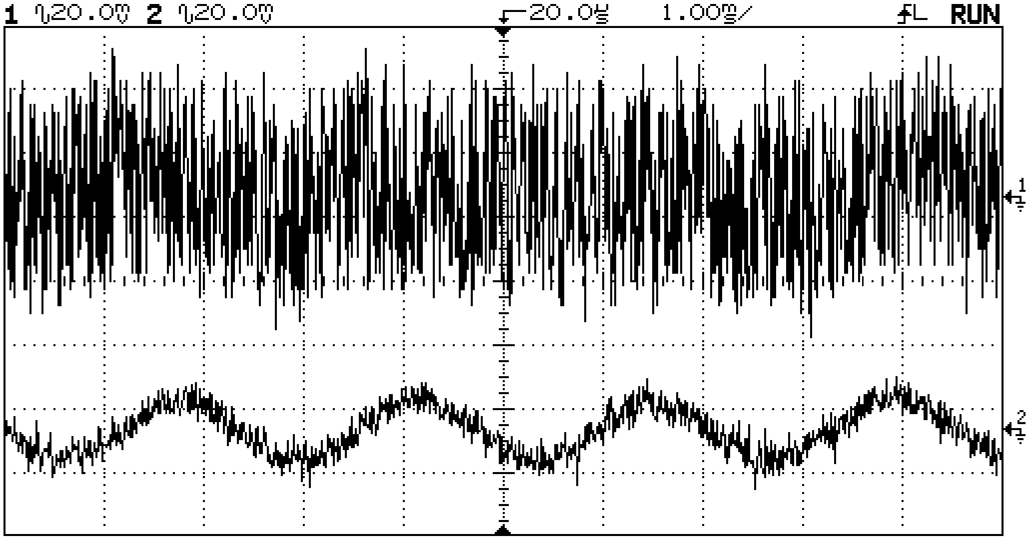

Fig. 8) Channel 1: Input to 630; Channel 2: Output from 630

Conclusions

Using an optical spectrum analyzer just to measure the attenuation of a fluid is an over-dedication of resources. Our goal was to design an effective, yet relatively inexpensive alternative to a high-cost optical spectrum analyzer. Our finished prototype meets all of our stated goals: low cost, large dynamic range, strong correlation, and high stability.

By including an on-board frequency source that can be modified in production to provide different frequencies, multiple instances of our product can be placed in parallel with LEDs of varying wavelengths to provide a crude absorption spectrum of the material under test. In final analysis, we have produced a circuit for under $50 that can provide similar optical measurement capabilities for a production line as a much more expensive (orders of magnitude) spectrum analyzer.

Recommendations

To replace the spectrum analyzer on the assembly line, multiple copies (most likely at least three) of our circuit will have to be used in parallel. Ideally a calibrated neural network that would detect variations in the attenuation and warn operators of an inappropriate composition would tie these circuits together. To use several of these circuits in close proximity the issue of crosstalk must be addressed. Using a more stable sine wave generator at the front end will reduce the number of frequency components in the signal and should significantly reduce crosstalk. The Wien Bridge oscillator can be modified with additional components to create a better waveform, or another oscillator could be built in its place.

Other changes that are needed before deployment in a production environment include repackaging the circuit, auto ranging of the amplification, and selection of proper wavelength LEDs for optimal detection of the desired variations.

This type of attenuation sensor has many applications in industry and elsewhere beyond monitoring the composition of epoxy components. Possible areas of future use include the health care industry –monitoring blood content, for example – and many manufacturing quality control applications. When used appropriately, our product provides a sensitive, cost efficient alternative to using laboratory-grade test equipment in a manufacturing environment.

Appendix A – *Circuit Schematic*

Appendix B – *Advisor Log*

Appendix C – *Circuit Photograph*