

Optoelectronic Fiber Interface Design

by

Matthew Edmund Spencer

S.B. E.E. MIT 2007

Submitted to the Department of Electrical Engineering and Computer
Science

in partial fulfillment of the requirements for the degree of
Master of Engineering in Electrical Science and Engineering

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May 2008

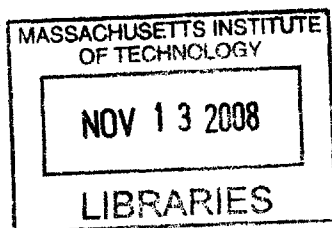
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Author
Department of Electrical Engineering and Computer Science
May 9, 2008

Certified by
Yoel Fink
Associate Professor
Thesis Supervisor

Accepted by
Arthur C. Smith
Chairman, Department Committee on Graduate Students



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Abstract

Recent developments in materials science have led to the development of an exciting, new class of fibers which integrate metals, semiconductors and insulators in the same codrawing process. Various electrical devices have been produced in these fibers including optical sensors, thermal sensors and even transistors. The use of these fiber devices in a variety of applications was explored. A large-scale, lensless imager, an optical communication system, a thermal sensing array and a logic gate were designed to use appropriate classes of electrically active fibers. These devices were constructed with a particular focus on testing the best ways to integrate these fibers with modern circuits. Several methods of making electrical contact with fibers are described and their failure modes are discussed and novel circuits for amplifying and measuring fiber signals are developed and presented.

Thesis Supervisor: Yoel Fink

Title: Associate Professor

Acknowledgments

I wish to thank Yoel Fink for providing the opportunity to perform this research. Ayman Abouraddy, Fabien Sorin, Sylvain Danto, Nick Orf and Ofer Shapira also deserve recognition and special thanks as contributors, mentors, assistants and supervisors. Danny Perry has been invaluable in helping with much of the assembly and design described in this thesis. Paul Yang and Agustya Mehta have also made significant contributions to the work here, particularly the optical communication system.

In addition to the help provided by my professional colleagues I must thank my teachers for helping me learn throughout my career at this institution. Special thanks goes to Professors Joel Dawson, Steve Leeb and Jim Bales for taking a helpful interest in my academic success.

Finally, I must thank my family and friends for their loving support throughout my life. I wouldn't be anywhere without them.

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Chapter 1

Optoelectronic Fibers and Their Operation

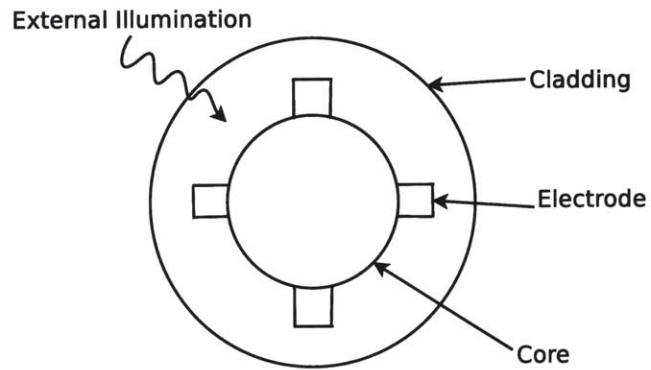
Optoelectronic fibers are a unique class of electrical device developed by Yoel Fink and his group at MIT. These fibers combine metals, insulators and semiconductors in the same codrawing process [6, 8]. This allows electrically active structures to be constructed inside of the fiber. Examples of such structures include optical detectors [1, 2], thermal sensors [5] and even communication systems [3].

These fibers were integrated with a wide variety of circuits to perform their sensing functions. In order to effectively discuss the integration of these fibers into circuits, it is first necessary to describe the behavior of the various kinds of fibers which were used in this research.

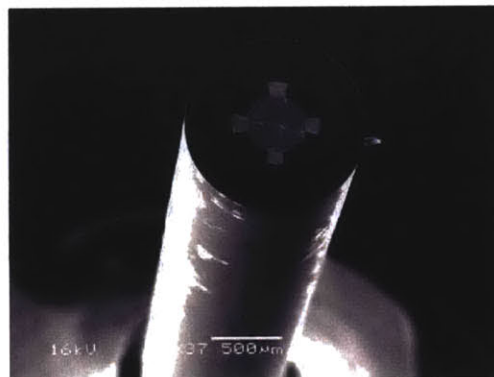
1.1 Optical Fibers

Optically sensitive fibers are amongst the earliest fibers integrated into circuits. The fibers consist of a transparent cladding material (polyether sulphone or PES), a number of tin electrodes and a core made of a glassy semiconductor which is usually based on As_2Se_3 with varying amounts of Te and Ge. A schematic of this kind of fiber appears in Figure 1-1.

Photons that are incident on the core of this device can excite electron-hole pairs



(a) Diagram of optical fiber.



(b) Image of optical fiber. Credit to Jeremy Arnold [4].

Figure 1-1: A light sensing fiber. Incident photons excite electron-hole pairs in the core. This change in available charge carrier density alters the conductivity of the device.

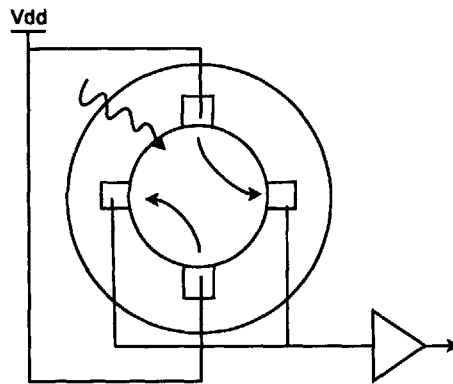


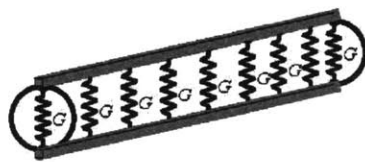
Figure 1-2: Voltages applied to the electrodes of the optical fiber produce a current which is proportional to incident light. The fiber acts like a two-terminal photodiode which integrates light along its length.

in the semiconductor. The change in charge carrier density in the device results in a change in its conductivity. When voltages are applied to the electrodes, the current passing through the device is modulated the intensity of incident light. This current can be measured by external circuitry.

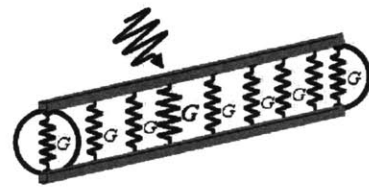
There are two ways to view the change in behavior of the fiber: as a change in the devices conductivity or as a change in the current flowing through it. Both of these views will be used in the following discussions. The selection of one paradigm over the other will be based on what grants greater insight for the current application.

As seen in Figure 1-2, two pairs of electrodes are usually shorted together in order to improve the current throughput of the device. This means that the fiber is modelled is a two port device when included in a circuit.

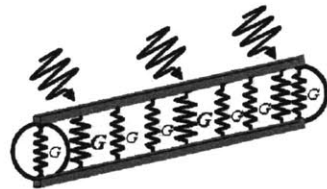
The total change in conductivity of the fiber is related to the total change in conductivity along its length. Light that strikes anywhere along the length of the fiber will form electron-hole pairs. As a result, the fiber integrates the light received along its length and acts as a one-dimensional sensor rather than as a zero-dimensional pixel. The concept of an integrating medium illustrated in Figure 1-3. The fact that the fibers behave as an integrating medium affects their use as imaging sensors as described in Section 3.2.



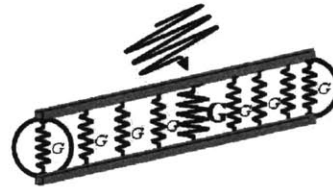
(a) A model of a fiber.



(b) Incident light changes fiber conductivity.



(c) Multiple sources of incident light result in a larger conductivity change.



(d) More intense sources of light result in larger changes in conductivity.

Figure 1-3: The conductivity of a fiber is a function of the total amount of light that falls along its length. This results in an inability to tell where radiation was incident along the length of a fiber. Images taken from Arnold [4].

1.2 Thermal Fibers

In optical fibers the band gap of the semiconducting glass is tuned such that the fiber is likely to respond to optical frequency radiation. It is also possible to tune the band gap of the fibers such that they are sensitive to infrared frequencies [5].

The band gap of the core must be much smaller for fibers to be sensitive to thermal radiation because infrared photons have much less energy than optical photons. As a result, thermally sensitive fibers have a much larger carrier density due to ambient thermal conditions than optical fibers due to ambient light. This results in a much higher conductivity under both illuminated and dark conditions. These devices are easier to integrate into a circuit than many others because of their higher conductivity.

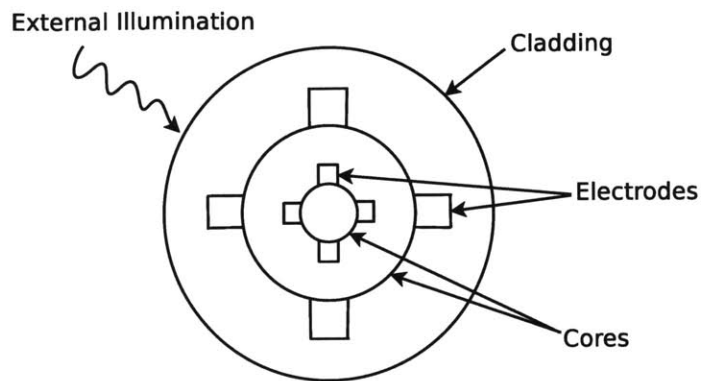
The geometry and operation of these fibers is similar to those described in the previous section.

1.3 Thin-Film Optical Fibers

In an optically or sensitive fiber a small number of electron-hole pairs are produced by thermal excitation of the semiconductor. The motion of these charge carriers is referred to as dark current. The dark current of the device lowers its sensitivity to optical excitation because current is already passing through the device in the absence of illumination; there is a smaller ratio of excitation to background in the presence of the dark current.

The dark current is dependent on the volume of material in which electrons and hole can be thermally excited. In order to reduce the dark current in the optical fibers while retaining optical sensitivity, a new generation of fibers was produced. In these fibers, the core was a thin film of the optical semiconductor rather than a solid mass. The thin film has the same surface area exposed to light and can have its thickness tuned to absorb almost all incident light at a frequency of interest. However, the film has a much smaller volume and will produce fewer thermal carriers.

The total current passing through these devices is lower because of the smaller



(a) Diagram of two layer fiber.



(b) SEM Image of two layer fiber. Credit to Dr. Fabien Sorin.

Figure 1-4: Two thin films of optically sensitive semiconductor material are nested inside of this fiber.

dark current and because less optical radiation is absorbed in a thin film than in a bulk core. Though the change between illuminated conductivity and dark conductivity is greater than in optical fibers, the conductivity of the device is lower. This property forces the use of elaborate amplifiers to measure fiber signals.

A second thin film can be grown inside of the first in order to make a bilayer fiber. By tuning the thickness of these fibers, the device can be made sensitive to multiple frequencies of light. A fiber of this design appears in Figure 1-4

These fibers are connected to a circuit in much the same way as the optical fibers discussed in Section 1.1. Two electrodes are shorted together and connected to power

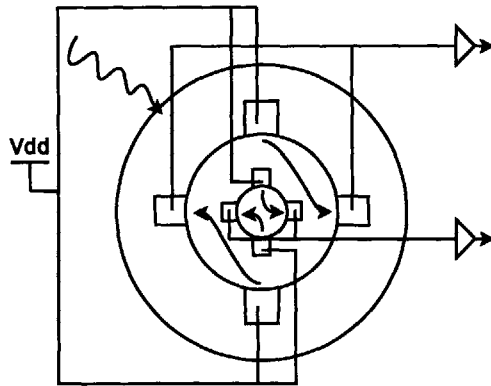


Figure 1-5: Both thin-film layers of these fibers are connected to external circuitry. Each thin film can be tuned to a different frequency of light making this fiber sensitive to two frequencies.

and two shorted together and connected to the output circuit as pictured in Figure 1-5. Because there are eight electrodes total in these fibers this results in a four port circuit element. This is most effectively modelled as two, sensitive, optical fibers which happen to share the same packaging.

These fibers have a greater signal-to-noise ratio than other fibers because of the reduced dark current and reduced thermal noise in the semiconductor. Thermal excitation of carriers in the semiconductor causes both dark current and thermal noise. Because of this connection, reducing the dark current also reduces thermal noise. These effects combine to improve the signal-to-noise ratio of these fibers.

1.4 Annealed Fibers

The semiconductor at the core of the fibers is amorphous after the drawing process. This creates a large number of localized electron states which manifest as deep level traps in the band structure that pin the Fermi level at mid-gap. This reduces the conductivity of the fibers.

By applying a low temperature to the fibers it is possible to improve the crystallinity of the fibers by annealing the semiconductor core. The relationship between annealing time and crystalline fraction is shown in Figure 1-6.

Improving the crystallinity of the fibers greatly improves their conductivity, which

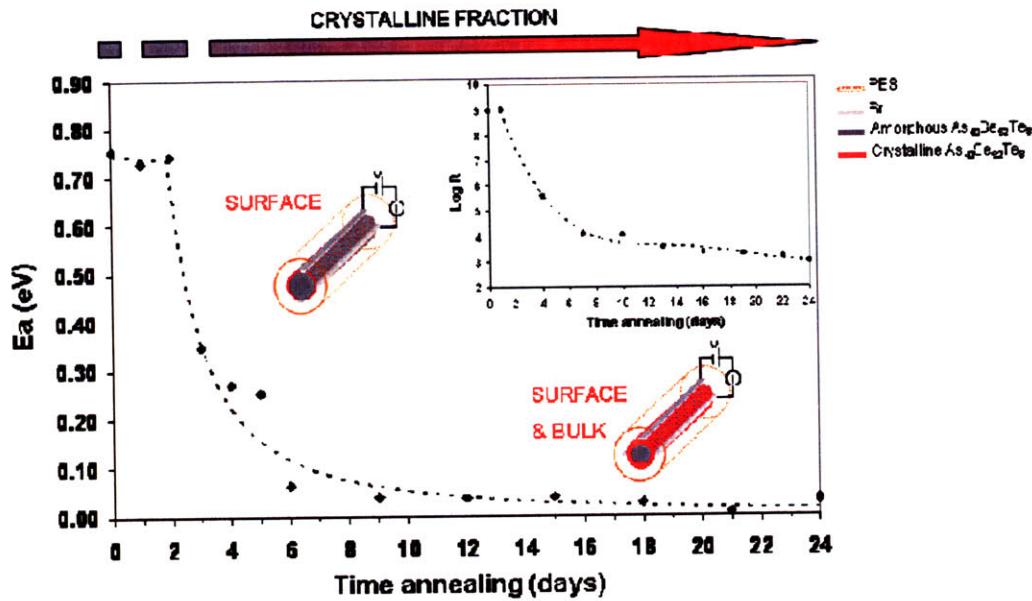


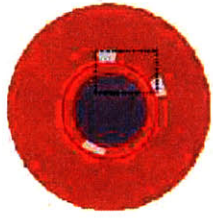
Figure 1-6: The crystalline fraction of the fiber can be changed with an annealing process. This alters the conductivity making the fiber more suitable for some optical and electrical applications. Credit for this figure goes to Sylvain Danto.

in turn improves the carrier lifetime of the semiconductor. Because more carriers can drift successfully to the electrodes, the output current and response time to optical signals is greatly improved. This allows the sensitivity of thin-film fibers to be obtained while mitigating the high-impedance seen in these devices. This also enables more complex fiber devices like the transistors described in Section 1.5.

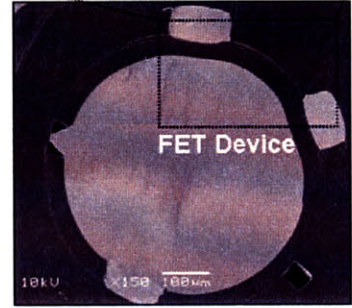
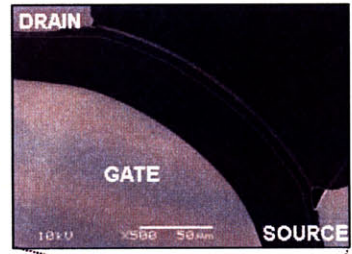
1.5 Integrated Fiber Transistors

It has recently been discovered that circuits can be integrated into fibers with proper design. Sections of the crystallized fibers behave like resistors, sections of PES behave like a low quality dielectric to form capacitors and that sections of the core behave like semiconductors. These circuit elements can be combined into a dazzling array of complex devices as demonstrated by the semiconductor industry. Work on an integrated fiber circuit began by developing an integrated fiber transistor structure which is shown in Figure 1-7.

By taking a fiber with this structure built into it and cutting it at the proper



(a) Diagram of Integrated Fiber Transistor.



(b) SEM image of integrated fiber transistor.

Figure 1-7: A cross-sectional view of an integrated fiber transistor. Credit for both of these images goes to Sylvain Danto.

places it it possible to realize many transistors and resistors spaced along the length of the fiber. These can be arranged into circuits such as logic gates.

Chapter 2

Making Electrical Contact with Fibers

In order for any of the optoelectronic fibers that have been produced to be of interest beyond the materials science community, they have to be electrically connected to external circuits. This is a daunting task; the PES layer surrounding the fiber is tough and flexible and the tin electrodes themselves are mechanically weak. The difficulties in connecting to the fiber can be overcome with careful, delicate, manual labor. However, this is time consuming and tedious.

In addition to being a difficult challenge, the outcome of the fiber contacting process affects the conductivity and the reliability of the fiber. A number of different contacting methods were tested in order to improve this costly, inconvenient and critically important step in the development of fibers for use in circuits.

2.1 Traditional Exposure Methods

There are two primary steps which need to be taken to make electrical contact with the electrodes of an optoelectronic fiber. (This process is also referred to as contacting the fiber.) The first is exposing the electrodes; the PES layer needs to be mechanically or stripped away or otherwise bypassed so that the tin electrodes can be manipulated. The second step involves bonding a conductor to the electrodes. The process of



Figure 2-1: Fibers are contacted by wrapping a small wire around an exposed section of the core and applying silver paint. Such a connection is pictured here.

exposure requires much more time and effort than the connection process, so much of this chapter focuses on the exposure of the fibers, though both aspects of the contacting process are considered throughout.

The state-of-the-art electrode exposure method involves taking a razor blade and very carefully cutting away the PES until the electrode is exposed. After the electrode has been exposed, #32 wire is wrapped around the fiber in the exposed area and clamped in place with tweezers. A small amount of silver paint is applied to the wire wrap in order to make it conductive and cause it to adhere to the fiber. After that, the contacting process is complete, though some practitioners add an additional layer of low temperature solder in order to improve electrical properties. A contacted fiber appears in Figure 2-1.

The process for contacting fibers with more complex internal geometries, such as the thin film fibers discussed in Section 1.3, is based on the idea of placing strategic cuts in the electrodes so that lower layers are not connected to a long length of upper layers. For example, for the thin-film fiber of Figure 1-5, three cuts would be introduced to contact one set of inner and outer electrodes as shown in Figure 2-2. In the figure, the outer layer is cut so that it is acceptable to reach the inner layer by shorting through a small portion of the outer electrode.

Though the success of these methods varies greatly depending on the manual dexterity and experience of the person performing the exposure, the yield of exposed

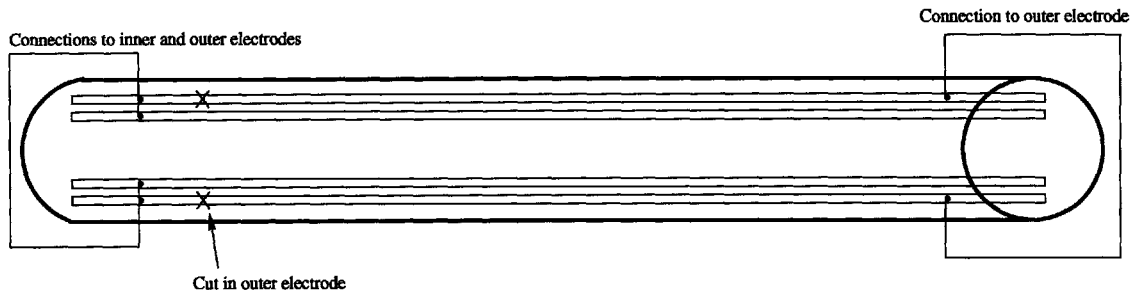


Figure 2-2: By cutting the outer electrode near the end of the fiber, the inner electrode can be contacted by shorting through the outer layer.

fibers with good structural and electrical integrity is very low; the very best contacters may achieve 70% yield. In addition, it takes minutes to contact a single fiber. Clearly more manufacturable alternatives are needed.

2.2 Axial PCB Attachment

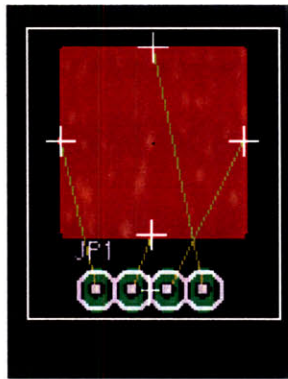
One particularly attractive alternative to exposure by hand involves simply mating the end of the fiber to a printed circuit board. The fiber electrodes are not covered by polymer where the fiber has been cut, so the end of the fiber presents a point for easy contact. In addition, connecting the end of the fiber to a printed circuit board provides a method of immediately including the fiber in a circuit.

In order to test this method of attachment a circuit board was developed to attempt end contacts. Schematics and photographs of the completed board are shown in Figure 2-3.

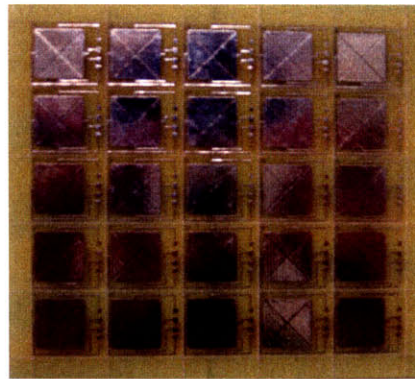
Tests were carried out to attach fibers to these boards using solder paste, conventional solder, and by trying to melt the electrodes so that they would make contact with the PCB pads. Several drawbacks to this method were discovered.

First, the fibers must very carefully aligned with the contact point in order to guarantee that the electrodes will be placed on different pads. While this is possible in an industrial setting where tools like robotic pick-and-place machines are available, it is inconvenient for laboratory purposes.

Second, It is difficult to make a high quality electrical contact with the fiber due



(a) Schematic of a fiber PCB attachment board



(b) Photograph of a an array of fiber PCB attachment boards

Figure 2-3: Though using PCBs to attach to the end of a fiber offers significant manufacturability benefits, it produces joints which still require careful alignment and which are mechanically unsound.

to the tightly designed thermal specifications of the fiber's building blocks. All of the fiber components have melting or glass transition temperatures near to one another in order to simplify the drawing process. Unfortunately, this means that attempting to reflow solder or tin near the fiber will result in PES being melted into the mixture. PES is an insulator, provides poor adhesion and is generally detrimental to the process of attachment.

Finally, the bonds that were successfully made were mechanically weak. This is because of the small bonding area, which provides little force to hold the fiber to the board. In order to keep the fiber pressed against the board a mechanical sleeve would have to be designed to hold it in place.

These flaws rendered the contacting board largely unsuccessful. In order to determine whether this strategy was worth pursuing further. A number of tests were carried out where a mechanical sleeve was improvised and the fiber was attached directly to a conductor (aluminum foil and later, solder paste) rather than a board with a complex geometry. The test structures are pictured in Figure 2-4.

None of these test structures were conductive along their length. Since a proof of concept could not be constructed, this idea was abandoned.

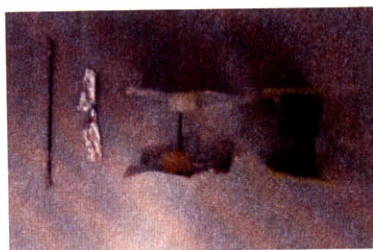


Figure 2-4: Many proofs-of-concept were attempted with end-connectors for the fibers but none were successful. The failure of the tests pictured here led to the abandonment of this strategy.

2.3 Chemical Exposure and Contact

Because the PES presents the largest difficulty in contacting the fibers, the next approach taken to the contacting problem was to attempt to remove the PES. After a short period of research it was discovered that *n, n* Dimethyl Acetamide (NNDA) will dissolve PES and not tin or the various As_2Se_3 compounds in the fibers.

A series of experiments were run to determine how best to expose the fibers. The end of different kinds of fiber (specifically, the thermal fibers described in Section 1.2 and the annealed thin film fibers described in section 1.4) were exposed to NNDA for varying amounts of time. Their thicknesses were recorded before and after exposure. A plot of the dependence of fiber thickness on time appears in Figure 2-5. This data for this plot was taken in room temperature, unstirred NNDA.

It was found that stirring and increasing temperature of the NNDA made the etch rate slightly higher. The temperature increased the etch rate by increasing the energy of the solvent which made the polymer easier to dissolve. It is speculated that stirring broke up the layer of PES-saturated solvent which formed next to the fiber.

It was also found that etching the fibers to near exposure then scraping residual PES off of the electrodes with a pair of wire strippers would yield electrodes that, when freed of the fiber, were much more mechanically robust than if the fiber had been allowed to etch completely to the core. It is speculated that this process left a film of PES on the fiber which helped adhere the exposed electrodes to the core and lent the electrodes some structural stability.

Once the ends of the fibers had been etched off, the electrodes could be separated

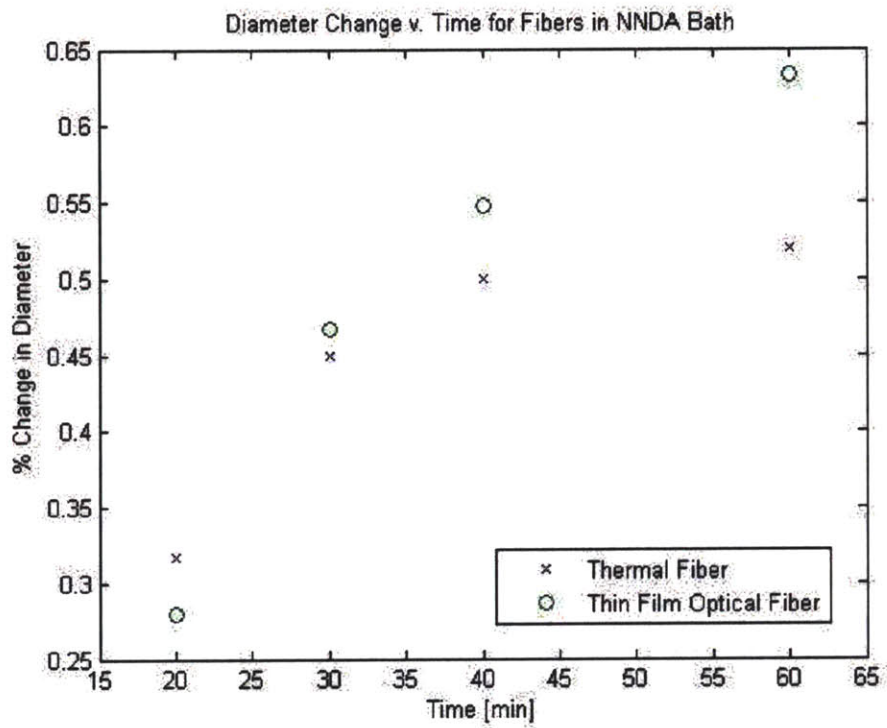


Figure 2-5: The fibers cladding was etched away in an NNDA bath. The values in the plot where change in diameter level off indicate that the entire cladding had been removed and the NNDA was working on the fiber core. This is an exponential process which may be limited by diffusion of the dissolved PES away from the fiber and into the solution.

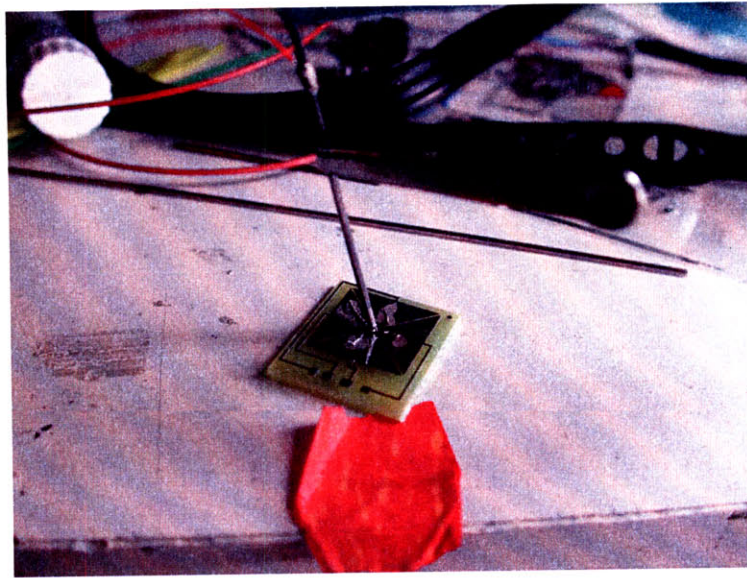


Figure 2-6: NNDA is used to expose the electrodes of a fiber which are attached to a PCB using silver paint and low temperature solder. This process has not been proven effective and is just as time intensive as other contacting methods.

from the core with careful use of tweezers. The core could be snapped off or preserved and the electrodes could be bonded to contact boards with silver paint. The end result of this process is pictured in Figure 2-6.

Unfortunately, the electrodes were brittle and electrical connections were unreliable. In addition, the careful manipulation of the exposed electrodes took nearly as long as the manual exposure process described in Section 2.1. As a result this approach was deemed inadequate to meet the needs of a manufacturable contacting process because it traded off time and effort spent on the exposure of the electrodes with time and effort spent connecting them to the circuit.

2.4 Mechanical Exposure and Contact

After this, a cue was taken from the fiber optics industry. Fiber optics have essentially the same structure as our fibers; a tough polymer coating surrounds a core which must, at certain points, be exposed and manipulated. Research was conducted on what industrial fiber optics tools could be applied to the fibers. In the process of this research it became clear that some standard electrical tools might accomplish



(a) PAL1117 Wire Stripper



(b) Paladin 1257 2-level coax stripper

Figure 2-7: Various electrical wire strippers were used in attempts to expose the fiber's core mechanically. All demonstrated the ability to cut through the cladding, but none could pull cladding axially off of the fiber.

the same goal. Modern wire consists of a conductive core with a polymer cladding that needs to be removed. Because of the lower price associated with these devices, research began with a variety of electrical tools.

The first devices that were tested were wire strippers for electrical wire. Two designs were tested. The first was the Paladin PAL1117, a single level coax stripper pictured in Figure 2-7(a). It was found to cut quickly to the core of the fiber, but was unable to remove sections of it without breaking the core. The second was the Paladin 1257 2-level coax stripper which is pictured in Figure 2-7(b). This tool also demonstrated the ability to cut cleanly to the core of the fiber, but was unable to strip the cladding from it.

Many other mechanical devices which could be press fit to the end of the fiber or wrapped around the fiber have been proposed, but none have been fabricated due to the difficulty of machining them and the requirement of precise alignment with the electrodes that many of them share. An example of this devices is sketched in Figure 2-8.

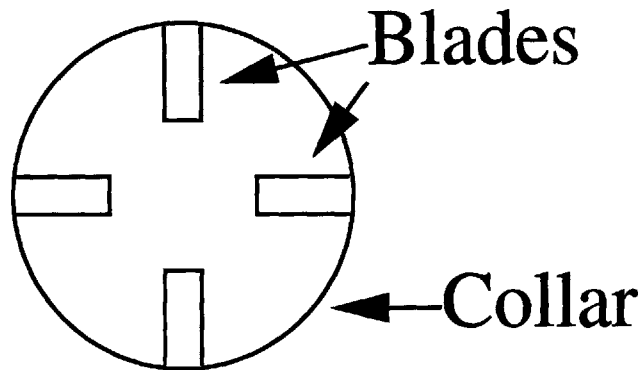


Figure 2-8: This connector would fit axially onto the end of the fiber. The blades could cut through the PES and Sn and make mechanical and electrical contact with the electrodes. Unfortunately, it requires precise alignment and difficult machining.

2.5 Thermomechanical Exposure, Chemomechanical Exposure and other Directions for Research

The lack of success with mechanical exposure was examined. The primary difference between the use of the devices under test in their intended role and in their application to the fibers is the degree to which the cladding is attached to the core. In a copper wire, the cladding is only 'loosely wrapped around the core and can be pulled off by hand using sufficient force. This is not the case with the fibers, where the cladding is very firmly affixed to the core based on the large Van-der-Waals force between the polymer and the core.

In order to enhance the effectiveness of the mechanical stripping process, it has been proposed that a chemical or thermal softening agent be applied to weaken the cladding's grip on the core. NNDA has demonstrated an excellent ability to strip cladding without damaging the core, which suggests that an NNDA bath combined with one of the wire strippers described in 2.4 could effectively remove the cladding of the fiber.

Another option for penetrating the cladding without removing it is the use of a heated pin inserted radially through the cladding. Such a device could be at a temperature above the glass transition point of the PES and the melting point of the tin and, in that manner, penetrate through the layers of the fiber. An advantage is that

this would be fixed in place the material around it as it cooled. This method unfortunately suffers from the same need of precise alignment that many other contacting methods require.

Chapter 3

Arrays of Fiber Sensors

The first application that these fibers were put to was large area sensing. Arrays of fibers can be made very large because the fibers can be drawn lengths of up to kilometers [7]. This is much larger than traditional CCD sensors. In addition, the mechanical ruggedness and flexibility make the fibers ideal for integration into a wide variety of large area sensing roles. For example, the fibers lend themselves easily to integration with clothing.

In order to test the feasibility of the fibers for large area sensing in a variety of applications, a number of arrays were designed and constructed to test the fibers in this capacity.

3.1 Large-Area Sensing

The fibers discussed in the Section 1.1 make exceptionally good large area optical sensors [1, 2]. There are three particular qualities that set the fibers apart from traditional silicon CCD sensors. The first is that the fibers can be drawn to very long length scales, up to kilometers, which allows for arrays much larger than the traditional twelve inch silicon wafer to be constructed at a vastly reduced cost.

The second quality that sets the fibers apart from their silicon counterparts is that they are an integrating medium: light that strikes the fiber anywhere along its length results in a change of the properties of the entire fiber. As a result, a two

dimensional pixel in a fiber imager has to be defined by the intersection of two fibers, one x-oriented and the other y-oriented. This is pictured in Figure 3-1.

Though this may seem like a drawback, it has the advantage of generating a larger number of pixels with a smaller number of sensing elements than a CCD imager. A square image with n^2 pixels made of CCDs requires an $n \times n$ array of the devices. In order to get n^2 pixels out of a fiber imager it is only necessary to provide $2n$ fibers. The intersections of the fibers define a $n \times n$ grid of pixels.

The fact that a pixel must be defined by the intersection of two fibers limits the spatial resolution of fiber imagers to the diameter of the fibers. This is not a concern when sensing over a large area because a pixel density is related to the number of pixels per unit area of sensing. A reasonable pixel density can be achieved on large areas in spite of the large size of the pixels.

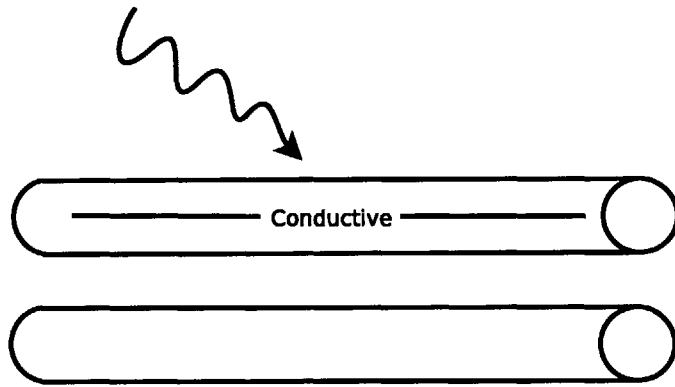
Finally, in order to effectively sense over a large area, a structure needs to be mechanically robust enough to be spread over the area. The fibers are flexible which allows them to be used on non-planar surfaces. The fibers are also mechanically tough which allows them to be used on a wider variety of surfaces.

These properties enable a wide variety of interesting applications for large area fiber sensors. Large-area optical field measurements, combined with phase retrieval algorithms can enable lensless imaging over large surfaces. In addition, the toughness and flexibility of these fibers lends them to incorporation in clothing. A large area thermal sensor incorporated into clothing could be used as a first line of diagnosis for medical conditions.

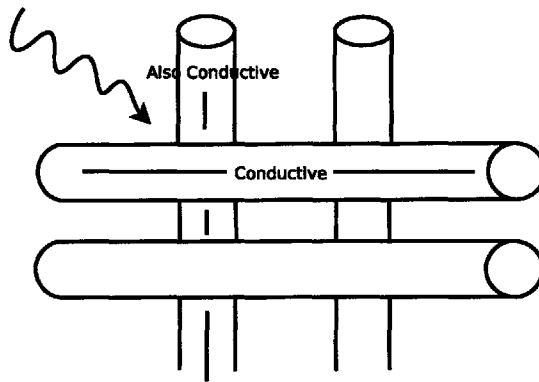
3.2 Optical Fiber Sensing

The first forays into the production of large area optical sensors were made by Jeremy Arnold and are detailed in his thesis [4]. His work consisted of creating an array of the optical fibers discussed in Section 1.1 and using it as a lensless imaging device. Relevant parts of this work are summarized in this section.

The ultimate goal of much of the electronics on the board was to amplify the



(a) Light on a fiber does not isolate a unique point in a plane



(b) Light on two fibers does isolate a unique point in a plane

Figure 3-1: After creating a two dimensional array of fibers, it is possible to identify a point in a plane by looking at the conductivity of the x and y oriented fibers separately.

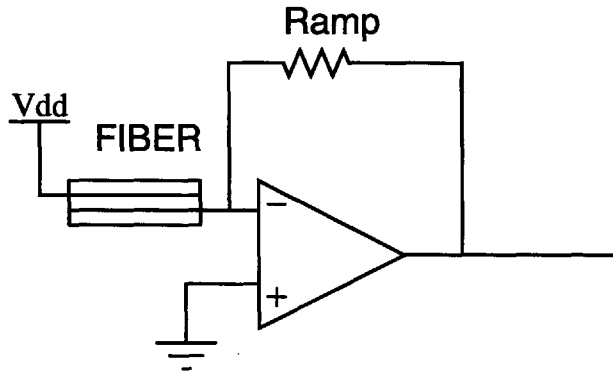


Figure 3-2: This single-stage, transimpedance amplifier measures the current output of the biased fiber. A JFET amplifier is used to minimize noise and input bias. R_{amp} is $1M\Omega$.

fiber's output signal to a level which was well above the minimum sensitivity of the ADC used to interface the fibers with a computer. The 10-bit SAR ADC provided a resolution of one millivolt between ground and the five volt supply.

The optical fibers used in this project had conductivities which ranged from tens to hundreds of megaohms depending on the level of illumination. As a result, the amplifier which interfaced the fibers to the rest of the circuit needed to provide a gain of a one million in order meet the sensitivity of of the ADC. There was no particular bandwidth requirement because this device was only used in a laboratory setting for optical imaging. In addition, using a $\pm 5V$ supply to bias the fibers provided enough signal current that it was well above the input-referred noise of the amplifiers used.

An amplifier which met these specifications was developed. It is pictured in Figure 3-2. An on-board voltage inverter provided $\pm 5V$ power rails which allowed the use of the inverting transimpedance amplifier pictured in Figure 3-2. This inverter generated all of the power rails on the board using a USB power supply.

One of these amplifiers was attached to the output each of 64 fibers in a 32 by 32 arrangement. Mechanical support for this structure was provided by the PCB on which the circuit was constructed. The information from these fibers was routed through four HC4067 16:1 multiplexers to a PIC16C745 which had an internal ADC. The microprocessor sampled each of the fibers in turn and sent the results over USB to a computer for further processing.

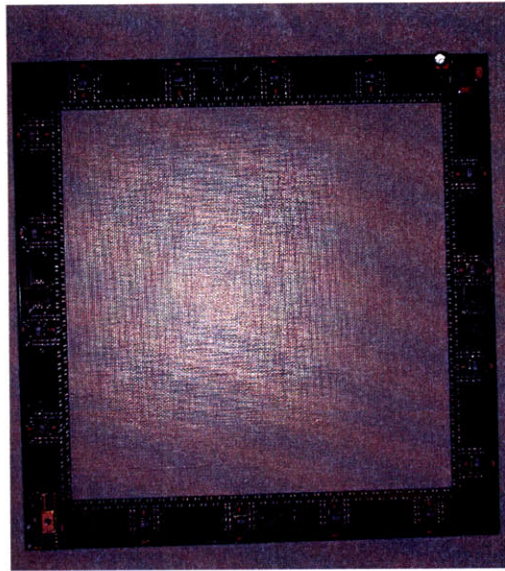


Figure 3-3: A photograph of the optical fiber array implemented by Jerimy Arnold [4].

The fibers for this array were contacted using the manual method detailed in Section 2.1. The finished product is pictured in Figure 3-3 and a full schematic appears in Appendix A.

This array was used successfully as a point detector and two of these devices were used for optical vector detection and for lensless imaging. Two devices were required for the imaging because the phase retrieval algorithm on which the imaging relies requires two measurements of λD , the wavelength of the measured light multiplied by the distance to the image source. These were provided by measuring the image at two different distances using two different arrays.

3.3 Thin Film Optical Fiber Sensing

Sensing multiple wavelengths of light in the same plane is useful because it allows a single sensor array to make two measurements of the commonly appearing optical parameter λD . By measuring this quantity at two different values of λ it is possible to determine λD using only one array for measurement.

In order to measure two wavelengths in the same place, the thin-film fibers described in Section 1.3 were incorporated into a sensor array. These fibers had harsher

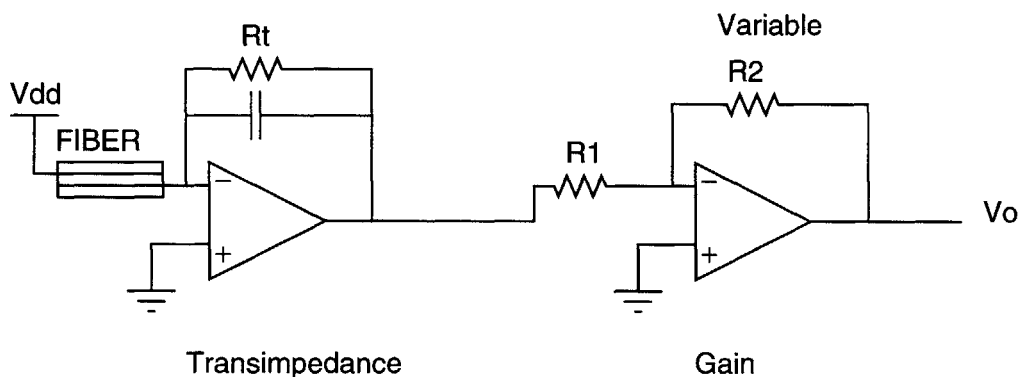


Figure 3-4: A two stage amplifier developed to amplify signals from thin-film fibers. The transimpedance stage converts a fiber signal from current to voltage. The gain stage allows the gain of the amplifier to be tuned to remove materials variations from the drawing process.

electrical requirements than the optical fibers in the previous array: the thin-film optical fibers have a much higher impedance than the optical fibers used in the previous fiber array. Further, there is higher variation between fibers because defects in the thin film are more volumetrically significant and cause more severe effects than in bulk material. This necessitates a much more aggressive amplification strategy. In addition, each of the fibers used in this array provides two channels of information instead of one, which makes it necessary to provide a more significant infrastructure for routing information from the fibers to its destination. One advantage of the thin-film fibers is that the signal to noise ratio of the fibers is improved by the lower dark current, but the overall amount of signal is reduced by the lower current passing through the device.

In order to meet the stricter requirements for the amplification of these fibers, a two-stage amplifier was designed. The first stage was a transimpedance amplifier designed to amplify the fiber signal above the noise-floor. The second was an inverting amplifier which ensured the signal had positive voltage. In addition, the feedback resistance in the second stage could be changed to tune out variation between the fibers. This amplifier is pictured in Figure 3-4. In this amplifier, V_{dd} is fifteen volts, the amplifiers are powered on $\pm 5V$ rails, R_t is $100M\Omega$ and the ratio of R_f to R_i was 100. Because of the stiff power requirements of this amplifier, it was powered off of a

laboratory power supply instead of the USB power bus.

This amplifier has several notable features. The first of which is the extremely large transimpedance resistor. The resistance provided a gain of one-hundred-million and severely limited the bandwidth of the amplifier. The device had a rise time on the order of tens of seconds!

This limitation guaranteed that the fiber imager could not be used for real time applications, but had several useful side effects. The amplifier was so slow that RF pickup, notably 60 Hz, was low-passed out of the signal. In addition, the system's white and pink noise was integrated out during the long rise time. This resulted in a very clean signal, which was suitable for laboratory applications, but very slow.

Later, a prototype of this amplifier was built in which the gain of the amplifier was balanced between the two stages; it was found to have usable levels of gain at frequencies of up to ten hertz, which corresponds to a hundred-fold improvement in bandwidth. Unfortunately, with this bandwidth, the signal measured by the fiber was modulated by 60 Hz pickup.

In order to prevent corruption of the signal by the amplifier, JFET operational amplifiers were used in the circuit. Their low input current bias guaranteed that as much of the signal as possible would pass through the transimpedance resistor and their low input referred noise helped to ensure that the fiber signal would be accurately measured.

The data routing infrastructure on the board was, once again provided by the venerable HC4067 16:1 multiplexer. However, eight multiplexers were required to route data from the 32 by 32 arrangement of fibers two channel fibers to the microprocessor. In order to accommodate the larger number of multiplexer output channels (and for the convenience of internal flash memory) the more modern PIC18F2455 microprocessor was used instead of the PIC16C745 used by Arnold. The change in processors necessitated writing new firmware for the device. Much of the work on the code was made easier by the USB framework provided by Bradley Minch of Olin College [9]. A block diagram of this arrangement appears in Figure 3-5

In order to accurately sample the response of fibers to incident light, a sample

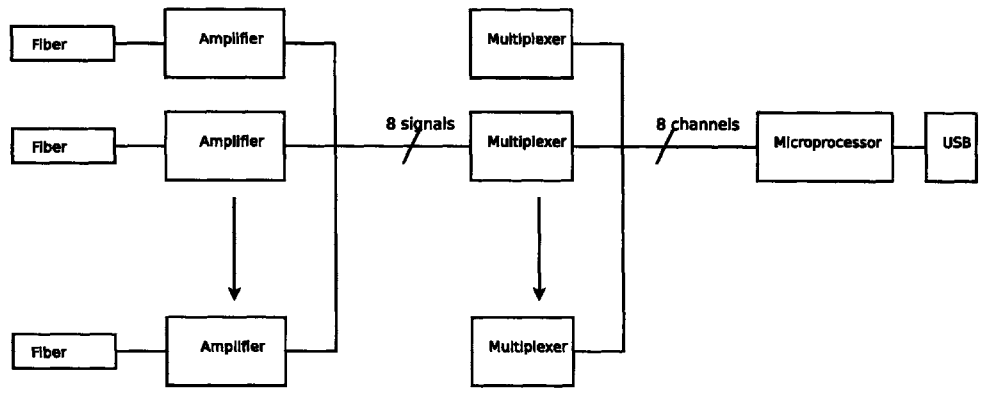


Figure 3-5: Data was routed from the fibers in the array to the host computer using HC4067 16:1 multiplexers and a PIC18F2455.

was taken in dark conditions to get a sample of the dark current of each fiber for normalization. Subsequently, light was applied and the fiber output current was sampled. The sample taken under light was divided by the dark current to obtain a normalized fiber response. An example of the output of the software suite responsible for this computation can be seen in Figure 3-6.

A picture of the completed array is in Figure 3-7. This array was used to take gather data about the fiber behavior and was used successfully to measure an image as seen in Figure 3-8.

3.4 Thermal Fiber Sensing

Large area thermal sensing is another interesting application of these fibers. The thermal fibers detailed in Section 1.2 are suitable for performing this kind of sensing. Because of their much lower resistivity, these fibers don't require an active amplifier. Their response is traditionally measured by placing the fiber in a resistor divider as pictured in Figure 3-9.

A board was designed in order to make an array of these fibers, but was never fabricated. It is pictured in Figure 3-10. A full schematic appears in Appendix A. Data routing and fiber connections for this array do not differ significantly from the examples discussed in previous sections.

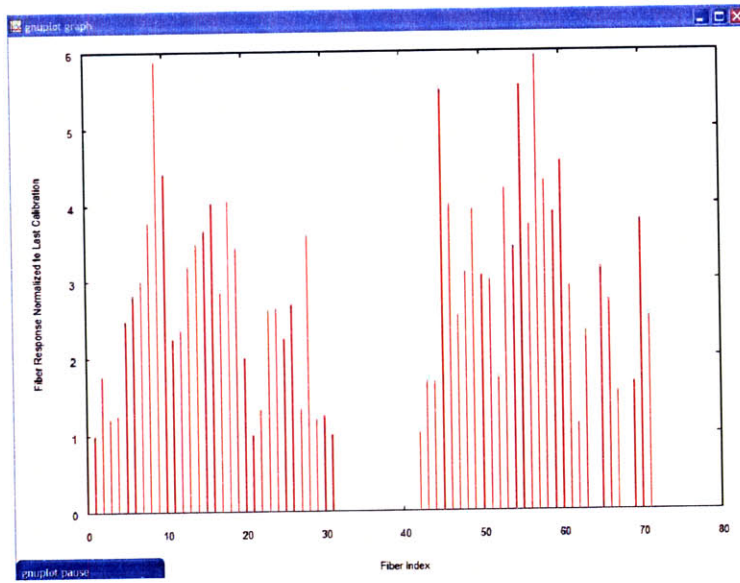


Figure 3-6: The output of the fiber array software suite under two dimensional Gaussian illumination. Each cluster of bars represents the data from one of the two dimensions.

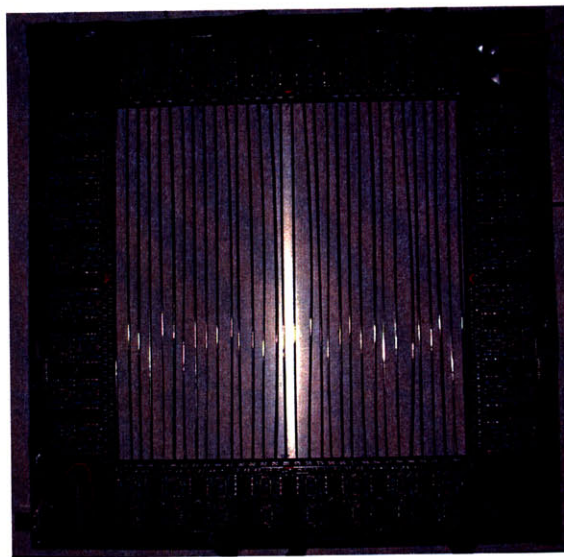


Figure 3-7: A picture of the thin-film fiber array.

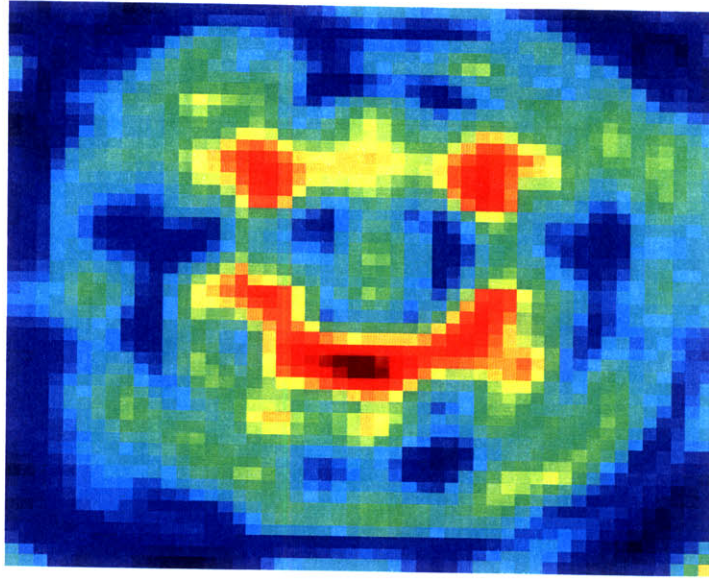


Figure 3-8: A smiley face was shined onto the fiber array and then reconstructed using a phase retrieval algorithm. The results are pictured here.

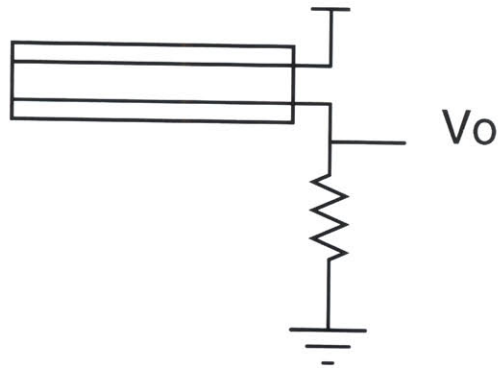


Figure 3-9: Thermal fibers have a high conductivity and their output currents under five volt bias can be measured with only a resistor divider.

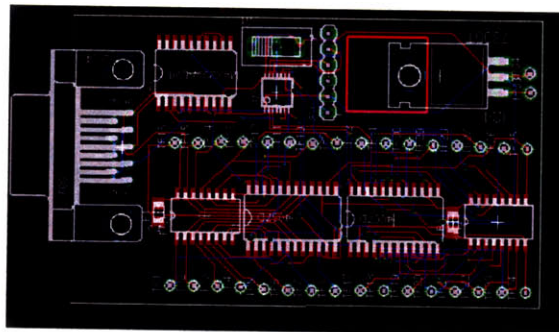


Figure 3-10: A board to sense the output of thermal fibers was designed but never fabricated. Chip resistors are used to form resistor dividers that measure changes in fiber conductance.

Chapter 4

Communication Systems Using Fiber Sensors

The optical fibers discussed in this thesis make an attractive basis for a communications system because of their ready integration into clothing, their mechanical durability and their ability to sense over large areas. A communication device was designed and built in order to demonstrate the fibers suitability for communications. This device was also used to experiment with high speed electrical interfaces to the fibers. The initial communication system developed was designed for integration onto a soldier's helmet. The electrical interfaces to the fibers required for this project are described here.

4.1 The Channel Capacity Problem and Fiber Selection

The most fundamental concern of any communications system is the channel capacity: the amount of information that can be communicated across the communication channel per second. Claude Shannon proved that the channel capacity of a link was proportional to the bandwidth and proportional to the natural logarithm of the signal-to-noise ratio of the channel. Clearly, in order to maximize the amount of

information that can be communicated across the link it is necessary to maximize both the bandwidth and the signal-to-noise ratio of the channel.

In order to maximize the signal-to-noise ratio of the channel it is necessary to pick the proper sensing device. The discussion of the thin-film optical fibers in Section 1.3 explains that a thin-film fiber has a greater signal-to-noise ratio than a fiber with a filled bulk. This makes a thin-film fiber a clear choice for the development of the communication system. The annealed fibers from Section 1.4 have greater conductivity than their non-annealed counterparts and this allows charge carriers to move more quickly through the fiber. The greater conductivity of these carriers gives the fibers a wider bandwidth.

With the selection of thin-film annealed fibers, the only design decision remaining is what part of the spectrum to sense. The thermal fibers from Section 1.2 demonstrate the largest swing in conductivity under an applied signal from the part of the electromagnetic spectrum to which they are most sensitive. Unfortunately, ambient thermal variations are large and occur often. In addition, making a beam of heat hot enough to overwhelm body heat at any reasonable range would require prohibitive amounts of power and be very uncomfortable to humans at the receiver.

An optical frequency radiation signal would have to compete with less ambient radiation than would a thermal signal, especially at night. However, in order for this communication system to be usable by humans it needs to be eye safe and, ideally, somewhat discreet. As a result the optical spectrum is largely ruled out.

A compromise was struck by deciding to design a fiber to be sensitive to $1.5\ \mu\text{m}$, near infrared radiation, which would be both eye safe and have little competition from local sources. Because this fiber was still being designed at the time of this thesis, all work was done on annealed fibers sensitive to the optical spectrum as described in Section 1.4 and InGaAs NIR photodiodes which simulated the desired fiber qualities.

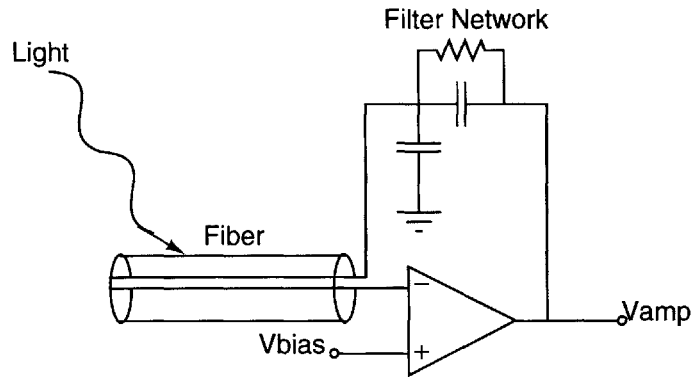


Figure 4-1: Current output by the fiber passes through the full, open-loop gain of the operational amplifier. The bias of the fiber is compressed based on the optical signal it receives.

4.2 Interface Circuits

In order to have any reasonable data rate across the channel, the bandwidth of the system must be much wider than that described in Chapter 3. The amplifier was the device which limited the system's bandwidth even though slow, low-signal fibers were used in the arrays. Clearly a new amplifier was required for this application.

The gain specification on the new amplifier can be relaxed slightly because the annealed fiber demonstrates a higher conductivity than a fiber which is not annealed. The conductivity is further improved by the greater carrier density expected from the smaller band gap for 1.5 μm sensing fibers. In addition, the communication system only needs to be able to sense whether a digital signal is being transmitted and does not need to report a precise analog value for the computation of an image.

However, the circuit designed for the communication must be more portable than the laboratory version and thus cannot run on a split rail power supply. In addition, this portability demands that power dissipation be kept low in order to maximize useful operation time on a single battery charge. This power constraint suggests that the amplifier should require a small number of operational amplifiers.

Bearing these specifications in mind, an amplifier was designed. It is pictured in Figure 4-1. The same amplifier was used both for the fibers and for the InGaAs detector. Inspiration for this amplifier was drawn from a similar device presented in

a ultra-low-power electronics course [10]. Again, JFET operational amplifiers were used for their low input-referred current noise and low input current bias.

The most notable feature of this amplifier is that the fiber is placed in the feedback path of the amplifier. This amplifies the optical signal by the full, open-loop gain of the amplifier through the following mechanism: Any light incident on the fiber excites charge carriers in the core which are swept to the node connected to the inverting input of the amplifier by the bias across its terminals. The current on this node generates an error signal which causes the output to decrease. This decrease is filtered through a passive network that shapes the frequency response of the system and the filtered signal compresses the bias across the fiber terminals which reduces the current being driven into the amplifier.

Another way to view the feedback in this amplifier is to note that V_{out} is constrained to move such that no current from the fiber passes into the inverting terminal of the operation amplifier. This links the output voltage with the level of incident light through the transfer function of the amplifier.

This has a number of significant advantages over the amplifier topology presented in Section 3.3. Because the output current of the fiber is amplified by the open-loop gain of the amplifier, the closed loop gain does not need to be as large as the transimpedance amplifiers presented in Section 3.2. This results in a much wider bandwidth. Only a single power rail is required because the amplifier output can be set by adjusting the bias on the non-inverting input of the operational amplifier. Finally, only one operational-amplifier is required which saves on power and on board real-estate. Further savings in the number of components required can be realized by hooking multiple fibers in parallel to the input of the amplifier; parallel connected fiber currents will add allowing a small mesh of fibers responsible for sensing the same area to be connected to the same amplifier.

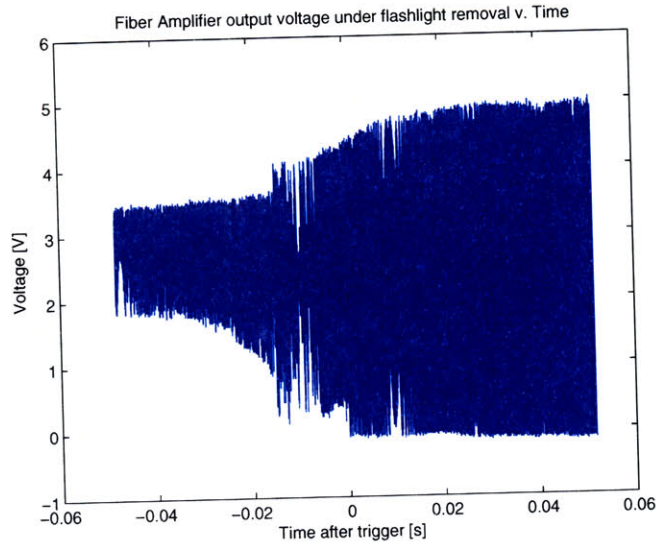


Figure 4-2: The voltage oscillations the fiber picks up while acting like an antenna are modulated by the amount of incident light. Incident light reduces the amplitude of the of the 60Hz pickup.

4.3 Filtering Local RF Pickup

The fibers used here resemble antennas: the electrodes are lengths of conductors which are attached to high-gain, low-noise amplifiers. This causes a great deal of radio frequency radiation to be coupled into the output signal of the circuit as seen in this scope trace of the output of one communication fiber amplifier 4-2. The 60Hz pickup dominates the normal output signal and is squelched by the negative feedback of the amplifier under illumination. In order to use these devices in a wide variety of radio frequency conditions and in order to simplify the measurement of the communication signal, the RF pickup has to be filtered out of the signal.

To do this, it was decided that multiple light sensing fiber meshes would be mounted on each helmet. This has the dual benefit of allowing the sensor to determine what direction incident light is coming from and collecting multiple samples of the local RF environment. By measuring sensors on opposite sides of the helmet differentially, any radio frequency pickup can be filtered out of the signal while preserving directional, optical signals.

The circuit designed to make this differential measurement is pictured in Figure

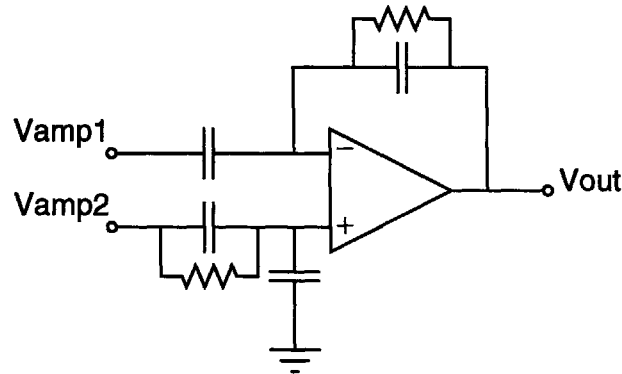


Figure 4-3: This differential structure filters RF pickup out of two sets of fibers. Additional RC filters target 60Hz.

4-3 The differential amplifier takes the output of two of the amplifiers described in Section 4.2 as its input. These pass through passive filters designed to specifically filter out the omnipresent 60Hz. Because all of the amplifiers that the differential amplifier takes as its input are biased to center their signal at $V_{dd}/2$, one of the input signals is AC coupled to eliminate its bias. This results in an output which is still nominally centered around $V_{dd}/2$. An output capacitor can be added to filter high frequency components of the output signal.

This circuit resulted in adequate filtering of RF pickup as seen in the oscilloscope capture of its output in Figure 4-4. The high frequency oscillation in the image is a steady 10 kHz oscillation which is present because of minor differences in the routing and performance of the two input amplifiers; it represents incompletely cancelled pickup. The envelope function which modulates the 10kHz signal is transmitted by an LED flashing at the circuit. This figure demonstrates the channel operating at its maximum data rate of 5 kHz.

4.4 Digitizing the Input

Careful timing on the sampling of the differential amplifier was necessary In order to avoid measuring the 10kHz carrier which the optical signal modulates. By deliberately under sampling the signal it is possible to filter out the carrier signal. This is done by transmitting at five kHz, half of the carrier frequency, and sampling at 10kHz to

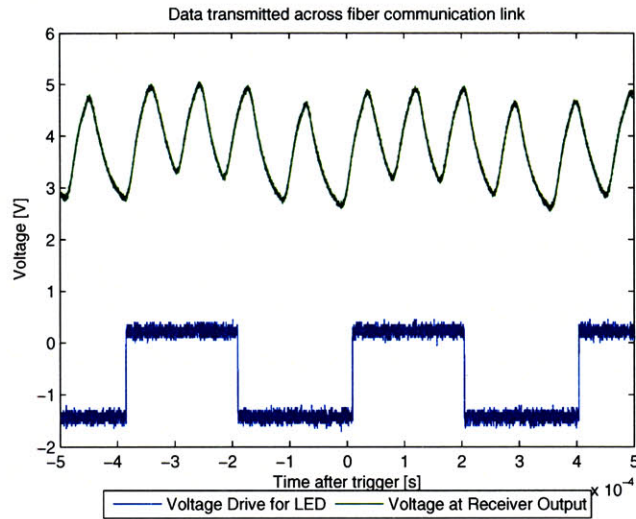


Figure 4-4: The output of the differential amplifier oscillates at 10kHz but the depth of the amplifier's troughs is modulated by the intensity of the signaling LED. Here, when the LED drive is positive, the device is giving off illumination.

alias the high frequency wave.

It is possible to guarantee that we sample only the lowest points of the carrier waveform by sampling at 10kHz and adjusting the phase at which the sample is taken. Once the sampling is locked onto the troughs of the carrier, the signal which is measured should only vary high and low based on optical transmissions because the optical transmission causes the depth of the trough to change.

This locking was carried out by the microprocessor at the heart of the communications system: a PIC18F4550. An ADC was set to convert at 10kHz and the ADC interrupt handler modified the special function registers necessary to get and maintain a lock on the low point of the transmission. This chip was also responsible for measuring audio input, talking to the DAC which generated audio output, reporting on the status of communication over USB for debugging and managing the power consumption of the system by turning unused components off.

The complete receiver is pictured in Figure 4-5. The schematic for the receiver appears in Appendix A.

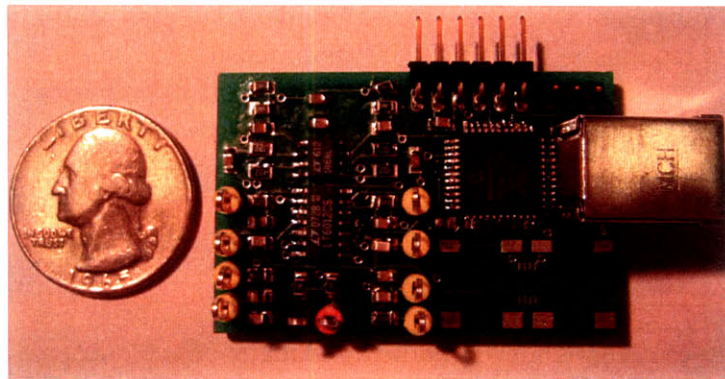


Figure 4-5: The receiver board for the fiber communication system is aggressively miniaturized. It features a USB communication system for debugging, an analog front end for the fibers and an audio DAC (not populated).

Chapter 5

Integrated Fiber Transistor Logic

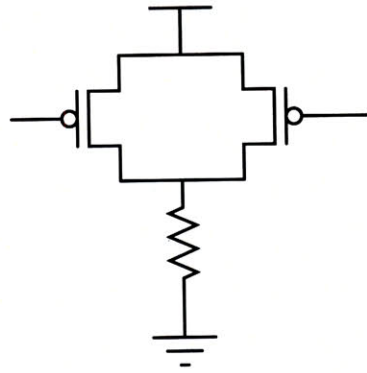
The advent of crystallized sections of fiber allowed for new topologies such as the integrated fiber field effect transistor discussed in Section 1.5. These devices raise the possibility of creating integrated circuits in an entirely new medium.

A fiber containing the integrated fiber transistor was fabricated and formed into a digital logic gate in order to test the applicability of this fiber structure to producing digital circuits.

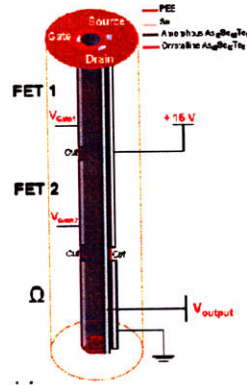
5.1 Selection and Construction of Circuit Under Test

The unmodified length of fiber produced for these experiments represents a single transistor which is distributed axially along the fiber. In order to design a digital logic gate it is necessary to cut the fiber electrodes at appropriate points to form useful circuit elements.

It is only possible to achieve accumulation with current fiber transistor architectures so only one type of transistor can be made. As a result, it was decided that an RTL gate should be produced for testing. Fabricating the transistors for this gate is straightforward; cutting the gate electrode forms a separate length of the fiber with an isolated gate. A voltage applied to the isolated length of gate will cause accumula-



(a) An RTL NOR gate.



(b) An RTL NOR gate realized in a fiber structure. Credit to Sylvain Danto.

Figure 5-1: A logic gate is integrated into a fiber transistor structure by introducing cuts in the transistor's gate along its length. It parallels the RTL NOR gate shown.

tion in the length of fiber attached to that gate but will not affect the other sections of the fiber. The resistor can be made from a standard transistor by using the drain-source resistance and grounding the gate to prevent stray signals from changing the conductance.

These modifications were made to the fiber which resulted in the structure pictured in Figure 5-1(b). This design implements an RTL NOR gate inside the fiber.

5.2 Experimental Setup and Supporting Electronics

The data most relevant to demonstrating the feasibility of this device as a logic gate is its switching transients; the behavior of the output voltage as a function of time in response to a change in the digital code at the input.

A static discipline was developed in order to quantify whether or not the device was behaving as a logic gate. A voltage of $-300V$ needed to be applied to the gate in order to cause accumulation so $V_g = -300V$ was defined as an input zero. $V_g = 0V$

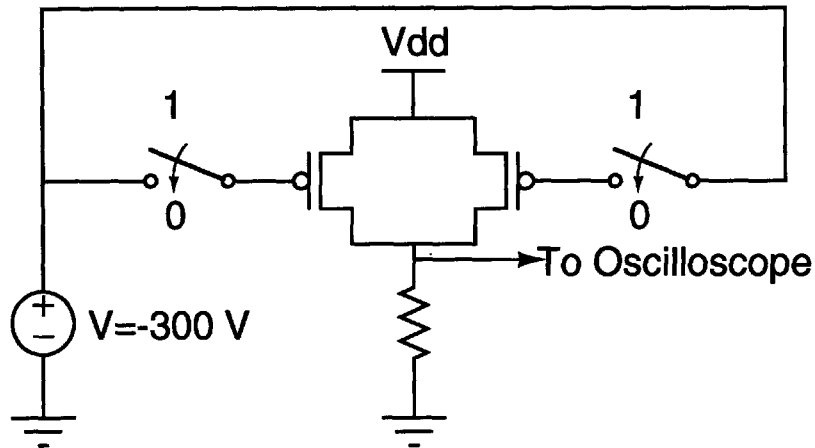


Figure 5-2: The fiber logic gate was tested by applying 0V or -300V to the gate of one or both transistors and watching the output node. V_{dd} was 15V for the majority of experiments and for the results reported in Figure 5-4

was defined as an input one. The output was expected to switch a smaller amount, but because of variations in the fiber it was infeasible to define output voltage levels before performing the experiment.

The high voltage applied to the gate was necessary to create accumulation in the semiconductor. Deep level traps in the semiconductor pin the Fermi level and it requires a strong potential to move it. It is impractical to expect a 300V supply to be used in a standard circuit, however with proper annealing of the semiconductor and optimization of the transistor structure it is expected that the required gate voltage can be reduced.

The switching transients were to be measured by hooking up a three-hundred volt power supply to one or both of the inputs and switching it from on to off while measuring the output voltage with an oscilloscope. This setup is pictured in figure 5-2.

A buffer was needed to measure the output of the fiber logic gate because the pull down resistance derived from the drain-source resistance of the transistor was very large. The pull down resistance was approximately $150\text{M}\Omega$, which is well in excess of the $10\text{M}\Omega$ load presented by the oscilloscope; the oscilloscope probe would load the circuit in such a fashion that it was unable to operate.

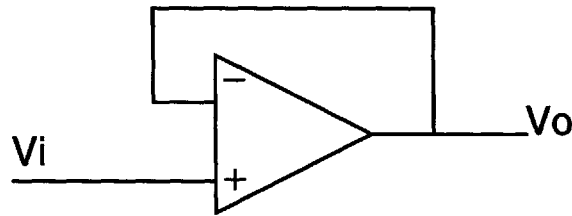


Figure 5-3: A simple JFET op-amp buffer was used to prevent the oscilloscope probe from loading the output node of the fiber logic gate. The probe would have prevented any current from flowing through the pull down resistor leading to no change in output voltage.

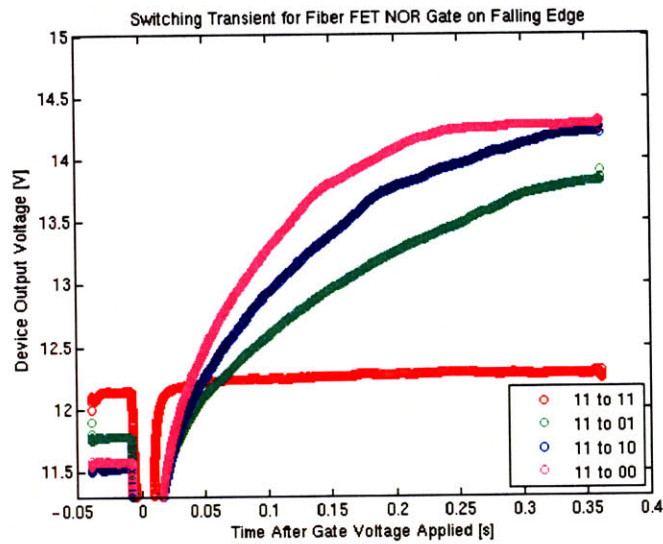
A simple operational amplifier buffer was constructed to mitigate this problem. Once again, a JFET amplifier was used for its superior noise performance and its low input current bias, which minimized the loading of the logic gate and the corruption of its output signal. The buffer used is pictured in Figure 5-3.

5.3 Results of Device Characterization

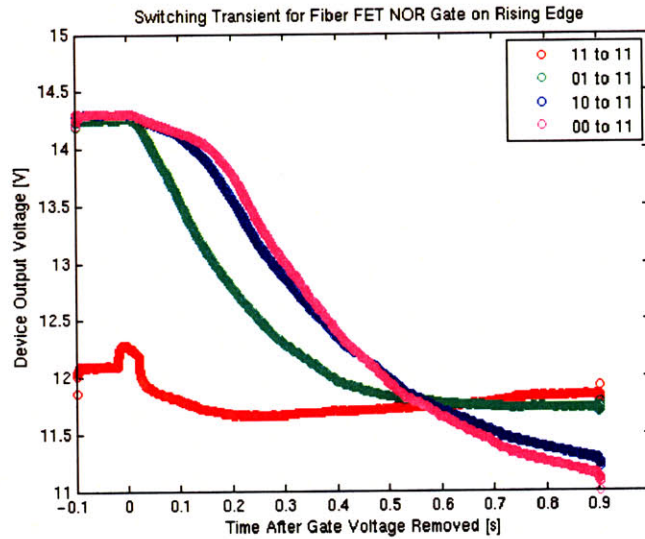
The switching transients for both rising and falling edges on the gate were measured and the output is shown in Figure 5-4.

This data features a noticeable disturbance at $t = 0$ s: the time when the power supply was turned on. This is due to the behavior of the power supply as it switches from applying zero to three hundred volts and does not reflect the performance of the fiber circuit.

The rise time of the NOR gate is significantly faster than the fall time. This is because the rise time is linked to the rate at which charge carriers are driven into the active transistors and fall time depends on the passive recombination of electrons and holes in the semiconductor.



(a) Switching transients for rising edges on the fiber logic gate's input



(b) Switching transients for falling edges on the fiber logic gate's input

Figure 5-4: Switching transients for Fiber NOR gate. The rising edge is significantly faster because the falling edge relies on inherent recombination processes to eliminate charge carriers.

Chapter 6

Conclusion and Future Work

6.1 Summary of Research

The process of contacting optoelectronic fibers produced by the Fink group was discussed. A number of possible contacting methods were illustrated and their failure modes were discussed.

An optical sensing array for two-level, thin-film fibers was developed. This included a novel fiber amplification circuit that filtered noise and RF pickup. This was used to generate an image.

An optical communication system based on annealed fibers was developed. This included a pair of novel interface circuits to talk with the fibers. The first circuit put the fiber in the feedback path of an operational amplifier so that light signals were amplified by the entire open loop gain of the op-amp. The second was a differential amplifier which filtered local RF pickup. The two resulted in a huge increase in usable fiber bandwidth.

An integrated fiber transistor was used to prepare the first fully integrated fiber logic gate. The device switching behavior was characterized.

6.2 Recommendations for Future Work

Based on the research that has been performed several avenues of future research present themselves.

The ability to contact fibers reliably is critically important. The methods in Section 2.5 should be explored and a manufacturable and efficient fiber contacting process should be developed.

In order to use fibers effectively in circuits it is important to characterize their frequency behavior so that the standard methods of control theory can be used to design around the fibers. It is also valuable to develop a circuit model for the fibers that clearly illustrates their parasitic and desired behavior. These will simplify the design of fiber circuits.

Steps should be taken towards more complete integration of fiber circuits because they are an exciting new medium in which to construct increasingly complex devices.

6.3 Concluding Remarks

Optoelectronic fibers are an exciting new medium and work has been done to interface them to the outside world. It should continue.

There are two primary contributions of this work. The first is the experience gained in fiber contacting processes in Chapter 2. Though a useful method of contacting fibers was not discovered, the work in that chapter eliminates a number of options. The second major contributions were the novel circuit topologies described in Sections 3.3, 4.2 and 4.3. These circuits should be suitable for amplifying the fiber signals over a wide range of applications.

It is critical that the frequency performance and parasitic capacitances and resistances of the fibers be characterized in order to improve the ability to design circuits around them. It is strongly recommended that research progress in this direction.

Appendix A

Schematics

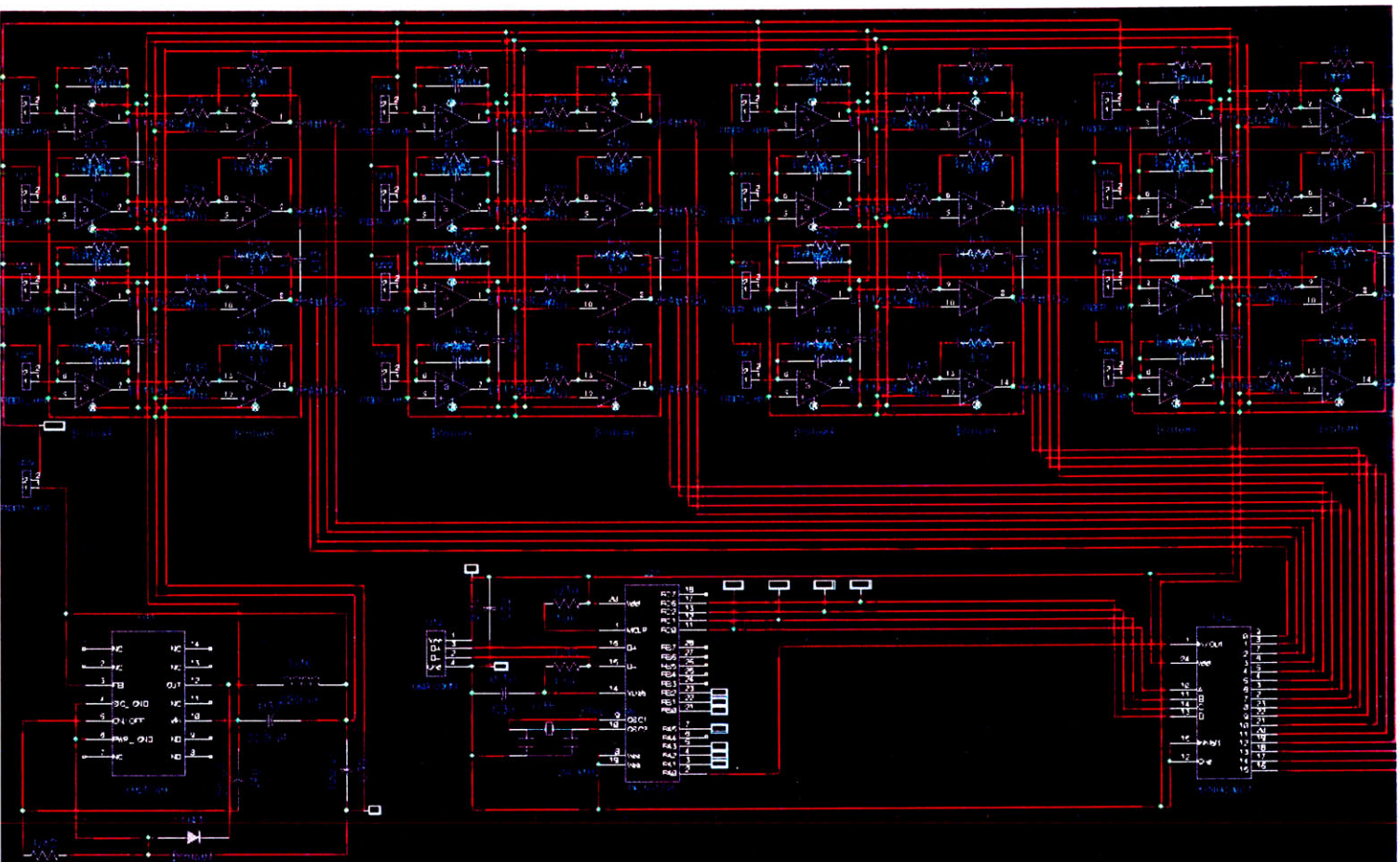


Figure A-1: Schematic of optical sensing array developed by Jeremy Arnold [4].

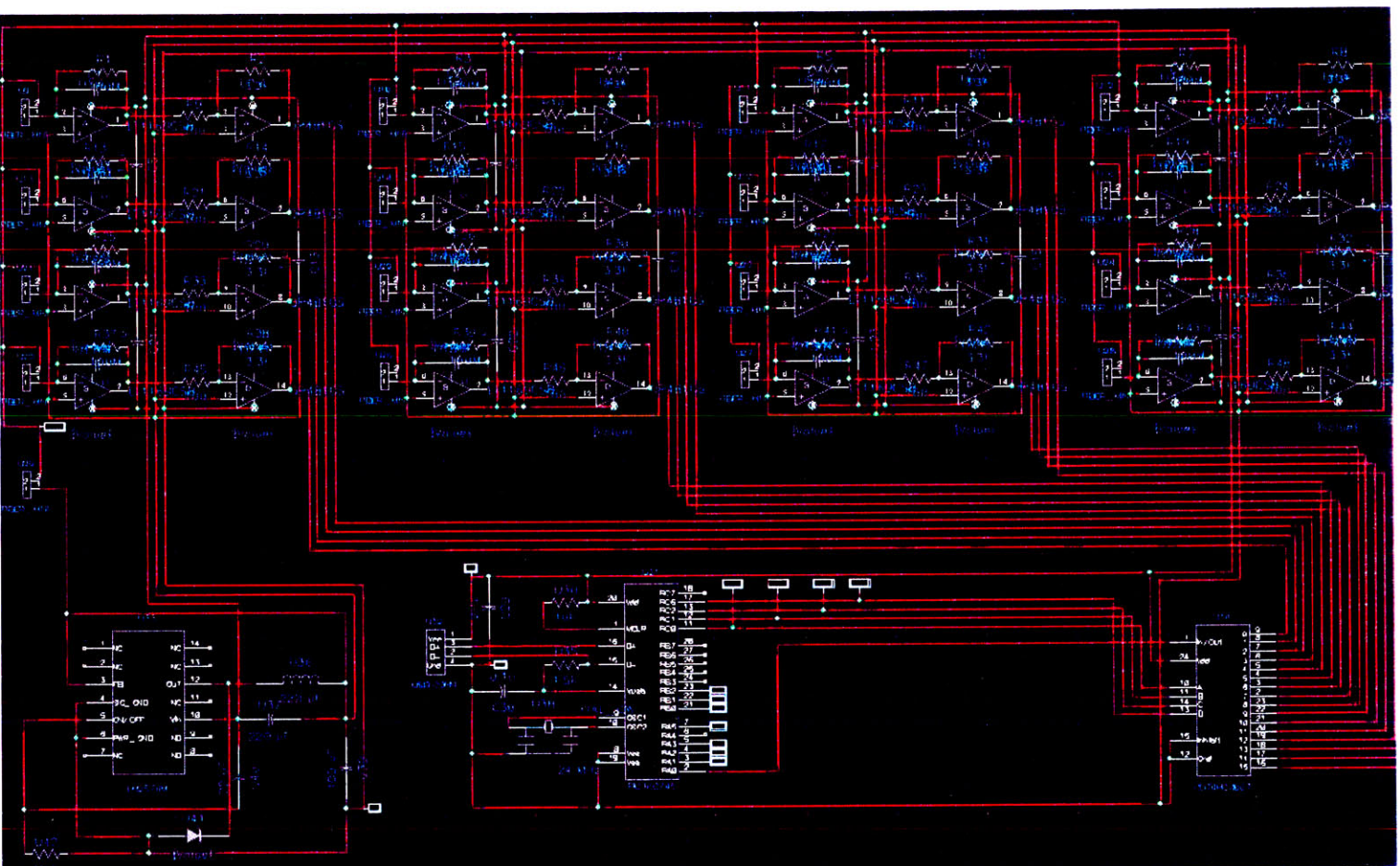


Figure A-2: Schematic of thin-film optical sensing array.

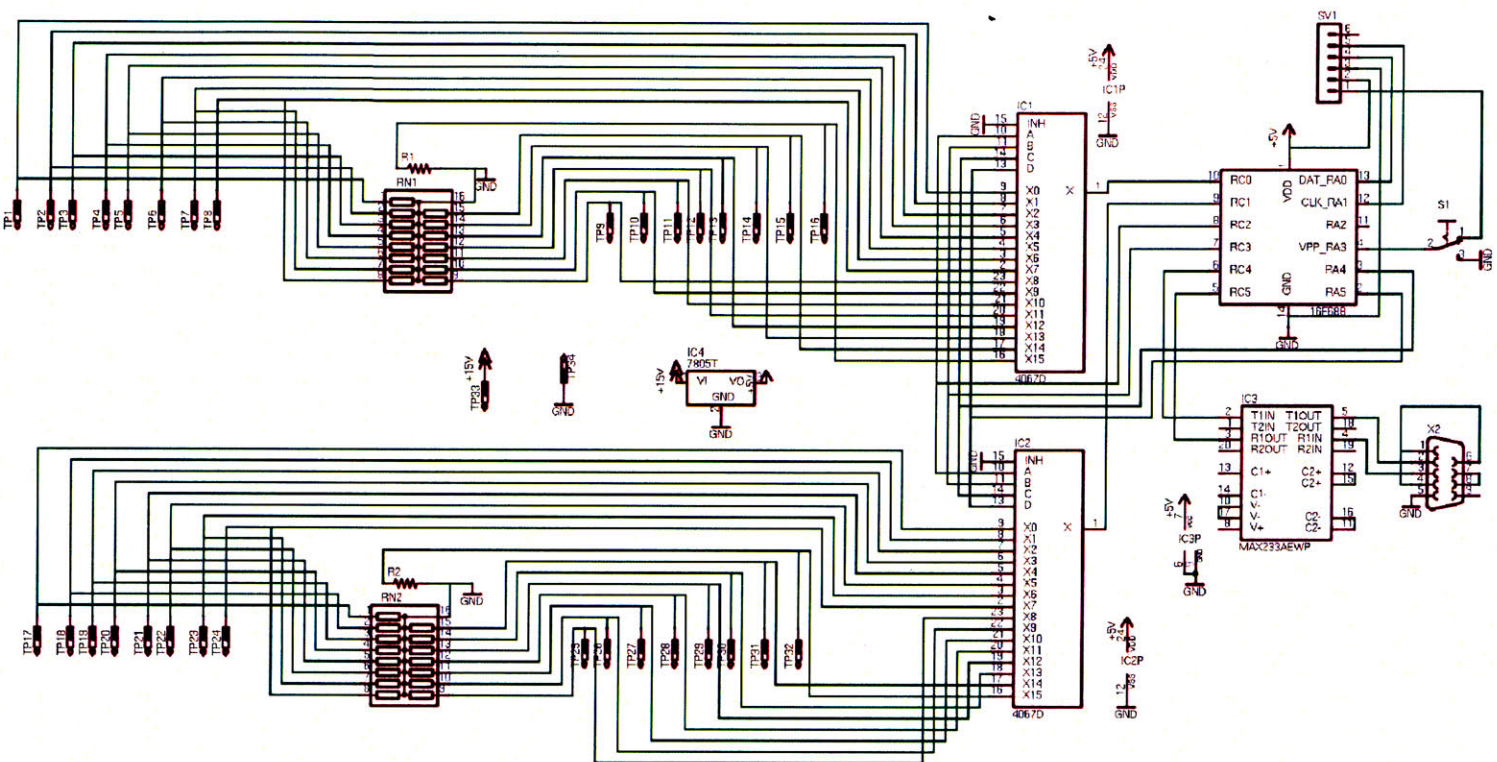
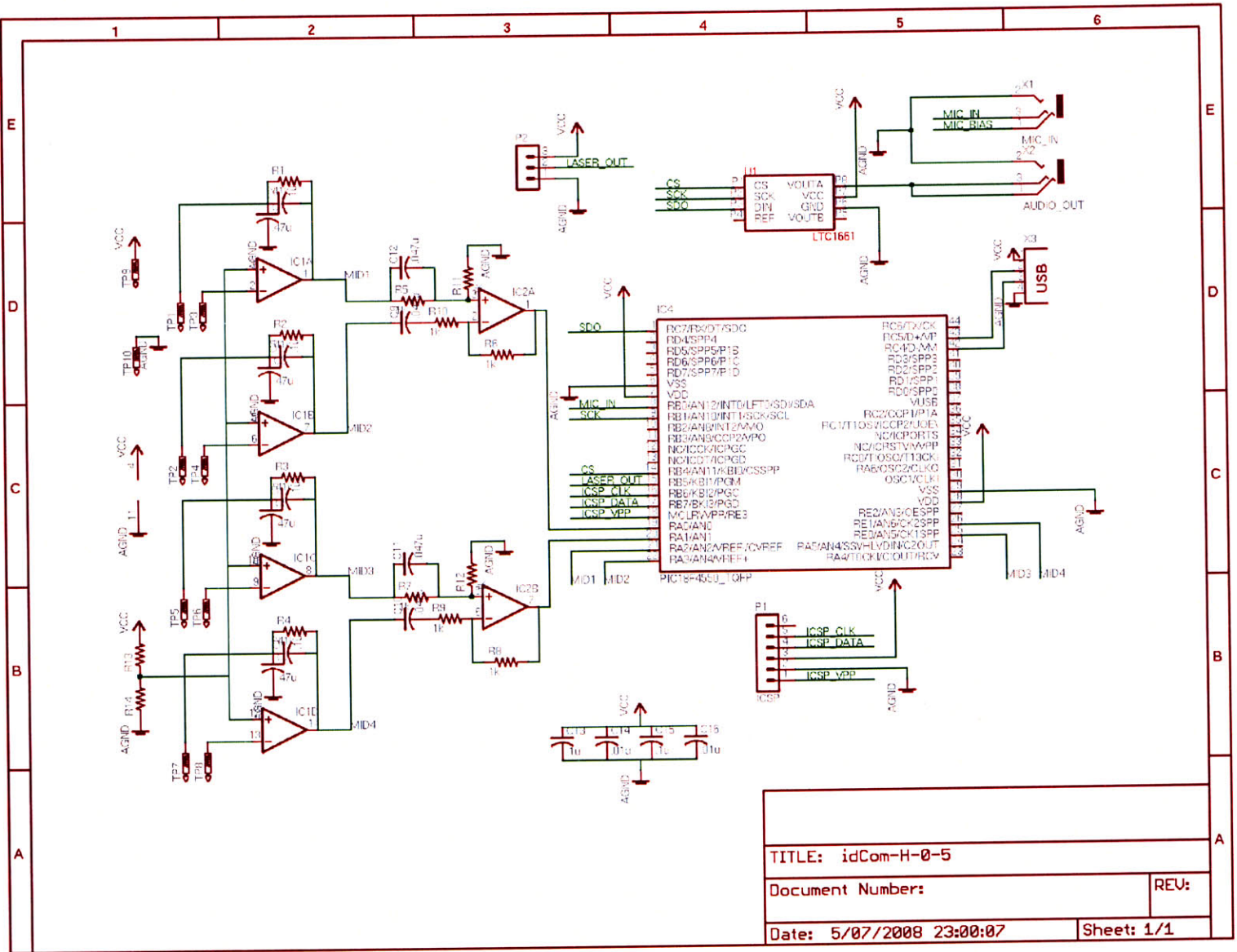


Figure A-3: Schematic of thermal fiber sensing array.



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Figure A-4: Schematic of fiber communication system receiver board

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