

COMPUTER INTERFACING A MICROWAVE SPECTROMETER: AN EDUCATIONAL APPROACH

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ABSTRACT

A laboratory procedure for introducing undergraduate students to the principles of analog to digital converters is described. The procedure involves interfacing an analog to digital chip, the ADC 0804, to a PC via a cable connected to the PC's parallel port. Exploiting the parallel port minimizes equipment cost and is safer for the students and the computers. Evidence that students are in a position to understand and use interface equipment properly is provided by describing a technique to computerize a microwave spectrometer for the purpose of studying the dielectric behavior of materials. A cylindrical microwave resonant cavity in the TE_{011} mode is used as a probe for dielectric relaxation studies as a function of temperature. The computer interface allows a very precise measurement of the frequency shifts and Q-changes of the microwave signal as the material under investigation goes through a dielectric change. These values of the frequency shifts and Q-changes translate into the real and imaginary parts of the dielectric constant through the Slater's perturbation equations.

INTRODUCTION

At Southeast Missouri State University, undergraduate research is an extremely important component to each student's education, especially with the current emphasis being placed on experiential learning. Southeast is primarily an undergraduate institution, and we rely heavily on undergraduate students to perform simple yet time-intensive research tasks. We have also been trying to automate the data collection process in many of our labs since powerful PCs are readily available even for poorly equipped lab rooms. However, it became evident to us that our students were lacking basic knowledge about A/D conversion when we asked them to design and build simple computer interfaces. A prime example of this occurred when we asked undergraduate students to build a temperature and frequency interface for a microwave spectrometer using off-the-shelf components. Students were unable to configure the equipment properly because they did not understand such terms as resolution, full-scale error, and step-size. To provide students with hands-on experience with A/D converters, we designed a laboratory procedure that allows the students to interface an A/D converter chip to a parallel port on a PC. The rest of this paper describes the microwave spectrometer alluded to earlier, the A/D parallel port laboratory procedure we developed, and the final interface design for the microwave spectrometer.

Microwave Spectrometer

A microwave spectrometer has become a standard tool for the dielectric relaxation studies of materials. A number of investigators have studied the dielectric response using the waveguide or the resonant cavity technique¹⁻⁷. In this research, a microwave resonant cavity in the TE₀₁₁ mode is used as a probe for dielectric studies as a function of temperature and frequency. The details of such a spectrometer have been given elsewhere⁴, but for the sake of continuity a block diagram of the complete system is given in Figure 1. A 2k25 klystron powered by a Hewlett Packard power supply produces a microwave signal in the x-band of frequencies. The modulated resonant signal from the cavity is in the form of a butterfly. The microwave signal is mixed with a standard frequency signal from an oscillator and a radio receiver is used to detect the difference of these two signals. Using the technique of frequency multiplication in this process of mixing frequencies, a series of markers are produced. These markers are then placed on the microwave resonant signal to detect the frequency shifts and the Q-changes of the signal. A picture of the actual signal taken from the oscilloscope is shown in Figure 2.

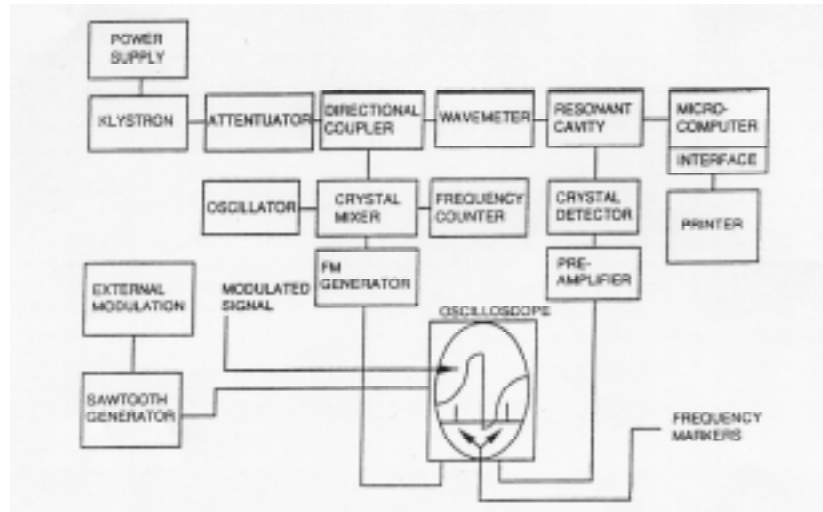


Figure 1: Block diagram of the microwave spectrometer.

During the dielectric relaxation studies of materials the marker is manually placed on the butterfly signal as the material under investigation goes through a phase change. During this process of the phase change there is a dramatic change in the dielectric response of the material. It becomes very hard to coordinate the position of the marker on the signal along with the corresponding temperature at which this dielectric change is taking place. One really needs to take a large number of data points to justify the dielectric behavior near the phase change of the material under investigation. A manual recording of the temperature along with the corresponding readings of the frequency shifts and the Q-changes introduces a large error in the data points for the dielectric relaxation studies.

Considering the above mentioned problems it becomes very important that something be done to coordinate the temperature with the corresponding readings of the dielectric change in terms of the frequency shifts and Q-changes of the microwave signal. A computer interfacing technique is useful to solve this problem. The thermocouple that is in direct contact with the

material under investigation for dielectric studies is interfaced to the analog to digital (A/D) converter. With this technique the computer is able to record the temperature and the frequency counter readings as the marker is placed on the left, center, and the right peaks of the butterfly signal; furthermore, a significantly large number of data points can be taken as the material under investigation goes through a dielectric change.

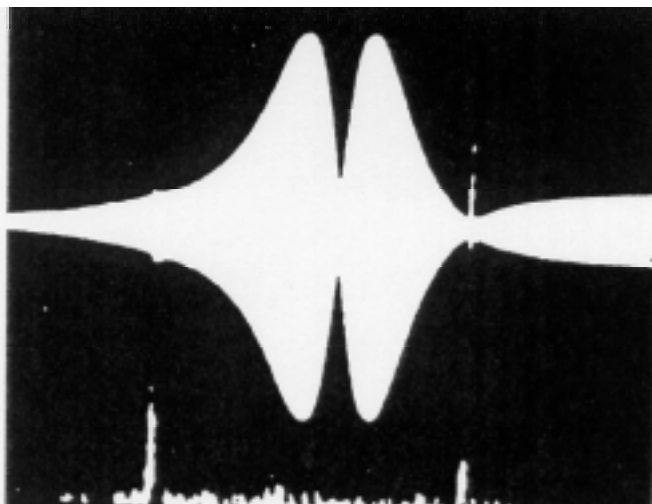


Figure 2: Dual trace oscilloscope display for frequency markers and cavity derivative profile for a typical scan.

A/D Conversion

Analog to Digital (A/D) conversion is a valuable tool for introducing the principles of digital electronics, aliasing, and computer interfacing to undergraduate students. Unfortunately, attaching an A/D converter to most personal computers can make experiments with A/D converters too lengthy to include in an introductory digital electronics course in which many topics must be covered. Furthermore, an A/D converter is interfaced to a PC via an ISA bus in most circumstances. Thus A/D experiments require students and/or schools to purchase some specialized equipment such as an expansion card with either breadboard segments or a perforated surface for installing electronic components. Another disadvantage to interfacing A/D converters to a PC in this manner is that the insides of the PCs must be exposed while students insert the expansion boards and remove them as they go through their testing and verification iterations. Obviously, the potential for damaging the computers, or even the students, is relatively high with this type of setup.

To overcome these problems, we have developed a laboratory procedure in which the students interface an A/D converter to a PC via the parallel port. With this arrangement, the computer cases do not come off, and no specialized equipment is needed other than a printer cable and the circuitry of the converter itself. Furthermore, interfacing through the parallel port teaches students the fundamentals of parallel port communication, multiplexing (since only 4 bits can be read through a printer port at once), and data manipulation. After students complete their parallel port A/D converter projects, they go on to interface a commercially available A/D converter to a microwave spectrometer. Although it may seem peculiar to not make use of the students' converters, we find the spectrometer requires a more user-friendly interface than what

the students can provide if they are to finish their spectrometer projects in a reasonable amount of time. Nonetheless, with the experience of designing, building, and testing their parallel port A/D converters behind them, the students are in a much better position for appreciating the terminology, limitations, and timing constraints of commercial-grade A/D converters.

PARALLEL PORT A/D CONVERTER

Interfacing to the parallel port

Before designing an A/D converter, students must become acquainted with the parallel port on a PC, so they start off by performing simple experiments involving the ERROR, SELECT, PAPER, ACKnowledge, and BUSY signals from the parallel port as inputs. In these procedures, the students exploit interrupt 17, function 00H (H denotes a hexadecimal value), to read switch settings and display the result on LEDs. The experimental arrangement is shown in Figure 3. Normally, the ERROR, SELECT, PAPER, ACK and BUSY signals are supplied by the printer as inputs to the computer to indicate printer status. For example, the PAPER signal tells the computer if the printer is out of paper. In this exercise, the students use the ERROR, SELECT, PAPER, and ACK signals in an unconventional way to read the switch settings of the switch bank. Since a logic high on BUSY indicates that the printer is busy printing a character, BUSY should be tied low in this application. BIOS interrupt 17, function 00H, returns the printer status (in register AH) and sends the bit pattern held in AL through the data lines of the printer port. Note that DX must be loaded with 00H to access LPT1 with interrupt 17. To read the switch settings, the students use debug, a dos utility, to write a short assembly language program:

```
100  MOV  AH, FF      ; Turn all LEDs on initially
102  MOV  DX, 0       ; Access LPT1
105  MOV  AL, AH     ; Transfer inputs to data out
107  MOV  AH, 0      ; Erase old inputs
109  INT  17        ; Use BIOS interrupt 17 to read/write data
10B  JMP  105       ; Infinite loop
```

Using the ADC 0804

After familiarizing themselves with the functioning of the parallel port, the students use an ADC 0804 analog to digital converter to digitize an analog signal and display it on the computer. Since the 0804 is an eight bit converter and the parallel port has only four inputs, the students multiplex the data into the computer using a 74LS157 2-to-1 multiplexer. Figure 4 shows the circuit configuration. Note that D_7 , the most significant bit on the printer's data bus, is used to initiate a conversion (pin 3 on the converter) and D_0 is used as the select input on the multiplexer. Thus writing a value less than 127 to the printer port initiates a conversion. Writing an odd value reads the most significant nibble and writing an even value reads the least significant nibble of the digitized data.

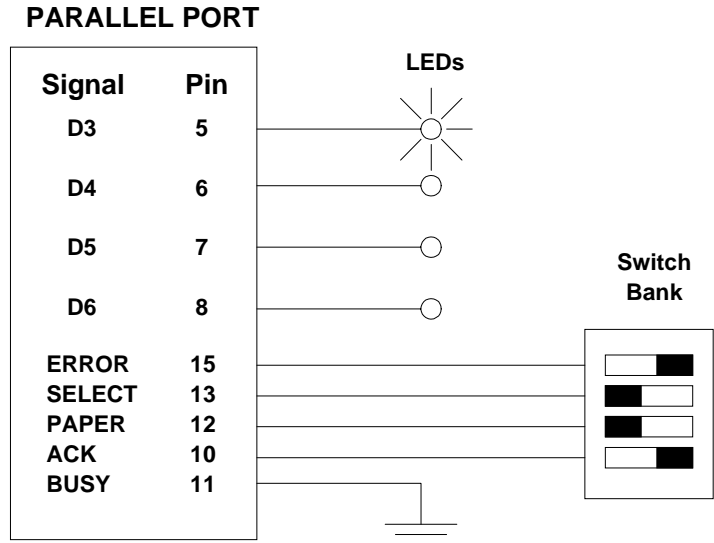


Figure 3: Parallel port pin connections.

Normally, one uses pin 5 of the converter, the interrupt signal, to guarantee that a conversion is not initiated while a previous conversion is in progress; however, due to the speed of parallel port communication, it can be left floating without causing any problems. Part of the laboratory procedure is to write an assembly language program to read in 256 digitized values. Since each converted byte of data occupies two bytes in memory, students must create a 512-byte buffer to store converted values. Once the buffer is full, each pair of nibbles is combined into a single byte by reading values into the accumulator and shifting bits as necessary. After building and testing their A/D converters, the students connect a function generator to the analog input of the 0804 chip and use it to create a sawtooth wave with a zero to five volt amplitude swing. Students vary the frequency of the function generator between 10 Hz and 10 kHz to learn about the effects of aliasing. To plot their data, they can use a spreadsheet, MathCAD, MatLAB, or any software they choose.

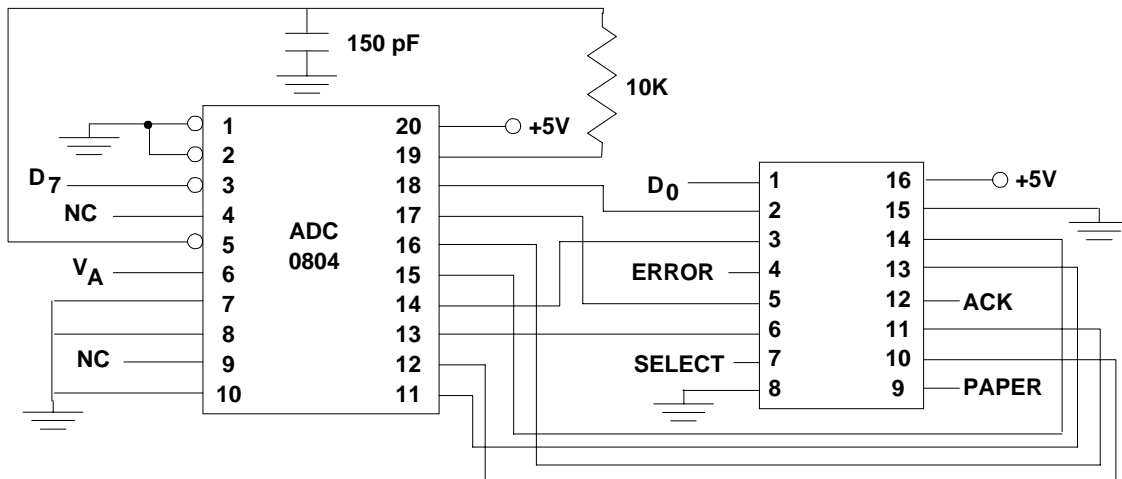


Figure 4: ADC 0804 circuit for interfacing to the parallel port on a PC.

COMPUTERIZED MICROWAVE SPECTROMETER FOR DIELECTRIC RELAXATION STUDIES

For simple computer interfacing applications, using a general purpose A/D chip often makes good sense; however, if the signals involved require sophisticated conditioning before being digitized, or if information must be extracted from the signals through analog processing, then it usually makes more sense to purchase hardware specifically formulated for the interface processing involved. Furthermore, in the interest of portability, it is advantageous if a computer interface can attach directly to standard ports (serial and/or parallel) on the computer. In light of these considerations, we chose off-the-shelf equipment that attaches directly to the printer port for the temperature recording interface, and directly to the serial port for the frequency recording interface. Using this straightforward design gives us the flexibility to swap computers, or to transport the interface and set it up to work in another lab, with minimal effort. Figure 5 shows how the interface equipment was connected to the control computer. Both the thermocouple interface and the frequency counter interface will be discussed in the remainder of this paper.

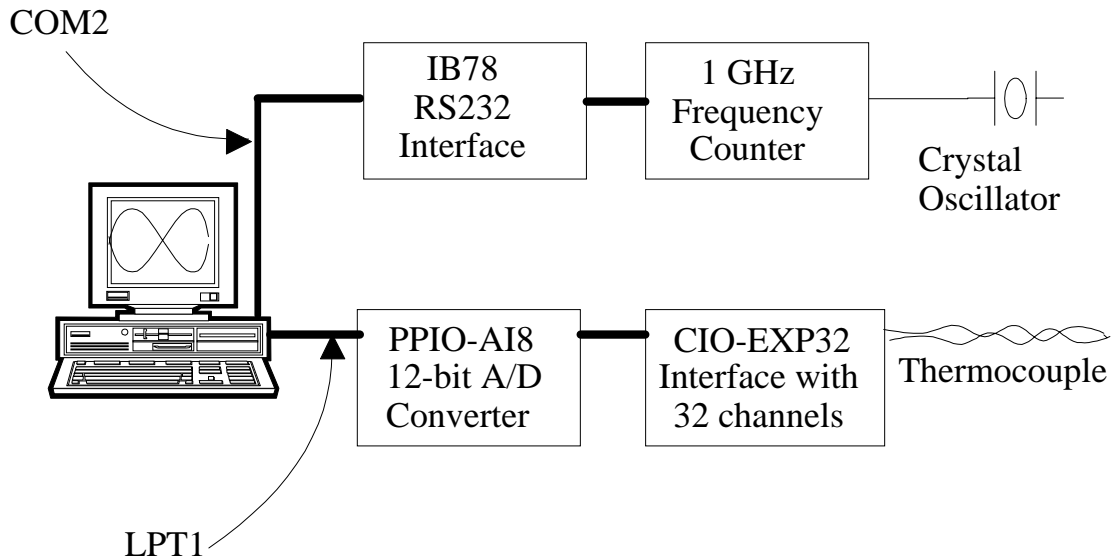


Figure 5: Interface connections between the PC and the frequency counter and thermocouple.

Thermocouple Interface

To interface the thermocouple to our computer, we purchased two boards from ComputerBoards Inc—a CIO-EXP32 board, with 32 analog input channels, and a PPIO-AI8 board, equipped with a 12-bit A/D converter. The 32 input channels of the CIO-EXP32 are divided into two banks of 16 channels each, but only one channel from each bank of 16 can be multiplexed to an output. Which channels are multiplexed to the outputs is determined by jumper connections on the board. Having 32 input channels may seem like overkill for this application; however, it comes in handy when thermocouples of different types are used. For example, channel 0 can be set up for a type J thermocouple and used for temperature variations between 0°C and 760°C, whereas channel 1 can be set up for a type T thermocouple, accommodating temperature variations between -160°C and 400°C. Using the correct

thermocouple for a given experiment is then simply a matter of changing a jumper from one pair of pins to another to multiplex the appropriate input channel to the output, and setting the gain for the new thermocouple.

Signal Conditioning

Since the source signal from a thermocouple typically floats with respect to ground of the measurement equipment, a floating differential input consisting of a signal high and low is required, especially when the lead lines of the thermocouple are long, or subject to EMI interference. Figure 6 shows how each input channel of the CIO-EXP32 is configured. The “V”, “C”, and “G” pads are, by default, open, but should all be closed with solder when the input channel is connected to a thermocouple. Closing the V-pad provides the high input of the thermocouple signal with a reference to the full scale negative of the board (-15 Volts) when the signal high input is left floating. Since it is highly unlikely that a full scale negative voltage will be read when a legitimate signal is present at the input, software can interpret the full scale negative reading as an indication that the input is open and alert the user. Thus closing the V-pad provides the interface with an open thermal detect (OTD) signal.

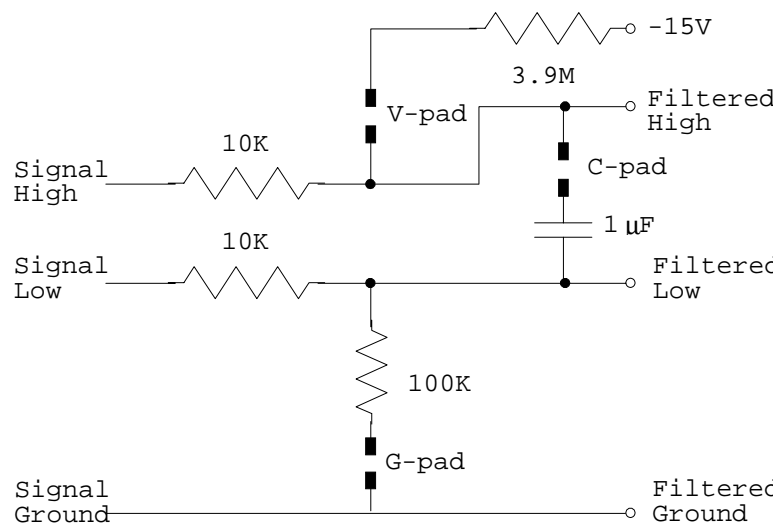


Figure 6: Signal conditioning on input channels.

Closing the C-pad effectively implements a low-pass filter across the terminals of the input signal with a 3-dB frequency of $\omega_{3dB} = 50 \text{ rad/s}$, or $f_{3dB} = 7.96 \text{ Hz}$. Since it is unlikely that meaningful temperature variations will fluctuate more rapidly than 7.96 Hz, the low-pass filter provides a convenient means of filtering out high-frequency noise.

Closing the G-pad provides a reference from ground to the filtered low signal via a 100K Ω resistor. The 100K Ω resistor ensures that only enough current passes to provide a reference to ground so that the filtered high and low signals can still float within the common mode range. With this arrangement, the differential input will reject up to 10 Volts of EMI energy on the signal wires⁸.

An especially important signal-conditioning component for a thermocouple computer interface is cold junction compensation. A thermocouple is produced when two dissimilar wires react electrically when in contact with one another⁹. A reaction in this circumstance refers to a voltage being produced that is dependent on temperature at the point of contact where the two wires touch. Since the point at which the leads from the thermocouple connect to the interface are dissimilar, an unwanted voltage will be impressed onto the signal. However, if the temperature is accurately known at the thermocouple/interface junction, then the thermocouple voltage produced at this “cold junction” can be subtracted out. Fortunately, the CIO-EXP32 is equipped with a semiconductor temperature sensor that provides an accurate measure of the board’s temperature. The output of this sensor is mapped to an A/D board so that the interface can compensate for the cold junction voltage in software.

Amplification

Since the voltages produced by a thermocouple are typically small, an amplifier is required to make efficient use of the resolution on an A/D converter. However, the level of gain is dependent not only on the range of analog voltage to be digitized, but also on the type of thermocouple being used, since the change in voltage with temperature is a function of thermocouple type. Considerations of gain versus thermocouple type will be addressed in the A/D converter section of this paper; however, it is important to point out that both amplifiers saturate at ±5 Volts, which has important ramifications on the maximum level of gain that should be used.

A/D Conversion

Output from the CIO-EXP32 board is sent directly to the A/D converter on the PPIO-AI8 board through a 37-pin ribbon cable capped with D-type connectors. The A/D converter provides 12 bits of resolution and can accommodate voltage ranges of ± 5 Volts (default), ± 10 Volts, or 0-10 Volts. Using the default input range of ± 5 Volts, the resolution of the converter is¹⁰:

$$resolution = \frac{range / gain}{2^N - 1} = \frac{10 / gain}{4095}, \quad (1)$$

where N = 12, the number of bits used to represent the converter’s output. Thus, when a gain of 100 is used, the resolution is $.1/4095 = 24.42 \mu\text{V/bit}$. To convert from $\mu\text{V/bit}$ to $^{\circ}\text{C/bit}$, we divide the resolution by the change in voltage per $^{\circ}\text{C}$ that is characteristic of the thermocouple used. For example, for a K type thermocouple that is characterized by a $40 \mu\text{V}$ change in voltage for each 1°C change in temperature, the temperature change represented by a change in the LSB of the converter’s output is:

$$\frac{24.42\mu\text{V} / \text{bit}}{40\mu\text{V}/^{\circ}\text{C}} = .61^{\circ}\text{C} / \text{bit} . \quad (2)$$

Table 1, below, lists the change in $^{\circ}\text{C}$ per bit for a gain of 100 as a function of thermocouple type. To apply this table to other gain values, simply divide the value in the last column by 100 and multiply by the appropriate gain.

Thermocouple type	Output $\mu\text{V}/^\circ\text{C}$	Min. temp $^\circ\text{C}$	Max. temp $^\circ\text{C}$	$\Delta^\circ\text{C}/\text{bit}$ for gain = 100
J	51	0	760	.48
K	40	0	1370	.61
T	40	-160	400	.61
E	62	-100	1000	.39
S	7	0	1760	3.5
R	7	0	1760	3.5

Table 1: Change in temperature represented by each bit for a 12-bit A/D converter as a function of thermocouple type.

It is important to keep in mind that changing the gain not only alters the temperature span represented by a one-step change in output of the A/D converter, but also dictates what the maximum temperature a sample can have without clipping. Since the amplifier saturates at 5 Volts, steps must be taken to ensure that the gain setting is compatible with the highest temperature the sample under study is expected to reach. Table 2, below, lists the maximum temperature a sample can have without driving the amplifier into saturation as a function of gain for various thermocouple types. Note that not all possible gain values are listed.

Thermocouple type	gain = 100	gain = 200	gain = 300	gain = 500	gain = 800
J	760	463	307	186	117
K	329	166	107	66	45
T	400	400	400	214	140
E	656	348	244	152	98
S	1760	1760	1760	1019	703
R	1760	1760	1760	948	663

Table 2: Maximum temperature in $^\circ\text{C}$ without clipping for five gain levels as a function of thermocouple type

Board Control

Since the PPIO-AI8 attaches directly to an parallel port, communicating with it is simply a matter of opening an LPT port and writing commands and receiving data. It is possible to write directly to registers on-board to control when a conversion takes place, and to read digital data with 12 or 8 bit resolution. However, the board comes with a library of C callable functions that makes interfacing to the board easier. An advantage to using the library functions is that the cold junction compensation is performed automatically. Using these functions, we were able to read the sample temperature with the stroke of a key.

Frequency Counter Interface

To interface the frequency counter to our computer, we purchased an accessory to a 1 GHz frequency counter from Sencore. The accessory, an IB78, is also from Sencore, and it permits the counter to be read through a serial port connection using RS232 formatted instructions. Controls on the back panel set the number of data bits, the number of stop bits, the parity, and echo status. A rotary dial on the front permits the baud rate to be changed. Communicating with the IB78 is straightforward. The serial port to which the IB78 is connected must be initialized with settings that are consistent with the switch settings. Once the port is initialized, reading the

output of the frequency counter is simply a matter of pinging the port by writing a byte (of any value) to it, and waiting to receive data. The delay between pinging the port and data being ready to send is variable, so a loop that continually checks the status of the port is necessary. Once the IB78 is ready to transmit data, it outputs 17 ASCII bytes that represent the frequency in exponential notation.

CONCLUSIONS

Undergraduate students are capable of designing and building useful computer interfaces when given the opportunity to gain hands-on experience with A/D converters. Setting up a laboratory procedure to interface a converter chip to a PC is generally cumbersome and time-consuming, but the task can be greatly simplified by working through a PC's parallel port. Using a parallel port eliminates the potential of short circuiting computer motherboards, and it reduces the need for expensive specialized equipment. Furthermore, once students understand how A/D converters operate via direct exposure, they are in a much better position to configure and use off-the-shelf interface equipment properly. For example, students simplified the process of recording data to find the dielectric constant of materials introduced into a microwave spectrometer by digitizing temperature and frequency data. Obtaining frequency shifts and Q-values of a resonant signal by adjusting markers on the left, center, and right peaks of a power absorption profile is time-consuming, and error prone. A computer interface allows frequency measurements to be obtained with the stroke of key; furthermore, it allows temperature values to be recorded with greater precision because the measurements are taken quickly enough to eliminate significant temperature fluctuations. Future enhancements to the interface will involve digitizing the modulated power absorption profile so that the characteristic butterfly of this signal can be placed directly on a computer monitor, making it possible to do away with the markers on the left, center, and right peaks altogether and increasing the accuracy of the measurements even more.

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BIOGRAPHY

Dr. Bret F. Draayer received his Ph.D. in electrical engineering from New Mexico State University in 1993. He worked two years in industry with Lockheed Engineering and Sciences Company, and has been at Southeast Missouri State University since the fall of 1995. He is actively involved with the Engineering Physics Program at Southeast, and his research interests include optical correlation, image processing, and statistical analysis.

Dr. Jai N. Dahiya received his Ph.D. in physics from North Texas State University in 1980. After completing his degree, he worked a couple of years at West Virginia Wesleyan College, and since 1984 he has been on the faculty in the Physics Department at Southeast Missouri State University. His research interests are microwave spectroscopy studying the dielectric behavior of materials.