

## 4

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# Infrared PWM Transmitter

## Overview

In this lab you will construct a circuit to produce a 40kHz analog pulse-width-modulator (PWM), to be used later in our one-way analog audio communication link. Later we will combine this modulator with the microphone circuit from an earlier lab to form a complete IR audio transmitter. In the following lab session we will build the IR receiver circuit to complete the communication link. The lab will explore:

- Basics elements of a communication link
- Analog PWM modulation in particular
- Some elements of optical signal propagation and detection
- Limitations on data rate due to circuit components

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## Pre-lab Preparation

You have one week to complete this lab. Read through the lab experiment to familiarize yourself with the components and assembly sequence, and complete the calculations below. Before coming to the lab, each group should obtain a parts kit from the ECE Shop. Bring your solderless breadboard, tools, & wire jumpers.

### **Required calculations:**

- Determine the capacitance C1 in the 555 timer circuit of Fig 1 that is needed to provide pulse frequencies of 4kHz and 40kHz, respectively.

$$4\text{kHz: } C1 = \underline{\hspace{2cm}} \mu\text{F} \qquad 40\text{kHz: } C1 = \underline{\hspace{2cm}} \mu\text{F}$$

- Coupling capacitor C3 and the resistor chain R1-R2-R6 form a high-pass filter. For the component values shown in the schematic, find the maximum and minimum cutoff frequencies as potentiometer R6 is varied over its full range.

$$f_{L\min} = \underline{\hspace{2cm}} \text{Hz} \qquad f_{L\max} = \underline{\hspace{2cm}} \text{Hz}$$

- Determine an appropriate value for the IR LED biasing resistor R9 to provide a 50 mA current flow, assuming a power supply voltage of 12V. The forward voltage drop of the diode can be determined from graphs provided in the data sheet.

$$R9 = \underline{\hspace{2cm}} \Omega$$

### **Optional:**

Simulate the PWM circuit using MultiSim or Circuit Maker™ (circuit files available on the course web site).

**Full Schematics for IR PWM Modulator**

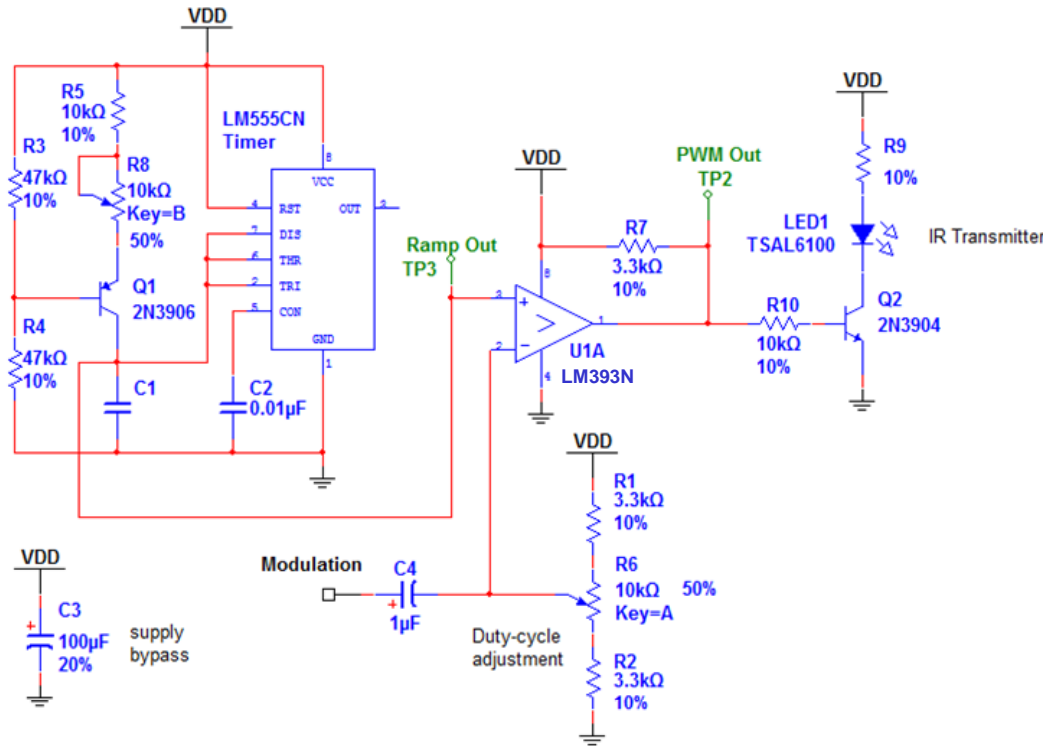


Figure 4-1 – Schematic for the Infrared Pulse-Width Modulated Transmitter.

**Parts List**

Qty	Description	Circuit
<b>Semiconductors</b>		
1	TIMER, LMC555CN (DIP-8)	U2
1	COMPARATOR, LM393N (DIP-8)	U1
1	Op-Amp, LF353N (DIP-8)	U3
1	BJT_NPN, 2N3904 (TO-92)	Q2
1	BJT_PNP, 2N3906 (TO-92)	Q1
1	IR High Eff. Emitter TSAL6100 (5mm)	LED1
1	IR Photodiode, BPV23F (side view)	IRD1
1	IR phototransistor (T1 3/4)	Q3
<b>Passives</b>		
1	RESISTOR, 1kΩ 10% 1/4W	R11
4	RESISTOR, 3.3kΩ 10% 1/4W	R1,R2,R7,R11
3	RESISTOR, 47kΩ 10%	R3, R4, R12
2	RESISTOR, 10kΩ 10% 1/4W	R5, R10
2	POTENTIOMETER, 10kΩ	R6, R8
1	CAPACITOR, 0.001μF 10% (low-volt ceramic)	C1
1	CAPACITOR, 0.0022μF 10% (low-volt ceramic)	C1
1	CAPACITOR, 0.0047μF 10% (low-volt ceramic)	C1
2	CAPACITOR, 0.01μF 20% (low-volt ceramic)	C1,C2
1	CAP_ELECTROLIT, 1μF	C4
1	CAP_ELECTROLIT, 100μF 20%	C3
<b>Hardware</b>		
2	8-pin low-profile IC socket	
1	2.5" x 3.25" Vectorboard (w/solder pads)	

## Background: Analog Communication Links

### Information and Bandwidth

Every communications link involves a transfer of energy from one point to another. The energy originates from a *transmitter*, travels through the “*channel*” (air, coaxial-cables, fiber-optics, etc), and is ultimately detected by a *receiver*. The distinctive feature of a communications system is that the signal is encoded with some *information* in some fashion. The relationship between the rate of *information* transfer and the bandwidth of the system is of critical importance in understanding the operation and limitations of communications systems.

To convey information a signal must change in some way. As a simple acoustic example, consider the sound of a train whistle. A variation in *amplitude* of the whistle provides some qualitative information regarding the proximity of the train; a loud whistle means the train is near, a faint whistle means it is far away. Similarly the variation in pitch of the whistle (*frequency*) might give some additional clues about the direction of motion via the Doppler effect: if the frequency is increasing the train is moving towards us; if the frequency is decreasing, the train is moving further away. Thus in this simple example, information about the distance and velocity of the train is effectively encoded in the signal by the variation of both amplitude and frequency of the sound wave.

Human speech is similar in that variations of amplitude and frequency also encode information, but the relationship is much more complex. Figure 4-2a illustrates the output of a microphone for a particular segment of speech. Interestingly, if we arrange for two different people to say exactly the same words, and thus communicate exactly the same information across the communication channel, the observed electrical signals will differ significantly due to variations in pitch, timbre, accent and articulation patterns of the different speakers. Although electrical systems now exist to decipher such signals, they often need to be tailored in advance or “trained” to the individual user. Our brains’ capacity for decoding such information is truly remarkable.

Fortunately we do not need to understand coding method perfectly in order to merely *transmit* speech or any other audio signal between two points. We only need to recognize or require that the information-bearing signal is *band-limited*—that is, the energy associated

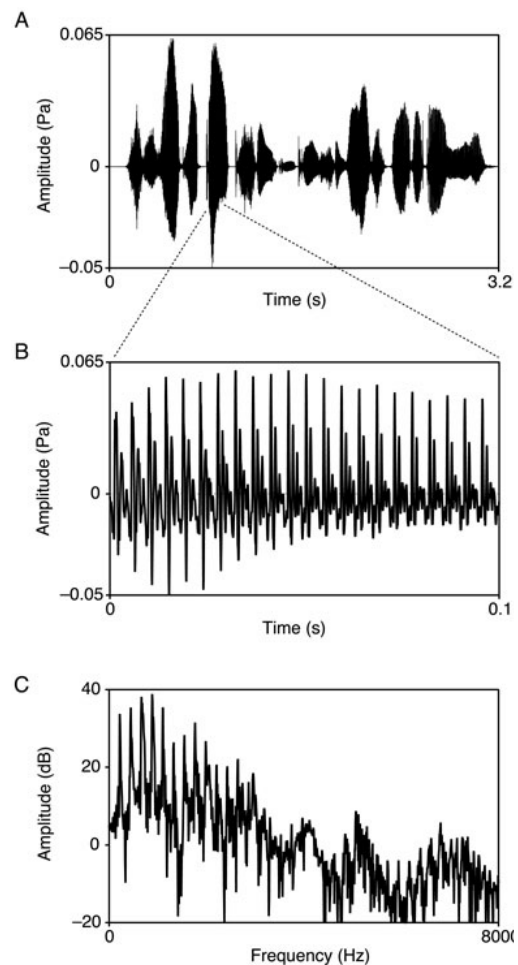


Figure 4-2 – A) Sound pressure vs. time for a vocal utterance of “She had your dark suit in greasy wash water all year”. B) Blowup of a 0.1s segment corresponding to the vowel sound in “dark”. C) Frequency spectrum of (B). (From <http://www.purveslab.net>).

with the information content must be concentrated in a finite range of the frequency spectrum. If the communication link can support the bandwidth associated with a given signal, this ensures that the information content of the signal will be accurately conveyed to receiver without distortion.

The spectrum of a certain spoken vowel sound in the previous example is shown in Figure 4-2c. After analyzing the spectra of many different speakers in this way, and observing the influence of various electrical filters on the reproduction of their voices, researchers have concluded that a limited range of frequencies from 200-300 Hz to about 3-4 kHz is required to communicate *intelligible* speech. A somewhat larger bandwidth of 8 kHz or more is required for a faithful reproduction of a typical human voice. High quality music transmission may require an even wider range of frequencies, from 50Hz through 16-20 kHz, to accurately reproduce the more complex acoustical characteristics of musical instruments such as violins and horns, sounds that are rich in spectral content. So, depending on the kind of audio signal we wish to transmit, an audio communications system must support bandwidths of anywhere from 3 kHz to 20 kHz. A typical phone or intercom system usually has a bandwidth of about 3 kHz.

We can generalize these ideas to all audio, video, and data communications: **every signal has a characteristic band of frequencies, or bandwidth, representing the essential information content of the signal. Conversely, the bandwidth of a communications link will determine its maximum rate of information transfer, or data-rate.** Thus in communications we will assume our information-bearing signals are band-limited; a *baseband* signal is one with a bandwidth concentrated at low frequencies, such as a voice or music signal as shown in Figure 4-3. Of course, real signals never perfectly fit within a finite bandwidth, and practical communication channels will never support an infinite bandwidth, so we must always expect some signal *distortion* in an analog communications.

### **Baseband Transmission vs. Modulated Carriers**

Signals can be transported from place to place using acoustic or electromagnetic waves. When low-frequency band-limited signals can be transmitted directly, for example over wires, coaxial cables, or as a simple acoustic wave (human speech or music), this is referred to as a *baseband* communication link. This is the simplest and easiest system to implement. For long-distance or wireless communications, however, baseband communications are rarely possible and we must use a *modulated carrier*. Why?

In order to *efficiently* radiate an acoustic or electromagnetic wave, any radiator (loudspeaker, ultrasonic transducer, antenna, etc.) must be comparable in size to the largest wavelength being transmitted. This is a fundamental property of all types of waves. The wavelength  $\lambda$  is related to the frequency  $f$  by the fundamental relation  $\lambda = v / f$ , where  $v$  is the wave velocity. At audio frequencies the acoustic wavelength is reasonably small, typical of the audio speaker systems you are familiar with. But *electromagnetic* waves at audio frequencies have *enormous* wavelengths; at 3kHz, the wavelength is 100 km! So it is usually impractical to transmit electromagnetic waves directly at such low frequencies. On the other hand, electromagnetic waves are generally more desirable than acoustic waves for long-distance communication in air, since acoustic waves are more strongly attenuated than electromagnetic waves in air (the opposite is true for undersea communication).

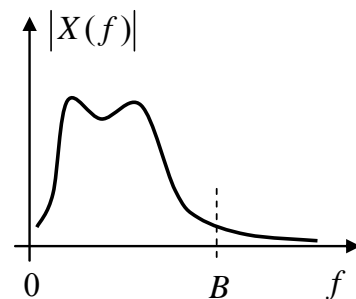


Figure 4-3 – Fourier spectrum of a baseband signal  $x(t)$ , concentrated in a bandwidth  $B$ .

Thus, in order to take advantage of improved propagation characteristics of electromagnetic waves but keep the radiators to a reasonable size, we need to transmit and receive in a frequency range that is often much higher than the bandwidth of the information. AM radio stations in the U.S., for example, broadcast at frequencies in the range of 530 kHz to 1.7 MHz, but the information content of each radio station is restricted to a bandwidth of 10.2kHz or less. The high-frequency signal effectively “carries” the narrow bandwidth of information from the transmitter to the receiver; this is the *carrier frequency* in the communication system. In this AM radio example, the information bandwidth represents less than 1% of the carrier frequency.

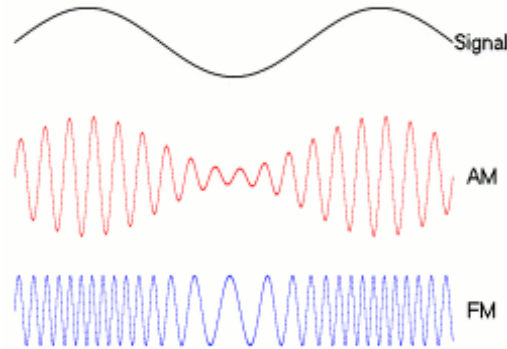


Figure 4-4 – Two simple modulation schemes.

**Modulation** is the process of shifting the information band onto a high-frequency carrier wave. The reverse process of extracting the information from the carrier after reception is called **demodulation**. There are many different ways to modulate a carrier. Two conceptually simple methods—Amplitude Modulation (AM) and Frequency Modulation (FM)—are illustrated in Figure 4-4. All modulation schemes have their own set of advantages and disadvantages. Some, like AM modulation, have the advantage of very simple hardware implementations but may be susceptible to noise and interference. Others, like FM, require more complex electronic implementations but have improved signal fidelity.

In the frequency domain, modulating a high-frequency carrier with some baseband information-bearing signal has the effect of shifting the information bandwidth to a range of frequencies around the carrier. The information thus appears as “sidebands” around the carrier, as illustrated in Figure 4-5. In general there are two sidebands above and below the carrier that are mirror images of each other, and thus a bandwidth of  $2B$  is required around the carrier for such “Double-SideBand” (DSB) transmission. AM radios in the U.S., for example, use DSB transmitters and have a channel bandwidth of  $2 \times 10.2 = 20.4$  kHz. It is possible to make a “single sideband” (SSB) transmitter, but this requires more complex hardware. It is even possible sometimes to suppress or eliminate the carrier before transmission. So there are a wide variety of signal spectra that are encountered in communications. The key idea is that we can shift our information to a higher-range of frequencies through the modulation/demodulation process. This enables us to pack a lot of information into a certain range of frequencies. Again returning to our example of the U.S. AM radio system, there is a total FCC-approved bandwidth of  $1700 - 530 = 1170$  kHz, so in any given geographical area, approximately 58 different AM stations could be broadcasting simultaneously ( $1170 / 20 \approx 58$ ).

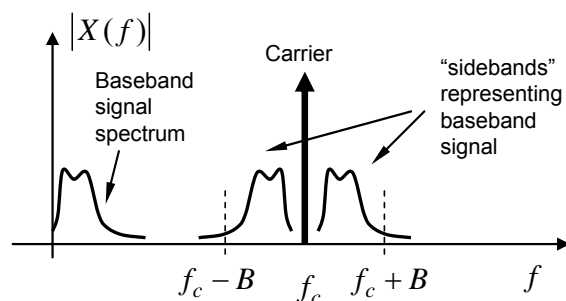


Figure 4-5 – Effect of modulating a sinusoidal high-frequency carrier with a baseband signal.

Moving to higher frequencies also makes it somewhat easier to increase the information bandwidth for a communication link. All transmitting and receiving systems will have a finite bandwidth, but a bandwidth of 5-10% of the carrier frequency is often possible with simple circuits and antennas. So, for example, a point-to-point wireless link operating at 24 GHz using antennas with a 5% bandwidth corresponds to an available information bandwidth of 1.4GHz, enough to support a rather large number of simultaneous voice, video, and data channels. Now you can appreciate the potential for fiber-optic communications; the carrier frequency is on the order of  $10^{14}$  Hz, so the intrinsic capacity of the optical fiber as an information conduit is enormous.

To summarize: it proves advantageous to modulate for either or both of the following reasons: (1) to take advantage of the superior propagation or radiation characteristics of high frequency acoustic or electromagnetic waves, or (2) to transmit multiple information-bearing signals simultaneously from one point to another. As time goes on, and the demand for ever-faster data rates increases, wireless communication devices will therefore continue to evolve towards higher carrier frequencies; count on it!

### **Pulse-Width Modulation (PWM) for Optical Communications**

Unfortunately it is beyond the scope of this course to probe the subject of analog and digital modulation techniques more deeply; that is firmly in the realm of more advanced junior- and senior-level coursework in communications theory. In this lab we will explore one modulation format in particular: so-called *pulse-width modulation* (PWM), which is well-suited to optical communications and is relatively easy to implement.

The basic idea of PWM is illustrated in Figure 4-6. The technique requires a pulse train at some frequency  $1/T$  with a variable pulse width or duty cycle. The modulating signal is used to control the duty cycle; that is, the instantaneous pulse width at any given time is proportional to the amplitude of the modulation signal. As the signal increases the pulse width and duty-cycle increase; as the signal decreases, the pulse width decreases.

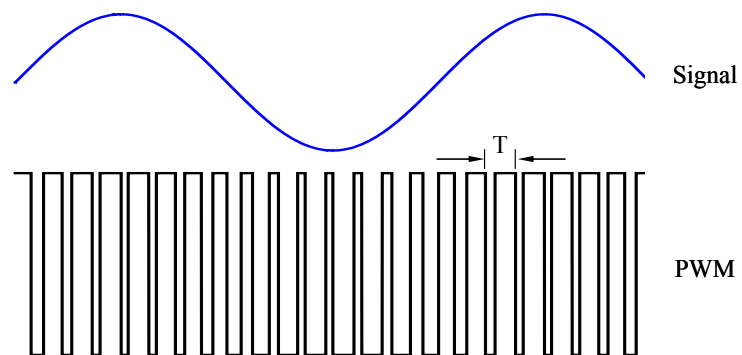


Figure 4-6 – Pulse-width modulation.

In optical communications the light source is usually an LED or Laser diode. It is relatively easy to construct a circuit to switch the device on and off quickly, so PWM is well-suited to diode-based emitters. All we need is a variable duty-cycle circuit to control the time the emitter is on or off, and you may recall that we already discussed how to make those last quarter in ECE 2B when we built a variable-duty-cycle fan speed controller. Demodulating the signal is relatively easy too; we will discuss this in more detail in the next lab, but you can see from the figure above that the average value of the PWM waveform over each carrier period is proportional to the pulse width, which in turn is proportional to the modulating signal. Thus all we need to do at the receiver end is low-pass filter the PWM waveform to eliminate the carrier and recover the modulating signal!

Clearly the PWM system will work best if the pulse train is set to a frequency that is much higher than the highest frequency of the information signal. On the other hand, we know that the Fourier series representation of a pulse train requires several higher harmonics in order to accurately represent the pulse train, so a 200 kHz pulse train might require a detector circuit bandwidth of  $> 2$  MHz or more, which is difficult using the cheap op-amps and transistors that we are familiar with in ECE2. The LF353, for example, has a gain-bandwidth product of only 4 MHz which gives it a useful operating bandwidth of roughly 400 kHz or less if we assume a minimum gain of 10 for proper operation. So we can't choose the frequency too high. But we can't choose it too low, either, because on the receiver side it would become difficult to filter out the carrier without adversely affecting the information signal bandwidth. So if we plan to transmit audio signals with a  $\sim 5$  kHz bandwidth, we must choose a pulse frequency that is (ideally) well above 5 kHz and also well below 400 kHz. A carrier of 40 kHz would therefore seem appropriate, and in fact that is a common choice of modulation frequency for commercial short-range infrared devices like TV remote control units, so that is what we will adopt in our system. Interestingly, this is also the same frequency of many popular ultrasonic transducers, so our receiver circuits are quite similar to what you will see in ultrasonic detectors as well as infrared remotes.

## In-Lab Procedure

### 4.1 Variable Duty-Cycle Circuit

In ECE 2B we built a simple motor speed-control using a variable duty-cycle oscillator based on the 555 Timer. We will use the same basic topology here to create our analog pulse-width modulator. This time you need to do some of the design work (outlined in the pre-lab section).

The basic 555 circuit for generating a sawtooth waveform is shown in Figure 4-7. It is essentially an ordinary pulse generator, but uses a transistor current source to charge the timing capacitor C1, this generating a linearly increasing voltage across the capacitor (instead of the normal exponential waveform). This circuit is essentially the same topology as that appearing in fig. 12, p.9 of the National Semiconductor 555 Data Sheet (on the course web site). Potentiometer R8 will be used for fine-tuning of the output frequency. Although our infrared transmitter will ultimately operate at 40 kHz, we are going to start with a lower frequency for the early prototyping stage.

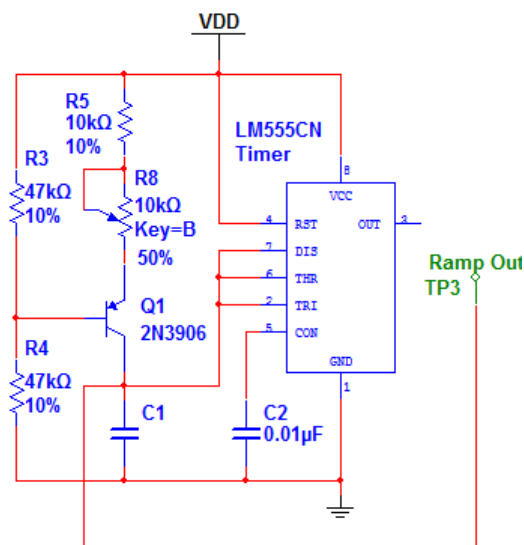


Figure 4-7 – 555-based linear ramp oscillator.

- Construct the 555 circuit in Figure 4-7 using the C1 you calculated in pre-lab for 4 kHz operation. There are a number of capacitors in the parts kit that you can choose from or use in combination to get the required capacitance C1.



- Apply power and observe the output waveform on the oscilloscope. The circuit should work well for a range of supply voltages, but 9-12V will be used here. Adjust the trimpot so that the circuit generates a 4 kHz sawtooth waveform, and record this in the lab record, noting the maximum and minimum voltages.
- Now add the comparator circuit as shown in Figure 4-8. Recall that the LM393 requires a pull-up resistor (R7). Also add a large supply bypass (C3) somewhere near the comparator: this is important because both the 555 timer and comparator generate sharp pulses which lead to undesirable fluctuations in the power rails.

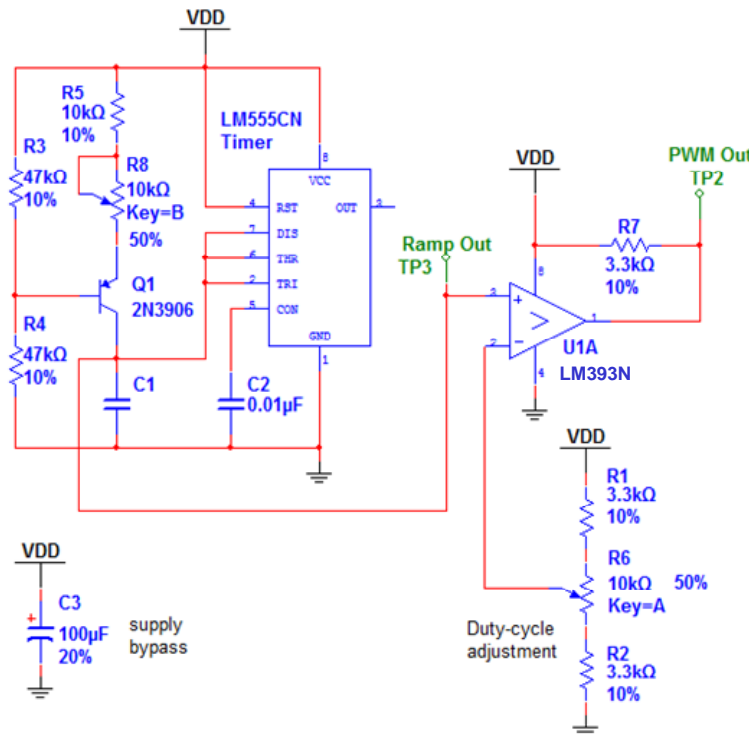


Figure 4-8 – Variable Duty-Cycle Circuit (similar to 2B Lab #5).

- Adjust potentiometer R6 until a 50% duty-cycle is obtained at the output. Record the resulting voltage at pin 2 of the comparator; this should be close to the average of the maximum and minimum voltages of your sawtooth waveform.
- Now determine the voltage change at pin 2 that is required to change the duty cycle to 30% and 70%. This will give us a target amplitude for the modulation signal in the next step.

## 4.2 Analog Pulse-Width Modulation

All we need now is a way to vary the duty-cycle of the carrier electronically, in proportion to some analog input signal (such as the output of our microphone circuit). It is almost ridiculously simple to accomplish this: we simply capacitively-couple the modulation signal to the reference voltage on the comparator as shown in Figure 4-9. The total voltage at pin 2

of the comparator is then the sum of the DC value set by the R1-R6-R2 divider, plus a time-varying modulation signal.

Remember that anytime we add a capacitor in this fashion we are potentially adding a pole in the AC frequency response. In this case, C4 and the resistor divider create a high-pass response for the modulation signal. The cutoff frequency will change a bit depending on the setting of R6, so we must be sure to choose a large enough capacitance to insure that the cutoff frequency is always well below our lowest desired frequency for all possible states of R6. In the prelab calculations you should have estimated the range of cutoff frequencies for C4=1 $\mu$ F as shown in Figure 4-9.

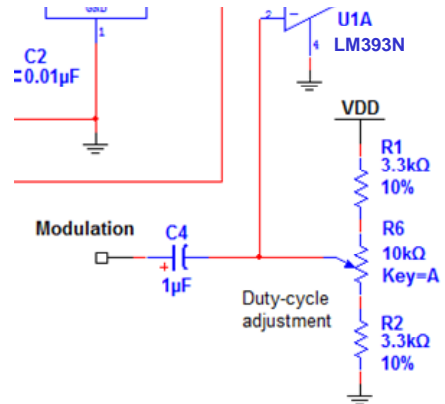


Figure 4-9 – AC-coupled modulation signal controls the duty cycle.

- Add the AC coupling capacitor C4 as shown in Figure 4-9.
- Set up your function generator to supply a low-frequency (1 Hz) sinusoidal modulation signal with a peak amplitude that is approximately what you recorded in the last step of section 4.1 for a 30% duty cycle. Apply this signal to the modulation terminal of your circuit and record your observations. Do you understand what is happening? Vary the amplitude of the function generator a little to enhance the effect. Note that you may need to adjust the oscilloscope for negative-edge triggering for clarity, since the falling edge of the waveform always coincides with the falling-edge of the sawtooth generator, and that provides a more stable reference for triggering the oscilloscope. The timing of the leading edge will vary with the modulation signal.
- Increase the frequency of the function generator to 100 Hz and record the waveform.

### Other PWM Circuits

Anyone who has bothered to read the 555 data sheet will note that there is a very simple PWM circuit that can be made using ONLY the 555 and a handful of passives<sup>1</sup>. You may wonder, then, why we bothered with the more complicated circuit in Figure 4-8. In fact we could probably get away with the simpler version too, but for reasons which will become clear later, we wanted a duty cycle that could be varied above and below 50%, whereas the simpler 555-only circuit is constrained to duty-cycles <50%.

## 4.3 A Simple Infrared Link

### Transmitter

Now we have all the circuit components we will need to assemble our transceiver system. The last ingredient is the infrared transducers: the devices that will generate or receive the infrared signal. You may recall that we used an infrared emitter and phototransistor pair in ECE2B to as part of a “chopper” circuit to generate a pulse train proportional to the speed of a fan blade.

<sup>1</sup> Fig. 8 on p.8 of the National 555 data sheet.

The transmitter portion of the link is simple, we just use the output of the PWM circuit to drive a transistor switch as shown in Figure 4-10. Here we have chosen a high-efficiency IR emitter, designed to operate at somewhat higher current levels than we normally encounter in LEDs in order to produce a high-intensity output.

- Using the value for biasing resistor R9 that you calculated in the prelab, add the IR transmitter circuit in Figure 4-10 to your PWM circuit.
- Observe the voltage across the LED or R9 to confirm that it is being driven by a pulse train.

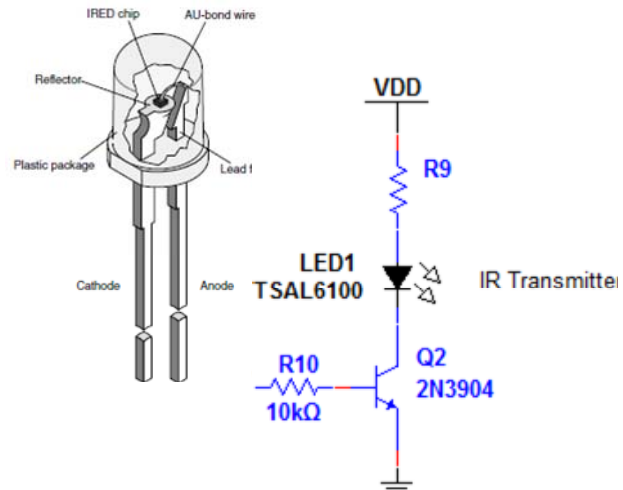


Figure 4-10 – Infrared emitter circuit.

### IR Detectors

Now add a simple phototransistor detector circuit as shown in Figure 4-11. This is again similar to the IR detector circuit that we used in 2B: when the base region of the phototransistor is illuminated, charge carriers are created which bias the transistor “on” and drive a current through the load resistor R11:

- Add the phototransistor-based detector as shown. In this phase, the emitter and detector should be spaced a few inches apart on your breadboard. To start with, use a 3.3k resistor for R11
- With the PWM transmitter operating at 4 kHz, observe the output waveform on the detector, noting the peak amplitude of the signal and the pulse shape. Can you estimate a rise-time and fall-time for this waveform?

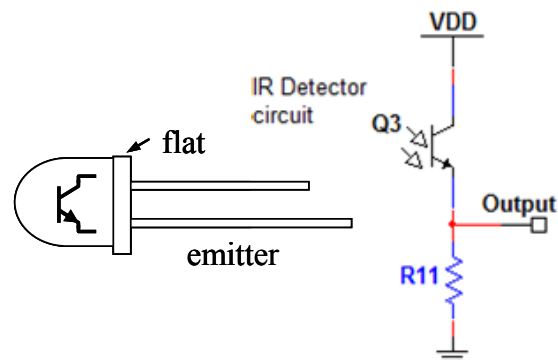


Figure 4-11 – Infrared emitter circuit using a phototransistor.

This simple test illustrates one of the challenges that always comes up when transmitting pulse trains. In this case, the internal capacitances of the phototransistor, along with R11 and  $r_e$ , create an RC low-pass response that distorts the signal. We can improve things a bit by using a smaller load resistor, which should reduce the RC time constant in the circuit:

- Replace R11 with a 1k resistor and record the output waveform again, noting the rise- and fall-times as before.

We could continue reducing R11 for further improvement, but note that each time we do, we also reduce the amplitude of the detected signal! Even so, you might think that what we have so far is “okay”: the detected signal is a reasonable approximation to a square wave, and we

could always amplify the signal if we have to. However, there is still a major problem: we're still at 4 kHz!

- Replace timing capacitor C1 with the value that gives a 40kHz output. You may have to re-adjust R6 at this stage to obtain a 50% duty-cycle. Record the waveform across Q2 or R9 to confirm that the emitter is still being driven appropriately.
- Now observe and record the output waveform on our photodetector circuit, using a 1k resistor for R11. Yikes!

Ultimately the problem here is the phototransistor capacitance. As a circuit designer there *are* some tricks we can use to mitigate the effects of the capacitance; for example, using a cascode arrangement where the phototransistor drives a fast CB or CG gain stage, or similarly using a trans-impedance (current-to-voltage) amplifier with a very low input impedance. But there are other issues too: the phototransistor itself is an amplifying device; it has a built-in current gain, and thus amplifies all incoming light indiscriminately. This is a disadvantage in situations like ours where the incoming signal could be relatively weak in comparison to ambient light and other potential sources of interference. Also, phototransistors tend to have rather large “dark” currents in comparison to other detectors, that is, the leakage current that flows even when no light is incident on the device. This shows up as additional background noise after amplification.

A better solution is to use an intrinsically faster detection device, one with smaller internal capacitance and (ideally) a greater sensitivity to low-level signals, and then build in some frequency-selective amplification to extract only the modulated carrier that we are interested in, rejecting other interfering signals. Enter the PIN photodiode. This is a diode that is designed to be operated under a large reverse bias. The leakage current that flows in the device is proportional to the incident light. Such devices are quite fast and very sensitive. The one we use also has a built-in IR filter to help reduce interference from ambient visible light, and optimized for use with the TSAL6100 emitter that we are using. It has a cutoff-frequency that is similar to the gain-bandwidth product of our LF353 op-amps (4 MHz), corresponding to an expected pulse rise-time of ~80 ns, which should be adequate for our 40kHz pulse train ( $T = 25 \mu s$ ).

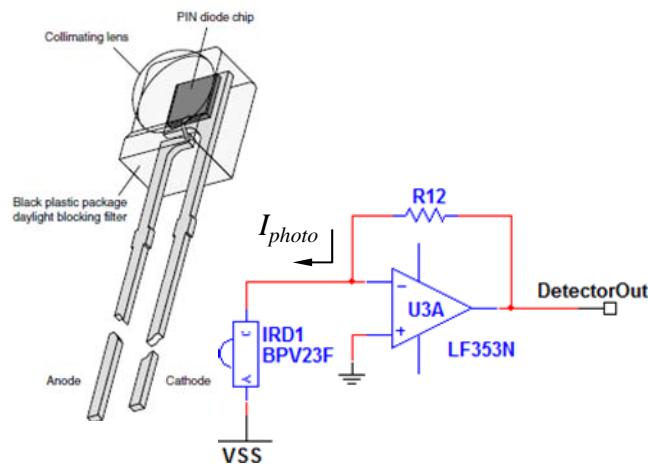


Figure 4-12 – Photodiode and detector circuit.

- Using the BPV23F PIN photodiode in your kit, construct the detector circuit shown in Figure 4-12. Note that the supply connections for the op-amp and decoupling capacitors are not shown. The decoupling capacitors are IMPORTANT!. Also, Note that the anode is connected to Vss, which is a NEGATIVE supply voltage, i.e.  $V_{ss} = -V_{dd}$ .

This detector circuit is a *current-to-voltage* amplifier, otherwise known as a *trans-impedance* amp: the input impedance seen by the photodiode is very small, and the photocurrent is forced to flow through R12. Thus we are free to make R12 reasonably large, constrained only by the gain-bandwidth limitations of the op-amp itself.

- Start with R12=10 k $\Omega$  and record the output waveform of the detector when transmitting a 40kHz IR pulse train, taking note of the rise-time. Repeat with R12=47 k $\Omega$ .

For large values of R12 you might see some deterioration in the rise-time, and you may also start to see some evidence of interference from the room lights. Try turning off the transmitter and observing the output of the detector, expanding the voltage scale and adjusting the time-base appropriately. Fluorescent and incandescent bulbs introduce a characteristic 120 Hz interference in optical detectors. In the next lab we will discuss how to deal with this issue.

You may also observe some interference from the transmitter circuit. This happens because the receiver and transmitter are sharing common supply rails, and some of the switching transients from the 555 timer and comparator circuit get coupled into the high-gain detector through the op-amp power supply connections. The decoupling capacitors help to some extent, but when we put the entire transmitter-receiver system together we will use separate power supplies to avoid the issue altogether.

#### 4.4 Hardwire the Transmitter Circuit

- Transfer your completed transmitter design to vectorboard. Leave the detector circuit on your breadboard, we will NOT be hardwiring the detector/receiver system. We will eventually include your microphone circuit from an earlier lab in the transmitter to modulate the carrier, but do not connect it to the PWM modulator just yet, as we will perform the initial testing using a function generator. Your completed board should have three power-supply connections (+/- 12V and GND), and two connections (Signal/Gnd) for hooking up the external function generator to the modulator.

Congratulations!  
You have now completed Lab 4

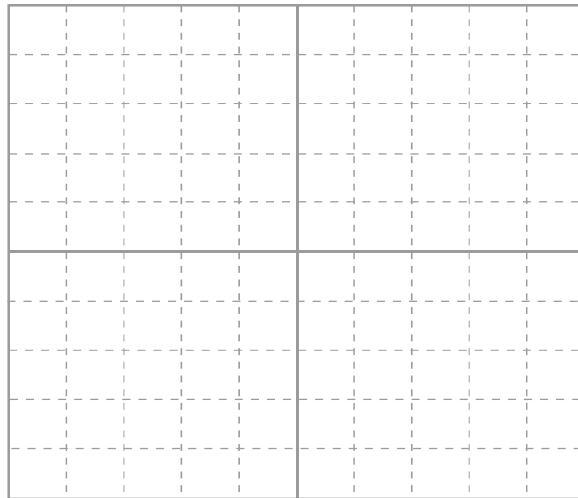
## Lab 4 Record

Section \_\_\_\_\_

Names: \_\_\_\_\_  
\_\_\_\_\_

### ***Variable Duty-Cycle and PWM Circuit***

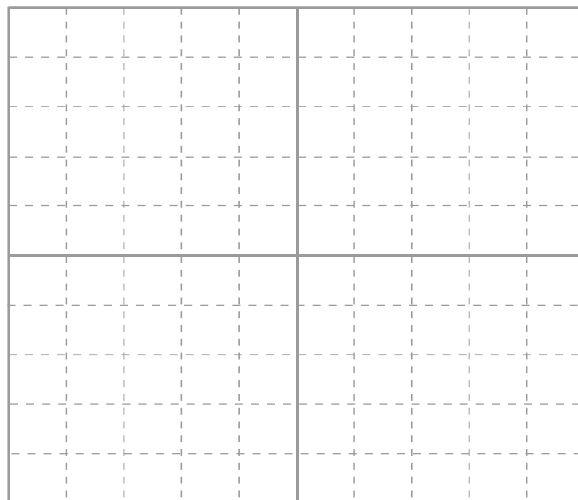
Record the 4kHz sawtooth output waveform from the 555 circuit (note max/min values):



Voltage required at pin 2 of comparator for 50% duty-cycle:      50%: \_\_\_\_\_ V

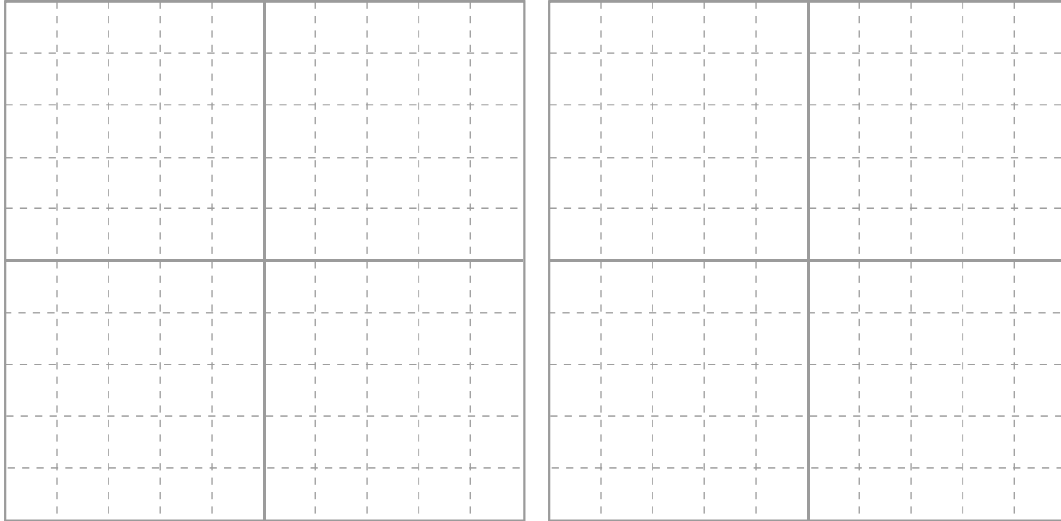
Voltages for 30% and 70% duty-cycle:      30%: \_\_\_\_\_ V      70%: \_\_\_\_\_ V

Record the output with a 100Hz modulation signal, annotated to describe what is happening:



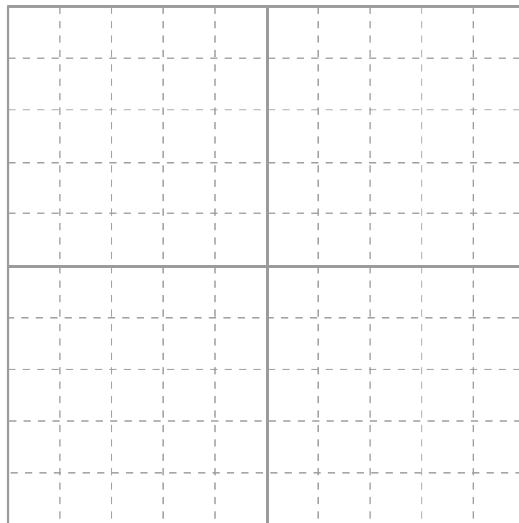
**Phototransistor-based Detector**

For transmitter operation at 40kHz (50% duty-cycle, no external modulation), record the transmitted and detected waveforms as described in the lab procedure.



**Photodiode-based Detector**

Under similar conditions as above, record the detected waveform using the PIN diode detector circuit



Above plot taken at a gain resistor value of: R12= \_\_\_\_\_ k $\Omega$

TA Certification: \_\_\_\_\_ Date: \_\_\_\_\_