AN OPTICAL SYSTEM FOR LINE-OF-SIGHT COMMUNICATION

BY

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ABSTRACT

We design and implement a system for short and medium range directional two-way wireless communication. The system uses infrared radiation to transmit and receive voice data digitally. We utilize narrow angle infrared light emitting diodes for transmission, directed across a reasonable angular range that allows the system to transmit across a narrow beam to the receiver, avoiding the dangers of detection, jamming, and eavesdropping that traditional omnidirectional radio transmission entails. On the receiving end, a wide-angle detector is used. The system is integrated inconspicuously into a military vest, allowing the wearer to communicate while on the field. In the working version of this system we use traditional semiconductor photodetectors and receivers. We also investigate the properties of optoelectronic fibers, novel semiconductor devices that can act as line detectors of light. We characterize these fibers, and analyze their potential for use as photodetecting devices in this system.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The ability for people to communicate wirelessly has revolutionized the way that society operates. Wireless systems based on transmission of data using radiofrequencies have become ubiquitous, both in specialized applications such as military communications systems and in commercialized consumer electronics. Optical frequencies can also be used for wireless transmission of data, and have been applied toward some applications such as wireless remote controls and IrDA-based short range data transmission. RF-based communication is a mature technology, but in some applications, optical-based communication offers some unique advantages.

Transmission of radiofrequency data for portable applications is generally omnidirectional, since phased array antenna configurations that allow for directional transmission of radio waves are generally quite large (the size of the antenna array for a given radiation pattern will increase with wavelength). Optical signals can be easily sent directionally using a variety of sources such as light emitting diodes with lenses or collimated lasers. Optical communication is line-of-sight, and generally short or medium range unless the beam is highly collimated, as in the case of a laser. While in many applications these are considered drawbacks, highly directional line-of-sight communication has some interesting advantages in applications such as covert communication on the field.

The system we are designing in this work is the Identification and Communication system (IdCOM), and it is being done in the Photonic Bangap Fibers and Devices group at the Research Laboratory of Electronics (RLE) at MIT. The work is funded by the Department of Defense and the Institute for Soldier Nanotechnology, and the system we are creating is intended to be a useful communications scheme for use on the field by members of the Special Operations Forces. Our aim is to develop an optical wireless communications system. The primary application for this system is a man-portable two-way communication system for covert military operations. The advantages that optical communication offers include high directionality, which is important to prevent third party eavesdropping and jamming of the signal or location of the operators. Such systems already exist for one-way communication. Our goal is to create a short-to-medium range two-way communication system as a proof of concept that such a system is both feasible and practical.

We also work to investigate different strategies for optical detection of the signal, including the use of optoelectronic fibers, novel semiconductor devices that are drawn in a similar manner to optical fibers rather than fabricated as wafers. These fibers are a developing technology, but offer some very exciting new ways of integrating electronics and optoelectronics into a portable, wearable system.

1.2 PREVIOUS WORK

A previous system, the IdCOM-H (Identification and Communications Helmet) was a one-way optical system built in the PBFD Group [1]. For transmission, the system used an eye-safe 1550 nm laser and on the receiving end it used a large area silicon photocell detector. Voice was sent in an analog fashion (amplitude modulation on a low bandwidth carrier wave) and transmitted by the laser. Fibers were mounted on the receiver but were not used to receive a signal; they were able to detect whether the receiver was being targeted by the laser. The receiver used a differential amplifier to detect differences in the signal from one side of the person verses the other. The receiver was incorporated into a military helmet, while the transmitter was a hand-held aimed device.

This system suffered from a number of limitations, especially low voice quality, non-digital transmission of data, extreme vulnerability to ambient light conditions, and requiring the user to precisely aim the laser transmitter at the receiver. Additionally, there is no easy way for somebody to respond to a transmission using this system, since transmission is one-way across a hand-aimed laser beam. We aim to address some of these issues in the two-way system, while maintaining the same advantages of directed optical communication that the previous system demonstrated.

Following this system, a number of concept ideas were developed for an all-digital system for communication. The first was a low-bandwidth, digital design intended to fit the bandwidth limitation requirements for the optoelectronic fibers. The system was tested only with a wired link, and not across an optical link. It used an evaluation board developed by Compandent, and was able to compress speech to a bitrate of 2.4 kbps. Unfortunately, the evaluation board was too bulky for portable use and licensing the compression algorithm for an independent design was prohibitively expensive.

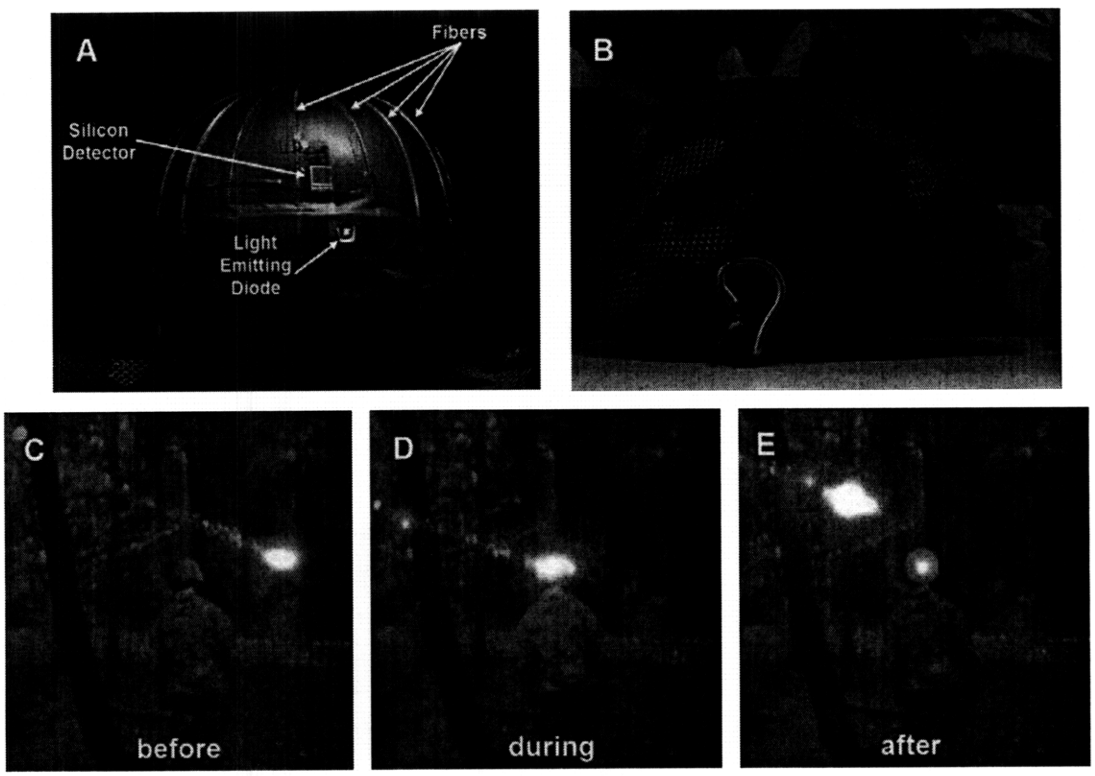

FIGURE 1-1. PREVIOUS, ANALOG ONE-WAY OPTICAL COMMUNICATIONS SYSTEM, SHOWING A DEMONSTRATION OF ACQUIRING A TRANSMISSION LINK USING AN IR VIEWER. IMAGE COURTESY YOEL FINK

The second digital system developed previous to the start of this project used a PIC microcontroller to process and send digital data across a modulated laser link [2]. The optical components to this system were similar to those used in the helmet (an InGaAs detector was used instead of a silicon photocell). The PIC was severely limited in processing power, and the maximum data rate that it could operate at was too low to sample and transmit audio data digitally without any sort of compression. It was able to transmit small data packets optically one way across a laser link, demonstrating the feasibility of digital optical communication with a similar setup and a microchip with more resources.

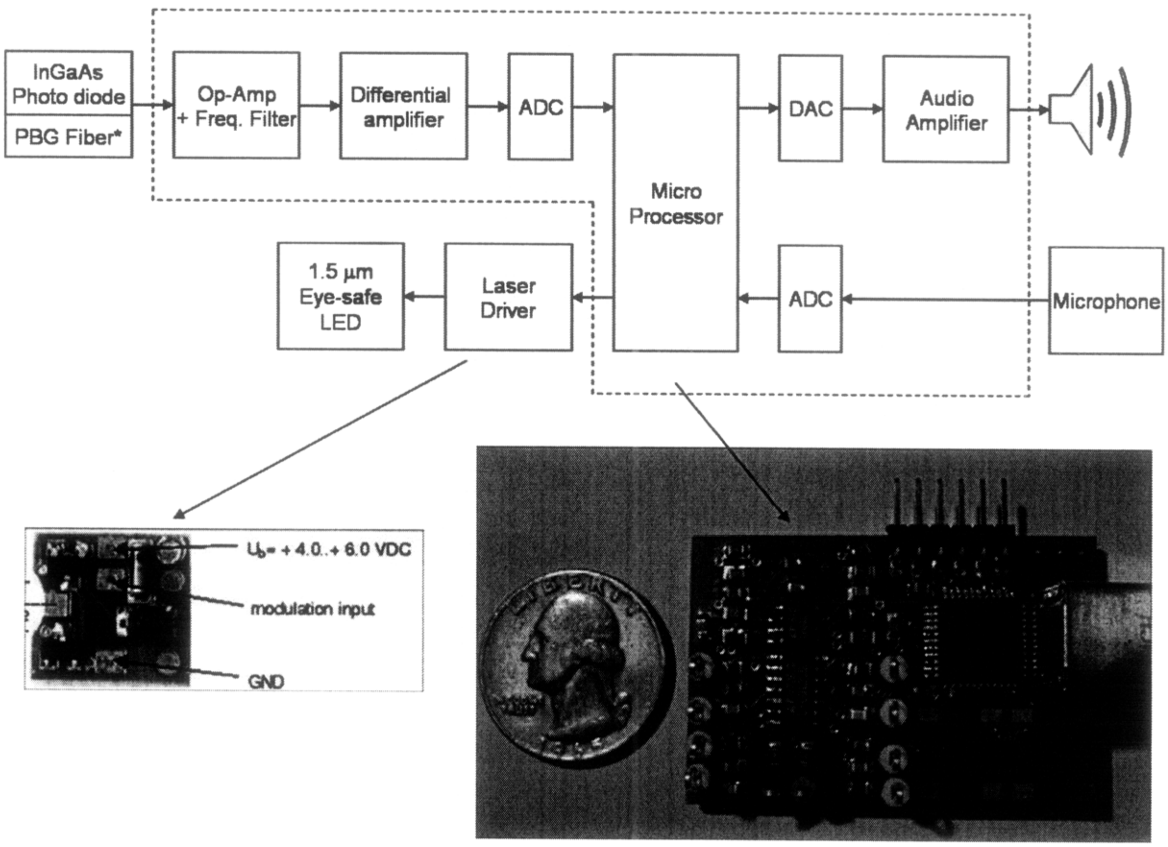

FIGURE 1-2. PREVIOUS, DIGITAL SYSTEM, CAPABLE OF A LOW DATA-RATE LINK. IMAGE COURTESY MATT SPENCER

1.3 PROPOSED WORK

Our aim in this work is to design a short to medium range directional two-way optical communications system that can be used by the United States military as an alternative to radio transmission of communication data. The system should be able to send voice intelligibly between two people over a useful range. The criteria for "useful range" here is a distance over which one would not be able to hear another person speaking softly, as in a covert operation. Teams in the Special Operations Forces often operate in groups of three, in the formation of an equilateral triangle with soldiers spaced 10 to 20 meters apart. Our aim is to get a range of at least 10 meters, and more if possible, with a 60 degree front and rear field of view to allow this kind of operation.

In this system, we transmit and receive data using infrared optical signals. The system should be eye-safe to a human retina. We investigate the use of both laser and narrow-angle LEDs as the transmission mechanism. We want to be able to transmit across a narrow angular range, and potentially have the system locate the receiver within this range to narrow it even further. We want to transmit voice digitally, and be able to send and receive packetized digital information. We also want to keep the system "fiber-ready"; while the development of optoelectronics is ongoing and it is uncertain whether or not they will be able to be incorporated into the final version of this system, we want to keep the communication system very low bandwidth and have adequate noise rejection in anticipation for using the fibers, which are restricted in their bandwidth and sensitivity.

Hence, even if we are using high-speed photodetectors in the final version of this system, we want to keep the bandwidth in the range of 10 KHz.

The system also must be portable. It must be able to be mounted unobtrusively on a soldier (via a standard military vest) so that the wearer can have full range of motion and operate in the field unobstructed. The system also must take portability into account in terms of power – the system must be able to operate independently of an outside power source for a reasonable period of time.

Finally, we investigate the properties of the new optoelectronic fiber semiconductor devices, test different methods for electrically contacting these fibers, evaluate their potential as optical receiving devices for this system, and design the system around their potential use in the future if they cannot be included in the system at their current stage of development. Our investigation of the properties of optoelectronic fibers is given in Chapter 2. The specific choices to attain the design goals for the system are investigated in detail in Chapter 3. Chapter 4 details the performance of the designed system and the outcomes of various methods for electrically contacting the fibers, and analyses the potential use of fibers in a communication system. Chapter 5 contains possible ideas for future work and a conclusion on this work.

CHAPTER 2

OPTOELECTRONIC FIBERS

2.1 OPERATION

Optoelectronic fibers are metal-insulator-semiconductor devices that, as their name suggests, have useful optical and electronic properties [3]. The fibers that are investigated in this work are drawn in a similar fashion to traditional optical fibers. Their operation is singularly different; in this context, the fibers are not used as a waveguide for light, but rather as a semiconductor device.

Modern electronic and optoelectronic devices derive their unique properties through the interaction of conductors, insulators and semiconductors. Traditionally, these devices are fabricated in a planar geometry as wafers. The principle of operation for optoelectronic fibers is the same as that of other semiconductor devices. The difference is in the geometry and method of fabrication – the device is created by drawing the metal, insulator, and semiconductor as a fiber.

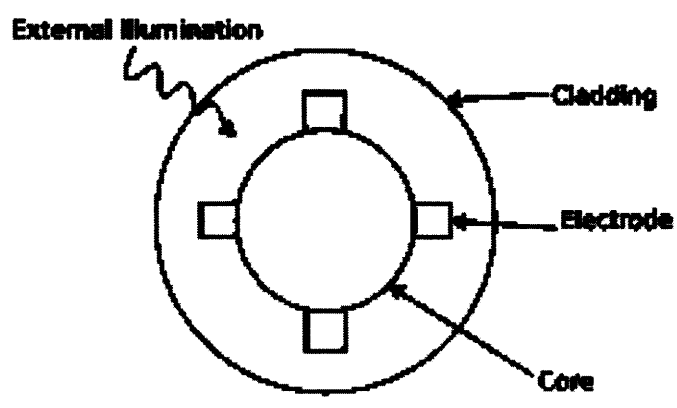

FIGURE 2-1. CROSS-SECTION DIAGRAM FOR OPTOELECTRONIC FIBER
DIAGRAM COURTESY MATT SPENCER

Figure 2-1 shows the cross section of a simple optoelectronic fiber with four conductors. The core of the fiber is composed of an amorphous semiconductor material (generally an arsenic selenide glass, As_2Se_3), and the cladding is composed of an insulator, polyethersulfone (PES). Sandwiched between the core and the cladding, tin conductors are drawn inside the fiber. The semiconductor, conductor, and insulator are chosen so that they can be formed into a pre-form of the desired geometry, drawn at the same temperature, and result in a fiber where the metal conductor maintains an intimate contact with the inner semiconductor layer. In theory, many kinds of devices can be created by drawing semiconductor devices as fibers, including photodetectors, transistors, light emitting diodes, and even lasers. In this work, we investigate the use of these optoelectronic fibers as photodetectors.

We can visualize the operation of an optoelectronic fiber photodetector as follows. An intrinsic semiconductor is a generally a poor conductor of electricity. When a photon with energy $h\nu$ greater than the band gap energy of the semiconductor material interacts with the core, an electron from the valence band of the semiconductor may be promoted into the conduction band. This results in the creation of charge carriers in the semiconductor – namely, the promoted electron acts as a negative charge carrier and the resultant "hole," or lack of electron in the valence band acts as an effective positive charge carrier. Thus, when incident light with high enough frequency strikes the semiconductor core of the fiber, the conductivity of the core increases because the number of charge carriers in the core is increased. The effective resistance between pairs of conductors in the fiber is thus decreased. This property can be used to detect light if two nearby conductors have a potential difference applied to them. When the fiber is illuminated, a current will flow between the biased conductors with current level proportional to the intensity of light.

There are some limitations of these optoelectronic fibers, some of which can be overcome by making modifications. The fibers' semiconductor material has a fairly high resistivity, even when illuminated. This means that optically excited currents are very small (in the order of picoamps). Additionally, even when the photodetector is not illuminated, there are still some free charge carriers in the semiconductor. This is because some charge electrons will possess enough energy to move from the valence to conduction bands due to thermal excitation (at any given temperature, some particles will have energy greater than the band gap as per the Maxwell-Boltzmann distribution, and this number will increase as temperature increases). The result of this effect is termed "dark current" – that is, current due to charge carriers that are not optically excited. The ratio between optically stimulated current and dark current in the fibers described above is fairly low, so even if the fiber signal is greatly amplified, the sensitivity of the fibers to illumination is still low. Finally, the high effective resistivity of the semiconductor means that the device has a large effective RC time constant, limiting the operational bandwidth of the fiber.

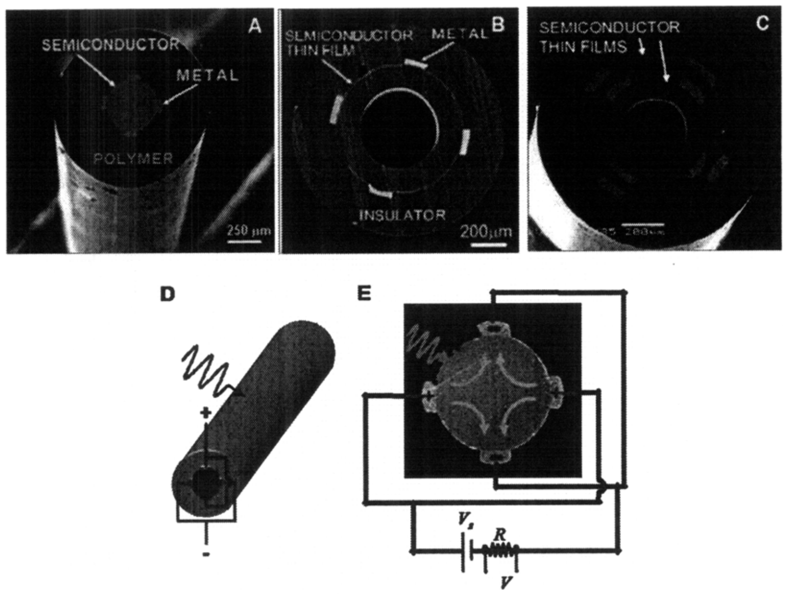

FIGURE 2-2. (A) CROSS-SECTION OF SIMPLE FOUR-CONDUCTOR OPTOELECTRONIC FIBER. (B) CROSS-SECTION OF THIN-FILM OPTOELECTRONIC FIBER. (C) CROSS-SECTION OF TWO LAYER THIN-FILM OPTOELECTRONIC FIBER. (D) MODEL FOR ILLUMINATED FIBER. (E) MODEL FOR CROSS SECTION OF ELECTRICALLY CONTACTED FIBER. IMAGE COURTESY YOEL FINK

There are several ways to improve the performance of an optoelectronic fiber photodetector. Figure 2-2 shows two variations on the basic fiber described in the beginning of this section. This variation, using thin films of semiconductor material, has been developed to reduce the volume of semiconductor material as much as possible while retaining the area available for illumination. The result is an optoelectronic fiber design with the same detector area as before but with much lower levels of dark current.

The thin film of semiconductor material provides enough thickness for interaction with incoming photons, and since it is still distributed throughout the entire fiber, the effective area of the photodetector is not changed. However, now that there is much less bulk semiconductor material, there are significantly fewer thermally excited charge carriers. The aim is to use only as much semiconductor as is needed for optical excitation, and to remove any superfluous material that can only provide thermally excited charge carriers. These thin film fibers have much lower dark current than the fibers described earlier, while maintaining the same level of optically excited current under illumination. The result is much greater sensitivity to light.

We can even include several separate layers of semiconductor material. A two-layer thin film fiber is shown in Figure 2-2. By adjusting the thicknesses of these layers and the type of semiconductor material used, we can design a fiber that is sensitive to a specific wavelength or multiple specific wavelengths of light

Another method of improving the characteristics of optoelectronic fibers is to reduce the effective resistance between conductors. This can be done in a number of ways. The number of conductors need not be four, nor must they be spaced evenly throughout the fiber. If we move pairs of conductors closer together, the effective resistance between them will be smaller. Additionally, if we lengthen the section of fiber we are using, the net resistance between leads will decrease because we are effectively adding resistance in parallel by lengthening the fiber. Finally, we can modify the structure of the semiconductor material itself and increase its conductivity. We do this by heating the fiber in an annealing oven so that the semiconductor material crystallizes.

The fibers that we have worked with in this project (both for developing a method of electrical contact and in evaluation of potential for use in a detection device) contain twenty closely-spaced conductors, are thin film, contain a polysulfone insulator and tin-zinc (SnZn) alloy conductors. The fiber uses a semiconductor thin-film layer based on selenium (Se97S). The fibers contain a layer of conductive polycarbonate between the conductors and semiconductor to ensure intimate contact. This geometry is slightly different than that described for the simpler case at the beginning of this chapter in that the semiconductor thin film is drawn outside the conductors. A scanning electron microscope image of the cross section of the fiber is given below.

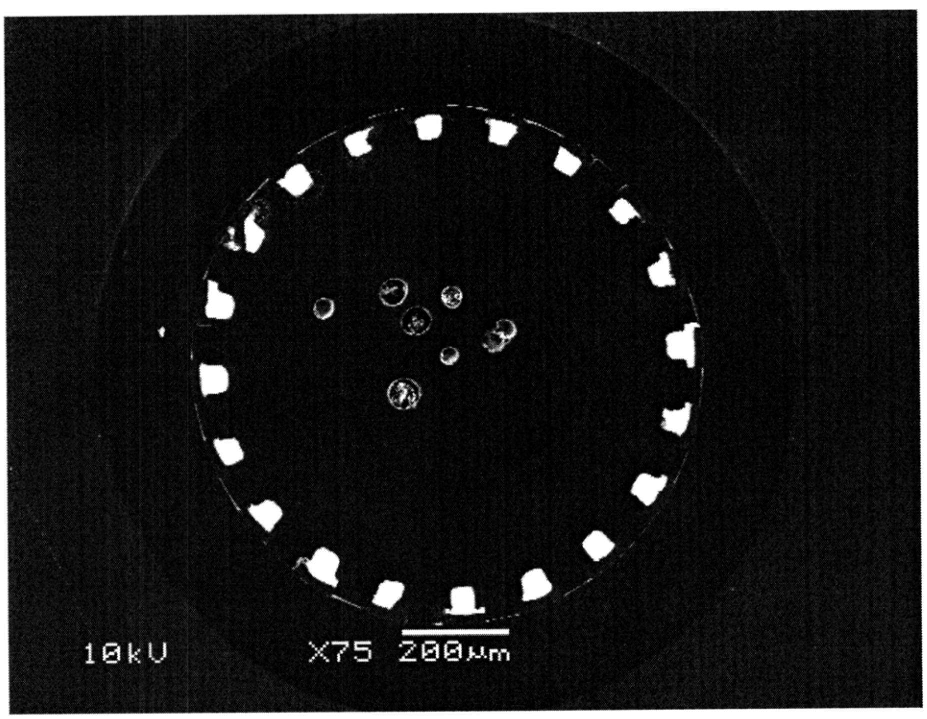

FIGURE 2-3. SEM CROSS-SECTION OF TWENTY-CONDUCTOR FIBER.
SEMS COURTESY OFER SHAPIRA

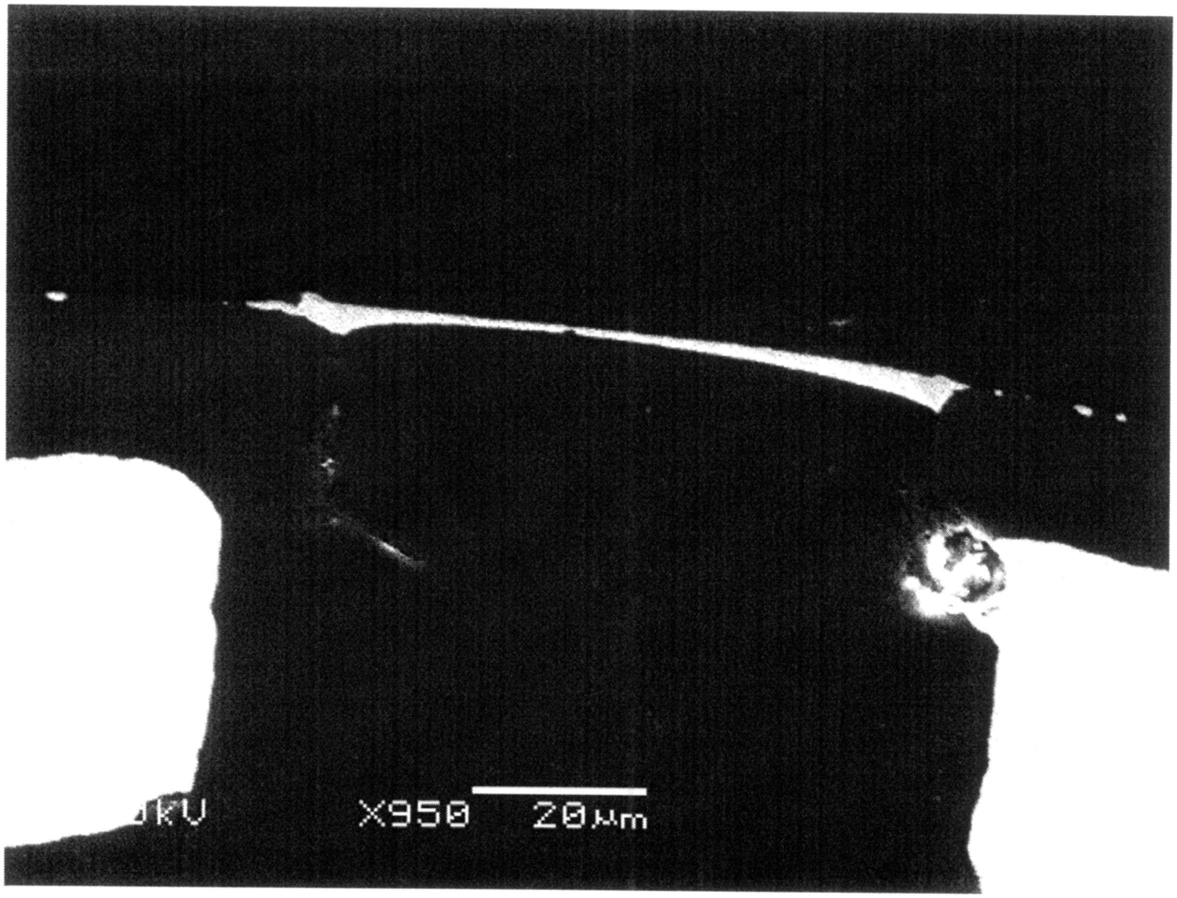

FIGURE 2-4. CLOSE-UP OF FIBER CONDUCTORS, SHOWING SEMICONDUCTOR THIN FILM AND CONDUCTIVE POLYCARBONATE.

2.2 MAKING ELECTRICAL CONTACT

One of the most challenging aspects of working with optoelectronic fibers is the problem of interfacing these devices with external circuitry. The feature sizes of the fibers can be as small as 100 nm. The metal conductors drawn through the fibers that we are using have a thickness and length of order 10 μm. Modern wafer-based semiconductor devices have feature sizes and metal contacts of sizes comparable to this and even much smaller, but semiconductor chip manufacturing and packaging is a mature technology that has been in development for decades. In contrast, the fibers used in this project are new devices, for which automated methods and sophisticated tools for processing and packaging have not been developed.

Currently, the most common method of contacting the fibers involves carefully slicing away cladding using a sharp razor blade while viewing the fiber under a microscope. A thin wire (#30) is wrapped around the section of fiber with the exposed conductor, and conductive silver paint is applied to create an electrical contact. Low temperature solder, such as bismuth-based solder, may be applied to the conductor or to the painted junction to add mechanical stability to the connection. Even with solder, the connection breaks if significant stress is placed on it. These joints are not as mechanically robust as a solder joint between, for example, a traditional through-hole or surface mount device and a circuit board.

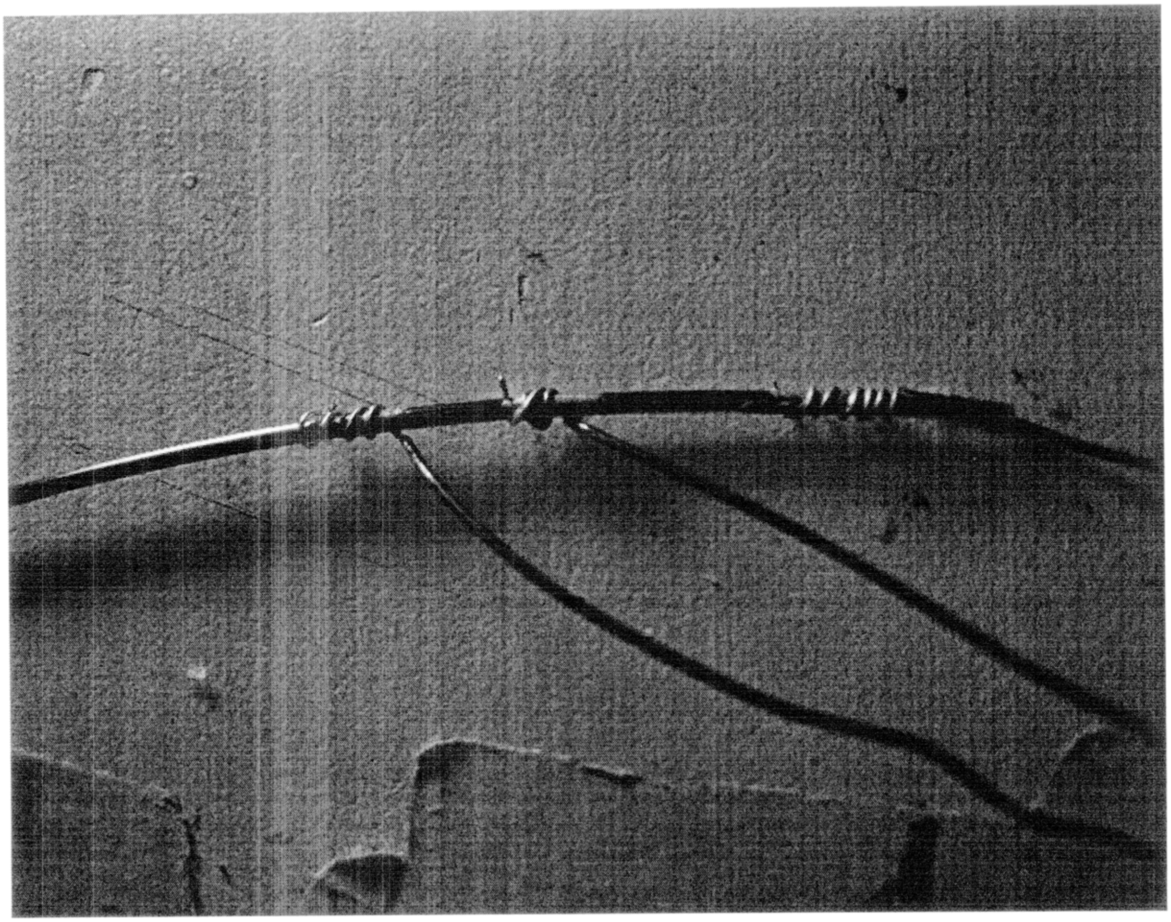

FIGURE 2-5. OPTOELECTRONIC FIBERS WITH CONDUCTORS CONTACTED. CLADDING HAS BEEN REMOVED, AND #30 WIRE IS CONTACTED TO THE CONDUCTORS WITH SILVER PAINT

The process described above is time-intensive and prone to failure due to the small width and thickness of the conductor. We attempt to electrically contact the twenty-conductor fiber, and try to evaluate and test easier and less-time intensive and failure prone methods of doing so. In this work, we evaluate the potential of a few different methods of connecting the fibers.

One method we use to contact the fibers involves using a Dremel rotary tool to mill away the cladding of the fiber. The principle is the same as the razor blade method described above, but the hope is that greater precision can be gained by milling away the cladding than by using a blade to cut it away. We attempt to use several different milling bits to try to expose a small enough area of cladding that only one conductor is contacted. Ideally, we want twenty points of contact, one for each conductor – then, we can take one set of ten conductors and connect it to ground, and apply a voltage bias to the other set of ten conductors we put a voltage bias on. If we interleave these two sets of ten conductors, we will have very narrow sections of semiconductor material. The low conductivity of these narrow sections will hopefully provide a good response to light.

We also evaluate the performance of the fibers with fewer than twenty points of contact – effectively, un-contacted conductors will assume a voltage bias between the voltage of contact fibers that surround it, so we will maintain the same ratio of dark current to light response with fewer points of contact, but will require a higher voltage bias on the contacted conductors to maintain the same level of current. If we are unable to contact all twenty conductors, we will maintain the same signal to noise ratio, but will produce lower net current for a given voltage bias. We also must take care that the conductors we do contact are spaced evenly around the fiber for angularly independent light response.

We also attempt to remove the cladding by using a solvent that will dissolve the polysulfone insulating layer of the fiber, but not the conductors. We use N,Ndimethylacetamide (NNDA) as the solvent, and evaluate the potential of using this as a quicker method of removing the cladding. Since this method will likely remove the cladding around the entire section of fiber exposed to it, we will need to disconnect some of the exposed conductors by cutting them under the microscope so that all the conductors are not shorted together. We can then just dip each exposed section of the fiber (we would expose one section on one side of the fiber and another section on the other side) into conductive silver paint. We cut ten conductors near one end (every other conductor) and ten conductors on the other end (the other set of "every other conductor"), to give us two independent contacts with interleaved conductors, providing a good response to light by maintaining minimum distance (and thus high conductivity) between conductors.

Another method we test involves connecting the fiber at the ends rather than from the side. We attempt to cover up some of the conductors with insulating epoxy, and then contact the remaining exposed fibers together with silver. The idea of which conductors we contact is similar to that described above – we short ten of the conductors together, so that if we go around the fiber, every other conductor is contacted (i.e., every pair of connected conductors has an epoxy-covered unconnected conductor between them). Then, on the other end of the fiber we cover the set of ten conductors that was shorted together on the first end with epoxy. We then connect the remaining ten conductors with silver. The result is two sets of ten conductors, which have minimum distance between them to maximize the fiber's sensitivity to light. One set of conductors is accessible from one end of the fiber, and the other set is accessible from the other end. We can improve our ability to isolate individual conductors on the cross-section by cutting our cross section at an angle, as shown in Figure 2-6. We still require the use of a microscope, and a very fine-tipped tool such as a syringe tip for placing the blobs of epoxy so that they only cover one conductor.

FIGURE 2-6. CROSS-SECTION OF FIBER CUT AT AN ANGLE TO AID IN ISOLATING THE CONDUCTORS FROM ONE ANOTHER.

We evaluate the potential for each of these methods and discuss their relative feasibility and reliability in Chapter 4.

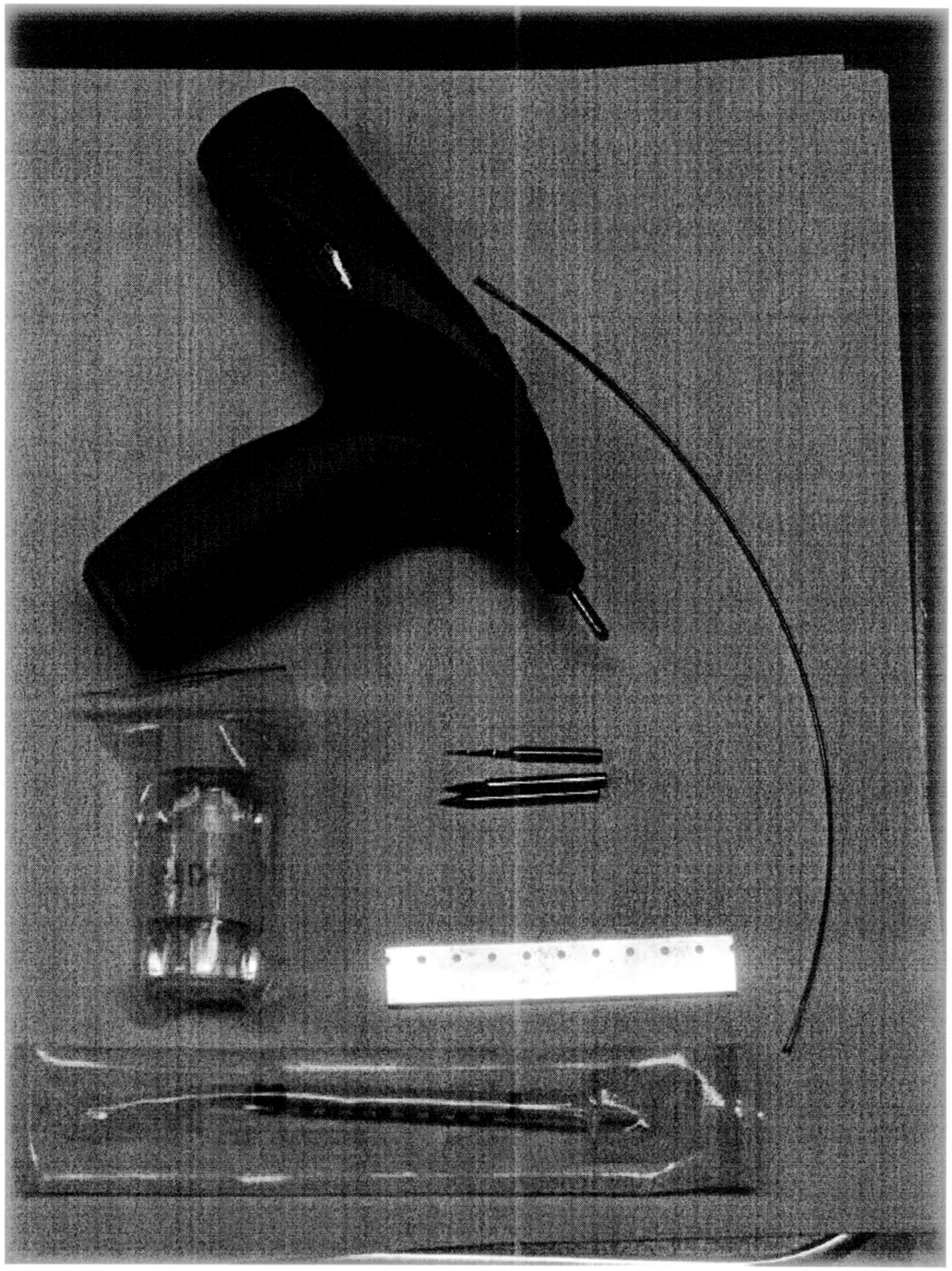

FIGURE 2-7. IMPLEMENTS USED TO CONTACT THE FIBERS. CLOCKWISE, FROM BOTTOM: SYRINGE TIP FOR PLACING EPOXY, NNDA SOLVENT, DREMEL TOOL, MICROSCOPIC MILLING BITS, AND RAZOR BLADE. ON THE RIGHT IS A FIBER WITH CRIMPED CONTACTS.

2.3 APPLICATIONS

The fibers investigated in this work play a promising role in the development of new optoelectronic devices. The primary application for them in a project like this is as a photodetecting device as a replacement of a traditional wafer-based semiconductor device.

Optoelectronic fibers work by the same principles of operation that traditional semiconductor devices do. They are composed of the same or similar materials, and they could fulfill the same roles. In principle we could construct other devices within a fiber besides photodetectors, such as diodes, transistors, or even emitters and lasers. The reason that the fibers deserve resources for further development are the possible advantages and unique roles that they can fill which are infeasible or expensive with traditional semiconductor devices.

Wafer-based fabrication results in semiconductor devices with a planar geometry. Optoelectronic devices (such as the traditional photodetectors we ultimately used in our communications system) are generally composed of a small semiconductor chip housed in a package. Fabrication of wafers is not cheap, so a large-area device, while possible, is very expensive. Optoelectronic fibers are manufactured in a similar manner to optical fibers – they are composed of heated plastic (or other ductile) material that can be drawn. This offers the possibility of fabricating large, one-dimensional geometries for semiconductor devices at a reasonable cost. As the drawing process becomes more reliable and fibers are able to be drawn thinner, this cost could drop to the same level as the cost of manufacturing synthetic threads such as nylon. This offers the possibility of weaving fabric that is composed of electronic or optoelectronic devices – truly "wearable" electronics. Applied to a wearable communication system like the one we are designing, this could mean that the vest itself would be the photodetector, or even (with the development of fiber-based transistors and logic) the entire electronic system.

An example of another interesting application that one-dimensional optical detectors can make possible is lens-less imaging [4]. An optoelectronic fiber acts as an integrating detector, so a single fiber cannot determine the location of light that hits it. An array of fibers, however, can provide information about the location of optical stimulation from the horizontal and vertical fiber in the ray that corresponds to where light entered the array. If we take this idea further, and use two arrays of fibers, we can get information about the vectors of light rays penetrating the detector. From this information, we can actually create an image without requiring a lens to focus all of the light onto a small planar detector (which is the method of operation of most imaging devices, including cameras and the human eye). We can even create a three-dimensional spherical array that can detect directional information of incoming light rays and create images from any direction, creating an effectively complete 360° field of view, something that cannot be done with a traditional lens-based device.

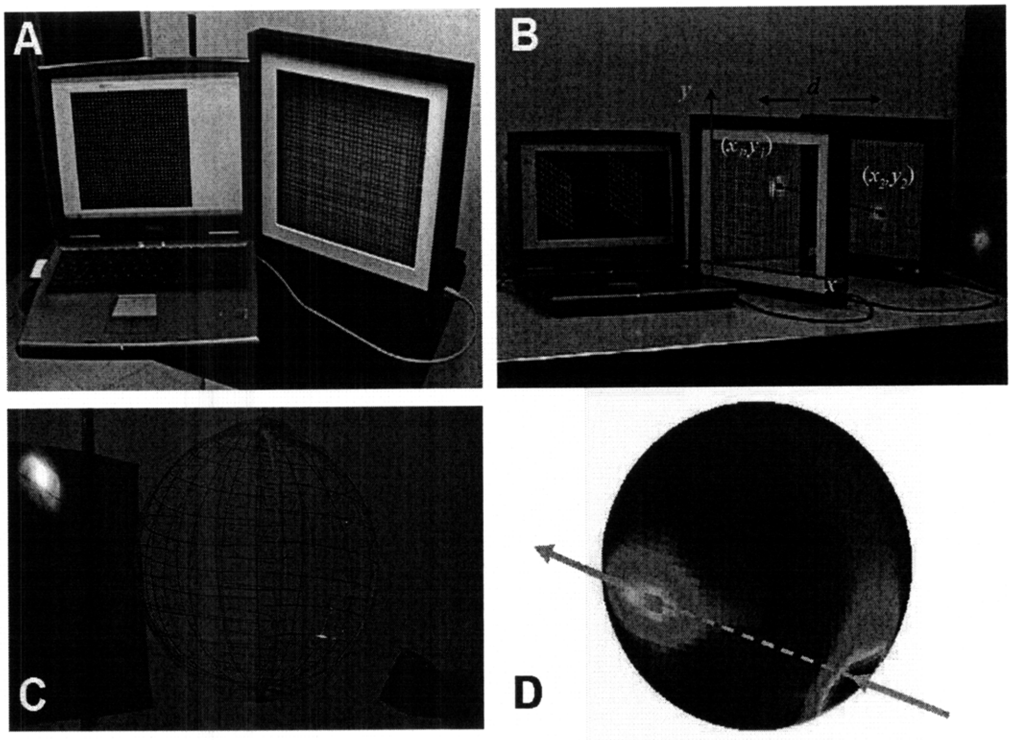

FIGURE 2-8. AN OPTOELECTRONIC FIBER ARRAY, AND TWO EXAMPLES OF A LENS-LESS IMAGING DEVICE THAT CAN DETECT THE DIRECTION OF INCOMING RAYS OF LIGHT. IMAGE COURTESY JERIMY ARNOLD

There are a number of other exciting applications for optoelectronic fibers. It is our hope that development of these devices continues, and that optoelectronic fibers become a widespread geometry for electronic and optoelectronic semiconductor devices.

CHAPTER 3

COMMUNICATION SYSTEM

3.1 OVERVIEW

In creating the system described in Chapter 1, we make a number of design decisions to satisfy the constraints and design specifications we are given. This section is broken up into parts that correspond to the different isolated modules that were designed independently – the transmitter, the receiver, and the system architecture. This project was completed as a joint effort with two other Masters students: Danny Perry was responsible for the system code and voice compression and digitization algorithm, as well as much of the design for the system board. Paul Yang was responsible for analog design of the power supply unit and the mechanical design for the transmitter module as well as the final layout of that circuit. This author's responsibilities included initial design of the transmitter scheme, including choice of emitting device and wavelength, as well as design, test, and layout for the receiver module. This thesis write-up makes an attempt to accurately document the design of the entire system, with a focus on the design choices of the transmitter and the design and layout of the receiver. For complete details of the working system, the author encourages the reader to also consult Danny Perry and Paul Yang's theses, which are included among the references [5] [6].

The overall system is set up as follows: the "system interface module" contains the audio subsystem (microphone, headphones, audio amplifiers for the microphone and headset, and analog-digital converter / codec), power supply unit, and digital signal processor. It takes in input from the receiver module, and sends output to the transmitter module. The transmitter module takes in serial input from the system interface and produces high-current pulses to drive the infrared light emitting diodes (IREDs). The receiver module receives pulses optically, produces a signal pulse, and converts these pulses to a serial bitstream to input to the system interface module. The entire system is portable, and is integrated and embedded into a military vest.

FIGURE 3-1. THE CONNECTED COMMUNICATIONS SYSTEM, BEFORE INTEGRATION INTO VEST. CLOCKWISE, FROM TOP: TRANSMITTER MODULE ATTACHED TO HEADBAND, RECEIVER MODULE IN SHIELDED ENCLOSURE WITH SHIELDED PHOTODIODE VISIBLE, RECEIVER WITHOUT ENCLOSURE, POWER SUPPLY UNIT COVERED IN PROTECTIVE HEAT-SHRINK, BATTERY PACK, ON/OFF BUTTONS, SYSTEM INTERFACE BOARD, AUDIO HEADSET.

3.2 SYSTEM INTERFACE MODULE

The system interface "module" is physically realized as a number of separate pieces of equipment: the batteries and power supply which power the system, the connection scheme between the boards, the user's interface with the system (headphone, microphone, and on/off buttons), and the system board which controls the flow of data from the inputs (the microphone and the receiver module) to the outputs (the headphones and the transmitter module).

The power supply board provides power to the rest of the system. The supply is sourced by a battery pack containing three AA 1.5 volt batteries in series. The 4.5 volts (actually somewhat higher when the batteries are fully charged – 4.8 volts for alkaline batteries and 5.4 volts for lithium cell batteries) power the logic of the power supply board, and are also sent to switched voltage regulators which provide the supply voltage for the rest of the board. We chose switched voltage regulators rather than linear regulators to prevent unnecessary power draw from the batteries, thus improving battery life and cutting down on heat produced by the power supply. Two LM3668 switched voltage buck-boost converters are used to produce a stable 3.3-volt rail for the system board logic and a stable 5 volt rail. The 5 volt rail is connected to the system board (which supplies the receiver, which requires 5 volts for its amplifier circuitry). The 5-volt rail is also directly connected to the transmitter module (so that the transmitter does not contaminate the rail on the system board). The switching frequency of this converter is in the 2 MHz range, and the rails are sent across a second order LC filter before they connect to the transmitter, system board, and receivers. The filters keep any ripple on the supply rails low, and the high frequency of switching does not interfere with the low-bandwidth operation of the transmission and receiving boards. The LM2664 converter uses a flying capacitor to create a negative 5-volt rail for operation of the dual-rail amplifiers on the receiver board. The power supply board is connected to two user-accessible buttons, to turn the system on and off. The supply is connected to the system board (+5, ground, -5, and +3.3) and to the transmitter (+5 and ground).

The system board contains the audio subsystem and the digital signal processor that controls the operation of the system. A standard, 3.5 mm TRS connector connects the microphone to the system. The speech signal is amplified and filtered by an RC op amp filter. Frequencies above 4 KHz are filtered – human speech is easily understandable and does not contain important information above this frequency. The audio signal is sampled at 8 KHz, so any frequencies above 4 KHz only lead to aliasing, hence they are removed.

The filtered audio signal is sent to the Wolfson WM8510 codec chip. This device serves the role of analog-digital converter, converting the audio to a 16-bit signal sampled at 8 KHz. It also digitally high-pass filters the signal to remove frequencies below 100 Hz (which are not needed for speech, can't be reproduced well by portable speakers, and contain the notorious 60 Hz hum if the system is used in an environment with noise from power lines). The digitized audio signal is sent from the codec to the digital signal processor across a serial link.

A digital signal processor, the Microchip dsPIC 33FJ256GP710 was chosen instead of the PIC used in the previous system. This device was chosen because it has a fast (8 MHz) instruction clock, a decent amount of memory on-chip and more processing power than the previous PIC microcontroller used. The dsPIC compresses the audio signal using the open-source Speex voice compression library. The compression scheme allows 20 milliseconds of voice data to be encoded into 160 bits (including error correction and header information, this results in 240 bit packets). Since 20 milliseconds of uncompressed audio contains 160 16-bit samples, this effectively means our compression ratio is 16:1. We want to minimize the bandwidth of the system in anticipation of using low bandwidth fiber receivers, so we choose to transmit at a rate of 14.5 kbps (the minimum possible bandwidth would be 240 bits / 20 ms = 12 kbps, but we want to provide some processing time for the dsPIC to handle encoding and decoding speech data).

The digital voice packets are sent asynchronously (since it is infeasible to transmit a clock signal along with the audio data). Packets are created according to the universal asynchronous receiver/transmitter (UART) system. A packet start is indicated with a two-byte header. This is followed by 20 bytes of compressed speech data. Finally, a two byte cyclic redundancy check based upon the CCITT standard is calculated from the speech data and appended to the end of the packet. The CRC is used to detect errors in transmission – since the Speex codec will produce unpredictable results from corrupt packets, if a received packet's speech data does not match up with its CRC, the packet is dropped and a null value is sent to the codec.

The UART packets are sent to the transmitter. The system board is connected to the transmitter by a three-wire interface: a clock signal, a signal to select which IRED to turn on, and a bit stream signal. (The transmitter connects directly to power and ground from the power supply). Initially, each transmitting IRED required a unique signal line (for the possibility of narrowing the angular range of the system by only using some of the IREDs for transmission). Each transmitter has fourteen IREDs, so this parallel scheme became cumbersome, since it would require fourteen separate wires. For the final version, the packets are sent serially to the transmitter, and a shift register in the transmitter module allows for different packets to be mapped to individual IREDs. Ultimately, this functionality was not implemented, and all of the IREDs transmit the same signal.

The system board also connects to the receiver by a five-wire interface: +5 volts, -5 volts, ground, and two signal lines for the two channels that each receiver board contains. The receiver produces a serial bitstream. Since the system uses two receivers, with the possibility of having multiple channels per receiver, each receiver is polled over a short period of time, and if a signal exists on one, the receiver data is sent to the dsPIC via a multiplexor. The dsPIC does the CRC check on the received data, and if the data is OK it decodes it using Speex and sends the decoded digital audio to the codec. The codec acts as a digital-to-analog converter, and produces an analog audio output. While the codec is capable of driving 16-32 Ω headphones, we add an amplifier stage to provide gain to the headphone signal. The codec digitally boosts the signal to as high a level as possible without clipping, so that the user can adjust the volume using the headphone cable's built in potentiometer volume control.

The system is set up so that transmission and reception never occur at the same time. The reasoning for this is described in Section 3.5, along with a description of a voice detection scheme that was added to the dsPIC to make this possible. A brief overview of the dsPIC software layer is as follows: the system samples the microphone. If voice is present, it encodes the samples and transmits a packet, while simultaneously sending this audio to the headphones (thus, the user hears himself speaking, providing feedback that the voice is being detected and transmitted). Otherwise, the system polls the receiver modules. If a receiver channel is receiving data, the dsPIC determines if the data is a valid packet (by checking the CRC). If the packet is valid, the system decodes the packet and sends the audio output to the headphones. If the packet is not valid or if no data is being received, the system goes back to detecting voice on the microphone.

After testing, the system board was aggressively miniaturized from the original dsPIC evaluation board. See Figure 3-2 on the following page.

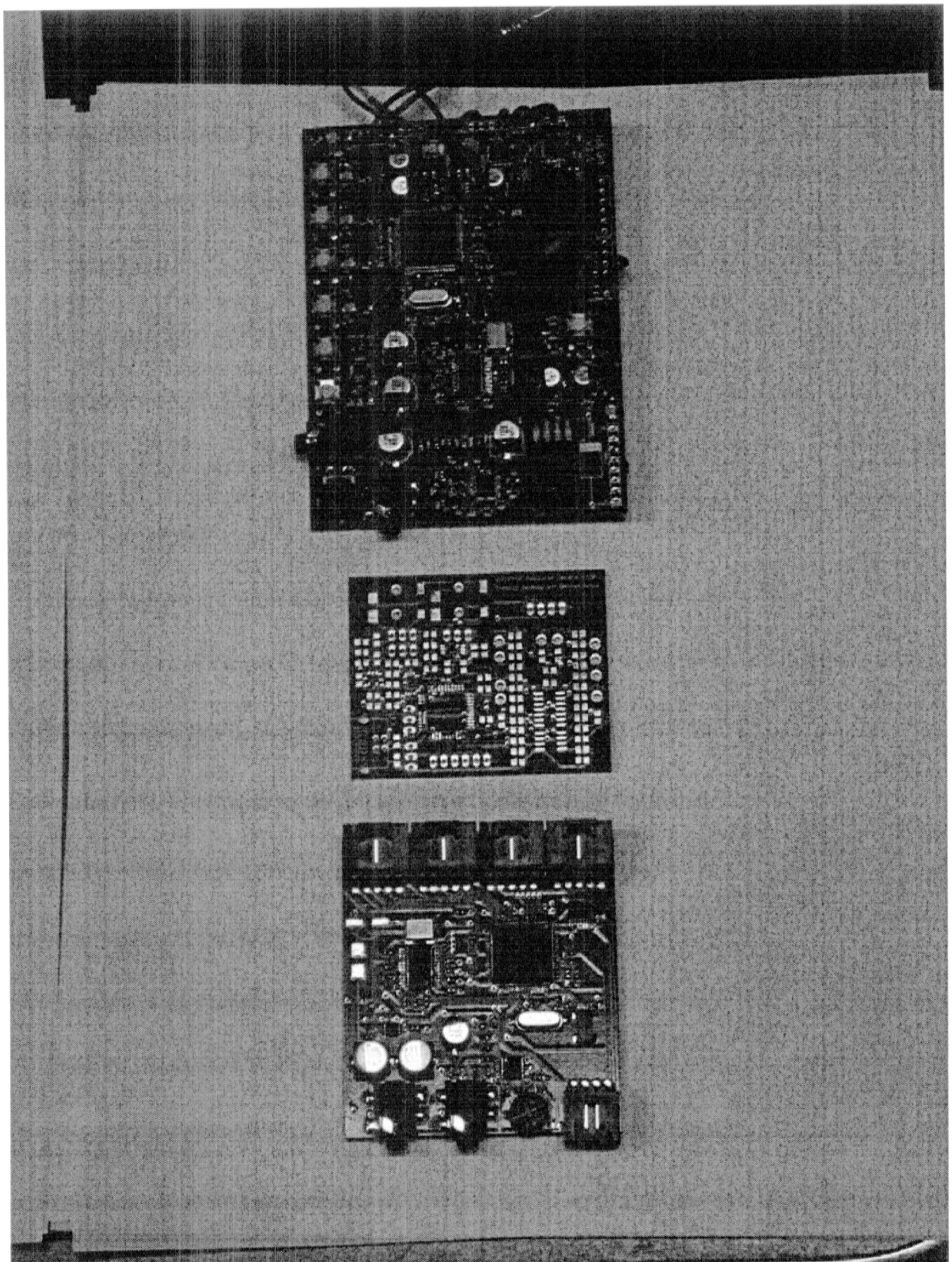

FIGURE 3-2. FROM TOP TO BOTTOM: THE dsPIC EVALUATION BOARD, THE PIC BOARD FROM THE PREVIOUS, ONE-WAY SYSTEM, AND THE FINAL, MINIATURIZED SYSTEM BOARD.

3.3 TRANSMITTER MODULE

The first design decision for the transmitter module was to choose an operating frequency for transmission. We chose to use 850 nm devices for transmission of optical data. We chose an infrared wavelength so that the system would not be visible, and we chose a wavelength of 850 nm because power-efficient devices are widely available in this part of the spectrum. For the previous system, 1550 laser light was used. Since this system uses narrow angle IREDs which output less power and spread it over a wider area than a diode laser, the 850 nm diodes are eye safe (although 850 nm laser light would not be).

We use the Osram SFH 4550 infrared emitting diode as our transmitter because of its low half-power viewing angle (+/- 3 degrees) ability to be pulsed with large amounts of current, and high output power (radiant intensity of approximately 5000 mW/sr within the viewing angle when pulsed with 1 amp) [7].

To calculate received power at 20 m, we calculate the radiant intensity in terms of area at 20 meters, which is $(5000 \text{ mW/sr})\cdot(4\cdot\pi \text{ sr}/(4\cdot\pi\cdot(20 \text{ m})^2 \text{ m}^2) = 125 \text{ mW/m}^2$.

For a photodiode (technically not part of the transmitter module, but relevant to this discussion), we chose the Vishay TESP5700. This device has a very wide (120 degree) half-power viewing angle because it has a hemispherical lens mounted on the package. It is sensitive to 850 nm, and has an effective area of $3\cdot10^{-6}$ m^2 [8].

Using our power density calculation for our transmitter diode, our received power is around 375 nW. The photodiode has a response of approximately 0.57 A/W at 870 nm (and similar response at 850 nm). So, our photocurrent response at this distance to our pulsed optical signal will be approximately $375 \text{ nW} \cdot 0.57 \text{ A/W} \approx 210 \text{ nA}$. The reverse dark current for this photodiode is rated as 1-10 nA, so our signal should be detectable at 20 meters using the photodiode and IRED that we have chosen.

A large transmission distance in this setup depends upon being able to drive a large current through the IREDs. The average power dissipated by these devices must remain low or the IREDs will be damaged – thus, we need to drive the large current through the IRED as very low duty cycle pulses. We convert our bit stream to a serial signal of pulses sent from the system board at the bitrate of the system (14.5 kbps). A pulse corresponds to a "1" and a missing pulse corresponds to a "0".

A simple solution for driving the IREDs is to use a power MOSFET device to act as a switch to allow current to flow through the device. We have a power MOSFET with source connected to ground, gate connected to our signal input line, and the drain connected to our IRED. We limit the current pulses to 1.2 A by using a small resistor in series with the IRED. This solution wastes quite a bit of power – the voltage drop of the IRED is approximately 1 V, so most of the power to the transmitter is getting dissipated by the resistor and being wasted. Optimizing the driving voltage to be close to the diode voltage (or voltages, if we string a few in series) helps to reduce power wasted in the resistors, but the forward voltage of an LED varies from device to device, so we cannot just pick a voltage value that will produce exactly the amount of intensity we would like on each diode, since the same voltage could produce significantly different currents through different devices.

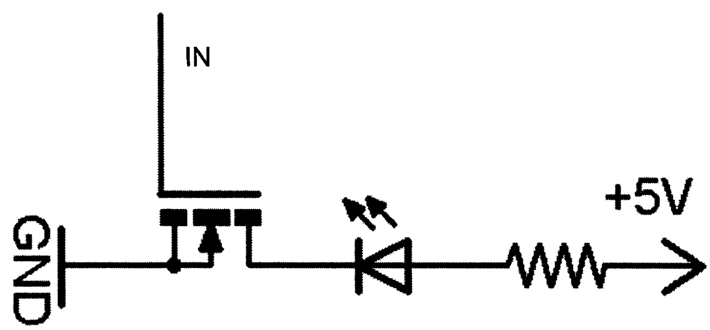

FIGURE 3-3. IRED DRIVER.

A more efficient solution is to regulate the voltage across the LED using a buck converter. A small current sense resistor in series with the LED can have its voltage fed back to the buck converter, stabilizing the current through the LED to the desired value. While ideally this is very efficient, it is difficult to find a buck converter scheme that can handle modulating the LED so that it can be used as a transmitting device at a reasonable bandwidth. These problems are probably surmountable given more development, but the buck converter transmitter is not implemented in this system. (The power board for the entire system, on the other hand, does use a switched power supply to produce the voltage rails required for the system more efficiently than a linear supply. This is discussed in Chapter 3.2). A prototype of a buck converter transmitter was assembled that can regulate the voltage across an LED, but it cannot switch the LED on and off faster than tens of times per second.

The IREDs for the transmitter are mounted in a housing that will be worn as a headband. Since it is intuitive to point one's head in the direction one is speaking, having the transmitter mounted on the head makes the IREDs accessible and easy to aim from many positions. Each transmitter module is composed of 14 IREDs, angled with precision so that a 60 degree range is covered within the viewing angles of the IREDs. The devices are also angled to give a vertical range of approximately 10 degrees. Each headband contains two transmitter housings – one on the front, and one on the rear, to allow the user to communicate with people both in front and behind, as described in Chapter 1. Since the 850 nm IREDs emit a very dull visible cherry glow when pulsed, the housings are covered by an infrared plastic filter. A very dim glow is still visible from behind the filter, but it is difficult to discern even in a dark environment unless the IREDs are stared into directly.

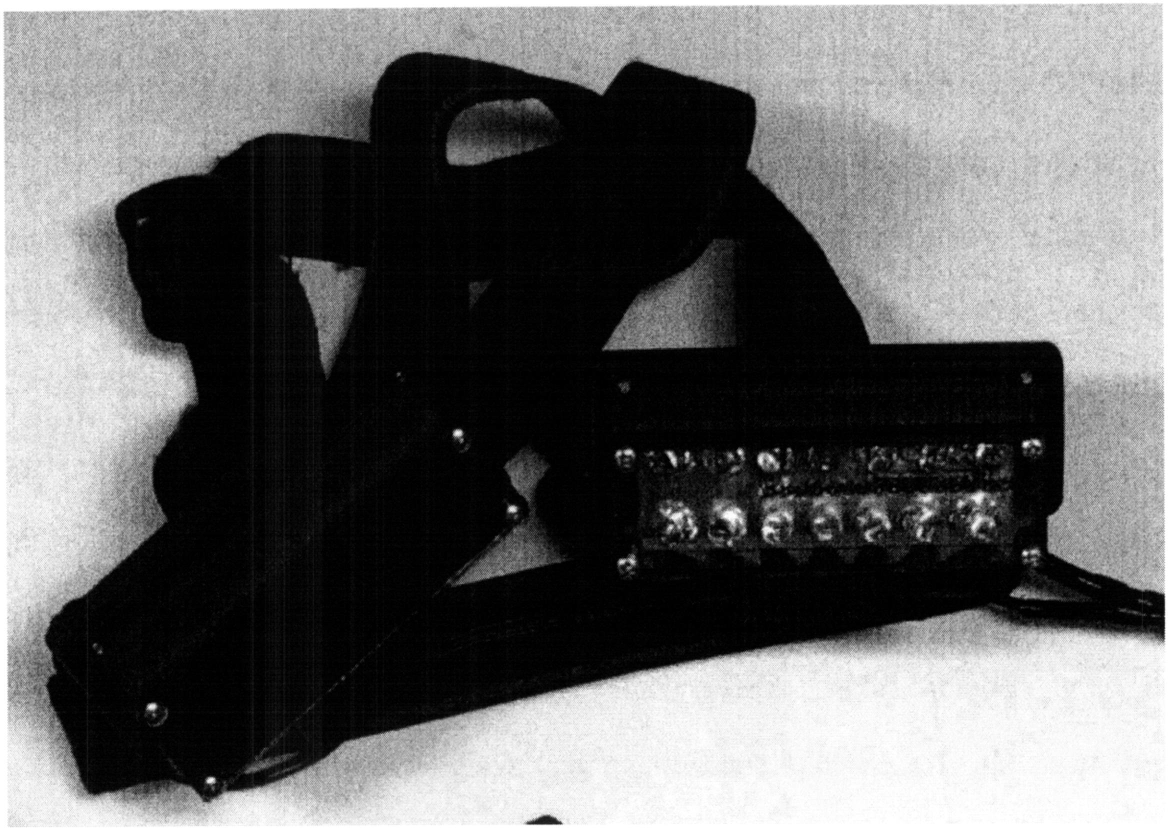

FIGURE 3-4. TRANSMITTER MODULE ON HEADBAND (WITH IR FILTER ON LEFT, WITHOUT FILTER ON RIGHT).

3.4 RECEIVER MODULE

The receiver module consists of four stages. First, the optical signal must be detected and converted into an electrical signal, photocurrent. Secondly, this photocurrent must be converted into a voltage and the useful part of the signal (the pulses which we are trying to detect) must be amplified. Thirdly, these amplified pulses need to be detected above the noise floor. Finally, the pulses must be converted into a digital signal, or in other words, the 1 μs pulses must be converted into bit-length pulses in such a way that the resulting output of the receiver is a serial bit stream with logic high corresponding to a detected pulse and logic low corresponding to a missing pulse.

Section 3.3 describes the reasoning behind our choice of photodiode – its specifications match our design goals. The photodiode is also fairly high bandwidth, although since we are designing the system around the eventuality of using low-bandwidth detectors, we do not capitalize on this.

There are two modes of operation for a photodiode to be used as a light sensor: the photoconductive mode and the photovoltaic mode [9]. In photoconductive mode, the photodiode is reverse biased, and the level of reverse current is measured. In photovoltaic mode, the photodiode is left unbiased. In photoconductive mode, the photodiode is capable of higher speed operation than in photovoltaic mode. This is because when the photodiode is put under reverse bias, the depletion region at the PN junction in the device becomes wider. Since capacitance is inversely proportional to the distance between the charge sheets, the wider depletion layer results in a lower capacitance, and thus a higher bandwidth device. The disadvantage of photoconductive mode is that the increased depletion width results in a higher level of dark current than in photovoltaic mode.

For this application, since we want to maximize sensitivity and we are operating at a low bandwidth, photovoltaic mode makes sense. However, we are designing this system with the future use of optoelectronic fibers in mind. Optoelectronic photodetecting fibers (at least at this stage of development) are not PN junction devices – they are simply composed of a layer of intrinsic semiconductor whose conductivity changes when under illumination. Thus, biasing the fiber is necessary for its operation. We create two amplifier channels on each board. One channel has an unbiased input, for use with the photodiode detector, and the other channel has a negative 5-volt bias, and is compatible with both the photodiodes and with fibers.

The photodiode is best modeled as a current source with current level changing in proportion to optical power received. Since we need a voltage signal to work with the rest of the system, we must somehow convert this small current signal into a voltage. We do this by using a transimpedance amplifier.

A transimpedance amplifier in its simplest form is simply a resistor. However, there are a number of drawbacks to simply driving a resistor with the photodiode and measuring the voltage across it. A large resistance is required to produce a significant amount of gain, but this also creates a large amount of noise and restricts the bandwidth by creating a large RC time constant with the junction capacitance of the photodiode. A smaller resistance will produce less noise and have better bandwidth, at the cost of low gain.

A better solution can be realized by operating an op-amp with negative feedback. The photodiode is placed at the negative input of the op-amp. For this setup, we chose the AD825 high speed JFET op amp. We chose this device for its low input offset and input bias current. The impedance of the path from output to input is called the *transimpedance gain*, and will be the ratio between the input current and the output voltage of the amplifier. In the simplest case, we use a resistor for feedback. The intrinsic capacitance of the photodiode can cause instability and oscillations if we do this. We also want to limit which frequencies we give gain to – we only want to amplify the 1 μs pulses. One solution is to have a feedback path with high impedance for the frequency we want to amplify. In this case, 500 KHz corresponds to the first Fourier component of a 1 μs pulse, so we want maximum transimpedance gain at this frequency. So, we choose an inductor and capacitor such that $(2\cdot\pi\cdot\text{sqrt}(LC))^{-1}$ is approximately 500 KHz. We choose an inductor (18 μH) with self resonance (that is, its parasitic parallel capacitance results in a resonance of) near 500 KHz, and add a 5 pF capacitor in parallel with it to get the desired frequency and provide stability to the system. We also place a 50 KΩ resistor in parallel to limit the maximum transimpedance gain – if the gain peaks too high at 500 KHz we will get oscillations and instability. (A different solution for pulse amplification will be needed for the fibers. Since fiber bandwidth is still approaching the 10 KHz range, in a system like this the fiber would not be able to resolve a pulse, but instead would result in a saw-tooth response with slow decay. We could detect the rising edge of this response.)

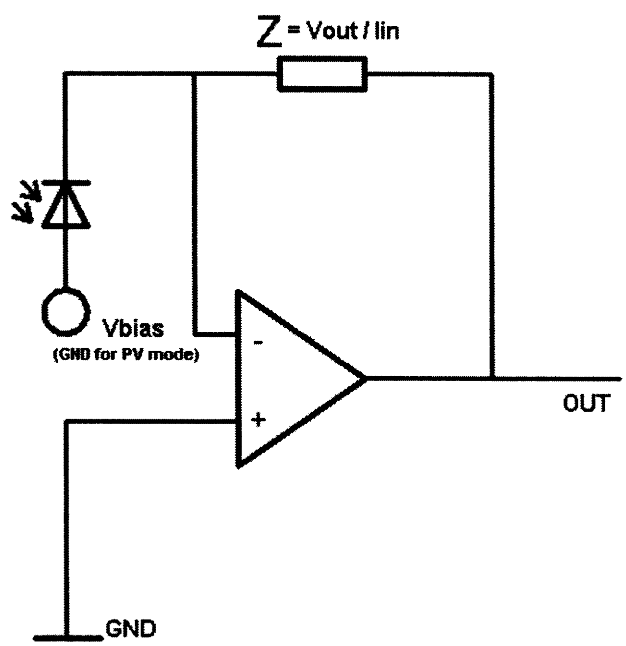

FIGURE 3-5. TRANSIMPEDANCE AMPLIFIER. IMPEDANCE Z IS THE TRANSIMPEDANCE GAIN

Since we limited the gain of the transimpedance stage with the resistor, we use a second stage amplifier to provide more gain to the system. We use the LM6171 low-distortion amplifier for its high speed and gain-bandwidth product. The gain of this stage is 50, and we include a small low-pass filter to attenuate high-frequency noise that made it through the transimpedance stage.

To create logic level pulses to correspond to detected pulses, we use an LM311 comparator setup with hysteresis. The inductor in the feedback path of the first transimpedance amplifier effectively blocks the DC component of the photocurrent (ambient light), and the output of the gain stage is capacitively coupled to the comparator to remove any remaining voltage bias on the signal. The signal is centered at 0 V, and the detected pulses go both positive and negative (since the transimpedance amplifier output gives so much gain to the fundamental frequency of the pulse, we get a waveform that corresponds to one period of a sine wave at 500 KHz; see Chapter 4 for oscilloscope traces). We measure the noise level to be approximately +/- 30 mV at the output of the gain stage, so we set a hysteresis band of width +/- 50 mV centered at 0 V. A pulse will be detected whenever it exceeds 50 mV in magnitude, and the comparator will output a logic level pulse. (The comparator's output is actually inverted – it produces 5 V when not triggered, and 0 V when it detects a pulse, as can be seen in the traces in Chapter 4. This does not matter, since the circuit that converts the pulses into bit-length pulses operates by detecting edges.)

Finally, the logic level pulses are sent to the 74LS123 retriggerable monostable multivibrator. When the multivibrator detects an edge on the comparator output, it outputs a logic level high for one bit-length (approximately 73 μs). This output is sent to the system board, where it is sampled and decoded into audio data.

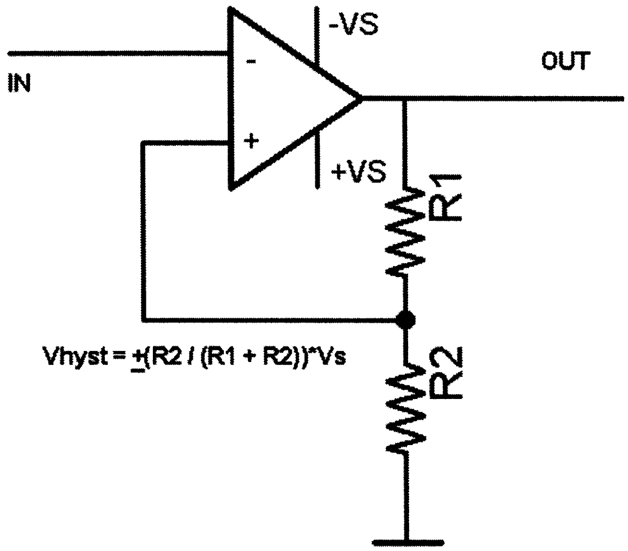

FIGURE 3-6. ZERO-CENTERED COMPARATOR WITH HYSTERESIS.

Shielding is very important for reliable operation of the receiver module. The photodiode input to the transimpedance amplifier is especially susceptible to noise, so the photodiode leads must be well shielded. We wrap the leads of the photodiode in copper tape, and enclose the entire receiver module in a tin metal container (we ground the foil and the container). The following figures show the final receiver board and its enclosure. The enclosure with a shielded photodiode connected can be seen in Figure 3-1 in the system overview section.

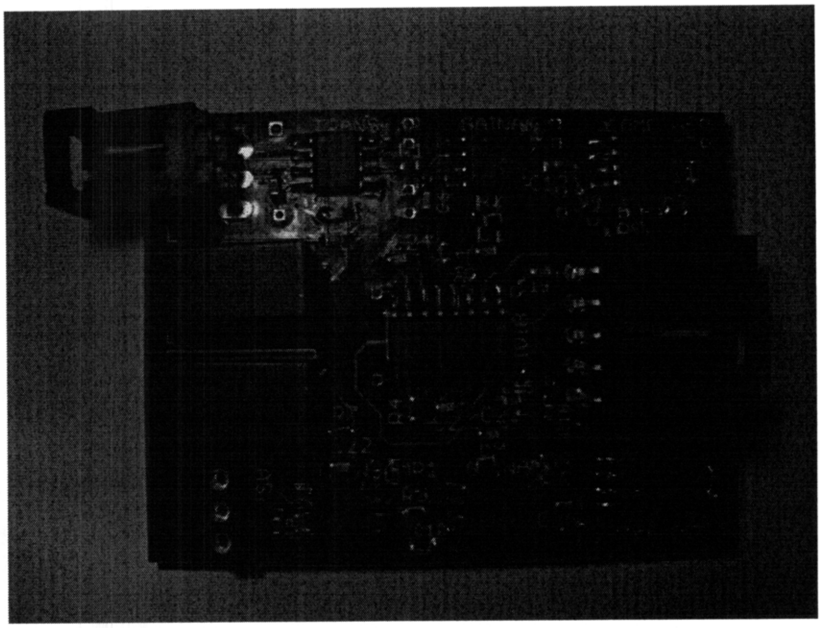

FIGURE 3-7. RECEIVER BOARD.

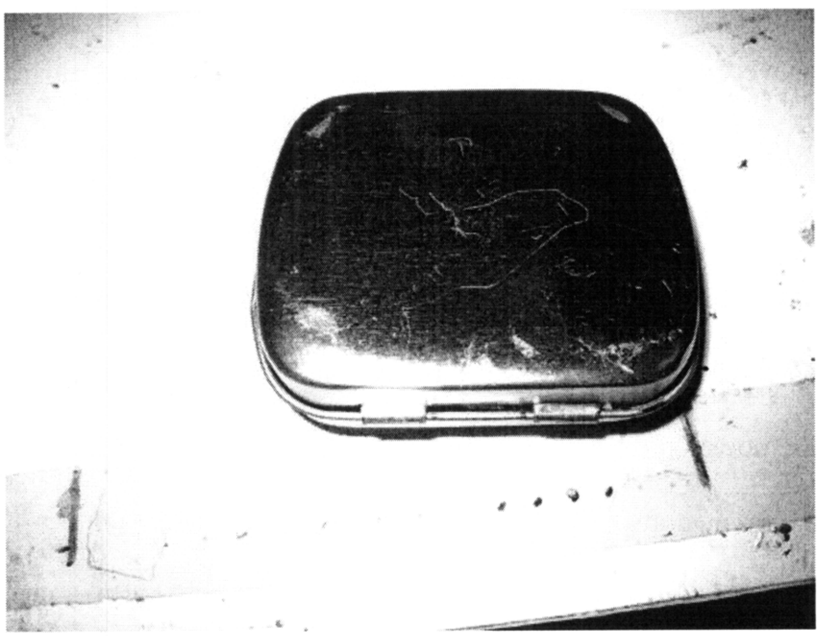

FIGURE 3-8. METAL RECEIVER ENCLOSURE.

3.5 System Integration

The entire system, aside from the transmitter, is designed to be fully integrated into a military vest. Velcro patches were sewn in to the inside surface of the vest, and the power module, battery pack, on/off buttons, system board, and receiver module were all mounted inconspicuously onto the inside of the vest in locations where they are neither noticeable nor interfere with the performance of the vest (for example, the internal housings for armor plates, etc). An external connector for the headphone and microphone are available at the side of the vest, and all the wiring (aside from wiring to the transmitter) is zip-tied and kept hidden inside the vest. Each of the boards (aside from the receiver) was wrapped in foam and heat shrink to protect the components, and Velcro patches were glued directly to the outside of these heat-shrink board "enclosures". Velcro fasteners were used so that the boards would be stably mounted inside the vest, but still could be easily removed for debugging purposes. The boards are connected to one another via Molex connectors, which carry both signal and power to each module. The transmitter module receives power directly from the power supply board, while other components are powered through connections to the system board. The reason for this is that the large current draw of the transmitter contaminates the 5 volt rail of the system board if it is connected directly to it. Each vest has one system board, battery pack, and power supply board, mounted inconspicuously in inserts on the back and side of the vest, one transmitter harness worn on the head (containing two transmitter enclosures, one on the front and one on the rear), two receiver boards and photodiodes (one on the front chest, one on the rear back), and two buttons (on/off) mounted on the front of the vest and accessible through the fabric.

The receiver has its own shielded enclosure, consisting of a small tin container. We considered replacing the tin with a secure wrapping of conductive copper tape to reduce thickness, but found that completely shielding the connection to the photodiode with this setup proved problematic. The metal enclosure is approximately ½ inches at its thickest point, but is still not noticeable when wearing the vest since the vest material is thick and rather sturdy in the chest and back areas where the receivers are mounted. The photodiode leads are shielded, and protrude through the vest. The leads and the neck of the photodiode are sewn against the fabric to prevent damage to the photodiode leads and shielding and to keep the device in a sturdy position on the vest. For the demonstration of this system, we used the Plantronics .audio 650 headset. The system is compatible with any standard headphone and microphone with 3.5 mm TRS connector. The model of headset we used was chosen for its comfort and voice quality, but it is large and bulky. For a more inconspicuous system, an incorporated headset/microphone such as those used commonly for cellular phones could be used instead.

One problem that arose upon connecting the modules of the system together was interference from the transmitter driving line to the receiver photodiode. Since the transmitter draws large pulses of current, it has the potential to magnetically interfere with nearby devices, especially the photodiode receiver on the back of the transmitting vest (since the transmitter wire runs nearby this photodiode). The photodiode receiver, while shielded with conductive foil to prevent electrostatic and electromagnetic interference, is not magnetically shielded. This self-interference was problematic – whenever the transmitter was active, the receiver was unable to receive outside signals because of interference from its own vest's transmitter. For the final demonstration, it was decided that due to the complication and lack of materials for magnetically shielding the photodiode, the system would be modified so that transmission of data disables the receiver, and so that the transmitter is only active when voice is detected. In order to implement this, a voice detection scheme was required. Advanced voice detection schemes exist which can analyze a signal and determine if speech is present by statistical information such as the autocorrelation of the signal. This is computation intensive (and would have been time intensive to implement) so we took a simpler approach. Some noise is always present on the microphone input to the system board, so we created a noise power threshold. When the integrated value of the signal on the microphone exceeds a threshold value (which was estimated by looking at the oscilloscope trace of the noise on the microphone and fine tuned via trial and error), the transmitter sends voice data and the receiver inputs are disabled. This prevents the close-range interference on the receiver, but is more sophisticated than simply using a comparator voltage threshold on the microphone input, since useful speech data can be at a level below the noise peaks.

Following this modification, the system behaved well. See Chapter 4 for details.

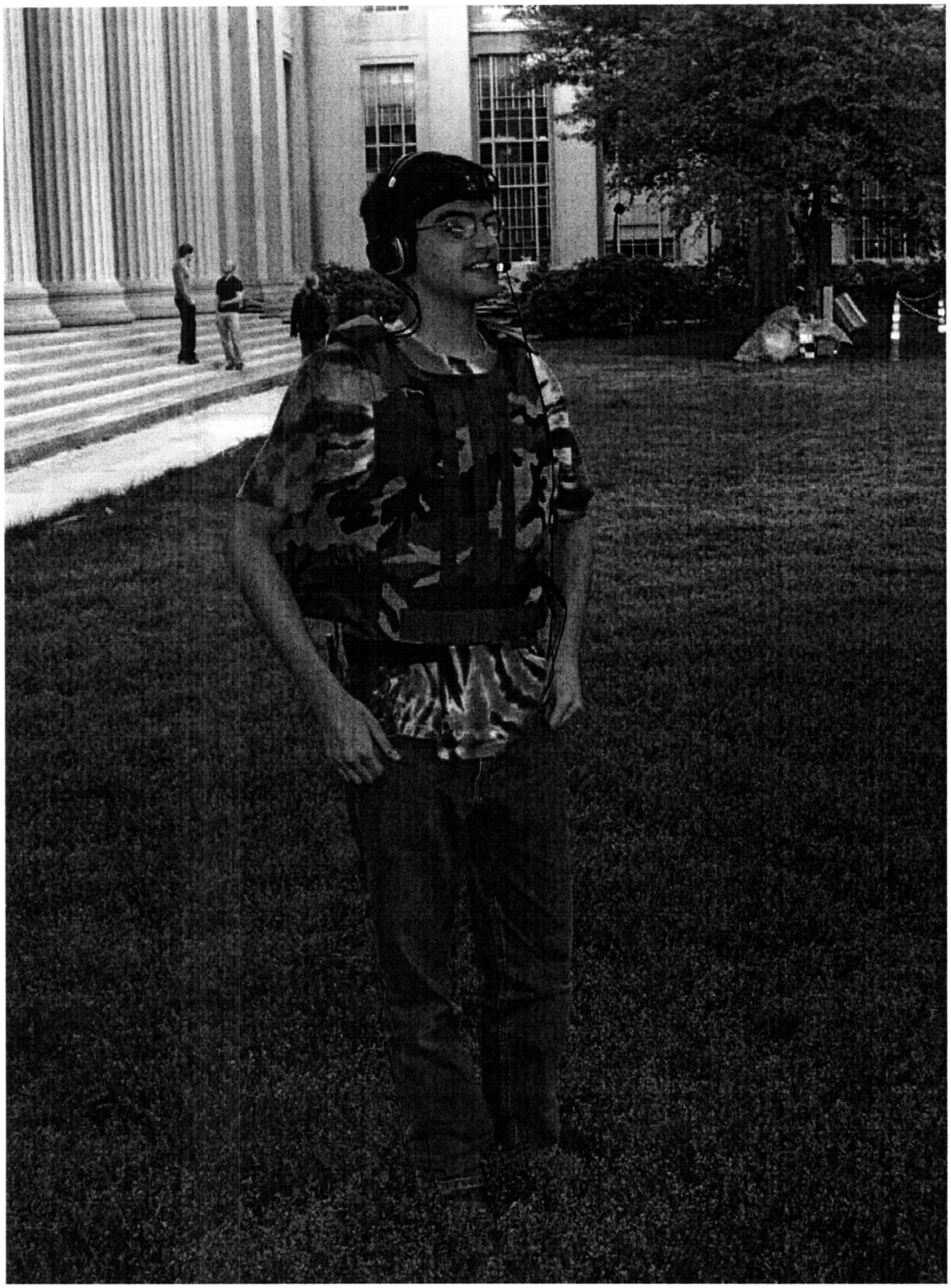

FIGURE 3-9. THE AUTHOR WEARING THE COMPLETED SYSTEM-INTEGRATED VEST

CHAPTER 4

RESULTS

4.1 SYSTEM IMPLEMENTATION

In designing and testing the analog end of the system, we created a test transmitter to emit a signal similar to that found in the actual transmission scheme. We used an LM555 timer to create a 5-volt pulse train. Each pulse is 1 μs width, and pulses occur at a rate of 10 KHz. This pulse signal is sent to the gate of an N-channel MOSFET, which is connected in series between ground and a 5-volt rail (created by a portable battery and a linear regulator) with one of the Osram IREDs and a current-limiting resistor that limits the current pulses through the IRED to 1.2 amps, as in the actual transmitter. The result is a free-running, portable 10 KHz "bit-stream" of ones using our transmission scheme.

We used this portable test transmitter to debug, and evaluate the performance and range of the receiver module, and to determine the noise threshold for our comparator stage. These tests were done indoors only, though an incandescent flashlight was used to test for ambient light rejection (which the system handled well). The receiver module was powered by two bench power supplies to supply the necessary positive and negative voltage rails. During testing, one person remained at the receiver end to measure the received signal, while another person walked steadily backwards while carefully aiming the transmitter. Figures 4-1 through 4-4 show oscilloscope traces at various stages of the (unshielded) receiver under illumination by the test transmitter at a range of 5 meters. In the indoor lab test, the receiver was able to detect and output a logic-level bitstream at a range of 30 meters.

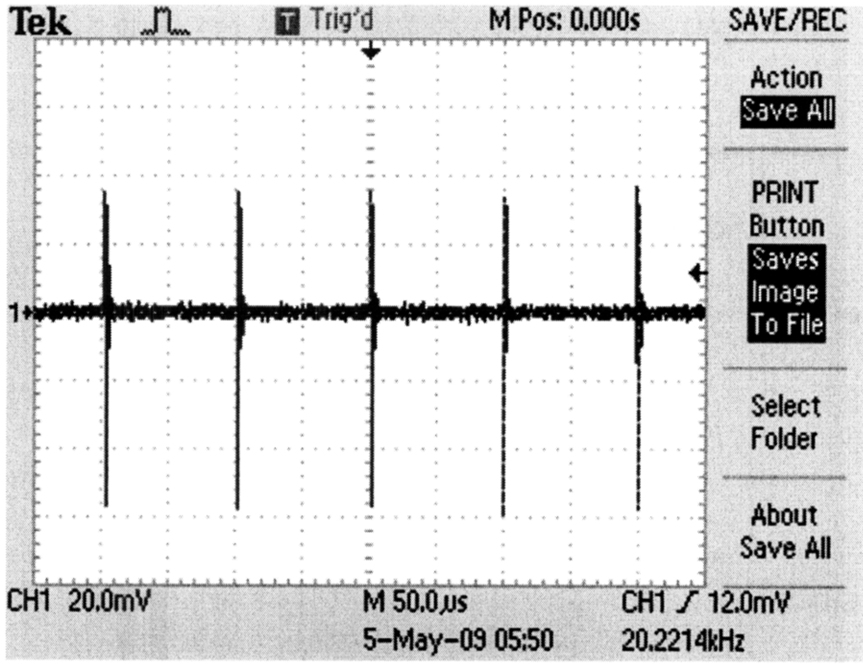

FIGURE 4-1. RECEIVED PULSE SIGNAL AT 5 M AFTER TRANSIMPEDANCE AMPLIFIER STAGE

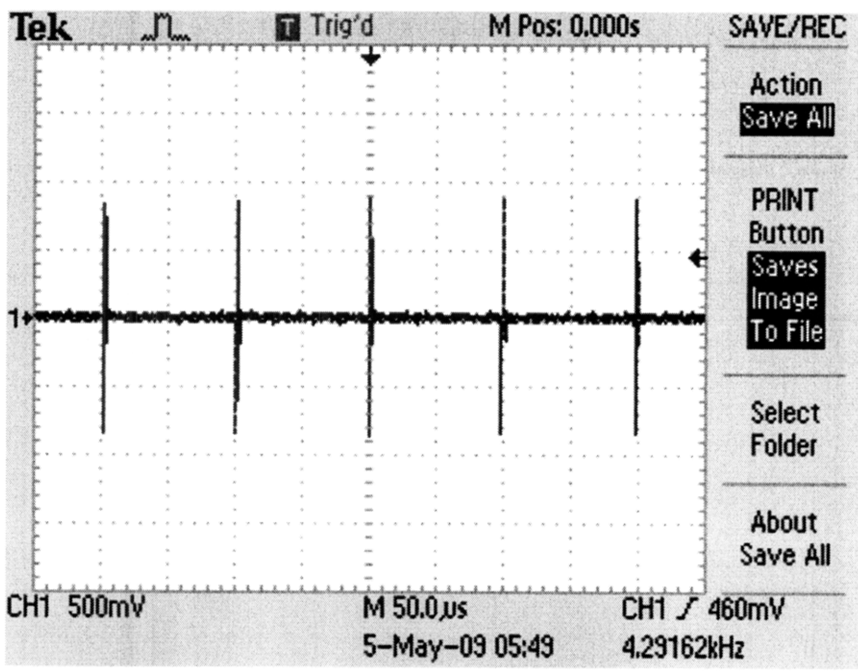

FIGURE 4-2. RECEIVED PULSE SIGNAL AT 5 M AFTER SECOND GAIN STAGE

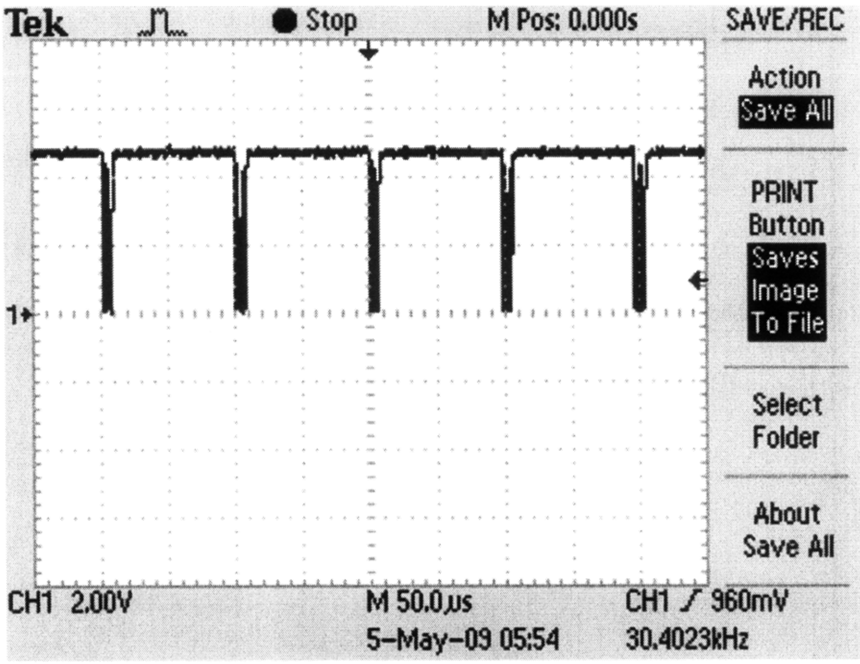

FIGURE 4-3. RECEIVED PULSE SIGNAL AT 5 M AFTER COMPARATOR STAGE

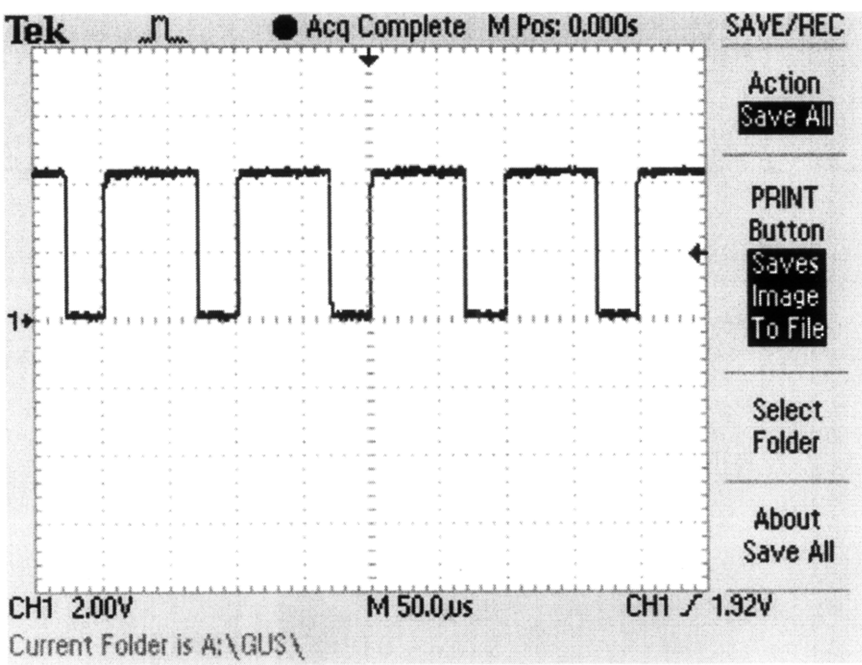

FIGURE 4-4. RECEIVED PULSE SIGNAL AT 5 M AFTER MULTIVIBRATOR STAGE

After tweaking the receiver and testing its performance with the test transmitter, we tested the system board by first having audio loop back. This allowed us to test that the codec, the Speex compression scheme on the dsPIC, and the headphone and microphone amplifier circuitry were working properly. Layout problems in the first version of the board for the headphone and microphone amplifier were corrected in the final version of the board, and a ground plane was added to reduce noise and capacitive coupling between signal lines. After the loop-back test was successful, we tested the receiver and the transmitter with the system.

The system worked upon connecting the modules together and transmitting voice, aside from a few problems involving magnetic coupling of the transmitter power supply rail to the receiver (see Section 3.5). After this problem was corrected by preventing reception and transmission at the same time, we evaluated the transmission scheme for range. In an indoor test, the system worked reliably to a range of 20 meters. The system could connect sporadically to a range of 30 meters, but was so angularly dependent that a reliable connection between people not actively adjusting the alignment of their transmitters is feasible only up to 20 meters. Angular range was 60 degrees, as expected. In an outdoor test, the system performed well even under ambient light conditions up to 20 meters. The system was tested both during the daytime and at night, and the nighttime test helped to demonstrate the usefulness in the system's range by allowing users to hear one another speak softly without being able to see one another simply by facing in the general direction of the intended recipient.

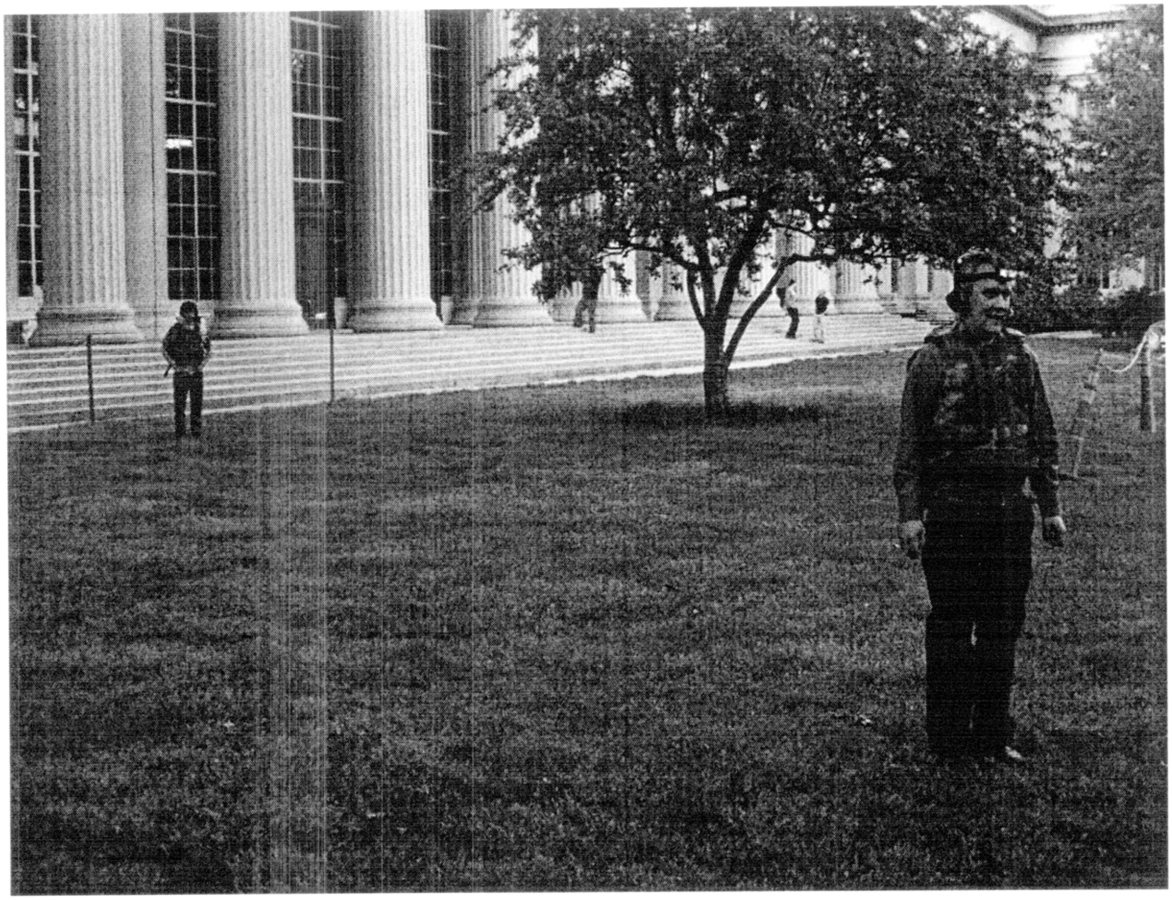

FIGURE 4-5. PROFESSOR YOEL FINK AND THE AUTHOR DEMONSTRATE THE WORKING SYSTEM AT A RANGE OF 20 M ON MIT'S KILLIAN COURT

The batteries on the power supply unit were able to power the system for about four hours. The majority of power is drawn by the transmitter. Some possibilities for reducing power are explored in Section 5.2.

The system satisfied the design specifications outlined in Chapter 1.

4.2 FIBERS

The twenty-conductor selenium fiber discussed in Chapter 2 was electrically contacted using the methods described in that section. Unfortunately, individual contact to each of the twenty conductors turned out to be infeasible with the given equipment, so a compromise was reached – four sections of the fiber, roughly corresponding to four quadrants of the cross section, would be individually contacted. Each point of contact actually connected together three or four conductors. This allowed us to measure the response to light of the fiber, but requires a higher biasing voltage to obtain the same current level that would have been available if all twenty conductors were contacted.

Using the NNDA solvent to dissolve away the cladding of the fiber proved infeasible. While the solvent does effectively dissolve the PES cladding, it acts slowly, requiring the desired section of fiber to be immersed for an extended period of time. Before completely dissolving the cladding, the NNDA significantly weakens the structure of the fiber, and runs up the fiber via capillary action. This means that by the time that the desired section's metal conductors are exposed, the mechanical integrity of the fiber near that section is greatly compromised. Furthermore, the metal contacts had a tendency to flake off when freely exposed and un-bonded from the core since they are extremely thin and fragile. The mechanical methods of cutting away cladding leave the conductors more securely bonded to the core of the fiber, avoiding this problem.

Another method that seemed promising for contacting the fibers but that proved ineffective was masking half of the conductors on the cross section and using silver paint. The first problem with this method was the extremely small size of the conductors. It took a great amount of time to develop the sill to manually place epoxy on the required conductors using a syringe tip without accidentally covering the wrong conductors. Adding to the difficulty, fast-curing epoxy was used to prevent the epoxy from flowing and unintentionally covering conductors while drying, so the entire operation of using a syringe tip under a microscope to cover conductors had to take place quickly. After much practice, the conductors were able to be successfully masked. However, the silver paint that was used to contact the other fibers would flow into the fiber at the thin-film semiconductor layer, and short conductors together that were not meant to be connected. This method might prove feasible with faster-drying silver paint or with fibers that are drawn with more intimate contact between core and cladding.

Ultimately, the most successful method for removing cladding to contact the fibers was the Dremel rotary milling tool. A major disadvantage of using a razor blade to mechanically remove cladding is that after many cuts of the razor, the excess hangnail-shaped pieces of PES prove difficult to remove without cutting too deeply and breaking the conductors. The milling tool removes this problem by quickly evacuating excess material away from the cutting site as it mills away the cladding. This method still required great care and practice, and it is still extremely difficult to expose only one conductor (as stated above, we exposed three or four conductors for each "point of contact"), but ultimately the milling tool proved easier to use than the razor blade and was the most effective tool for contacting the fibers.

All of these methods still require a great deal of skill, experience, and manual dexterity. The development of a standard connector that can be crimped onto the fibers would be very useful. Once widespread production of optoelectronic fibers becomes possible, reliably contacting optoelectronic fibers will rely upon the development of specialized tools and machinery, rather than the imprecise methods that we have explored. After contacting the fiber, the old method of wrapping and painting wire to the fiber as discussed in Chapter 2 was a mechanically unreliable joint. After exposing the desired points of contact on the fiber, we use a small metal sleeve of similar diameter to the fiber and crimp it to the painted section of exposed fiber. This provides a solid, reliable electrical contact, a sturdy mechanical joint, an also protects the fragile conductors in the exposed part of the fiber.

After electrically contacting the fibers, we measured their response to light. Our test setup consisted of a pico-ammeter, a voltage source (to bias the fibers) and a light source (a large incandescent flashlight). Since the amount of light illuminating the fibers was not precisely regulated, we did not determine a precise response curve for the fiber; however, our aim was simply to determine the order of magnitude of the photocurrent produced to see if optoelectronic fibers would be feasible as receiving devices in our system.

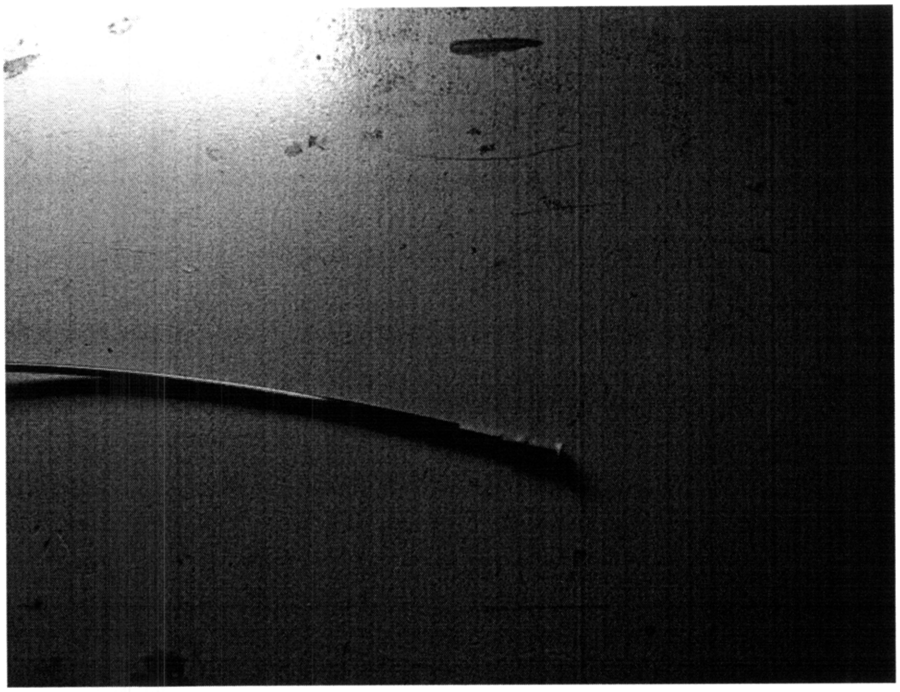

FIGURE 4-6. AN ELECTRICALLY CONTACTED FIBER WITH CRIMPED METAL SLEEVE.

Unfortunately, these fibers still produce a much smaller level of photocurrent than standard semiconductor photodetectors, and are still not high-bandwidth enough to detect a 14 kilohertz signal (they do not need to resolve the individual pulses, which would require even higher bandwidth of 500 KHz). However, this fiber does show a marked improvement over previous generations of fibers, which is promising. The fiber produces a level of approximately 10-100 nanoamps when illuminated directly with a bright flashlight, with a dark current level approximately half of the photocurrent produced when the fiber is saturated with high intensity illumination. Previous optoelectronic fibers produced photocurrent in the 100 picoamp to 1 nanoamp range, so this does show marked improvement. With further development, these devices will become competitive with traditional semiconductor photodetectors.

CHAPTER 5

CONCLUSIONS

&

FUTURE WORK

5.1 APPLICATIONS

The system that we have constructed offers some interesting advantages over traditional radiofrequency wireless communication. This particular system was designed as a proof-of-concept that two way optical communication is feasible and practical, and even at the limited range of the demonstrated version, the system can be useful. One application that short-to-medium-range directional optical communication could become relevant for (even in the 20 meters range) is covert operations, especially nighttime operations. The night-time demonstration of this system showed that users can comfortably communicate with one another at a voice level low enough to prevent being heard from a distance of approximately 5 meters – in effect, allowing people to whisper to one another while avoiding detection.

This communication scheme can be useful even as a one-way transmitter or receiver. The one-way system described in Chapter 1 was significantly limited by low voice quality and did not transmit information digitally. A system like this could transmit a long-distance signal across a laser or receive a one-way signal. For example, a signal on a laser gun sight could warn friendly forces to evacuate an area. These forces would then be able to act upon the information, even if unable to locate the transmitter and respond. This system is also not limited to transmitting voice. Since it transmits data as digitized packets, the communicator can easily be reconfigured to send any digital data over the link. The limit is bandwidth, but a secure, directional link between people or vehicles could be very useful.

Aside from person-to-person communication on the field, a directional link has many applications. For example, a row of people moving one in front of the other (for example, a row of marching infantry) could communicate with one another and instructions could be sent throughout the line of people without broadcasting in all directions. Similarly, a transmitter and receiver could be placed on the front and rear of an automobile, allowing information to be transferred back and forth between two vehicles (or even a large number of vehicles travelling in a line). The system as it stands has few conspicuous parts – in the applications described here, the transmitter size could be reduced and the future incorporation of fibers could make the receiver even less noticeable.

5.2 FUTURE WORK

While we believe that the system designed and created in this project provides a novel and useful alternative to RF-based wireless communication, there are a number of areas upon which it could be improved. These generally fall into two categories: design improvements which could be realized with more time and resources for further development of the current system, and design improvements which depend upon further advances in technology (especially in relation to the optoelectronic fibers).

General improvements to the system to polish off appearance would be necessary for a production version of the system. For example, the crimped wire connectors used to connect boards are vulnerable to breakage if pulled and are clumsy to connect and disconnect. Using a standardized connector, such as mini-USB, between boards, could solve this problem. Similarly, a custom designed shielded enclosure for the receiver and a shielded coaxial cable to connect the photodiode (or fiber) would provide a more reliable, robust connection that is less vulnerable to noise. The receiver amplifier could also be further tweaked to provide a better signal to noise ratio. In fact, we could even get a very large amount of "noise-free" gain on the optical receiver by including a lens. This course of action was not taken for this project because of the complication of mounting a lens in an inconspicuous manner, without the lens protruding from the vest (a large area lens generally has a focal length in proportion to the diameter of the lens).

One improvement on the current system, which could be realized with further development of the system code, involves using only those infrared emitting diodes that are necessary for transmission to the receiver and keeping those in the rest of the angular range of the device shut off. This would be done as follows: one person's system would send out a signal on each of its IREDs, in all directions; each one would indicate a unique signature. The other would respond in turn with all of its IREDs with a signal conveying the signature of the received signal as well as its own unique transmission signature. Now, the first person's system knows exactly which of its IREDs are being received, so it can respond on this device with the second person's transmitter signature. Now both systems known which IRED's angular range covers the recipient, and they can transmit only on these devices thus saving power and avoiding interception of the signal. (This could be refined to intermittently include a check on neighboring IREDs to account for movement between the two people communicating.

Once a system that allows for a narrow range of transmission following an initial "handshake" is implemented, IREDs could be mounted across the entire angular range of the system, allowing communication without having to point in the general direction of the recipient. Infrared output in all directions would be constrained to a very short time, only at the beginning of transmission, while the transmitted data itself would be kept to a narrow beam including only the intended recipient.

The communications system could be made even more directional, have improved range, and be more power efficient if it were to incorporate a collimated laser as its emitter rather than a traditional IRED. The collimated beam of a laser can have very low divergence, maintaining a receivable power density even in the range of kilometers. Indeed, this is a disadvantage when we are considering eye safety to be a requirement of the system. We would need to use a lower frequency of radiation that would not damage a human retina, such as 1.5μm laser radiation, for transmission. One-way systems which use this idea and require manual aiming of a transmitted laser beam already exist (such as the helmet described in Chapter 1), but in order to be feasible as a two-way communication system, there would need to be a method for locating the intended recipient and only transmitting to him. A system such as that described above could be used, where a CPU-controlled mirror could direct the signal beam across some angular range while transmitting its orientation. The receiver would respond with the transmitter's orientation and its own orientation, following which both devices could transmit directly to each other (and intermittently check within the nearby angular range, in case of movement).

Another improvement that could be realized with further development of the current system involves saving power. An embedded communications system needs to be portable, which means it must be able to operate for an extended period of time without external power. The current system can operate for a few hours between charges, and requires three AA batteries. Barring the trivial solution of simply including more batteries, the system could save quite a bit of power by not transmitting on unnecessary IREDs, with the method described above. A considerable amount of power is also wasted in the current-limiting resistors in the transmitter. A separate power source for the transmitter that operates as a current-limited switched power supply would save a considerable amount of power. Such a system is described in Chapter 3, but further development would be necessary to create a system with switching frequency high enough to allow the diodes to be switched fast enough to send data.

Reducing the visible footprint of the emitters is also important because the high level of infrared emission makes the current system vulnerable to detection by infrared-sensitive devices such as night vision goggles. Improving directionality will mitigate this problem, especially by using lasers, but another improvement that might make the system less detectable by traditional IR sensitive gear is to reduce the duty cycle of transmitted pulses, so that the effective power in infrared integrated over a small time period (which is what night vision goggles will see) is less. Unfortunately, the limits on this are the bandwidth of the system (which cannot be reduced without compromising voice quality significantly), the switching time for the diodes, and the ability of the detector to resolve small pulses, which can be a significant problem with the optoelectronic fibers.

One of the more exciting aspects of working on this project was in working with the new optoelectronic fiber devices. It was unfortunate that fibers were unable to be used with this system without a severe limit on operational range and bandwidth. The use of the system with optoelectronic fibers as photodetectors is limited by the low sensitivity and bandwidth of current generation fibers. The properties of these fibers are continuously improving, with fibers being available near the conclusion of this project with bandwidths in the 10 KHz range and sensitivities orders of magnitude greater than those of previous generations, as discussed in Chapter 2. Ultimately, it was decided that the still superior sensitivity of the traditional photodiodes allowed a more useful range of operation to be demonstrated. As the technology of drawing semiconductor devices as fibers improves, these optoelectronic fibers have the potential of serving a role in this kind of system with a number of advantages over traditional wafer-based optoelectronic devices.

Optoelectronic fibers are fabricated in a process similar to that of a traditional optical fiber. At an industrial scale, this could potentially be much cheaper than the fabrication process of traditional semiconductor devices. Additionally, as the technology matures, thinner optoelectronic fibers will be feasible, to the point where these devices could be woven into fabric. Since optoelectronic fibers have a large effective detection area, and act as integrating line detectors of light, their development has the potential for yielding exciting applications both as the receiving end of a communications system such as this one, and also as a part of some of the applications discussed in Chapter 2, such as lens-less imaging. An important development, aside from higher performance in the fibers themselves,that will need to be attained before fibers can be integrated easily with electronics is a reliable connection method. A specialized tool or crimp could be designed that would be faster, easier to use, and more reliable than the methods described in Chapter 2. With further development, it may be possible to incorporate electronic devices directly into the fabric of clothing – a communications system like the one designed in this work could utilize the vest itself as the optical detector.

5.3 CONCLUDING REMARKS

The primary goal of this work was to create a two-way wireless optical communications system capable of transmitting and receiving voice data digitally. In this end, the project was a success, and the demonstration of its performance was well received. There are a number of ways that the system can be improved, but its construction as a proof-of-concept was important, and more resources should be spent on developing it as well as similar systems, as well as on developing the optoelectronic fiber devices.

It is this author's conviction that with further development, similar communications systems based upon optical transmission of data will become important not only in military applications but also commercially in the coming years. The further development of optoelectronic fibers will not only benefit these kinds of systems, but will facilitate integration of semiconductor devices into everyday life in new ways, and open up exciting new possibilities for electronic and optoelectronic devices. The weaving of clothing that can communicate and that has electronics embedded within its fabric, while science fiction today, may be a feasible reality in the near future.

APPENDIX

SCHEMATICS AND LAYOUTS

The following pages include schematics and layouts for the system and receiver modules.

In the following schematics, credit is given to Danny Perry and Paul Yang for their designs for the system and power supply boards. Design for the transmitter is described in Chapter 3; mechanical design and final electrical layout for the transmitter headpiece was done by Paul Yang, and electrical and mechanical drawings and specifications can be found in his thesis, *A Line-of-Sight Voice Communication System with Optoelectronic Fibers* (2009). For the complete system code, which was largely developed by Danny Perry, please see his thesis, *Source and Channel Coding for Low-Bandwidth Speech Communication between Optoelectronic Devices* (2009), for reference.

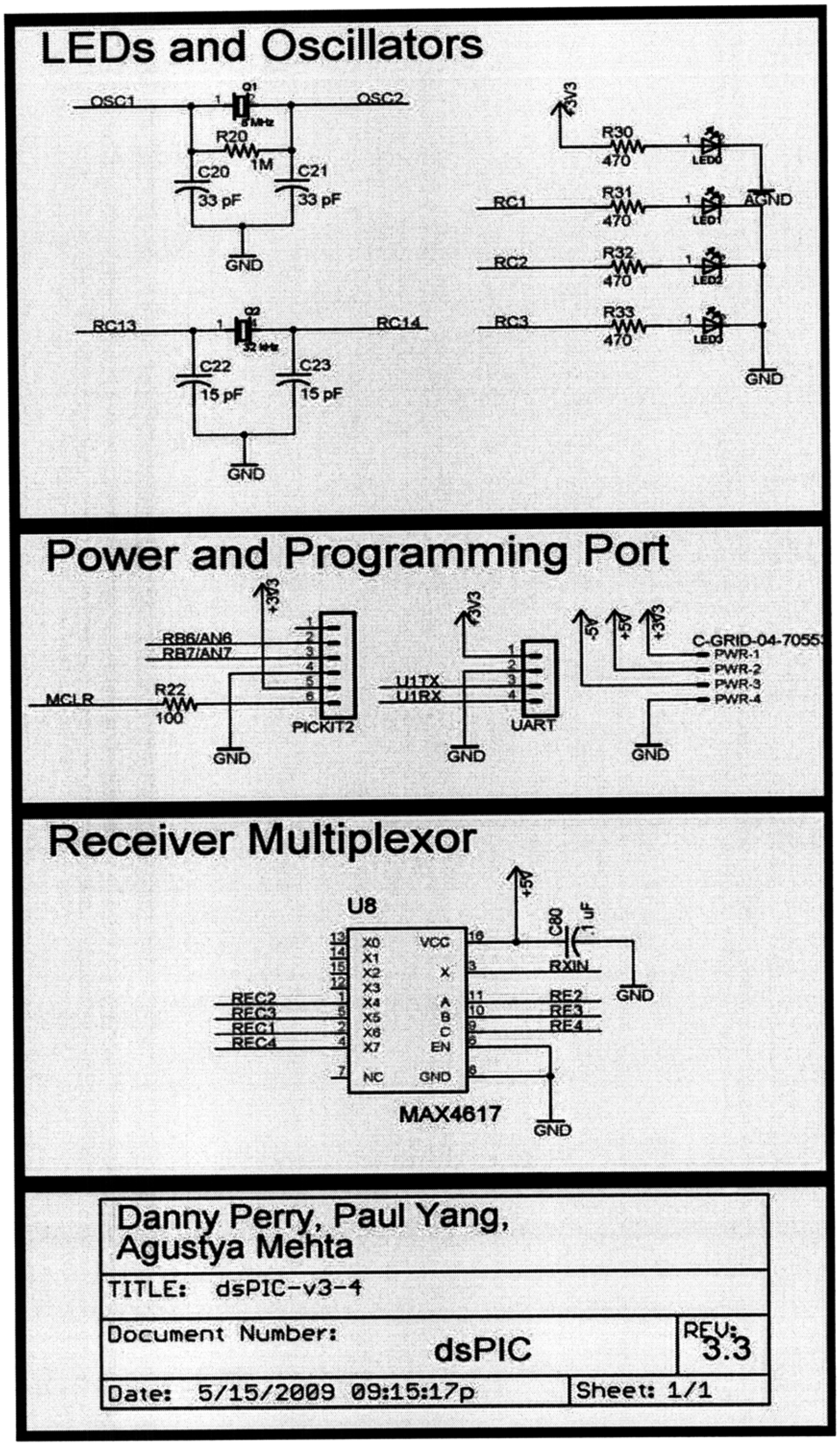

FIGURE A-1. SCHEMATIC FOR SYSTEM BOARD (PART 1 OF 3)
SCHEMATIC AND LAYOUT DEVELOPED BY DANNY PERRY

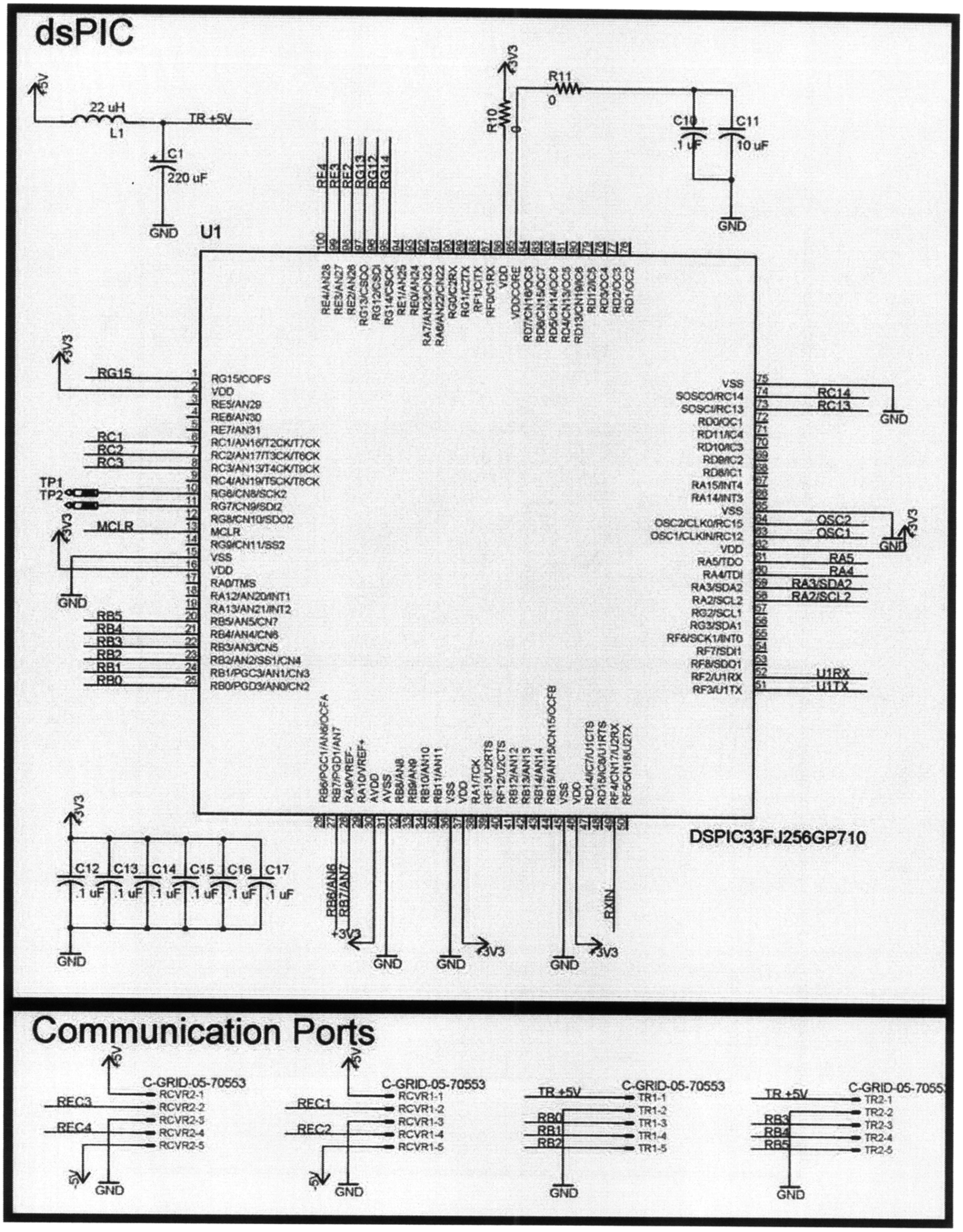

Figure A-2. Schematic for System Board (Part 2 of 3)

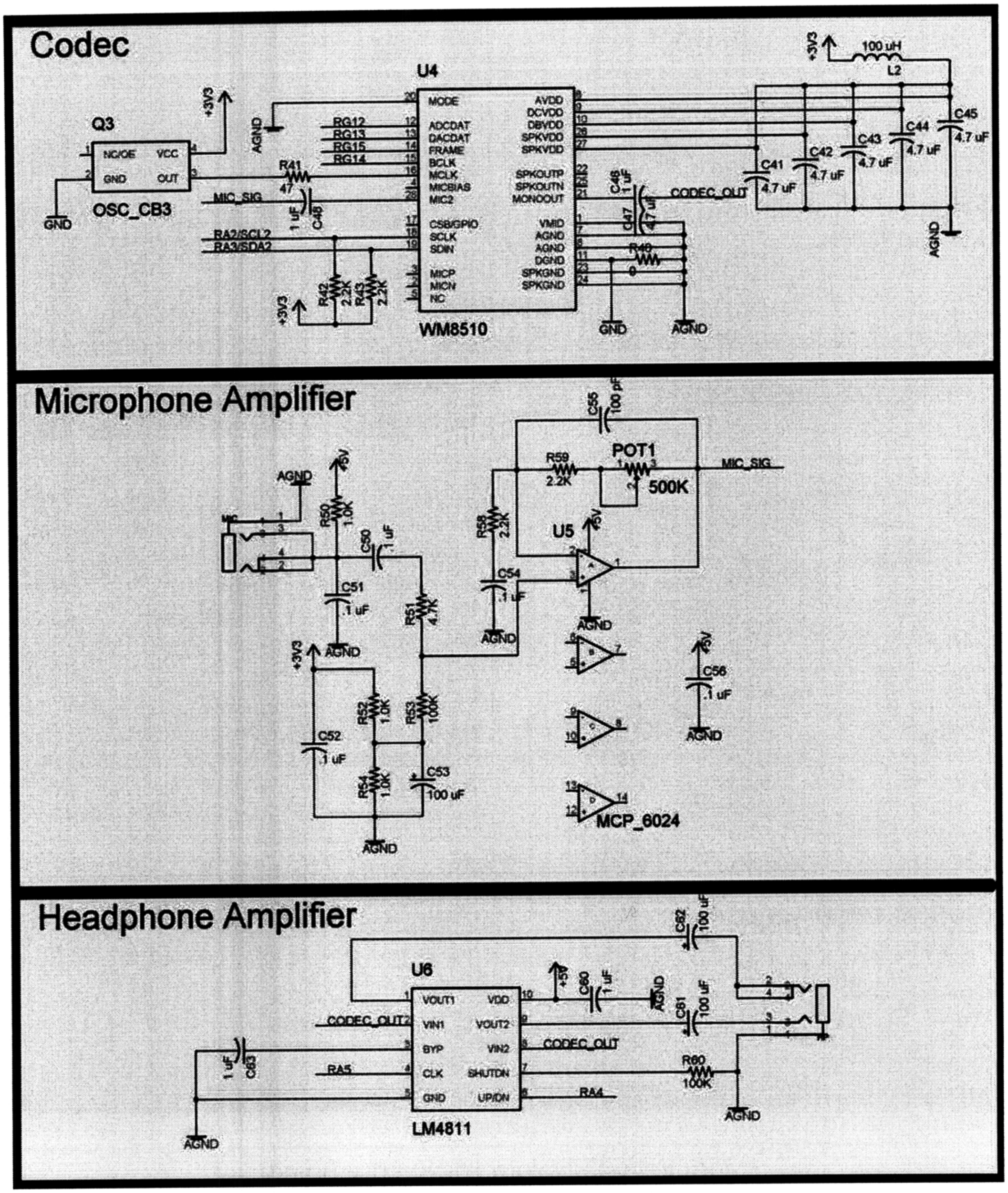

FIGURE A-3. SCHEMATIC FOR SYSTEM BOARD (PART 3 OF 3)

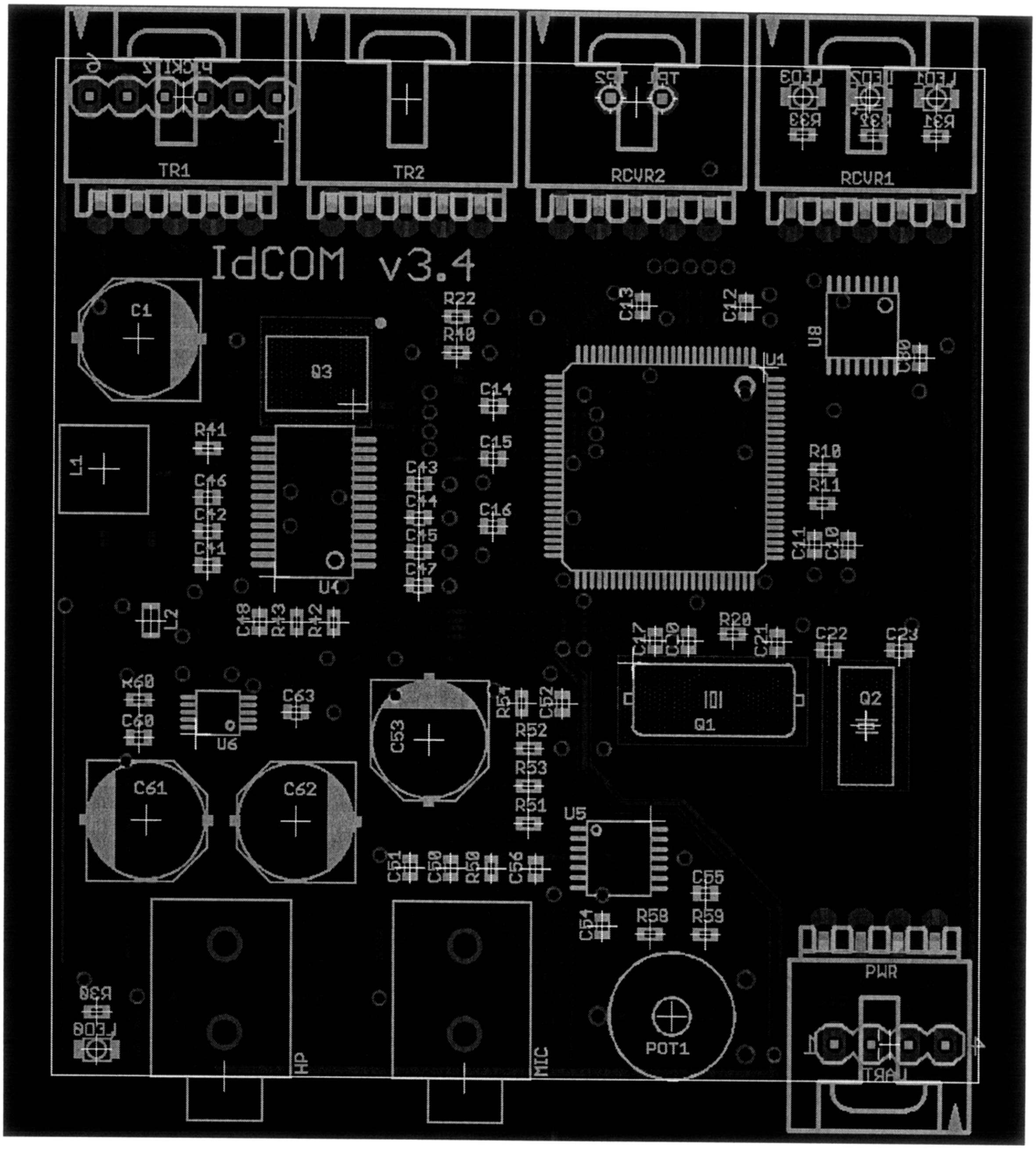

FIGURE A-4. LAYOUT FOR SYSTEM BOARD

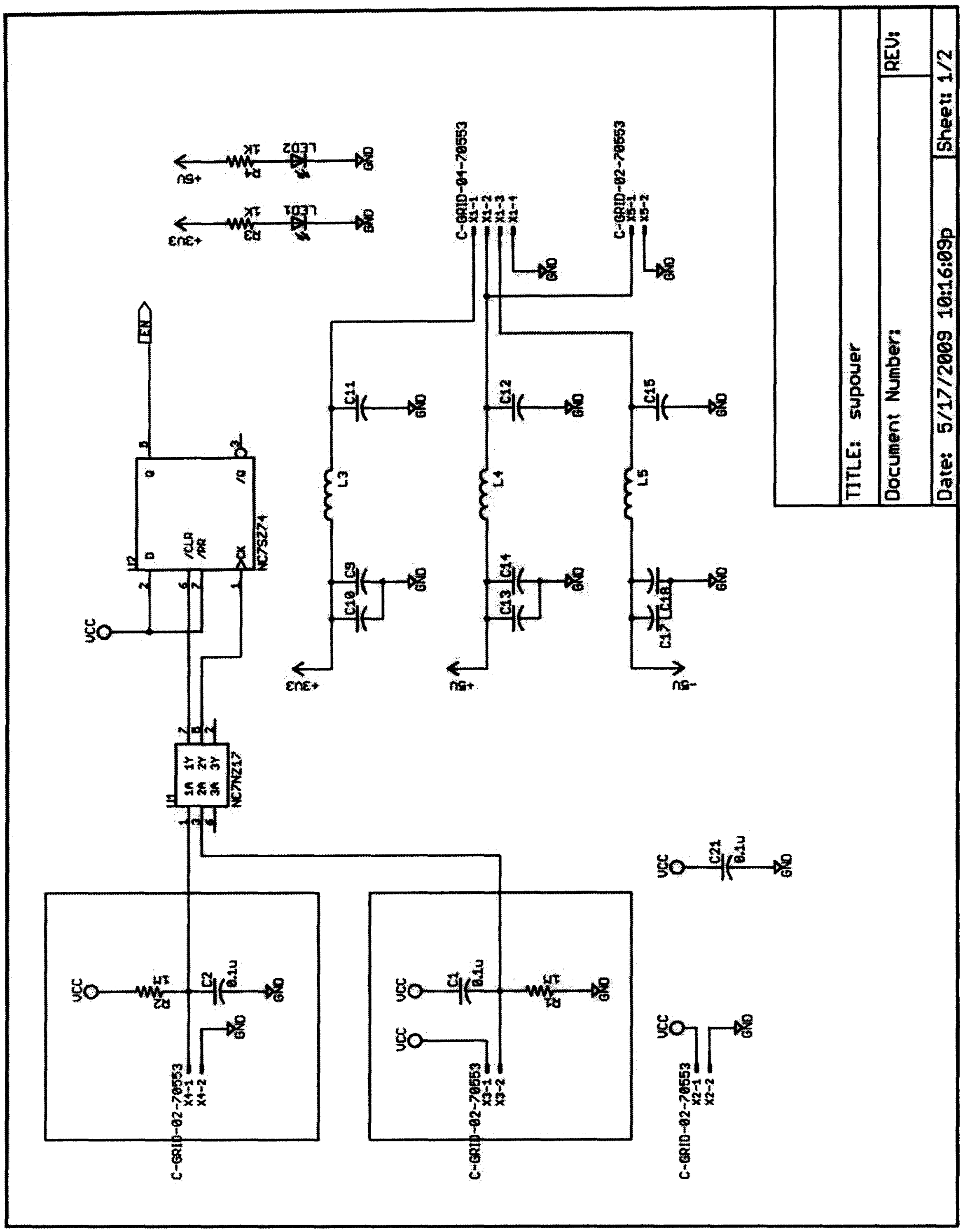

FIGURE A-5. SCHEMATIC FOR POWER SUPPLY BOARD
SCHEMATIC AND LAYOUT DEVELOPED BY PAUL YANG

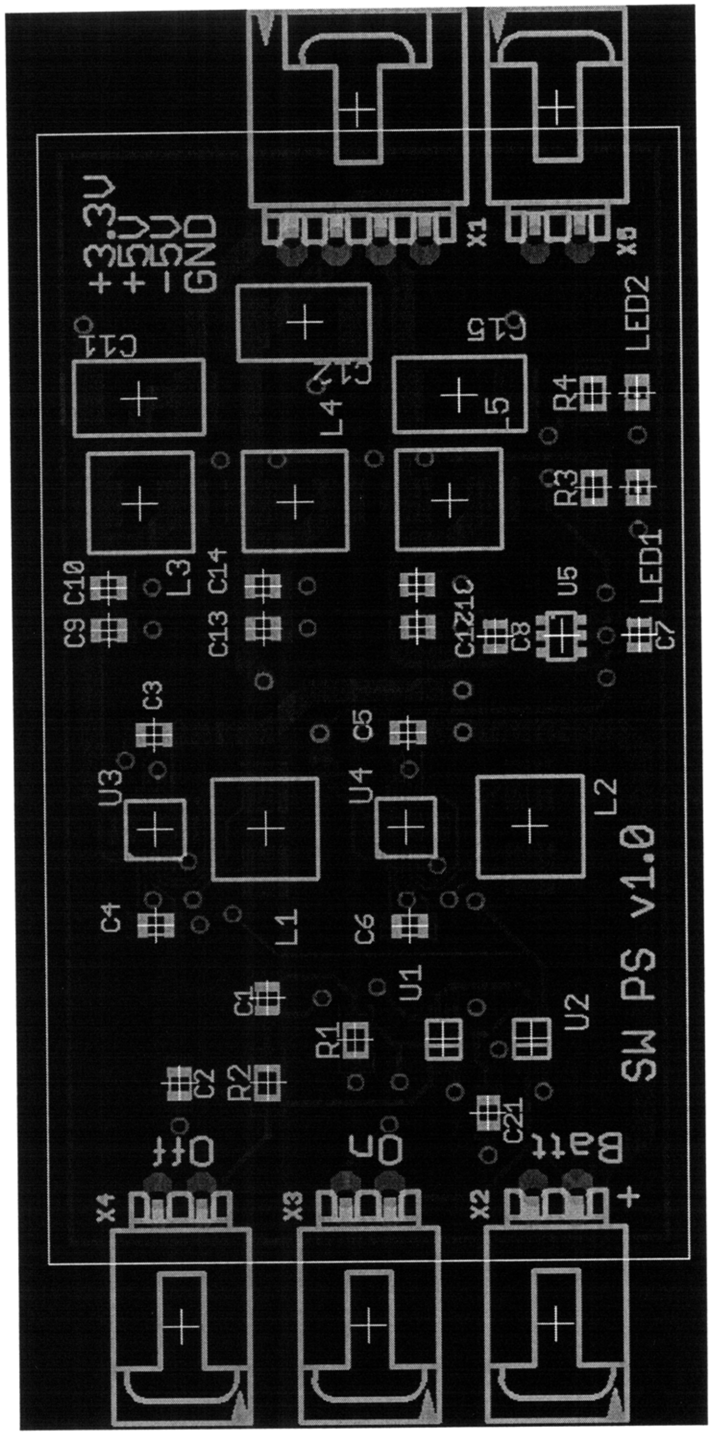

FIGURE A-6. LAYOUT FOR POWER SUPPLY BOARD

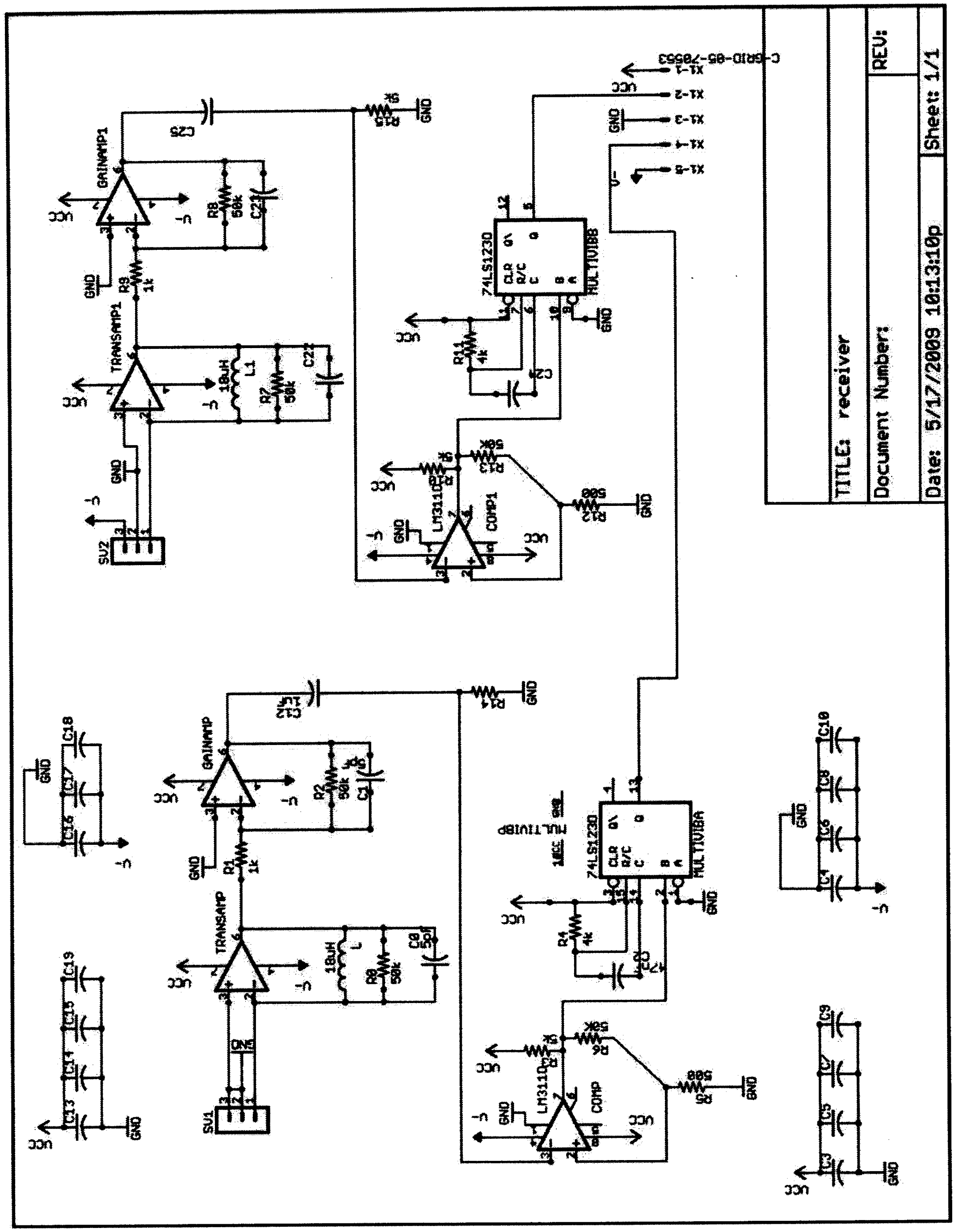

FIGURE A-7. SCHEMATIC FOR RECEIVER BOARD
SCHEMATIC AND LAYOUT DEVELOPED BY AGUSTYA MEHTA

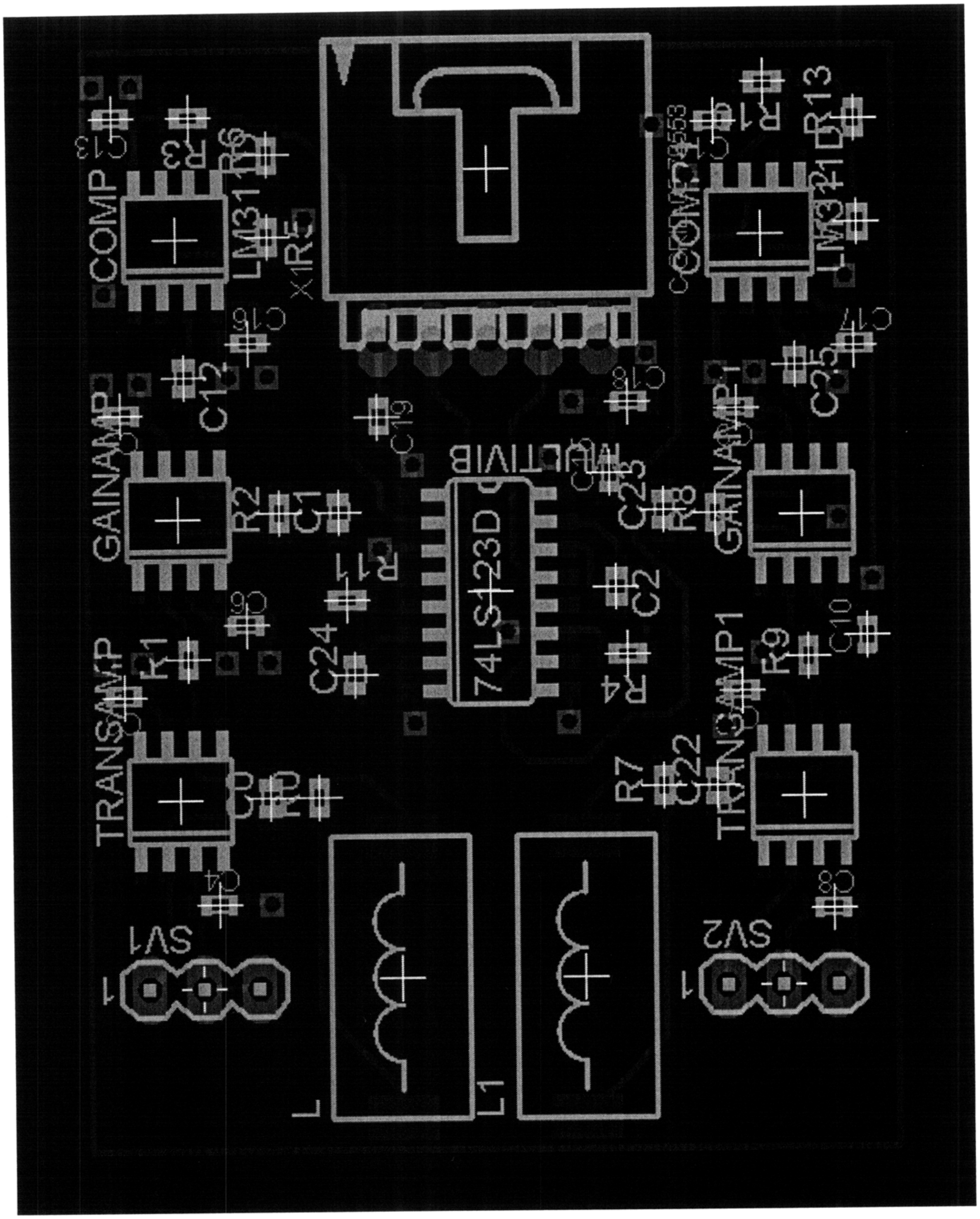

FIGURE A-8. LAYOUT FOR RECEIVER BOARD

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Lastly (but certainly not least importantly!) I would like to thank my friends and family for keeping me motivated. I want to especially thank my parents Gyan and Laurie and my brother Abhijit for their love and support in all my work, and for always encouraging the curiosity that drives my love for science and engineering.

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