# Design and Construction of a Variable Gain Amplifier for Tunable Diode Laser Spectroscopy

by Robert Moffatt

*I designed and built an amplifier with automatically controlled gain for the amplification of signals from a photodiode. The photodiode was part of a Tunable Diode Laser Spectroscopy system, which used the absorption of light by air to determine oxygen concentration in the presence of water mist. An amplifier with automatically controlled gain was needed to amplify the photodiode signals because the varying mist concentration caused large fluctuations in the signal amplitude.*

*My circuit consisted of four separate modules: an amplifier circuit, a comparator circuit, a gain control circuit, and a timer circuit. The amplifier circuit used the PGA202 and PGA203 from Texas Instruments. The gains of these chips were controlled by digital inputs which came from the gain control circuit. The output was then compared to two reference voltages by the comparator circuit to determine if the signal amplitude had exceeded the predetermined range. The gain control circuit used a 74LS169 counter with additional logic circuitry to control the gain of the amplifier module based on the results of the comparator. The gain setting changed once a clock pulse arrived from the timer circuit. A function generator was used to produce synchronization pulses which periodically reset the timer circuit. After being reset, the timer circuit allowed a certain amount of time to elapse before generating a clock pulse for the gain controller.*

*After the main circuit was complete, I added manual gain controls, an LED readout, and a gain setting output which allowed a computer to see the current gain setting.*

*The circuit was able to keep the signal amplitude within the range required for accurate measurements, while adding acceptable levels of noise to the signal. With the circuit, a computer was able to make continuous, valid oxygen concentration measurements during times of varying mist density.*

## Introduction

Measuring oxygen concentration in the presence of water mist is difficult, because often all water must be removed before the measurement can be made. TDLAS, or Tunable Diode Laser Spectroscopy, avoids this problem by measuring the light absorption due to oxygen at around 760nm, from which the oxygen concentration can be calculated. The laser diode's wavelength may be swept across the absorption line by changing either the current (a fast process) or the temperature (a slower process). In this experiment, the temperature was held constant, and the laser was rapidly tuned by varying the current. The laser's current followed a triangle wave, causing it to reach a minimum wavelength, and a maximum light intensity at the current peak.

In this experiment, the beam from a laser diode was sent through a container of water mist and detected by a silicon photodiode (UDT Sensors, Inc., model PIN-10D). When the concentration of the mist changed, the signal experienced large fluctuations. The existing amplifier had a manually set gain, and no single gain setting sufficiently covered the wide range of signal amplitudes. Because of this, an amplifier was needed that would always provide an acceptable signal: either an amplifier with multiple gains, or an amplifier with automatically controlled gain.

## Methods and Materials:

### Multiple Fixed Gain Amplifier:

The first circuit that I built, shown in Figure 1 (*PSpice* generated figure), was designed by Dr. Volker Ebert. This circuit used three model OP27 and OP37 high precision op amps in the non-inverting configuration. The OP27 was used for the smallest gain, and the OP37 was used for the two larger gains because of its larger bandwidth. In addition, each of the three gains could be switched manually between two values: 3 or 6, 10 or 40, and 30 or 250. The circuit was soldered onto a printed circuit board and placed inside an aluminum project enclosure. Isolated BNC connectors were used for the inputs and outputs, and banana plugs were used for the dual +15V power supply. All of the outputs were sent to a computer's Analog to Digital Conversion (ADC) card and monitored simultaneously. This allowed multiple gain settings to be measured at the same time, preventing loss of data during gain switching.

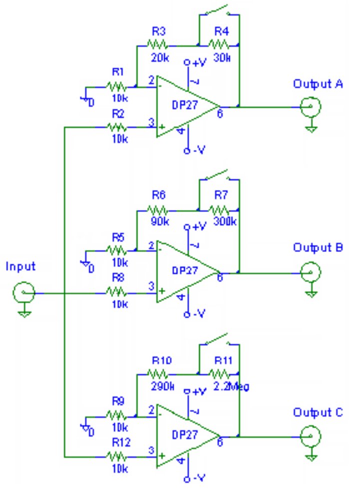

*Figure 1: Multiple Fixed Gain Amplifier*

### Amplifier with Automatically Controlled Gain:

The second circuit, shown in Figure 2, was my own design. It consists of three separate modules: a digitally controlled amplifier, a sample-and-hold circuit, and control and logic circuitry. I chose to use a digitally controlled amplifier because of the reliability of its gain settings and the possible use of the Femto DLPCA-100 Current

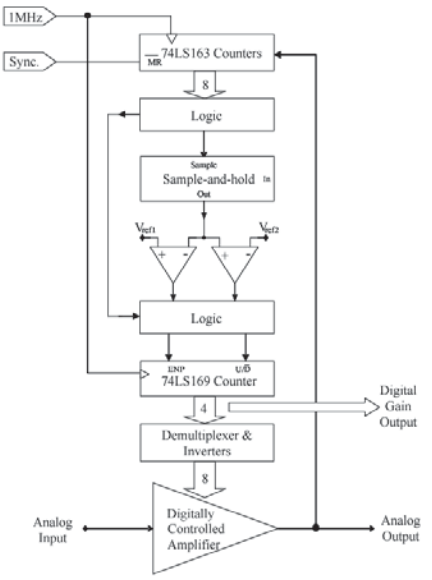

*Figure 2: Amplifier with Automatically Controlled Gain*

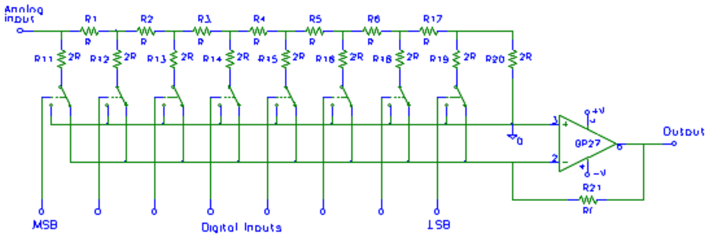

*Figure 3: Sample-and-Hold Circuit using the DS1804 Digital Potentiometer*

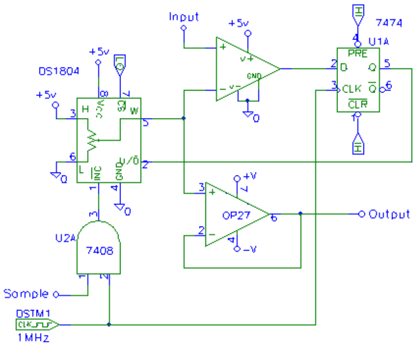

*Figure 4: Amplifier with Digitally Controlled Gain*

Amplifier which has digital external control.

The circuit makes use of the R/2R ladder inside the Dual 8-bit Multiplying Digital to Analog Converter (DAC), Maxim MX7628, to form an amplifier with digitally controlled gain. An equivalent circuit is shown in Figure 3. The switches and resistors are inside the DAC, and the OP27 is external. Any amplifier with digital control, such as the Femto DLPCA-100 Variable-Gain Low-Noise Current Amplifier, may be used in place of this circuit.

The sample-and-hold circuit samples the output once every cycle and compares it to two reference voltages. Comparators and logic circuitry subsequently determine whether the gain should increase or decrease. The sample time is determined by two 74LS163 counters, a 1MHz crystal oscillator, and logic circuitry. The Ripple Carry Out (RCO) of the second counter is inverted and sent to the Enable Parallel (ENP) inputs of both counters. Once the counters reach the maximum count value, RCO becomes high, making ENP low and disabling the counters. The counters remain in this state until they are reset by the low half of the function generator's synchronization output. This digital output is a square wave, in phase with the function generator's triangle wave output. Once the synchronization output becomes high again, the counters stop resetting and begin to count again. Several logic gates produce the sample pulse based on the counters' outputs.

The sample-and-hold circuit uses a Maxim DS1804 digital potentiometer and a comparator to sample and hold the output of the digitally controlled amplifier. The DS1804 contains 99 resistors in series, and 100 tap points. The two ends of the string of resistors are connected to the High (H) and Low (L) pins of the chip. The Wiper (W) pin is connected through transistor switches to one of the 100 tap points, determined by an internal counter and demultiplexer. The DS1804 has two control inputs: an increment (INC) input, and an up/down (U/D) input. In addition, it also has a Chip Select input and an internal EEPROM, which were not used. The sample-and-hold circuit operates in the following way: the High pin of the DS1804 is connected to +5V and the Low pin is connected to 0V. With every falling edge of the INC input, the wiper position will either increase or decrease by one position. This causes the voltage at the W pin to increase or decrease by 0.05V depending on the state of the U/D pin. A comparator compares the voltage of the W pin to the input voltage, and sets the U/D input high if W is lower and low if W is higher than the input voltage. This output is latched on the rising edge of every clock pulse by the 74LS74 D flip-flop, whose Q output goes to the U/D input of the DS1804. A 1MHz clock signal is compared with the sample pulse using an AND gate, and sent to the INC input. While the sample pulse is high, the output of the sample-and-hold circuit will follow its input voltage to within +0.05 volts. When the sample pulse is low, the INC input to the DS1804 is always low, preventing the wiper position from changing.

The output of the sample-and-hold circuit is then compared to upper and lower reference voltages ($V_{ref}$ 1 & 2 in Figure 2). The outputs from these comparators are also latched by D Flip-flops, whose Q outputs go to logic circuitry.

The logic circuitry controls a 74LS169 up/down counter. The Q0-Q2 outputs of this counter go to a demultiplexer and then through inverters to the D0-D7 inputs of the MX7628 DAC. An enable pulse is produced by the 74LS163 counters and 74LS85 binary comparators. When this enable pulse reaches the 74LS169 counter, it will either increment, decrement, or remain at the same value, depending on the signal level. The gain then remains the same, increases, or decreases by a power of two.

This circuit was constructed on four solderless breadboards and placed inside an aluminum project enclosure. The input came from a Femto DLPCA-100 amplifier and the synchronization output of a function generator (Stanford Research Systems, Model DS345). The output was sent to an Analog to Digital Conversion card (Datel, model PCI 416). The power supply (Leader, model LP5-152) provided a dual +15V supply and a separate 5V supply for the logic circuitry.

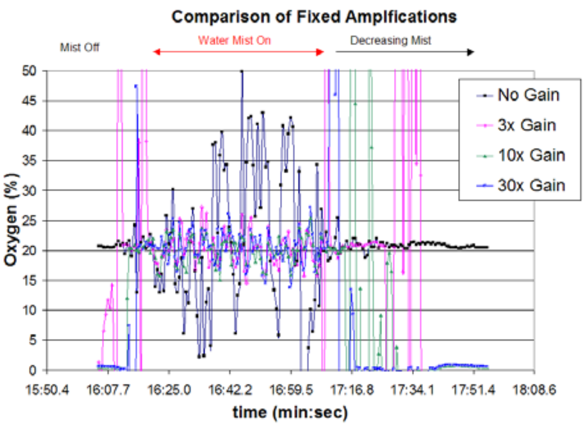

*Figure 5: Measurement of $O_2$ Concentration Using the Fixed Gain Amplifier*

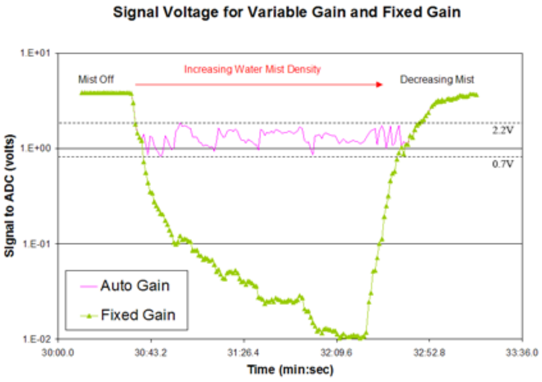

*Figure 6: Signal Voltages into the ADC*

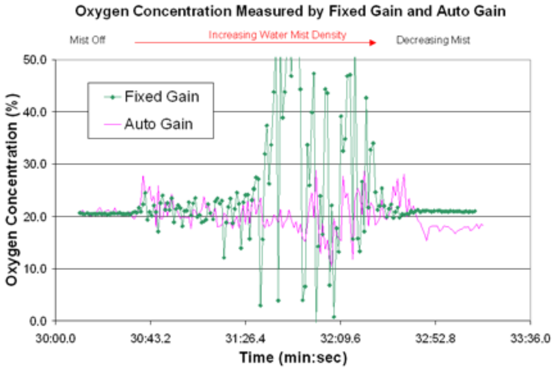

*Figure 7: $O_2$ Concentration Measurements Using the Auto Gain Amplifier*

# Results:

## Multiple Fixed Gain Amplifier:

To test the circuit, a 760nm laser beam was sent through a plastic cylinder to a photodiode. The cylinder contained water and a mister at its bottom. The output from the photodiode was sent through a Femto amplifier and the multiple fixed gain amplifier before going to the ADC card. A LabView program was used to record the four channels into the computer: no gain, 3x, 10x, and 30x. A second LabView program was used to calculate the light absorption due to oxygen, from which the oxygen concentration was calculated. The actual concentration was assumed to be constant, so the fluctuations in the measured concentration are due to noise. The results are shown in Figure 5.

## Amplifier with Automatically Controlled Gain:

The same experiment was performed with the second circuit, while the unamplified and the amplified signals were recorded by the LabView program. The results are shown below in Figures 6 and 7. The "Fixed Gain" signal was the output from the Femto amplifier, and the "Auto Gain" signal was the output from the Auto Gain Amplifier.

## Amplifier with Automatically Controlled Gain, Version 2:

I designed this circuit based on problems I observed with the pervious version. These problems were:

1. The amplifier introduced too much noise when the signal amplitude was low, probably because the D to A converter it contained was not designed for use in an amplifier.
2. A signal voltage below about 2 volts resulted in quantization noise by the in the computer's ADC, and any signal voltage below 1 volt would not allow the absorption signal to be measured reliably. The maximum voltage that the ADC could measure was 5 volts, so gain steps of powers of two or lower would be required to keep the signal above 2 volts at all times. This precluded the use of the femto amplifier, which had gain steps of powers of 10.
3. The counters and the sample-and-hold circuits created too much noise when the signal amplitude was low.

The following schematics and block diagram (Figures 8 to 11) show the revised circuit. The delay counters were replaced by an analog timer, and the sample-and-hold circuit was removed, leaving only the asynchronous logic circuitry.

## Results of $O_2$ measurements using Version 2:

Version 2 of the auto-gain amplifier was able to keep the signal amplitude between 5 volts and 2.5 volts, avoiding the quantization noise of the ADC. The right axis shows the signal voltage, and the left axis shows the measured area under the absorption feature which is proportional to the oxygen concentration.

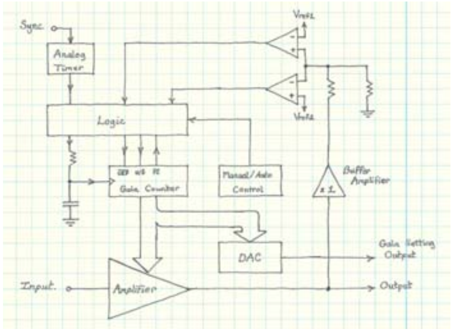

*Figure 8: A.G.C. Block Diagram (page 91 Engineering Notes)*

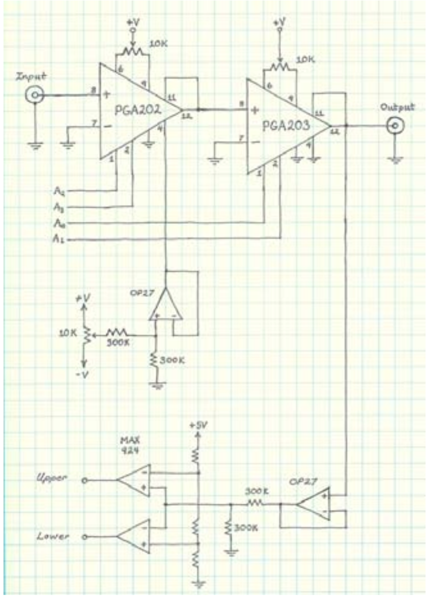

Figure 9: Amplifier
(page 93 Engineering Notes)

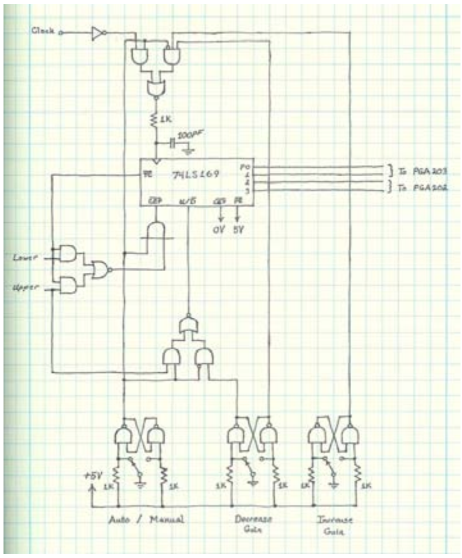

Figure 10: Gain Counter and Logic
(page 95 Engineering Notes)

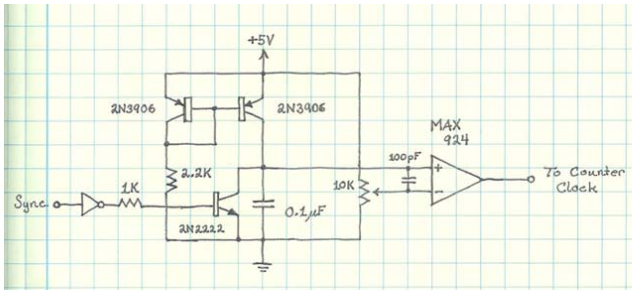

Figure 11: Analog Timer
(page 97 Engineering Notes)

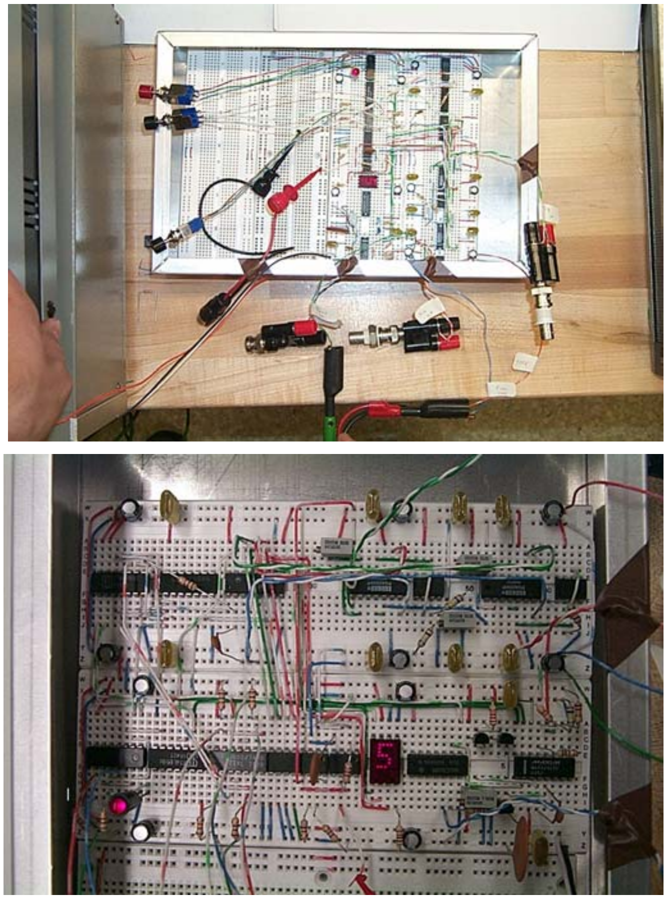

Figure 12: Pictures of the circuit

# Discussion and Conclusions:

## Multiple Fixed Gain Amplifier:

With no mist present, Figure 5 shows that the amplified signals (3x, 10x, and 30x) exceeded the maximum voltage of the ADC, resulting in invalid oxygen concentration measurements. As the concentration of mist increased, the amplified signals no longer exceeded the input limit of the ADC and began to provide valid measurements. When the mist density was at its highest, the oxygen concentration measurements from the unamplified signal were extremely noisy, most likely due to its small amplitude and poor signal-to-noise ratio. The amplified signals were much less noisy, especially the 10x gain, which had the least noise during the peak mist density. Once the density of the mist decreased, the amplified signals became too large for the ADC to measure and were cut off. The unamplified signal again gave the only valid measurement of all four channels.

Although the best measurements were made by the unamplified signal in the absence of mist, the multiple gain amplifier permitted the measurement of oxygen concentration during the times of high mist density.

## Amplifier with Automatically Controlled Gain:

The first version of this circuit was very successful in keeping the signal to the ADC between the reference voltages (0.7 and 2.2

volts) for an input range of over two orders of magnitude (Figure 6). In addition, the amplified signal contained much less noise than the unamplified signal during the period of highest mist density. However, at the lowest signal amplitudes, the signal still contained too much noise, both from the amplifier and from the computer's ADC to give good O2 measurements.

The second version used new digitally controlled amplifier chips which reduced both causes of noise significantly. This circuit was successful in providing valid oxygen concentration measurements during periods of high mist intensity.

In conclusion, the multiple fixed gain amplifier did allow oxygen concentration measurements to be taken during times of high mist densities. The auto-gain circuit was able to maintain the signal level within the preset values at the 2 KHz modulation of the laser while the input varied over 2.5 orders of magnitude, and successfully provided the computer with a continuous valid signal.

## Acknowledgments:

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