A Study of Single Mode Optical Fiber Test System

A Thesis

Submitted to the College of Graduate Studies and Research

in Partial Fulfillment of the Requirements

for the Degree of

Master of Science

in the

Department of Electrical Engineering

University of Saskatchewan

by

JIAN XIN CHEN

Saskatoon, Saskatchewan

January 1989

In Memory of

My Beloved Father

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ACKNOWLEDGEMENTS

The author would like to express his gratitude and appreciation to Dr. Hugh C. Wood for his guidance and consistent encouragement throughout the course of this work. His advise and assistance in the preparation of this thesis is thankfully acknowledged.

The author would like to thank Mr. Bennete Wong and Mr. Larry Posavad of the Northern Telecom Ltd. for their help during the study.

Special thanks are extended to his mother and brothers for their constant supports and encouragement. The author would also like to take this opportunity to thank all friends for their help during the years.

Financial assistance provided by the Northern Telecom Canada Ltd. in the form of the Northern Telecom Scholarship is thankfully acknowledged.

UNIVERSITY OF SASKATCHEWAN

Electrical Engineering Abstract 89A306

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M. Sc. Thesis Presented to the

College of Graduate Studies and Research

January 1989

ABSTRACT

This thesis is based on a study of single mode optical fiber test systems in the optical fiber manufacturing process. The study focussed on the operating procedure used in the testing of four important single mode fiber parameters. These parameters are the fiber attenuation, cutoff wavelength, mode field diameter and geometry. The automation of the fiber test process was also investigated. An integration of the existing test setup, which currently consists of three seperate test stations, could provide an opportunity to streamline the test procedure and, consequently, improve the test efficiency and quality. The design and testing of an automatic fiber alignment unit to be used with the fiber test system is also presented. This system could be used to automate the test fiber end alignment with the light source and detector in the test procedure.

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1. INTRODUCTION

1.1. Optical Fiber Technology

Optical fiber technology has matured over the last eighteen years. Since the pioneering work on producing high purity glasses (the prerequisite for light propagation with low attenuation) was done in the USA in 1970 [1], progress has been made in the mass production of high quality optical fiber and fiber cables and many other optical/electronics components, such as laser diodes and photodetectors [2].

The major applications of optical fiber technology are in the area of digital communication [3]. Low attenuation and huge transmission capacity make optical fiber an attractive alternative to copper cable and other signal transmission media. Numerous optical fiber communication systems have been successfully installed around the world. It has proven to be a promising technology and to have an important role to play in future information and communication systems.

In addition to the advantages manifested in communication applications, some other merits of optical fiber, such as immunity to electromagnetic interference, have promoted numerous industrial applications [4], particularly applications under adverse operating conditions. Studies have shown that optical fibers can be used as sensors to measure many physical variables [5]. Some integrated optical fiber systems, including optical fiber sensing, telemetry, information transferring and processing, and control, are expected to emerge. This would further open up a wide range of optical fiber applications [6].

Optical fibers are threadlike structures, which are made of highly transparent material, such as silicate glasses or plastics. The physical structure of an optical fiber consists of a light-guiding region, referred to as the core, and a coaxial outer region, known as the cladding. To protect the fiber from abrasion, a plastic jacket is also coated on the fiber cladding surface during the fiber drawing process. Figure 1.1 shows the cross-section of two types of optical fiber [6].

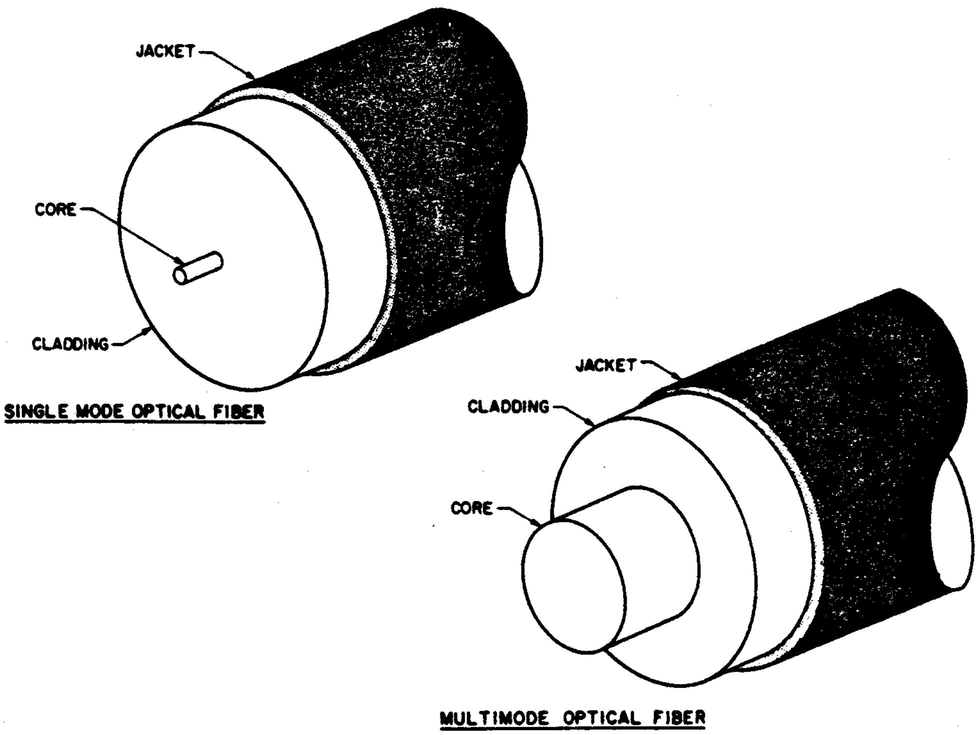

Figure 1.1: Cross-Section of Two Types of Optical Fibers.

There are several different types of optical fibers in the marketplace. However, based on their radial refractive index profile and modal properties, optical fibers can generally be categorized into three basic types, i.e., multimode step index fiber, multimode graded index fiber, and single mode fiber [7]. Figure 1.2 illustrates these three basic types of fibers. A multimode step index fiber has a uniform refractive index in the core region and an abrupt change of refractive index at the core-cladding boundary. It has a relatively large core size and supports many electromagnetic wave propagation modes. In a graded index fiber, the refractive index of the core region changes gradually from the center to the core-cladding boundary. Because of reduced dispersion effects, multimode graded index fiber provides a much better information carrying capacity than multimode step index fiber and, therefore, is the major type of multimode fiber used. Single mode fiber usually has a step index profile and a small core size. As its name indicates, single mode fibers support only one mode of light transmission. These features make single mode fiber significantly different from multimode fiber in term of transmission characteristics. This important issue, single mode vs. multimode fiber, will be elaborated later in this section.

Light propagation over optical fibers can be, approximately but adequately, modelled by ray optics. The ray optics model of fiber propagation is illustrated in Figure 1.3. When a light is projected onto a fiber end face, it enters the fiber core region and bends toward the fiber axis. The angle, θ, of the refracted ray is related to the entrance angle and to the refractive indices of the fiber core and air by Snell's law. The travelling light wave strikes the fiber core-cladding interface as it propagates through the fiber core region. If the incident angle of the light relative to the interface normal is greater than the critical angle at the interface, the light is totally reflected back into the core region. The reflection is due to the core refractive index being slightly larger than the refractive index of the cladding. This total reflection will repeatedly occur as the light travels through the core region. The travelling light is, therefore, confined to the core of the fiber and its propagation takes a zig-zag path. This propagation is depicted as ray 1 in Figure 1.3.

Figure 1.3 also shows that some of the rays that enter the fiber core are not propagated through the fiber. Ray 2 in the figure shows that the

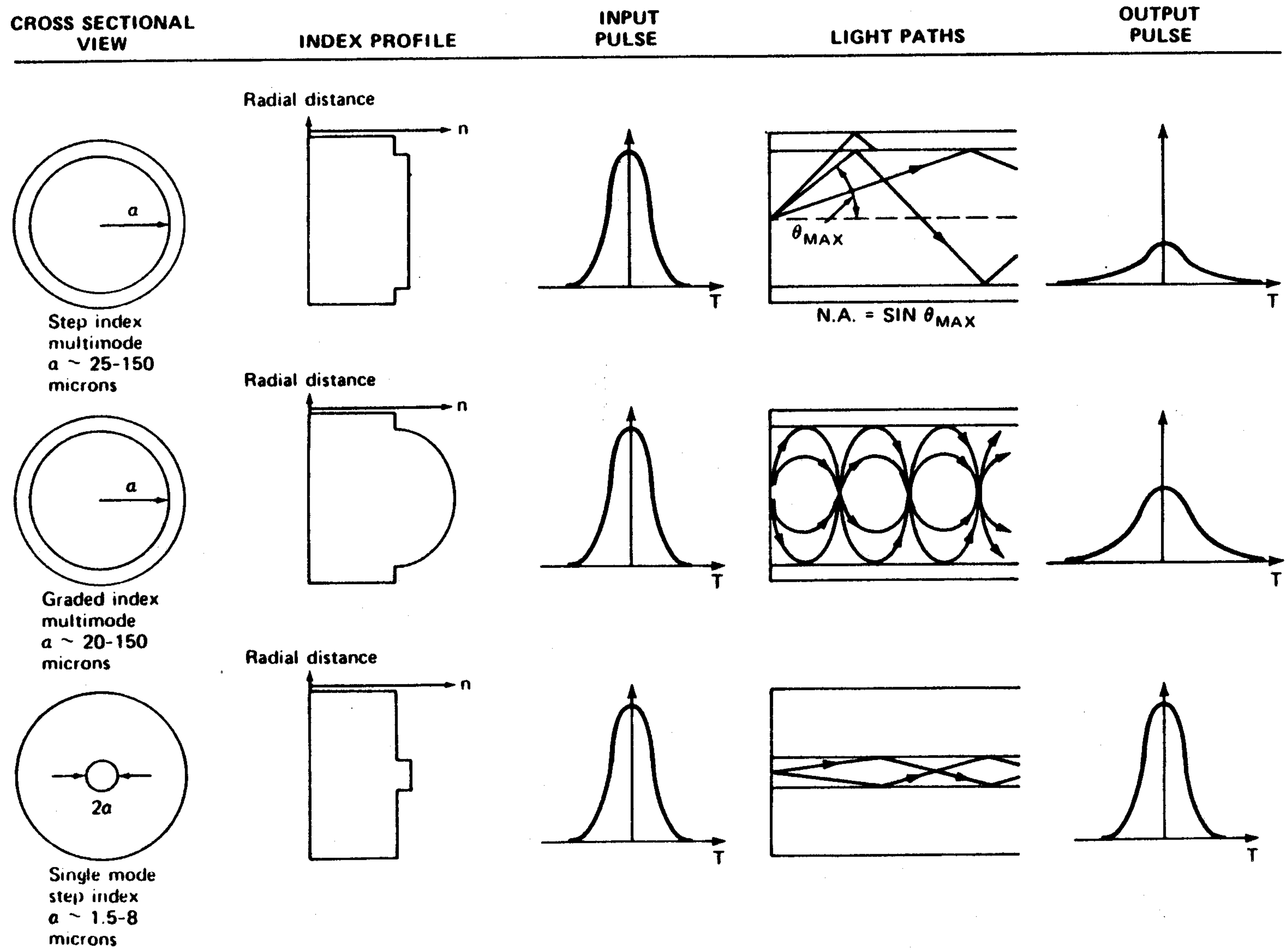

Figure 1.2: Major Types of Optical Fiber.

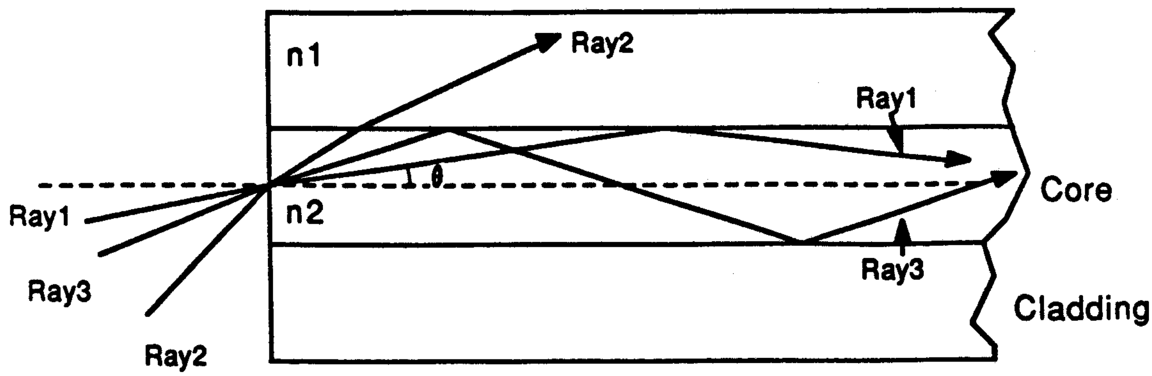

Figure 1.3: Rays Propagation in Optical Fiber.

light wave is refracted, not reflected, at the core-cladding boundary. The light propagation ceases in this case with the refraction. The maximum angle between the incident light and the fiber axis, at which the incident light can propagate in the fiber, is determined by the refractive indices of the fiber core and cladding. The sine of this maximum acceptance angle is defined as the numerical aperture of the fiber.

Light propagation is a form of electromagnetic wave propagation. Therefore, a complete analysis of the light transmitting behaviour in a fiber requires the consideration of the fields which exist within the dielectric fiber [8]. The fiber core-cladding interface forms a wave guide. The propagation mode property of the fiber can be determined from the eigenvalue solutions to Maxwell's equations, which describe mathematically the field properties of a boundary value problem. The number of modes in a fiber corresponds to the number of eigenvalues obtainable from the solution of Maxwell's equations for that fiber. It is also regarded as the number of discrete optical ray paths that exist in the fiber. The number of modes which can exist in a fiber is determined by the core diameter and the numerical aperture of the fiber, as well as the wavelength of the light.

The mode property of a fiber has a prominent effect on the fiber transmission characteristics. As has been discussed earlier in this section, fibers are classified as multimode fibers and single mode fibers, depending upon the number of modes a fiber can support. The transmission capacities of these two types of fibers are significantly different. In multimode fiber, as shown in Figure 1.3, many transmission modes exist and each of these modes takes a different path while propagating along a fiber. As every mode travels at the same velocity, a transmitting time delay between any two different modes launched at the same time is observed at the transmission destination due to the fact that each of the modes has travelled through different paths. Ray 1 and Ray 3 in Figure 1.3 illustrate two different propagation modes. A pulse spreading phenomenon is observed in this type of fiber. This effect, known as intermodal dispersion, limits the information carrying capacity of the fibers.

Single mode fiber supports the propagation of only one mode. It eliminates intermodal dispersion and greatly enhances the information carrying capacity of the fiber. Single mode fibers are widely used in long haul digital communication systems. They provide low signal attenuation and a huge signal bandwidth up to 40 GHzkm, compared to 2 MHzkm in the multimode fibers [9]. However, in order to support only one transmission mode, single mode fiber has a relatively small core size, usually less than 10 microns. This gives rise to some difficulties in connecting and splicing fibers, and also in coupling of light signals from the light source into the fiber and from the fiber into a detector.

Multimode fibers have a larger core size than single mode fibers. This provides some advantages, such as ease of fiber handling and less costly connection devices. In multimode graded index fibers, the gradual change of refractive index in the core region has the effect of refocussing the propagating light (rays) toward the fiber core axis. This refocussing effect greatly improves the intermodal dispersion problem and enhances the signal transmission bandwidth. Multimode graded index fibers are used in some applications, such as local area networks and intermediate distance communication.

1.2. Characterization of Single Mode Optical Fiber

In order to fully appreciate and utilize the merits of single mode optical fiber, a characterization process has been developed in the production line. This characterization provides information for the quality control of the fiber fabrication, and specifications for fiber application designs.

The characterization of single mode optical fiber includes the measurements of fiber attenuation, cutoff wavelength, chromatic dispersion, mode field diameter, and geometry. The first three fiber parameters mentioned above are directly related to the fiber transmission characteristics. The other parameters are concerned with the fiber connection, splicing, and system installation.

Fiber attenuation refers to the loss of light energy as a light pulse propagates through a fiber. The best reported attenuation obtained in a single mode fiber is 0.16 dB/km at the wavelength of 1550 nm [10].

The cutoff wavelength measurement is used to determine the shortest wavelength at which no propagation modes other than the fundamental mode are present in the fiber. To ensure single mode operation in single mode fiber, the cutoff wavelength must be smaller than the wavelength of the light to be transmitted.

Chromatic dispersion measures the pulse broadening effect of a fiber due to the combined effect of the material dispersion and waveguide dispersion of that fiber. The material dispersion is associated with the wavelength dependence of the refractive index, n, of a material or of the light velocity in this material. Waveguide dispersion results from the wavelength dependence of the field distributions and group velocities of the modes of an optical fiber. The group velocities are determined by the ratio of fiber core diameter to the light wavelength, λ. The chromatic dispersion limits the information carrying capacity of an optical fiber.

Mode field diameter (MFD) is a measure of the near field radiation pattern of the optical power at the fiber end face. This field distribution, which depends upon the refractive index profile of the fiber and the optical wavelength, is used to estimate the fiber splicing and bending losses.

Fiber geometry refers to the measurements of the outer diameter, core-cladding concentricity, and core circularity of a fiber. All these fiber parameters have significant impact on the overall performance of an optical fiber system.

1.3. Existing Test Setup in a Production Line

There is not a universal and unique setup for the tests of optical fiber accepted by all manufacturers. The manufacturers can use whatever techniques they consider suitable. However, they usually followed the recommendations made by some standardization bodies, such as EIA (Electronic Industry Association) and NBS (National Bureau of Standard). The study undertaken here has been with a local optical fiber manufacturer. All the subsequent discussions, therefore, pertain to this specific setup.

The test setup in this study has three separate test stations for the test of attenuation and cutoff wavelength, mode field diameter, and geometry, respectively. This arrangement gives rise to some concerns about the operational efficiency and the repeatability of the test results. The present test procedure requires extra handling and repeated preparation of the fiber for each of the tests.

1.4. Objective of this project

The objective of this project is to study the existing optical test system and investigate the possibility of integrating the three separate tests into a single system. The most desirable result would be a reliable, streamlined, and fully automated test system. However, at the present stage, a more realistic goal would be to have an efficient integrated system with some of the test procedures being automated. As a major task of this study, it was decided to design, build and test a prototype of a microcomputer-based control unit to automate the process of fiber alignment in the test procedure.

1.5. Outline of the thesis

The thesis is organized into six chapters and two appendices. The first chapter briefly reviews some of the basic concepts about the optical fiber technology and introduces the subject of this thesis. In Chapter 2, the single mode optical fiber parameters of interest are defined. The measuring techniques for these important fiber parameters are also described in this chapter.

Chapter 3 discusses the equipment layout for the existing fiber test setup and the operating procedure for carrying out the fiber tests. Some comments about the need to improve the present optical fiber test process are also given in this chapter.

In Chapter 4, the design of a fiber auto-alignment unit is described in detail. It includes the descriptions of the hardware design as well as the software design.

Chapter 5 describes the laboratory work with the prototype auto-alignment unit. It discusses the problems encountered in the prototype development and the performance evaluation of the design.

Chapter 6 presents the conclusions of the study detailed in this thesis. Further study of the subject is proposed in this chapter.

2. The Characterization of Single Mode Optical Fiber

2.1. Introduction

The characterization of fibers typically serves two different purposes, which are to provide feed-back information to a fiber designer for the quality control of fiber fabrication, and to give specifications to an application engineer for the design of optical transmission system or other applications.

Some optical fiber parameters are of practical significance to the system designer. For a long haul, wide band optical communication system, the primary design requirement is to maximize the distance between repeaters. This distance is limited by the signal attenuation and distortion which generally increase with the fiber length. The overall attenuation includes not only the inherent scattering and absorption loss of the fiber, but also the loss incurred when coupling optical power from the source to the fiber and those losses due to jointing[1]. Signal distortion arises mainly from pulse dispersion or bandwidth limitation which can be caused, for example, by a multipath effect in a fiber due to the differing propagation times of the various modes. Therefore, attenuation and dispersion as a function of length are key system parameters, together with some other parameters such as fiber outside diameter, circularity, and concentricity, which affect the fiber jointing and the efficiency of signal launching.

---

[1]Including temporary and permanent fiber join, such as connection by splicing or using mechanical connector.

Four parameter tests are included in the fiber characterization process in the fiber production line under study. These parameters are the attenuation, cutoff wavelength, mode field diameter, and geometry. The cutoff wavelength is required to ensure the single mode operation condition in which the transmission signal is free of modal noise[2] and intermodal dispersion. The other three are mainly concerned with the total losses of a fiber system.

Numerous techniques could be used to obtain these parameters [11]. No single universal method has been used by all optical fiber manufacturers. The consensus in the industry is that each manufacturer should disclose the measurement techniques which are used to obtain the fiber parameters. The techniques discussed in the following are some standardised methods recommended by the EIA (Electronic Industry Association).

2.2. Attenuation Test

2.2.1. Attenuation

The attenuation of a fiber causes optical energy to be dissipated along the waveguide during transmission and reduces the available energy at the destination. The mechanisms causing loss are mainly absorption and scattering.

The fiber absorption and scattering, and consequently the total attenuation, vary significantly with the wavelength of the light in the fiber. For a single mode fiber made of silica glass, there are two transmission windows in the power spectrum of the fiber transmission within which the total attenuation is at a minimum. These windows are located around the wavelengths of

[2]Fluctuations in the light power being transferred, which results from the change of modes interference pattern at every discontinuity, such as misaligned joint, along a fiber link. It is the more severe the better the coherence of the laser light.

1310 nm and 1550 nm, respectively. A reasonable choice of operating wavelength for a fiber system is, therefore, the wavelength of 1310 nm or 1550 nm. In addition to the advantage of lower loss, the chromatic dispersion at the vicinity of the 1310 nm wavelength can approach zero in a properly designed fiber. As a consequence, most of the single mode optical fiber communication systems today are operating at the wavelength of 1310 nm. Research interests are also focused on the 1550 nm wavelength because the fiber loss has a minimum at this wavelength. The attenuation test must, therefore, include the measurement of losses at the wavelengths of both 1310 nm and 1550 nm. It also includes a measurement at wavelength of 1284 nm at which a loss peak occurs due to absorption by OH^- ions. These ions result from very small amounts of water included in the fiber during fiber fabrication. Figure 2.1 illustrates the loss spectrum of an ultra low loss single mode fiber for the wavelength range from 700 nm to 1800 nm.

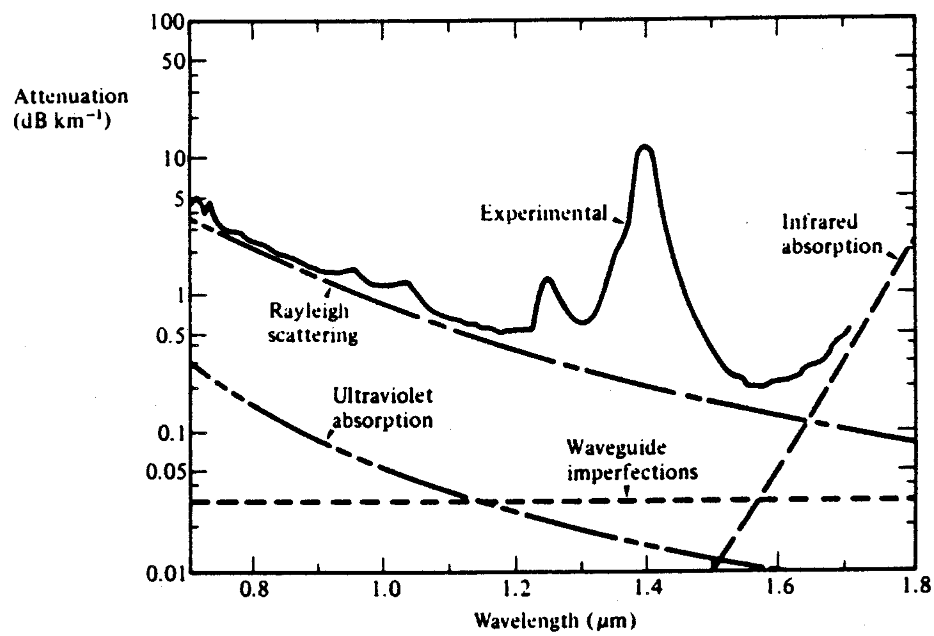

Figure 2.1: Loss Spectra of a Single Mode Optical Fiber. [10]

2.2.2. Cut-back Technique

A commonly used technique for determining the total fiber attenuation per unit length is the cut-back technique [12]. The physical principle of the cut-back technique is shown schematically in Figure 2.2. A fiber of length L is excited with a suitable source. Because the measurement must be made at several specific wavelengths, an incandescent source is used. A monochromator is used to select the test wavelength. The detector registers the power $P_l(\lambda)$ with the long length fiber. Next, the fiber is cut, and without changing the light source and launch conditions, the output power $P_s(\lambda)$ of the short length is measured with the same detector. The attenuation at any given wavelength is determined with the following formula:

$$Att(\lambda) = -10 \times \frac{log\{P_l(\lambda)/P_s(\lambda)\}}{L}, \tag{2.1}$$

where λ is the measurement wavelength, L is the test fiber length in km, $P_l(\lambda)$ is the long length power measured at wavelength λ, $P_s(\lambda)$ is the short length power measured at wavelength λ. Att(λ) is the calculated attenuation in dB/km.

The advantages of this technique are its simplicity and ease of implementation. If the light source and other system components are stable and the tests are carried out carefully, good test accuracy and repeatability can be obtained.

2.3. Cutoff Wavelength Test

2.3.1. Cutoff Wavelength

In a system using fibers which are intended to operate in a single mode, it is essential that higher order modes are not propagated. Significant amounts of second- or higher- order mode power are undesirable since pulse spreading arising from differential mode delays reduces system bandwidth,

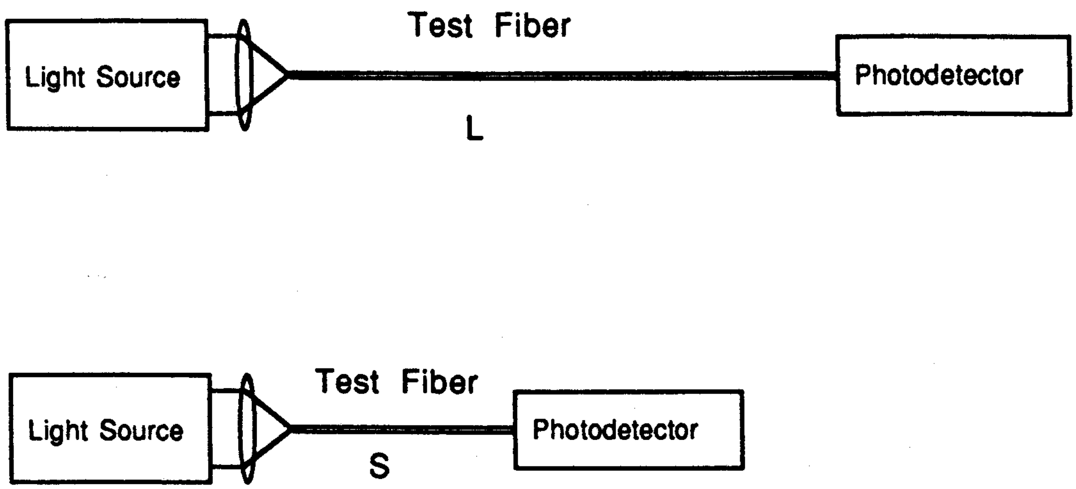

Figure 2.2: Cut-Back Technique.

and interference between first and second order modes can result in modal noise at fiber joints [13].

The cutoff wavelength is defined as the wavelength above which second and higher order mode power is below a threshold level. Theoretically, the number and the propagation characteristics of guided modes in a fiber are determined by a V-value:

$$V = \frac{2\pi}{\lambda} an(2\Delta_n)^{1/2}, \tag{2.2}$$

where n is the refractive index of the fiber, Δ_n is the index difference between the core and cladding, a is the core radius and λ is the optical wavelength. The theoretical single mode condition is to have the V-value equal to or smaller than a value of 2.4. However, experiments have shown that the cutoff wavelength derived from the V-value is always less than the cutoff wavelength obtained from direct measurements [14]. The relationship between these two values is still unknown. Therefore, a direct test of cutoff wavelength is necessary in the fiber characterization process.

2.3.2. Single Bend Attenuation Technique

The single bend attenuation technique [15] is based upon the observation that as a higher order mode approaches its cutoff wavelength, it becomes weakly guided. Under this condition, a bend in a fiber will cause a remarkable loss in the guided power due to radiation of the weakly guided mode through the side of the fiber. Figure 2.3 illustrates the physical principle of this technique. The test procedure is to measure first the spectral power transmitted through the perturbed fiber sample $P_b(\lambda)$, by wrapping a single loop around a mandrel, then to measure the transmitted spectral power $P_s(\lambda)$ through the same but unperturbed fiber sample. This is done by unwrapping the single loop and keeping the sample straight. The light source and launch condition must not be altered during the process. The attenuation spectrum in decibels is given by:

$$Att(\lambda) = log(\frac{P_s(\lambda)}{P_b(\lambda)}), \tag{2.3}$$

where $P_s(\lambda)$ is the straight sample power measured at wavelength λ, $P_b(\lambda)$ is the bent sample power measured at wavelength λ, and $Att(\lambda)$ is the calculated attenuation spectrum.

Figure 2.4 shows the plot of the ratio of two attenuation spectra recorded from the straight fiber and bent fiber, respectively. The spectrum has an attenuation maximum, followed by a decrease to 0 dB as the fiber sample enters single mode operation. The cutoff wavelength is defined as the wavelength where the long wavelength edge of the attenuation has increased by 0.1 dB over the baseline.

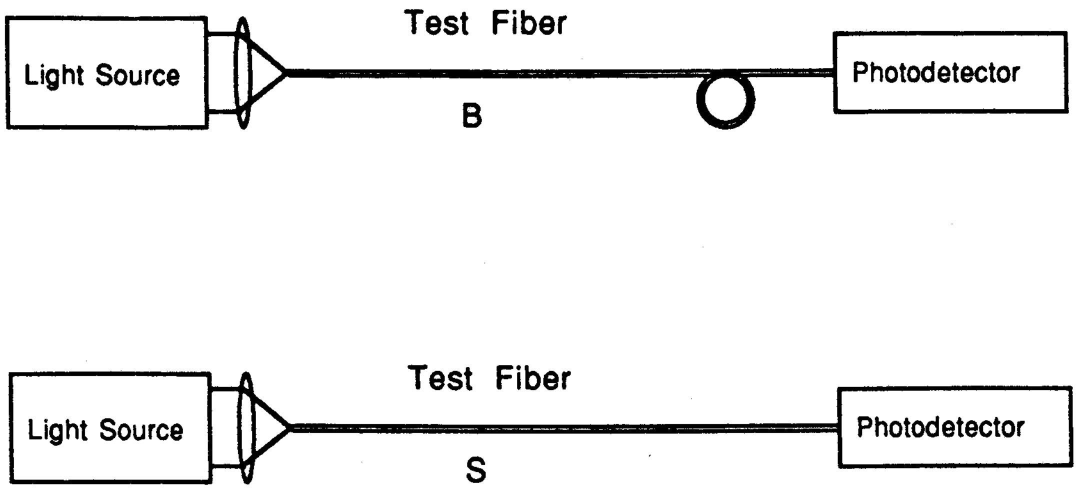

Figure 2.3: Single Bend Attenuation Technique.

An inherent problem with this technique is a relatively poor test repeatability when conducting many tests on the same test sample. This is due to the fact that the cutoff wavelength is determined by observing the abrupt increase of the power loss induced by fiber bending. Any additional and irregular bending in handling the test fiber may induce greater loss in the fiber as the wavelength approaches cutoff. A wide spread of results, then, could be obtained. This method, however, is simple and straightforward with no requirement of special skill from the test operator.

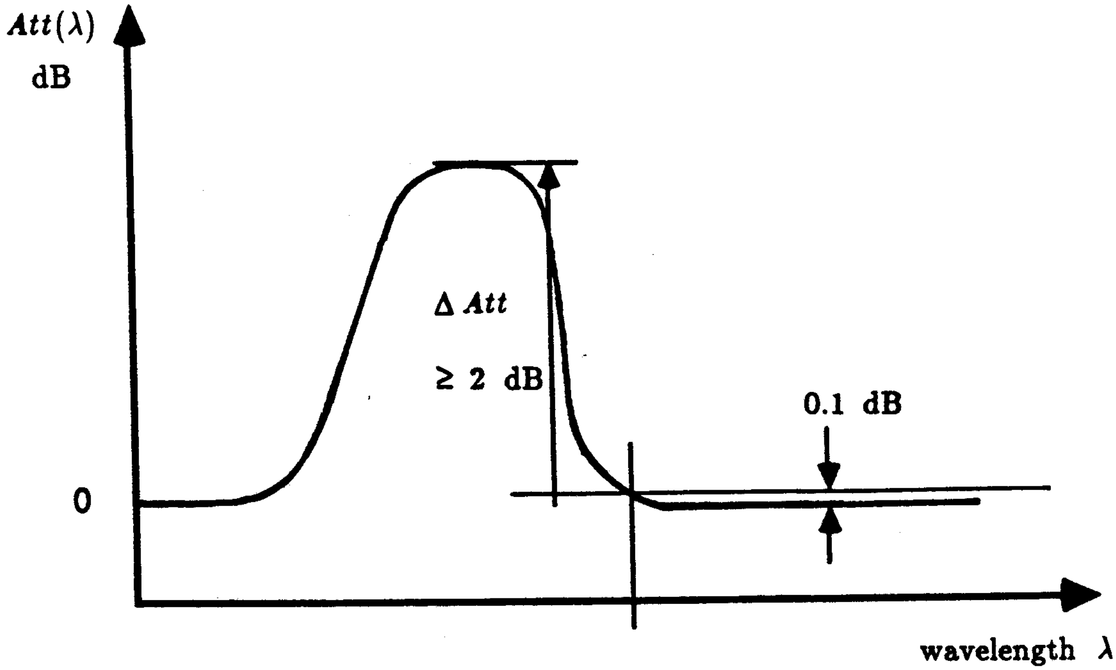

Figure 2.4: Ratio of Two Attenuation Spectra for the Determination of Cutoff Wavelength.

2.4. Mode Field Diameter Test

2.4.1. Mode Field Diameter

The mode field diameter of the fundamental mode is conventionally defined as the radial coordinate at which the intensity of the light in the fiber transverse section is reduced by a factor of $\frac{1}{e^2}$, with respect to its axial value[3]. Figure 2.5 shows the intensity profile of the fundamental mode observed at the fiber output end face and the definition of mode field diameter. In a single mode step index fiber, such as considered in this study, the intensity profile resembles a Gaussian distribution.

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[3]There exists a number of MFD definitions. One of the other commonly used is the far field RMS spot size.

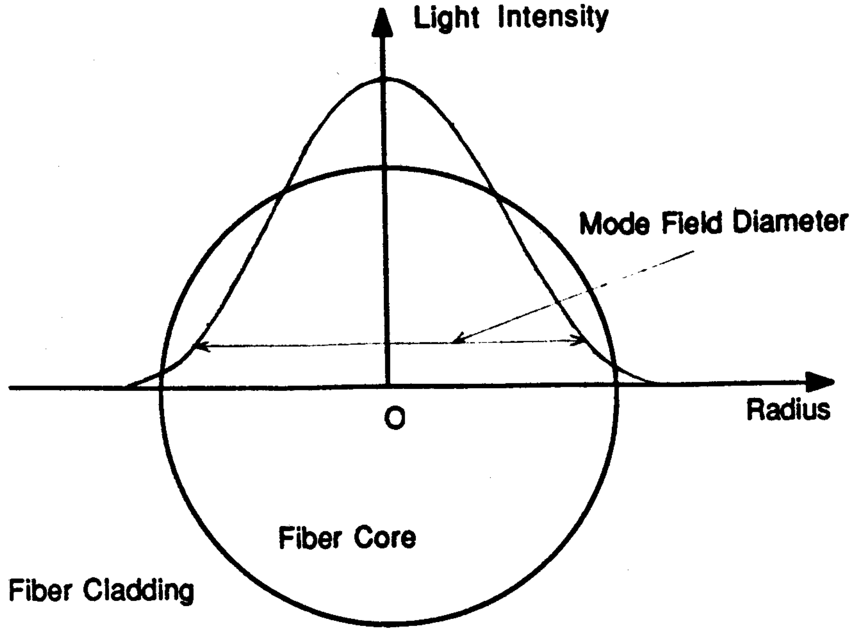


Figure 2.5: The Near Field Distribution of the Fundamental Mode at the Fiber Core Region.

The mode field diameter can be used to predict certain fiber characteristics such as microbending loss and, more importantly, the jointing loss of two different pieces of fiber.

2.4.2. Variable Aperture Technique

The variable aperture technique [16] is based on the assumption of Gaussian radial intensity distribution in the far field. By far field is meant the field distribution at a large distance, usually 100 λ, from the end face of the fiber. Figure 2.6 illustrates the physical principle of this technique. An apertured-disk is positioned between the fiber end face and the photodetector. The apertures on the disk have different radii and the centers of each aperture are on the same circumference. When the disk rotates, each of the centers will align to the detector and various aperture sizes are provided for the field calculation.

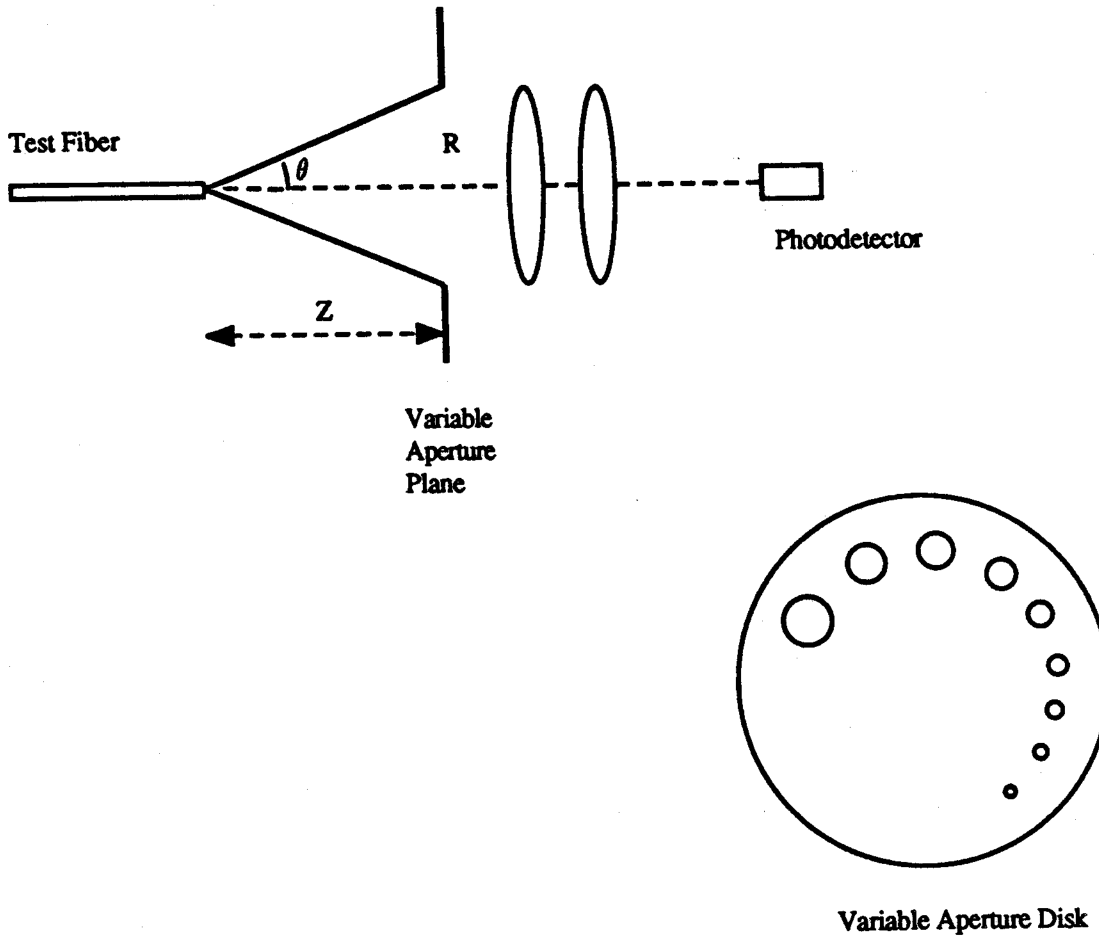


Figure 2.6: Variable Aperture Test.

Integrating the Gaussian intensity distribution in the transverse plane and assuming azimuthal symmetry [17],

$$P(R) = P_{max}\{1 - exp[-\frac{2R^2}{W^2(Z)}]\}, \tag{2.4}$$

where R = radius of aperture, P_{max} = total power, Z = axial distance from the fiber to aperture plane, and W(Z) = $\frac{1}{e^2}$ intensity point in the traverse direction.

The true far field of typical step-index single mode fibers is only approximated by the Gaussian shape. Thus it is necessary to determine the best-fit to the data from several different aperture sizes. Finally, a transformation to the near field is accomplished using the expansion law for Gaussian beam propagation derived from the Kirchhoff-Huygens diffraction integral:

$$W^2(Z) = W^2(0)\{1 + [\frac{\lambda Z}{\pi W^2(0)}]^2\}. \quad (2.5)$$

W(0) in the near field is related to W(Z) in the far field by Eqs. 2.6,

$$W(Z) \rightarrow \frac{\lambda Z}{\pi W(0)}. \quad (2.6)$$

Combining Eqs. 2.4 and Eqs. 2.6, the far field data are fitted using a two-parameter least-squares method to the expansion:

$$P(\theta) = P_{max} \; [1 - exp(-m \; tan^2\Theta)], \quad (2.7)$$

where $\theta = tan^{-1}(R/Z)$, the half angle subtended by the aperture $m = (\frac{2\pi^2}{\lambda^2}) \; W^2(0)$, and P_{max} = total power in the best-fit 2-D fitted Gaussian distribution parameters.

The final calculation of the near-field mode radius ($\frac{1}{e^2}$ intensity) is

$$W(0) = \frac{\lambda}{\pi} \; (\frac{m}{2})^{1/2}. \quad (2.8)$$

The test accuracy and repeatability of the variable aperture technique are significantly influenced by two major factors. These factors are the end face preparation of the test fiber sample and the alignment of this end face to the photodetector through the optical lens system. In practice, it is found that the repeatability of the test is not always as good as desired. The cause of the problem is that the light power projected from the fiber end face on to the photodetector is altered with different surface plane angles of the end face of the test fiber, and the alignment condition. Therefore, the preparation of the test fiber end face and alignment of the fiber end face to the photodetector should be carefully carried out in this test [18].

2.5. Geometry Test

2.5.1. Geometry

The geometry of a fiber consists of three important parameters, namely, the outer diameter, core-cladding concentricity, and core circularity. Each of these has a significant impact on the fiber connection or splicing loss and, therefore, the overall system performance.

The outer diameter is a very important parameter since during the splicing or connecting of two fibers, the outer boundaries of the two fibers (with stripped off plastic jackets) are used for mutual reference and support. The control of the fiber outer diameter also ensures control of the core diameter because the ratio of core to cladding diameter is strictly maintained during the fiber pulling process.

The core-cladding concentricity (actually eccentricity) is defined as the distance between core and outer reference surface centres, divided by the core diameter. Eccentricity does not cause propagation characteristics to vary, however, it becomes a major problem when two fibers are to be joined together. If the alignment is referenced from the outer diameter, fiber core-cladding eccentricity will cause jointing loss to increase.

The core circularity is the difference between the largest and the shortest center-crossing chord of the core-cladding interface, divided by the core diameter. The effect of noncircularity is to cause a polarisation dependence. For single mode fiber, an elliptical fiber can support two orthogonal modes, one along the minor and the other along the major axis of the waveguide. These modes have different group velocities and hence cause a decrease in the effective bandwidth of the fiber.

2.5.2. Direct Fiber End Face Inspection

The direct fiber end face inspection is accomplished with a video camera and data processing computer to eliminate the human subjective judgement and improve test accuracy and efficiency [19]. The basic system is shown in Figure 2.7.

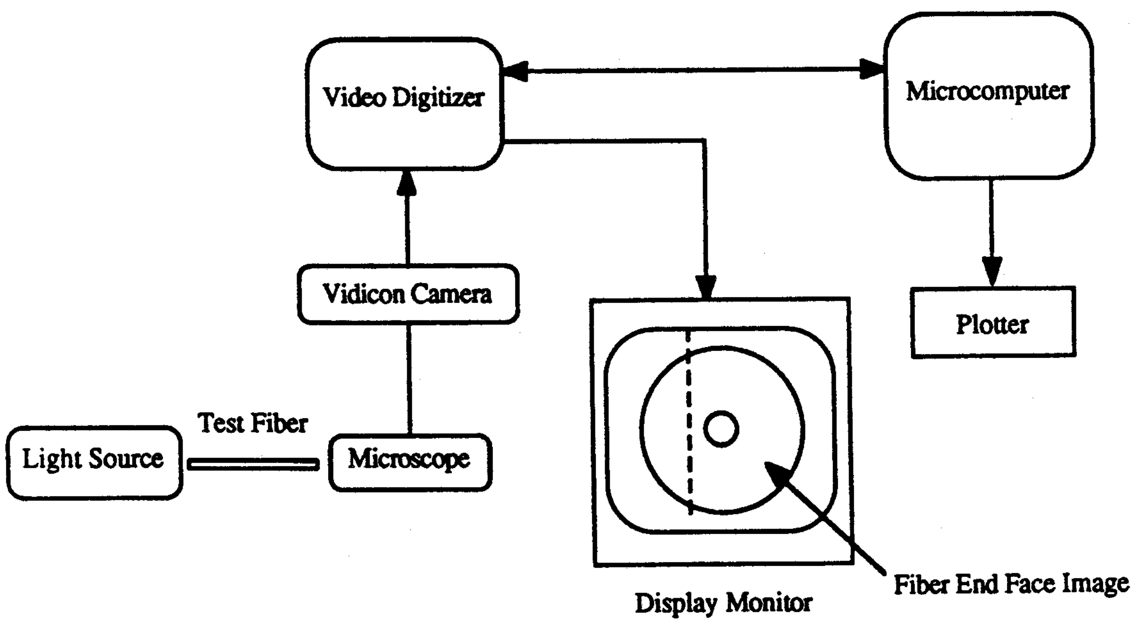


Figure 2.7: Geometry Test.

The core region of the test fiber sample is illuminated by launching an incandescent light into its far end face. It appears bright in the inspected end face because of the guidance properties of the fiber. The cladding region, which has a lower refractive index, appears as a dark annular surface. When a light is also projected toward the end face and illuminates the background, a fiber end face image is obtained with acceptable contrast on both the interface between the core and cladding and the cladding and the background. This image is enlarged with a microscope objective lens and captured by a video camera. The output of the video camera is digitized and mapped under computer control. Given a starting point, the digitizer collects data along a vertical sampling line by addressing points on each successive video scan line. Because the video signal voltage is proportional to the light intensity in the optical image viewed by the video camera, the computer can calculate the fiber outer diameter, core-cladding eccentricity, and the core noncircularity by processing the data received from the digitizer. The results are displayed on a screen and printed out on a hard copy.

This section has described the basic setup and principle of the geometry test. A fairly complicated data processing technique and software algorithm are involved in obtaining these geometric parameters with high accuracy. The detail of the data processing technique is not covered here. In using this method, the major factors which affect the test accuracy and repeatability are the test fiber end face preparation and the focus of the fiber end face image to the video camera. Any defect in the test fiber end face, caused by improper fiber cleaving, will result in a degraded image of the fiber end face boundary. The accuracy of the three calculated parameters is then decreased. The same problem results from the malfocus of the fiber end face. Except for these two concerns, this method works well and it can be handled very easily.

2.6. Summary

The explanations of several important parameters of single mode optical fiber have been given in this chapter. All of the parameters are important and are required for the characterization of single mode optical fiber. They each have an impact on the transmission performance of the optical fiber system. Measurement techniques and laboratory setups for the four fiber parameters have also been discussed briefly in this chapter. The tests are widely accepted among optical manufacturers and are used in the subsequent study of the fiber test system. In general, these test setups are working satisfactorily and they are easy to operate. The next chapter discusses the operational procedures to use these tests in the production environment.

3. Fiber Test In Industry

3.1. Introduction

The apparatus for the optical fiber test is a delicate system in which a small size of fiber and low level of optical signal are involved. Accuracy, stability, and reliability are the basic requirements of this setup. In a manufacturing environment, the ease of handling and the efficiency of the test procedure become major concerns in the day-to-day operation.

The existing test setup being studied has been functioning satisfactorily for a few years. Though the system is sound, there are recent concerns about its equipment layout, the efficiency of the operating procedure, and the test repeatability. Some changes are, therefore, desired to streamline the test process and to improve the overall performance of the system.

The following sections discuss the equipment layout in the existing setup, the operating procedures involved in the tests, and some possible steps for improvement. The discussion is focused on the issues relevant to the test operating procedure, and not the details of all the components.

3.2. Test Setup

3.2.1. Test Equipment Layout

The test setup being studied consists of three test stations, one each for the tests of attenuation and cutoff wavelength, mode field diameter, and geometry, respectively. Each station is housed on a single test bench. This arrangement dictates the operating procedure involved in carrying out the fiber tests and, therefore, the efficiency of the overall test process.

Figures 3.1, 3.2 and 3.3 illustrate the test equipment layout of the three test stations on separate test benches.

3.2.2. Major Test Equipment

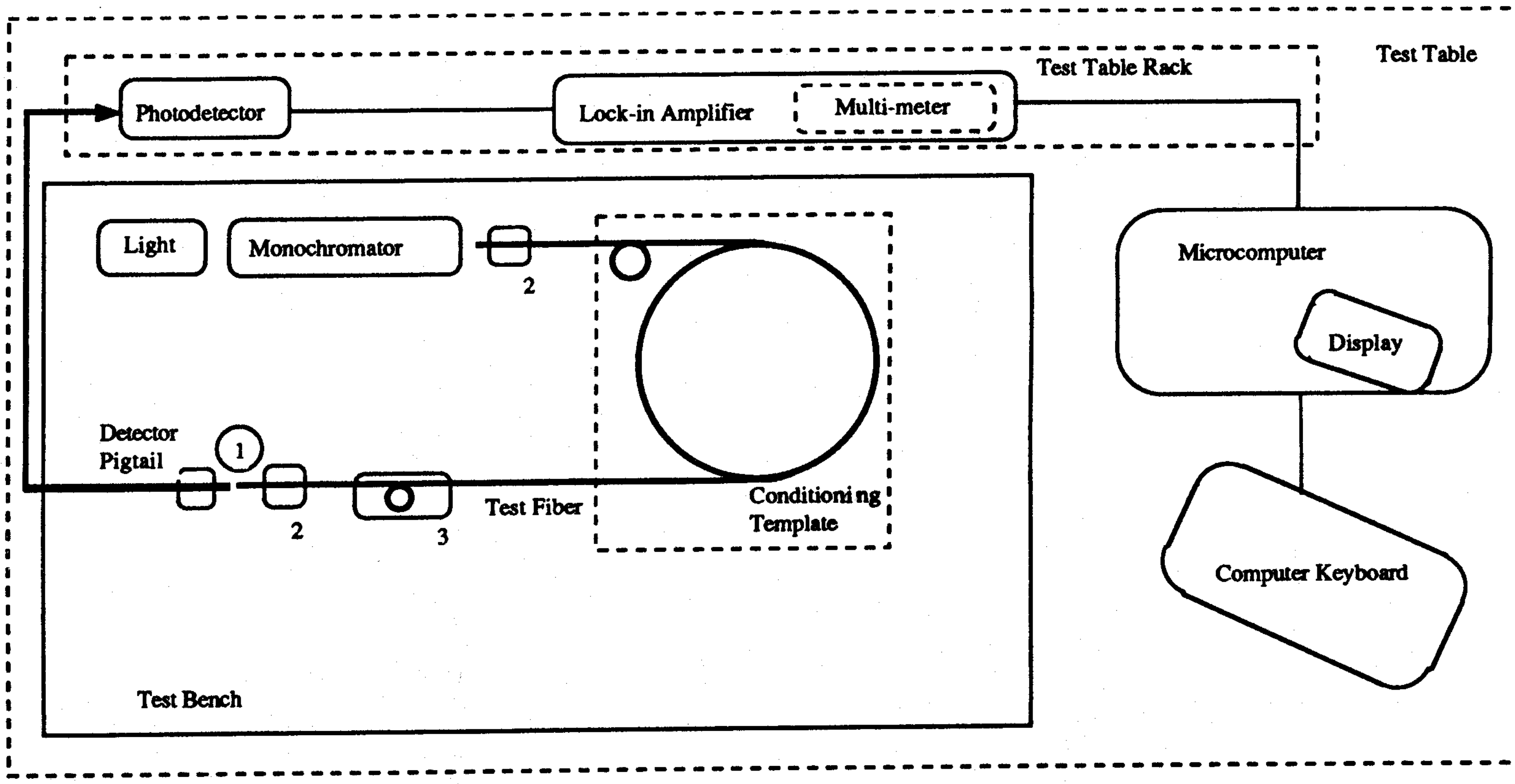
This section describes the functions of some of the major equipment used in the test setups.

3.2.2.1. Optical Source

The optical source consists of two basic elements. One is an ordinary incandescent source of light and the other is a monochromator. The source of light is a high radiance tungsten halogen lamp, which exhibits a known spectrum of emission in the spectral region of interest. The light from the source is passed through a monochromator. The monochromator is a dispersing instrument which, using a diffraction grating, is able to select a narrow wavelength band from a wide source spectrum. The output of the monochromator, as an optical source, is used in the attenuation, cutoff wavelength, and mode field diameter tests. For the geometry test, an ordinary light source is used with no requirement of selective wavelength. However, an optical filter is used with the light source to prevent the camera image from saturating.

3.2.2.2. Lock-in Amplifier

A lock-in amplifier (Model SR510 from Standford Research System, Inc.) is an AC voltmeter which is used to evaluate very small signals in the presence of noise. The basic element of the lock-in amplifier is a phase-sensitive detector which measures a differential voltage using a synchronous reference voltage derived from an input modulator [20]. Figure 3.4 illustrates the application of the lock-in amplifier in the test system. The lock-in amplifier is represented here by its principal element --- a synchronous detector. In principle, the operation depends on the high degree of correlation between a periodic signal of interest s(t), and the reference r(t). In the synchronous detector, the reference r(t) is multiplied with the unknown signal



1. Microscope
2. Fiber Positioning Stage
3. Mode Striper Mandrel

Figure 3.1: Test Station for the Attenuation and Cutoff Wavelength Test.

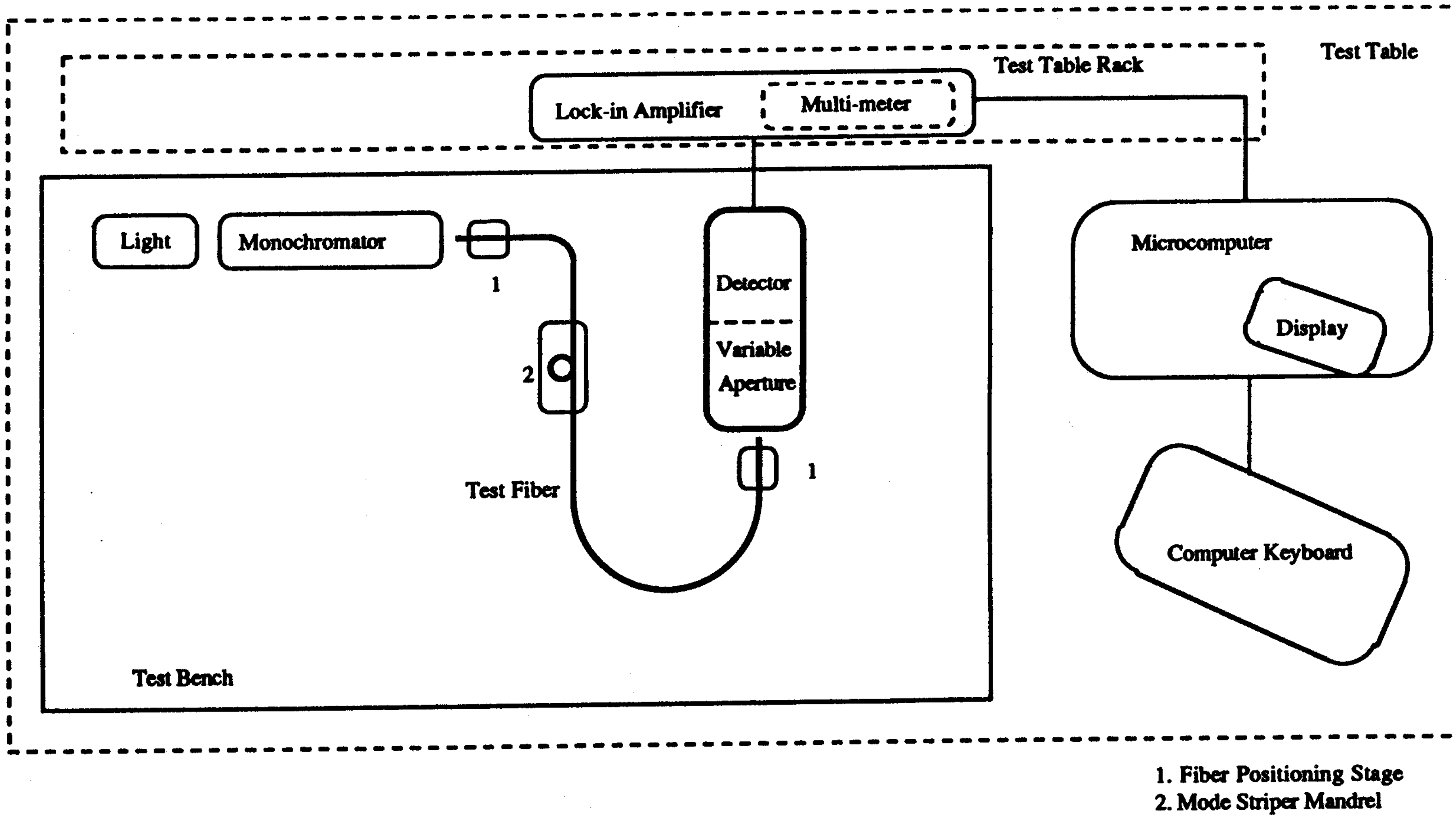


Figure 3.2: Test Station for the Mode Field Diameter Test.

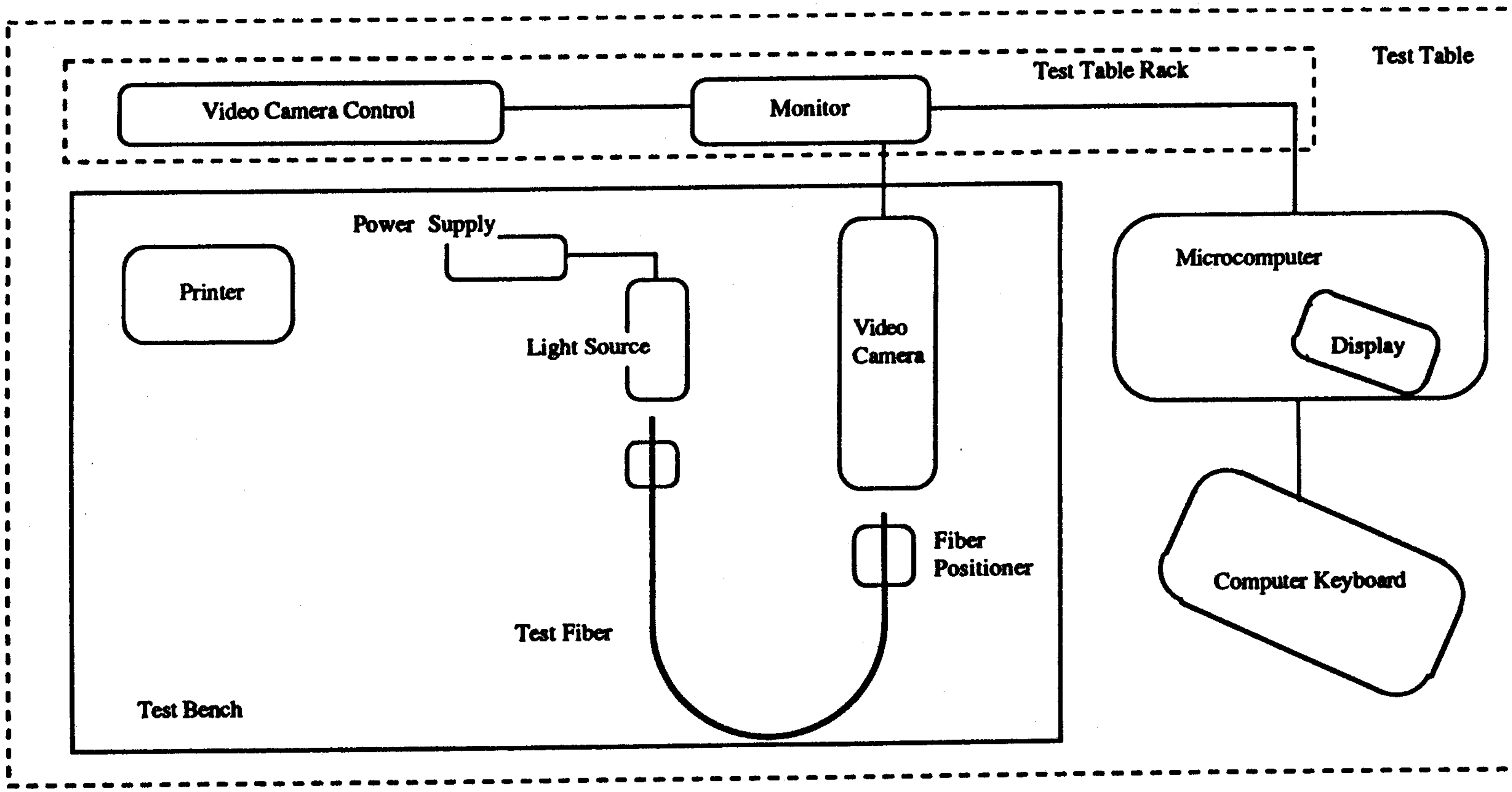


Figure 3.3: Test Station for the Fiber Geometry Test.

s(t) plus the disturbance n(t) due to additive noise and interference, resulting in a product,

$$Vp(t) = r(t)[s(t) + n(t)].$$

For random noise, there is no correlation with the reference, and the average value of the noise product r(t) x n(t) is zero in the final output. However, r(t) and s(t) are from the same source and closely correlated, and their product gives rise to a distinctive response which depends upon the amplitude of the signal and its phase relative to the reference. The low-pass filter following the signal multiplier separates the fundamental element from the high-order products of multiplication. The output from the low-pass filter is a DC voltage which is proportional to the unknown signal level.

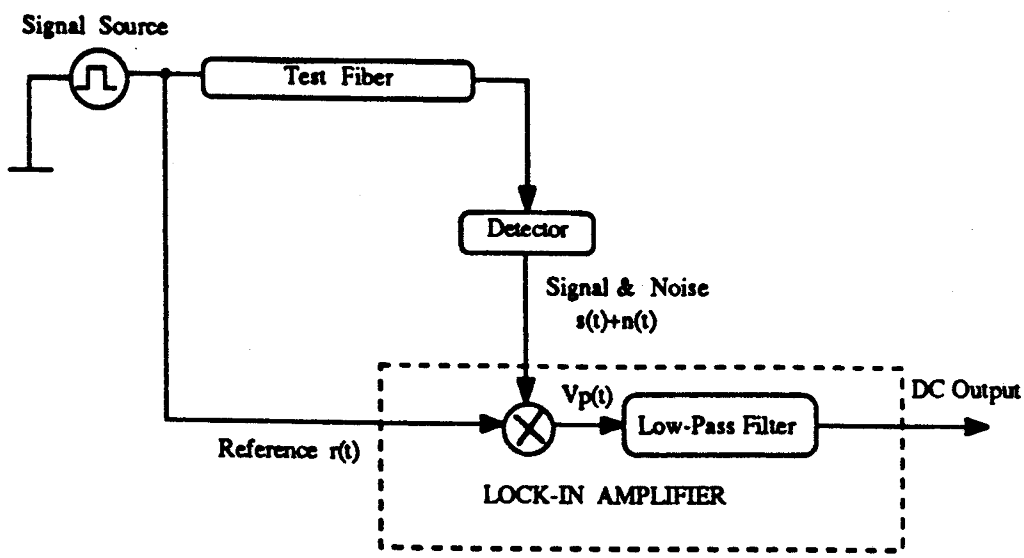


Figure 3.4: The Application of Lock-in Amplifier in The Fiber Test.

The lock-in amplifier provides the principal signal amplification in the test system. The reference signal for the operation is a square wave which is generated with a mechanical chopper at the light source. This device chops the light signal at a frequency of 400 Hz. The output of the lock-in amplifier has two different forms, a 0 to 10 volt analog output and an 8-bit digital output. It can be interfaced with a computer directly with the digital output, or through a multimeter when using the analog outputs.

3.2.2.3. Photodetector

The function of the photodetector is to convert the incident light to an electrical current that can be subsequently amplified and processed. Because the light wavelength of interest in the single mode optical fiber tests is in the range from 900 nm to 1600 nm, the photodetector selected must be able to detect light signals at these wavelengths. The photodetector used in the test system is an InGaAs PIN detector. The photoresponsivity (0.5--0.6A/W) of this device is almost flat over the entire wavelength region of interest. At an operating reverse voltage of 10 volts, it exhibits junction capacitance below 0.5 pF, dark current of about 1 nA, quantum efficiency of about 90%, and rise and fall times of less than 200 ns. Because the electrical signal from the PIN detector is very low, a low-noise preamplifier is required to increase the signal from less than one microvolt to several millivolts. Further amplification is still necessary to increase the signal level as well as the signal-to-noise ratio (SNR) to facilitate a good measurement of the parameters of interest. This function is provided by the lock-in amplifier in the test system.

3.2.2.4. Computer

The computer used in the test setup is a HP 9000-200 series 16-bit microcomputer. It has good computing capacity and Input/Output facilities for the measurement tests. The computer has three basic functions in the test system. Firstly, as a data processing unit, it acquires and analyses data collected in testing the fiber sample and computes the optical fiber parameters. Secondly, it provides control to other equipment in the test system. In the attenuation test, for example, the fiber attenuation at three separate wavelengths is of interest, and the computer must control the monochromator to select the light of required wavelength. The selection of wavelength through the monochromator is determined by changing the orientation of the optical grating inside the monochromator. In practice, this is done by using the computer output facility to control a stepper motor which is used to rotate the grating. Thirdly, the microcomputer provides the human-machine interface for the test system. The computer screen displays the test instructions, system operating status, error messages, test results, and product grading. In response to this information, the operator can enter relevant data and/or commands to the system through the computer keyboard.

All of the test software has been written in the HP-BASIC language. The HP-BASIC is easy to use and runs fast enough to perform the required function. Easy access to the I/O facilities and an extensive program library are available.

3.2.2.5. Video Camera

The video camera is used to capture the fiber end image and convert the image's intensity level into electrical (video) signals that can subsequently be digitized and processed. The camera used in the test system is a type of solid state camera called a vidicon. It uses a Chalnicon tube as its imaging device and provides a stable image and good time-base accuracy for scanning. In order to provide data suitable for computer processing, a camera control unit is used to provide the functions of video processing, A/D conversion, and computer interfacing. The video signal from the camera head is processed in the control unit prior to digitization in the A/D converter. Instructions from the computer next cause conversion to take place at specified times during the scan. The resulting intensity/positional data are then transferred via the camera/computer interface into the computer memory. However, the data rate and quantity for a complete image, with 1024 x 1024 pixels, are too high for the computer used. Thus, a sampling line method is used. Instead of transmitting all pixels on a scan line sequentially, each coded as 8-bit data, only one pixel per line per field is sent. The position of the vertical sampling line can be set by the computer and displayed on the monitor for operator convenience.

3.3. Test Procedure

3.3.1. Fiber Cleaving & Alignment

Two operations have predominant roles in the test procedure. These operations are fiber cleaving and fiber alignment with light source and detector. These are time consuming and require careful handling to ensure good test results. Details of these two procedures are discussed in this section.

Fiber cleaving is an operation to prepare the test fiber end for the fiber tests. Properly prepared ends must be smooth, flat and perpendicular to the fiber axis. The tolerance of the end angle of the plane surface with respect to the perpendicularity is less than 1 degree. The usual technique for cleaving is the score-and-break technique. This technique involves scoring the fiber surface by using a sharp edge of a hard material such as diamond and then pulling to break the fiber. Fracture commences at the scored site and propagates across the fiber. Figure 3.5 shows a typical cleaved end surface. A fracture surface of a brittle solid is usually comprised of three regions known as the "mirror", the "mist", and "hackle" zones. The mirror zone is an optically smooth surface adjacent to the fracture origin, the hackle zone corresponds to an area where the fracture has forked and the specimen is separated into three or more pieces, and the mist zone is a transition region between these two zones. The ideal cleaving is to break an optical fiber with the mirror zone extending across the entire fiber. This requires judicious control of the nature of the applied forces. The quality of the fiber cleaving is critical to the accuracy and repeatability of the mode field diameter (MFD) and fiber geometry tests. However, high quality of fiber cleaving, with the end angle of less than the tolerance of 1 degree, is not always achievable

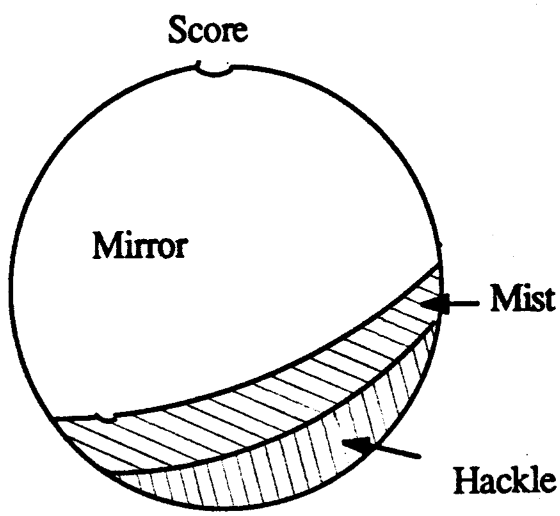


Figure 3.5: The Fiber Cleave.

even by an experienced operator. The end angle of the cleaved fiber can be inspected using interference effects of monochromatic light. This test is not currently used in the test procedure.

The fiber alignment discussed here includes two operations in the test procedure. These are first to fasten the fiber end to a clamp which has a V-groove on the base and mounted on a movable stage, and, later, to fine tune the stage in different axes to maximize the signal response in the test system. All of these procedures are performed manually. The control of the stage movement in each axis is done by turning a micrometer. The alignment jobs are different at the light source end and the detector end. Table 3.1 illustrates the different requirements for different alignment jobs.

Except for the case of the geometry test, the criterion for a good fiber alignment is the maximum signal response that the test system can obtain

Table 3.1: The Fiber Alignment Jobs.

Test\Alignment	Source End	Detector End
Attenuation	Point to the light source optics	Butt against an end of the detector pigtail
Cutoff Wavelength	Point to the light source optics	Butt against an end of the detector pigtail
MFD	Point to the light source optics	Point to the detector optics
Geometry	Point to the light source optics	Point to an objective lens of the video camere

with the alignment condition. For the geometry test, the light source alignment is not difficult to obtain since a good illumination is easy to acquire. The focus of the fiber end image is, however, critical to the test result. The detector side alignment of the attenuation and cutoff wavelength test is not difficult to achieve because the test fiber end is butted against the multimode fiber pigtail, which has a much larger core diameter than that of the test sample. However, the detector side alignment of the MFD test poses some difficulties on the test operator because the signal to noise ratio (SNR) is relatively low in this test. The low SNR is due to the fact that the light signal has to travel through an air path and a lens system before it reaches the PIN detector. The source side alignment for the attenuation, cutoff wavelength, and MFD test are identical. It is a three dimensional movement to search for the focus point of the optical source at the wavelength of interest.

3.3.2. Operating Procedure

The test procedures have the most important impact on the test efficiency and quality, assuming the test system equipment and software are stable and reliable. A detailed description of the operating procedure for the four fiber parameter tests at three test stations is given in this section. The major objective in the study of this procedure is to identify any repeated or non-productive operations in the existing test procedures. The following descriptions are presented in an order which is identical to the actual process of testing a reel of fiber in the production line. The procedures have been observed and recorded during production in a factory, and they provide the basis for analysis of the test efficiency.

3.3.2.1. Test of the Attenuation & Cutoff Wavelength

The test of the fiber attenuation and cutoff wavelength is carried out with the following steps.

Attenuation & Cutoff Wavelength Test:

1. Take a reel of fiber from the storage rack.
2. Type in relevant data, fiber length and OTDR[4] result, etc., from the attached tag.
3. Extract a minimum of 100 cm of fiber from the INSIDE end[5] of the reel.
4. Strip[6] and Cleave the INSIDE end of the fiber.

---

[4]The Optical Time Domain Reflectometer (OTDR) measurement is done prior to the four test procedures described in this section.

[5]The fiber end which was first wrapped onto the fiber reel.

[6]Take off the protection jacket on the fiber outer surface.

5. Align the INSIDE end with the detector pigtail[7].

6. Extract over 200 cm of fiber from the OUTSIDE end[8] of the reel.

7. Measure and Mark the OUTSIDE end of the fiber at a point of 200 +/- 5 cm from the end.

8. Align the OUTSIDE end to monochromator output.

9. Place the fiber sample into the cutoff conditioning template.

10. Make a single 3 cm diameter loop in the OUTSIDE end of the fiber, using the supplied loop mandrel.

11. Ensure that the fiber is laid as straight as possible on the test bench.

12. Maximize both the source and detector coupling by observing the lock-in amplifier output and adjusting both 3-D micrometer adjustment stages for maximum amplitude reading. (fine-tune)

13. Acquire the long length signals. (execute the computer program and wait for its completion.)

14. Break the fiber at the 200 cm mark on the OUTSIDE end of the fiber.

15. Strip and Cleave the end of the short length sample leaving the other end aligned with the monochromator and the 3 cm loop on the mandrel.

16. Align the end of the short length sample with the detector pigtail.

17. Ensure that the fiber is laid as straight as possible.

18. Maximize the detector coupling.

19. Acquire the short length signals. (execute the computer program and wait for its completion.)

---

[7]A short length of optical fiber for coupling optical components, e.g. a photodetector, to a connector.

[8]The fiber end which sits on top of the fiber wrapped on a reel.

20. Record the results onto a sticker on the fiber reel.

    *** The attenuation test is completed by this point. Next follows the cutoff wavelength test. The short length sample is kept for this test.

21. Acquire the signals with the bent fiber.

22. Unwrap the 3 cm diameter loop.

23. Acquire the signals with no fiber bending.

24. Remove and Discard the short length sample.

25. Record the result.

26. Extract and Cut a length of 200 cm +/- 5 cm fiber from the INSIDE end of the reel.

27. Strip and Cleave one fiber end of the short sample.

28. Align it with the source optics.

29. Strip and Cleave the other fiber end of the short sample.[9]

30. Align it with the detector pigtail.

31. Place the fiber sample into the cutoff conditioning template.

32. Make a single 3 cm diameter loop, using the supplied loop mandrel.

33. Ensure that the fiber is laid as straight as possible on the test bench.

34. Maximize the source and detector coupling.

35. Acquire the signals with the bent fiber.

36. Unwrap the 3 cm diameter loop.

37. Acquire the signals with no fiber bending.

---

[9]The original cleavage cannot be used as it is fragile and can be damaged in handling.

38. Remove and Discard the fiber sample.

39. Record the test result.

40. Move the fiber reel back to the storage rack.

3.3.2.2. Test of Mode Field Diameter

The test of the fiber mode field diameter is carried out with the following steps.

Mode Field Diameter Test:

1. Get a piece of fiber sample from a reel.
2. Strip and Cleave one fiber end.
3. Align it with the source optics.
4. Make a 3 cm diameter loop, using the supplied loop mandrel.
5. Strip and Cleave the other fiber end.
6. Align it with the detector optics.
7. Type in relevant data.
8. Maximize the source and detector coupling. (fine-tune)
9. Initialise the test system. (execute the computer program)
10. Maximize the detector coupling again. (adjusting the micrometer stage)
11. Acquire the signals. (execute the computer program and wait for its completion)
12. Record the result.
13. Remove and Discard the fiber sample.
14. Get another piece of fiber from the other end of the same reel.
15. Strip and Cleave one fiber end.

16. Align it with the source optics.

17. Make a 3 cm diameter loop, using the supplied loop mandrel.

18. Strip and Cleave the other fiber end.

19. Align it with the detector optics.

20. Maximize the detector coupling again. (adjusting the stage)

21. Initialise the test system.

22. Maximize the source and detector coupling. (fine-tune)

23. Acquire the signals. (execute the computer program and wait for its completion)

24. Record the test result.

25. Remove and Discard the fiber sample.

3.3.2.3. Test of the Fiber Geometry

The test of the fiber geometry is done with the following steps.

Geometry Test:

1. Get a reel of fiber from the storage rack.

2. Get a sample from one end of the fiber.

3. Type in the relevant data.

4. Strip and Cleave one end of the sample fiber.

5. Align it with the light source.

6. Strip and Cleave the other end.

7. Align it with the objective lens of the video camera using 3-D micrometer stage.

8. Adjust the focus of the fiber end face image.

9. Acquire data. (execute the computer program and wait for its completion)
10. Rotate the fiber sample by 180° at the camera end only.
11. Readjust the image focus of the fiber end face.
12. Acquire data. (execute the computer program and wait for its completion)
13. Copy the results on the screen onto the tag on the fiber reel.
14. Remove and Discard the fiber sample.
15. Get a sample from the other end of the fiber.
16. Strip and Cleave one end of the sample fiber.
17. Align it with the light source.
18. Strip and Cleave the other fiber end.
19. Align it with the objective lens of the video camera.
20. Adjust the image focus of the fiber end face.
21. Acquire data. (execute the computer program and wait for its completion)
22. Rotate the fiber sample by 180° at the camera end.
23. Readjust the image focus of the fiber end face.
24. Acquire data. (execute the computer program and wait for its completion)
25. Record the test results.
26. Remove and Discard the fiber sample.

3.4. Observations and Comments

The manual operation involved in the four tests can be grouped into three main categories. The first group is the test sample preparation. The second is the fiber alignment with the light source and the detector (or video camera). The third is the computer operation. It is observed that some of the operations in each category are repeated in following the present test procedure. The following sections discuss the duplicate operations in more detail.

3.4.1. Test Sample Preparation

Test sample preparation includes the two jobs of getting the fiber sample, and stripping and cleaving the fiber end faces of the test sample. The number of these operations for testing each reel of fiber is summarised in Table 3.2.

Table 3.2: Number of Test Fiber Preparations in Test of A Single Fiber.

Operation\Test	Att.	Cutoff	MFD	Geom.
Extracting (may include measuring)	2	1	2	2
Stripping & Cleaving	3	2	4	4

Except for the attenuation test, two samples must be taken from the INSIDE end and the OUTSIDE end of the fiber, respectively, for each test. In the characterization of a single fiber, the total number of the two operations discussed is seven and thirteen, respectively. As discussed in the previous section, the stripping and cleaving of the test fiber are considered important and even critical in some tests. It would be desirable to perform these operations a fewer number of times. The reason that so many fiber stripping and cleaving operations are required is that these tests are carried out in three different test stations. The stripped and cleaved ends of one fiber sample can not be used again in other tests because the cleaved end of the fiber is fragile and can be easily damaged once the protective coating on the fiber is removed. If one sample, from either end of the fiber, is used for more than one test, the number of stripping and cleaving operations could be reduced significantly. For example, if a test sample taken from the INSIDE end of the fiber reel were used for the geometry, MFD, and cutoff wavelength test, the total number of stripping and cleaving operations could be reduced by four. Obviously these tests, then, must be carried out consecutively at the same test bench.

3.4.2. Fiber Alignment

The number of fiber alignment jobs to test one reel of fiber is summarised in Table 3.3. Some of these jobs are identical from test to test, although some are not the same. Similar to the discussion in Section 3.4.1, if all tests were carried out at the same test bench, some of these jobs could be combined and the number of alignments required could be reduced. For example, if one fiber sample was used for more than one test, the source side alignment of the cutoff wavelength and the MFD test could be combined and the total number of alignments would be reduced by one.

The alignment condition has a significant impact on the test accuracy and repeatability of some tests. However, the alignment relies solely on the subjective judgement of the test operator. No other method is used to ensure that the alignment job will be carried out correctly. A solution to this problem might be automating the process using a computer control system. By directly monitoring the signal level in the test system, the control system could drive the motion mechanisms and make decisions based on the actual

Table 3.3: Number of Fiber Alignment Jobs Required.

Job\Test	Att.	Cutoff	MFD	Geom.
Alignment jobs	3	2	4	4

response of the test system to the alignment condition. This could eliminate some of the several factors which are identified with the poor test repeatability sometimes observed.

3.4.3. Computer Operation

The existing computer operations are simple and straightforward. These include some operations as simple as pressing a key on the computer keyboard. The only concerns are two operations. One is the entering of the relevant data before each test. The other is the recording of the results onto a sticker on the fiber reel after each test. Complete specifications of the test fiber are provided at the end of the geometry test, the last in the fiber test procedure. Some of the computer operations are not necessary as they are the consequence of the separate test setups. For example, in the attenuation and cutoff wavelength test, the test fiber length and the previous OTDR test result need to be entered at the beginning of the test, and the test results, five items in total, are copied down by hand at the end. The same data, seven in total now, are reentered during the geometry test in order to create the complete record of fiber specifications. This repetition does not pose any problem if the tests are required only once in a while, but, in the production environment, these duplicate operations consume a considerable amount of time. Practically, these duplications are not difficult to eliminate. The data required can be entered once for all tests of a single fiber and a record of all data, including the new test results, could be created and kept in the computer memory. After all tests are complete, the computer can print out a hard copy of this record, giving complete specifications of the fiber being tested. This once again suggests a new test procedure which will perform all four tests at the same test bench.

3.4.4. Comments

The discussions in the previous three sections suggest that changes in the present test procedure are desirable to improve the overall test process. An integration of the three test stations seems to be the necessary step for streamlining the whole test process. Here, integration means to put together all test equipment required for the four fiber tests into a single test bench and modify the test procedure accordingly.

With an integrated test set, it becomes possible to use the same test sample for more than one parameter test. In general, the time savings from eliminating the duplicate operations are significant. A new test procedure could allow a reduction of 8 fiber stripping and cleaving and 4 fiber alignment jobs. In addition, the number of other minor operations, such as data entering and results copying, would be reduced. If the human factor, the involvement of the test operator, is taken into consideration, the impact of employing the integrated test set would be more significant. In a day-to-day and long hour operation, the seemingly simple jobs become tedious and tiresome. A streamlined test procedure, having only necessary operations, should boost the morale of the test operator, or at least release some of the repetitive burden. The operator, then, could concentrate on a few delicate operations, such as fiber cleaving and alignment. A quality inspection of the fiber cleaving, which is not employed in the present test procedure, could now be added. As a consequence, the test quality, such as the test repeatability, could be improved.

The system integration is also the preliminary step towards an automatic test system. A totally automatic system is the ultimate goal in designing a new test system. The benefits of automation are not only the time saving but also, and maybe more importantly, the improvement of test quality by eliminating the human involvement in doing the tests. In manual operation, it is impossible to carry out tests in exactly the same manner repeatably. Discrepancies among test results, under the same condition, with the same test sample, are attributed to the human handling of the tests, and to some operations such as mis-alignment of the fibers to the detector. A machine could operate precisely in performing some repetitive jobs. This feature, hopefully, would improve the test repeatability when used with the test setup. However, a total automation of the test set is beyond the scope of this research project.

A partial automation scheme is more appealing at the present time. The process of fiber alignment with the light source or detector is a good candidate for automation. It is a major operation in the test procedure. It is performed frequently, and the quality of the job done, which now relies on the subjective judgement of the test operator, has great impact on some parameter tests.

The total number of pieces of test equipment required in the test set could be reduced significantly by system integration. For example, the present setups require three microcomputers, one each for the attenuation and cutoff wavelength test, MFD test, and the geometry test. After system integration, only one would be required. As well, the integrated test set would use only one set of lock-in amplifier, monochromator and accessories instead of two identical sets used in the existing setup for the attenuation and cutoff wavelength test and the MFD test, respectively. Some benefits that would be obtained are reduced capital cost, reduced equipment maintenance, and the saving of work space. A single test bench should be able to house all the equipment required. As for the software design, the core of the original software would be basically unchanged. Some modifications would be needed to provide easy access to, and linkage of, different test subprograms.

3.5. Summary

In this chapter, the test setups for single mode optical fiber in a production environment have been described. The operational procedures for using these setups have also been discussed. Some observations show that several operations in the existing test procedures could be eliminated to improve the overall test efficiency. The analysis of the test procedure indicates that complete integration is feasible. An integrated test set should provide for streamlining the overall test process and improving the test quality. The complete integration would be a large task, and only a small portion of this task has been selected for design and implementation in this project; that portion is the automatic fiber alignment with source and detector optics.

4. An Automatic Fiber Alignment System

4.1. Introduction

A major task of this study is to design and built an automatic fiber alignment system. This system would automate the procedures of aligning the test fiber end face to the light source, for both attenuation and mode field diameter tests, and to the detector, for the mode field diameter test. The purpose is to reduce the time required for manual alignment and, more importantly, to eliminate the human subjective judgement in the manual operation and thereby improve the test repeatability.

This chapter describes the details of the system design, including the hardware design and software design.

4.2. Overall Design Consideration

The automatic alignment system provides three major functions; it receives commands from the host test system, determines the maximum signal level appropriate for each test, and provides control to an alignment mechanism.

The system should operate independently with a minimum of intervention from the host system. The host test system should need only little modification from its original setup and no operational disruption should occur when the automatic alignment unit is installed. To complete the job, the system should be able to provide the function of communicating with the host system, learn the present fiber alignment condition, and, based on this knowledge, control the fiber alignment.

A microprocessor-based design provides a very good solution to meet all of the requirements stated above. Some powerful single-chip microprocessor/controllers are available with many enhanced functions, such as on-chip Timer/Counter and Input/Output facility. If these functions are fully utilised, the system hardware required and the physical size of the complete system would be small.

The software design is to provide all the basic control functions, such as communication interface and the mechanical drives. In addition to these, a properly designed algorithm is required to complete the task of finding the best fiber alignment in real time. A modular design should be used in the software development so that system development, debugging, and maintenance would be easily managed. In general, simplicity is the objective in designing every part of the system, including the hardware and the software.

4.3. Hardware Design

4.3.1. Functional Blocks

The hardware design can be divided into four functioning sections, namely, controller, communication interface, data acquisition, and driver. Figure 4.1 shows the block diagram of the auto-alignment system. The controller is the core section which has complete control over the three other sections. It receives commands from the host test system and generates proper control signals to the other sections to perform the specified tasks. The major alignment operations include monitoring the signal obtained from the host test system during alignment, and controlling the mechanical assembly to move the test fiber end faces past the light source and the detector. As soon as the maximum signal is obtained, the driver is stopped and the alignment job is completed.

The major part of the communication interface is a signal multiplexer controlled by the controller section. Because of a limitation of the number of

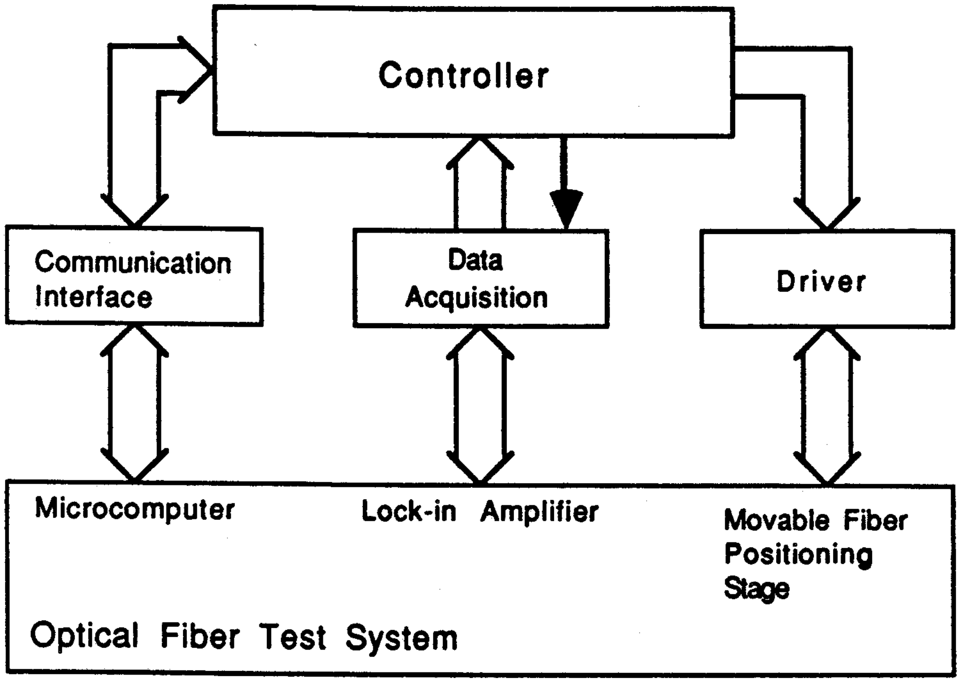


Figure 4.1: Functional Blocks of the Fiber Auto-Alignment System.

I/O lines available, the I/O lines used for communication purposes are shared with the data acquisition section. The host system, when requesting the auto-alignment system service, puts command codes on the interface and signals the auto-alignment system by causing an interrupt. The auto-alignment system responds to the host system by reading the command and placing a status code on the communication interface. Some signal conditioning circuitry is also provided in this section to meet the physical output requirement of the host system.

The data acquisition system section consists of a sample and hold circuit and an 8-bit analog to digital converter (ADC). This system monitors the test signal level obtained from the host test system and converts the analog signal into a digital form to be used by the auto-alignment controller. This direct monitor of the test system signal is necessary to find the best fiber alignment.

The driver section performs a conversion of low level control signals to high driving power for the mechanical motion. To prevent the drive mechanism from overheating, a variable power supply is required. This system also provides an isolation between the low voltage microsystem and the high voltage drive circuitry. Further detail of the mechanical alignment system and the electrical drive components is given in Section 4.3.6.

4.3.2. Microcomputer Selection

An INTEL 805i family single chip microcomputer was selected and used as the core of the auto-alignment system design. This microcontroller chip contains many facilities required in the system design, such as on chip hardware timer, and I/O lines. The advantage of using this chip is significant. It simplifies the system design, and minimises the number of chips and the physical size of the system, compared to a similar system built from discrete components.

Some major features of the Intel 805i microcontroller family are :

- 8-bit CPU,
- 256 bytes on chip internal RAM,
- 64K address space for external data memory,
- 64K address space for external program memory,
- 32 I/O lines,
- 2 16-bit timer/counters,
- on-chip oscillator and clock circuitry,
- a six-source interrupt structure with two priority levels,
- full duplex serial port,
- Boolean processor,

- on-chip ROM BASIC,
- HMOS technology.

In addition to the features listed above, the availability of an Intel Microprocessor Development System in the Department of Electrical Engineering had an influence on the selection of the Intel 805i controller chip. Because some of the software must be written in assembly language codes in order to function fast enough, some software development tools, such as an assembler and an EPROM programmer, are very desirable.

A prototype alignment unit was built with a BCC-52 microcomputer, which is a single board controller/development system. This board contains an INTEL 8052AH-BASIC chip, RAM and/or EPROM chips, an EPROM programmer, 3 parallel ports, and 2 serial ports. It has all the features described above for the 805i family.

4.3.3. BCC-52 Microcomputer

The 8052AH-BASIC chip is the programmed version of the INTEL 8052 microcontroller. It contains 256 bytes of internal RAM, 8K bytes of on-chip ROM, three 16-bit timers/counters, 6 interrupts and 32 I/O lines. The 32 I/O lines are divided into four groups (ports), each with 8-bits. The I/O lines are predefined to address, data, and control lines for constructing a complete system or they can be used as ordinary I/O lines if the other functions are not implemented. In the BCC-52 board, seven of these I/O lines can be used for the application I/Os. An 8255 Programmable Peripheral Interface (PPI) chip provides extended input/output capacity for the BCC-52 board with three software configurable 8-bit parallel I/O ports. There are another two serial ports on the BCC-52 board; one for a console I/O terminal and the other for an auxiliary serial output port. This port can be used as the output to a line printer.

The BASIC interpreter stored in the internal ROM is a useful tool for the system development. It provides access to the internal registers, I/O lines, and internal and external memory space. It also provides some utility subroutines which can be called directly from an application program. Another powerful development tool in the BCC-52 board is its on-board EPROM programmer. The control signals needed to program 2764/128 EPROMs are generated directly from the 8052AH chip. Any program stored in the EPROM can be executed automatically and immediately after the system is reset.

The instruction set of the Intel 8052 chip is completely compatible with the Intel 8037 chip, an EPROM version of the 805i chip. A successful software development on the BCC-52 could be transfered into the 8037 chip without much modification. This would provide for further simplifying the system and shrinking the product size if a large number of the systems are in demand in the future.

4.3.4. Communication Interface

The system is designed to communicate with an HP computer, through its General Purpose Input Output (GPIO) port, in the host test system. The interface circuit schematic is shown in Figure 4.2. There are a total of 13 lines needed to connect the two systems. Eight of these are data lines used by the host system to send commands to the alignment unit. Three of the remaining lines are status lines used by the alignment system to display its present operating status. The last two lines are used, one by either system, to signal the opposite side using an interrupt technique.

The I/O port B of the 8255 (PPI) chip is devoted as the input channel for the microcontroller. This port provides 8 bits of input. Due to the limitation of the number of I/O lines available in the BCC-52 microcomputer board, this input port serves as the Command input channel as well as the data input channel for the A/D conversion. Therefore, multiplexing must be

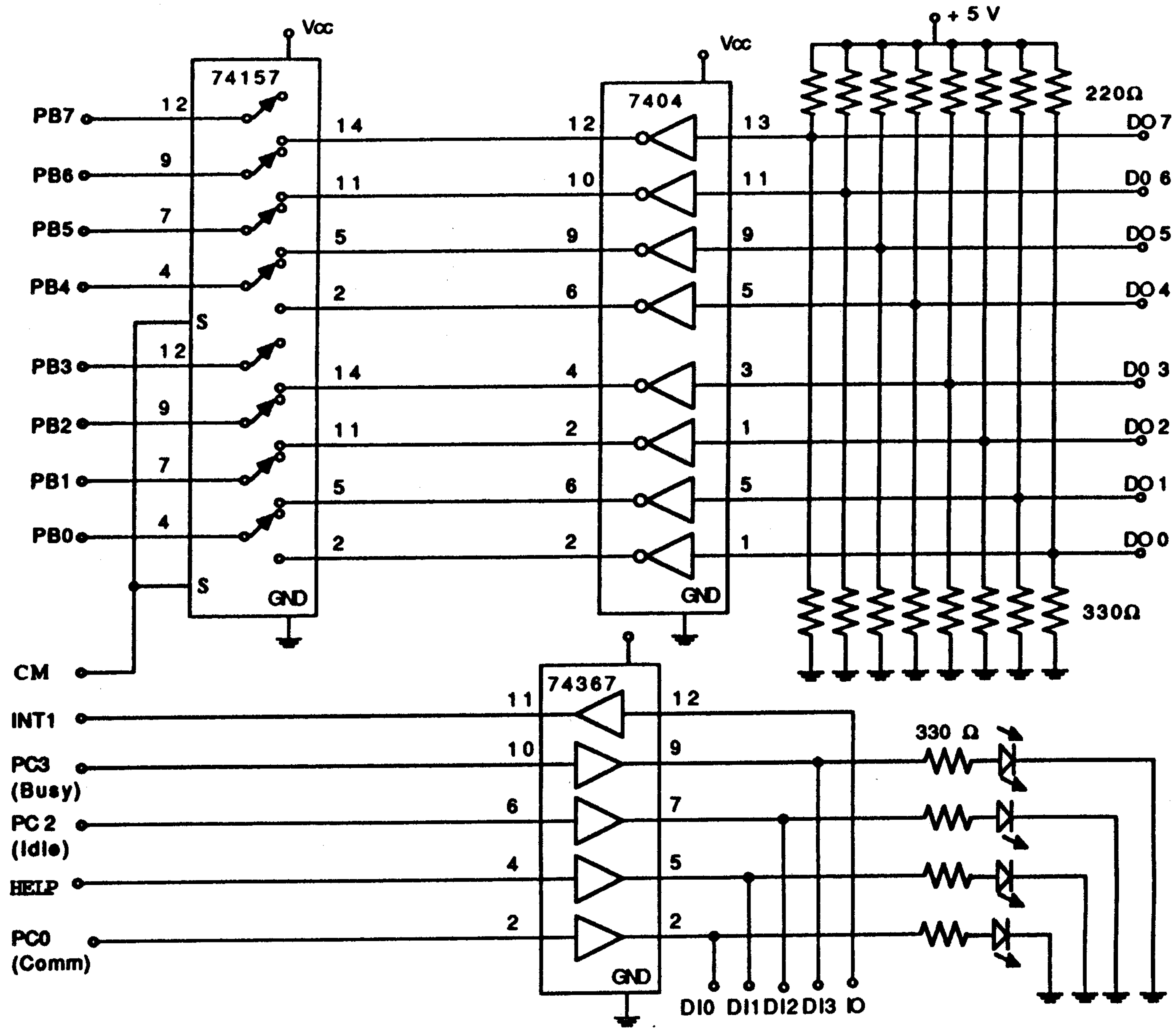


Figure 4.2: Communication Interface.

provided at the port B of the PPI chip. Two Quad 2-lines-to-1 data multiplexer chips (SN74LS157) are used to serve this purpose. Table 4.1 gives the function table of the data multiplexer chip. The SELECT pins of the multiplexer chips are connected to the CM line, an I/O line of the 8052 microcontroller chip. Upon request of the host system, the controller will execute an interrupt service routine in which it pulls down the CM line, SELECT, and reads the data on the output of the LS157s as the command sent by the host system.

Table 4.1: Function Table of the Multiplexor Chip.

INPUTS				OUTPUT
STROBE	SELECT	A	B	
H	*	*	*	*
L	L	L	*	L
L	L	H	*	H
L	H	*	L	L
L	H	*	H	H

The output lines of the GPIO port are from open-collector circuits. A positive pull-up voltage must be provided for the proper connection to this port. Table 4.2 gives the input and output requirements for the driver and receiver interfacing to this port.

Table 4.2: Input and Output Requirements for the Interface to the HP GPIO port.

Receiver Specifications (Output Requirement)	
V_{out} low (I_{out} low = 16mA)	0.4 V max
V_{out} high (open collector)	30 V max
I_{out} low	40 mA
I_{out} high (V_{out} = 30 V)	250 mA

Data Input Lines	
I_{in} low	2.3 mA (V_{in} low=0.4V)
V_{in} max	5.5 V
V_{in} high	> 3 V
V_{in} low	< 0.7 V

4.3.5. Data Acquisition

To guide the search for the finest fiber alignment position, the data acquisiton section must directly collect data from the test signal path of the host test system. There are two signal amplifiers cascaded in the test signal path; one is a lock-in amplifier and the other is a digital multimeter (DMM). To avoid the long time delay caused by the slow conversion rate of the DMM, data have been acquired directly from the output of the lock-in amplifier.

Figure 4.3 shows the circuit diagram of the data acquisition section. An ADC 0809 chip is used to perform the analog to digital conversion. It is a monolithic device with an 8-bit analog-to-digital converter, 8-channel multiplexer and microprocessor-compatible control logic. It eliminates the need for external zero and full scale adjustments. Table 4.3 gives the specifications of the ADC 0809 chip.

To simplify the design, the clock of the ADC chip is provided by a frequency scaler (two D-type flip flops), taking the clock pulses from the clock (ALE signal line) of the BCC-52 board. The reference voltage is provided from a constant voltage obtained with a precision reference diode. Because the absolute conversion accuracy is not critical and what is of concern in the software algorithm is the relative values of two samples, this simplified scheme works satisfactorily. For the same reason, the relatively low conversion resolution of an 8-bit ADC (0.4%) should not pose a significant problem in the system.

The output from the lock-in amplifier is in the range from 0 to 10 volts; however, the input of the ADC 0809 chip can only operate in the range from 0 to 5 volts. A voltage divider is required to scale down the input of the maximum 10 volts to 5 volts. The divider is constructed by a voltage follower and two high precision resistors. The resistors are of 10 KΩ each, with an accuracy of 1%. The voltage follower is required to minimise the disturbance to the original test signal if a low impedance device is attached.

As mentioned before, the microcontroller reads the A/D conversion results through the I/O port B of the 8255 In reading the A/D conversion results, the controller software must set the CM bit at the I/O port 1 to select the inputs of the multiplexer (LS 157) from the ADC data output. The controller software also provides the control signals required for the A/D conversion. The ADC chip requires three control signals, Address Latch En-

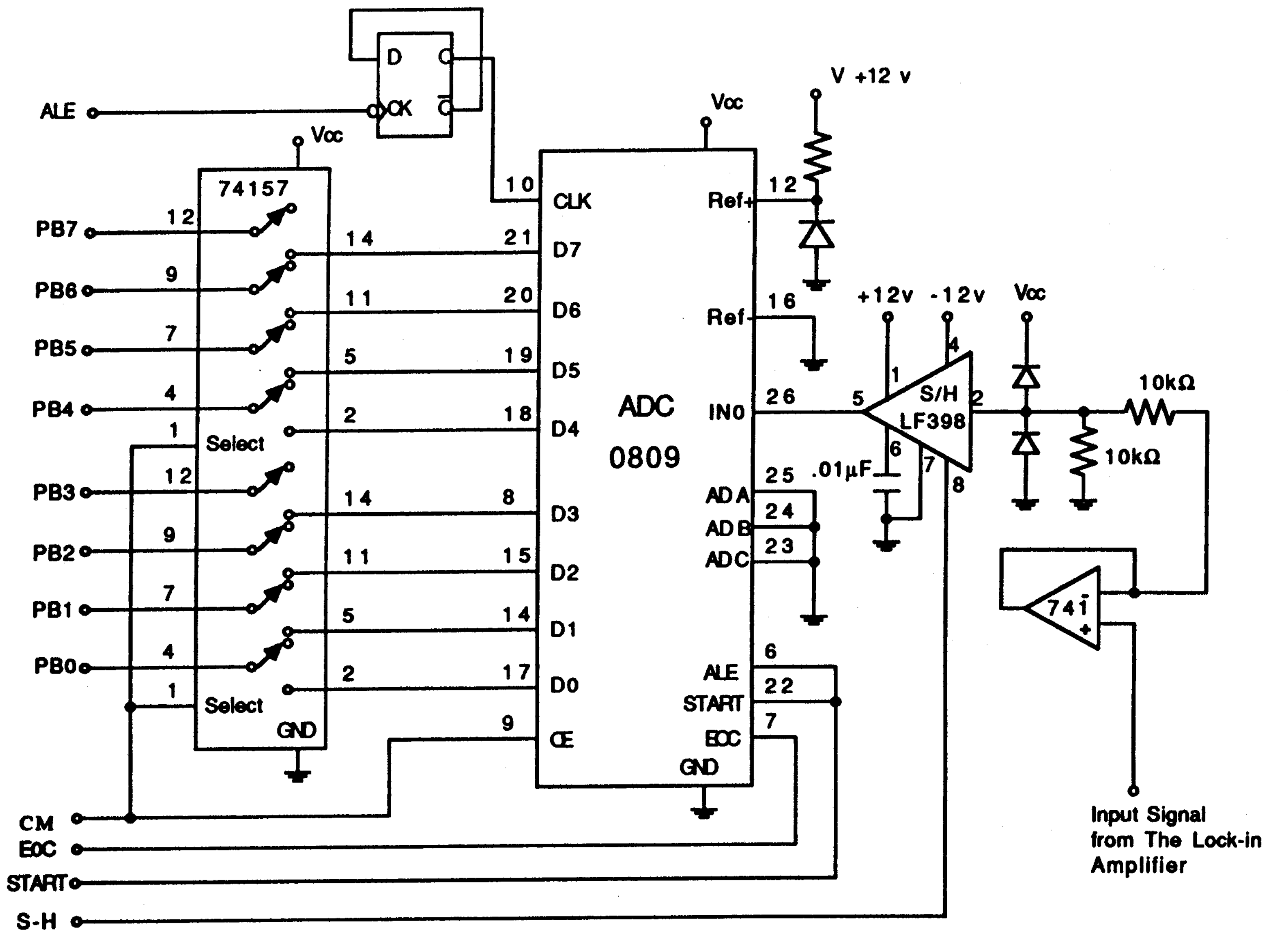


Figure 4.3: Circuit Diagram of the Data Acquisition Section.

Table 4.3: The specifications of the ADC 0809 chip.

PARAMETER	VALUE	UNIT
RESOLUTION	8	BITS
TOTAL UNADUSTED ERROR	+/- 1	BIT
INPUT RESISTANCE	2.5 K	Ω
ANALOG INPUT	0 TO 5	VOLT

able (ALE), Start conversion (Start), and Output Enable (OE), and provides one status flag, End Of Conversion (EOC). Each of these lines is interfaced with the controller through its I/O port 1.

4.3.6. Driver, Mechanics & Circuitry

The mechanics involved in the alignment system includes a three axis movable stage, holding the test fiber end with a clamp, and three "Stepper Mike" drives, each containing a stepper motor and a precision mechanical motion translator.

4.3.6.1. "Stepper Mike" Drive

The Stepper Mike [21] is a commercial product of Oriel Corporation (U.S.A). It contains a precision nonrotating spindle driven by a four phase unipolar stepper motor through a fine pitch screw. The Stepper Mike produces linear travel in discrete steps, 1 micron per half step or 2 microns per full step, over a range of 13 mm. Table 4.4 gives the specifications of the Stepper Mike Drive.

Table 4.4: The Specifications of the Stepper Mike.

Range of Travel	13 mm (0.5 inch)
Step Size Half Step Mode Full Step Mode	 1.0 micron 2.0 micron
Repeatability-bidirectional	+/- 3.0 micron
Max. Step Rate Half Step Mode Full Step Mode	 1000 steps/sec. 500 steps/sec.
Max. Spindle speed	1.0 mm/sec.
Maximum Spindle Force	15.5 lb (7 kg)

The selection of the half-step and full-step operation in the Stepper Mike is determined by the phase and the sequence of energization among the four windings of the stepper motor. The proper winding energization phase and sequence for the stepper motor control are listed in Table 4.5 and Table 4.6 for full-step and half-step operation, respectively. The full step mode of operation is used in this design.

Two limit switches are built into the Stepper Mike. They are miniature microswitches and are wired in the "normally open" mode. The switches are mounted at either end of the indicator scale and must be wired to the drive logic circuitry in order to shut the motor off before the mechanism runs into its stops. Running the motor into the mechanical stops can cause jamming and possible damage to the Stepper Mike.

Table 4.5: Control of a Four Phase Unipolar Stepper Motor (1).

Stepper Motor Phase Control (Full Step Drive)				
Step\Phase	A	B	C	D
1	ON	ON	OFF	OFF
2	OFF	ON	ON	OFF
3	OFF	OFF	ON	ON
4	ON	OFF	OFF	ON
1	ON	ON	OFF	OFF

Table 4.6: Control of a Four Phase Unipolar Stepper Motor (2).

Stepper Motor Phase Control (Half Step Drive)				
Step\Phase	A	B	C	D
1	ON	ON	OFF	OFF
2	OFF	ON	OFF	OFF
3	OFF	ON	ON	OFF
4	OFF	OFF	ON	OFF
5	OFF	OFF	ON	ON
6	OFF	OFF	OFF	ON
7	ON	OFF	OFF	ON
8	ON	OFF	OFF	OFF
1	ON	ON	OFF	OFF

The Stepper Mike also has a knurled spindle at its rear to allow manual adjustments when the Mike is not energised. It is a useful feature for this application.

4.3.6.2. Driving Circuitry.

As discussed in the previous section, the motion of the Stepper Mike and the stage requires the proper control of the energization of the stepper motor windings. The control is done by turning on and off semiconductor switches, each in series with a stepper motor winding, with a proper phase and sequence. Figure 4.4 is the circuit schematic for the driver control. The motor control signals are generated in software by the microcontroller.

The semiconductor switches used in the motor control are HEXFET transistors (IRFD 110), a type of power MOSFET transistor. The specifications of the IRFD 110 are given in Table 4.7. This transistor has a very low on-state resistance combined with high transconductance and good device ruggedness. It also features all of the established advantages of MOSFETs such as voltage control, freedom from second breakdown, very fast switching, and temperature stability of the electrical parameters. To turn on the IRFD 110 transistor, the voltage imposed between the Gate and Source of the transistor must be greater than 4 volts; the resistance between the Drain and Source of the transistor is then less than 0.6 Ω.

There are a total of five stepper motors to be controlled in this design. Therefore, twenty switching transistors are used and twenty control lines are required. However, the I/O lines from the BCC-52 board are limited. There are only 12 I/O lines available from the 8255 chip, eight lines from port A and four lines from port C. The other four lines from port C are used as the output of the system status flags. A multiplexer with storage feature is required and it is constructed with three 8-bit latches (LS373). The functions of the LS373 are shown in Table 4.8.

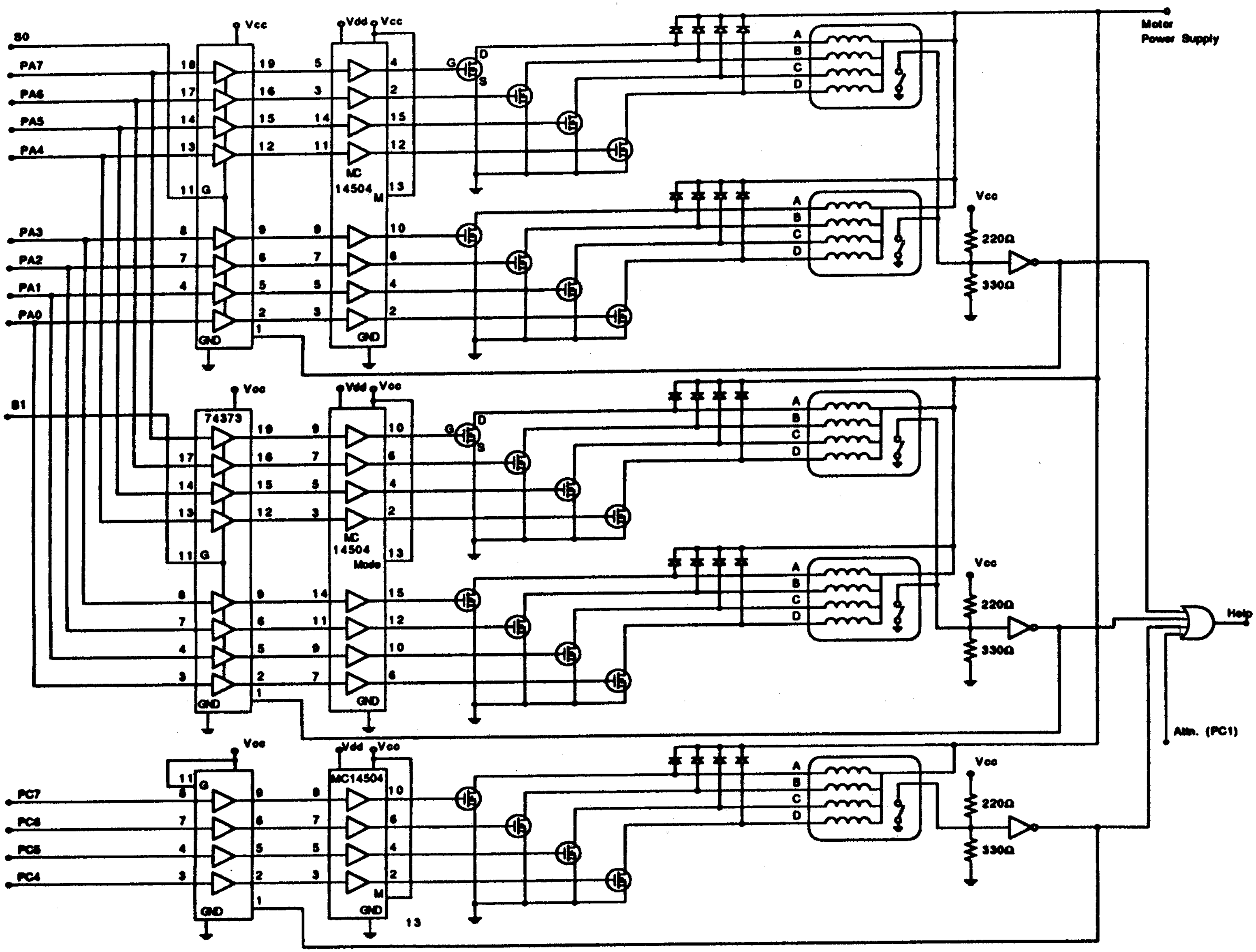


Figure 4.4: Circuit Diagram of the Stepper Motor Control.

Table 4.7: The Specifications of the IRFD110 Transistor.

IRFD110 HEXFET TRANSISTOR	
R_{ds} (ON State Drain-Source Resistance)	0.6 Ω
I_d (ON State Drain Current)	1.0 A
V_{gs} (Gate Threshold Voltage)	4.0 V Max
BC_{dss} (Drain-Source Breakdown Voltage)	100 V

Table 4.8: Function Table of the LS373 Latch.

$\overline{OE}$	G	D	Q
L	H	H	H
L	H	L	L
L	L	*	Q
H	*	*	Z

When a motor state is to be changed for any motor from #1 to #4, the controller puts the winding control signals on port A. For motor #5, the signals are output through port C of the **8255** chip. The controller then pulls up the motor selection line, which is one bit at the I/O port 1 and is connected directly to the G line of the LS373 chip. The new excitation pattern is passed through and the semiconductor switches are turned on or off accordingly. The Motor-Select line (s0 or s1) is pulled down immediately after and the new pattern of the excitation control is latched into the LS373. The energization pattern of the selected motor is kept unchanged until the new pattern is passed through the latch in the next operation. The I/O lines of the **8255** chip are now free for passing control signals to the other motors should it be requested. The 8-bit latch can provide control signal paths for two stepper motors.

The three-state outputs of the LS373 are active when OE is low, and high-impedance when OE is high. The OE pin is connected to the Stepper Mike limit switches through an inverter chip. The limit switch is "normally-open" when the Stepper Mike is operating within its range of travel. While the output of the inverter is kept low, the control signals can traverse the LS373 latch freely in the normal operation state. When the Mike crosses the travel limit, the limit switch is closed. The output of the inverter goes high and the control signals are blocked from reaching the semiconductor switches. The stepper motor will stop its motion. The limit switches are also wired together through an OR gate to inform the host system that some abnormality has occurred. This line can be regarded as a status flag polled by the host system or used to cause interrupt to the host system.

The operating voltage of the Stepper Mike is specified as 24 volts. However, if the motor is kept in stand still state with this voltage supply for a long time, it becomes overheated. To prevent this, a lower voltage power supply must be used to reduce the current flowing in the motor windings. The power supply has to be switched back to 24 volts before the motor makes a transition. This is controlled by a bit in the I/O port of the controller chip, being set or reset by the software program. The power switch is constructed of two HEXFET transistors, a directional diode and two resistors (Figure 4.5). In the idle state, the Busy line from the controller, an I/O bit at port 1, is kept in the low state; the transistor T_2 is shut off and so is the power switch transistor T_1, a P-channel HEXFET transistor. The second power supply voltage is about 4.3 volts from a 5 volt source through a directional diode. Before any operation takes place, the Busy line is pulled up and both transistors T_1 and T_2 are turned on. The motor power supply is then switched to 24 volts and the 5 volt source is switched off because the diode is in reverse bias. After the complete transition is over, the Busy line is pulled down once again and the power supply for the motor is set back to 4.3 volts.

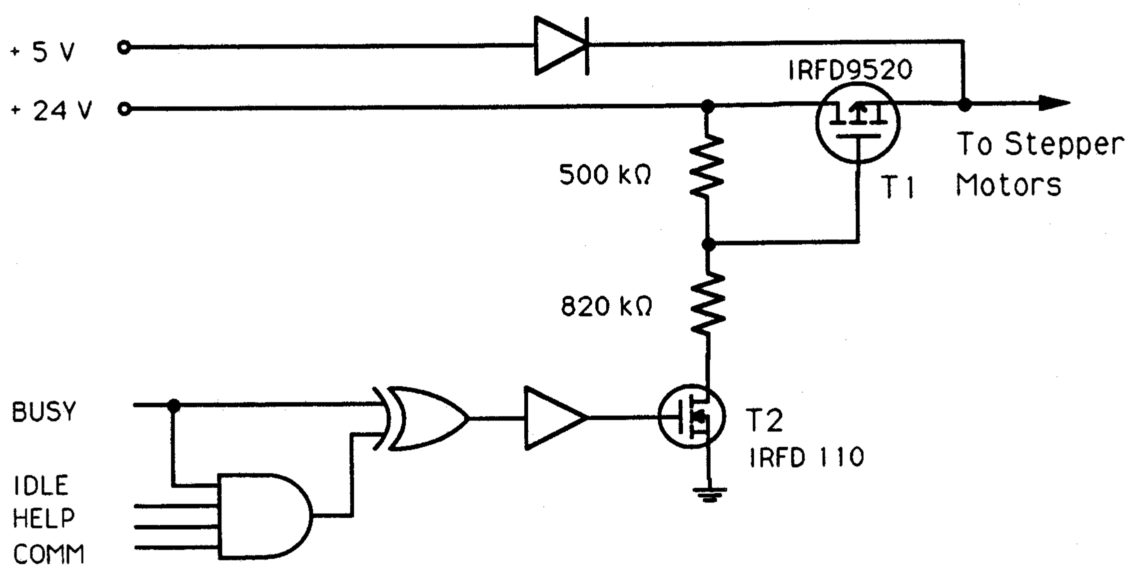


Figure 4.5: The power supply for the stepper motors.

4.4. Software Design

4.4.1. Design Specifications

This section lists the requirements for the software that is to be incorporated in the prototype system:

- Command Driven

  As a self-contained system, it should provide controls and the functions requested all by itself, with minimum intervention of an external system. It should be designed to be used with the HP 9000 computer. Practically, it could be interfaced with any digital system. It should react only to the command code placed in the command input.

- Multiple Functions

  - Stepper Motor Drive Controller

    It should generate proper control signals, with the correct control sequence, to the selected stepper motor. The motor selected, the direction of movement, and the number of steps are specified in the Command.

  - Alignment Task1

    It should monitor the test signal level in the test system and control the stepper motors to align the test fiber end to the light source optics. This process continues until the maximum system response is observed. The stage movement control is in three dimensions.

  - Alignment Task2

    This is similar to the Alignment Task1, but, the alignment is to the photodetector (for MFD test only). The stage movement control is in two dimensions.

  - Abortion of any process

    Any on-going process could be stopped at will. A new function request can then be executed immediately.

- Modular Design

  The software is to be structured as several modules. Each module should contain a program subroutine which performs a single function, such as driving the stepper motor, or timing a delay. The program development, debugging, and maintenance should be simple.

- Search Algorithm

  A practical and efficient method is required to determine that the finest fiber alignment condition has been achieved. An optimization scheme should be incorporated in the software to efficiently complete the job.

4.4.2. Operating System

When the alignment system is initially turned on, reset, or finished performing any task, the operating system takes control of the system. It first goes into a loop to check if a new command flag (NEWCOM) has been set. This flag is set by an interrupt request to indicate that a new operation is waiting. When the new command is received, the operating system interprets the new command and goes to execute the proper subroutine according to the task requested.

Because of the 8052 Boolean processor feature, the command interpretation is rather simple. The command format is shown in Figure 4.6. It is stored as one byte in the bit addressable space of the internal RAM. The most significant bit (MSB) of the command byte is used to indicate whether it is an auto-alignment task or a motor control job. If this bit is set, the processor will check the least significant bit (LSB) to determine whether it is Task1 or Task2. If the MSB is reset, more bits are required to specify the selection of a motor, the direction of movement, and the number of steps to drive.

COMMAND FORMAT

Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0

Bit 7: 1 Fiber Alignment

Bit 0: 0 Task 1
1 Task 2

Bit 7: 0 Stepper Motor Driver

Bit 5: 0 Forward
1 Backward

Bit 4	Bit 3	Bit 2	
0	0	0	Motor #0
0	0	1	Motor #1
0	1	0	Motor #2
0	1	1	Motor #3
1	0	0	Motor #4

Bit 6: 0 Normal Operation
1 Test Mode
Subroutine exits to
the controller's BASIC

Bit 1	Bit 0	Step #
0	0	1 **
0	1	2
1	0	5
1	1	10

Bit 7 - Bit 0 = 00000000 : Abort any on-going operation

** Single step operation not applied to Motor #0

Figure 4.6: Command Format.

4.4.3. Search Algorithm

The auto-alignment tasks involve a searching process for the finest test fiber end face alignment with the light source or the photodetector of the test system. The alignment with the light source is a three dimensional search and the alignment to the photodetector is a two dimensional search. Figure 4.7 illustrates the alignment set up for the source side alignment.

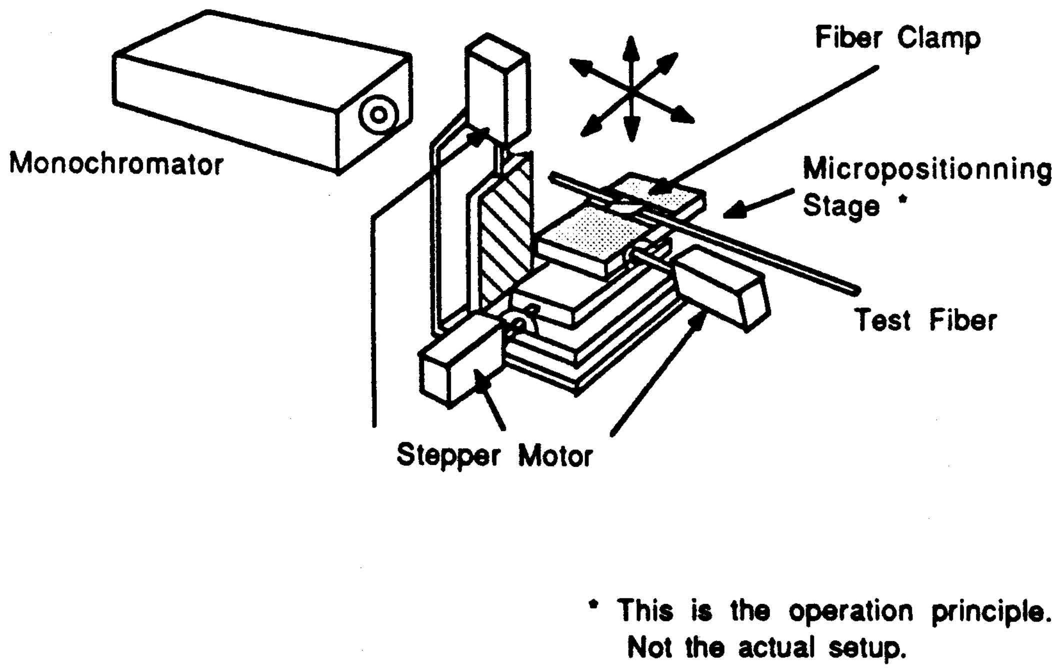


Figure 4.7: Light Source Side Alignment.

The finest alignment achieved is considered as that when the test fiber end face is in a position at which the signal in the test system obtains a global maximum level. However, this maximum value is unknown before the alignment is complete, and it varies with different testing conditions, such as different test fiber samples and fiber end face preparation. The alignment process can only rely on monitoring the system response to the change of the alignment condition. Therefore, the search algorithm is based on the basic principle of altering the alignment condition until no better system response can be observed. In approaching the maximum response position, many data samples must be taken and each new sample is compared with the previously recorded sample which has the largest value so far encountered. The spatial coordinate of the alignment condition corresponding to this largest sample is recorded. This process continues until the maximum system response is found.

There are some constraints in actually carrying out the searching task because the test system has a relatively large response time constant. The number of samples and the span of each variation of the alignment condition determine the searching time, and the resolution of the alignment process. An optimization method is incorporated in the searching algorithm to reduce the number of samples required and, consequently, minimise the time needed in the searching process. Several multi-variable optimization methods were considered [22]. The one selected is called the "sectioning" search method. By this method, one of the several variables is adjusted until the function of these variables reaches a maximum, while the other variables are kept constant. Each variable then in turn is adjusted to give a value which is a maximum for the function. This process continues until all of the variables are adjusted. In practice, the alignment condition can be represented by the coordinate of the stage holding the test fiber sample. For the light source alignment, the stage has three movable axes, each driven by a stepper motor. For the detector alignment, the stage has two axes, each also driven by a stepper motor. The change of a variable is equivalent to the movement of the stage in any one axis. Hence, the search is carried out by moving the stage in each axis one at a time to give a maximum signal response to the test system. This process is repeated four times in completing the alignment task. This operation has a resemblance to the manual operations in the present test procedure. More of the searching algorithm will be discussed in Chapter 5.

4.4.4. Motor Control

The motor control signals are generated by software. The control of the stepper motor movement consists of two basic elements. One is the correct sequence of change of the binary bit pattern which is used to control the energization of the motor windings. This also determines the direction of the motor movement, i.e. moving forward or backward. The other is the timing of transitions between two consecutive control patterns. This determines the speed of the stepper motor because the number of the pattern transitions per second represents the number of steps per second the stepper motor moves.

The control bit pattern is generated using a table-look-up technique. The bit patterns for all consecutive motor steps are stored in a table called the Motor-Winding-Control (MWC) table. There is another table which contains pointers to the entry of the MWC table. One bit of the pointer entry is used for the direction bit. The set or reset of this bit indicates the two different directions of movement. One more table, called Output-Record (OR) table, is used to keep the record of the present control patterns of all five stepper motors. The contents of each entry are what are actually written out onto the hardware, consisting of the I/O port of the 8255 chip and the data latches. The relationship of these tables and pointers is illustrated in Figure 4.8. When a motor driver is requested, the subroutine fetches the pointer of the designated motor. According to the setting of the direction bit, it then increments or decrements the pointer pointing to the next entry in the MWC table. With the new pointer value, the processor fetches the new control bit pattern from the MWC table. This new bit pattern is then merged with the corresponding entry in the OR table. Since only one motor at a time is driven, only half of the output record byte is affected in the merging. The other half is intact. The new record byte is then sent to the I/O port. Control signals for the output interface are also sent. Figure 4.9 gives the flowchart of the primitive stepper motor control.

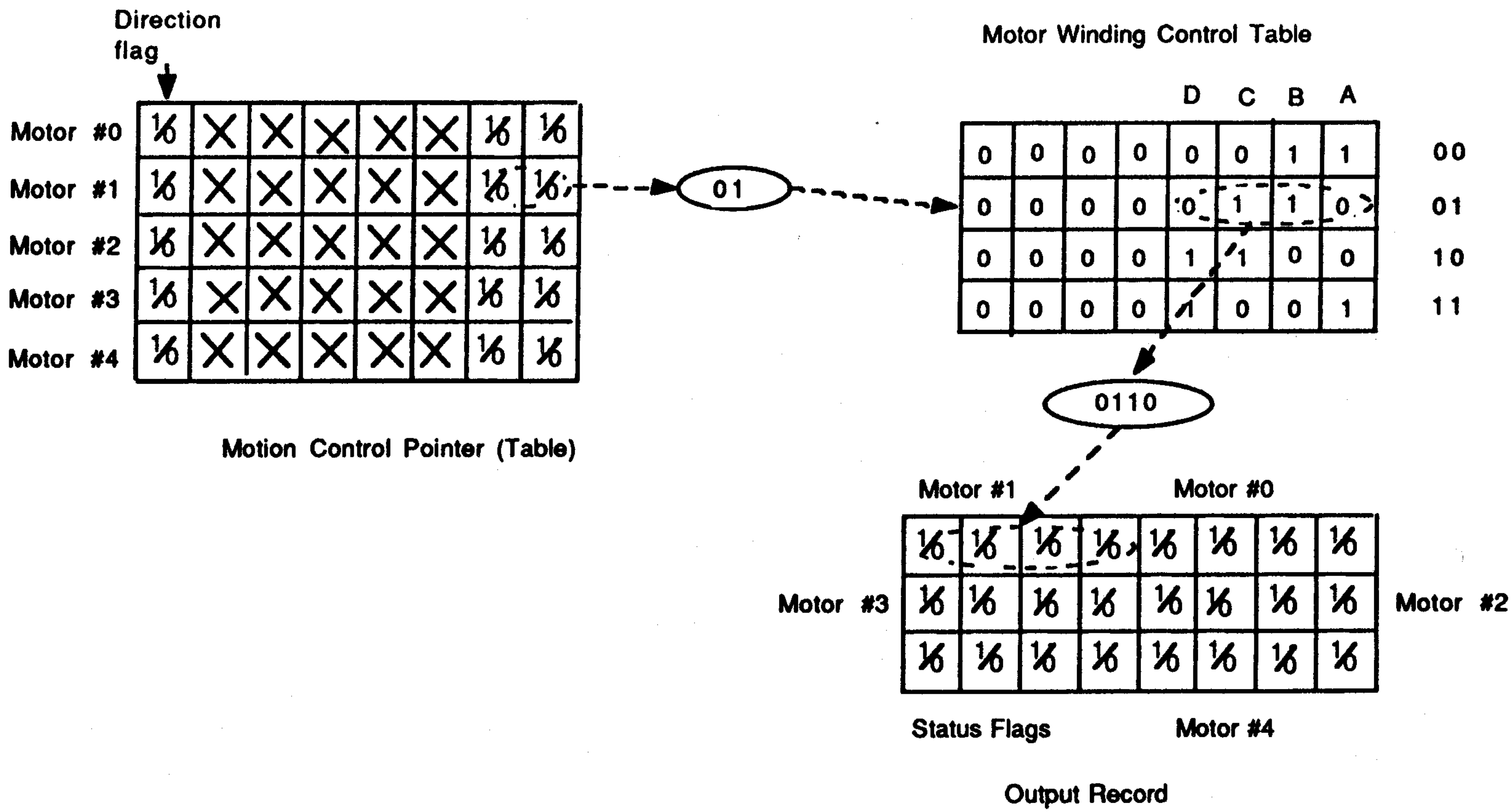


Figure 4.8: Tables Used For the Stepper Motor Control.

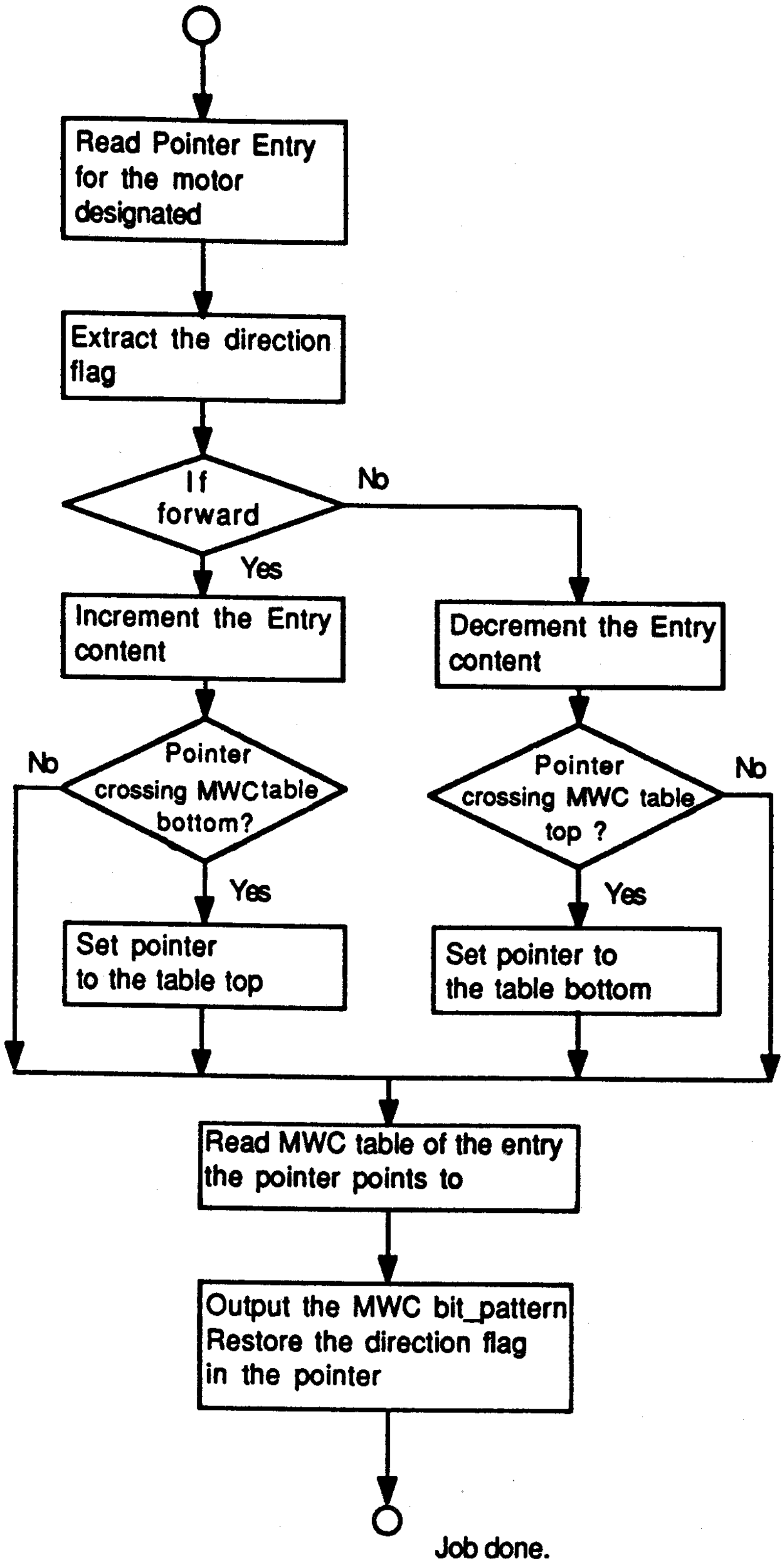


Figure 4.9: Program Flowchart for the Stepper Motor Control.

For multi-step operation, a timing delay subroutine is called to provide a time interval between the stepper operations. The speed of the stepper motor is kept constant during its multi-step operation, i.e. no acceleration or deceleration scheme is employed. Since in this controller, most of the motor operations are expected to be only a few steps each time, it is not practical to include acceleration and deceleration in the motor control.

4.5. Summary

This chapter has discussed in detail the design of a fiber auto-alignment unit. The unit is used to automatically align the test fiber with the light source and/or detector of the host test system, giving a maximum signal response for the optical fiber parameters tests. The design is based on the INTEL 8052 microprocessor/controller chip. The hardware design contains four sections, namely, controller, communication interface, data acquisition, and motor driver. The software design provides an algorithm to search for the finest fiber alignment condition from an offset as well as the controls of the basic system operation. The laboratory test of the system is described in the next chapter.

5. Algorithm Development And Laboratory Testing

5.1. Introduction

The prototype of the fiber auto-alignment system was built and tested in the laboratory in an environment that is similar to the actual test setup in the production line. This chapter will discuss the development of the software algorithm and the performance evaluation of this prototype.

5.2. Realities of Fiber Alignment

5.2.1. Non-Unique Light Intensity Profile

In the development of the searching algorithm for the fine fiber alignment, the profile of the light intensity (equivalently the electrical signal amplitude seen by the test system) with the coordinate of the fiber alignment condition should be known. In reality, however, it can only be obtained by experimentation. Figure 5.1, Figure 5.2, and Figure 5.3 show the light spot intensity profile at the source-side alignment. Figure 5.4 and Figure 5.5 give examples of the light spot intensity profile at the detector-side alignment in the MFD test. The source-side alignment has three coordinate axes and the detector-side alignment has two coordinate axes. The profile noted (a) in respect to each of the axes illustrated in Figure 5.1 to Figure 5.5 is obtained when the other axes are kept at the coordinate corresponding to an intensity maximum. The other profiles, designated as (b) and (c) in the figures, were obtained while one of the other axes was in an offset position. The vertical motion in the plane parallel to the light source is denoted as the Y axis, the horizontal motion is denoted as the X axis, and the motion moving towards or away from the light source is denoted as the Z axis.

It can be observed from the spot intensity profiles that there exists only a small zone, for both the source side alignment and the detector side alignment, within which the fiber end must be positioned in order to have a detection signal with which to guide a search algorithm. If the initial alignment of the fiber is out of this zone, the alignment process will be prolonged or even fail, if an alignment machine is used, because no signal is available to guide the alignment. This is also true for the manual operation. It is quite difficult to recapture the signal if the fiber initial position is well out of alignment. Fortunately, it is not a problem in the usual operation. The fiber clamp on the stage has a V-groove. If the previous alignment operation was done correctly, a new test sample, when clamped into this V-groove, will normally provide a signal large enough to guide the alignment. However, a fool proof measure must be incorporated in the software design to prevent any abnormal operation.

The major problem found in the experiments was that the intensity profile of the light spot is not unique and it may even vary when the lamp in the optical source is changed. The non-unique feature of the light spot intensity profile assures that no a priori knowledge of the best fiber alignment position is available to be used for the derivation or prediction of the correct position for maximum signal. In other words, it is not possible to have a simple algorithm to directly predict the optimized alignment position, i.e., the relative spatial coordinate with respect to the present position, using only a few samples. A trial-and-error method may be the only way to determine the fine alignment condition.

The experiments have also shown that the light spot intensity profile may exhibit double peaks, which may have an unpredictable pattern, in some situations. This makes the alignment search algorithm even more complicated in order to avoid being trapped at a secondary peak of the intensity profile. The cause of this problem is related to the optical source structure used. The so-called fiber alignment is in practice positioning the test fiber end to a

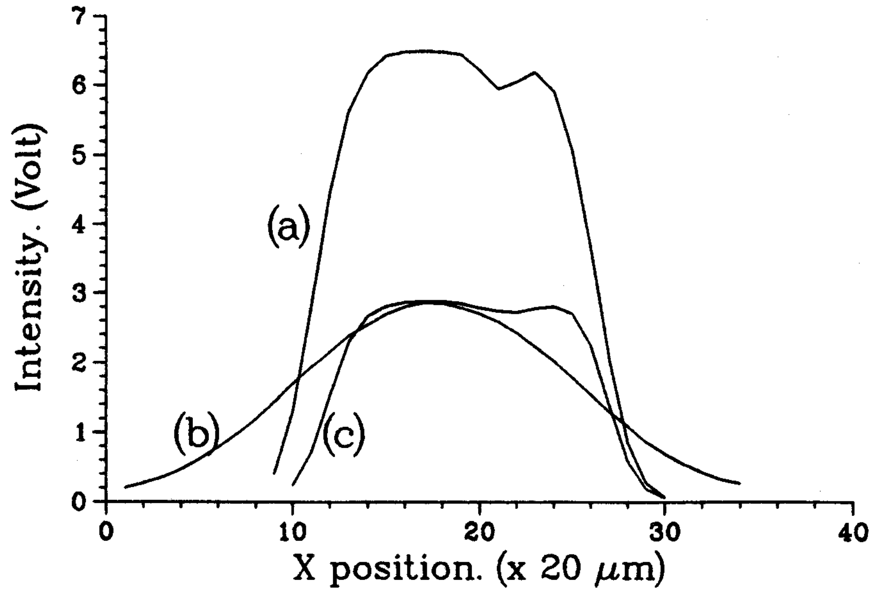


Figure 5.1: Example of the Light Spot Intensity Profile at X Axis of the Source-Side.

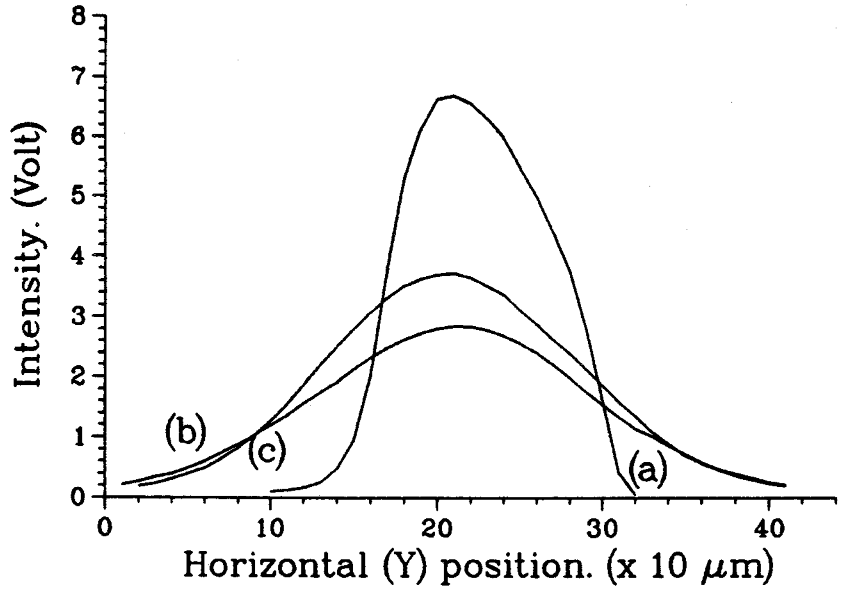


Figure 5.2: Example of the Light Spot Intensity Profile at Y Axis of the Source-Side.

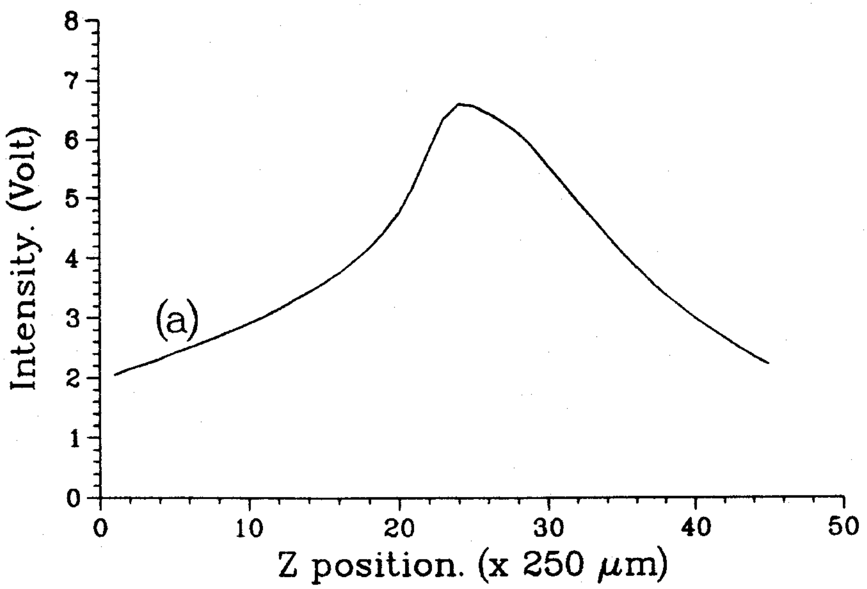


Figure 5.3: Example of the Light Spot Intensity Profile at Z Axis of the Source-Side.

spot which is the image of the brightest spot of the lamp filament. Figure 5.6 gives a graphical explanation of this phenomenon. Intentionally, the slit opening in an opaque disk, which is inserted between the lamp and the monochromator input, is shaped to allow only the light from one filament to pass through. The output from the monochromator should therefore be the image of this single filament. It is expected to have only a single peak at the center of the intensity profile. However, this is not always guaranteed and any change of the lamp, such as a replacement of an old lamp, will alter the profile at the spot at which the alignment is taking place. As a result, two types of double-peak phenomena may be observed. Figure 5.7 and Figure 5.8 show the two examples of the double-peak profile observed in the experiments. The first example indicates that the filament adjacent to the selected one is not completely blocked. This contributes to the formation of a second, but much smaller, peak of the spot intensity profile. The cause of the second

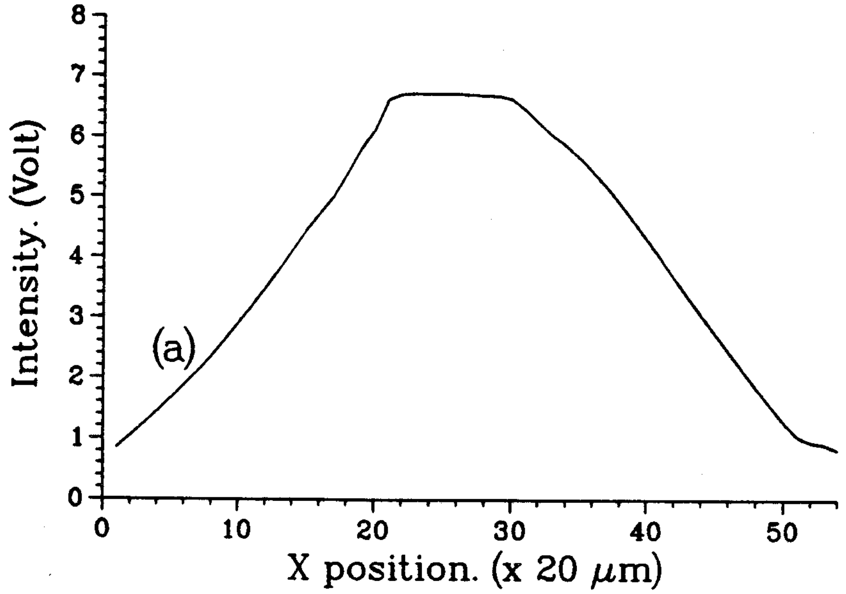


Figure 5.4: Example of the Light Spot Intensity Profile at X Axis of the Detector-Side.

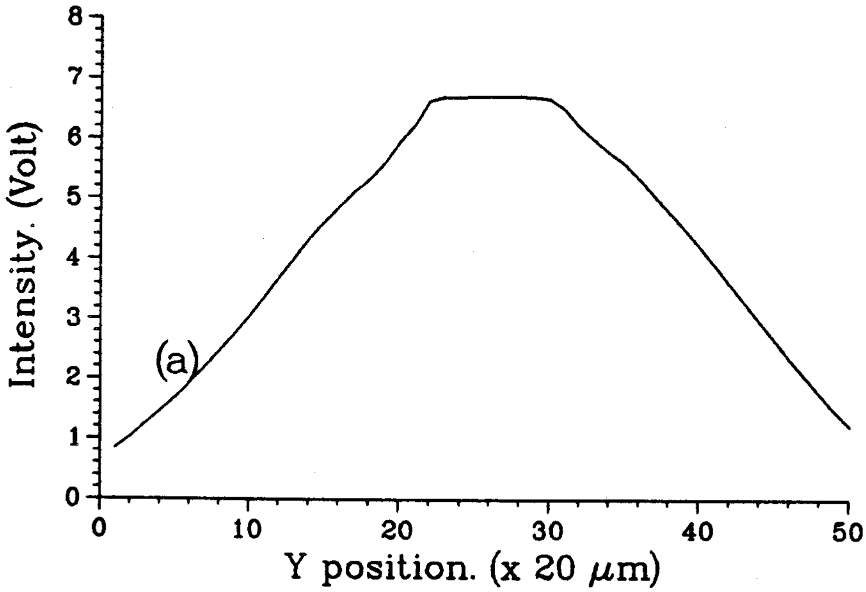


Figure 5.5: Example of the Light Spot Intensity Profile at Y Axis of the Detector-Side.

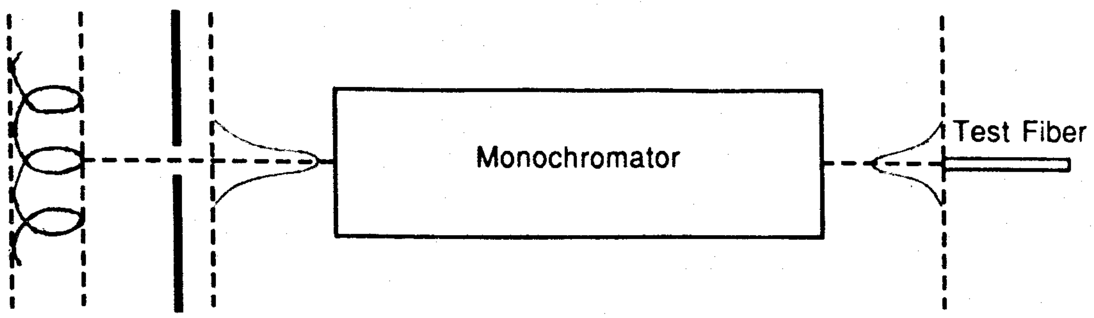


Figure 5.6: Light Source and Fiber Alignment.

example is still obscure. It may be related to the illumination mechanism of the filament. By carefully adjusting the lamp's orientation and the shape of the slit, it may be possible to eliminate the second peak in the first example.

5.2.2. Search Method

In actually implementing any search algorithm, many samples of the test system response must be taken to determine the finest fiber alignment condition. The sampling rate of the searching operation is restricted mainly by the response time of the lock-in amplifier. The lock-in amplifier has a low-pass electrical filter after the synchronous detector. Sometimes, some other signal filters, such as a signal bandpass filter, are switched in to improve the signal-to-noise ratio. In general, the larger the time constant of the filters selected, the better the signal recovered. The selection of the time constant of the main low-pass filter is in a range of one millisecond to one hundred second. The value chosen is determined by the signal and noise condition of the system tested. In the setup for this study, the time constant of

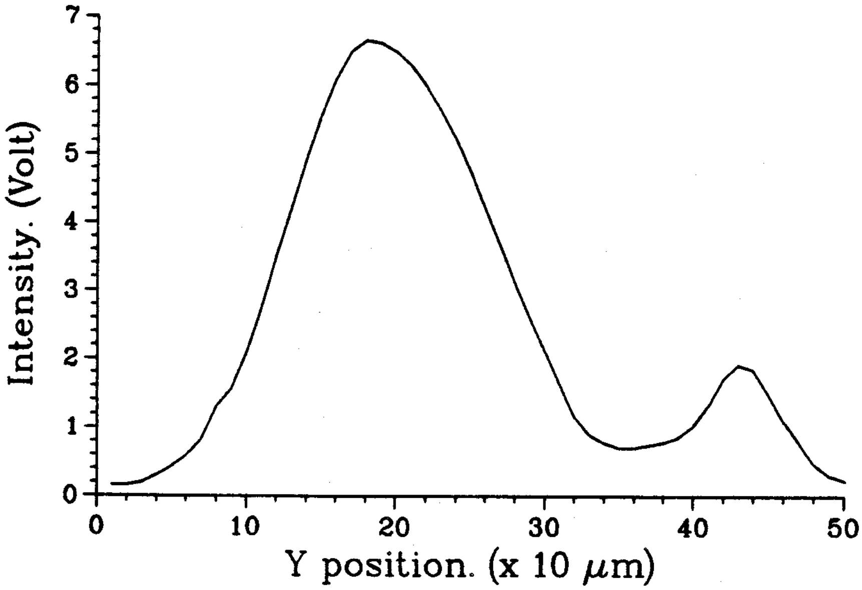


Figure 5.7: Example 1 of the Double-Peak Phenomenon.

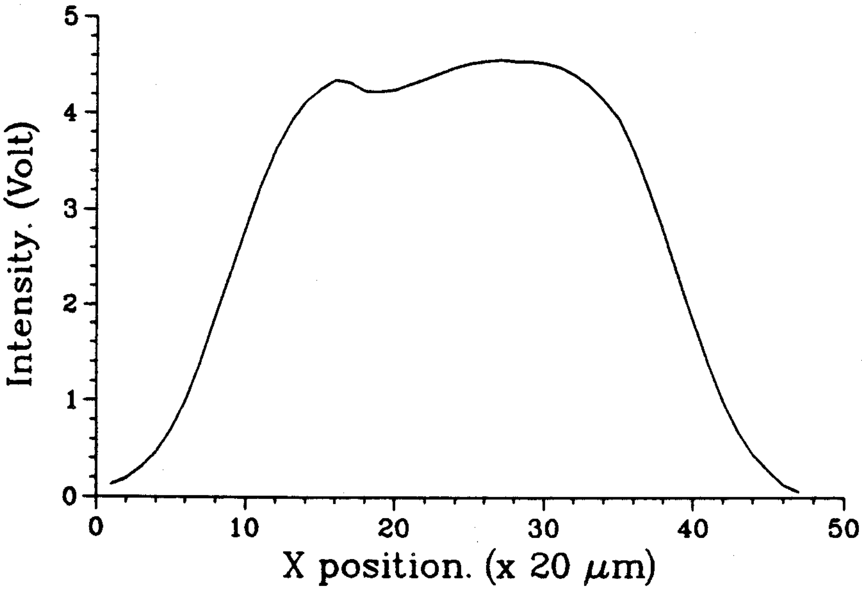


Figure 5.8: Example 2 of the Double-Peak Phenomenon.

the post-detection filter is set to 100 ms. No other filter is switched in. In response to a change at the amplifier input, the output will take several time constants to reach its final value. This has a significant impact on the total time required for the alignment job when several successive samples must be taken and compared. The total search time is mainly determined by the time to move the fiber positioning stage and the time to wait for the signal response to reach its final value. With the stepper motor used in this project, the speed of motion can be a maximum of 1000 microns per second at a stepping rate of 500 full steps per second. A search step in the algorithm is usually in the range from several motor steps to several tens of motor steps. Therefore, the movement of the stage will take only a few milliseconds, which is a small fraction of the total search time. The waiting time for the system response to stabilize has the major effect on the speed of the overall process. It became clear during laboratory testing that a small number of samples are desirable in the searching operation to reduce the time required. Since the spot pattern is a few hundred microns wide, the positioning stage can be moved about this distance between the taking of two successive samples. For such a large distance between initial and final alignment positions, the time between samples means a fewer number of samples and therefore a shorter time required to approach the final alignment position. However, a poor search resolution may result from an arbitrarily long search distance. In this case, the final position of the fiber positioning stage will likely settle at a point far from the finest alignment position but still within the search distance. A subsequent suitable search step size can be determined by analyzing the intensity profiles and by conducting experiments with the actual test system.

A more effective method to reduce the number of samples needed is to use standard optimization methods. In principle, the alignment task can be considered as a multivariable optimization task, in which each coordinate axis of the fiber positioning stage is treated as an independent variable and the test system response is the function to be maximized. The optimization methods suitable for this task are some direct search methods [22] which use function evaluation. The direct search methods use tests near to an estimate of the solution. The tests determine the direction in which the maximum is expected to lie. The maximum is then either found by a single variable search or, by a linear search in the direction determined, or approached by taking a fixed step towards it. After each maximization step, further searches are carried out until the desired maximum is found.

Two basic search methods were studied in looking for a solution for the fiber alignment task. One is a modified "pattern search" method and the other, which was eventually adopted in the software design, is a "sectioning" method.

The pattern search consists of two basic operations -- the local exploration, and the pattern move. Starting from a selected original base point x_{b1}, the local exploration changes a single variable (x_i) at a time by a preset step size (d_i) which can be tailored for each variable. The exploration algorithm evaluates the function at its original base point and at either or both points of the perturbations in the search variable about this point of $+/- d_i$ and, then, locates a temporary base point. Another independent variable is selected, and an exploratory search is carried out with respect to this variable about the temporary base point. Again, a new temporary base point is established to replace the old one. The process is repeated sequentially until all the independent variables have been explored. The final temporary base point is identified as the second base point, x_{b2}.

The original and second base points create a pattern which is used to locate the first pattern point, x_{p1}. Point x_{p1} is the terminal point of a directed line segment from the point x_{b1} through x_{b2}, twice the length of the line between x_{b1} and x_{b2}.

The function is evaluated at x_{p1} to determine if $f(x_{p1}) > f(x_{b2})$. If it is, the pattern move has been successful, and local exploration is made about the new pattern point x_{p1}. This exploration will result in a third base point x_{b3}. The base points x_{b2} and x_{b3}, then, are used to make another pattern move, which locates the second pattern point x_{p2}. This process will continue with the same sequence of operations. If $f(x_{p1}) < f(x_{b2})$, the pattern move will go back one half the length of the original move. A local exploration resumes from that point. The termination condition for the process is when no improvement is observed in the local exploration for each variable. Figure 5.9 shows an example of a two-variable pattern search. The points X_{b1}, X_{b2} and X_{b3} in the figure represent the base points obtained in the searching process, points X_{p1} and X_{p2} are the destination points of the first and second patter move, and d_1 and d_2 are the local exploration step size for variable x_1 and x_2, respectively. Because of its simplicity, pattern search is easily programmed for a digital computer.

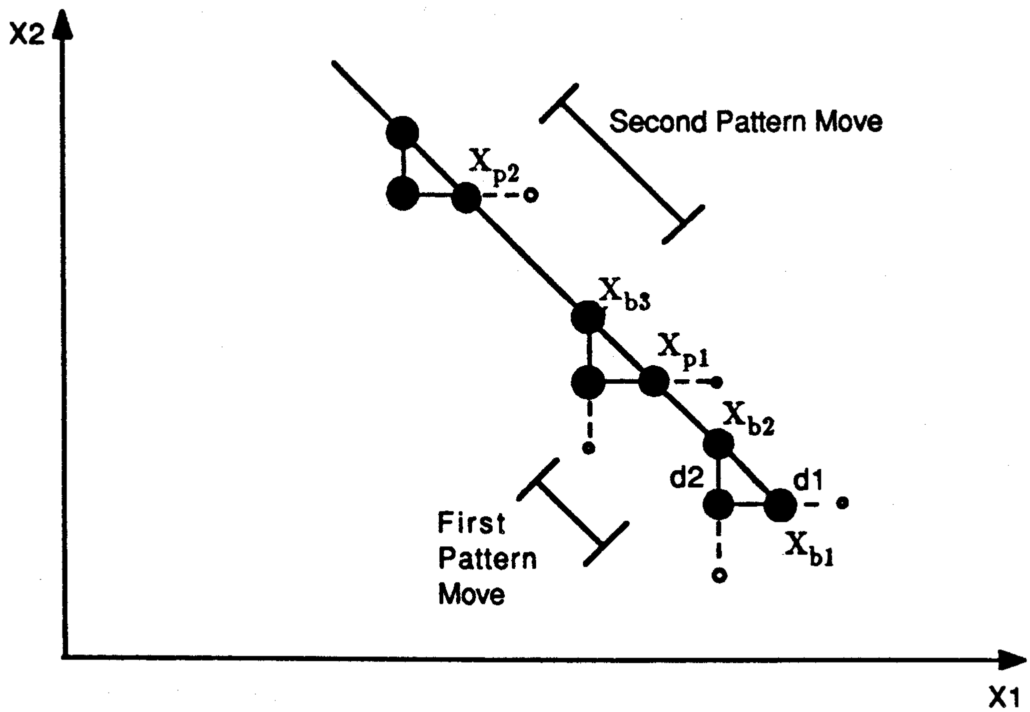


Figure 5.9: Example of Two-Variable Pattern Search Method.

However, the tests of the implementation of the pattern search failed to provide satisfactory results. Poor reproducibility was sometimes observed. It is attributed to the double peak phenomenon observed in the light intensity profile discussed in the preceding section. The pattern search method can only locate the local maximum in the vicinity of the initial search position and is not able to determine whether it is a global maximum, i.e. the maximum in the whole area of interest. If multi-local maxima exist, the pattern search may terminate its operation at any one of the local maxima but not the global maximum, depending on the initial search condition and direction. In implementing this method in the fiber alignment task, the search for the finest alignment may settle at either of the two positions and give two different signal levels to the fiber test system in successive tests, if the double-peak phenomenon can not be eliminated. The difference between the two signals obtained could be significant if the second peak in the light intensity profile is much different from the first peak.

The second search method, the "sectioning" search, uses a more primitive way to approach the maximum. To avoid the problem of settling down at a non-global maximum, a scanning method, if necessary, is incorporated in the alignment algorithm to determine the global maximum. This method bears a resemblance to the manual operation carried out in the fiber alignment process. It proceeds to search for the maximum in an independent axis while keeping the other axes unaltered. After the maximum with respect to an axis is found, the search continues in the next axis, while all other axes are kept unaltered, until all axes are tried. This process is iterated several times.

With this method, the criterion for the maximum being located is the appearance of a drop in the system response after a rise in the system response has been recorded. Referring to the signal intensity profile, the maximum is considered located if the search has gone through the ascending edge and then the descending edge of the profile. To minimize the number of signal samples needed in the search, different methods are used in different stages of the searching operations. In the first stage, the aim is to approach the vicinity of the maximum as quickly as possible with the search resolution not a major concern. The length of the search step varies in the process. At the beginning, it takes a small step to determine the proper search direction. It then takes a long "jump" with a length of several times the small step. Another test is taken and it is compared with the test sample before the "jump". If the comparison is favourable, it will take a small step and, then, a test sample to determine whether it is heading towards or going away from the maximum position before taking another long "jump". In other words, the small step trial is to determine whether the search is on the ascending slope or the descending slope of the intensity profile. If the comparison is unfavourable or the small step trial indicates a descending tendency, the search will move backward by half the length of the long "jump". The following operations use a successive halving method to find the maximum position. The first stage of search is carried out with each independent axis in a sequence of X, Y, and Z.

When the first stage of the search is complete, the fiber alignment should be in a region close to the desired position. However, more stages of search are still required because practically the search for the maximum in a single axis is not completely independent of the search in other axes. This means that after the searches for maxima in other axes are done, further improvement in the search for a maximum with respect to one axis, even though the search in this axis has been previously carried out, may still be possible. Some iterations of searching are necessary to acquire a finer fiber alignment. In the following stages, the technique used is to scan through a small region to locate both of the falling edges on the top of the light intensity profile and then calculate the mid-point between them. The search step becomes shorter gradually in going through the different searching stages to provide a finer search resolution. By experiment, it has been determined that three stages of scanning are necessary to complete the alignment job. Each stage of searching includes the search in all different axes.

To prevent the alignment from settling at the second peak of the intensity profile discussed before, a scanning search through a wider region is included to identify the largest peak (global maximum) in the profile should a second peak appear. The wider range of scanning is defined as the scanning between the positions on each side of the intensity profile which provide a test system response of half the maximum value observed. This wide range scanning is employed before the last stage of the scanning search because the difference between the two peaks on the intensity profile is not significant in the early searching stage. A reference to the example of the intensity profile (c) in Figure 5.1 illustrates that an earlier employment of the wide range scanning would be futile. The wide range scanning takes a longer time to complete than the small range scanning. Flexibility is provided to include or exclude the wide range scanning into or from the alignment search algorithm, depending on the working condition of the system setup. The inclusion of the wide range scanning is decided by observing whether the second peak exists. This is determined by executing an auxiliary subroutine when setting up the system. Because the double-peak phenomenon does not appear simultaneously in all axes, the use of the wide range scanning for each axis is also separately considered.

5.3. Performance Tests

The performance tests of the prototype unit consist of two parts. One is the test of the fiber alignment repeatability using the auto-alignment unit and the other is a measure of its impact on the fiber test results. In the test of the alignment repeatability, the variable of interest is the signal level of the system response to the fiber alignment condition. The same fiber samples were used in the testing, and the test setup, including the sample preparation, was kept unaltered. The only condition changed was assumed to be the fiber alignment position and each initial alignment condition was manually set at different mal-align positions. The test results using the auto-alignment unit at the light source side are tabulated in Table 5.1.

Table 5.1: Test Results of the Use of Auto-Alignment Unit at the Light-Source-Side Alignment.

Readings of the Test System Response in volts
(Light-Source-Side Alignment)

4.80	4.68	4.70	4.79	4.78
4.79	4.70	4.72	4.79	4.77
4.78	4.76	4.77	4.74	4.73
4.76	4.76	4.77	4.78	4.78
4.78	4.74	4.75	4.75	4.77
4.76	4.77	4.74	4.77	4.72
4.77	4.77	4.76	4.77	4.79
4.76	4.78	4.77	4.78	4.77
4.75	4.76	4.78	4.78	4.65
4.77	4.77	4.74	4.77	4.77

The test results using the auto-alignment unit at the detector side (MFD) are listed in Table 5.2.

In testing the impact of the use of the auto-alignment unit on the fiber test results, the variables of interest are the test results of the fiber parameters required, namely, the fiber attenuation at the wavelength of 1310 nm and 1550 nm, and the mode field diameter. The same test sample was used during testing. Except for the process of fiber alignment, which is now done by using the auto-alignment unit, the normal fiber test procedures were followed. The test results of the fiber attenuation at the wavelength of 1310 nm and 1550 nm are shown in Table 5.3 and Table 5.4.

Table 5.5 shows the test results of the mode field diameter with the use of the fiber auto-alignment unit.

Table 5.2: Test Results of the Use of Auto-Alignment Unit at the Detector-Side Alignment.

Readings of the Test System Response in volts
(Detector-Side Alignment)

6.22	6.21	6.23	6.23	6.24
6.22	6.22	6.23	6.22	6.23
6.22	6.21	6.25	6.26	6.26
6.27	6.25	6.25	6.21	6.24
6.23	6.20	6.22	6.19	6.21
6.23	6.22	6.21	6.20	6.18
6.21	6.23	6.21	6.22	6.19
6.21	6.21	6.19	6.17	6.22
6.22	6.23	6.21	6.23	6.22
6.21	6.21	6.21	6.20	6.20

The standard deviations of the test results, a measure of the test repeatability, are 0.03 volt and 0.02 volt for the source side alignment and the detector side alignment, respectively. These figures give an assessment of the performance of the auto-alignment unit. They are at the resolution limit of the 8-bit A/D converter used in the unit. One area of concern is the fiber test repeatability of the fiber parameters of interest. Some requirements for the fiber test repeatability are available in the test procedures. They are proposed and set by the manufacturer. The fiber test repeatabilities, which are considered acceptable, are 0.01 dB/km for the attenuation test and 0.07 μm for the mode field diameter test. The standard deviations of the test results, shown in Table 5.3 and Table 5.4, are 0.0053 dB/km and 0.0097 dB/km for attenuation test at the wavelength of 1310 nm and 1550 nm, respectively. For the mode field diameter test, the standard deviation is 0.048 μm. They all satisfy the fiber test repeatability requirements mentioned

Table 5.3: Test Results(1) of the Fiber Attenuation with the Use of Auto-Alignment Unit.

Tests of Fiber Attenuation at λ=1310 nm in dB/km				
0.39	0.39	0.38	0.40	0.39
0.39	0.39	0.38	0.39	0.39
0.39	0.40	0.38	0.40	0.39
0.39	0.39	0.39	0.39	0.38
0.39	0.39	0.39	0.39	0.39
0.39	0.39	0.39	0.39	0.38
0.38	0.39	0.39	0.38	0.39
0.39	0.39	0.38	0.39	0.39
0.38	0.38	0.39	0.39	0.39
0.38	0.38	0.38	0.38	0.38

Table 5.4: Test Results(2) of the Fiber Attenuation with the Use of Auto-Alignment Unit.

Tests of Fiber Attenuation at λ=1550 nm in dB/km				
0.29	0.29	0.28	0.28	0.29
0.29	0.30	0.30	0.30	0.27
0.29	0.30	0.30	0.28	0.28
0.27	0.28	0.29	0.29	0.29
0.28	0.29	0.29	0.28	0.29
0.28	0.28	0.30	0.29	0.30
0.30	0.28	0.29	0.30	0.27
0.30	0.29	0.27	0.28	0.29
0.28	0.28	0.27	0.27	0.29
0.29	0.28	0.27	0.29	0.28

Table 5.5: Test Results of the Fiber Mode Field Diameter with the Use of Auto-Alignment Unit.

Tests of Fiber Mode Field Diameter in μm				
9.47	9.47	9.40	9.51	9.49
9.51	9.43	9.43	9.41	9.35
9.44	9.48	9.53	9.41	9.50
9.44	9.52	9.46	9.56	9.43
9.55	9.50	9.45	9.51	9.48
9.48	9.42	9.38	9.51	9.52
9.46	9.42	9.50	9.55	9.46
9.48	9.49	9.49	9.50	9.51
9.36	9.40	9.42	9.45	9.50
9.46	9.46	9.44	9.45	9.44

above. The fiber alignment in the fiber test procedure, though a major factor, is only one of the many factors which affect the fiber test repeatability. It is difficult to have an absolute assessment of the improvement by using the auto-alignment unit on the fiber test repeatability. However, by observing the test results, a conclusion can be made that the use of the auto-alignment unit provides a satisfactory fiber test repeatability.

The hardware and software design of the auto-alignment unit were also tested successfully. Its communication with the host computer system and the control over the stepper motors all functioned properly. The design specifications stated in the preceding chapter were met and the prototype design and testing are considered complete.

5.4. Summary

This chapter has discussed the light spot intensity profile, its variability, and the double-peak phenomenon encountered during the fiber alignment process. All these matters imposed some difficulties on the development of the fiber alignment algorithm. Two optimization techniques, which were to be incorporated with the fiber alignment algorithm, are also described in this chapter. The one selected is the "sectioning" direct search technique.

The hardware and software of the fiber auto-alignment unit were tested in the laboratory and the design specifications are all met. The performance evaluation showed that the use of the auto-alignment unit provides a satisfactory fiber test repeatability.

6. Conclusion

The characterization of single mode optical fiber is a very important process both for the optical fiber fabrication, and for applications. Characterization consists mainly of measurements of several optical fiber parameters. In the fiber manufacturing environment, the fiber parameters of interest are the fiber attenuation, cutoff wavelength, chromatic dispersion, mode field diameter, and geometry. The attenuation, cutoff wavelength, and chromatic dispersion have direct impact on the fiber transmission characteristics. The mode field diameter and fiber geometry are mainly concerned with the fiber connection and splicing. They also have close relationship with the fiber transmission characteristics in application systems.

The technology of single mode optical fiber characterization has matured during the last several years. Many different techniques for the measurements of the fiber parameters of interest have been developed and some of them provide satisfactory results in terms of test accuracy, repeatability, and ease of implementation. This study focused on the optical fiber test setup in the production line of a local optical fiber manufacturer. The fiber parameters concerned are the single mode optical fiber attenuation, cutoff wavelength, mode field diameter, and geometry. The objective of this study is to have a good understanding of the existing test setup and to investigate the possibility of integrating the existing three separate test systems into a single test system.

The study demonstrated that some changes to the existing test setup are desirable to improve the overall efficiency of the fiber test process. The existing setup uses three different test stations for the four fiber parameter tests. This arrangement results in an inefficient test operating procedure due to the duplication of many operations, such as the fiber test sample preparation, involved in testing a single fiber. These duplications are present because the tests are carried out in three different locations. They are not difficult to eliminate if the test systems are integrated.

The study strongly recommends that a system integration is feasible and applicable. System integration would reduce the number of duplicate operations in the existing test procedure and improve the overall test efficiency. In addition to these improvements, the system integration would provide a better test quality, particularly the test repeatability, since with the new test procedure the test operator can concentrate on a fewer number of operations, such as fiber sample preparation and the fiber-end-with-light-source and/or detector alignment, which are considered critical in the fiber test quality. The system integration is also necessary for future development of an automatic test system. A totally automated test system, using a robot for example, may not justify the high development cost and long time required at the present stage; however, a partial automation of some of the test processes becomes attractive with the new integrated test setup. A good candidate for automation is the process of aligning the test fiber end with the test system light source and/or detector.

A prototype of an auto-alignment unit was designed and built to perform the fiber alignment task and replace the manual operations. It is a command-driven independent unit built around a microprocessor/controller chip, the Intel 8052. The aim of using this unit is to substitute the human subjective judgement involved in the fiber alignment with the machine's unbiased determination. It is also used as the first trial step towards a higher level of test system automation. The prototype design was tested experimentally and the results were satisfactory. More of these units are going to be employed in the fiber test setups by the manufacturer.

With the new integrated fiber test set, more studies are still required to refine the equipment layout and the operating procedure. An efficient and optimized operating procedure could be achieved by employing traditional Work Study techniques, including time and motion study techniques. The elimination of unnecessary motions and operations from the properly designed equipment layout and test procedure should be beneficial both to the test operator and to production. Automation subsystems for some of the test procedures, such as fiber auto-cleaver and auto-alignment units, have been separately developed recently. Further system automation is possible and the goal of a totally automated test set should become reality in the near future.

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A. The MCS-51 Architecture [23]

A.1. General

The 8052AH is the highest performance member of Intel's MCS-51 family of 8-bit microcomputers. It is fabricated with Intel's highly reliable +5V depletion-load, N-channel, silicon gate HMOS-II technology and is packaged in a 40 pin IC.

The 8052AH contains 256 bytes of read/write on-chip data memory; 32 I/O lines configured as four 8-bit ports; three 16-bit timer/counters; a six-source, two-priority level nested interrupt structure; a programmable serial I/O port; and an on-chip oscillator with clock circuitry. It also has 8K bytes of nonvolatile read-only program memory on-chip and has memory expansion capabilities of up to 64K bytes of data storage and 64K bytes of program memory.

The 8052 chip provides extensive BCD/binary arithmetic and bit-handling facilities. Forty-four percent of the instructions are one-byte, 41% two-byte and 15% three-byte. The majority of the instructions execute in just 1.0 μs at 12 MHz operation. Figure A.1 shows the architecture of the 8052AH. The connection diagram of 8052 chip is shown in Figure A.2.

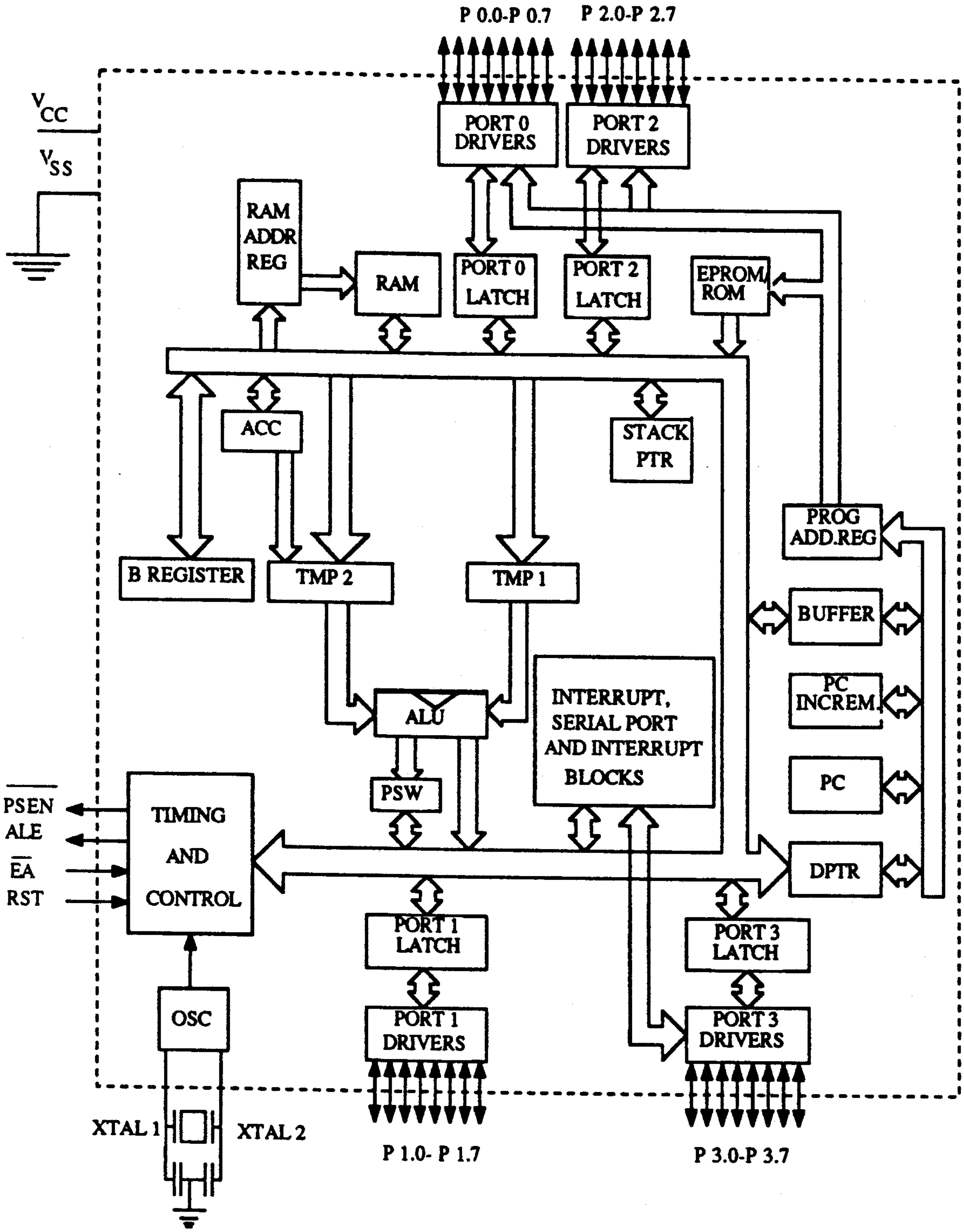

Figure A.1: MCS-51 Architectural Block Diagram

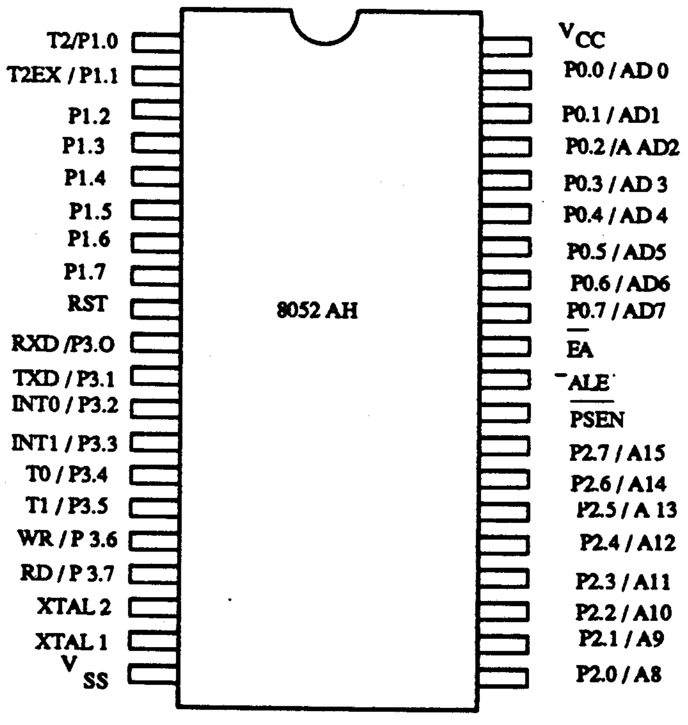

Figure A.2: Pin Configuration of 8052AH Microprocessor

A.2. Memory Organization

The MCS-51 architecture provides on-chip memory as well as off-chip memory expansion capabilities. Several addressing mechanisms are incorporated to allow for an optional instruction set.

The 8052AH has three basic memory address spaces:

- 64K-byte Program Memory;
- 64K-byte External Data Program Memory; and
- 384-byte Internal Data Memory.

A.2.1. Program Memory Address Space

The 64K-byte Program Memory space consists of an internal and an external memory portion. If the EA pin is held high, the 8052 executes out of internal program unless the address exceeds 1FFFH. Location 2000H through 0FFFFH are then fetched from external Program memory. If the EA pin is held low, the 8052 fetches all instructions from external Program Memory. In either case, the 16-bit Program Counter is the addressing mechanism.

Locations 00 through 2BH in the Program Memory are used by interrupt service routines as indicated in Table A.1.

Table A.1: Addresses for Interrupt Service Routines

Source	Address
External Interrupt 0	0003H
Timer 0 Overflow	000BH
External Interrupt 1	0013H
Timer 1 Overflow	001BH
Serial Port	0023H
Timer 2 Overflow	002BH
/TZEX Negative Transition	

A.2.2. Data Memory Address Space

The Data Memory address space consists of an internal and an external memory space. External Data Memory is accessed when a MOVX instruction is executed. Internal Data Memory is divided into three physically separate and distinct blocks: the lower 128 bytes of RAM; the upper 128 bytes of RAM; and the 128-byte Special Function Register (SFR) area. While the upper RAM area and the SFR area share the same address locations, they are accessed through different addressing modes.

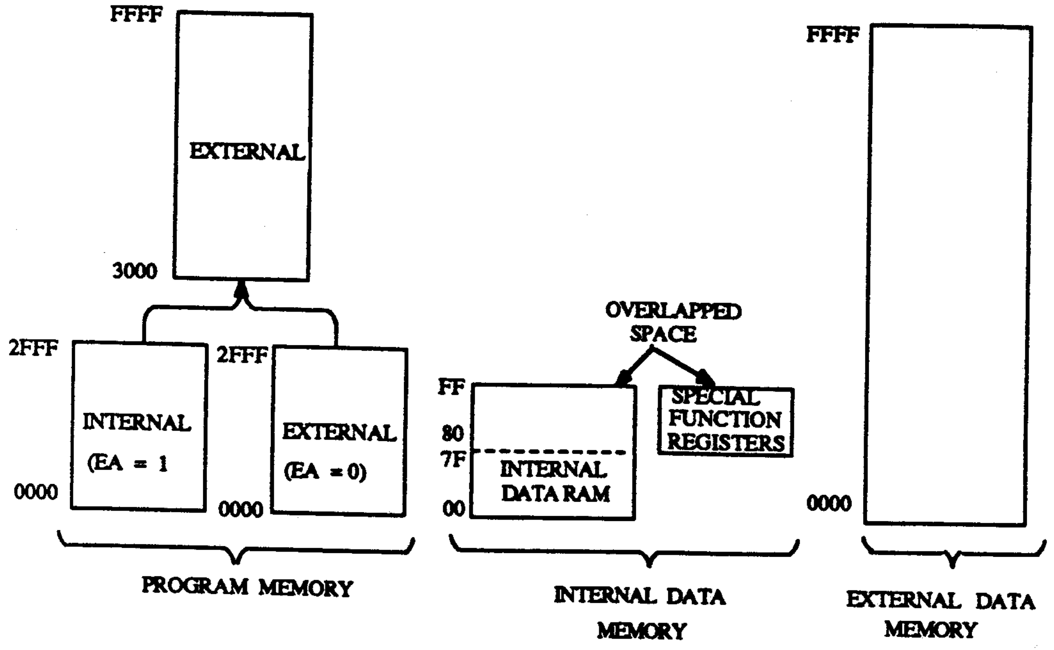

Figure A.3: Memory Map

Figure A.3 shows the MCS-51 memory maps. Figure A.4 shows a mapping of Internal Data Memory. Four 8-Register Banks occupy locations 0 through 31 in the lower RAM area. Only one of these banks may be enabled at a time (through a two-bit field in the PSW (Program Status Word)). The next sixteen bytes, location 32 through 47 contain 128 bit addressable locations. Figure A.5 shows the RAM bit addresses. The SFR area also has bit addressable locations.

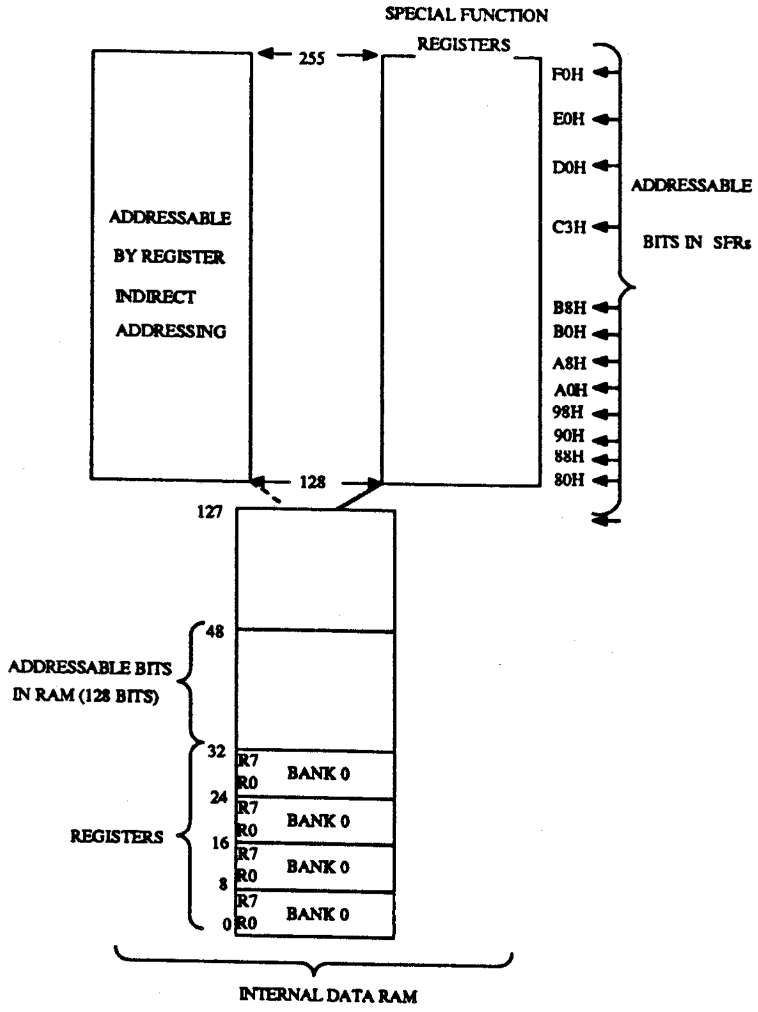

Figure A.4: MCS-52 Internal Data Memory Map

A.3. Addressing Modes

The 8052 uses five addressing mode:

- Register
- Direct
- Register Indirect
- Immediate; and

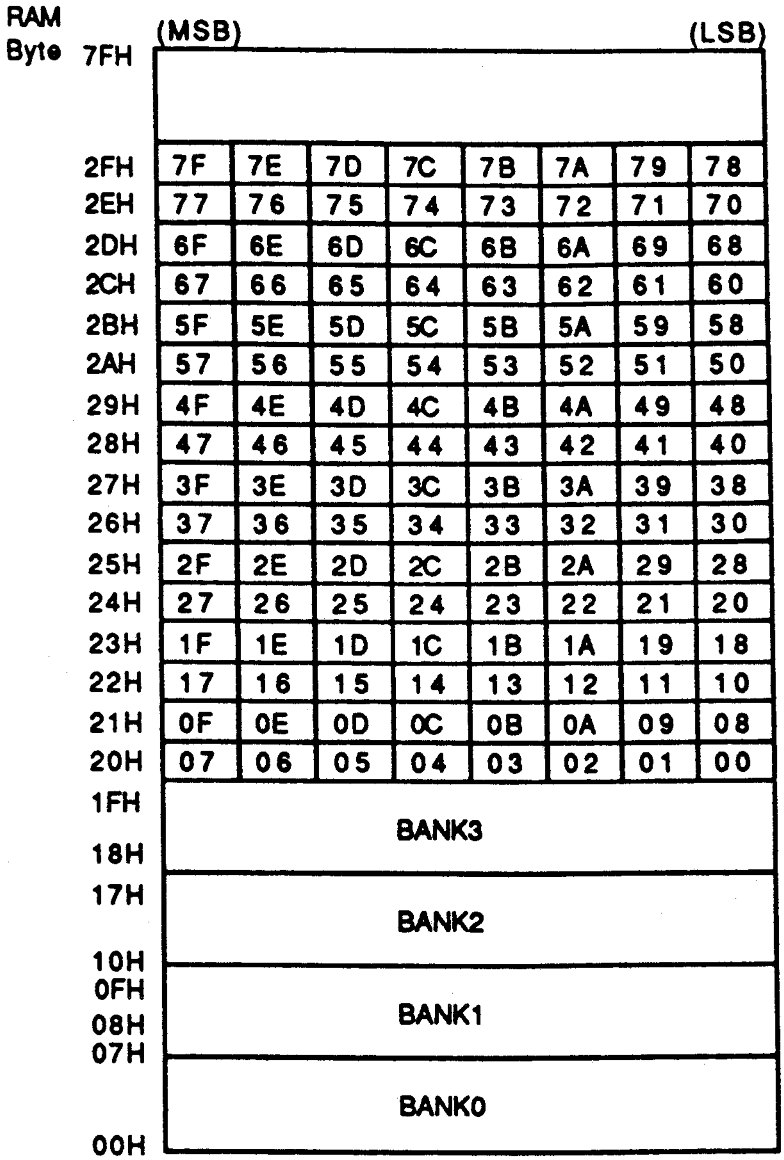

Figure A.5: Special Function Bit Addressable Locations

- Base-Register plus Index-Register Indirect.

Table A.2 summarizes which memory spaces may be accessed by each of the addressing modes.

Table A.2: Addressing Method and Associated Memory Spaces

Register Addressing	- R0-R7 - ACC, B, CY(bit), DPTR
Direct Addressing	- Lower 128 Bytes of internal RAM - Special Function Registers
Register Indirect Addressing	- Internal RAM (@R1, @R0, SP) - External Data Memory (@R1, R0, @DPTR)
Immediate Addressing	- Program Memory
Base-Register plus Index-Register Indirect Addressing	- Program Memory - (@DPTR+A,@PC+A)

A.3.1. Register Addressing

Register Addressing accesses the eight working registers (R0-R7) of the selected Register Bank. The least significant three bits of the instruction op code indicate which register is to be used. ACC, B, DPTR and CY, and the Boolean Processor accumulator, can also be addressed as registers.

A.3.2. Direct Addressing

Direct Addressing is the only method of accessing the Special Function Registers (SFR). The lower 128 bytes of Internal RAM are also directly addressable.

A.3.3. Register-Indirect Addressing

Register-Indirect Addressing uses the contents of either R0 or R1 (in the selected Register Bank) as a pointer to locations in a 256-byte block: the lower 128 bytes of internal RAM; the upper 128 bytes of internal RAM; or the lower 256 bytes of external Data Memory. Note that the Special Function Registers are not accessible by this method. Access to the full 64K external Data Memory address space is accomplished by using the 16-bit Data Pointer. Execution of PUSH and POP instructions also use Register-Indirect addressing. Stack Pointer may reside anywhere in Internal RAM.

A.3.4. Immediate Addressing

Immediate Addressing allows constants to part of the op code instruction in Program Memory.

A.3.5. Base-Register Plus Index Register-Indirect Addressing

Base-Register plus Index Register-Indirect Addressing allows a byte to be accessed from Program Memory via an indirect move from the location whose address is the sum of a base register (DPTR or PC) and index register, ACC. This mode facilitates look-up-table access.

A.4. Boolean Processor

The Boolean Processor is an integrated bit processor within the 8052. It has its own instruction set, accumulator (the carry flag), and bit addressable RAM and I/O. The bit-manipulation instructions allow a bit to be set, jump-if-set-then-cleared and moved to/from the carry. Addressable bits, or their complements, may be logically ANDed or ORed with the contents of the carry flag. The result is returned to the carry register.

B. BCC-52 Microcontroller Board [24]

B.1. Introduction

The BCC-52 computer/controller board is based on the 8052AH-BASIC chip which is a preprogrammed version of the Intel 8052AH microcontroller. Details about the 8052AH chip are given in Appendix A. The 8052AH-BASIC has a 16-bit address and 8-bit data bus. When the chip is powered up, it sizes consecutive external memory from 0000H to the end of memory (or memory failure) by alternatively writing 55H and 00H to each location. A minimum of 1K bytes of RAM is required for BCC-52 to function and the RAM locations must begin at 0000H.

BCC-52 reserves the first 512 bytes of External Data Memory to implement two "software" stacks. These are the control stack and the arithmetic stack or Argument Stack.

B.2. Address Decoding

The 8052AH uses most of the first 32K (00H-7FFFH) as split memory. Data (RAM) is enable by the 8052AH RD line and Program memory (EPROM) is enabled by 8052AH PSEN Line. The three most significant lines (A13-A15) are connected to a 74LS138 decoder chip which separates the addressable range into eight 8K memory segments, each with its own chip select. A second 74LS138 decoder partitions either C800H to CFFFH or E800H to EFFFH as eight 256 byte I/O blocks. This is done to allow multiple peripherals to share the same 256 bytes of address space.

B.3. Parallel I/O

The BCC-52 contains an 8255 PIA (Programmable Interface Adapter) which provides three 8-bit input/output software configurable parallel ports. The three I/O ports, referred to as Port A, Port B and Port C, and a write only mode configuration port occupy 4 consecutive addresses in one of the 8 jumper selectable I/O blocks. The three parallel ports are connected to a 26 pin flat ribbon cable connector. The outputs are TTL compatible.

B.3.1. Serial I/O

There are two serial ports on the BCC-52 board. One is for the console I/O terminal and the other is an auxiliary serial output frequently referred to as the line printer port. When using an 11.0592 MHz crystal, the console port does auto baud rate determination on power up (a preset baud rate can alternatively be stored in EPROM as well). It will function at 19200 bps with no degradation in operation.

The main purpose of the software line printer port is to let the user make a "hard copy" of program listing, and/or data. The BASIC command LIST# and the statement PRINT# direct outputs to the software line printer port. The maximum baud rate for this port is 4800 bps.

MC1488 and 1489 level shifters on the BCC-52 board convert the TTL logic levels from the console and line printer ports to RS-232C. The BCC-52 requires only about 200 milliamps at +5V to function. +/- 12v is required for external RS-232 communication and +21v for the EPROM programming.

B.3.2. EPROM Programmer

One of the more unique and powerful features of the BCC-52 is that it has the ability to execute and save programs in an EPROM. The 8052AH chip actually generates all of the timing signals needed to program 2764/27128 EPROMs. Saving programs in EPROMs is a much more attractive and reliable alternative to cassette tape, especially in control and/or noisy environments.

BCC-52 does not save a single program on an EPROM (unless the size of the program and the EPROM are the same). In fact, it can save as many programs as the size of the EPROM memory permits. The programs are stored sequentially in the EPROM and any program can be retrieved and executed.

The PROG Command is used to program the resident EPROM with the current selected program (this is the only time that the +21v programming voltage needs to be applied). The current selected program may reside in either RAM or EPROM. Normally, after power is applied to the BCC-52 device, the user must type a "space" character to initialize the 8052AH's console port. As a convenience, BCC-52 contains a PROG1 Command which programs the resident EPROM with the baud rate information. Whenever the BCC-52 is "powered up", i.e. reset, the chip will read this information and initialize the serial port with the stored baud rate. A "sign-on" message will be sent to the console immediately after the BASIC device completes its reset sequence. One more useful utility of the EPROM Programmer is its PROG2 Command. The PROG2 Command does everything the PROG1 does, but instead of "signing-on" and entering the command mode, the BCC-52 immediately begins executing the first program stored in the resident EPROM. This is ideal for control applications. It allows a program to run from a reset condition and never requires connection of the BCC-52 board to a console.