WORKREADY ELECTRONICS

lab activity

Fast Fourier Transform Lab Exercise

Acknowledgements: Developed by JD Neglia, P.E., Electronics Program Director at Mesa Community College, Mesa, Arizona.

Lab Summary: This laboratory experiment demonstrates the use of the Fast Fourier Transform (FFT) to display the spectral content of audio signals. For a better understanding of the Fourier Theory, please review Frequency Domain View of Electronic Signals: Practical Application of the Fourier Theory Module.

Lab Goal: The goal of this lab is to build a working audio spectrum analyzer, observe its operation, and perform measurements of its performance.

Learning Objectives

1. Assemble a simple microcontroller circuit while following accepted ESD practices.
2. Evaluate the input and output capabilities of the system.
3. Observe the system operate as a simple, low speed spectrum analyzer.
4. Calibrate the system and use it to observe the spectral content of sine waves, square waves, and music.
5. Observe the effect of exceeding the Nyquist sampling frequency.

Grading Criteria: Your lab grade will be determined by your performance on the experiment, the lab questions, and the content and quality of your laboratory report (if assigned).

Time Required: Approximately 6 to 7 hours

Special Safety Requirements

Electrostatic Discharge can damage the USB port of your computer as well as the microcontroller device used in this lab. Use appropriate ESD methods to protect the devices. A grounded wrist-strap is provided in the parts list for this circuit. Be sure to wear it at all times while handling the electronic components in this circuit. The wrist strap need not be worn after the circuit construction is complete.

No serious hazards are involved in this laboratory experiment but be careful to connect the components with the proper polarity to avoid damage.

Lab Preparation

- Read the WRE Digital Signal Processing Module.
- Read this document completely before you start on this experiment.
- Acquire required test equipment and appropriate test leads.
- Gather all circuit components and the three-panel solderless breadboard.
- Print out the laboratory experiment procedure that follows.

Equipment and Materials

Each group of students will need the items listed in the tables below. It is suggested that students work in teams of two.

Equipment	***Quantity***
Digital Multimeter	1
Function Generator	1
Frequency Counter	1
PIC Programmer (Note: Only one PIC Programmer is required *per class*.)	1
Solderless Breadboard, 3-panel	1
"Y" adapter: one mini plug to two mini receptacles	1
CD player or MP3 Player with your favorite music	1

Tools	***Quantity***
Needle-Nose Pliers	1
Wire strippers	1
Wire cutters	1
ESD Wrist Strap	1

Parts	***Quantity***
Microcontroller, dsPIC30F4013-30I/P	1
Crystal, 7.3728 MHz	1
Operational Amplifier, Dual, MCP6002-E/P	1
Resistor, 820 Ohm, 1/4 W	1
Resistor, 1 kOhm, 1/4 W	1
Resistor, 470 Ohm, 1/4 W	1
Resistor, 10 kOhm, 1/4 W	4
Resistor, 100 Ohm, 1/4 W	2
Capacitor, 0.1uF, disk	5
Capacitor, 100 uF, electrolytic	3
Power Supply, Regulated, 5.0 VDC	1
LED, Red	1
LED Dot Matrix, 5x7, Cathode Rows, Anode Columns LTP-747R	2
Mini Audio Receptacle	2
Cable Tie	2
Tie Mount	2
Wire (as needed)	-

Required Software: The file listed below contains the firmware that will be needed to perform the exercises in this document. You will need to program this hex file into your PIC chip.

File	***Description***	***Web URL***
Fft4013.hex	PIC Firmware	www.jneglia.com

Introduction

In the Fourier module, you learned that all signals are composed of one or more sinusoids of various frequencies, amplitudes, and phases. The device you will build in this exercise detects the amplitude and frequency of these component parts in any audio signal and displays them on an LED dot matrix. The system operates in real time, taking samples of the audio signal at 44.1 kHz, and displaying the resulting spectrum approximately 100 times per second. Although this system is relatively low performance, it will give you hands-on experience that will prove useful using higher performance commercial spectrum analyzers.

Theory of Operation

As shown in the schematic diagram (at the end of the lab), there are four major subsystems in this spectrum analyzer: the power supply, the analog input, the microcontroller, and the LED dot matrix display.

The power supply is a standard 5-volt DC regulated supply available from numerous commercial sources.

The analog input subsystem accepts an audio frequency signal at standard, line amplitude[1]. The input signal is AC-coupled, biased up to half the supply voltage, and amplified by a factor of 4.7. Since a single-supply op-amp is used, a second amplifier is used to create a reference voltage at half the supply voltage. Normally, the analog input signal is filtered to remove frequencies above the Nyquist frequency. Such an input filter is omitted from this design, as one of the exercises will demonstrate the effects of ignoring the Nyquist frequency. After the analog signal passes through the input stage, it is applied to an analog input of the microcontroller.

The microcontroller in this system is a Microchip dsPIC30F4013. This is essentially an ordinary PIC on steroids; it contains additional circuitry to perform arithmetic operations extremely quickly, and runs at a much higher clock rate than most microcontrollers. This type of device has many of the capabilities of a traditional digital signal processor (DSP) chip. The oscillator on this device runs at 7.3728 MHz. This frequency is multiplied by 16 with an internal phase locked loop (PLL), resulting in an effective operating frequency of 118 MHz. This results in 30 million instructions per second (MIPS) execution, a high speed that is needed to perform the required computations to in real time.

The microcontroller firmware samples the analog signal at 44.1 kHz, and converts each sample into a 12-bit binary number using its internal analog-to-digital converter (ADC). If the amplitude of the analog input signal exceeds the ideal range, the firmware briefly illuminates the "saturation" LED to notify the user that the input signal amplitude should be reduced for proper operation. (Be sure to keep this in mind as you do the exercises in this document; you always want the input amplitude to be as large as possible without illuminating this LED.)

The 12-bit samples are collected in groups of 64. Then, a Fast Fourier Transform (FFT) is applied to each group of 64 samples. This FFT converts the input time domain samples into the frequency domain; resulting in a viewable frequency spectrum of the input signal. This resulting frequency spectrum is then scaled. Because the display is small and cannot display the entire spectrum, a gain jumper is provided which allows the user to select how the information is displayed. Some averaging of the signal is also provided when the signals are displayed so that fast transients are not completely invisible to the user.

[1] Normally, only one input is used; the second input is needed in only one of the exercises below. When not in use, leave the extra input unconnected. Do not ground it.

Once the resulting frequency spectrum has been scaled and averaged, it is ready to be output to the LED dot matrix. The display is scanned as follows: the first column of data is output to pins 34 through 38, and then pin 15 is pulled low to illuminate the first column of the LED dot matrix. Then, the data for the second column is output to pins 34 through 38, and pin 11 is pulled low, illuminating the second column. The process is repeated for the remaining 12 columns. The scanning is performed quickly enough such that it appears that all columns are illuminated simultaneously.

The actual LED dot matrix displays are normal, "5x7 character" displays that are normally positioned vertically. In this exercise, these displays are placed horizontally, adjacent to each other. Note that many different sizes and styles of these devices are available and may be used in this exercise. It is important, however, that they be of type "Anode Columns, Cathode Rows". Keep in mind that the terms "columns" and "rows" in the vendor's part descriptions refer to the device in its *normal* orientation. In this exercise, we are turning these devices on their side.

Before starting the lab procedure, answer the questions in the Questions and Report section following the lab procedure.

Lab Procedure

Part I: Construction of the Spectrum Analyzer

1. Examine the dsPIC30F4013 Data Sheet.
   a. Access the Microchip web site at www.microchip.com.
   b. Locate the data sheet for the dsPIC30F4013 digital signal controller.
   c. Examine the first page of the data sheet. This device provides our circuit with fast mathematics capability that can execute FFT's quickly enough to display the spectral content of audio signals in real time.
2. Download the required firmware listed in the table at the beginning of this document.
3. Program the dsPIC30F4013. Use a PIC programmer to burn the Fft4013.hex file into your dsPIC30F4013. (Note: Your instructor may have already performed this step for you.)
4. Build the circuit.
   a. Use the schematic drawing and the completed prototype circuit shown in Illustration 1 to build this circuit. There is nothing unusual about this circuit; build it using your standard solderless breadboard techniques.

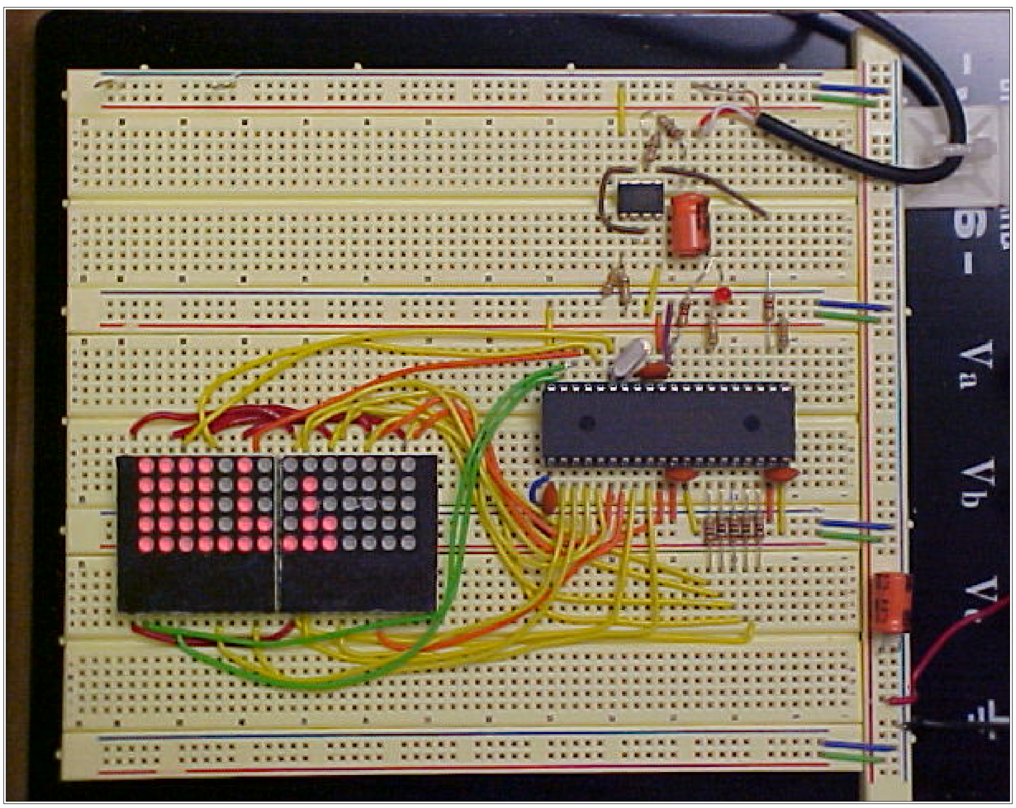


Illustration 1: Completed Breadboard

b. The 7.3728 MHz crystal should be located adjacent to the appropriate microcontroller pins for proper operation. See Illustration 2 for the suggested placement of this crystal.

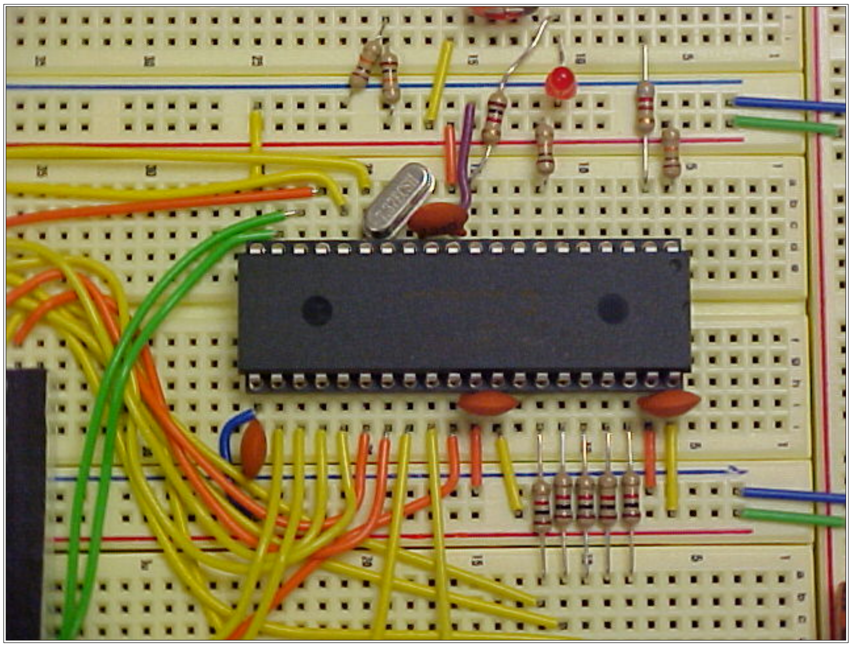


Illustration 2: Microcontroller Wiring

NOTE: A three-panel solderless breadboard is listed for this project. Although this will provide plenty of room for prototyping and experimentation, it is not strictly necessary. The entire circuit could be constructed on a two-panel board if desired.

c. Illustration 3 shows the circuit with only one of two audio inputs.

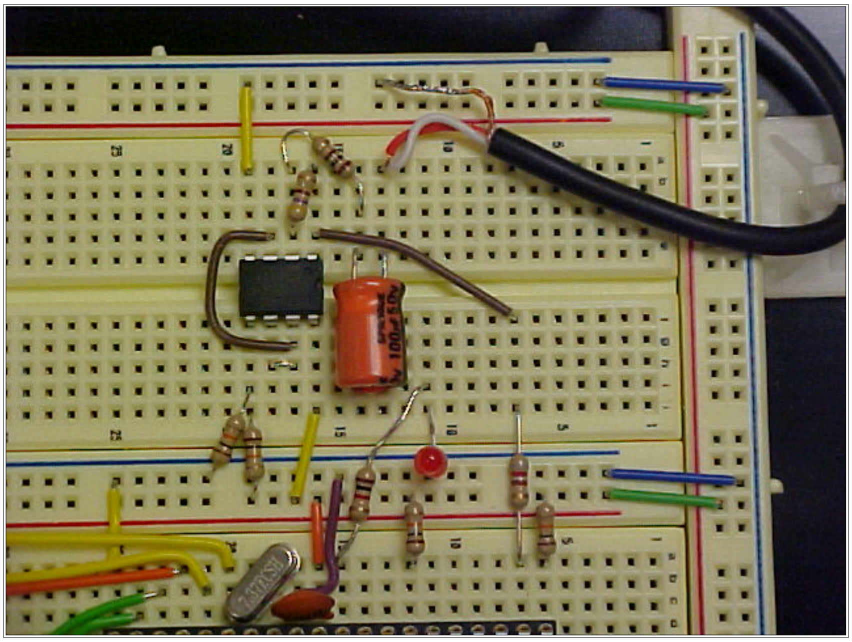


Illustration 3: Audio Input

d. Illustration 4 shows the LED dot matrix.

NOTE: If you are using a different LED dot matrix than the one listed in the parts list above, determine its pinout. It is important, however, that the columns are the common anodes, and the rows are the cathodes. Note that these rows and columns refer to the LED dot matrix when it is positioned in its normal (vertical) orientation. In this exercise, however, these LED modules are located horizontally.

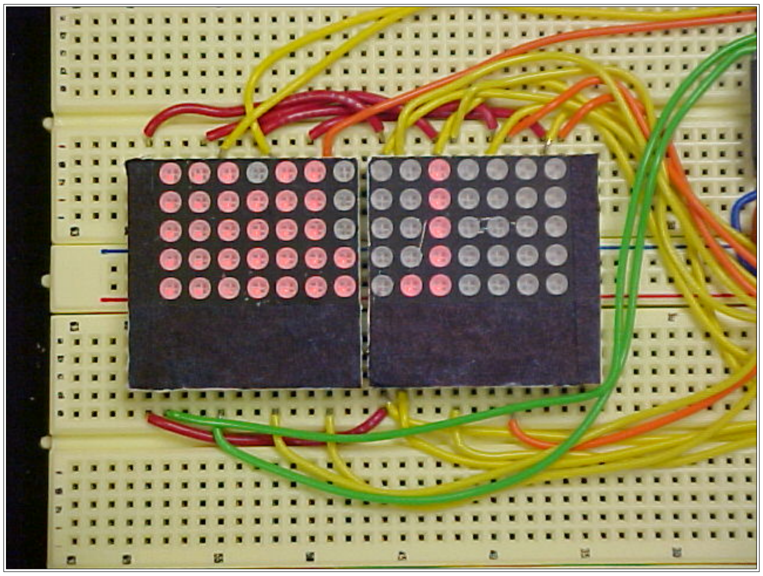


Illustration 4: LED Dot Matrix

5. Test the circuit

   a. After you have completed assembling the circuit, double check all your connections.

   b. Use an ohmmeter and verify that there is at least 50 Ohms resistance between +5V and GND.

   c. Apply power. The microcontroller will perform two POST (power on self test) sequences:

      i) Each column in the display will illuminate momentarily, testing each element in the array. If an entire column is not illuminated, check the wiring to the appropriate column. If an entire row is not illuminated, check the wire to the appropriate row. If an individual LED is not illuminated in this test, then that LED in the display is likely bad.

      ii) The second power on self test will display an increasing binary count to each column in turn. This verifies that the wiring to each row and column is unique and each LED can be addressed individually.

d. Connect a function generator to your spectrum analyzer as shown in Illustration 5.

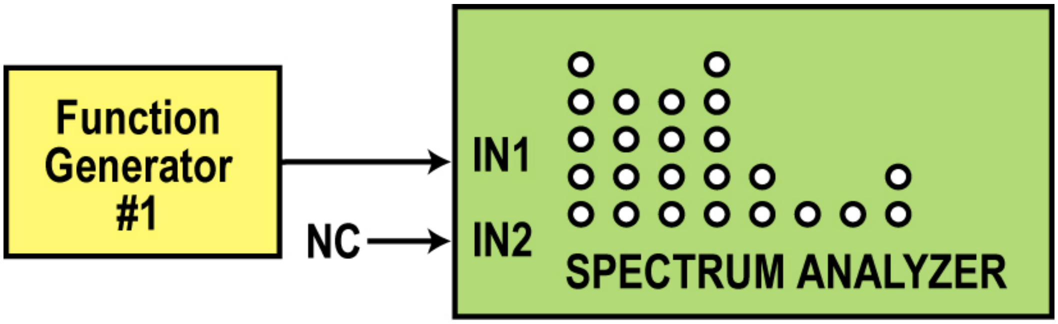


Illustration 5: Basic Spectrum Analyzer Operation

e. Leave the other audio input unconnected.

f. Place the gain jumper in the circuit, connecting microcontroller pin 7 to ground. (Leave this jumper in place for the entire lab exercise except for the very last exercise where you will observe the spectrum of an audio source.)

g. Set the function generator to minimum amplitude, sine wave, 1.4 kHz.

h. Apply power, and gradually increase the sine wave amplitude. As you increase the amplitude, you should observe the third column of LED's illuminate. At full amplitude, all 5 LEDs in this column should be illuminated; at minimum (zero) amplitude, no LEDs should be illuminated at all on the entire display.

i. Vary the sine frequency from DC up through about 10 kHz and notice that different columns illuminate as a function of the input frequency.

j. If you do not see any LEDs illuminate, get an oscilloscope and trace your analog signal from the function generator through the analog input stage of the spectrum analyzer all the way up to pin 2 of the microcontroller. The sine wave at pin 2 should be about 3 Vpp for full amplitude (all 5 LEDs illuminated in the appropriate column).

Part II: Operation of the Spectrum Analyzer

6. Calibrate the spectrum analyzer. With the function generator still attached, calibrate the amplitude scale of the Spectrum analyzer as follows.
   a. Set the function generator to SINE, 1.4 kHz.
   b. Adjust the amplitude so that column 2 is (just barely) fully illuminated. (Note: The columns are numbered from the left, starting at column number 0, and proceeding up through column number 13.) Do this by slowly increasing the amplitude on the function generator until the full column is illuminated. If necessary, adjust the frequency slightly so that no LEDs in any other columns are illuminated. Recall that the input amplitude should be as high as possible without illuminating the saturation LED.
   c. Record the amplitude of the sine wave in Table 1 in the Questions and Report section.
      i) If you are using a DMM, record the RMS amplitude.
      ii) If you are using an oscilloscope, record the peak-to-peak amplitude. Either way (RMS or peak-to-peak) is fine but be consistent and take all your measurements the same way.
   d. Reduce the amplitude of the sine wave so that LED number 4 is just barely illuminated.
   e. Record this amplitude in the table.
   f. Repeat this process for LEDs 3, 2, and 1.
   g. Graph the LED amplitude versus the input amplitude on the graph in the Questions and Report section.
   h. Verify that this amplitude relationship holds over the entire frequency range on the display.
7. Now that the amplitude display has been calibrated, proceed to calibrate the frequency display.
   a. With the frequency still set to a sine wave at approximately 1.4 kHz so that column 2 is fully illuminated, vary the frequency slowly such that each column is fully illuminated, one at a time, and record the precise frequency at which each column is fully illuminated with no other LEDs in any other columns illuminated.
   b. Record each frequency in the first row of the Table 2
   c. Answer Question 1 in the Lab area of the Question and Report section.
8. Now calculate the theoretical frequency at which each of these columns should be fully illuminated. FFT theory predicts that indicates each of these columns ideally should be illuminated at $f_n = (f_{sample}/N)*n$ where f_n is the column frequency for columns 0 through 13, f_{sample} is the sampling rate of this system (44.1 kHz), N is the number of "bins" used in the FFT calculation (64), and n is the column number (0 through 13).
   a. Perform this calculation for each of the 14 columns.
   b. Enter your results in the second row Table 2.
   c. Calculate the percent deviation between the predicted and measured results and enter these results in the third row of the table.

9. Observe Nyquist limit of spectrum analyzer. As you are aware, if frequencies are present that exceed one half the sampling frequency (the Nyquist frequency), "aliasing" can occur. However, it is rare to observe this phenomenon. Here is your chance!
   a. Be sure that your sine wave is at maximum amplitude (without saturating, of course), and sweep your input sine wave up beyond 10 kHz.
   b. Slowly and gradually increase the input frequency. You will not see any columns illuminated for several kilohertz. This is because your spectrum analyzer is only displaying the first 14 columns of 64 columns total that are being calculated. However, when you increase the sampling rate beyond the Nyquist limit, you will eventually observe aliasing occur. In the space provided in the Questions and Reports section, describe what you observe (Question 2).
10. Observe the sum of two separate sinusoids.
   a. Connect a second function generator to the second analog input as shown in Illustration 6.

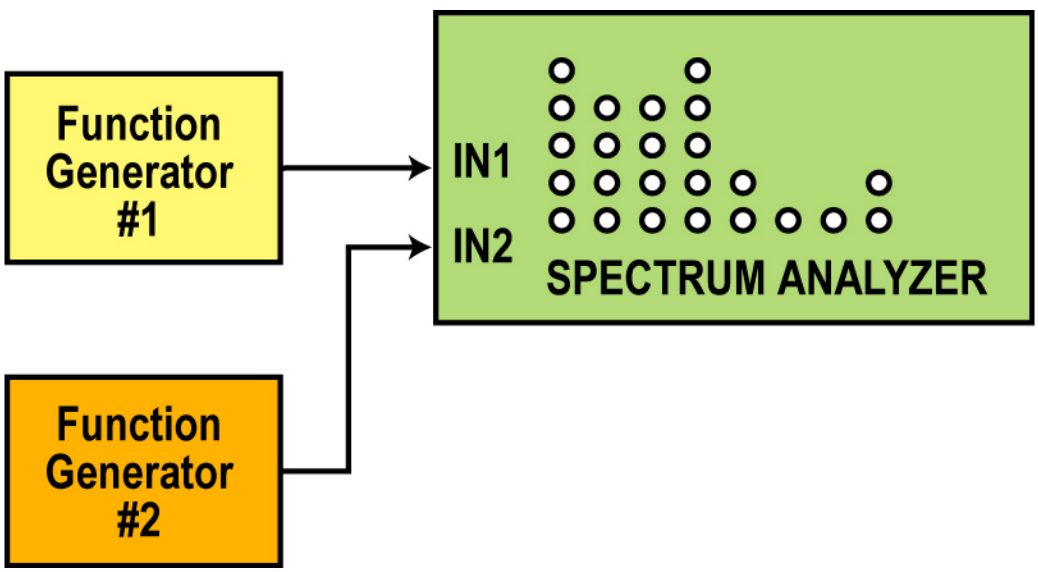


Illustration 6: Function Generator with Second Analog Input

      i) Apply a second sinusoid to the spectrum analyzer starting at zero amplitude and gradually increasing the amplitude as before so that you do not damage the microcontroller.
      ii) Set this second function generator to a different frequency than the first function generator. Vary it up and down. Notice that the frequencies are independently displayed, even though the signals are summed together in the input amplifier. The FFT can detect and extract these two distinct frequencies.
   b. After you have completed observing the two frequencies, turn off and disconnect the second function generator. Answer questions 3 and 4.

11. Observe a square wave.
    a. Set your sine wave again to 1.4 kHz with maximum amplitude without saturation.
    b. Column 2 should be fully illuminated with no LEDs in any other columns illuminated.
    c. Switch the function generator to square wave mode.
    d. Describe what you observe. (Question 5)
    e. Illustration 7 shows a signal containing the sum of 1.41 kHz and a 6.28 kHz sinusoids. Illustration 8 shows the spectrum. Illustration 9 shows the spectrum of a square wave. Note: The amplitude of the fundamental frequency is larger than shown here because the display has only 5 levels.

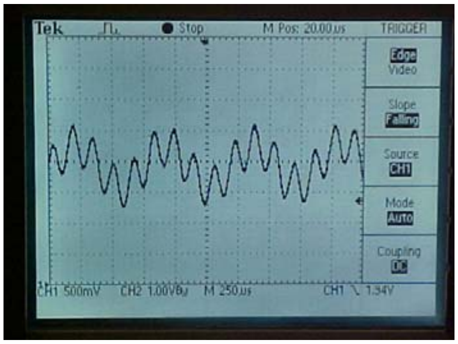


Illustration 7: Signal

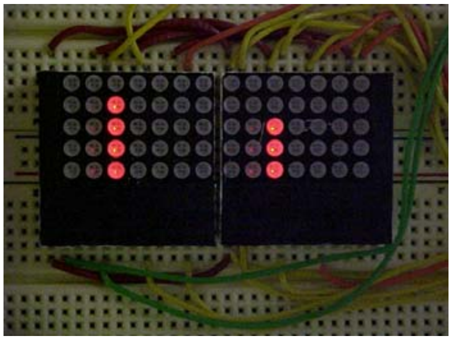


Illustration 8: Spectrum

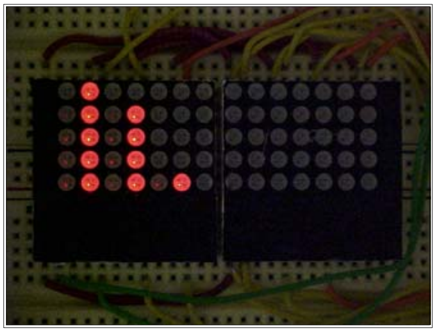


Illustration 9: Spectrum of Square Wave

12. Now vary the input frequency. Answer question 6.
13. Observe an audio signal on the spectrum analyzer as shown in Illustration 10.
    a. Power down and remove the function generator from your spectrum analyzer.
    b. Connect an audio source such as a CD player or an MP3 player to your spectrum analyzer.
    c. Use an audio mini-plug to mini-plug patch cable.
    d. Remove the gain jumper that connects Pin 7 of the microcontroller to ground. This will increase the gain of the signal which is necessary only when you are displaying audio signals. (This jumper should be present on all the other exercises in this document. Only this one omits it. Remember to replace this jumper when you have completed this step.)

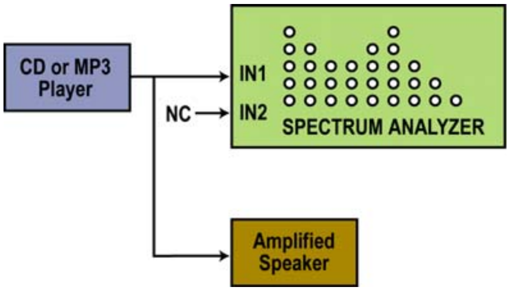


Illustration 10: Observing the Audio Signal

e. If you want to *hear* the signal that you are watching (you probably do), you must also send the audio signal to an amplified speaker.

   i) A "Y" adapter (one mini plug to two mini sockets) would be useful for this purpose.

   ii) Apply power to your spectrum analyzer and your audio source.

   iii) Adjust the volume on your audio source such that it is as high as possible without causing the saturation indicator LED to illuminate.

   iv) Watch the LED dot matrix display. Samples are shown in Illustration 11.

   v) Attempt to correlate the sounds and instruments you hear with the columns on the display.

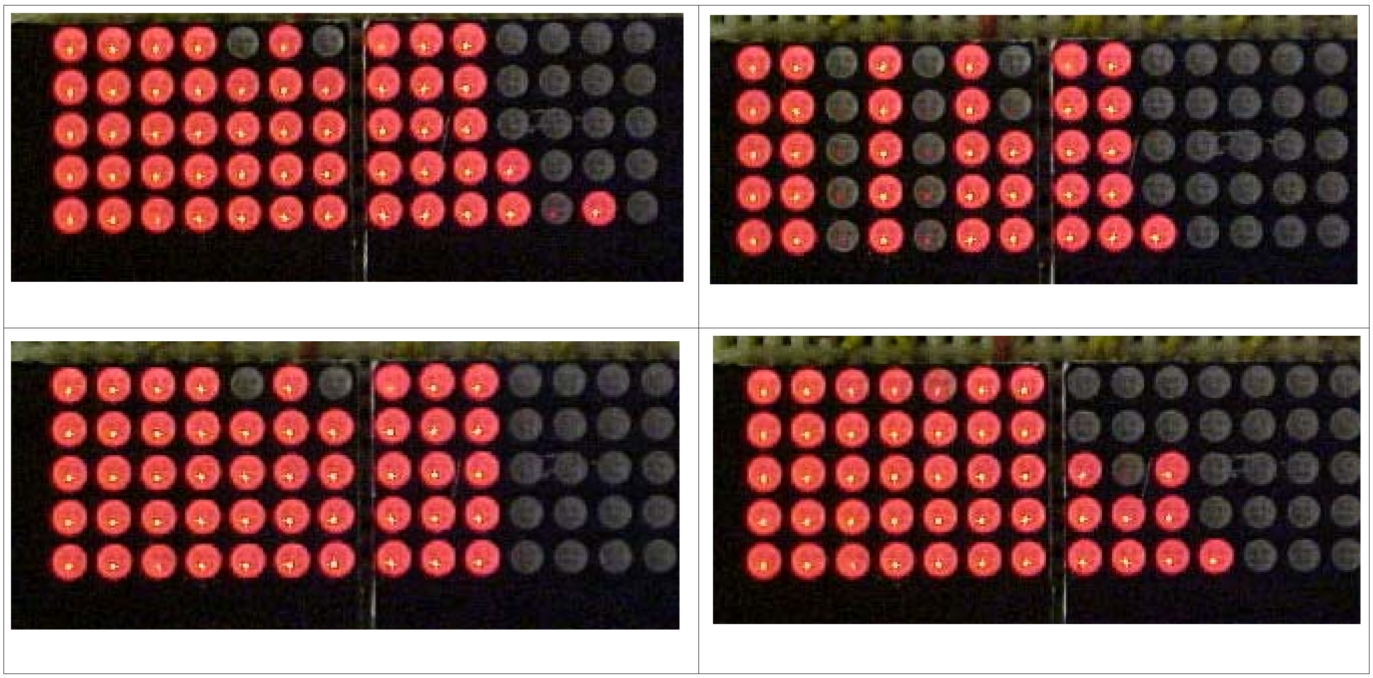


Illustration 11: Typical spectral displays while music is played into the spectrum analyzer.

Questions and Report

Introduction Questions

1. What is the diode current of the "saturation" LED when illuminated? (Assume $V_F = 1.7$ V)

2. What is the type and gain of the amplifier circuit used to amplify the input audio signal?

3. What is the purpose of all the 0.1uF capacitors connected between Vdd and Vss?

Lab Tables, Graphs, and Questions

Table 1

LED's Illuminated	***Input Voltage (peak-to-peak or RMS)***
1	
2	
3	
4	
5	

Graph 1:

Graph the number of LED's illuminated vs. input voltage here.

1. The audio spectrum covers a range of 20 Hz through 20 kHz. How much of this range does your spectrum analyzer cover?

Table 2

Bin	***0***	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***
Measured Fc (kHz)														
Predicted Fc (kHz)														
Deviation (%)														

2. Describe what happened when you increase the sampling rate beyond the Nyquist limit.

3. How could this be useful in a real application?

4. Is there any interaction between the two displayed frequencies? (I.e. does varying one of the frequencies or amplitudes affect the display of the other frequency or amplitude?)

5. Describe your observation of the square wave.

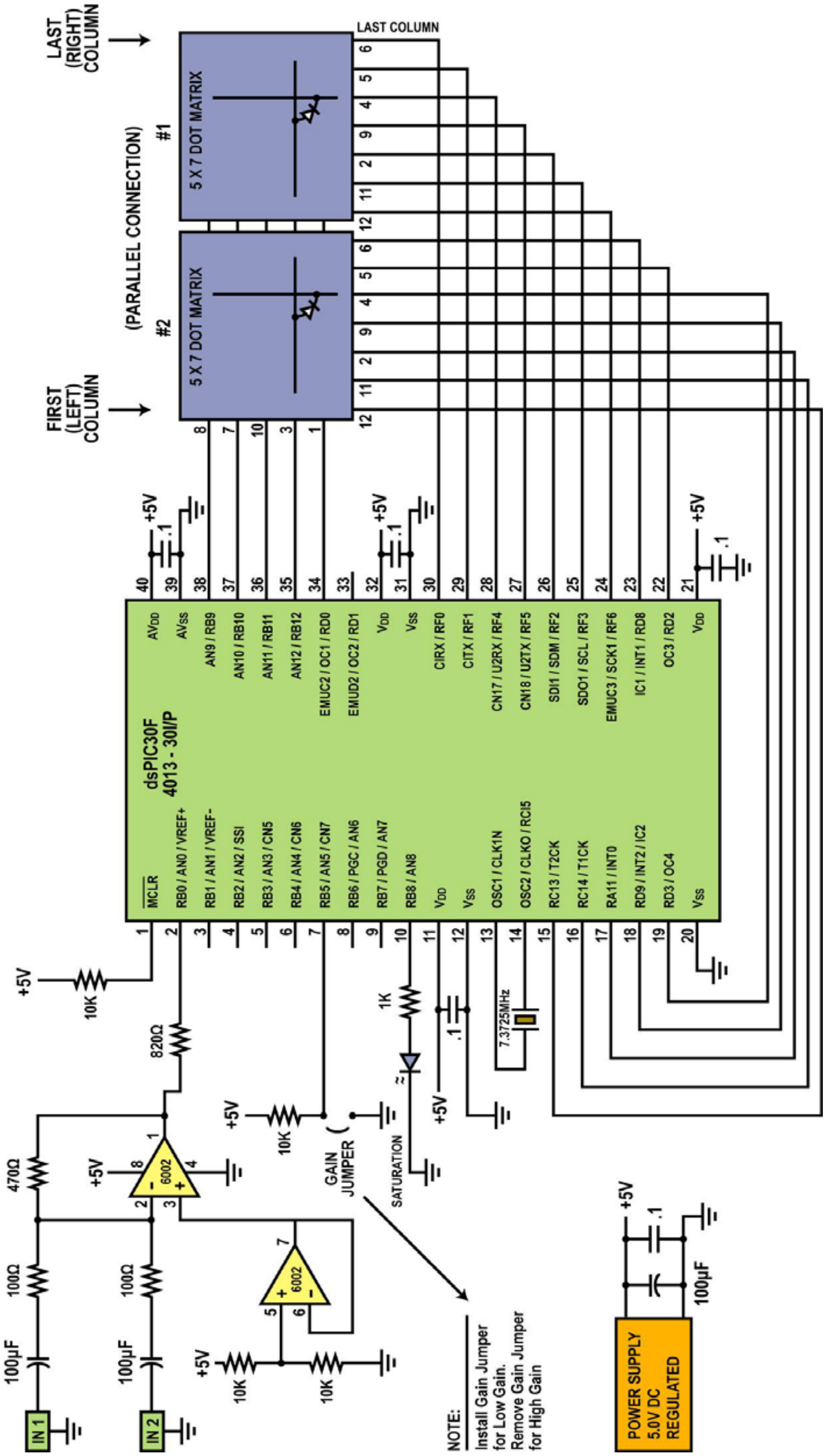
6. What happens to the harmonics?

Lab Report

Write a brief report on the current state of the art in spectrum analyzers. Do some online research on commercial spectrum analyzers and be sure your report addresses the following issues.

1. What are the most popular brands, models, and, importantly, prices?
2. What approximate maximum sample rates are available?
3. What are some of the suggested applications for these commercial analyzers?
4. How well did the spectrum analyzer we built compare with the commercial systems on all of these dimensions?

Schematic



LAST (RIGHT) COLUMN
FIRST (LEFT) COLUMN
(PARALLEL CONNECTION)
#1 5 X 7 DOT MATRIX
#2 5 X 7 DOT MATRIX
LAST COLUMN
dsPIC30F 4013 - 30I/P
MCLR
RB0 / AN0 / VREF+
RB1 / AN1 / VREF-
RB2 / AN2 / SSI
RB3 / AN3 / CN5
RB4 / AN4 / CN6
RB5 / AN5 / CN7
RB6 / PGC / AN6
RB7 / PGD / AN7
RB8 / AN8
VDD
VSS
OSC1 / CLK1N
OSC2 / CLKO / RC15
RC13 / T2CK
RC14 / T1CK
RA11 / INT0
RD9 / INT2 / IC2
RD3 / OC4
VSS
AVDD
AVSS
AN9 / RB9
AN10 / RB10
AN11 / RB11
AN12 / RB12
EMUC2 / OC1 / RD0
EMUD2 / OC2 / RD1
VDD
VSS
CIRX / RF0
CITX / RF1
CN17 / U2RX / RF4
CN18 / U2TX / RF5
SDI1 / SDM / RF2
SDO1 / SCL / RF3
EMUC3 / SCK1 / RF6
IC1 / INT1 / RD8
OC3 / RD2
VDD
7.3725MHz
GAIN JUMPER
SATURATION
IN 1
IN 2
100µF
100Ω
470Ω
820Ω
10K
1K
6002
+5V
NOTE:
Install Gain Jumper for Low Gain.
Remove Gain Jumper for High Gain
POWER SUPPLY 5.0V DC REGULATED